Interference-induced optical gain without population inversion in cold, trapped atoms

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Continuous-wave (cw) optical gain of 1.3×10^{-2} cm^{-1} is obtained on a probe transition in a driven, three-level, V-type atomic system. The atoms exhibit no population inversion between the probe excited state and the dressed ground states of the combined atom-drive Hamiltonian. This gain without population inversion is interpreted as direct evidence of quantum interference, arising from coherences established in the atom by the applied optical fields. Agreement with a simple four-level theoretical model is excellent.
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Quantum coherence and interference in atomic systems have a number of important consequences, including gain and lasing without population inversion (GWI, LWI) [1,2], the subrecoil cooling of atoms [3], and potential for sensitive measurements of magnetic fields [4]. In particular, LWI holds promise for facilitating the generation of blue or ultraviolet coherent radiation by reducing the minimum excited state population required for net stimulated emission on these short wavelength transitions. Within the wider framework of interference-related contributions to the nonlinear optical susceptibility [5], it is widely accepted that there are two distinct mechanisms that can contribute to the gain in LWI experiments [6]. The first is related to the well known phenomenon of coherent population trapping [7]. Although no population inversion is present within the bare atomic state basis, the gain can be viewed naturally as resulting from an inversion present in some other atomic basis. The second mechanism involves no population inversion in any commonly considered basis. In this case, the gain is a direct result of quantum interference, related to Fano interference [8], which prevents the stimulated absorption of probe radiation while leaving the stimulated emission unaffected [1,9].

LWI effects can be studied using driven, three-level atoms [5,10] in which a strong driving field and weak probe field are each resonant with a separate transition between the atomic levels. Several recent experiments have been performed in the Λ and cascade configurations [11]. While these experiments demonstrated gain and lasing without population inversion in the bare atomic state basis, none of them confirmed gain without inversion in all bases. In most cases, it was clear that a dressed-state inversion was indeed present. Other experiments have been carried out in the V configuration [12]. Here, there are two regimes in which gain can occur [13]. When the drive is tuned close to the atomic resonance, the gain is a result of quantum interference between single-photon and resonantly enhanced multiphoton transitions, with no population inversion of any kind present. However, when the drive is detuned far from the resonance, the probe gain can occur as a type of two-photon gain that requires a two-photon (dressed-state) inversion. In this case, quantum interference between the two-photon contribution to the susceptibility and either the single-photon or higher order multiphoton contributions does not play a significant role. For measurements done in Doppler-broadened media, a substantial burden is placed on the theoretical analysis in distinguishing these types of gain and in determining the role of quantum interference.

The difficulties associated with a broad atomic velocity distribution can be avoided by using cold atoms. In the limit where the Doppler broadening is substantially smaller than the natural linewidth, the quantum interference can be clearly distinguished and quantitative comparisons with simple theoretical models can be performed. Several recent results dealt with coherence in a sample of cold atoms [14]. While these experiments have demonstrated electromagnetically induced transparency in Doppler-free atomic samples, the existence of a dressed-state inversion, or lack of inversion, and the physical mechanism for the transparency, have not been addressed.

We present here a clear experimental demonstration of optical gain without population inversion and clarify the origin of this interference-induced gain as being distinct from the well understood two-photon gain. This is carried out using a sample of cold atoms trapped in a magneto-optic trap (MOT) [15], for which the natural line width dominates over all other broadening mechanisms. As much as 0.2% gain per pass is measured on a probe laser at 795 nm in the presence of a strong drive laser at 780 nm. Direct experimental measurements establish that there is no population inversion between the probe excited state and the stationary (dressed) ground states of the atom/drive field system. We conclude, therefore, that neither does any population inversion exist in the bare state basis. Strong experimental evidence is also provided that the gain is unlikely to be caused by a direct Raman process in the atom. We therefore interpret this gain as a consequence of quantum interference between the dressed states of the atom.

About 5×10^7 ^{87}Rb atoms were laser cooled and trapped in a vapor cell MOT [16]. The cooling fields consisted of three pairs of counterpropagating σ_+/σ_- laser beams originating from an external cavity diode laser (ECDL). This laser was tuned 10 MHz to the red of the $F=2\rightarrow F''=3$ cycling transition of the ^{87}Rb $D2$ line [see Fig. 1(a)]. Near the

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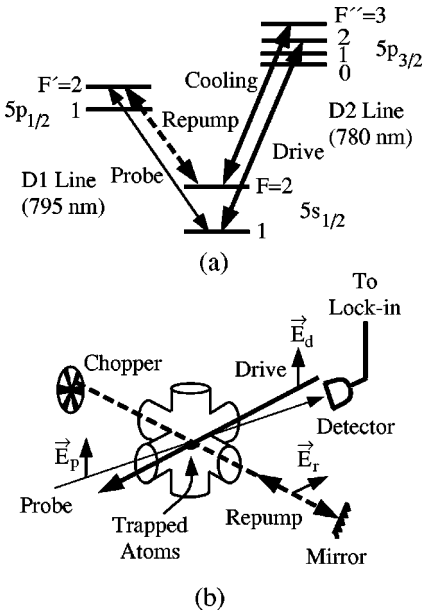

FIG. 1. (a) Level diagram for ^{87}Rb indicating the tuning of the lasers used in the experiment. (b) Geometrical arrangement and polarizations of the beams with respect to the trapped atoms.

trapping region, each of these beams was ~ 2 cm in diameter and had an intensity of 0.9 mW/cm^2. A weaker laser, again produced by an ECDL, prevented loss of atoms from the trap due to off-resonant optical pumping of the cooling fields into the F=1 ground state. This laser was tuned to the $F=1\rightarrow F''=2$ transition of the $D2$ line and had an intensity of ~ 100 μW/cm^2 in each of four beams overlapping in the trapping region. Since the intensity of this beam was far smaller than that of the drive laser beam discussed below, its effect on the experiment other than repumping the MOT is expected to be small. The resulting atom cloud had a diameter of ~ 1.5 mm, resulting in an atomic density of $\sim 3\times 10^{10}$ atoms/cm^3. While the temperature of the atoms was not directly measured, it is expected that the atoms were cooled to a few tens of μK, as reported in other MOT experiments [16]. At such temperatures, the residual Doppler width contributes negligibly to the transition line widths.

Spectroscopy on the atomic sample was performed in the following way. A weak (20 nW), linearly polarized probe beam from an ECDL was focused several cm beyond the center of the trapped cloud of atoms. The absorption due to the trapped atoms was then measured as the probe was scanned over the $F=1\rightarrow F'=2$ transition of the $D1$ line. A strong drive beam, again from an ECDL, with a maximum intensity at the trap center of ~ 300 mW/cm^2 was also focused into the atom cloud, roughly counterpropagating ($\Delta\theta=3°$) with the probe. This laser was detuned by a variable amount from the $F=1\rightarrow F''=2$ transition of the $D2$ line and was polarized parallel to the probe. Together, the drive and probe connect three levels of the atoms in a V configuration.

Finally, a spectrally broadened, free-running diode laser ($\Delta\nu=230$ MHz) tuned to the $F=2\rightarrow F'=2$ $D1$ transition and with an intensity of 30 mW/cm^2 was applied to the trapped atom cloud. It provided an incoherent repumping mechanism to put population into the atomic levels coupled to the probe transition. This laser beam propagated in a direction perpendicular to the drive and probe beams (and their polarizations) and had a polarization oriented along the drive/probe axis of propagation. It was retroreflected after passing through the trap in order to reduce the optical forces on the atoms. The geometrical arrangement and polarizations of the beams is shown in Fig. 1(b).

One advantage of this arrangement of laser tunings is that neither the drive nor the probe laser couples to levels involved in the cooling of the atoms. The cooling field is therefore expected to have very little effect on the coherence of the levels in the V system. There are several ways that the cooling field could affect the V system coherence. One is through the addition of atoms to the $F=1$ ground state by off-resonant optical pumping through the $5p_{3/2}$, $F''=2$ level. With the laser power and detuning used in the experiment, this optical pumping rate should be at least two orders of magnitude smaller than that of the incoherent repump into the $F=1$ ground state; this is consistent with probe absorption measurements. Thus the additional decoherence, and the population transfer, due to this process should be minimal. Another is a possible Raman coupling between the two hyperfine ground states by the combination of cooling field and drive field. Since the cooling field is detuned from Raman resonance by 110 MHz, this coupling is expected to be extremely weak. Finally, the cooling field affects the distribution and coherence of atoms among the Zeeman sublevels of the $F=2$ ground state. Since there is no dark state with respect to this $F=2\rightarrow F=3$ cycling transition, we do not expect any long-lived coherences to be present among those Zeeman sublevels. A steady-state population distribution among the levels can be accounted for in our theoretical model described below.

In light of these considerations, we performed the spectroscopy cw rather than shutting off the cooling fields during the probe absorption measurements. This not only facilitated the measurement process but also allows for the future possibility of cw lasing. In addition, because of the decay rates and level degeneracies in this configuration, it is impossible to create a population inversion on the probe transition [17].

The probe absorption was measured as the probe laser frequency was scanned over the atomic transition. This was performed by chopping the repump beam with a mechanical chopper, detecting the transmitted probe power using a photodiode and then sending the resulting signal into a lock-in amplifier. A small Doppler-broadened background due to noncooled atoms, which contributed a signal small compared to that from the trapped atoms, was recorded with the trap off and was subtracted from each absorption trace. With the repump blocked and the drive present, the atoms were quickly and efficiently optically pumped into the $F=2$ ground state, resulting in zero measurable probe absorption due to the trapped atoms. With the drive field blocked and the repump present, a maximum probe absorption of 67% was measured. With both drive and repump applied to the atoms, a two-peaked absorption spectrum was observed, as shown in Fig. 2, trace *A*. The drive was stabilized within 1 MHz of the line center; the residual drive detuning is probably the cause of the asymmetry in the measured line shape. Between the absorption peaks, 0.07% of probe gain was observed, although as much as 0.2% was observed under optimum alignment conditions. When the repump laser frequency was changed

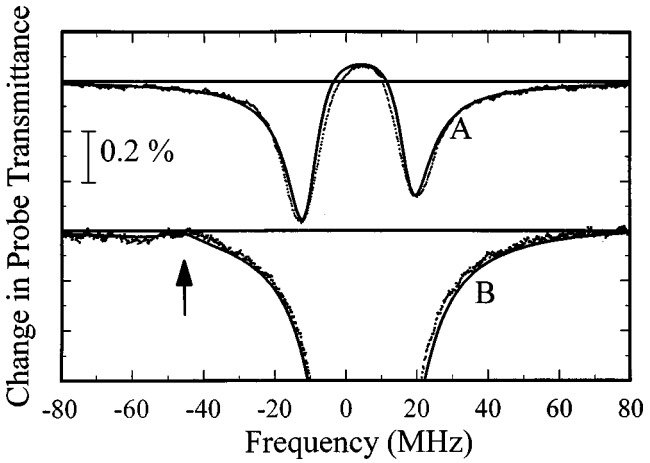

FIG. 2. Change in probe transmittance in the presence of the strong drive field on resonance (trace *A*) and detuned by 45 MHz (trace *B*). The horizontal solid lines indicate zero net absorption. The two-peaked structure in trace *A* is a result of absorption from the dressed ground states of the system. A gain of 0.07% can be seen between the peaks.

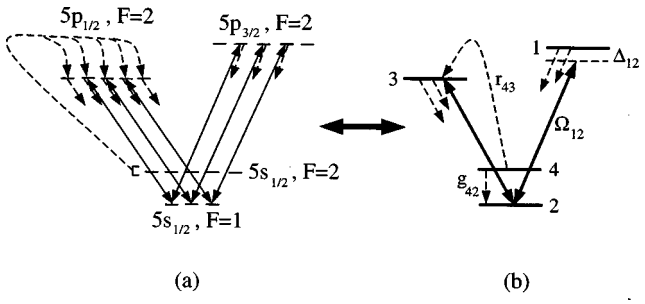

FIG. 3. (a) Energy levels of ^{87}Rb that couple to the optical fields. When the quantization axis is taken along the direction of polarization of the drive and probe fields, the decoupling of the V manifolds for different Zeeman levels becomes transparent. This decoupling allows the use of a substantially simplified model, shown in (b) to describe the experiment theoretically.

to the $F=2\rightarrow F'=1$ line, absorption, rather than gain, was observed at the line center. This is consistent with an absence of significant population in the probe excited state for this repump tuning.

To interpret these data, we consider the ground state of the probe transition in terms of the dressed states of the coupled atom, drive field system. In this basis there are two ground states, separated by twice the drive Rabi frequency, coupled to the probe transition excited state. Absorption from these two dressed states can be clearly seen in the experimental data, indicating that there is less population in the probe excited state than in either of these dressed ground states. We attribute the gain that is observed at the center of the spectrum to the effects of Fano-type quantum interference resulting from an atomic coherence created between the drive and probe excited states. Alternatively, the spectrum can be described in terms of interference between one-photon and multiphoton processes in the atom [5]. When the probe is tuned between the dressed states, the interference suppresses the stimulated absorption of probe photons but does not affect the stimulated emission process [9]. Consequently, net stimulated emission occurs between the probe excited and ground states without the usual requirement for a population inversion. Trace *B* in Fig. 2 shows the probe absorption when the drive is detuned from the atomic resonance by 44 MHz. In this case, the spectrum is clearly composed of two distinct components: a large single-photon absorption peak at the single-photon resonance and a small, superimposed, two-photon gain peak at the detuning corresponding to two-photon resonance with the drive (indicated by the arrow in the figure). The solid line fit to the data in trace *B* is indistinguishable from a sum of two simple Lorentzians, in dramatic contrast to the fit from trace *A*. We therefore conclude that the type of gain in trace *B* is distinct in origin from the interference-induced gain of trace *A* in that the single-photon and multiphoton processes do not interfere.

A simple theoretical model was compared with the experiment. With a quantization axis taken along the direction of polarization of the drive and probe fields, the π-polarized optical fields couple only those transitions with $\Delta m_F=0$, as shown in Fig. 3(a). The three V systems shown are therefore completely decoupled and the interaction can be described by a simple four-level model, Fig. 3(b). In this model levels 1, 2, 3, and 4 represent, respectively, $(5p_{3/2},F=2)$, $(5s_{1/2},F=1)$, $(5p_{1/2},F=2)$, and $(5s_{1/2},F=2)$.

The effects of the $F=2$ ground-state Zeeman distribution can be accounted for in the following way. For a given repump polarization, some of the atoms in the $F=2$ level will make transitions to the $F'=2$, $m_F=\pm 2$ levels. Since these levels are not coupled to the probe field, they decay via spontaneous emission and provide an effective incoherent decay mechanism between the two hyperfine ground states, represented in Fig. 3(b) by g_{42}. On the other hand, those atoms that make transitions to the $F'=2$, $m_F=\pm 1,0$ levels do couple to the probe field and therefore contribute to the probe gain. This pumping is represented in Fig. 3(b) as r_{43}. The spontaneous emission from the two excited states is also included in the model; the excited-state lifetimes are taken as $\tau_{D1}=29.4$ ns, $\tau_{D2}=27.0$ ns, with equal branching ratios from each excited state into the two hyperfine ground states. Finally, the model includes the drive field coupling levels 1 and 2, with Rabi frequency Ω_{12} and detuning Δ_{12}. The density matrix equations for the populations and coherences are solved analytically to obtain an expression for the steady-state gain on the probe transition. An overall scaling factor is also present.

The solid lines in Fig. 2 are predictions from the model with $g_{42}=0.35$ MHz, $r_{43}=2$ MHz, $\Omega_{12}=14.6$ MHz, and $\Delta_{12}=0.4$ MHz ($\Delta_{12}=-44$ MHz) for trace *A* (*B*). Agreement between experiment and theory is good despite the model being a considerable oversimplification of the experimental system. The parameters used in the model agree roughly with those that we were able to estimate from the experiment.

In order to further verify experimentally the absence of population inversion, the probe laser was tuned to the $F=1\rightarrow F'=1$ transition on the $D1$ line. This dramatically alters the probe level populations, since the decay rate for $F'=1\rightarrow F=1$ is three times slower than for $F'=2\rightarrow F=1$ due to the different Clebsch-Gordon coefficients. When the repump is also tuned to this $F'=1$ state, there should be a population

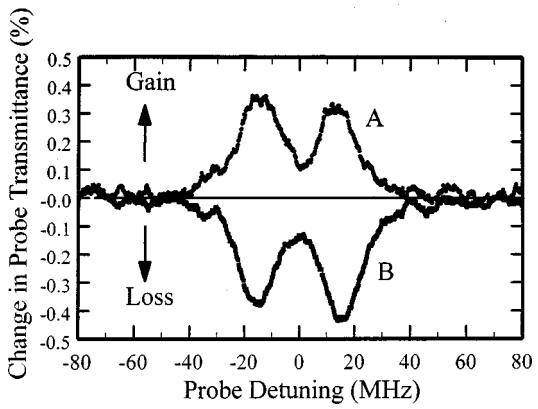

FIG. 4. Probe transmission spectrum with the probe tuned to the $F'=1$ excited state. Trace *A*, taken with the repump also tuned to $F'=1$, shows gain indicative of a population inversion on the probe transition. Trace *B*, taken with the repump tuned to $F'=2$, shows absorption, indicating no inversion.

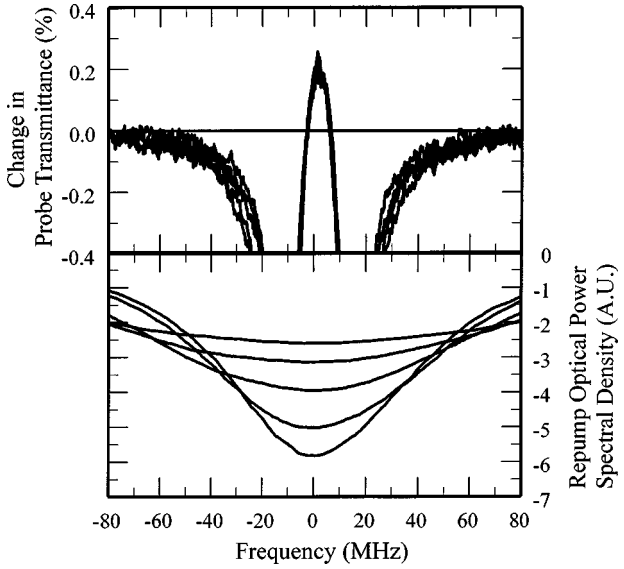

FIG. 5. Probe transmission spectra (upper plot) for several repump linewidths (lower plot). If the gain were caused by direct Raman processes between the repump and probe, the probe gain in the center of the line would be expected to change relative to the wings as the repump linewidth changes. No evidence of Raman gain is observed for broad bandwidth repumping.

inversion between the probe excited state and the dressed ground states. In Fig. 4, trace *A*, the probe absorption spectrum in this configuration is shown. Instead of a two-peaked absorption profile, a qualitatively different two-peaked gain profile is observed, indicating the presence of a population inversion. If the repump is returned to the $F'=2$ excited state, the probe excited state once again contains very little atomic population, and a two-peaked absorption profile is measured, as shown in trace *B* of Fig. 4. The data of Fig. 4 indicate a qualitative difference between cases in which there is and is not a population inversion. We conclude, therefore, that for the gain shown in Fig. 2, there is no population inversion between the probe excited state and the dressed ground states of the probe transition. Also, theory [13] predicts that with both drive and probe tuned on-resonance, neither is there a population inversion in the bare state basis. This type of GWI is therefore distinct from GWI in which a hidden inversion is present.

Another process that can affect the probe intensity in this optical configuration is Raman gain, in which a repump photon is absorbed while a probe photon is emitted and the atom makes a transition from $F=2$ to $F=1$. This type of interaction is well known and is different from the interference-induced gain we are trying to study. Several experimental checks were carried out in order to rule out the possibility that the gain observed in Fig. 2 was caused by this type of Raman process. Perhaps the most convincing of these was the dependence of the probe gain on the repump laser spectral line width, shown in Fig. 5. The probe gain was measured for a series of repump line widths varying between 90 MHz and 230 MHz. The peak gain observed in each of the five probe spectra showed no deviations outside the measurement error, despite a sevenfold change in the relative repump spectral density between the center of the line and the wings. The shape of the probe gain profile also showed very little dependence on repump tuning. Finally, the simple observation that the repump spectrum was smooth and showed no features with a width comparable to that of the gain peak is another indication that Raman gain involving the repump was not occurring.

In conclusion, gain without population inversion of up to 0.2% per pass (1.3×10^{-2} cm^{-1}) has been measured with cold atoms on a probe transition at 795 nm in the presence of a strong drive field coupled to the probe lower level. We interpret this gain as a direct consequence of quantum interference, which prevents the stimulated absorption of probe radiation while leaving the stimulated emission process unaffected. Finally, it has been suggested that this type of gain without atomic population inversion is in fact driven by an inversion in the radiation fields used to pump the atoms (i.e., a nonthermal photon distribution) [18]. We have not addressed this question, but expect it to be true in the experiment described here.

The results of this experiment appear immediately useful in generating shorter wavelength coherent radiation. For example, the $6p_{3/2}$ level in ^{87}Rb could be populated with a small number of atoms through a resonant, two-step excitation to the $5d_{3/2}$ level via the $5p_{3/2}$ level, followed by spontaneous decay. It should then be possible to produce optical gain and lasing at 420 nm, in the presence of a strong drive field on the $D2$ line at 780 nm. Even shorter wavelength, ultraviolet gain might be possible if a suitable incoherent pumping mechanism pumping to a level with appropriate branching ratios can be found. We anticipate that it should be possible to carry out such experiments using the current trap setup.

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