Experimental Demonstration of Electromagnetic Induced Transparency and Dispersion Effects in Cs Atom Vapour *

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The effects of the electromagnetically induced transparency and dispersion of a Λ-type three-level atomic system are experimentally measured with a vapour cell of Cs atoms. The steep dispersion at low absorption is observed. Thus a small group velocity for the probe beam is inferred from the measured dispersion curve.

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Recently, the storage of light in atomic media has attracted much interest for its potential applications in quantum information processing.[1] The physical mechanism is the atomic coherence[2] between atomic states established in three-level Lambda-type or ladder-type systems by coupling a strong light field to the transition between the upper state and one of the lower states while the probe light field is tuned to the transitions between two lower states. In a coherence electromagnetically induced transparency (EIT) medium, a weak probe field at the resonant frequency can propagate with less dissipation and a substantially reduced group velocity.[3] Since the light group velocity is very slow in the EIT medium, it can be trapped and stored in the atomic coherence and later be converted back into the light. In addition to the interest in quantum information science, the effects of EIT have been extensively applied in nonlinear optics,[4,5] highly sensitive magnetometers[6] and in reducing the line width of a cavity.[7]

Compared to normal optical materials, the EIT media have some advantages. When the refractive index is increased and the light velocity is reduced, the medium still keeps the optical transparency. The EIT effect with continuous wave (cw) has been carried out in different atomic systems.[8–10] Apart from the absorption reduction, the group velocity reduction due to the rapid variation of the refractive index at the resonant transition via EIT was predicted,[11] and a number of experiments have also been reported for accomplishing the light speed reduction via the EIT effect. Early direct measurements of light pulse transmission in a coherently prepared Rb media have shown a pulse velocity as slow as $c/165$,[12] and the measurements of steep dispersion of cw light transmission in Rb and Cs atomic vapours indicated the group velocity reduction of $c/13.2$ and $c/3000$.[13,14] An extremely slow light group velocity of 17 m/s was demonstrated in an ultracold atomic sample.[13] Recent theoretical analyses and experiments show that very slow group velocity of light with the same order obtained in the ultracold atoms can be observed using heated and room temperature vapour cells with buffer gas or with anti-relaxation wall coating at a proper atomic density and optical intensity.[16–18] Most of the experimental works on EIT have been performed with Rb atoms. Although for a long time similar effects have been expected in Cs vapour, experiments on it have been rare, since the Doppler broadening is over 30 times larger than the natural linewidth, which is comparable to the spacing of different fine structure in the D_2 line. For a Λ-type system within the cesium D_2 line, the large spacing of two lower hyperfine states (9.2 GHz) gives the large residual Doppler width of the two-photon transition, which is disadvantageous for the EIT effect. The above-mentioned characteristics increased the experimental difficulty in Cs vapour with respect to that in Rb atoms. In this letter, we present the results of our studies on the electromagnetically induced transparency in the cesium vapour cell. The simultaneous measurement of absorption and dispersion properties of the EIT medium show that the group velocity of the probe light is reduced to $c/418$ and at the same time the transmission is increased 60% (c is the velocity of light in vacuum).

The atomic level used in this experiment is the Λ-type level configuration within the D_2 lines of cesium atoms (^{133}Cs)(Fig. 1). A strong laser light, called the coupling laser, is locked to the transition between $6S_{1/2}$, $F = 4$ and $6P_{3/2}$, $F' = 4$, while a weak probe laser is scanned across the transitions, $F = 3$ $(6S_{1/2}) \rightarrow F' = 4(6P_{3/2})$. It has been demonstrated that when the medium interacts simultaneously with both coupling and probe laser tuned at its resonance

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A new semiclassical model to analyze sub-Poissonian light in high-impedance-driven semiconductor light emitters

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Abstract

We propose a new and simple semiclassical model to analyze sub-Poissonian light in high-impedance, constant-current-driven semiconductor light emitters, and obtain some new and interesting results. Our study shows that the model gives a simple and distinct physical picture to explain the suppression mechanism of intensity noise in high-impedance-driven semiconductor light emitters. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Sub-Poissonian light (i.e., amplitude-squeezed light) are of great fundamental and practical interest, which can be widely applied in precision measurements [1], optical communication [2], quantum optical tap (or repeater) [3,4] and generation of non-classical array light [5–7], laser Doppler anemometry [8], and so on.

There are four main methods to generate sub-Poissonian light [9], but high-impedance, constant-current (HICC) driven semiconductor light emitters, including light-emitting diodes (LED) and laser diodes (LD), is the simplest and most successful one, which was first proposed and demonstrated by Yamamoto's group [10,11], and has been widely studied, both theoretically [10,12–17] and experimentally [11,18–22]. Nearly all of experimental results [11,18–22] can be explained well by the corresponding quantum theory [10,12–14], or semiclassical theory [15,16], even classical theory [17]. However, the treatments for quantum-noise squeeze and correlation mechanisms in quantum theory are rather complicated and overelaborate (tedious), whereas the physical picture for the description of quantum-noise correlation and suppression in semiclassical or classical theory are not too clear and not audio-visual, and no any theory to date has given a simple and analytical expression to directly describe the relationship between the Fano factor F, or the squeezing S of amplitude noise and the series-coupled source resistance R (i.e., self-

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Enhanced Kerr Nonlinearity via Atomic Coherence in a Three-Level Atomic System

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We measure the Kerr-nonlinear index of refraction of a three-level Λ-type atomic system inside an optical ring cavity. The Kerr nonlinearity is modified and greatly enhanced near atomic resonant conditions for both probe and coupling beams. The Kerr nonlinear coefficient n_2 changes sign when the coupling beam frequency detuning switches sign, which can lead to interesting applications in optical devices such as all-optical switches.

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One of the intriguing aspects of atomic coherence in multilevel atomic systems is its ability to enhance the efficiencies of nonlinear optical processes. The atomic coherence induced by coupling and probe laser beams can reduce the resonant absorption of the probe beam through electromagnetically induced transparency (EIT) [1–3] and enhance the resonant nonlinear interaction strength in multilevel atomic systems. Furthermore, the steep dispersion slope [4] in such EIT systems can significantly reduce the group velocity of probe pulses [4,5] and, therefore, greatly increase the effective interaction length of a probe pulse with the atomic medium, which makes it possible to perform nonlinear optical processes with very low light intensities [6–8]. In the past few years, several experimental demonstrations of enhancing nonlinear optical processes (such as optical harmonic generation [9], frequency conversion [10], and near-degenerate four-wave mixing [11,12]) were reported in multilevel atomic systems. Also, EIT-induced beam focusing [13] and elimination of optical self-focusing by atomic coherence [14] were observed in three-level atomic systems. Although these enhanced nonlinear processes can be experimentally demonstrated by observing the generated nonlinear optical signals, it is still a difficult task to directly measure the nonlinear coefficients associated with these nonlinear processes because of the existence of the linear absorption and dispersion effects. A large Kerr-nonlinear index of refraction is particularly interesting in multilevel atomic systems, since it can be used for many interesting applications, such as cross-phase modulation for optical shutters, self-phase modulation for generating optical solitons, four-wave mixing processes for frequency conversion, and entangled states for quantum information processing [6–8]. Direct measurement of the Kerr-nonlinear coefficient will greatly help us to understand and to optimize the nonlinear optical processes in these multilevel atomic systems, to make direct comparison with theoretical predictions, and to find more practical applications of this Kerr-like nonlinearity.

In this Letter, we report an experimental demonstration of how this Kerr-nonlinear coefficient n_2 in a three-level atomic system can be directly measured by using an optical ring cavity through enhanced nonlinear phase shift and suppressed linear effects. We consider a typical three-level Λ-type ^{87}Rb atomic system, as used in Ref. [15], with $F = 1$ (state $|1\rangle$) and $F = 2$ (state $|3\rangle$) states of $5S_{1/2}$ as the two lower states and $F' = 2$ (state $|2\rangle$) of $5P_{1/2}$ as the upper state. The coupling laser beam (with frequency ω_c and Rabi frequency Ω_c) couples states $|3\rangle$ and $|2\rangle$ while the probe laser beam (with frequency ω_p and Rabi frequency Ω_p) interacts with states $|1\rangle$ and $|2\rangle$. The coupling frequency detuning is defined as $\Delta_c = \omega_c - \omega_{23}$ and the probe frequency detuning as $\Delta_p = \omega_p - \omega_{12}$. With a relatively strong coupling beam, e.g., $\Omega_c \gg \Omega_p$, most atoms will be optically pumped into the ground level $|1\rangle$. To calculate the nonlinear susceptibility for the probe beam, we keep the probe intensity to higher (third) order and derive the following expression for the susceptibility between states $|1\rangle$ and $|2\rangle$ as

$$\chi \approx \frac{iN|\mu_{21}|^2}{\hbar}\frac{1}{F}\left[1 - \frac{2\gamma_{31}}{2\gamma + \gamma_{21}} - \frac{|\Omega_p|^2}{(2\gamma + \gamma_{21})}\frac{F + F^*}{|F|^2}\right], \quad (1)$$

with $F \equiv \gamma - i\Delta_p + (|\Omega_c|^2/4)/[\gamma_{31} - i(\Delta_p - \Delta_c)]$. $\gamma \equiv (\gamma_{21} + \gamma_{23} + \gamma_{31})/2$; γ_{21} and γ_{23} are the spontaneous decay rates of the excited state $|2\rangle$ to the ground states $|1\rangle$ and $|3\rangle$, respectively; γ_{31} is the nonradiative decay rate between two ground states. N is the atomic density in the cell and μ_{21} is the dipole matrix element between states $|1\rangle$ and $|2\rangle$. The first term in Eq. (1) is the linear susceptibility as given in Ref. [3], the second term is the contribution to linear susceptibility from the higher-order density matrix element, and the third term is the third-order (or Kerr-like) nonlinearity due to the finite probe intensity as defined by $\chi \approx \chi^{(1)} + 3\chi^{(3)}|E_p|^2$ and is modified by atomic coherence. $E_p = -\Omega_p\hbar/\mu_{21}$ is the probe field amplitude. The Kerr nonlinear index of refraction n_2 is defined by

$$n_2 = \frac{12\pi^2}{n_0^2 c}\mathrm{Re}\chi^{(3)} = \mathrm{Re}\left[-\frac{i4\pi^2 N|\mu_{21}|^4}{cn_0^2\hbar^3}\frac{1}{(2\gamma + \gamma_{21})}\frac{F + F^*}{F \cdot |F|^2}\right], \quad (2)$$

where n_0 is the linear index of refraction. For atoms in a vapor cell, one can take into account the higher-order

Three-level atoms inside a degenerate optical parametric oscillator: Steady-state behaviors

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We study a composite system consisting of N three-level Λ-type atoms and a degenerate optical parametric oscillator (DOPO). The standard DOPO threshold is modified by the presence of the three-level atoms. Bistability (in the intracavity field intensity versus pumping intensity for the DOPO) appears for certain atomic detunings and coupling field strengths between the intracavity field and one of the atomic transitions. The effects of the coupling field (for the auxiliary transition in the three-level atomic system) are discussed. The susceptibility of the three-level atoms is calculated for the lower and upper branches of the bistable curve. Both analytical (for certain special cases) and numerical (for more general cases) results are presented.

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I. INTRODUCTION

In the past few years, atomic coherence effects in multilevel atomic systems, such as electromagnetically induced transparency (EIT) [1,2] and gain without inversion (GWI) [3–6], have attracted great attention. Absorption and dispersion properties of near ideal three-level atomic systems in different configurations (Λ-type, *ladder*-type, and V-type) interacting with continuous wave (CW) diode lasers were studied both theoretically and experimentally [2,7,8]. Due to the atomic coherence effect, the absorption and dispersion properties of the weak probe field coupling to one of the atomic transitions can be controlled by the coupling field interacting with the other atomic transition. When the three-level atoms are placed inside an optical cavity, many interesting effects, such as optical bistability, frequency pulling, and cavity linewidth narrowing, can exist in the steady state and be controlled by the coupling field [9–11]. It has also been predicted that quantum noise in one quadrature of the output field may be suppressed in the system with three-level atoms inside an optical cavity [12].

A composite system consisting of a degenerate optical parametric oscillator (DOPO) [13] with N two-level atoms has been studied previously [14]. Optical bistability with interesting features at steady states is predicted and studied in detail. Due to the special properties of this composite system, i.e., the mean intensity of the lower branch of the bistability curve is always zero, one can analytically calculate the spectra of squeezing and the amount of intracavity squeezing [15,16]. It is predicted that the DOPO intracavity squeezing can be enhanced by the presence of the two-level atoms.

In this paper, we will study the composite system consisting of the DOPO and N Λ-type three-level atoms. Due to the EIT effect, when the intracavity field (or subharmonic field of the DOPO) is on resonance with the probe transition of the three-level atoms (which is coupled by a strong resonant coupling field at another transition), the atom will not interact with the cavity field. The maximum interaction occurs when the frequency of the cavity field is tuned to the dressed transition states due to the coupling field [17]. Steady-state behaviors, such as bistability of the intracavity field versus external pumping field for the DOPO and bistability of intracavity field versus the strong atomic coupling field, are studied. Due to the modified absorption and dispersion properties in the three-level atomic system, we explore the absorption and dispersion properties along the upper branch and lower branch of the bistable curve, respectively. Other than characterizing the bistable behaviors and conditions to realize such behaviors, we pay special attention to the controlling of such bistable behavior with the coupling field. The optical parametric process in this composite system makes different, interesting effects, such as zero mean-field intensity at the lower branch of the bistable curve and modification of threshold behaviors, which do not exist in previously studied systems with three-level atoms inside an optical cavity [9–12].

The paper is organized in the following way. Section II establishes the model and presents the basic equations for this composite system. Section III gives the analytical (for the case of a special detuning) and numerical (in general) calculations for the bistability as functions of various parameters. At the end of this section, we briefly look at the absorption and dispersion properties of the bistable curve. Section IV serves as a conclusion.

II. HAMILTONIAN AND EQUATIONS OF MOTION

We consider a composite system consisting of a set of N three-level atoms and a nonlinear crystal inside an optical cavity. The atoms have two lower states $|1\rangle$ and $|3\rangle$, and an excited state $|2\rangle$ (such a three-level atomic system is usually referred to as a Λ-type system), as illustrated in Fig. 1. With small modifications, the following treatment can easily apply

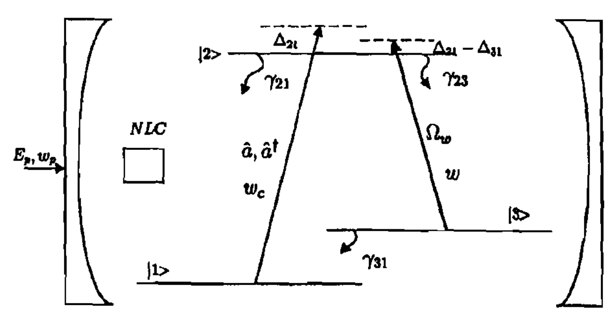

FIG. 1. Energy schematic for a three-level system inside an optical cavity with a nonlinear crystal. $|2\rangle \to |1\rangle$ is the lasing frequency.

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Inhomogeneous broadening-dependent spectral features in a four-level atomic system

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New spectral features in an inhomogeneously broadened N-type four-level atomic system are analyzed and discussed. The atomic-level scheme uses an incoherent pumping rate in place of the incoherent recycling pump. We show that the gain profile includes an extra dip that appears only in the Doppler-broadened case. The dependence of this feature on various parameters, as well as consequences for the dispersion, are explored theoretically. For certain combinations of temperature and incoherent pump rate, this gain is shown to be independent of temperature fluctuations. [S0740-3224(00)01602-7]

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1. INTRODUCTION

Quite a lot of work has been done in the past ten years or so related to atomic coherences. Two phenomena in particular have received a substantial amount of attention. Electromagnetically induced transparency (EIT) has been observed in a number of atomic systems, including strontium[1] and rubidium.[2,3] Each of the cited papers includes the effects of Doppler broadening, which play an important role in our results. The other coherence effect that has been intensively studied recently is gain without inversion (GWI) and its companion, lasing without inversion.[4–6] Experiments in lasing without inversion have been conducted in the Doppler-broadened[7] and nonbroadened[8] regimes, in both sodium[7,8] and rubidium.[9] In addition to gain considerations, the dispersion properties of a medium exhibiting GWI have also been studied.[10] There are, in addition, several review papers[11,12] available that cover much of the early work in this field.

Several groups have undertaken the task of constructing theoretical results that specifically model the effects of Doppler broadening on gain both in two-level systems with atomic recoil[13] and in four-level GWI[14–16] arrangements. We have also chosen to study the coherence effects of a four-level system; however, our theory differs from previous ones in several respects, particularly the specific level scheme and the incoherent pumping mechanism. For our system we have found the existence of novel spectral features, such as the appearance of an extra dip in the gain peak, which is caused by a coupling-field-induced saturation phenomenon that is effectively the same as spectral hole burning. The system also exhibits an independence of gain on the density of the medium for certain combinations of parameters. In this paper we theoretically investigate these phenomena by a semiclassical model using the density-matrix equations, eventually deriving expressions for the absorption coefficient and dispersion. These are then solved numerically to generate our results.

Although the gain processes discussed in this paper are not exclusively limited to inversionless systems, we have chosen to introduce them in this manner because of the contemporary relevance of steady-state GWI. When we present the results of our analysis later in the paper, our examples will primarily occur in the case of positive inversion. The reason we chose this region is because the gain is larger in this area and is therefore easier to compare visually in our plots. The same spectral features, however, also appear in the GWI region.

In Section 2 we discuss the atomic structure of our system, the effective pump model, the lasers, and the mathematical formulation of our theory. In Section 3 we present our numerical results for gain and dispersion for a variety of parameter dependencies, and Section 4 gives conclusions and a discussion of the physical nature and implications of our results.

2. PHYSICAL AND MATHEMATICAL MODELS

In this paper we analyze an N-type four-level system with inhomogeneous broadening that has some interesting spectral features that are not present, to our knowledge, in other systems. This model is also attractive owing to its experimental accessibility and its relation to certain recent publications on EIT[2,3] and lasing-without-inversion[9,16] systems. Inspection of Fig. 1(a) reveals that it is identical to the familiar EIT Λ system,[2] except for the presence of the extra level $|4\rangle$. We drive the $|3\rangle$–$|2\rangle$ transition (frequency ω_{23}) with a strong coupling field of Rabi frequency $\Omega_c = -\mu_{23}E_c/\hbar$ and frequency ω_c. Similarly, the $|1\rangle$–$|2\rangle$ transition (frequency ω_{21}) is coupled by a weak probe ("weak" will be qualified in the theory section) of Rabi frequency $\Omega_p = -\mu_{21}E_p/\hbar$ and frequency ω_p. E_p and E_c are the field amplitudes of the probe and coupling fields, respectively, and μ_{23} and μ_{21} are the dipole moments of the two transitions. Furthermore, we allow for detuning of the lasers from atomic resonance with the parameters $\Delta_c = -\omega_c + \omega_{23}$ and $\Delta_p = \omega_p - \omega_{21}$. The spontaneous decay rate from level $|i\rangle$ to level $|j\rangle$ is given

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A degenerate optical parametric oscillator coupled with N two-level atoms: effects of detuning in the optical spectra

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Abstract. We study the effects of atomic detuning in a composite system consisting of a degenerate optical parametric oscillator and a set of N homogeneously broadened two-level atoms. The stability regions and the optical spectra of this composite system are investigated as a function of atomic detuning and other parameters. Near the lower turning point of the bistable curve, the unsqueezed field quadrature couples into the squeezed field quadrature through the atomic detuning.

Keywords: Light–atom interaction, squeezed states, nonlinear optics

(Some figures in this article are in colour only in the electronic version; see www.iop.org)

1. Introduction

Squeezed states in a degenerate optical parametric oscillator (DOPO) and an absorptive optical bistability (AOB) system have been studied extensively both theoretically and experimentally [1–3]. A composite system combining these two systems (i.e., N two-level atoms inside a DOPO cavity) has also been studied theoretically [4–6]. Steady-state behaviours (i.e., optical bistability) [4], optical spectra [5] and total intracavity squeezing [6] were calculated under the condition of resonance between the atomic transition frequency and the frequency of the sub-harmonic intracavity field. Optical bistability exists in both good- and bad-cavity limits of this composite system. An interesting feature in the bistability of this composite system is that the lower branch of the bistable curve always has a zero steady-state intensity, as in the case of a DOPO below threshold. This property allows us to use the Schwinger representation [5, 7] for the fields and atomic variables in the entire lower branch of the bistable curve and to write down a set of coupled linear operator equations for the field operators and atomic polarization operators. By transforming both the field and atomic operators into selected quadratures, we found that, at atomic resonance, these operator equations separate into two independent pairs of equations. The squeezed field quadrature of the DOPO couples to only one atomic quadrature, and the unsqueezed quadrature of the DOPO couples to the other atomic quadrature. This decoupling between the squeezed field quadrature and unsqueezed field quadrature gives us a clear picture of the underlying physics of how the squeezed and unsqueezed field quadratures of the DOPO affect the atomic dynamics. Also, the decoupling of equations at atomic resonance allows us to obtain simple analytical expressions for the optical spectra with arbitrary cavity linewidth and coupling strength between the atoms and the cavity field.

In this paper, we consider the influences of the atomic detuning on the steady-state behaviours, the stability boundaries and the optical spectra of this composite system. Due to the coupling between the squeezed and unsqueezed quadratures of the field for finite detuning, the squeezed spectra are altered by the unsqueezed field quadrature. This influence is only evident near the lower turning point of the bistable curve, where the field intensity of the unsqueezed quadrature becomes very large. At the good-cavity limit (i.e., the atomic decay rate is much larger than the cavity decay rate) the system is stable all the way up to the turning point of the lower branch, and the increase in the detuning only produces changes in the structure of the spectra. However, in the bad-cavity limit, the system becomes unstable before it reaches the lower turning point. The stability boundary remains almost constant as the detuning increases, and the instability point reaches the turning point of the lower branch only for a sufficient large detuning.

The arrangement of this paper is as follows. In section 2, we give the basic equations for this composite system with atomic detuning. In section 3, we discuss the stability regions of the system in both the good- and bad-cavity limits. In section 4, we give numerical calculations of the optical spectra with atomic detuning. Section 5 serves as a conclusion.

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Wavelength locking of multiple diode lasers by multiplexed gratings in a photorefractive crystal

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We propose a technique to simultaneously stabilize relative wavelengths among multiple diode lasers by using multiplexed photorefractive gratings. Each grating is designed to be Bragg matched for the counter-propagating reflection at a specific diode laser wavelength. Experimental results from stabilization of two diode laser wavelengths by using two photorefractive gratings exhibit excellent short- and long-term wavelength stability. We show that this technique can be extended to stabilize relative wavelengths of many diode lasers. The thermal stability of the photorefractive gratings and the signal-to-noise ratio (or the bit-error rate) are discussed. © *2000 American Institute of Physics.* [S0003-6951(00)00241-2]

Wavelength-division multiplexing (WDM) is an important technique for increasing information capacity of a fiber by transmitting signals at different wavelengths. This demands separate laser sources emitting at different desired wavelengths and multiplexing devices to couple all the signals at different wavelengths into a single fiber. Then, these different wavelength channels are separated at the other end of the fiber.[1] Currently, 40 wavelength channels have been employed in real systems and channels up to 100 are in the testing stage. In order to provide ultrahigh transmission capacity with close channel space, less cross talk, and low bit-error rate, relative wavelengths at multiplexed channels require to be stabilized.[1] Finding an easy and effective way to simultaneously lock relative wavelengths of a large number of lasers is important in the WDM application. Lasers with multiple stabilized wavelengths also have applications on laser interferometry and optical metrology.[2] In this letter we propose a technique to simultaneously stabilize multiple diode laser wavelengths by using multiplexed photorefractive gratings formed in a single crystal.

Photorefractive effects in crystals have attracted considerable interest owing to the high information-storage capacity and the possibility of programmable parallel interconnection.[3] Among various recording techniques angular[4] and wavelength multiplexings[5] are two most prominent approaches to form multiple gratings in a single crystal. Ten thousand high-resolution holograms have been successfully recorded by using the angular multiplexing techniques in a 1 cm^3 bulk crystal. In order to prevent the erasure of photorefractive holograms during readout process, techniques have been developed for fixing holograms.[6–8] Thermal[6] and electrical[7] fixing techniques are commonly used methods now to fix the photorefractive gratings. Alternatively, holograms can be sustained by periodic refreshing or nonvolatile holographic memory.[8]

The wavelength of a diode laser drifts due to fluctuations in temperature or driving current. When many diode lasers are used at different wavelengths, the relative wavelengths between different diode lasers are constantly changing due to random wavelength driftings. The spectral response of a volume grating is a sinc function and the relative peak diffraction wavelengths from the fixed gratings in a crystal are immune to the fluctuations of ambient temperature, which are well-defined locking positions for different diode lasers. The wavelength of each diode laser is locked at the peak wavelength of each fixed grating through current feedback, such that the relative wavelengths of the diode lasers are determined by the relative positions of the peak diffraction wavelengths of the fixed gratings.

Figure 1 shows the principle of recording a number of gratings by angular multiplexing. In certain materials such as $LiNbO_3$, the gratings can be recorded using 488 nm illumination from an Ar-ion laser, where the photorefractive response is strong. The writing beams are incident on the *a*-face of the crystal and the angular is adjusted so that each hologram is Bragg matched for counter-propagating reflection of a specific infrared wavelength incident on the *c*-face of the crystal.[9] The infrared wavelengths from diode lasers are chosen in the optical fiber communication band, for example near 1.55 μm. $LiNbO_3$ exhibits poor photorefractive response in such spectral regimes and the gratings can be rendered unaffected by the illumination.[8] To further prevent

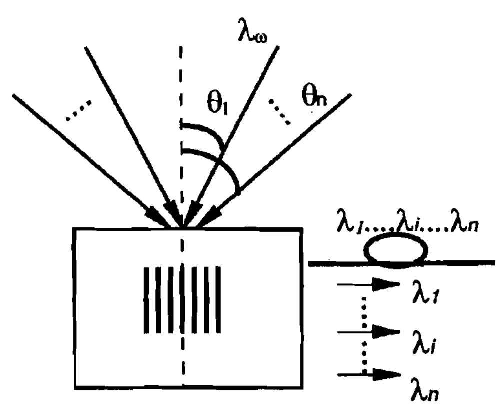

FIG. 1. Angular multiplexing gratings in photorefractive crystal with a set of writing beams. Each channel is designed for counter-propagation reflection at a desired diode laser wavelength.

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Compression and broadening of phase-conjugate pulses in photorefractive self-pumped phase conjugators

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Pulse propagation and shaping are investigated in photorefractive self-pumped phase conjugators in both transmission- and reflection-grating regimes. The dispersion properties of self-pumped phase conjugators are analyzed by taking into account both the grating dispersion and the angular dispersion. The complex transfer functions are obtained by treating the crystal as a linear dispersive medium. We show that the pulse width as a result of the self-pumped phase conjugation is much wider in the reflection regime than in the transmission regime. The experimental results are consistent with the results calculated for the transmission-grating regime, indicating that this type grating is the dominant mechanism in the case of a femtosecond self-pumped phase conjugator. [S0740-3224(00)00908-5]

OCIS codes: 190.5040, 190.5330, 190.5530, 320.5520.

1. INTRODUCTION

Pulse propagation in dispersive media, especially in optical fibers, has been extensively studied and is governed by the combined effects of group-velocity dispersion (GVD) and nonlinear effects.[1-3] In the anomalous-dispersion regime the combined effects of GVD and nonlinear effects can give rise to the generation of optical solitons in a fiber.[4] Recently, pulse propagation in periodic media with strong dispersion in and around the stop band, such as fiber gratings, has attracted considerable attention.[5-11] Winful[12] proposed the application of a fiber grating for correction of a nonlinear chirp to compress a pulse in a long-transmission fiber grating. Russell[13] pointed out that gratings exhibit strong dispersion for the frequencies close to the Bragg resonance. This dispersion is due to the strong frequency dependence of the group velocity of light propagating through a grating. Eggleton *et al.*[14,15] reported the generation of Bragg solitons in optical fiber gratings, which rely on the strong GVD provided by the Bragg grating at the bandgap edge.

Propagation of light through gratings in photosensitive materials (such as photorefractive crystals) has also attracted a lot of research.[16,17] However, the effect of dispersion on the incident pulse propagation has not been sufficiently well modeled, for example, in configurations such as the self-pumped phase conjugator. Since dispersion determines the temporal profile of the self-pumped phase-conjugate pulse, all components contributing to the magnitude of dispersion, such as grating dispersion, angular dispersion, and the intrinsic dispersion of the material, have to be taken into account.

Femtosecond self-pumped phase conjugation (SPPC) at various wavelengths has been observed in $BaTiO_3$.[18-23] But its temporal characteristics have not been investigated yet. Although Yariv *et al.*[24] proposed that the process of nonlinear optical phase conjugation could be utilized to compensate for channel dispersion, they discussed only the phase conjugation achieved by four-wave mixing in nondispersive media. In this paper we explore the effect of the dispersion in a self-pumped phase-conjugate mirror (SPPCM) on the temporal characteristics of femtosecond SPPC, taking account of the grating dispersion and the angular dispersion.

Photorefractive SPPC is generated by certain gratings formed by the pump and the fanning beams. Owing to the slow response time of a photorefractive crystal, for instance, $BaTiO_3$, the grating is formed by the accumulating effect of a number of pulses. In this paper we will therefore consider only the steady-state case and take into account the linear pulse compression and chirp compensation.

Generally, transmission gratings, reflection gratings, and $2k$ gratings may all coexist in SPPCM.[25] There are two typical configurations of SPPCM's. In the first one, a transmission grating dominates both a reflection grating and a $2k$ grating.[26] We will call it transmission-grating-based SPPCM (TG-SPPCM) [see Fig. 1(a)]. In the other configuration a reflection grating dominates a transmission grating. We will call it a reflection-grating-based SPPCM (RG-SPPCM).[27,28] $2k$-grating based SPPCM [see Fig. 1(b)] can be considered as a special case of the RG-SPPCM.[29]

In Section 2 we analyze the dispersion properties of the TG-SPPCM and the RG-SPPCM. In Section 3 we introduce the complex transfer functions for the two SPPCM configurations. In Section 4 the femtosecond SPPC's

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Pulse Evolution in a Photorefractive Self-Pumped Phase Conjugator with Transmission Grating Geometry

Changxi Yang and Min Xiao

Abstract—**The effect of grating dispersion on pulse evolution in a photorefractive self-pumped phase conjugator is analyzed. The broadening factors and the time-dependent phases of self-pumped phase-conjugate pulses of unchirped and chirped Gaussian pulses are obtained. When the grating dispersion and the angular dispersion cancel the material dispersion, the self-pumped phase-conjugate pulse has a minimum width, which is determined by the first-order dispersion of the grating. The self-pumped phase conjugation of an unchirped Gaussian pulse broadens and is linearly chirped whereas the self-pumped phase conjugation of a chirped Gaussian pulse is compressed when the dispersion-induced chirp cancels the initial chirp.**

Index Terms—**Chirped and unchirped pulse, dispersion, gratings, nonlinear optics, optical phase conjugation, optical propagation in dispersive media, optical pulse compression, optical transient propagation, photorefractive effect.**

FEMTOSECOND self-pumped phase conjugation (SPPC) has been observed in $BaTiO_3$ at 800 nm [1], [2] and 450 nm [3]. In [4], Yang analyzed the angular dispersion of a self-pumped phase conjugator and assumed that the amplitude response of the transmission grating was a constant. In fact, the diffraction of the grating is not a constant across the spectrum of the femtosecond pulse. In this paper, we explore the effect of grating diffraction on the pulse evolution in a photorefractive self-pumped phase-conjugate mirror (SPPCM). The SPPC's of unchirped and chirped Gaussian pulses are also discussed.

In a manner similar to that of [4], self-phase modulation, cross-phase modulation, and cubic and higher order dispersion are neglected. The phase conjugator can be represented by a complex transfer function in the frequency domain [5]–[8]: $H(\Omega) = R(\Omega) \exp[-i\Psi(\Omega)]$, where $R(\Omega)$ is the amplitude response and $\Psi(\Omega)$ is the phase response. $\Psi(\Omega)$ can be expanded to $\Psi(\Omega) = \sum_0^\infty b_n(\Omega-\omega_l)^n$, where $b_n = (1/n!)d^n\Psi(\Omega)/d\Omega^n|_{\omega_l}$ and ω_l is the center frequency of the pulse. $\Psi(\Omega)$ has been discussed in [4].

The generation of femtosecond SPPC is a two-wave mixing process, not a four-wave mixing process such as that for CW and long-pulse SPPC's [3]. We may consider the SPPCM as consisting of only one transmission grating, which is formed by the center frequency component of the pump beam and its fanning beam (Fig. 1). The grating period is $\Lambda = \lambda/2n \sin\theta_B$,

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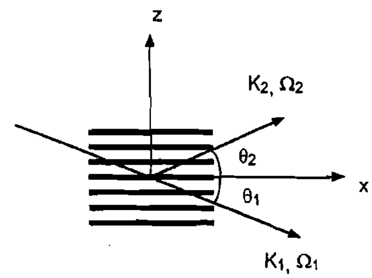

Fig. 1. Configuration of the transmission grating for Bragg diffraction. (k_1, Ω_1) indicate the pump beam. (k_2, Ω_2) indicate the diffracted beam. θ_1 and θ_2 represent the incident and diffracted angles, respectively. The grating period $\Lambda = \lambda/2n \sin\theta_B$. The grating wavevector is along the z axis.

where n is the refractive index of the crystal and θ_B is the Bragg angle. Using coupled-mode theory, the slowly varying envelope approximation, and the nondelepted-pump approximation, the diffraction of the grating can be obtained [9]

$$R(\Omega) = R_0 \exp\left[i\left(\frac{l\Delta\alpha(\Omega)}{2}\right)\right] \sin c\left(\frac{l\Delta\alpha(\Omega)}{2}\right) \quad (1)$$

where R_0 is a complex constant, l is the thickness of the grating, and the term $\Delta\alpha$ is the phase mismatch along the x axis (see Fig. 1) and is given by

$$\Delta\alpha(\Omega) = k_2(\Omega)\cos\theta_2(\Omega) - k_1\cos\theta_1 \quad (2)$$

where $k_{1,2}$ and $\theta_{1,2}$ are the propagation constants of the incident and diffracted beams and the incident and diffracted angles, respectively. We assume that the incident beam has constant values of k_1 and θ_1.

We expand $\Delta\alpha$ at the center frequency of the pulse ω_l as

$$\Delta\alpha(\Omega) = \alpha_0 + \alpha_1(\Omega-\omega_l) + \alpha_2(\Omega-\omega_l)^2 + \cdots \quad (3)$$

where the expansion coefficients are given by $\alpha_n = (1/n!)d^n\Delta\alpha(\Omega)/d\Omega^n|_{\omega_l,\theta_B}$. The phase-matching condition requires that $\alpha_0 = 0$. From (2), we obtain

$$\alpha_1 = \left(\frac{dk_2}{d\Omega}\cos\theta_2 - k_2\sin\theta_2\frac{d\theta_2}{d\Omega}\right)\bigg|_{\omega_l,\theta_B} \quad (4)$$

and

$$\alpha_2 = \frac{1}{2}\left[\frac{d^2k_2}{d\Omega^2}\cos\theta_2 - 2\sin\theta_2\frac{dk_2}{d\Omega}\frac{d\theta_2}{d\Omega} - k_2\cos\theta_2\left(\frac{d\theta_2}{d\Omega}\right)^2 - k_2\sin\theta_2\frac{d^2\theta_2}{d\Omega^2}\right]\Bigg|_{\omega_l,\theta_B} \quad (5)$$

Li, Guzun, and Xiao Reply: The conclusion (no improvement in signal-to-noise ratio in our experiment [1]) made by Ralph [2] was based on Eqs. (1) and (2) in the Comment. As indicated by the Comment, these equations were derived for a system of intracavity second harmonic generation (SHG) with a cw pumping beam, which is very different from our experimental situation. Our experiment was done in a single-pass type-I phase-matched SHG with femtosecond pulses (the frequency width of the laser pulses is much broader than the phase-matching width of the nonlinear crystal). The Comment uses a cavity with cw input and assumes that "this does not change the physics of the setup, provided we consider only frequencies well within the cavity linewidth." However, this is definitely not suitable to our experimental situation in which 100 fs pulses (frequency spectral width about 10 nm, which is much, much larger than any reasonable cavity linewidth), were used. We have checked the model used in Ref. [3] [which gives Eq. (1) and (2) of the Comment] and the existing theoretical treatments of the traveling-wave SHG. We conclude that the theoretical model used in the Comment can not be directly applied to our experimental situation. For example, the theoretical calculation on which the Comment was based cannot explain the classical SHG efficiency curve and squeezing behaviors in our experimental situation [4]. According to the model used in the Comment, a new component at a frequency of $+7.5$ MHz from the input fundamental (IR) field should appear, but we did not observe this new IR component at output in our experiment. The Comment does not give a physical mechanism that reduces the weak blue signal beam (the absorption and scattering are not considered here). Actually, in a previous paper pertaining to SHG with femtosecond pulses [5], it is clearly indicated that the reverse process is very weak comparing to the SHG process for femtosecond pulse experiment. Notice that the input blue signal is very weak (about 6.7×10^{-3} photons per pulse on average) and cannot have a high nonlinear conversion efficiency in the single-pass configuration. However, in a cw intracavity situation (which is used by the Comment as the model), the nonlinear conversion efficiency can be enhanced by the cavity even for a relatively weak beam (single-photon nonlinear processes have been theoretically and experimentally studied in intracavity situations). Thus, we believe that the weak input blue signal in our single-pass configuration is not reduced as a vacuum field component and, therefore, the objection raised in the Comment about our paper is unjustified.

We are currently working on a new quantum calculation to treat the situation as in our experiment.

Yongqing Li*

15 June 2000

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Blue light generation in single-pass frequency doubling of femtosecond pulses in $KNbO_3$

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Abstract

We study the generation of blue light in single-pass frequency doubling of femtosecond pulses in a thick $KNbO_3$ crystal. Depending on the input IR power, the maximum amount of generated blue light is a function of the position of the nonlinear crystal relative to the focusing lens. At certain focusing distance, the efficiency of blue light generation is substantially degraded. The issue of beam quality of the generated blue light is discussed. © 2000 Published by Elsevier Science B.V. All rights reserved.

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The generation of blue light has been the topic of interest to many researchers in the field of nonlinear optics from both fundamental and application points of view. With the development in blue light emitting diode lasers, the constructions of super-high density magneto-optic memories, CDROMs, and full color displays become feasible tasks. Yet, there are still many applications, where high power, short pulses, and wavelength tunability are required. The most direct and efficient way to generate a high intensity, frequency tunable blue light is through nonlinear optical processes, such as second-harmonic generation (SHG).

Over the years, the approach to the problem of nonlinear optical frequency conversion, including SHG, has expanded from considering nonlinear interactions of plane wave light fields [1] to investigating the nonlinear interactions of light pulses with the media [2]. With the decrease of pulse width, higher peak intensity of the field is achieved. Since the efficiency of SHG is dependent on the peak intensity of the pump field, then larger amount of second-harmonic field can be generated with shorter light pulses for the same average input power. Due to larger group velocity dispersion (GVD) of the shorter pulses, one would normally expect to have to decrease the thickness of the nonlinear crystal (NLC) in order to gain high conversion efficiencies. Also, the group velocity mismatch (GVM) of the pump and generated SH pulses becomes an important limiting factor when SHG is considered in a thick NLC.

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Cavity-linewidth narrowing by means of electromagnetically induced transparency

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Received July 6, 2000

Cavity-linewidth narrowing in a ring cavity that is due to the high dispersion and reduced absorption produced by electromagnetically induced transparency (EIT) in rubidium-atom vapor has been experimentally observed. The cavity linewidth with rubidium atoms under EIT conditions can be significantly narrowed. Cavity-linewidth narrowing was measured as a function of coupling beam power. © 2000 Optical Society of America

OCIS codes: 270.1670, 260.2030, 140.4480, 020.1670, 260.5740, 300.3700.

Generally, laser light passing through an atomic medium will be strongly absorbed if the laser frequency is near a transition frequency of the atoms. Recently, however, it was demonstrated[1-4] that, because of atomic coherence in multilevel atomic systems, the transparency of the medium to a probe beam near an atomic transition frequency can be controlled by a second coupling beam interacting with another atomic transition. This effect, known as electromagnetically induced transparency (EIT), has attracted great attention because of the properties of large dispersion and almost-vanishing absorption in such systems.[1-5] More recently, EIT systems were used to achieve ultraslow group velocity of light.[5-8] Whereas some theoretical calculations have been made that predicted such effects as optical bistability,[9] frequency pulling, and linewidth narrowing[10] for an EIT system inside an optical cavity, we are aware of no reported experiments to demonstrate these interesting effects. In this Letter we report the experimental observation of cavity-linewidth narrowing of an optical ring cavity with three-level Λ-type rubidium atoms inside. Typically, an absorbing medium inside an optical cavity will increase the cavity linewidth. However, because of the large dispersion change and reduced absorption in the EIT system, the cavity linewidth can be significantly narrowed.

We consider a three-level Λ-type atomic system, as shown in Fig. 1, within a heated vapor cell of length l in an optical ring cavity of length L. The susceptibility χ of the medium to a probe beam of frequency ω_p can be separated into real (χ') and imaginary (χ'') parts. The real part gives the dispersion $\partial\chi'/\partial\omega_p$, and the imaginary part gives the absorption coefficient $\alpha = (n_0\omega_p/c)\chi''$, where n_0 is the background index of refraction. Owing to the dispersion of the intracavity medium, the resonant frequency ω_r of the cavity with the Rb vapor cell is pulled according to the relation[10]

$$\omega_r = \frac{1}{1+\eta}\,\omega_e + \frac{\eta}{1+\eta}\,\omega_{21}\,, \tag{1}$$

where $\omega_e = mc/L$ (for integer m) is the resonant frequency of the empty cavity and ω_{21} corresponds to the probe transition frequency of the Rb atoms. $\eta = \omega_r(l/2L)(\partial\chi'/\partial\omega_p)$ describes dispersion changes as a function of probe frequency. By considering both the absorption and the dispersion of the medium simultaneously, one can show that the ratio of the linewidth $\Delta\omega$ of the cavity with the medium to that of the empty cavity is [10]

$$\frac{\Delta\omega}{C} = \frac{1-R\kappa}{\sqrt{\kappa}(1-R)}\,\frac{1}{1+\eta}\,, \tag{2}$$

where C is the linewidth of the empty cavity and R is the reflectivity of both the input and the output mirrors; $\kappa = \exp(-\alpha l)$ describes the absorption of the medium per pass. In a two-level system, when the cavity plus medium resonant frequency ω_r is close to the natural resonant frequency ω_{21} of the Rb atoms, dispersion $\partial\chi'/\partial\omega_p$ becomes larger, which causes narrowing of the cavity linewidth; but, at the same time, absorption χ'' also becomes larger near resonance, which cancels the narrowing effect. If, however, an EIT occurs in three-level Rb atoms, the absorption is reduced and a larger dispersion is created,[5] which results in a substantial narrowing of the cavity linewidth.

In the experiment, the Rb atoms, as shown in Fig. 1, interact with a weak (probe) laser field with Rabi frequency $\Omega_1 = -\mu_{21}E_1/\hbar$ and a strong (coupling) laser field of Rabi frequency $\Omega_2 = -\mu_{23}E_2/\hbar$, where E_1 and E_2 are the strengths of the respective fields and μ_{21} and μ_{23} are the relevant dipole moments. The complex susceptibility of the EIT system is given by[4]

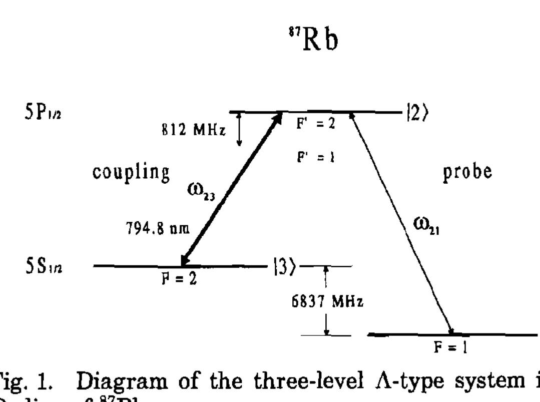

Fig. 1. Diagram of the three-level Λ-type system in the D_1 line of ^{87}Rb.

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Quantum-noise measurements in high-efficiency single-pass second-harmonic generation with femtosecond pulses

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The quantum-noise properties of single-pass second-harmonic blue-light generation with femtosecond pulses have been measured. A conversion efficiency of as much as 63.5% of second-harmonic generation at 428.8 nm was observed in a $KNbO_3$ crystal with femtosecond (130-fs) pulses with wavelengths centered at 857.6 nm. The quantum noise on the generated blue light was measured to be 1.0 dB (1.4 dB of squeezing inferred) below the shot-noise limit. The noise reduction was found to be sensitive to the average power and the center wavelength of the input fundamental pulses under the condition of strong pump depletion. © 1999 Optical Society of America

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The quantum-noise properties of high-efficiency nonlinear optical frequency-conversion processes have attracted great attention because of the potential generation of novel quantum states of light.[1,2] In particular, second-harmonic generation (SHG) was an attractive process for generating amplitude-squeezed light with a large amount of photon-number squeezing.[3–5] In those experiments a nonlinear crystal was placed inside an optical cavity (intracavity SHG) to enhance the nonlinear interaction by multiple passes through the crystal and the input fundamental field was frequency locked to the cavity such that the power of the input fundamental field was kept at a relatively low level for quantum-noise detection with photodetectors. Such systems may provide good sources of amplitude-squeezed light for applications in sub-shot-noise laser Doppler anemometry[6] and spectroscopic measurements.[7]

Recently, single-pass traveling-wave (TW) SHG was proposed[8] and experimentally demonstrated in a bulk crystal[9] and in a quasi-phase-matched nonlinear waveguide.[10] In the TW SHG experiment with a type II phase-matched KTP crystal,[9] pulses from a Nd:YAG mode-locked laser (1064 nm in wavelength and 140 ps in pulse width) were used, and 0.3-dB (6%) amplitude squeezing in SHG was observed with a conversion efficiency of 15%. In the experiment with a $LiNbO_3$ waveguide,[10] 0.8-dB amplitude squeezing in the transmitted fundamental field and 0.35-dB squeezing in the generated harmonic light were observed, with a conversion efficiency approaching 60%.

However, no amplitude squeezing has been observed to our knowledge in the conceptually simpler system of type I TW SHG in a bulk crystal. The basic obstacle is that hundreds of watts of peak power are typically required for significant harmonic conversion and for squeezing in bulk crystals. This high optical power will saturate the photodiodes that are used to detect the amplitude noise and make the squeezing difficult to measure. This difficulty can be overcome by use of high-efficiency nonlinear crystals and ultrashort pulses, which permit significant harmonic conversion with low average input power. Recently, $KNbO_3$ crystal was used in highly efficient blue-light generation.[11] In cw SHG the single-path conversion efficiency is 2% W^{-1} for a 10-mm-long crystal.[12] In a femtosecond pulsed TW SHG a slope efficiency of 300% nJ^{-1} for harmonic conversion was observed with a 3-mm long crystal.[13] Thus, single-pass SHG in $KNbO_3$ crystal with femtosecond pulses promises to be a simple system for the study of quantum noise.

In this Letter we report quantum-noise measurements in a high-efficiency single-pass SHG system with a mode-locked femtosecond (130-fs) pulse laser in a noncritical type I phase-matched $KNbO_3$ crystal. In this system the spectral profile of the input femtosecond pulses (with a typical bandwidth of 12 nm at 857.6 nm) is much broader than the phase-matching bandwidth (~0.7 nm for a crystal length of 6.7 mm) of the $KNbO_3$ crystal.[13] The conversion efficiency from fundamental pulses (centered at 857.6 nm) to blue-light pulses (at 428.8 nm) can be greater than 60%, which is in the strong depletion region for the fundamental field. The quantum noise on the blue light was observed to be 1.0 dB below the shot-noise limit in certain conditions and to be highly sensitive to the center wavelength of the input pulses.

The experimental arrangement is shown in Fig. 1. Short pulses (~130 fs wide) at an 82-MHz repetition rate emitted from a mode-locked Ti:sapphire laser are

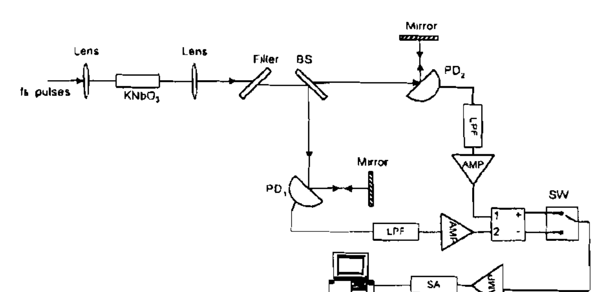

Fig. 1. Experimental arrangement: BS, beam splitter; PD1, PD2, photodiodes; LPF's, low-pass filters; AMP's, amplifiers; SW, switch; SA, spectrum analyzer.

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Possibility of an Optically-Trapped Bose-Einstein Condensation *

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We propose a novel gravito-optical atom trap composed of a blue-detuned, conical dark-hollow-beam propagating upward and the gravity field. When cold atoms are loaded into the conical dark-hollow-beam from a magnetic-optical trap and bounce inside the hollow beam, they experience an efficient hollow-beam induced Sisyphus cooling and repumping-beam induced geometric cooling. Our investigation shows that an ultracold and dense ^{87}Rb atomic sample with an equilibrium 3D temperature of about 1 μK can be obtained and the appearance of an optically-trapped Bose-Einstein condensation may be possible in this pure optical trap.

PACS: 32.80.Pj, 33.80.Ps, 39.10.+j

Since the first Bose-Einstein condensation (BEC) in a ^{87}Rb atomic gas was observed by a JILA group in 1995,[1] a series of experimental observations and investigations of BEC in various atomic gases (such as ^{7}Li, ^{23}Na, and ^{87}Rb) have been reported[2-8] and an atom laser has been demonstrated.[9] However, all of these BECs to date were observed in magnetic atom traps,[1-8] no BEC has been realized in a pure optical atom trap. Recently, a MIT group successfully transferred an Na BEC sample from a magnetic trap to a fat-off-resonance, red-detuned optical trap,[10] which shows that BEC should be achievable in a suitable optical trap. Ketterle *et al.* pointed out that magnetic atom traps impose some limitations on the studies of BEC and atom lasers, whereas optical atom traps may be more advantageous in these studies.[10] So it would be interesting and worthwhile to find a suitable optical trap and explore the possibility to directly realize an optically-trapped BEC.

A far-off-resonant, blue-detuned doughnut-beam trap for cold atoms and a gravitational laser trap (GOT) for atoms with evanescent-wave cooling were proposed and demonstrated by Kuga *et al.*[11] and Ovchinnikov *et al.*,[12,13] respectively. In both Refs. 11 and 13, a fat-off-resonant, blue-detuned cylindrical-hollow beam was used to confine the Rb and Cs atoms in the transverse direction, but no dark-hollow-beam (DHB) induced cooling was mentioned and presented. Recently, we presented a new atomic guiding scheme with DHB-induced Sisyphus cooling.[14] In this letter, we propose a novel gravito-optical atom trap using a blue-detuned, conical DHB, and study the DHB induced Sisyphus cooling and repumping-beam induced geometrical cooling in the GOT. We also estimate an equilibrium 3D temperature, trapping losses and density of the trapped ^{87}Rb atoms in the GOT and discuss the possibility to realize BEC in this optical trap.

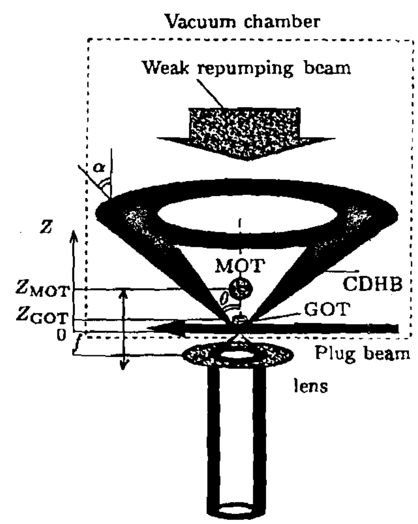

Fig. 1. Scheme of the gravito-optical atom trap with a conical dark-hollow laser beam. DHB, MOT and GOT stand for a dark hollow beam, magneto-optical trap and gravito-optical trap, respectively. Z_{GOT} and Z_{MOT} are the positions of the GOT and the MOT, respectively. The focal length of lens f can be adjusted.

The scheme of the conical dark-hollow-beam GOT is shown in Fig. 1. A blue-detuned, collimated DHB[15] propagating upwards is focused by a lens with a variable focal length f and a conical dark-hollow-beam GOT is formed above the focal point. A plug beam overlaps with the conical DHB, which can be moved up or down so that the position of GOT can be adjusted and the trapped atomic density can be changed. In order to introduce an efficient Sisyphus cooling and geometrical cooling, a weak, near-resonant repumping beam is propagated down and overlaped

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Transient spectroscopy with a current-switched semiconductor diode laser

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Abstract. We describe transient spectroscopic measurements with a current-switched semiconductor diode laser. Following a fast pulse modulation in the injection current of the diode laser, the diode laser frequency is switched by a few hundred MHz and, then, is scanned over 10 GHz range in a short-time evolution (<0.5 μs). Free-induction decay based on the frequency switching and transient absorption spectroscopy of rubidium D1 lines based on the fast frequency-scan are experimentally demonstrated. These fast spectroscopic measurements are accomplished in a single-shot pulse modulation and are, thus, applicable to short-lived samples such as in flowing or combustion systems.

Keywords: Coherent transient, current-switching, diode laser

1. Introduction

Semiconductor diode lasers have been widely used in atomic physics and laser spectroscopy [1]. Recently, the current-switching technique of a semiconductor diode laser has been used to study optical coherent transient effect [2–5]. Due to the frequency chirping effect in semiconductor diode lasers [6, 7], current switching provides a simple, cost-effective method to achieve frequency switching in the laser field. As the laser field is used to drive an absorbing system, coherent transient phenomena such as free-induction decay (FID) and optical nutation can be observed in the transmitted laser field when the laser frequency is switched out of or into resonance with an optical transition of the absorbing system. From these measurements, useful information (such as dephasing time) about optical transitions of the materials can be determined. Since low-cost semiconductor laser diodes are available in a wide range of wavelengths, this current-switching technique may have broad applications in coherent transient measurements of various materials. Using this current-switching technique, coherent transients such as FID have been demonstrated in atomic (rubidium) gas [2, 3], molecular (iodine) gas [4], and solid materials with long radiative lifetime [5]. Coherent transient effects of atoms in a magneto-optical trap were also observed by sinusoidally modulating diode laser frequency at a high speed [8].

In the experiments of observing FID [2–5], it was found that following a step-function current switching, the frequency of the diode laser is first switched from ω_0 to ω_1, as shown in figure 1, and, then, dynamically shifted by a slower frequency chirp (from ω_1 to ω_2 within the time duration of t_1-t_0). The fast response of the laser frequency was attributed to the carrier concentration change (carrier effect) and the slower response was attributed to the temperature change of the semiconductor lattice (thermal effect) [9]. For the case of a relatively short dephasing time (such as an atomic resonance with a dephasing time of nanosecond scale), a large current pulse (up to 10 mA) has to be used to obtain a large frequency switching (a few hundred MHz or more). In this case, the dynamic frequency shift following the frequency switching becomes large enough to significantly affect the observation of FID signals for a photodetector with a given response time because the heterodyne beat signal between the excited dipole of the sample and the probe laser becomes too fast in time evolution for the photodetector to respond [3].

In this paper, we show that the dynamic frequency shift of a solitary semiconductor laser following a step-function pulse modulation can be used in a new spectroscopic technique (e.g. transient absorption spectroscopy). That is, the laser frequency is rapidly scanned across an optical resonance of the sample and the dynamic absorption is recorded. When the sweeping time of the laser frequency across an optical resonance is shorter than the optical depopulation time and the dephasing time of the resonance, this transient spectroscopy is a coherent process. In our experiment, up to 12.5 GHz dynamic frequency shift was observed over a 0.5 μs time interval with a 26 mA pulse current (imposed on a dc-bias current of 145 mA). FID based on the frequency switching and transient absorption spectroscopy of rubidium D1 lines based on the fast frequency-scan are experimentally demonstrated.

Sub-Shot-Noise-Limited Optical Heterodyne Detection Using an Amplitude-Squeezed Local Oscillator

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We experimentally demonstrate a novel sub-shot-noise-limited heterodyne detection scheme to measure a weak optical signal field by employing amplitude-squeezed light as the local oscillator (LO) field. The amplitude-squeezed LO field at 428.8 nm is generated from a high efficiency single-pass second-harmonic generation in a $KNbO_3$ crystal pumped by femtosecond (130 fs) pulses at 857.6 nm, and the signal field is combined with the generated squeezed LO field through the crystal. An enhancement of 0.7 dB (1.4 dB inferred) in signal-to-noise ratio beyond the shot-noise limit is directly observed. [S0031-9007(99)09410-7]

PACS numbers: 42.50.Dv, 42.50.Lc, 42.68.Wt

Coherent heterodyne detection is now widely used to detect weak scattered or reflected radiation in many electromagnetic spectral regions including radiowave, microwave, infrared, and optical spectra. In the optical region, heterodyne detection has been used in coherent laser radar (Lidar) [1], communications, spectroscopy, and radiometry due to its advantages in high sensitivity, frequency selectivity, and strong directionality. As a detection technique, heterodyne detection can measure the amplitude and phase of an incident signal field (at frequency ν_S) with the help of a strong local oscillator (LO) field (at frequency ν_{LO}). In a typical one-port heterodyne detection scheme, the signal and LO fields are combined by an optical beam splitter combiner and received by a photodector. The information of the signal field can be extracted from the photocurrent signal at the intermediate frequency (IF) $\nu_{\mathrm{IF}} = \nu_S - \nu_{\mathrm{LO}}$. Assuming that both the signal and LO fields are in coherent states, the mean square IF signal current is $\langle i_S^2 \rangle = 2(e\eta/h\nu)^2 P_{\mathrm{LO}} P_S$, where η is the detector quantum efficiency, $h\nu$ is the photon energy, and P_{LO} and P_S are the powers of the LO and signal fields, respectively. The average photocurrent is $\langle i_{\mathrm{dc}} \rangle = e\eta P_{\mathrm{LO}}/h\nu$. As the LO power is increased, the standard shot-noise power of the LO field ($\langle i_n^2 \rangle = 2e^2\eta B P_{\mathrm{LO}}/h\nu$) associated with the average photocurrent $\langle i_{\mathrm{dc}} \rangle$ exceeds the other technical noises in the detection system (e.g., dark current of the detector and thermal noise of the electronic amplifier) and eventually becomes the dominant noise source of the detection system. The signal-to-noise ratio (SNR $= \langle i_S^2 \rangle / \langle i_n^2 \rangle$) of the shot-noise-limited heterodyne detection is given by [2]

$$\langle i_S^2 \rangle / \langle i_n^2 \rangle = \eta P_S / (h\nu B), \qquad (1)$$

which gives a minimum detectable signal power of $P_{S(\min)} = h\nu B/\eta$, where B is the receiver bandwidth. If the LO field has additional (classical) intensity fluctuations, a balanced heterodyne detection [two-port heterodyning shown in Fig. 1(a)] [3] can be used to eliminate the LO intensity noises, and the SNR in Eq. (1) can be recovered.

An amplitude-squeezed state of light is a good radiation source for using as the LO field in heterodyne detection applications since it has less quantum fluctuations in intensity than the standard shot-noise limit while still keeping high optical power. Recently, amplitude-squeezed light with a large amount of squeezing has been generated from the second-harmonic generation (SHG) process (up to 5.2 dB squeezing) [4,5], pump-noise-suppressed semiconductor lasers (up to 10 dB squeezing) [6,7], optical parametric amplifier (7.2 dB squeezing) [8], and asymmetric fiber interferometer (6.2 dB squeezing) [9]. However, one major difficulty of using squeezed LO in the standard heterodyne detection lies in the combination of the weak signal beam and the strong squeezed LO. When an optical beam splitter is used to combine these two

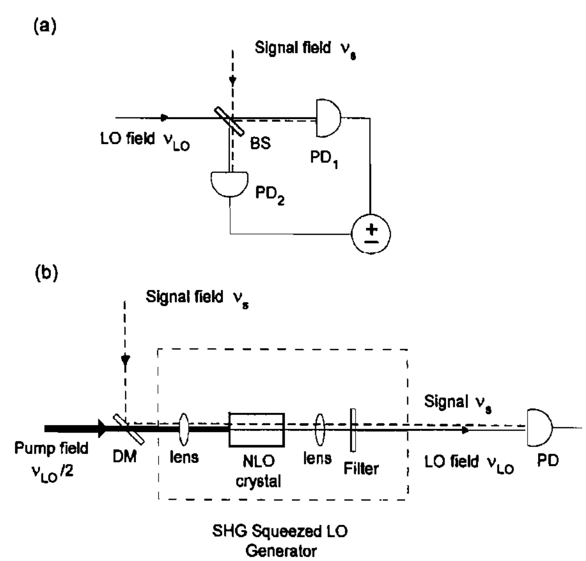

FIG. 1. (a) Balanced heterodyne detectors. BS: beam splitter; PD_1, PD_2: photodetectors. (b) Sub-shot-noise-limited heterodyne detector with an amplitude-squeezed local oscillator combining with the signal field through the NLO crystal by a dichromic mirror (DM).

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N two-level atoms in a driven optical cavity: Quantum dynamics of forward photon scattering for weak incident fields

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We investigate the photon statistics of the light transmitted from a driven optical cavity containing N two-level atoms, with emphasis on the weak driving field limit. This limit is of most interest from the point of view of quantum fluctuations. We find that various types of nonclassical behavior are possible, even with large numbers of atoms in the cavity, under conditions of strong atom-field coupling, which we refer to as the cavity quantum electrodynamics limit. We describe the system with a pure-state formalism valid for weak fields, and also use a Fokker-Planck equation obtained by a small fluctuation linearization. We examine the conditions under which the linearized theory is appropriate, and explore the sensitivity of nonclassical effects in the system to atom number, transit-time broadening, and detunings. [S1050-2947(99)04803-9]

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I. INTRODUCTION

In this paper we report on extensions of previous work on dynamical cavity quantum electrodynamics (cavity QED) effects, namely, the photon statistics of an ensemble of two-level atoms inside a driven optical cavity. The field of cavity QED can be said to have been born more than 40 years ago with the prediction by Purcell [1] that the spontaneous emission rate for an atom inside a conducting cavity can be greatly enhanced in comparison with the rate in free space if the dimensions of the cavity are of the order of the transition wavelength. The subject was only of theoretical interest until experimental techniques became available to observe such effects. In the first such measurement, Drexhage [2] observed the enhanced and inhibited decay rates of dye molecules located close to a dielectric surface. This effect can be interpreted as the reaction of the molecule to the image charges that effectively replace the reflecting surface [3]. The first experiments with atoms in a cavity were those of Vaidnaythan, Spencer, and Kleppner [4], Goy *et al.* [5], and Jhe *et al.* [6]. Several later experiments have been carried out to investigate various features of the change in spontaneous emission rates due to the presence of boundaries which alter the electromagnetic field mode density from its free space value [7,8]. Accompanying the experimental work is a large body of theoretical literature concerning the same subject [9–12]. For a more detailed history of the field, as well as current developments, we refer the reader to the reviews of Hinds [13] and Haroche [14], and the compilation edited by Berman [15].

Another approach to what is now known as cavity QED had its beginnings in the work of Jaynes and Cummings [16] on the interaction of a single two-level atom with one mode of the electromagnetic field, and extensions of that work by Tavis and Cummings to consider many atoms [17,18]. This too was originally viewed as a purely theoretical construct, with no immediate realization in the laboratory possible, particularly as dissipation is not included in the model. However, with suitable modifications to allow for atomic and cavity field damping, there has been a great deal of work done, both theoretical and experimental, to gain a deeper understanding of this fundamental, and very rich, quantum system. Experiments to observe the dynamics of this system include maser action from a collection of several atoms or even one atom interacting with a single field mode in a resonator [19–23]. Nonclassical properties of the steady state in the cavity have also been investigated [23]. In the optical domain as well as at microwave frequencies there have been experiments to look at the so-called ''vacuum-Rabi'' splitting [24–30].

Yet another class of theory and experiments relevant to our discussion is the body of literature on resonance fluorescence, where a two-level atom interacts with a classical driving field. The three peaked Mollow spectrum and nonclassical effects such as photon antibunching and sub-Poissonian photon counting statistics have been predicted [31,32] and observed [33,34]. A review is given by Cresser *et al.* [35]. Squeezing has also been predicted [36], but not yet observed.

The model we consider here assumes N two-level atoms interacting with one mode of a resonator of arbitrary Q, with a driving field present, and we take into account both atomic and cavity field losses. This model can be thought of as resonance fluorescence in a cavity, the Tavis-Cummings model with a driving field and losses added, or an extension of previous work on optical bistability. We wish to stress that damping is not to be considered as an unfortunate consequence of modeling a real system, but rather as a fundamental property of the system we consider. The presence of a driving field and dissipation results in a nontrivial steady state for the system. Of course the ultimate importance of this work is the possibility of testing the theoretical results obtained herein in the laboratory, with a real dynamical system. We also stress that we will be interested in effects that can only be explained by quantization of the electromagnetic field, i.e., nonclassical effects.

In cavity quantum electrodynamics, one is concerned with

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An alternative approach for deriving a positive P-representation

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Abstract

Using the technique of integration within an ordered product of operators and adopting similar procedures as for the theory for quantizing a gauge field, we derive the Drummond–Gardiner positive P-representation directly from the Glauber–Sudarshan P-representation. The analogy between the extra phase-space dimensions in the positive P-representation and the gauge transformation freedoms for gauge field quantization is pointed out. © 1998 Elsevier Science B.V.

1. Introduction

In quantum optics, several different approaches are commonly used to solve the problem of fluctuations in nonlinear optical processes. One standard technique is to construct phase-space Fokker–Planck equations that correspond to quantum master equations for the density operator [1,2]. The commonly used Glauber–Sudarshan P-presentation [3] is a diagonal expansion of the density operator in a coherent state basis, which is given as

$$\hat{\rho} = \int \frac{d^2\gamma}{\pi} P(\gamma)\, |\gamma\rangle\langle\gamma|, \tag{1}$$

where $|\gamma\rangle = \exp(-\frac{1}{2}|\gamma|^2 + \gamma\hat{a}^\dagger)|0\rangle$. The function $P(\gamma)$ satisfies the Fokker–Planck equation and, therefore, is considered as a quasi-probability function for classical optical processes. However, it was found that this function $P(\gamma)$ becomes negative or has a singularity stronger than the delta-function (such as first-order and higher-order derivatives of the delta-function) in optical processes that generate nonclassical photon statistics, such as squeezed states, photon anti-bunching, and sub-Poissonian photon statistics. To avoid this difficulty, Drummond and Gardiner [2,4] introduced a generalized P-representation, e.g.,

$$\hat{\rho} = \iint d^2\alpha\, d^2\beta\, \hat{\Lambda}(\alpha,\beta)\, P(\alpha,\beta), \tag{2}$$

where

$$\hat{\Lambda}(\alpha,\beta) = \frac{|\alpha\rangle\langle\beta^*|}{\langle\beta^*|\alpha\rangle} \tag{3}$$

is a non-diagonal coherent state projection operator and

$$P(\alpha,\beta) = \frac{1}{4\pi^2}\exp(-|\alpha-\beta^*|^2) \times \langle\tfrac{1}{2}(\alpha+\beta^*)|\hat{\rho}|\tfrac{1}{2}(\alpha+\beta^*)\rangle \tag{4}$$

has all the mathematical properties of a genuine probability. It proves a most useful representation, in particular, for problems where the Fokker–Planck equation in other representations may have a non-positive definite diffusion matrix.

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Electromagnetically induced grating: Homogeneously broadened medium

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A strong coupling standing wave, interacting with three-level Λ-type (or ladder-type) atoms, can diffract a weak probe field (propagating along a direction normal to the standing wave) into high-order diffractions, a phenomenon which we name electromagnetically induced grating (EIG). We develop in this work a theory for studying EIG in a homogeneously broadened medium consisting of three-level Λ-type atoms. We show that by taking advantage of the absorption and dispersion properties of electromagnetically induced transparency one can create an atomic grating that can effectively diffract light into the first-order direction. [S1050-2947(98)03902-X]

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I. INTRODUCTION

It is commonly believed that a weak probe beam will be strongly absorbed at its resonance frequency if most of the atoms are in the lower level. However, recent studies show that by coupling additional coherent fields with other atomic transitions, one can form coherent population trapping (CPT) [1,2] states that render a medium transparent to the weak probe radiation. This phenomenon is known as electromagnetically induced transparency (EIT) [3–5]. CPT and EIT are the principal mechanisms behind many recent applications, such as lasing without population inversion [6–12], enhancement of second- and third-order nonlinear processes [13–15], velocity selective laser cooling [16–18], atomic mirrors [19–20], matching pulses [21,22], electromagnetically induced focusing [23], and elimination of optical self-focusing [24]. In this paper we explore a new possibility of their application: electromagnetically induced grating (EIG).

Consider a system as shown in Fig. 1(a). It consists of two strong coupling fields of frequency ω_c and wave number k_c, a weak probe field of frequency ω_p and wave number k_p, and an atomic sample. The atomic sample hosts three-level Λ-type (or ladder-type) atoms whose energy diagram is shown in Fig. 1(b). As usual, the coupling fields drive the $2 \leftrightarrow 3$ atomic transition (which has a transition frequency Ω_{23} and a dipole moment μ_{23}), while the probe field induces the $2 \leftrightarrow 1$ atomic transition (which has a transition frequency Ω_{21} and a dipole moment μ_{21}); the $3 \leftrightarrow 1$ atomic transition is a dipole forbidden one. Here, the two coupling fields, while being symmetrically displaced with respect to z, are incident upon the atomic sample at such angles that they intersect and form a standing wave inside the medium. Because of the weak nature of the probe field, levels 2 and 3 remain virtually empty no matter what the intensities of the coupling fields are. As a result, the standing wave has an amplitude and space period that are immune to the interaction of light with the atoms. Since the absorption and dispersion coefficients of the probe field depend on the strength of the coupling fields, they are expected to change periodically as the standing wave changes from nodes to antinodes across x dimension. Such a medium will exert both amplitude and phase modulations across the probe beam profile in much the same way that a hybrid (amplitude and phase) grating does to the amplitude and phase of an electromagnetic wave. We name this phenomenon EIG.

The principal mechanism behind EIG is EIT. To illustrate this point, we compare in Fig. 2 the absorption and dispersion in the absence of the coupling field (dashed curves) with the ones in the presence of a strong resonant coupling field (solid curves). We further assume that the intensity of the coupling field (used for producing the solid curve in Fig. 2) corresponds to the peak intensity of a standing wave. Then, the dashed curves are what the probe field at nodes "sees," and the solid curves are what the probe field at antinodes "sees." The medium within the EIT window, while being quite opaque to the probe field at nodes, is almost transparent to the probe fields at antinodes as shown in Fig. 2(a). This

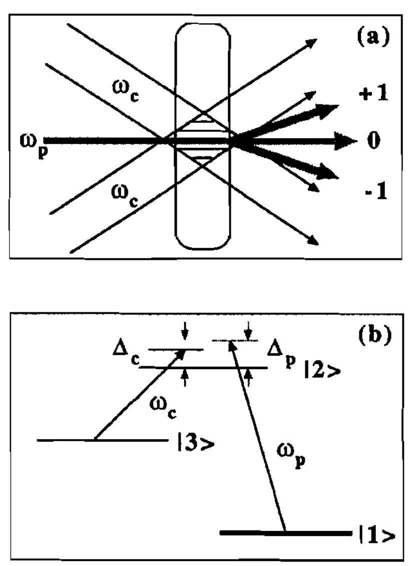

FIG. 1. (a) A sketch of a prototype experimental setup. (b) The energy diagram of three-level Λ-type atoms.

Generation and applications of amplitude-squeezed states of light from semiconductor diode lasers

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Abstract: We describe recent experiments on generation and applications of amplitude-squeezed states of light from a semiconductor diode laser. Amplitude-squeezed light with intensity noise 2 dB below the standard shot- noise limit was observed from a diode laser with a weak optical feedback from an external grating. Applications of this amplitude-squeezed light as a local oscillator in heterodyne detection in Doppler velocity measurement and weak light-scattering measurement are discussed.

OCIS code: (270.6570) Squeezed states; (140.2020) Diode lasers.

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1. Introduction

Amplitude-squeezed states (or photon-number squeezed states) of light [1,2] have less quantum fluctuations in photon numbers of the light fields than the photon number fluctuatons of coherent states with Poissonian statistics. A photon number state can be considered as an idea single-mode amplitude-squeezed state. When detected by a photo-detector, the mean square noise $<i_n^2>$ in the photocurrent is suppressed below the standard shot-noise limit ($2e^2\eta<I>B$), where $<I>$ is the mean intensity of the amplitude-squeezed light (in the unit of photons per second), η the quantum efficiency of the photo-detector, and B the bandwidth of the detector system. Unlike squeezed vacuum states [3], amplitude-squeezed states of light can have intense optical power (e.g. a few tens of milliwatts), which allows a direct replacement of coherent lasers in precision optical measurements where quantum shot-noise associated with the laser field needs to be suppressed. Amplitude-squeezed states of light have been successfully generated both from pump-noise-suppressed semiconductor lasers [1,4-8] and from second-harmonic generation (SHG) process [9-13]. Amplitude-squeezed states generated from a pump-noise-suppressed semiconductor laser (which must have a high quantum efficiency of conversion from pumping electron stream to output photon stream) have large squeezing bandwidths, intermediate optical power, and rich wavelengths. By using some line-narrowing techniques such as injection-locking to an external tunable master laser [5] or dispersive optical feedback from an external grating cavity [6,7], the multiple sub-threshold longitudinal side modes in the laser diodes can be effectively suppressed, and, therefore, collimated amplitude-squeezed laser fields with a squeezing typically up to 3-dB or more [14] were generated from the diode lasers.

The applications of squeezed vacuum states and amplitude-squeezed states have also been experimentally demonstrated to improve the sensitivity of precision optical measurements beyond the shot-noise-limit [15-19]. For example, squeezed vacuum states have been used to improve the precision of shot-noise limited measurements of weak absorption and in an interferometer [15-17]. A frequency-tunable squeezed light source has been used to demonstrate improvement in the sensitivity of saturation spectroscopy of atomic cesium and to demonstrate fundamental phenomena in the atom-photon interactions [18]. Conversion of amplitude-squeezed states to squeezed vacuum states has also been proposed [19]. Several experiments were carried out showing that amplitude-squeezed light from diode lasers can be used to improve the sensitivities of spectroscopic measurements [21-23].

In this paper, we present in details our recent experiments on the generation of amplitude-squeezed light from a semiconductor diode laser with a weak optical feedback from a highly dispersive grating in a simple configuration and, then, on applications of the amplitude-squeezed light as a local oscillator in sub-shot-noise Doppler velocity

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Nondegenerate four-wave mixing in a double-Λ system under the influence of coherent population trapping

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Nondegenerate four-wave mixing (NDFWM) in a double-Λ system of Rb atomic vapor was achieved for collinear pump fields. By comparison of different pump–probe configurations, direct experimental evidence of influence of coherent population trapping on the output power of the NDFWM signal was established. A maximal efficiency for generating the NDFWM signal exists for a moderate pump power in this double-Λ system. © 1998 Optical Society of America

OCIS codes: 190.0190, 020.0200, 270.0270.

The atomic coherence effect has been used to enhance the efficiency of nonlinear optical processes.[1–6] In particular, four-wave mixing in the double-Λ systems recently gained attention because it was found to be advantageous in using coherent population trapping to enhance the efficiency of a generated signal.[4,5] Generally speaking, linear absorption competes with the nonlinear signal generation at the exact one-photon resonance condition. However, in the double-Λ scheme (Fig. 1), one can, in principle, reduce or even eliminate the linear absorption by preparing the system in the coherent population trapping state[7] if long-lived levels 1 and 2 are used. Continuous four-wave mixing with high conversion efficiency was achieved in a double-Λ system of Na_2.[4] However, the quantum interference effect is not strong in the system used in Ref. 4, because the residual Doppler broadening (~100 MHz) in that system is much larger than the natural linewidth of atomic transitions and the pump fields do not propagate collinearly. The influence of coherent population trapping, therefore, could not be clearly demonstrated in that experiment.

In this Letter we report an experimental demonstration of nondegenerate four-wave mixing (NDFWM) in a double-Λ configuration of Rb atomic vapor. Unusual behavior of signal output power as a function of pump power was experimentally observed; i.e., a maximum in the generated signal power is reached as the pump power increases. By comparing several related systems, we have concluded that coherent population trapping is the mechanism underlying this interesting effect. Our double-Λ system involves four magnetic sublevels of ^{87}Rb (see Fig. 1). Such hyperfine-type double-Λ systems are not suitable for frequency upconversion owing to the limited separations between the hyperfine levels involved. However, the advantage of this configuration is that the residual Doppler linewidth (~0.01 MHz) is much less than the natural linewidth (~6 MHz) of the transitions. If the laser beams are copropagating in the same direction, the two-photon resonance (as well as the coherent population trapping) is, therefore, preserved for all atoms, offering an ideal case for investigation of the influence of coherent population trapping in a double-Λ system.

The experimental setup is shown in Fig. 2. Laser diode LD1 serves as the pump field, with frequency ω_1. The pump field's frequency can be scanned across the two transition lines $F = 1 \rightarrow F' = 1$ and $F' = 2$. Laser diode LD2 is tuned to the transition of $F = 2 \rightarrow F' = 1$ and is modulated by an 812-MHz rf signal. Consequently, the carrier and one sideband of LD2 are resonant with transition lines $F = 2 \rightarrow F' = 1$ and $F' = 2$, respectively, which act as pump fields with frequencies ω_2 and ω_3, as shown in Fig. 1. All three beams propagate collinearly and are focused upon a temperature-stabilized Rb vapor cell that consists of both ^{87}Rb and ^{85}Rb isotopes. Power levels of 25 and 1 mW for pump fields ω_2 and ω_1 produce pump intensities of 80 and 15 W/cm^2, respectively, inside the vapor cell. Photodiode D1 is used to monitor the transmission spectrum of pump beam ω_1 when it is scanned. A deflected beam is obtained from pump beam ω_1 by use of an acousto-optic modulator configured for upshifting and driven with a rf signal of 80 MHz. The ω_1 + 80 MHz beam is then combined with pump beam ω_1 and the generated nonlinear signal at a fast photodiode, D2 (S4752). Finally, the beat signal is monitored by a spectrum analyzer.

The NDFWM process is efficient when the conditions $\phi_4 = \phi_1 - \phi_2 + \phi_3$ and $\Delta_4 = \Delta_1 - \Delta_2 + \Delta_3$ are satisfied, where ϕ_i are the phase variations of the fields and $\Delta_i = \omega_i - \omega_{jk}$ are the detunings of field frequency ω_i from the corresponding line centers ω_{jk}. Note that the fields ω_2 and ω_3 have fixed phase and frequency differences ($\phi_3 - \phi_2$ = constant, $\Delta_3 - \Delta_2 = 0$), so the conditions for efficient NDFWM are

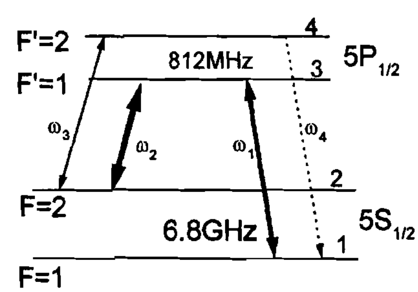

Fig. 1. Schematic of the four-level double-Λ system of the Rb atom.

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Frequency matching effect in electromagnetically induced transparency

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Abstract

The influence of the linewidth of the probe laser on the absorption reduction in a lambda-type three-level system of rubidium atoms is studied experimentally. We measure the transmission spectral profile of the probe laser and find that only the resonant frequency components of the probe field pass through the absorbing atomic medium.

1. Introduction

In recent years much interest has been focused on the effect of electromagnetically induced transparency (EIT) [1–3] because of its potential applications in lasing without inversion [4], pulse matching [5,6], modified dispersion properties [7,8], and nonlinear optics [9–11]. The continuous-wave EIT effect has been observed in ladder-type, lambda-type, and V-type three-level systems in atomic Rb vapor [2–4,8,12].

It is well known that coherent transparency in a Doppler-broadened three-level medium depends not only on the two-photon EIT position, but also on the positions of the Autler–Townes components for all velocity groups of atoms. In short, the Autler–Townes splittings induced by the pumping laser increase both the width and the amplitude of the transparency window of the probe field [13]. However, when the pumping field and the probe field have nearly the same wavelength, the two-photon resonance is almost Doppler free and occurs simultaneously for all atoms regardless of their velocities. In this case, the two-photon EIT effect dominates the transparency and ...mines the position of the transparency peak of the probe field. In this paper, we report an experimental investigation of the frequency matching effect in a lambda-type three-level EIT system of rubidium atoms using cw diode lasers. The linewidth of the probe laser is adjustable and can be broadened from less than the natural linewidth of the atomic transitions (~ 6 MHz) to be much larger than that (up to 200 MHz). By increasing the probe linewidth, the absorption reduction becomes successively smaller, which means that the EIT effect is degraded. The degradation in the absorption reduction is caused by the frequency components that are not matched with the frequency of the pumping laser and do not satisfy the EIT condition in the frequency domain. To confirm this, we measure the spectral profile of the probe laser after it has passed through a high-density (optically-thick medium) rubidium vapor cell. Our experimental results clearly show that the rubidium EIT system is transparent only for the frequency components that satisfy the two-photon resonance condition for a given linewidth of the pumping laser. In this case, the filtered probe field is locked in frequency relative to the pumping field.

2. Experimental arrangement

As shown in Fig. 1, our lambda-type three-level system consists of ^{87}Rb atoms in a Doppler-broadened vapor cell.

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Electromagnetically induced transparency with variable coupling-laser linewidth

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Resonance transmission in a three-level Λ-type system of the rubidium $D1$ line is controlled by adjusting the linewidth of the pumping (coupling) laser. With the change of pumping-laser linewidth from several MHz to about 100 MHz, the absorption reduction degrades from about 70% to less than 15%. The experimentally measured results are in good agreement with a simple theoretical calculation. [S1050-2947(97)09007-0]

PACS number(s): 42.62.−b, 42.65.Tg, 32.90.+a

I. INTRODUCTION

In recent years, much theoretical and experimental work has been focused on the phenomena related to atomic coherence, such as coherent population trapping (CPT) [1–4] and electromagnetically induced transparency (EIT) [5–7]. These effects are caused by the population trapped states formed by the atomic coherence due to coherent coupling of different atomic states. The EIT phenomena, which have applications in achieving lasing without inversion (LWI) [8] and in enhancing efficiencies in nonlinear optical processes [9,10], were demonstrated recently in both ladder-type and Λ-type three-level atomic systems by using continuous diode lasers as both the pumping and the probe beams in two-photon Doppler-free configurations [6,7]. A simple theoretical treatment of the EIT effect in a three-level Doppler-broadened medium was developed, which gives quite clear physical explanations to the experimental results including the absorption reduction [6,7], dispersion properties [11], and hyperfine spectroscopy [12]. Quantitative comparisons between experimental results and the simple theoretical calculations are impressive in these previous studies. However, there are still many interesting aspects in these multilevel atomic systems interacting with laser fields that need to be studied for a full understanding of the EIT effect and its applications. For example, although the exact formulas for the influence of laser linewidths on the EIT effect were calculated [6], to our knowledge, there has been no report on the experimental demonstration of such a phenomenon. These linewidths effects are important for the understanding and applications of the EIT in enhancing nonlinear optical processes [10], spectroscopy [12], and phase noise correlation in multilevel systems [13].

In this paper, we report the experimental measurements of absorption of a weak probe laser beam passing through a rubidium vapor cell in a three-level Λ-type system while the pumping (coupling) laser linewidth is varied from several MHz to about 100 MHz. The experimental results are in good agreement with theoretical calculations, which provides direct evidence of the influence of the laser linewidth on the EIT process.

II. THEORETICAL TREATMENT

It is well known that for a three-level Λ-type system, the two-photon transition is almost Doppler free, provided the pumping laser beam and the probe laser beam have nearly the same wavelength and propagate colinearly through the atomic vapor cell. The Doppler shifts of the probe laser and the pumping laser for the same group of atoms with velocity v are canceled in the first order. The steady-state solution of the density matrix equations can be easily obtained with the assumptions that the strong pumping laser will pump almost all the population from one of the lower states (for the pumping laser) to the other lower state (for the weak probe laser) and that the velocity distribution of the atomic vapor is Maxwellian. The linear susceptibility of the atomic system for the weak probe beam can then be written in the following compact form [6,7]:

$$\chi=\frac{4i\hbar c g_{12}^2 N_0\sqrt{\pi}}{\varepsilon_0 u\,\omega_p}e^{z^2}[1-\operatorname{erf}(z)], \tag{1}$$

with the argument

$$z=\frac{c}{u\,\omega_p}\left[\gamma-i\Delta_1+\frac{\Omega_c^2/4}{\Gamma_{31}-i(\Delta_1-\Delta_2)}\right], \tag{2}$$

where erf(z) is the error function with a complex argument z, detunings Δ_1 and Δ_2 are defined as the nominal detunings for an atom at rest, $u/\sqrt{2}$ is the root-mean-square atomic velocity, $2\hbar g_{12}$ is the dipole moment matrix element for the probe transition, and Ω_c is the Rabi frequency of the pumping field. Γ_{31} is the dephasing rate for the two lower levels of the Λ-type system. $\gamma\equiv\frac{1}{2}[\Gamma_{21}+\Gamma_{23}+\Gamma_{31}]$, where Γ_{21} and Γ_{23} are decay rates from the upper state to the two lower states, respectively. N_0 refers to the number of the atoms per unit volume, and ω_p is the angular frequency of the probe laser. The real and imaginary parts of the susceptibility lead to the dispersion and absorption characteristics of the atomic medium in the usual way; i.e., the intensity absorption coefficient is given by $\alpha=\omega_p n_0\chi''/c$, where n_0 is the background index of refraction. At the center of the absorption curve and for a perfectly tuned pumping laser ($\Delta_1=\Delta_2=0$), the absorption coefficient α is reduced by a factor given by

$$\frac{\alpha(\Omega_c)}{\alpha(0)}=\left[\frac{1}{\sqrt{\pi}z_0 e^{z_0^2}(1-\operatorname{erf}z_0)}\right]\frac{1}{1+\Omega_c^2/4\gamma\Gamma_{31}}, \tag{3}$$

Influence of Injection–Current Noise on the Spectral Characteristics of Semiconductor Lasers

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Abstract—**The spectral characteristics of a semiconductor laser are altered by injecting additional noise current into its current-drive port. A continuously varying spectral linewidth from about 5 MHz to above 100 MHz is achieved experimentally in this semiconductor laser. The conditions under which the line shape changes from a standard Lorentzian shape to a Gaussian shape as functions of laser power and noise current are investigated and compared with an existing theoretical treatment.**

Index Terms— **Current fluctuations, Gaussian, line shape, linewidth, noise, semiconductor laser, spectrum.**

I. Introduction

Semiconductor lasers are widely used in many areas of atomic physics research, such as atomic trapping and atomic spectroscopy [1]–[4]. The spectral characteristics of laser sources such as linewidths and line shapes have great significance in the study of atom–laser interactions. There are a number of factors which can influence the linewidth and the line shape of a semiconductor diode laser. For example, the linewidth, line shape, and frequency stability depend on the temperature of the laser, the dc bias current across the heterostructure, and the random fluctuations inherent to that bias current. It is important in many applications of semiconductor lasers to have as narrow a linewidth as possible. Normally, a diode laser is temperature and current stabilized to maintain the frequency stability and a linewidth below a few megahertz to 40 MHz, depending on the specific laser model and stabilization technique. A great deal of research has gone into developing methods to further reduce linewidths of semiconductor diode lasers with optical feedback techniques [1], [2], [5], [6]. The influences of temperature and dc bias current (and therefore output power) on the linewidth of a diode laser driven by a current with a small amount of intrinsic noise were studied in detail by several groups, both experimentally [7]–[9] and theoretically [8]–[10]; it has also been suggested that the increased current fluctuations of a noisy power supply may be partially responsible for linewidth broadening in distributed Bragg reflector (DBR) lasers [11]. Later, Agrawal and Roy developed a new theoretical treatment, which improved some assumptions used in earlier theoretical models for treating injection–current fluctuations [12]. For example, Agrawal and Roy assumed a non-Markovian random process for the injection–current fluctuations, which modifies the noise force terms in the Langevin equations. With these modifications, they developed a complete theory to calculate the linewidth and line shape of a semiconductor laser, with laser output power and noise current as parameters. For different values of power and noise current, the linewidth and line shape of the semiconductor laser can be quite different.

In this paper, we present detailed experimental studies of the linewidth and line shape of a typical semiconductor diode laser as a function of noise current for different laser powers, paying particular attention to the power-independent contribution to the line shape function, which becomes dominant for sufficiently high powers (this is a sort of saturation phenomenon). In our experiments, the rms amplitude of the current fluctuations is a continuously variable parameter. We found that with a modest increase of noise current added to the injection current driving the laser, the linewidth can be continuously changed from its free-running value of a few megahertz to above 100 MHz. The line shape of the output field changes from a standard Lorentzian shape to a Gaussian shape as the noise current increases. These experimental results are in good agreement with the theoretical calculations of [12]. Our study of this linewidth modification has been motivated by the need for a laser source that can have a continuously changing linewidth from below the natural linewidth of an atomic transition (6 MHz for the rubidium D2 line) to well above it. The previous work on a semiconductor laser source with a continuously varying spectral linewidth using external modulation techniques can only achieve a linewidth tunable range of 100 kHz–5 MHz [13], which would not be enough for our applications.

In Section II, we will briefly review the main theoretical results given by [12] that are relevant to our experiments and deduce some simple equations that apply to our experimental conditions. In Section III, we describe our experimental arrangement and conditions. In Section IV, the experimental measurements on linewidths and line shapes for different dc bias current and noise current combinations are presented and discussed. Section V serves as a conclusion.

II. Theoretical Background

It is known that the linewidth of a semiconductor laser beam decreases as the laser power increases. Intuitively, one would expect that the linewidth would increase with an increase in the driving current fluctuations. Not only is this the case, but it will be shown that the increase in linewidth due to fluctuations in the driving current is actually accelerated at lower laser

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Sub-Shot-Noise laser Doppler Anemometry with Amplitude-Squeezed Light

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Amplitude-squeezed light from a quantum-well semiconductor laser with weak optical feedback from a highly dispersive grating is employed for laser Doppler anemometry. Up to 2 dB noise reduction below the shot-noise level is observed with a feedback factor of 1.5×10^{-4}. Enhanced sensitivity is demonstrated in the Doppler measurement of a gas flow velocity with an improvement in the signal to noise ratio of 1.0 dB above the shot-noise limit. [S0031-9007(97)02955-4]

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In recent years, squeezed light exhibiting fluctuations below the standard quantum limit (SQL) in one quadrature amplitude or in the amplitude of the field has been shown to enable precision measurements with sensitivities beyond the SQL [1–4]. Quadrature squeezed states of light, characterized by reduction of the mean square fluctuation in one quadrature component of the field below that of the vacuum state, have been used to improve the precision of shot-noise limited measurements of weak absorption [2] and in interferometry [3]. A frequency-tunable squeezed light source has been used to demonstrate improvement in the sensitivity of the saturation spectroscopy of atomic cesium [4] and to demonstrate fundamental phenomena in the atom-photon interaction [5]. Amplitude-squeezed states of light, featuring photon number fluctuations below those of Poissonian statistics, have been generated from semiconductor lasers [6–8], and have been recently used for nonlinear spectroscopy and dark fringe interferometry [9]. Low noise amplification has also been demonstrated using sub-Poissonian light generated by semiconductor junction light emitters [10].

In this Letter, we demonstrate the application of amplitude-squeezed light to laser Doppler anemometry with consequent improvement in the sensitivity of velocity measurements above the shot-noise limit. The amplitude-squeezed light was produced from a cooled quantum-well semiconductor laser with weak grating feedback of $\sim 10^{-3}$–10^{-4}. Up to 2 dB of photon number squeezing was observed. We have utilized this squeezed light source to achieve an improvement in sensitivity of 1.0 dB beyond the shot-noise limit for the heterodyne detection of Doppler-shifted light scattered from a gas flow containing smoke particles.

The laser Doppler technique has been widely used in laser Doppler anemometry (LDA), laser radar (LIDAR), and in light scattering measurements where an intense coherent light source is required [11,12]. Laser Doppler anemometry is a precise optical technique for the measurement of velocity based on the determination of the Doppler shift of light scattered from moving particles. The LDA technique has been employed to measure the velocity distribution of cold atoms trapped in an "optical molasses" [13] and in molecular scattering. The small Doppler frequency shifts in the weakly scattered light may be detected by an optical heterodyne technique using a reference laser beam. The velocity and density of moving particles in a fluid can be obtained from the beat frequency and beat amplitude. For the experimental arrangement shown in Fig. 1, the Doppler shift of the scattered light (dashed line directed to the detector) is given by [12]

$$\nu_D = (n/\lambda)\mathbf{u} \cdot (\mathbf{k}_s - \mathbf{k}_0) = (2nu/\lambda)\sin(\alpha/2), \quad (1)$$

with n the index of refraction of the flow medium, $\mathbf{u}$ the velocity vector of the flow with amplitude u, λ the wavelength of the laser beam, $\mathbf{k}_0$ and $\mathbf{k}_s$ the unit vectors in the directions of the illuminating and scattering (reference) beams, respectively, and α the angle between them.

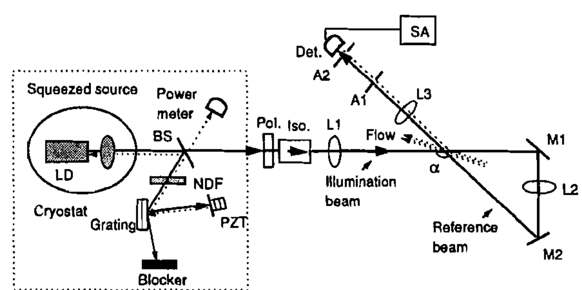

FIG. 1. Experimental setup. Squeezed source: LD—laser diode; BS—beam splitter with 94% transmission; NDF—neutral density filter; Pol.—polarizer; Iso.—optical isolators; L1, L2, L3—optical lenses; PZT—PZT-controlled mirror; M1, M2—mirrors; A1, A2—apertures. The laser beam from the squeezed source passes through a gas flow twice at an angle of α. The scattered light and the transmitted reference beam are collected by a large area pin photodetector (Det.) and the output photocurrent is amplified, and fed into a spectrum analyzer (SA).

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PHYSICS LETTERS A

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Number-difference–phase uncertainty relation for NFM operational quantum phase description

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Abstract

For the Noh, Fougers, and Mandel (NFM) operational quantum phase description, which is based on an eight-port homodyne-detection, we propose the number-difference–phase (ND-P) uncertainty relation and, then, discuss the mechanism of generation of ND-P squeezed states.

1. Introduction

It is well known that a state is defined to be photon-number squeezed if its photon number uncertainty falls below that of a coherent state, which happens at the expense of stretching the corresponding phase uncertainty [1,2]. The photon-number (or amplitude) squeezed state is often referred to as sub-Poissonian light because its standard deviation falls below that of the Poisson distribution that characterizes the coherent state. A photon-number squeezed state is an ideal minimum-uncertainty one when the condition $\Delta\hat{n}\Delta\,\widehat{\sin\phi} = |\langle\widehat{\cos\phi}\rangle|$ is satisfied. Based on Susskind–Glogower phase operators [3], a number-phase interaction is proposed that is analogous to the usual single-mode quadrature-squeezing Hamiltonian [4]. However, the Susskind–Glogower phase operator is not unitary and cannot be a function of a Hermitian angle operator ϕ. According to the definition

$$\widehat{e^{i\phi}} = \frac{1}{\sqrt{\hat{n}+1}}\hat{a}, \quad \widehat{e^{-i\phi}} = \hat{a}^\dagger\frac{1}{\sqrt{\hat{n}+1}},$$
$$\hat{n} = \hat{a}^\dagger\hat{a}, \tag{1}$$

and

$$\widehat{\cos\phi} = \tfrac{1}{2}\left(\widehat{e^{i\phi}} + \widehat{e^{-i\phi}}\right), \quad \widehat{\sin\phi} = -\tfrac{1}{2}i\left(\widehat{e^{i\phi}} - \widehat{e^{-i\phi}}\right), \tag{2}$$

one gets the number-phase uncertainty relations

$$\left[\widehat{\cos\phi}, \hat{n}\right] = i\,\widehat{\sin\phi}, \quad \left[\widehat{\sin\phi}, \hat{n}\right] = -i\,\widehat{\cos\phi}, \tag{3}$$

and

$$\left[\widehat{\cos\phi}, \widehat{\sin\phi}\right] = \tfrac{1}{2}i|0\rangle\langle 0|,$$
$$\left(\widehat{\cos\phi}\right)^2 + \left(\widehat{\sin\phi}\right)^2 = 1 - \tfrac{1}{2}|0\rangle\langle 0|. \tag{4}$$

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Enhancement of nondegenerate four-wave mixing based on electromagnetically induced transparency in rubidium atoms

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We report an experimental observation of the enhancement of nondegenerate four-wave mixing (NDFWM) based on electromagnetically induced transparency (EIT) in a lambda-type three-level system of rubidium atoms. We measured both the linear susceptibility Im $\chi_D^{(1)}$ (absorption) and the third-order nonlinear coefficient $\chi_D^{(3)}$ separately for the NDFWM process at a low atomic density. We found that, owing to the EIT effect, the linear absorption term Im $\chi_D^{(1)}$ is greatly reduced, while the nonlinear generation term $\chi_D^{(3)}$ is resonantly enhanced, permitting us to observe a significant enhancement of the NDFWM signal in an optically dense medium.

Recently there has been much interest in electromagnetically induced transparency[1–4] because of its potential applications in nonlinear-optical processes,[2,5] lasing without inversion,[6] pulse matching,[7] and quantum noise reduction.[8] Continuous-wave EIT effects have been observed both in a ladder-type three-level system[3] and a lambda- (Λ-) type[4] three-level system in atomic Rb vapor. In particular, quantum interference between the lifetime-broadened dressed states has been observed directly, and the dispersion properties of EIT have been measured.[3,4] Enhanced nonlinear-optical processes using EIT have also been demonstrated in optically dense media with pulsed laser fields.[2,5] A high phase-conjugate gain owing to coherent population trapping was reported recently in a four-level double-Λ system of sodium vapor by Hemmer *et al.*[9]

In this Letter we report a clear experimental observation of an enhanced nondegenerate four-wave mixing (NDFWM) process, using the EIT effect in a three-level Λ-type system of Rb atoms with cw diode lasers. The key idea of enhancing nonlinear-optical processes by use of EIT (Ref. 5) is that the absorption of the generated field [related to the linear susceptibility Im $\chi_D^{(1)}$] can be substantially reduced as a result of the EIT effect while, at the same time, the nonlinear coefficient $\chi_D^{(3)}$ associated with the nonlinear-optical generation process is resonantly enhanced. This leads to a significant enhancement in nonlinear-optical generation in an optically dense medium, in which there would be a large absorption for the generated field without the EIT effect. In our experiment we first measured both the linear susceptibility Im $\chi_D^{(1)}$ (absorption) and the third-order nonlinear coefficient $\chi_D^{(3)}$ for the NDFWM process under a low-atomic-density (optically thin-medium) condition. The results confirmed the predictions that Im $\chi_D^{(1)}$ is reduced while $\chi_D^{(3)}$ is resonantly enhanced as a result of the EIT effect.[5] Then we observed the enhancement in the generated NDFWM signal under high-atomic-density (optically thick-medium) conditions.

Our Λ-type three-level system consists of Rb^{87} atoms in a Doppler-broadened vapor cell. As shown in Fig. 1, the two hyperfine levels $F_g = 1$ and $F_g = 2$, spaced by 6.8 GHz, of the ground-state $5S_{1/2}$ serve as the two lower states of the Λ system. The excited state $5P_{1/2}$, $F_e = 1$ serves as the common upper state.[4] The other hyperfine level of the excited state ($5P_{1/2}$, $F_e = 2$) is 814 MHz away (outside the Doppler-broadening linewidth), and its effect can be neglected. The NDFWM is in a forward configuration, i.e., one pumping wave (with frequency ω_2) is on resonance with the $F_g = 2$ to $F_e = 1$ transition, and the other pumping wave ω_1 is far off resonance (with 450-MHz detuning) with the $F_g = 1$ to $F_e = 1$ transition. As the weak probe wave ω_p is tuned to be $\omega_2 - 450$ MHz, a phase-conjugate wave ω_c will be generated at a resonant frequency with the $F_g = 1$ to $F_e = 1$ transition, satisfying the phase-matching condition of $\omega_1 + \omega_2 = \omega_p + \omega_c$. In steady state most atoms will be optically pumped to the ground state $F_g = 1$. If there were no EIT effect, the generated conjugate wave at frequency ω_c would be greatly absorbed by the

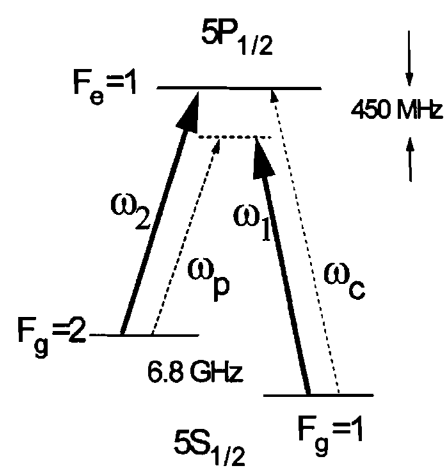

Fig. 1. NDFWM based on EIT in a three-level Λ-system of Rb^{87} atoms. Pumping waves are at frequencies ω_1 and ω_2, and the probe wave is at frequency ω_p. The phase-conjugate wave is generated at the frequency $\omega_c = \omega_1 + \omega_2 - \omega_p$ and experiences transparency produced by the pumping wave at frequency ω_2.

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Coherent population trapping and electromagnetically induced transparency in multi-Zeeman-sublevel atoms

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We present a general formalism for studying the interaction between laser fields and degenerate-Zeeman-sublevel atoms correct up to the first order in the weak probe field. We derive from this theory the equations of motion for a Λ-type system involving $S_{1/2}$, $F=2 \leftrightarrow P_{1/2}$, $F'=1 \leftrightarrow S_{1/2}$, $F=1$ transitions in ^{87}Rb atoms. These equations are used to numerically investigate the coherent population trapping (CPT) schemes in the $S_{1/2}$, $F=2 \leftrightarrow P_{1/2}$, $F'=1$ transition induced by a linearly polarized pumping field and the electromagnetically induced transparency exhibited in the weak probe spectrum in the $S_{1/2}$, $F=1 \leftrightarrow P_{1/2}$, $F'=1$ transition. We discuss the effects of the CPT on the probe spectrum with and without the Doppler broadenings by comparing the probe spectrum derived from the real system with that derived from an ideal Λ-type system. We show that the atoms in the CPT states are shielded from interacting with the probe field while those in the absorbent states make contributions to the weak probe by the Raman anti-Stokes process, and the effect of the real system on the probe field becomes equivalent to the ideal Λ system only in the strong CPT parameter regime.

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I. INTRODUCTION

Electromagnetically induced transparency (EIT) and lasing without inversion (LWI) were originally predicted from theoretical studies of three- or four-level atomic systems (simple models) interacting with scalar fields [1–8]. However, the experimental demonstrations [9–17] of these phenomena were often carried out in atoms such as sodium [10,14] and rubidium [15–17], where each energy level consists of several Zeeman sublevels, interacting with polarized fields. The theoretical analysis based on simple models indicates that the foundations of EIT and LWI are the atomic coherence and the destructive quantum interference among different transition pathways. However, the atomic coherence terms and the possible interference pathways increase quadratically with the total number of levels (including the Zeeman sublevels), which can easily exceed 10 in the energy schemes of real atoms. One may question whether the main features predicted from simple models can survive in real atomic systems.

Consider an ideal Λ system in Fig. 1(a), where the excited level 3 is coupled to level 2 by a pumping field and to level 1 by a weak probe field, and level 1 holds all the atoms. Harris, Field, and Imamoglu [4] have shown theoretically that such a medium becomes transparent to the weak probe at its resonance frequency, assuming that level 2 is metastable (or, equivalently, has a very small decay rate). This phenomenon (known as EIT) can be interpreted simply as a result of destructive interference between the $1 \leftrightarrow 3$ single-photon transition and the $1 \leftrightarrow 3 \leftrightarrow 2$ two-photon transition via the $2 \leftrightarrow 1$ atomic coherence. The experimental demonstration of EIT has been reported by Harris, Field, and Imamoglu in a heated Sr atomic vapor [9]. In their experiment, because level 2 differs from level 1 in the order of optical frequency, a very high pumping power was used to overcome the Doppler and collisional broadenings. Recently, Li and Xiao [16] have conducted an EIT experiment by employing two ground hyperfine levels in the ^{87}Rb atom as levels 2 and 1. Since the two lower levels differ from each other in the order of microwave frequency, the two-photon-resonance condition in a copropagating configuration becomes almost Doppler free

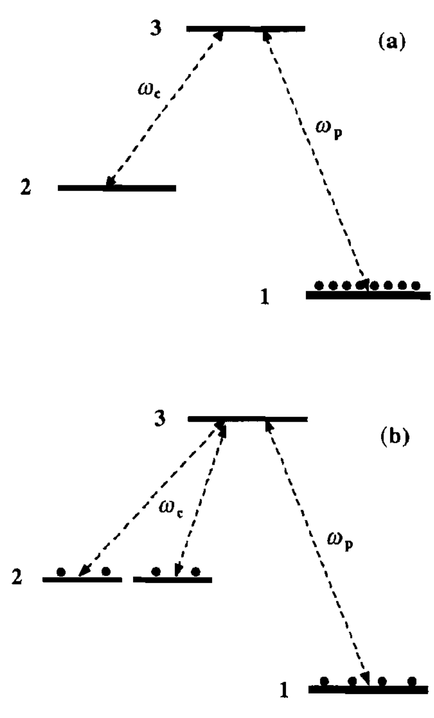

FIG. 1. Schematics of (a) the ideal Λ system and (b) the Λ system with level 2 being a degenerate doublet.

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PHYSICS LETTERS A

ELSEVIER

Physics Letters A 222 (1996) 299–303

A convenient representation for the two-mode phase operator $\sqrt{(\hat{a}+\hat{b}^\dagger)/(\hat{a}^\dagger+\hat{b})}$

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Abstract

We find a representation in which the two-mode phase operator $\sqrt{(\hat{a}+\hat{b}^\dagger)/(\hat{a}^\dagger+\hat{b})}$ manifestly exhibits its phase behavior. With this representation, the phase operator is more applicable to further illustrating the Shapiro–Wagner phase measurement approach. The technique of integration within an ordered product of operators is essential in our discussion.

1. Introduction

The question of defining a quantum phase operator for the electromagnetic field is a great challenge in quantum mechanics and quantum optics. Quite a few proposals were made to define quantum phase operators that would be consistent with quantum mechanics and coincide with an experimental measurement, of which the frequently discussed are issued by Susskind and Glogower [1], Pegg and Barnett [2], Paul [3], Noh, Fougires, and Mandel [4], and Shapiro and Wagner (S–W) [5]. The main problem for illustrating the quantum phase lies in the lack of a suitably defined quantum phase operator, which is Hermitian and is measurable experimentally. In this work, we concentrate on the concept of a feasible phase measurement scheme proposed by Shapiro and Wagner in 1984 [5], which was based on the simultaneous detection of quadrature components using a heterodyne detection method. In this S–W scheme, the phase of the complex amplitude of the signal and idler (image) fields is measured with a heterodyne detection arrangement. The output of the heterodyne detection is associated with the measurement of the complex amplitude,

$$\hat{Y} = \hat{a} + \hat{b}^\dagger, \tag{1}$$

where $\hat{a}$ and $\hat{b}$ are signal and idler modes, respectively, with $[\hat{a},\hat{a}^\dagger] = [\hat{b},\hat{b}^\dagger] = 1$. Since $\hat{Y}^\dagger = \hat{b}^\dagger + \hat{a}$ commutes with $\hat{Y}$, $[\hat{Y},\hat{Y}^\dagger] = 0$. This is essential in simultaneous measurements of the two quadrature components.

Hradil [6,7] then pointed out that the detection of the same quantity, as given in Eq. (1), can be achieved with a double homodyne detection scheme. By extending the idea of the Susskind–Glogower phase operator introduced as a polar decomposition of the annihilation operator [1], he defined a phase operator (or phase-like variable) as

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PHYSICS LETTERS A

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A special type of squeezed coherent state

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Abstract

We introduce a new type of single-mode squeezed coherent states $|z\rangle_g$, which differs from the conventional squeezed states in that its displacement parameter depends on its squeezing parameter. By tuning the relative strength of the two complex parameters involved, this new state $|z\rangle_g$ can reduce to the simple coherent state, the coordinate eigenstate, or the momentum eigenstate. The properties of the new state $|z\rangle_g$ including its overcompleteness relation are investigated.

PACS: 42.50.Dv; 42.50.Lc; 03.65.Ca

As is commonly known in quantum optics, single-mode coherent squeezed states, which are generated through nonlinear optical interactions between coherent optical fields and nonlinear media (for a review of squeezed states, see, for example, Ref. [1]), are constructed either by [2]

$$|z,\lambda\rangle \equiv \hat{D}(z)\hat{S}(\lambda)|0\rangle = \operatorname{sech}^{1/2}\lambda \exp\left[-\tfrac{1}{2}|z|^2 + z\hat{a}^\dagger + \tfrac{1}{2}(\hat{a}^\dagger - z^*)\tanh\lambda\right]|0\rangle, \tag{1}$$

which is called *ideal squeezed state* in Ref. [2], or by

$$\begin{aligned}|\lambda,z\rangle &\equiv \hat{S}(\lambda)\hat{D}(z)|0\rangle \\ &= \operatorname{sech}^{1/2}\lambda \exp\left[-\tfrac{1}{2}|z|^2 + z\hat{a}^\dagger \operatorname{sech}\lambda + \tfrac{1}{2}\tanh\lambda\,(\hat{a}^{\dagger 2} - z^2)\right]|0\rangle,\end{aligned} \tag{2}$$

which is called *two-photon coherent state* in Ref. [2]. $\hat{S}(\lambda)$ is the single-mode squeezing operator given by

$$\hat{S}(\lambda) = \exp\left[\tfrac{1}{2}\lambda(\hat{a}^{\dagger 2} - \hat{a}^2)\right], \tag{3}$$

and $\hat{D}(z)$ is the displacement operator given by

$$\hat{D}(z) = \exp(z\hat{a}^\dagger - z^*\hat{a}), \tag{4}$$

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PHYSICS LETTERS A

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Complex P representation of the density matrix obtained via creation operator eigenvectors

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Abstract

We point out that the eigenkets $|z\rangle_*$ of the boson creation operator $\hat{a}^\dagger$ can be used to construct the complex P representation with the contour encircling the origin. A completeness relation composed of $|z\rangle_*$ and the unnormalized coherent state $\langle z\|$ provides the basis for these complex P representations.

1. Introduction

In quantum optics theory, the density operator $\hat{\rho}$ is often used to describe nonlinear optical processes and transform the operator equations into c-number Fokker–Planck (FP) equations with the use of the Glauber–Sudarshan (GS) P representation [1,2]. Faced with the difficulty that, for some systems, a steady solution to the FP equation in terms of GS P representation does not exist, Drummond and Gardiner proposed the so-called complex P representation of $\hat{\rho}$ by defining [3,4]

$$\hat{\rho}=\oint_C\oint_{C'} \mathrm{d}\alpha\, \mathrm{d}\beta \frac{|\alpha\rangle\langle\beta^*|}{\langle\beta^*|\alpha\rangle} P(\alpha,\beta), \tag{1}$$

where α and β are complex variables to be integrated on individual contours C and C'. $|\alpha\rangle$ and $\langle\beta^*|$ are the coherent states [5]. This special representation may take on complex values so that in no sense can it have any probability distribution interpretation. However, it is useful to give exact results for certain problems and physical observables such as all the single correlation functions (see Refs. [3–5]).

On the other hand, there exists a contour integration form of the completeness relation in fundamental quantum mechanics which had been overlooked for many years. This completeness relation is composed by both the unnormalized coherent-state eigenvector $\|z\rangle$ of the annihilation operator $\hat{a}$ and the eigenvector $|z\rangle_*$ of the creation operator $\hat{a}^\dagger$. As shown in Refs. [6] and [7], the eigenket $|z\rangle_*$ of $\hat{a}^\dagger$ (called the dual vectors of $\|z\rangle$) can be constructed by the contour integration form of the δ-function. This motivates us to think about the relationship between $\hat{a}^\dagger$'s eigenvector and the complex P representation. In this work, we shall point out that, like the GS P representation originated from the coher-

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WIGNER OPERATOR AND SQUEEZING FOR ROTATED QUADRATURE PHASES

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We introduce the Wigner operator $\widehat{\Delta}_\theta(x, p)$ for the rotated quadrature phases and use the technique of integration within an ordered product of operators to derive its explicitly simpler form. Based on this, the mutual relations between $\widehat{\Delta}_\theta(x, p)$ and the corresponding marginal probability distribution operator can be easily revealed. The Wigner function theory is thus be recasted into a more elegant and concise formalism. The squeezing in rotated quadrature phase is discussed with the same method.

1. Introduction

For quantum mechanical system, it is impossible to specify simultaneously the position $\widehat{x}$ and the momentum $\widehat{p}$ of the particles. As a result, it is hard to define a distribution function on the phase space which can be interpreted as a probability density. However, Wigner[1] was the first to introduce a function which is formally analogous to the classical probability density. In Ref. 2 Feynman introduced the Wigner function as follows: If there is any density function $f(x,p)$ in quantum mechanics that satisfies

$$P(p) = \int f(x, p) dx \,, \tag{1}$$

$$P(x) = \int \frac{dp}{2\pi} f(x, p), \qquad \hbar = 1, \tag{2}$$

where $P(x)$ $(P(p))$ is proportional to the probability for finding the particle at x (at p in momentum space). The solution is the Wigner function

$$f_{\mathrm{W}}(x, p) = \int \rho\left(x + \frac{v}{2}, x - \frac{v}{2}\right) e^{-ipv} dv, \tag{3}$$

where ρ is a density matrix.[2,3]

Coherent transient amplification in inhomogeneously broadened rubidium atoms by diode-laser frequency switching

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We report observation of coherent transient amplification that is due to free-induction decay and optical nutation in inhomogeneously broadened rubidium atoms by a sudden switch of diode-laser frequency. An amplification coefficient of 2.2×10^{-2} cm^{-1} is observed when the diode-laser frequency, initially tuned to the blue side of the Doppler-broadened absorption profile, is switched to be out of resonance by application of a step-function pulsed injection current. The transition from free-induction decay to optical nutation is observed and discussed.

PACS numbers: 42.50.Hz, 32.70.-n, 42.25.Bs, 42.65.An.

Optical coherent transients are interesting and useful phenomena in the study of matter–radiation interaction.[1,2] In an atomic system driven by a coherent laser field, when the frequency of the field is suddenly switched from on resonance to off resonance or vice versa, coherent transients, e.g., optical free-induction decay (FID) and optical nutation, could be observed in the transmitted amplitude of the probe field. This optical coherent transient technique was applied to the measurement of the long decay times of solid materials.[1] In the early studies[3] frequency switching was achieved when a Stark field or a strong light pulse was suddenly applied to shift the atomic levels to be on or off resonance with the frequency of the weak probe laser. Later, laser frequency-switching techniques were used to shift the probe-laser frequency, and the atomic levels were left unperturbed.[4,5] In those experiments laser frequency switching was achieved by three different techniques that used an extracavity acousto-optic modulator, an intracavity electro-optic modulator, or an extracavity electro-optic modulator. However, as pointed out in Ref. 1, some substantial disadvantages were present in these techniques and have limited their applications in optical coherent transients.

In this Letter we report an optical coherent transient experiment in which a simple, new technique is used to switch the laser frequency of a diode laser. In a free-running diode laser one can achieve a large frequency shift by simply applying a small pulse current to modulate the bias current of the diode laser.[6] One can tune the initial frequency of the diode laser by changing the dc bias current and the temperature. Using this new technique, we study the transition from FID to optical nutation in an inhomogenously broadened two-level atomic system. Under the appropriate circumstances, when the amplification that is due to FID is larger than the absorption that is due to optical nutation, transient amplification can be observed for the probe laser beam. Because only one weak coherent (probe) laser beam is used in this experiment the observation of coherent transient amplification for the laser beam is accomplished with most of the atoms in their ground state (or without population inversion between the upper level and the lower level). The observed coherent transient effects in a Doppler-broadened two-level transition by frequency switching of a diode laser are related to the recently developed diode-laser noise spectroscopy,[7] in which the diode-laser frequency shift is random in time with a randomly fluctuating amplitude. Recently a nutation effect that was due to dynamic Stark switching in a three-level system of nuclear magnetic transitions was reported,[8] and transient gain without population inversion with enhanced dispersion was discussed in an electromagnetically induced transparency in three-level Λ-type and cascade-type atomic systems.[9]

The experiment is done with the ^{87}Rb $D1$ line ($5S_{1/2}-5P_{1/2}$). As shown in Fig. 1, a negative pulse voltage from an electrical pulse generator is applied to the bias current of a multi-quantum-well diode laser through a wideband bias T (Mini-Circuits ZFBT-6GW). Both the fall time and the rise time of the pulse are ~2.5 ns. The pulsed injection current generated in the laser diode is 0–4.0 mA, imposed on a dc-bias injection current of 130 mA, which causes a decrease of less than 5.0% in the output intensity of the diode laser. This pulsed injection current will cause a large frequency shift from 0 to 360 MHz. As Ref. 6

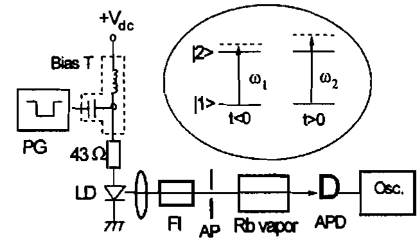

Fig. 1. Experimental arrangement. The frequency of the diode laser is switched by application of a negative pulsed injection current: LD, laser diode; FI, Faraday isolator; PG, pulse generator; AP, aperture; APD, avalanche photodiode; Osc., sampling oscilloscope. Inset: laser frequency switching related to atomic transition.

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Single-mode diode laser with a large frequency-scanning range based on weak grating feedback

Shaozheng Jin, Yongqing Li, and Min Xiao

A single-mode GaAlAs diode laser with over 90% output-coupling power and a large frequency-scanning range is reported. Based on grating feedback in the Littrow configuration, it is demonstrated that, with weak feedback (1.5×10^{-3} in this experiment), over a 7.5-GHz continuous tuning range can be achieved around tuning gaps of free-running operation. A frequency self-locking effect is also demonstrated in this system.

Key words: Diode laser, dispersive feedback.

1. Introduction

In recent years, diode lasers have been widely used because of their flexible tunability, reliability, and simple operation. With the successful improvements in the spectral properties of these lasers, such as linewidth narrowing (sub-megahertz) and a large continuous tuning range (up to a few nanometers) without mode hopping, diode lasers are used as tunable coherent sources in many fields, including atomic spectroscopy[1] and quantum optics.[2] Several high-power laser systems are even injection locked in frequency with diode lasers as seeding sources.[3,4]

However, it is a well-known fact that the wavelength of a free-running diode laser usually cannot be tuned continuously over its whole gain range above the lasing threshold because of the existence of discontinuities (or gaps) in the wavelength-tuning curve over temperature and injection current. In many cases, a desirable wavelength is not achievable with simple adjustments of temperature and current in the free-running condition. In order to get a desired wavelength that lies in one of those gaps, several different techniques are developed by the use of optical feedback from a diffraction grating,[5] an external reflector,[6] a thin étalon plate,[7] a confocal Fabry–Perot (CFP) cavity,[8] and so on. Among these methods, the grating feedback and the CFP cavity feedback are the most common ways for obtaining a large tuning range. The dispersive feedback from a CFP cavity forces the frequency of the diode laser to be locked to the cavity-resonance frequency, and such a frequency-stabilized laser output with a narrow linewidth (a few tens of kilohertz) can be achieved with weak feedback of as low as 10^{-2} to 10^{-5}. However, this method is very sensitive to the returning phase of the feedback beam. When the output wavelength is tuned by changing the resonant frequency of the CFP cavity, servo electronics is needed to control the distance between the diode laser and the CFP cavity synchronously, and the injection current for the diode laser has to be modulated with a rf frequency to get the error signal.[9] Grating feedback is another effective but relatively simple method to achieve a large frequency-tuning range (although with less improvement over the laser linewidth, simply for the reason that the dispersive FWHM of a common grating is usually 3 orders of magnitude larger than that of a normal CFP resonator[10]) and no servo electronics is needed. However, a conventional wisdom is that a relatively large amount of feedback intensity (typically more than 25%) is required to achieve a scanning range of a few gigahertz.[11] This will obviously introduce a big loss in the output power of the diode-laser system. For many applications of diode lasers, one needs not only a large scanning range, but also as much usable output power as possible.

In this paper, a system of a single-mode GaAlAs diode laser with a high output-coupling power and a large frequency-scanning range without mode hop-

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Dual eigenkets of the Susskind-Glogower phase operator

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By contour integration we show that the phase operator $\widehat{e^{-i\phi}}$ (one of the pair of Susskind-Glogower operators) also possesses eigenkets $|\gamma\rangle_*$, which are the dual vector of $\widehat{e^{i\phi}}$'s eigenkets. The properties of $|\gamma\rangle_*$ are studied and we see that $|\gamma\rangle_*$ and $\widehat{e^{i\phi}}$'s eigenkets can also make up a phase-state representation. [S1050-2947(96)01212-7]

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I. INTRODUCTION

The phases of optical fields play the decisive role in many optical phenomena, particularly in diffraction and interference of light. Therefore much attention has been paid to the problem of defining and measuring an appropriate phase for radiation fields [1–3]. There are quite a few ways to propose phase operators. For example, Paul [4] defined the phase operator by the diagonal coherent state representation (called Glauber-Sudarshan P representation) as

$$\int \frac{d^2z}{\pi} e^{i\theta}|z\rangle\langle z| = \widehat{e_P^{i\theta}}, \quad \text{with } z=|z|e^{i\theta}, \tag{1}$$

where $|z\rangle$ is the coherent state.

One can also use Weyl correspondence [5,6] to map a classical phase $e^{i\theta}$ onto a quantum-mechanical operator by

$$\int d^2\alpha \hat{\Delta}(\alpha,\alpha^*)e^{i\theta} = \widehat{e_W^{i\theta}}, \quad \alpha=|\alpha|e^{i\theta} \tag{2}$$

where $\hat{\Delta}(\alpha,\alpha^*)$ is the Wigner operator, usually expressed as an integration,

$$\hat{\Delta}(\alpha,\alpha^*) = \int \frac{d^2z}{2\pi^2} e^{-z^*(\alpha-\hat{a})+z(\alpha^*-\hat{a}^\dagger)}. \tag{3}$$

Using the technique of integration within an ordered product (IWOP) of operators [7], one can derive the explicit normally ordered form of $\hat{\Delta}(\alpha,\alpha^*)$ [see Eq. (2.1) in Ref. [8]],

$$\hat{\Delta}(\alpha,\alpha^*) = \frac{1}{\pi} :e^{-2(\hat{a}^\dagger-\alpha^*)(\hat{a}-\alpha)}: \tag{4}$$

and [7]

$$|z\rangle\langle z| = :e^{-(\hat{a}^\dagger-z^*)(\hat{a}-z)}:. \tag{5}$$

Substituting Eqs. (4) and (5) into Eqs. (1) and (2), respectively, one can obtain the explicit form of $\widehat{e_P^{i\theta}}$ and $\widehat{e_W^{i\theta}}$.

Another widely used and apparently easier phase operator is the Susskind-Glogower (SG) phase operator [2]. This phase operator comes from classical optics by introducing the phase as the "approximate" polar decomposition of the annihilation and creation operators, e.g.,

$$\hat{a}^\dagger = \widehat{e^{-i\phi}}\sqrt{\hat{a}\hat{a}^\dagger}, \quad \hat{a} = \sqrt{\hat{a}\hat{a}^\dagger}\ \widehat{e^{i\phi}}. \tag{6}$$

Although the SG phase operators are nonunitary, as

$$\widehat{e^{i\phi}}\,\widehat{e^{-i\phi}} = 1 \quad \text{and} \quad \widehat{e^{-i\phi}}\,\widehat{e^{i\phi}} = 1-|0\rangle\langle 0|, \tag{7}$$

where $|0\rangle$ is the ground state, and $|0\rangle\langle 0|$ effectively vanishes for those states with a negligible vacuum component, they are still widely used and studied in theoretical calculations in quantum optics [9]. Despite the fact that a more practical way is to operationally define a phase operator for a given experimental arrangement as was done by Mandel and coworkers [10], an appropriate phase operator can still be very useful in theoretical investigations of quantized radiation fields. Thus it will be helpful to investigate the SG phase operator in more detail. In Ref. [11], the relation between SG phase operators and the inverse operators $\hat{a}^{-1}$ and $(\hat{a}^\dagger)^{-1}$ are shown as

$$\widehat{e^{i\phi}} = (\hat{a}^\dagger)^{-1}\sqrt{\hat{N}} \quad \text{and} \quad \widehat{e^{-i\phi}} = \sqrt{\hat{N}}\hat{a}^{-1}, \tag{8}$$

which indicates that the nonunitarity of SG phase operators is intrinsically related to the noncommutative property of $\hat{a}$ and $\hat{a}^{-1}$ [$\hat{a}^\dagger$ and $(\hat{a}^\dagger)^{-1}$], e.g.,

$$[\hat{a},\hat{a}^{-1}] = [(\hat{a}^\dagger)^{-1}, \hat{a}^\dagger] = |0\rangle\langle 0|, \tag{9}$$

which implies that $\hat{a}$ and $\hat{a}^\dagger$ cannot have regular polar decompositions due to their singularities. $\hat{N} \equiv \hat{a}^\dagger\hat{a}$ is the number operator.

The eigenstate of $\widehat{e^{i\phi}}$ is given by [12]

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Inversionless lasing and photon statistics in a V-type atomic system

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We analyze intensity and statistical properties of lasers without population inversion in a closed three-level V-type system. We derive the threshold condition and examine the intensity dependence on various system parameters. Unlike other inversionless laser systems that generate amplitude-squeezed light, the intensity fluctuation of the inversionless laser from the three-level V-type system is above the shot-noise limit in a wide parameter range studied here.

PACS number(s): 42.55.Ah, 42.50.Hz, 32.80.Bx

I. INTRODUCTION

Recently considerable attention has been directed to the study of lasing without the requirement of population inversion (LWI). Quite a few models have been proposed, and the conditions for the onset of lasing action have been examined [1–10]. Experimentally, laser action related to a noninverted population in a strongly driven two-level system has been demonstrated before [11–13], and light amplification without population inversion in multilevel atomic systems has been reported in a number of recent publications [14–18]. Interestingly, the optical coherence and quantum interference associated with the light amplification may lead to unusual statistical properties in inversionless lasers. Agarwal showed that lasers without inversion may have a narrower linewidth than that of conventional lasers [19]. Gheri and Walls [20] found that amplitude-squeezed light can be generated in an inversionless, three-level Λ system. Amplitude-squeezed lasing may also be found in a four-level cyclic atomic system pumped by a single coherent field [21].

Sub-Poissonian photon statistics have been measured in diode lasers with noise-suppressed pump current [22]. Recently it has been shown that sub-Poissonian light can also be generated by dynamic pump noise suppression [23–26]. The basic principle is that the recycling of many incoherent steps leads to highly regular pumping, and results in sub-Poissonian photon statistics. In an inversionless laser, two factors may contribute to the noise deduction: first, the fast coherent cycling of electrons between states connected by a two-phonon scattering process leads to the highly regulated absorption and emission processes; second the disappearance of the population inversion leads to a depleted atomic population in the upper lasing state, which decreases the spontaneous emission noises. The combination of these two mechanisms can reduce the laser amplitude noise to below the shot noise limit. For laser without inversion in the three-level Λ system, overall the maximum amplitude squeezing of 50% is predicted [20]. For the four-level inversionless system, the amplitude squeezing may reach a level of more than 50% below the shot-noise limit [21]. Naturally, a question arises: does an inversionless laser always generate amplitude-squeezed light? In this paper, we present an analysis of laser intensity and statistical properties of an inversionless three-level V system, and show that under reasonable operating conditions, no amplitude-squeezed light can be generated in the inversionless V system.

II. THREE-LEVEL V-TYPE SYSTEM

Our model consists of an ensemble of N closed three-level V-type atoms confined in an optical cavity with photon loss rate 2κ. The atoms have ground state $|1\rangle$, and excited states $|2\rangle$ and $|3\rangle$, as illustrated in Fig. 1. The transition $|1\rangle \leftrightarrow |2\rangle$ of frequency ω_{21} is driven by a strong coherent field of frequency ω_1 with Rabi frequency 2Ω. The transition $|1\rangle \leftrightarrow |3\rangle$ of frequency ω_{31} is incoherently pumped with a rate Λ. g is the cavity-atom coupling coefficient. $2\gamma_{ij}$ is the spontaneous decay rate from state $|i\rangle$ to state $|j\rangle$. We treat classically the external coherent field which drives the transition $|1\rangle \leftrightarrow |2\rangle$, but keep the cavity field quantized. In the electric-dipole and rotating-wave approximations, the system Hamiltonian (setting $\hbar = 1$) can be written as

$$\hat{H} = \sum_{j=1}^{N} \{\omega_{31}\hat{\sigma}_{33j} + \omega_{21}\hat{\sigma}_{22j} + \Omega(e^{-i\omega_1 t}\hat{\sigma}_{21j} + e^{i\omega_1 t}\hat{\sigma}_{12j})\} + \sum_{j=1}^{N} g(\hat{a}\hat{\sigma}_{31j} + \hat{a}^{\dagger}\hat{\sigma}_{13j}) + \omega_c \hat{a}^{\dagger}\hat{a}, \tag{1}$$

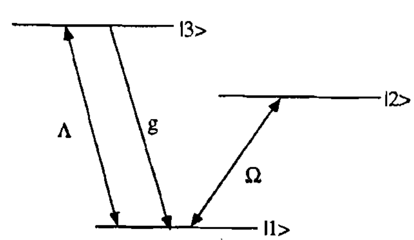

FIG. 1. V-type three-level model for lasing without population inversion. $|3\rangle \rightarrow |1\rangle$ is the lasing transition.

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OPTICS COMMUNICATIONS

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Hyperfine spectroscopy of highly-excited atomic states based on atomic coherence

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Abstract

The hyperfine structures of highly-excited atomic states can be determined by electromagnetically-induced transparency experiment based on atomic coherence. We report an experiment on the excited states $5D_{5/2}$ in ^{85}Rb atoms in a vapor cell. A theoretical model is presented and is in good agreement with the experimental results.

1. ·oduction

Recently, lasing without inversion (LWI) [1–4], electromagnetically-induced transparency (EIT) [5–7], and enhancement of dispersion with reduced absorption [8–10] in atomic systems have attracted many interests. The physical mechanism behind these effects is the atomic coherence, i.e., a well-defined phase relation between atomic states. In a three-level Λ-type system with the lower levels being a near-degenerate state pair (the transitions between the upper state and the two lower states are dipole allowed), coherent superposition states between the two lower states (atomic coherence) can be established when a coherent coupling field is tuned to be on resonance with the atomic transition between the upper state and one of the lower states and a weak probe field is tuned to the other transition [6]. In a three-level cascade atomic system, as another example, atomic coherence can be established between the ground state and the highly-excited state by applying a coherent coupling field to the upper transition and a weak probe field to the lower transition [7]. As a direct result of the atomic coherence, EIT for the weak probe field is achieved, as demonstrated by recent experiments in different atomic systems [5–7]. Applications of this atomic coherence effect in enhancing the efficiency of nonlinear optical processes were also demonstrated [11].

In real atomic systems, the atomic states related to the coupling field usually have many hyperfine levels which may contribute to the atomic coherence. When the FWHM linewidth of the coupling field or the power-broadened natural linewidth of the associated atomic transition is broader than the separations between the hyperfine components, one can not resolve these components simply due to the fact that the hyperfine structures are completely concealed by these broad linewidths. The interesting case is that, when the linewidths of the coupling field and the power broadening are much smaller than the hyperfine separations, the hyperfine components will contribute to the atomic coherence separately. In such a case, one will be able to resolve the closely spaced hyperfine components as the probe frequency is scanned through the whole range of the hyperfine structures and the absorption

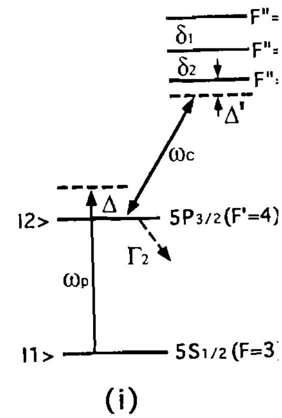

Fig. 1. Cascade atomic system (^{85}Rb
hyperfine structures. Δ and Δ' are ato
are atomic natural decay rates; (ii) dr

spectrum of the probe beam i
by this basic idea, we propose
method with high resolution a
the hyperfine structures of highl
[12]. Compared with conventic
resolution spectroscopic metho
absorption [13], this method h
For example, the coupling fie
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tion method). The hyperfine st
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In this communication, we
structure measurement of the
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2. Hyperfine spectroscopy i

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RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 51, NUMBER 3 MARCH 1995

Observation of an electromagnetically induced change of absorption in multilevel rubidium atoms

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A 64.4% reduction in absorption at the rubidium $D2$ line is observed when a pumping field at 775.8 nm is tuned on resonance to the transition between the excited states $5P_{3/2}$ and $5D_{5/2}$. As the pumping field is tuned off resonance, an absorption peak appears at the side of the Doppler-broadened $D2$ line. This modification in absorption is related to pumping-induced atomic coherence in this three-level ladder-type system. This experiment is done in a Rb vapor cell at room temperature and with cw diode lasers for both pumping and probe beams in a Doppler-free configuration.

PACS number(s): 42.50.Rh, 42.50.Md, 32.80.Wr, 42.65.Ky

Atomic coherence in a three-level system interacting with two near-resonant monochromatic fields was studied many years ago [1–4]. The effect of an electromagnetically induced transparency (EIT) observed recently [5] is a result of atomic coherence induced between atomic levels and a special case of the general formalism given by Whitley and Stroud [1] and others [3]. However, the EIT effect is different from the previous known effects in three-level atoms; e.g., coherent population trapping [1,2] and three-level laser spectroscopy [3,4]. The EIT effect is a modification of the absorption profile of an atomic transition when the upper level is coherently coupled to a third level by a strong laser field. Under the proper conditions, the absorption of a weak probe beam at the resonance frequency with the probed transition can be substantially reduced. Due to the reduced absorption, the EIT effect in an optically thick medium has possible applications in nonlinear optics [6], lasing without inversion [7], enhancement of dispersion [8], and quantum noise reduction [9]. Harris's group demonstrated the EIT effect with pulsed lasers in a three-level Λ-type system of strontium and a three-level ladder-type system of lead [5]. In their experiment with three-level ladder-type lead atoms, the probe beam and the pumping (or coupling) beam propagate collinearly through the lead vapor cell. The essential requirement for observing EIT in their experiments is that the Rabi frequency of the pumping field has to exceed the inhomogeneously broadened width of the transition line, which requires a strong pulsed laser as pumping field.

In this paper, we report the observation of an electromagnetically induced modification of the absorption in the three-level ladder-type system of rubidium atoms with cw diode lasers. In our experiment, the probe beam and the pumping beam are in a counterpropagating configuration, which enables us to lower the requirement of pumping power and, therefore, use cw diode lasers for both pumping and probe beams. The relevant energy levels are shown in Fig. 1. The pumping laser at 775.8 nm couples the upper transition from state $5P_{3/2}$ (state $|2\rangle$) to state $5D_{5/2}$ (state $|3\rangle$) and the probe laser at 780.0 nm couples one hyperfine transition of state $5S_{1/2}$ ($F=3$) (state $|1\rangle$) to state $5P_{3/2}$ (state $|2\rangle$), which is the Rb $D2$ line. Since frequencies of the pumping and probe lasers are continuously tunable within several gigahertz in our experiment, we can study the transition from on-resonance pumping, which reduces probe absorption (the EIT effect), to off-resonance pumping, which increases probe absorption due to the two-photon transition. Due to the Doppler-free nature of the two-photon excitation scheme ($5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$) in this three-level system, we can use lower-power lasers to observe the EIT effect in an inhomogeneously broadened vapor medium.

To understand the modification of the probe absorption, noting Fig. 1, in the absence of the 775.8-nm pumping laser, the 780.0-nm probe beam will be absorbed by the Doppler-broadened $|1\rangle$-$|2\rangle$ transition with about 540 MHz full width at room temperature. With the pumping laser present, the atomic coherence between states $|1\rangle$ and $|3\rangle$ is produced via a two-photon transition from $|1\rangle$ to $|3\rangle$. When the resonance condition ($\Delta\omega_p+\Delta\omega_c=0$) is satisfied, the absorption of the probe laser on the $|1\rangle$-$|2\rangle$ transition will be greatly modified, where $\Delta\omega_p=\omega_p-\omega_{12}$ is the detuning of the probe laser, $\Delta\omega_c=\omega_c-\omega_{23}$ is the detuning of the pumping laser, ω_p,ω_c are the frequencies of the probe and pumping (or coupling) lasers, and ω_{12},ω_{23} are the resonant frequencies of the $|1\rangle$-$|2\rangle$ and $|2\rangle$-$|3\rangle$ transitions, respectively. Two effects on the $|1\rangle$-$|2\rangle$ absorption are expected by the modification of the two-photon transition. One is two-photon absorption, which enhances the absorption for the probe laser, and the other effect is the EIT effect, which leads to a reduction in absorption. As pointed out in Ref. [5], when the Rabi frequency Ω_c of the pumping laser is much less than the square root of the product of the Doppler width $\Delta\omega_D$ of the $|1\rangle$-$|3\rangle$ transition and the detuning $\Delta\omega_p=\omega_p-\omega_{12}$ of the probe

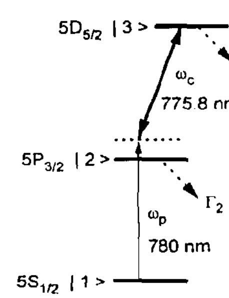

FIG. 1. Relevant energy levels of the neutral rubidium atom.

Transient properties of an electromagnetically induced transparency in three-level atoms

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We describe the transient behavior of an electromagnetically induced transparency in three-level atomic systems. When the coupling field is switched on, the absorption for the probe field is oscillatorily damped to its new steady-state (transparent) value. Transient gain without population inversion and enhancement of dispersion are discussed. A realistic system for experimental testing of these effects is presented.

It has recently been shown that when a strong (coupling) field is applied to one transition ($|2\rangle - |3\rangle$) of a three-level system, as shown in Fig. 1, a weak probe field tuned to the other transition ($|1\rangle - |2\rangle$) sees reduced absorption even with most of the atoms in the ground state $|1\rangle$.[1–4] This electromagnetically induced transparency (EIT) effect is an essential mechanism for lasing without inversion[5,6] and has attracted much recent theoretical interest, e.g., for the reduction of quantum noise,[7] for quantum correlation,[8] and for pulse matching.[9] The EIT effect has promising applications in nonlinear optics[2] and also exists in solid materials.[10] The dispersive properties of EIT have been discussed[11] and measured experimentally.[4] Transient behaviors of lasing without inversion systems were also discussed.[12]

In this Letter we discuss the transient properties of EIT in three-level atomic systems. The motivation arises from cw-induced transparency experiments[3,4] in which the absorption and dispersion properties in steady states were measured. The questions are: When the coupling field is switched on, how fast can the atomic medium become transparent for the probe field? Is this response time limited by atomic decay rates or by the Rabi frequency (Ω_2) of the coupling field? The transient properties of EIT are very important for its potential application in an optical switch, in which the transmission of a highly absorptive medium is optically controlled by an additional coupling field. By solving the time-dependent density-matrix equations, we found that, as the coupling field is switched on, under the right circumstances the amount of probe absorption by the atomic medium acts as the amplitude of a damped harmonic oscillator. The absorption becomes negative (or gain) at time scale Ω_2^{-1} and then oscillatorily approaches its steady-state (transparent) value at the time scale of lifetime of the state $|2\rangle$.

We begin with the density-matrix equations of a ladder-type three-level system, as shown in Fig. 1(a). All the results and discussions are applicable to the Λ-type three-level system. We assume that a cw weak probe field is tuned to the transition $|1\rangle - |2\rangle$. The cw coupling field tuned to transition $|2\rangle - |3\rangle$ is switched on at time $t = 0$. The equations for the matrix elements of the atomic density operator take the form[3]

$$\dot{\rho}_{21} = (i\Delta_1 - \gamma_{21})\rho_{21} + i\frac{\Omega_1}{2}(\rho_{22} - \rho_{11}) - i\frac{\Omega_2^*}{2}\rho_{31}, \quad (1a)$$

$$\dot{\rho}_{32} = (i\Delta_2 - \gamma_{32})\rho_{32} + i\frac{\Omega_2}{2}(\rho_{33} - \rho_{22}) + i\frac{\Omega_1^*}{2}\rho_{31}, \quad (1b)$$

$$\dot{\rho}_{31} = [i(\Delta_1 + \Delta_2) - \gamma_{31}]\rho_{31} - i\frac{\Omega_2}{2}\rho_{21} + i\frac{\Omega_1}{2}\rho_{32}, \quad (1c)$$

$$\dot{\rho}_{11} = -i\frac{\Omega_1^*}{2}\rho_{21} + i\frac{\Omega_1}{2}\rho_{21}^* + \Gamma_2\rho_{22}, \quad (1d)$$

$$\dot{\rho}_{33} = i\frac{\Omega_2^*}{2}\rho_{32} - i\frac{\Omega_2}{2}\rho_{32}^* - \Gamma_3\rho_{33}, \quad (1e)$$

with the condition $\rho_{11} + \rho_{22} + \rho_{33} = 1$. $\gamma_{ij} = (\Gamma_i + \Gamma_j)/2$; Γ_2 and Γ_3 are the decay rates from level $|2\rangle$ to level $|1\rangle$ and from level $|3\rangle$ to level $|2\rangle$, respectively; level $|1\rangle$ is the ground state ($\Gamma_1 = 0$); $\Delta_1 = \omega_1 - \omega_{21}$ and $\Delta_2 = \omega_2 - \omega_{32}$ are the detunings of the probe and coupling fields, and Ω_1 and Ω_2 are their Rabi frequencies; and ω_{21} and ω_{32}

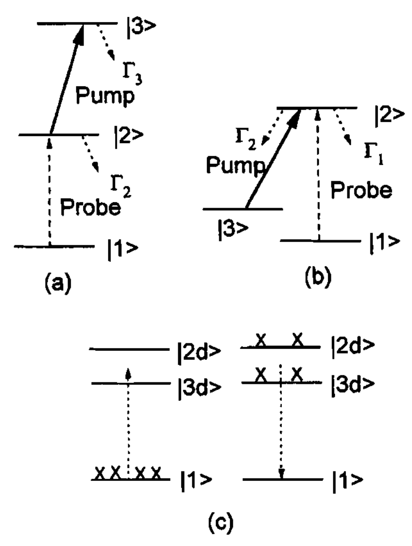

Fig. 1. (a) Ladder-type three-level system; (b) Λ-type system. The coupling laser is denoted by the solid line and the probe laser by the dashed line. (c) Dressed-state pictures: left, atoms in level $|1\rangle$ will not absorb probe laser light; right, stimulated emission of the excited atoms by the probe laser.

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Observation of quantum interference between dressed states in an electromagnetically induced transparency

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We report on an experimental observation of quantum interference between two dressed states created by a coherent pumping laser in an electromagnetically induced transparency. In a Λ-type three-level atomic system in rubidium vapor, we reduce the Rabi frequency of the pumping laser in one arm down below the spontaneous decay rate of the common excited state and still observe a narrow dip with subnatural linewidth in the absorption curve of a probe beam in another arm. This clearly demonstrates that the absorption reduction at the low pumping intensity is mainly due to the interference between the two dressed states, not due to the ac–Stark-shift effect.

PACS number(s): 42.50.Rh, 42.50.Md, 32.80.Wr, 42.65.Ky

Recently, Imamoğlu and Harris have shown that destructive interference between dressed lifetime-broadened states created by an additional (pumping) electromagnetic field produces a zero absorption (dip) in the absorption profile of a weak probe field in a three-level atomic system [1]. This destructive interference between the transition probability amplitudes from the ground state to the excited doublets (dressed states) is a Fano-type interference and plays an important role in lasing without inversion [2,3] and in electromagnetically induced transparency (EIT) [4–7]. However, in all the previous EIT experiments [4–7], the pumping Rabi frequency is relatively large compared to the lifetime-broadened decay rate of the dressed states and, therefore, the reduction in the absorption at resonance is the result of a combination of the ac-Stark shift and the interference of dressed states [4]. In this paper, we report an experiment done in a Doppler-broadened rubidium vapor cell with the pumping Rabi frequency well below the decay rate of the dressed states. A narrow dip with subnatural linewidth in the center of the absorption profile was observed. Due to the fact that the ac-Stark shift has a negligible contribution to the dip in the absorption profile for the pumping Rabi frequency used in our experiment, the observed reduction in the absorption profile is direct evidence of interference between the dressed lifetime-broadened states.

Note in Fig. 1, when a resonant pumping field (with Rabi frequency Ω_2) is applied to the transition $|3\rangle-|2\rangle$, the common excited state $|2\rangle$ can be viewed as two dressed states ($|2d\rangle$ and $|3d\rangle$), separated by pumping Rabi frequency Ω_2 through the ac-Stark splitting or Autler-Townes effect. When a weak probe beam (with Rabi frequency Ω_1) is tuned to the transition from state $|1\rangle$ to the middle of the two dressed states $|2d\rangle$ and $|3d\rangle$ (which is the transition $|1\rangle-|2\rangle$ in the bare-state picture), two effects will contribute to the absorption reduction of the probe field. One is the ac-Stark shift (states $|3d\rangle$ and $|2d\rangle$ are shifted by $\pm\Omega_2/2$ from the probe resonance, respectively) and the other is the interference between the two transition paths of $|1\rangle-|2d\rangle$ and $|1\rangle-|3d\rangle$. Since these two quantum-mechanical paths couple to the same final level $|2\rangle$ by the coherent pumping field, Fano-type destructive interference [8] occurs and leads to zero absorption. Following Refs. [1] and [2], the equations for the time-varying amplitudes of ground level $|1\rangle$ (C_1) and of upper dressed levels $|2d\rangle$(C_{2d}) and $|3d\rangle$ (C_{3d}) can be expressed as

$$\frac{\partial C_1}{\partial t}=-\frac{\Gamma_3}{2}C_1-i\frac{\Omega_1^*}{2}(C_{2d}\cos\theta+C_{3d}\sin\theta)\ ,$$
$$\frac{\partial C_{2d}}{\partial t}=\left[-\frac{\Gamma_{2d}}{2}+i\Delta_{2d}\right]C_{2d}-i\frac{\Omega_1}{2}C_1\cos\theta+\kappa_{23}C_{3d}\ , \quad (1)$$
$$\frac{\partial C_{3d}}{\partial t}=\left[-\frac{\Gamma_{3d}}{2}+i\Delta_{3d}\right]C_{3d}-i\frac{\Omega_1}{2}C_1\sin\theta+\kappa_{23}C_{2d}\ .$$

The quantities in these equations and the relations between bare states ($|2\rangle$ and $|3\rangle$) and dressed states ($|2d\rangle$ and $|3d\rangle$) are given by

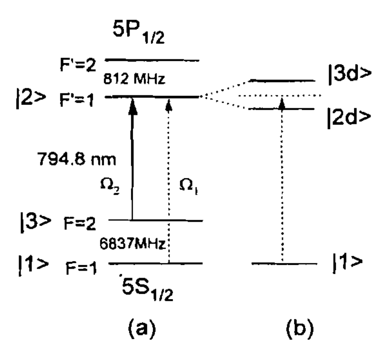

FIG. 1. Relevant energy diagram of the $D1$ line of the Rb^{87} atom. (a) Bare-state picture; (b) dressed-state picture. The pumping laser is represented by the solid line and probe laser is represented by the dashed line.

Measurement of Dispersive Properties of Electromagnetically Induced Transparency in Rubidium Atoms

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The dispersive properties of the atomic transition in the rubidium D_2 line ($5S_{1/2}$–$5P_{3/2}$) at 780.0 nm are measured with a Mach-Zehnder interferometer when an additional coupling field at 775.8 nm is applied to an upper transition ($5P_{3/2}$–$5D_{5/2}$). This ladder-type system is observed to exhibit electromagnetically induced transparency together with a rapidly varying refractive index. A reduction in group velocity for the probe beam ($v_g = c/13.2$) is inferred from the measured dispersion curve with 52.5% suppressed absorption on resonance.

PACS numbers: 42.50.Hz, 32.70.–n, 42.25.Bs, 42.65.An

Electromagnetically induced transparency (EIT) is a modification of the absorption profile of an atomic transition when the upper level is coupled coherently to a third level by a strong laser field. Under the right circumstances, the absorption of a weak probe beam at the resonance frequency can then be substantially reduced. There exists by now a large amount of literature on this subject [1–5]. A number of experiments have also been carried out [2]. In addition to the possible applications of the reduced absorption effect [3] (including lasing without inversion), the dispersion properties of these systems have also been predicted to be of interest: Harris, Field, and Kasapi have predicted a reduction in the group velocity of a pulsed probe beam [4] due to the rapidly varying refractive index near line center. Scully and Fleischhauer have considered the possibility of using the enhanced index of refraction without absorption in a novel atomic magnetometer [6].

We report here the direct measurement of the dispersive properties of an EIT medium [a gas of rubidium (Rb) atoms, with the three interacting levels arranged in a cascade configuration, see Fig. 1]. In addition to the large and rapidly changing index of refraction predicted by the theory, our experiment shows that, because of the two-photon nature of the effect, it is possible to observe it in a Doppler-broadened medium with much lower laser powers than have been used previously, by making use of a Doppler-free configuration. In particular, we are able to use a cw laser diode for the coupling beam and to let the coupling Rabi frequency (i.e., the dynamic Stark shift of the upper level) be much smaller than the full Doppler width of the probe transition.

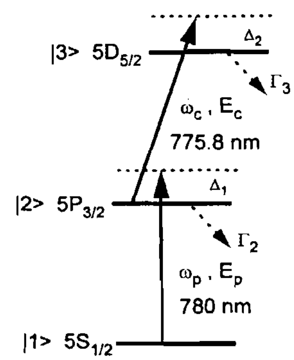

FIG. 1. Relevant energy levels of neutral rubidium atom.

In Fig. 1, the weak beam E_p at frequency ω_p probes the transition $|1\rangle \to |2\rangle$, while the levels $|2\rangle$ and $|3\rangle$ are coupled by the strong beam E_c at frequency ω_c. Under these conditions the reduced absorption has been explained as a combination of the ac-Stark splitting and quantum interference in the decay of the dressed states created by the coupling field [2,7]. In the bare-state picture, on the other hand, the EIT and the rapidly varying index of refraction can be thought of as being due to the coherence between the levels $|1\rangle$ and $|3\rangle$ which is induced by the probe and coupling fields [8]. When the atomic velocity distribution cannot be neglected, as is the case in our experiment, a straightforward semiclassical analysis [9] shows that the contribution of the atoms with velocity v to the complex susceptibility of the probe transition is given by

$$\chi(v)\,dv = \frac{4i\hbar g_1^2/\epsilon_0}{\gamma_{21} - i\Delta_1 - i\omega_p \dfrac{v}{c} + \dfrac{\Omega_c^2/4}{\gamma_{31} - i(\Delta_1 + \Delta_2) - i(\omega_p - \omega_c)v/c}} N(v)\,dv\,, \qquad (1)$$

where the detunings Δ_1 (detuning of the probe laser from the transition $|1\rangle \to |2\rangle$) and Δ_2 (detuning of the coupling laser from the transition $|2\rangle \to |3\rangle$) are defined as the nominal detunings for an atom at rest, and the

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Electromagnetically induced transparency in ladder-type inhomogeneously broadened media: Theory and experiment

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We develop a theory of electromagnetically induced transparency in a three-level, ladder-type Doppler-broadened medium, paying special attention to the case where the coupling and probe beams are counterpropagating and have similar frequencies, so as to reduce the total Doppler width of the two-photon process. The theory is easily generalized to deal with the Λ configuration, where the ideal arrangement involves two copropagating beams. We discuss different possible regimes, depending on the relative importance of the various broadening mechanisms, and identify ways to optimize the absorption-reduction effect. The theory is compared to the results of a recent experiment (on a ladder-type system), using the Rb $D2$ line, with generally very good agreement. The maximum absorption reduction observed (64.4%) appears to be mostly limited by the relatively large (~ 5 MHz) linewidth of the diode lasers used in our experiment.

PACS number(s): 42.50.Hz, 32.80.Wr, 42.65.Ky

I. INTRODUCTION

Electromagnetically induced transparency (EIT) is the effect behind some recent proposals for lasing without inversion [1]. A possible level scheme for EIT is shown in Fig. 1(a). Under normal circumstances, with most of the population in the lower level $|1\rangle$, the probe beam on resonance with the $|1\rangle \rightarrow |2\rangle$ transition would be strongly absorbed. When a strong "coupling beam" resonant with the $|2\rangle \rightarrow |3\rangle$ transition is added, however, absorption of the probe beam can be greatly reduced (although most of the population is still in the ground state). This possibility of controlling the transparency of a medium by using another beam of light may have useful applications in electro-optical devices and nonlinear optics, in addition to the lasing without inversion applications mentioned earlier [2]. Also, systems similar to the one in Fig. 1(a) have been predicted to exhibit unusual dispersive properties which might also lead to useful new devices [3].

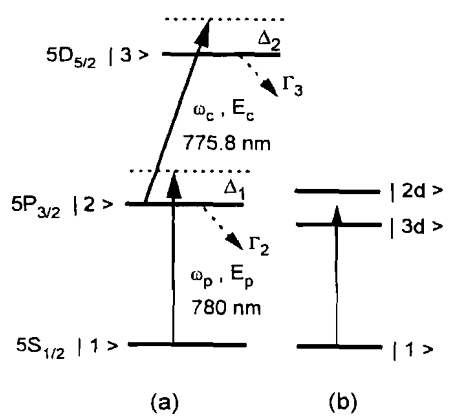

FIG. 1. (a) Relevant energy levels of neutral rubidium atom. (b) Dressed-state picture.

We present here the theory of a recent experiment [4] we carried out on the system of Fig. 1(a) (a gas of rubidium atoms). We believe this experiment to be the first one to observe EIT in an inhomogeneously broadened medium, with cw lasers continuously tunable over a broad range of frequencies [5]. This makes a detailed, quantitative comparison to a relatively simple theory possible and this is one of the main purposes of this article. As regards the theoretical treatment itself, its main new feature is the explicit inclusion of inhomogeneous broadening, which is treated exactly (to lowest order in the weak probe field) so that the influence of the various broadening mechanisms may be assessed in a variety of different regimes and in particular in the "almost Doppler-free" configuration of our experiment. Our formulas for the ladder system can easily be extended to the Λ configuration and we also indicate how to do it here.

Our paper is organized as follows. In Sec. II we present the theoretical results and in Sec. III a discussion of the experiments and detailed comparison to the theoretical predictions. Section IV contains some brief concluding remarks. Section II is further divided into several subsections, dealing with the derivation of the general, analytical results, their generalization to the Λ level scheme, numerical and analytical study of various limits of interest, and a brief summary of the main points.

II. THEORY

A. General results for the ladder system

Consider the three-level system in Fig. 1(a). Let ω_{21} be the frequency of the $|1\rangle \rightarrow |2\rangle$ transition, ω_p the frequency of the probe laser, and $\Delta_1 = \omega_p - \omega_{21}$ its detuning, and similarly let ω_{32} be the frequency of the $|2\rangle \rightarrow |3\rangle$ transition, ω_c the frequency of the "coupling" laser, and $\Delta_2 = \omega_c - \omega_{32}$ its detuning. Using standard semiclassical

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Electromagnetically induced transparency in a three-level Λ-type system in rubidium atoms

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An electromagnetically induced transparency is observed at one arm of a three-level Λ-type system in a rubidium $D1$ line (794.8 nm) with an 85% reduction in absorption, when a pumping field is present at the other arm. This reduction in absorption for the weak probe field is due to the atomic coherence produced by the strong pumping field. This experiment is done in a Rb vapor cell at room temperature with cw diode lasers for both pumping and probe beams in a Doppler-free configuration. A simple theoretical treatment including Doppler broadening is in good qualitative agreement with the experimental measurement.

PACS number(s): 42.50.Rh, 32.90.+a, 42.65.−k

Electromagnetically induced transparency (EIT) in multilevel atomic systems has attracted great attention in recent years due to its possible applications in nonlinear optics [1–3]. The EIT effect is also the mechanism behind the recently demonstrated gain without population inversion in multilevel atomic systems [4]. Although many theoretical papers have been published in recent years, only a few experimental demonstrations of the EIT effect in simple atomic systems have been reported [1–3]. Among them, the only experiment done in a Λ-type system was by Harris and coworkers [1]. In their experiment, a heated Sr atomic vapor was used and all the relevant levels were excited states. Due to the requirement for very high pumping power to overcome the collisional and Doppler broadenings, a pulsed laser was used as the pumping beam. The existence of gain is predicted when both coherent and incoherent pumping fields are present [5]. Population trapping states [6] have been observed in an atomic beam experiment [7] and an atomic vapor experiment [8]. Quantum-statistical properties were calculated with 50% squeezing predicted in the output beam of an inversionless laser built in such a system [9]. Matched photon statistics and correlation effects have also been predicted [10]. However, due to the complication of the optical pumping and nonlinear Faraday effects in real atomic systems, to our knowledge, experimental demonstration of the EIT effect has not been reported in an ideal *closed* Λ-type system until now.

In this work, we have chosen a closed three-level Λ-type system in ^{87}Rb atoms to show the EIT effect. The $D1$ line of the ^{87}Rb is shown in Fig. 1. The hyperfine level $F'=2$ of $5P_{1/2}$ serves as excited state $|2\rangle$. The hyperfine levels $F=1$ and $F=2$ of the ground state $5S_{1/2}$ serve as two ground states $|1\rangle$ and $|3\rangle$ of the Λ-type system, respectively. Another hyperfine level $F'=1$ of the excited states $5P_{1/2}$ is 812 MHz away (outside the Doppler width of the transition line) and can be neglected. The atoms are pumped between the $5S_{1/2},F=2$ and $5P_{1/2},F'=2$ states by a pumping laser with Rabi frequency Ω_2 (solid lines) and probed between the $5S_{1/2},F=1$ and $5P_{1/2},F'=2$ states by a weak probe laser with Rabi frequency Ω_1 (dotted lines). The EIT effect means that, when the pumping laser is present, the weak probe laser is affected by reduced absorption at the resonant frequency, although almost all the atoms are optically pumped to populate the $5S_{1/2},F=1$ state. This pump-probe experiment in a three-level system is different from the previous experiments in a two-level system [11], where a strong laser resonantly dresses a two-level system via the ac Stark effect, a weak probe laser probes the sideband transitions, and then Mollow-sideband gain is found.

Although there are many degenerate magnetic sublevels in each of these hyperfine levels, they can be considered simply as an effective three-level Λ-type system for the EIT effect. This can be understood as follows: the strong pumping laser pumps all the populations from state $|3\rangle$ to the sublevels of state $|1\rangle$, and the probe laser is weak enough so that its effect on atomic populations can be neglected. Assuming that the pumping and probe lasers are orthogonally linearly polarized, it is easily shown that each probed transition (π transition on the right-hand side of Fig. 1) from a sublevel of state $|1\rangle$ to state $|2\rangle$ is coupled to a σ^+- or a σ^--pump transition from a sublevel of state $|3\rangle$ to state $|2\rangle$ with an effective Rabi frequency. Due to the fact that the atomic population of state $|3\rangle$ is small and can be neglected, the coherence between the magnetic sublevels of state $|3\rangle$ is unimportant for the transparency of the probed transitions. Due to the weakness of the probe laser, the probed transitions can be thought of as being independent. Thus this system really can be considered as an ideal closed three-level Λ-type system for the purpose of EIT. Similarly, $F'=1$ of the $5P_{1/2}$ excited state can serve as the upper level $|2\rangle$, which is also a closed Λ-type system.

For a closed three-level Λ-type system, the equations of motion for the slowly varying off-diagonal matrix elements

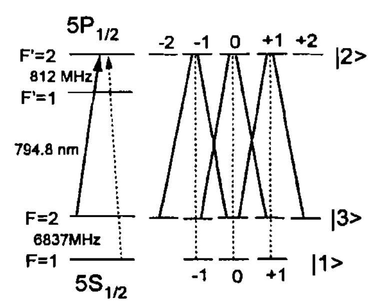

FIG. 1. Relevant energy diagram of the $D1$ line in the ^{87}Rb atom. Solid line, pump transition; dotted line, probe transition. The right-hand part is the diagram with magnetic sublevels.

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Intensity characteristics of inversionless lasers from induced atomic coherence

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We analyze a laser system consisting of N closed three-level atoms confined in a single-mode cavity and derive the conditions for the onset of lasing without inversion or with inversion. We calculate the steady-state gain and lasing in the system and show that far above the lasing threshold, depending on the pumping and decay rates, the inversionless laser may operate in three different regimes, where the intensity of the laser depends linearly on N, is proportional to $\sqrt{N}$, or independent of N.

PACS number(s): 42.55.−f, 42.50.Hz, 32.80.Bx

I. INTRODUCTION

The optical gain and lasing without the requirement of population inversion has been the subject of much interest recently. Light amplification without inversion can be induced by optical coherence among the coupled states driven by laser fields, or by the difference between the absorption and emission paths manifested by quantum interference. Many models have been proposed, and the conditions for the onset of lasing action have been examined [1–7]. The concept of lasing without inversion (LWI) may be useful in the generation of coherent radiations in the wavelength regime where lasing with population inversion is difficult to achieve by conventional pumping mechanisms. It has been shown that the optical coherence and quantum interference associated with the light amplification may lead to novel statistical properties in inversionless lasers, such as reduced laser linewidth and amplitude squeezing [8–11]. Recently, light amplification without population inversion in the transient regime has been observed experimentally by several groups [12–15]. In general, the mechanism of LWI depends on the specific model [7], and particularly, the context of noninversion depends on the specific state basis. In atomic systems driven by external coherent fields, one can find model systems where there is no population inversion in the bare atomic states, but there is population inversion in the dressed states (for example, a strongly driven two-level system [16]). Nevertheless, a few model systems have been shown to exhibit lasing without inversion in any state basis [17,18].

Here we present an analysis of a laser model (see Fig. 1) that consists of an ensemble of N closed three-level atoms incoherently pumped to the upper state $|3\rangle$, and a coherent field drives the transition between states $|1\rangle$ and $|2\rangle$. Lasing occurs from state $|3\rangle$ to state $|2\rangle$. Similar three-level systems have been treated by Fleischhauer *et al.* [19], where the enhanced refractive index without absorption via atomic coherences was analyzed. Here the steady-state gain and lasing will be analyzed. We show that depending on the pumping and decay parameters, this three-level system may exhibit lasing with inversion or LWI (light amplification by coherence), so it serves as a model for both a conventional laser and an inversionless laser. Also, the system may demonstrate a transition from lasing with inversion to LWI [11], indicating that such a transition is common in a coherent driven laser system. Well above the threshold, the intensity of this inversionless laser may show different functional dependence on the total atomic number N, which is correlated to the specific population distributions.

The paper is organized as follows. In Sec. II, we will derive the system Hamiltonian and the semiclassical laser equations of motion. In Sec. III, we derive the conditions for the existence of gain in the system with or without population inversion. In Sec. IV, we discuss the steady-state lasing for the resonant excitation and present calculations for the threshold condition, the lasing intensity, and population distributions above the threshold. In the limit of a large atomic number N, we show that the laser intensity dependence on N is determined by the lasing mechanisms. In Sec. V, we summarize our calculations and discuss the experimental feasibility for the model system.

II. THREE-LEVEL LASER MODEL

Our model consists of an ensemble of N closed three-level atoms confined in a single-mode cavity with photon loss rate 2κ at the output port. The atoms have ground state $|1\rangle$, and excited states $|2\rangle$ and $|3\rangle$ as illustrated in Fig. 1. The excited state $|3\rangle$ is populated from the ground state $|1\rangle$ by incoherent pumping with a rate Λ. The transition $|1\rangle\leftrightarrow|2\rangle$ of frequency ω_{21} is driven by a laser of frequency ω_1 with Rabi frequency 2Ω. g is the single atom-cavity coupling coefficient on the lasing transition $|3\rangle\leftrightarrow|2\rangle$. γ_{ij} $(i,j=1-3)$ is the spontaneous decay rate from state $|i\rangle$ to state $|j\rangle$. We treat classically the external coherent field which drives the transition $|1\rangle\leftrightarrow|2\rangle$, but keep the cavity field quantized. For the convenience of the calculation, Ω and g are chosen to be real. In the dipole approximation, the system Hamiltonian can be written as

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COMMENTS

Comments are short papers which criticize or correct papers of other authors previously published in the **Physical Review**. *Each Comment should state clearly to which paper it refers and must be accompanied by a brief abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.*

Comment on "Lasing without inversion in a V system due to trapping of modified atomic states"

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We point out a mistake in a recent paper [Tan, Lu, and Harrison, Phys. Rev. A **46**, R3613 (1992)] and show that, contrary to the authors' claim, lasing without inversion is impossible in a closed V system driven by a single coherent field only.

PACS number(s): 42.50.Hz, 42.55.−f

Recently one of us proposed a closed three-level V system that exhibits lasing without inversion in any state basis [1]. As illustrated in Fig. 1, the V system requires both *incoherent pumping and coherent pumping* in order to have the optical gain on the transition $|3\rangle \rightarrow |1\rangle$. Such a pumping scheme is similar to that in a three-level Λ system proposed by Imamoglu, Field, and Harris [2], and a three-level cascade system proposed by Prasad and Agarwal [3]. Very recently, Tan, Lu, and Harrison analyzed the three-level V system driven by a single coherent field [4]. They derived the results which indicate that lasing without inversion occurs in their V system. As shown in Fig. 2, their model is the same as in Fig. 1, except that no incoherent pumping is present. We wish to point out that with only a single driving field, it is impossible for the V system to exhibit lasing without population inversion. We show that there is a mistake in their evolution equations for the atomic populations, which inevitably leads to unphysical results.

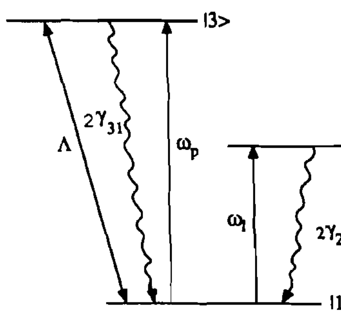

FIG. 1. The three-level V system for lasing without population inversion proposed in Ref. [1]. $2\gamma_{ij}$ $(i,j=1-3)$ is the spontaneous decay rate from state $|i\rangle$ to state $|j\rangle$. ω_p (ω_1) is the frequency of a weak probe field (a strong driving field). Λ is the incoherent pump rate.

Intuitively, with only a *single* coherent field driving the transition $|1\rangle \leftrightarrow |2\rangle$ as shown in their model (see Fig. 2), it is a two-level system (the transition frequency ω_{31} is far different from ω_{21}, so the coherent field does not couple state $|3\rangle$ to either state $|2\rangle$ or state $|1\rangle$). The electron cannot make the transition to state $|3\rangle$; consequently no photon will emit from state $|3\rangle$ and light amplification around the frequency of the transition $|3\rangle \leftrightarrow |1\rangle$ will never occur.

To put the above argument in a rigorous mathematical form, we start from the semiclassical Hamiltonian for the V system in Fig. 2 without the incoherent pumping [1]:

$$\hat{H} = \omega_{31}\hat{\sigma}_{33} + \omega_{21}\hat{\sigma}_{22} + \frac{\Omega}{2}(e^{-i\omega_1 t}\hat{\sigma}_{21} + e^{i\omega_1 t}\hat{\sigma}_{12}) + \frac{g}{2}(e^{-i\omega_p t}\hat{\sigma}_{31} + e^{-i\omega_p t}\hat{\sigma}_{13}) \ . \qquad (1)$$

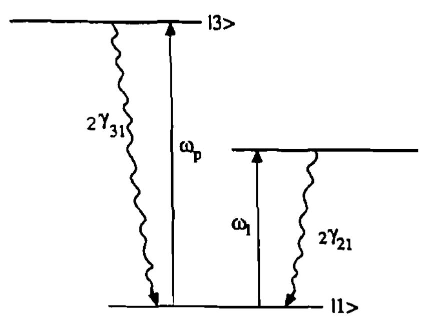

FIG. 2. The three-level V system for lasing without population inversion proposed by Tan, Lu, and Harrison [4]. No incoherent pumping is applied. We show that it is impossible to achieve lasing without population inversion in this system.

Observation of localized domain reversal of iron-doped potassium niobate ($Fe: KNbO_3$) single crystal

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Localized reversal of patterns formed by ferroelectric domains on the naturally grown surface in an iron-doped potassium niobate ($Fe: KNbO_3$) single crystal has been observed. Surface-profile measurement, scanning electronic microscopy, and the metalomicroscopy methods were used to verify the observation. The mechanism of forming this domain structure is discussed.

Potassium niobate ($KNbO_3$) crystal is a kind of oxygen octahedral ferroelectric crystal which has perovskite structure. When cooling down, it transforms from cubic to tetragonal, orthorhombic, and rhombohedral phases at temperatures of 435, 225, and $-10\,°C$, respectively.[1] Recent experiments showed that iron doping in potassium niobate could greatly enhance the photorefractive effect in the near-IR spectral range.[2–4]

It is well known that domain structures are very common in ferroelectric crystals, such as $KNbO_3$, due to the local variation of electric field when cooling down from the melting temperature in the growth process. Mishra and Ingle showed that impurities play a significant role in domain formation in $KNbO_3$ single crystals.[5] The impurities in the crystal nucleate microdomains around them through the mechanism of domain-wall nucleation. The mechanism is operative both at the Curie transition and when switching under externally applied dc electric fields.[6]

Iron-doped potassium niobate ($Fe:KNbO_3$) single crystal was first grown by Fluckiger and Arend in 1978 using the Czochraski method.[7] Because of the doping of Fe^{3+} ions in the crystal, nucleations occur under the influence of the doping ions and, therefore, the domain walls in the iron-doped potassium niobate crystal in most cases are easier to move and to grow than in the undoped potassium niobate crystals. Since the nucleation process also depends on strains and defects, the domain pattern does not always correspond to the absolute minimum of the free energy and is only metastable. It is also possible that domains have stabilization effects. Therefore, it is difficult to eliminate completely these domains during the growing process. On the other hand, however, the complicated domain structures are very unique characteristic properties that belong to ferroelectric crystals such as $Fe:KNbO_3$ and other similar crystals which have excellent photorefractive and other properties. Study of domain structures is very important not only for eliminating them, but also for the implication of possible future applications.

In this communication, we report observation of the localized reversal of a kind of comb pattern formed by lens-shaped ferroelectric domains in an iron-doped potassium niobate crystal. We will first describe the preparation of the sample used in this experiment along with the procedure for our study of this new structure. Possible causes for generating this pattern are discussed next.

The crystal used for this study was grown by using the modified top-seeded flux method from a K_2O rich solution of $K_2O+Nb_2O_5$. A table summarizing the KN crystal growth experiments can be found in Ref. 8. Fe^{3+} ions were doped into the raw material by the form of Fe_2O_3. The as-grown crystal turned out to have very complicated domain structures inside and on the surfaces of the crystal. A Fe^{3+} concentration of about 50 ppm in this sample is determined by using atomic absorption spectroscopy. The measurements and studies were done on the shoulder of the crystal. The shoulder surface, where the pictures were taken, remains uncut and unpolished.

We first used a metalomicroscope to look at the shoulder area of the sample. Figure 1(a) was taken with 50× amplification. Those parallel lens-shaped domain structures are aligned to form several slash-line shaped patterns which are parallel to each other. The angle between these patterns and the growth edge is approximately 58°. Figure 1(b) is a picture taken using the metalomicroscope with 100× amplification. One can see that the domain structures are clearly divided into several regions. The dark field and bright field images change signs in certain regions. In other words, images in these different areas are supplementary.

In order to study the relative flatness of these domain structures, SPM (surface profile measurement) plots were taken on the same area of the sample. Figure 2 shows a typical SPM plot which confirms the observation made by using the metalomicroscopy method. Although, only stage/step patterns above the background are shown in this plot, other plots (which are not presented here) do show patterns below the background. Due to the existence of growth patterns and traces on the shoulder of the as-grown crystal, the background is not flat across the measurement range. From the profile plot, we find: after the etching treatment, (a) the domain pattern is about 2 μm above or below the background; (b) the width of domain is about 10–20 μm; (c) the length is about 100–200 μm; and (d) the distance between every slash-line pattern is about 1000 μm.

To get a better understanding and to confirm our results, we also took some SEM (scanning electronic microscope) pictures on the same surface of the sample. Figure 3(a) was taken with 200× magnification, which clearly shows the domain patterns with very sharp and uniform altitude variation-like steps. Figure 3(b) was taken with 950× amplification in which the domain reversal found in metalomicroscope pictures and SPM plots is clearly shown. The original and re-

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Extra intracavity squeezing of a degenerate optical parametric oscillator coupling with N two-level atoms

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Although an ideal degenerate optical parametric oscillator (DOPO) can generate perfect squeezing at the output of a one-sided optical cavity when operating just below threshold, its intracavity squeezing is limited to less than one-half (50%) of its perfect value. However, when two-level atoms are introduced into the DOPO cavity, the amount of intracavity squeezing can be enhanced, from its maximum value of 50%, to a maximum value of 75% in the good-cavity limit due to the strong interaction between the two-level atoms and the subharmonic field mode. This extra intracavity squeezing is significant in studying spectroscopy of atoms interacting with a squeezed field mode inside an optical cavity.

PACS number(s): 42.65.Pc, 42.50.Lc, 42.65.Ky

I. INTRODUCTION

Since the first paper published by Gardiner in 1985 about the effects of squeezed vacuum states on a two-level atom [1], several schemes had been proposed to study atomic spectroscopy with squeezed states of light [2–4]. Although applications of squeezed states of light have been demonstrated in increasing signal-to-noise ratio of phase and amplitude measurement beyond the shot-noise limit [5–7], the true experimental demonstration of atomic spectroscopy, as originally proposed by Gardiner, has not been achieved. The difficulties in real experiments are seen in several aspects. One difficulty is the effective coupling between squeezed fields and the atomic dipole moments of the two-level atoms. Another difficulty is due to the fragile nature of the squeezed states of light for any losses in propagation and the amount of squeezing available at the source.

All the proposed schemes of studying atomic spectroscopy with squeezed states of light can basically be divided into two categories, namely, "passive" and "active" systems. Since a squeezed vacuum in the 4π solid angle surrounding an atom, as proposed by Gardiner [1], is not practical in a real experiment, the most realistic "passive" scheme will be to "feed" atoms inside an optical cavity with squeezed vacuum field or squeezed coherent field from a squeezed light source externally [2]. The optical cavity provides cavity modes which can match the atomic-dipole-radiation pattern and enhance the coupling between the squeezed fields and the atomic dipole. By careful designing, the solid angle sustained by the cavity modes as seen by the atoms can be a large portion of the 4π solid angle, which provides a good approximation for the originally proposed arrangement. The difficulty with this proposal is to "feed" the limited amount of squeezing into the optical cavity containing the atoms. Due to the finite linewidth of the optical cavity, the original assumption of "white" squeezed vacuum (broadband spectrum) has to be compromised and the reduction of the amount of squeezing will also be an important factor. We propose the use of the other approach (the "active" system) by putting the two-level atoms directly inside the "squeezing generator," e.g., the degenerate optical parametric oscillator (DOPO) cavity [4]. By doing so, the coupling between the squeezed field modes and the atoms can be enhanced and the losses in propagation will be eliminated. When the two-level atoms are strongly coupled to the subharmonic field mode inside the DOPO, one cannot talk about the individual system anymore. Instead, we have a composite system whose dynamic evolution is determined by its normal modes. In the weak-coupling limit, the existence of atoms will not greatly alter the DOPO fields and one can consider this system as two-level atoms driven by squeezed field [8] or two-level atoms inside partially squeezed vacuum fields. However, one concern about this approach was the fact that, although the output squeezing of a subthreshold DOPO can be perfect, the amount of intracavity squeezing is limited to 50% [9]. When two-level atoms interact with a 50% squeezed field, the effects, such as decay-rate splitting and linewidth narrowing, will be greatly reduced. In such a case, this scheme may not be better than the one which "feeds" squeezed fields from an external squeezed light source.

In this paper, we show that, under strong-interaction limit, the existence of the two-level atoms inside the DOPO can actually increase the amount of intracavity squeezing from its maximum value of 50% to a maximum value of 75%. This increase of intracavity squeezing is significant in enhancing effects of squeezed fields on the two-level atoms. Also, since the best intracavity squeezing occurs in the good-cavity limit, some interesting new effects will be observed in the atomic fluorescence. This composite system itself is an interesting one to study, because it combines the two simplest, but most distinguished nonlinear systems in the field of quantum optics. The relation between intracavity squeezing and output squeezing in this system will be discussed. We will also discuss the broadening of the intracavity field spectrum due to atoms, which will be a better realization of the "white" spectrum of squeezed vacuum fields.

The paper is arranged in the following way. In Sec. II,

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PHYSICAL REVIEW A VOLUME 48, NUMBER 5 NOVEMBER 1993

Amplitude squeezing and a transition from lasing with inversion to lasing without inversion in a four-level laser

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The steady-state lasing and the photon statistics have been analyzed for a closed four-level-laser system pumped only by a single coherent field. The system exhibits a transition from light amplification by population inversion to light amplification by coherence. Under suitable operating conditions, the laser-intensity fluctuations may be reduced more than 50% below the shot-noise limit.

PACS number(s): 42.55.−f, 42.50.Hz, 32.80.Bx

Considerable attention has been directly recently to the study of lasing without the need of population inversion. Quite a few models have been proposed, and the conditions for the onset of lasing action have been examined [1–9]. The optical coherence and quantum interference associated with the light amplification may lead to interesting statistical properties in inversionless lasers. Agarwal showed that lasers without inversion may have a narrower linewidth than that of conventional lasers [10]. Gheri and Walls [11] found that amplitude squeezed lasers can be generated in an inversionless, three-level Λ system proposed by Imamoglu, Field, and Harris [8]. Amplitude squeezing has also been found in a similar Λ-type Raman laser by Ritsch, Marte, and Zoller [12]. It is recognized that the gain mechanism and the context of noninversion depend on the specific model [7], as do the statistical properties of inversionless lasers [11].

Here we analyze a laser model that consists of an ensemble of N closed four-level atoms driven by a single coherent field [9] (see Fig. 1). Unlike conventional lasers, where population inversion is maintained and kept at the threshold value for arbitrary laser output, the four-level laser analyzed here can start lasing from population inversion and evolves from the population inversion into noninversion with the increasing atomic pumping. In other words, the system makes transition from light amplification by stimulated emission due to population inversion into light amplification by coherence. On the other hand, the system can be also made to start lasing without population inversion in any state basis. In both cases, initial inversion and noninversion, which are controlled by the ratio of spontaneous decay rates, γ_{34}/γ_{21}, the laser well above threshold is always maintained by lasing without inversion (light amplification by coherence) and the laser intensity fluctuations may drop below the shot-noise limit.

Sub-Poissonian photon statistics have been measured in diode lasers with noise-suppressed pump current [13]. Recently it has been shown [14–16] that sub-Poissonian light can also be generated by dynamic suppression of pump noise. The basic principle is that the recycling of many similar incoherent steps leads to highly regular pumping and results in sub-Poissonian photon statistics. For the laser without inversion in the three-level Λ system, both external incoherent pumping and coherent pumping are required. The suppression of intensity fluctuations for the lasing field is achieved at the expense of the enhanced intensity fluctuations in the external driving field. Overall, the maximum amplitude squeezing of 50% is predicted [11]. For the multilevel Raman laser in Ref. [12], the upper lasing state is coherently populated by the driving laser and the maximum squeezing up to 80% below the shot-noise limit has been calculated. For the four-level system analyzed here, the upper lasing state is populated by the incoherent spontaneous decay and the amplitude squeezing of about 70% below the shot-noise limit may be achieved. In these model systems, two factors contribute to the noise reduction: first, the disappearance of the population inversion leads to the depleted atomic population in the upper lasing state, which reduces the spontaneous-emission noises; second, the fast coherent cycling of electrons driven by the coherent pump field and the lasing field leads to the highly regulated absorption and emission processes.

Our model consists of an ensemble of N closed four-

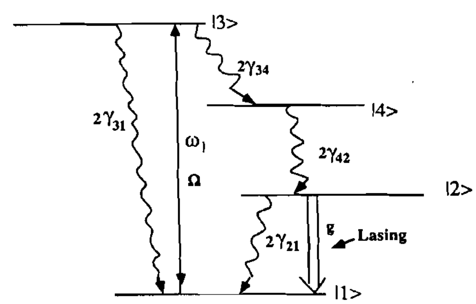

FIG. 1. Four-level model for lasing without or with population inversion. $|2\rangle \rightarrow |1\rangle$ is the lasing transition.

PHYSICAL REVIEW A VOLUME 47, NUMBER 1 JANUARY 1993

Inversionless laser from a closed multilevel system

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We show that a closed four-level system can exhibit lasing without population inversion in any state basis. The same system can be also made to exhibit lasing without population inversion in the bare-state basis but with population inversion in the dressed-state basis. We derive the conditions of lasing without inversion and examine the dependence of the gain on various system parameters. The lasing threshold and the steady-state photon numbers are calculated. Comparison with a V-type, three-level model is presented.

PACS number(s): 42.50.Hz, 42.55.−f, 32.80.Bx

I. INTRODUCTION

Lasing without the requirement of population inversion is a subject of current interest. Lasers based on inversionless systems may have interesting statistical properties, such as reduced spontaneous-emission noise [1]. In addition, the concept of lasing without population inversion may be useful in the generation of coherent radiation in the spectral ranges where lasing with population inversion is impractical with conventional pumping schemes. Mollow showed that a driven two-level system exhibits gain without population inversion [2]. His prediction was later confirmed experimentally by Wu *et al.* [3]. Recently lasers with an ensemble of driven two-level atoms as the active medium have been demonstrated [4,5]. For practical applications, driven two-level systems are not very useful sources of coherent radiation because their lasing frequencies are too close to that of the strong driving field. An inversionless laser becomes useful if it can generate coherent light at frequencies that are quite different from that of the coherent driving source.

Many schemes for lasing without population inversion have been proposed and the dependence of the optical gain on various system parameters has been examined [6–13]. Among the proposed schemes, some are based on the interference effects which result in different emission and absorption profiles in the atomic system; others depend on the utilization of external coherent fields that generate atomic coherence leading to optical gain in the absence of population inversion. In many of these schemes, although there is no population inversion in one state basis (often the bare atomic states), there is a population inversion in the other state basis. An example can be found in the experimentally demonstrated two-level-atom lasers [4,5] where lasing occurs without inversion in the bare states, but the nonresonant excitation leads to a population inversion among the dressed states. So the question of noninversion or inversion depends on the selected state basis. True noninversion should be independent of state bases. For a laser-driven atomic system, there are two meaningful state bases: the bare-state basis, which is the eigenstate basis of the isolated atomic system, and the dressed-state basis, which is the eigenstate basis of the coupled atom-plus-field system. It is desirable to find the model systems exhibiting lasing without population inversion in any of these state bases. It is known that a *resonantly* driven two-level system exhibits lasing without inversion in any state basis [2]. Imamoglu, Field, and Harris proposed a model consisting of a coherently pumped Λ-type, three-level system [14]. They showed that under certain conditions the system exhibits gain for a weak probe laser without the need of population inversion in any atomic state basis. Subsequently, Agarwal presented a dressed-state analysis and concluded that the optical gain in their system can be attributed to the coherence between the dressed states generated by the strong driving field [15]. Recently, we proposed a closed V-type, three-level model [16]. The V-type system is pumped incoherently on the lasing transition, while the other transition is coherently driven by a strong, external field. This system can be made to exhibit lasing without population inversion in both the bare states and the dressed states, or lasing without population inversion in bare states but with population inversion in the dressed states. In many aspects, the gain in a driven V-type system is similar to that in a driven two-level system. For example, both systems exhibit gain without population inversion in any atomic state basis under the on-resonance excitation of an external coherent field. For the off-resonance excitation, both systems exhibit gain without population inversion in the bare atomic state basis but with population inversion in the dressed-state basis. However, important differences exist in the optical gain for these two systems. For a resonantly driven two-level system, the gain occurs at the two Rabi sidebands and presents a dispersive line profile; while for a resonantly drive V-type, three-level system, the gain line profile is absorptive and maximized at the frequency of

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Optical spectra from a degenerate optical parametric oscillator coupling with N two-level atoms

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We study transmitted optical spectra from a realistic system which consists of a degenerate optical parametric oscillator (DOPO) and N two-level atoms. Optical bistability appears when parameters are suitable. Below the modified threshold of the DOPO (lower turning point of the bistable curve), the coherent intensity is always zero at the lower branch, which allows us to describe this system with a set of linear differential equations. By transforming the field and atomic variables into corresponding quadratures, we find that, for the resonance case, one atomic quadrature will only couple to one field quadrature. By separating these two quadratures, we are able to study the effects due to squeezed and unsqueezed quadratures on the atoms. The optical and atomic spectra of this system are obtained, analytically, for arbitrary coupling strength and cavity linewidth.

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I. INTRODUCTION

Subnatural atomic linewidth has been predicted in several systems [1–4]. For different systems, the atomic linewidth narrowing comes from different mechanisms. When a single two-level atom is placed in a squeezed vacuum, the atomic polarization decay rate will be split into two distinguishable rates, with one going to zero and other to infinity as the degree of squeezing increases [1]. This original prediction by Gardiner has created a great deal of interest in this subject and numerous theoretical papers were published since then [2]. Rice and Carmichael have shown that a subnatural linewidth also occurs in ordinary resonance fluorescence, in the absence of the squeezed vacuum [4]. In this case, squeezed light does not irradiate the atom. Squeezed light is produced in the interaction between the driven atom and the modes of the usual vacuum. When one or many two-level atoms are placed in an optical cavity and driven by an external field (atomic optical bistability or AOB), the atomic linewidth narrowing can come from two different sources, as discussed by Carmichael *et al.* [3]. When the cavity field and the atoms are strongly coupled, the composite system will decay with an averaged decay rate of the cavity and the atoms. If the cavity field decays much more slowly than the atoms, the transmitted or fluorescence spectra will be dominated by the atomic decay, which will approach one-half of the natural atomic decay rate. Other than this dynamic averaging effect, squeezing produced in this interaction will also contribute to a maximum of 36% linewidth narrowing to the optical spectra. The atomic linewidth narrowing in this system was experimentally observed in the transmitted optical spectrum [5].

In this paper, we consider a different system, which consists of a degenerate optical parametric oscillator (DOPO) and N two-level atoms [6]. Since DOPO is a "perfect squeezer " [7], we study how this squeezed cavity mode affects the atomic spectra and how the atoms affect the squeezed spectra for different coupling strengths and arbitrary cavity linewidths. At a weak interaction limit, atoms will not change the squeezed cavity field much when the external pumping power is just below the modified DOPO threshold value. The situation is similar to atoms inside a partially squeezed vacuum or atoms driven by a squeezed field. In the strong-coupling limit, the field and the atoms will affect each other and we have to consider this system as a composite one. In such a case, the dynamic averaging effect will play an important role. The essential difference between this system and the one studied by Carmichael *et al.* (atoms inside an optical cavity driven by an external field) [3] is the phase-sensitive gain feature near and above the DOPO threshold. It is this phase-sensitive gain that produces the optimal squeezing near the DOPO threshold. In some respects, this system resembles the model of a laser with a saturable absorber, but with a phase-sensitive gain.

Agarwal and Gupta studied a similar system. They considered the cavity field as a reservoir and atoms as an effective harmonic oscillator [8]. Using a Wigner function, they calculated the optical spectra from such a system. Several assumptions and shortcomings were present in that paper. First, due to the initial assumption of the atoms being a harmonic oscillator, their method cannot be used to analyze the steady-state dynamic behavior of the field modes; for example, they cannot predict the bistability of the output intensity versus the pumping intensity. Second, they did not consider the modification of the DOPO threshold due to the atomic absorption. Third, they only considered the resonance case with no atomic detuning. Fourth, in their calculation, they always took the adiabatic limit in which the atomic linewidth is zero. Finally, in that calculation, the effects of squeezed and unsqueezed quadratures on the atoms were not clear.

We start with a general Hamiltonian to derive a set of nonlinear differential equations [6]. Steady-state solutions of this system exhibit bistability in the output intensity versus pumping intensity. We calculate the new threshold of the DOPO modified by the atomic absorp-

Enhancement of photon antibunching by passive interferometry

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Photon antibunching in intracavity second-harmonic generation and intracavity atomic absorption inside a high-Q optical cavity is discussed. A linearized description of quantum dynamics in the weak-field limit is used because the system size, as characterized by the number of photons n_0 needed to probe the nonlinearity of the system, is often quite large for realistic parameters. In both cases standard results are recalled that demonstrate that antibunching is a small effect given by $g^{(2)}(0)-1\approx -1/n_0$ for large values of n_0. We show that when higher-order terms that are usually ignored in linearized treatments are retained, $g^{(2)}(0)$ satisfies the lower bound $g^{(2)}(0)\geq 0$ even for small values of n_0. It is further shown that by employing a high-Q cavity to suppress the coherent part of the spectrum of field fluctuations, perfect antibunching can be achieved even for large systems. Conditions under which this is possible are derived and curves are presented to illustrate the behavior.

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I. INTRODUCTION

Many nonlinear dissipative systems in optical physics involving, for example, the atom-field interaction or the parametric interaction between different modes of a cavity exhibit nonclassical features [1–6]. These features are conveniently described in terms of the statistical properties of the electromagnetic field. Unfortunately, most of these systems are such that many photons are needed to explore the nonlinearity of the system so that system dynamics are such that a very small quantum noise evolves around a classical steady state. The smallness of quantum noise makes a linearized treatment of the quantum dynamics of the system possible, with quantum effects inherently small compared to the size of the classical steady state. Examples of case in point are photon antibunching effects predicted in second-harmonic generation [1,3] and multi atom optical bistability [4–6]. In both cases the antibunching effect is inversely proportional to the size of the system as characterized by some parameter n_0. For multiatom bistability in the good-cavity limit this parameter is the saturation photon number, and for intracavity second-harmonic generation it is the threshold photon number. In principle, at least, it is possible to enhance the relative size of quantum effects by reducing the system size. In optical bistability, for example, the system-size parameter n_0 (the saturation photon number) was of the order of 10^3 for the work of Ref. [7]. The corresponding antibunching effect is then predicted to be considerably less than 1%. By searching for appropriate atomic species (Cs, for example) and working with short (~ 1 mm in length) optical cavities of small mode volume, the saturation photon number can be reduced down to below unity. By further utilizing a high-finesse ($\mathcal{F}\geq 10^4$) cavity and employing an atomic cooperativity parameter $C\sim 20$, the antibunching effect can be increased [6] to about 20% as has been observed in recent experiments [17]. The corresponding problem of reducing the system size in second-harmonic generation is more formidable [3]. For most experimental situations the threshold photon number is of the order of 10^6–10^{-8}. The corresponding antibunching effect is of the order of 10^{-6}–10^{-8}. By using high-finesse optical cavities and crystals with a large nonlinear coefficient, the threshold photon number can perhaps be lowered to 10^3-10^4. The resulting antibunching effect (of order 10^{-3}–10^{-4}) is still woefully small. Thus the approach of system-size reduction is not always feasible. Furthermore, with a reduction in system size the simplified linearized treatment of quantum dynamics may be rendered invalid. From the experimental point of view then the general problem we face is this: how do we enhance and therefore measure a small quantum effect riding on a strong classical (coherent) background. One approach to this problem, based on an interference experiment, was discussed by Bandilla and Ritze [8]. Here we explore yet another approach [9], which employs a passive filter cavity, external to the system producing quantum effects, to provide a variable for the classical (coherent) carrier while leaving the spectrum of quantum fluctuations largely intact, thereby enhancing otherwise small quantum effects. The quantum effects of interest to us throughout this paper are photon antibunching and sub-Poissonian photon statistics [3,5]. The fields considered in this paper also exhibit squeezing. In general, however, squeezing and antibunching refer to different nonclassical properties of the electromagnetic field. We are not concerned here with squeezing of the fields, although the method of this paper can also be applied to a discussion of squeezing. In Sec. II we present a general approach to the problem of filtering by a high-Q optical cavity. Section III applies these results to antibunching and sub-Poissonian photon

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Bistable behavior in a system of an optical parametric oscillator coupling with N two-level atoms

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We consider a composite system consisting of a degenerate optical parametric oscillator (DOPO) and a set of N homogeneously broadened two-level atoms. When the atoms are on or near resonance with the subharmonic-frequency field generated through the frequency down-conversion process, bistability appears in the intracavity field near the DOPO threshold. The bistability region will decrease as the detuning between the atomic transition frequency and the frequency of the subharmonic field increases. When the detuning becomes large enough, the atoms decouple from the cavity field and the system behaves like a normal DOPO. There are several features distinguishing this bistable behavior from the usual atomic optical bistability occurring with atoms in an optical cavity driven by an external field.

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I. INTRODUCTION

An optical parametric oscillator and a set of N homogeneously broadened two-level atoms inside an optical cavity are two of the most simple systems used in studying interactions between radiation fields and nonlinear media. Due to their simplicity as theoretical models and as experimentally realizable systems, they have been studied extensively as individual systems both theoretically and experimentally [1–5]. First-principle theoretical calculations and experimental results in these systems can be compared without the use of adjustable parameters to provide testing for the fundamental theories and predictions [2–4].

Although these two systems are simple, each of them has some very interesting properties in the steady state as well as in correlations due to quantum fluctuations. When atoms are put into an optical cavity which is externally driven by a pumping field with a frequency near the atomic transition frequency, optical bistability occurs at steady state. This atomic optical bistability (AOB) has been a very active research area both theoretically and experimentally in the last decade [3–5]. Agreement between experimental results and theoretical predictions is excellent in determining properties of the steady-state bistable behavior of this system [3]. Effects due to quantum fluctuations which include squeezed-state generation and photon antibunching have also been studied [4]. When a nonlinear crystal is placed inside an optical cavity and externally pumped with a field of frequency ω_2, with suitable phase-matching conditions a subharmonic field of frequency ω_1 ($\omega_2 \approx 2\omega_1$) will be produced. For pumping power below a threshold value, the subharmonic field is a fluorescence field with zero mean power. When pumping power reaches the threshold value, the gain will overcome the losses (cavity loss and crystal absorption) and a strong field will be created [1]. This system has been used as an ideal squeezed-state generator below threshold. A large degree of squeezing has been experimentally observed in this degenerate optical parametric oscillator (DOPO) system [2]. The experimental data agree very well with the first-principle calculations of this simple system.

When these two systems are put together to form a composite system, some properties of the individual system survive. Also new features appear due to the coupling of the atoms with the pumping field through the intracavity subharmonic field produced in the nonlinear crystal. The coupling strength of the atoms to the field depends on the detuning between the frequency of the subharmonic mode of the DOPO and the atomic transition frequency. When the detuning is zero, we have the resonance interaction which is the strongest. When this detuning increases, the effective coupling strength decreases. In the limit of very large detuning, the system behaves like a normal DOPO. However, when the detuning is small, bistable behavior appears in the steady-state solutions of this composite system. This bistability is different in several aspects from the normal AOB system. Since the pumping field is at a frequency of twice the intracavity fundamental mode, the lower branch of the bistable curve is always at zero mean field (one steady-state solution is always zero for the intracavity field). The DOPO threshold value of the pumping field is increased due to the loss through the atoms. Before reaching this new threshold, atoms absorb the fluctuation field collectively until they reach saturation. At that point, atoms will not absorb any more photons and the gain will exceed the losses in the optical cavity. This is the condition for DOPO to oscillate with a finite-mean intracavity field. As soon as this field appears in the cavity, due to the stimulated emission, atoms will give up all the energy that was collectively absorbed and the intracavity field will jump to a much higher value (up branch of the bistable curve). So, the lower turning point of the new bistability is just at the threshold of the DOPO. When coming down from the up branch, the intracavity field will not drop to zero at the DOPO threshold because the energy stored in atoms will be given to the intracavity field. For far up branch, the atoms are saturated and the steady-state behavior is again being governed by DOPO. Atoms are important only near the bistable region. It

