Lasers without inversion: interference of dressed lifetime-broadened states

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Received July 25, 1989; accepted October 4, 1989

We describe the use of a coupling electromagnetic field to provide a general method of producing inversion-free laser systems. The interference between dressed states produces a zero in absorption while allowing gains of the order of that of the uncoupled system.

It has recently been shown that if two upper states of a three-state laser system (Fig. 1) are purely lifetime broadened and decay to an identical continuum, this decay couples these states and results in nonreciprocal emission and absorption profiles.[1,2] One may obtain a zero in the absorption cross section and, for states that are spaced by several inverse lifetimes, obtain nearly the full gain cross section of a single transition.

The problem is that it is not easy to find nearby states that decay strictly to the same continuum. For states that decay by autoionization and Auger processes there are almost always several channels into which the state may decay. For states that decay by radiation, the decay rate is determined by interaction with the vacuum fluctuations, while their spacing is determined by electrostatic interactions; such states are therefore most often spaced by many inverse lifetimes.

In this Letter we show how to use an additional electromagnetic field to create a pair of interfering dressed states that *a priori* decay to the same continuum. Figure 2(a) shows the bare states and the electromagnetic field that is applied; Fig. 2(b) shows the equivalent dressed-state system. In the following we show that the effect of the interference of these dressed states is to create a zero in the absorption profile of state $|1\rangle$ atoms. In all cases this zero occurs at an energy that is the sum of the energies of (bare) state $|2\rangle$ and the coupling electromagnetic field. The emission profile of excited state $|2\rangle$ atoms does not exhibit this zero and, in fact, may have a gain cross section at the frequency of the zero that is of order of the gain cross section of the bare $|3\rangle$–$|1\rangle$ transition. This method thereby permits a general class of lifetime-broadened lasers that may operate without inversion.

In Fig. 2(a) we view the strength Ω_{23} and frequency ω_c of the coupling electromagnetic field as fixed and consider the gain and loss as a function of the probe frequency ω_p. We take the probe intensity Ω_{13} to be small as compared with Ω_{23} and Γ_3, where Γ_3 is the decay rate (to an arbitrary continuum) of state $|3\rangle$. The frequency detunings of the bare system are defined as $\Delta\omega_c = \omega_3 - \omega_2 - \omega_c$ and $\Delta\omega_p = \omega_3 - \omega_p - \omega_1$.

We transform to the equivalent dressed-state[3] system of Fig. 2(b). We assume that only a single pair of dressed states is in the vicinity of the probe frequency and that all other pairs may be neglected. The transformation from bare states $|2\rangle$ and $|3\rangle$ to dressed states $|2d\rangle$ and $|3d\rangle$ is

$$|2d\rangle = \cos\theta|2\rangle - \sin\theta|3\rangle,$$
$$|3d\rangle = \sin\theta|2\rangle + \cos\theta|3\rangle,$$
$$\tan 2\theta = \frac{-\Omega_{23}}{\Delta\omega_c}. \tag{1a}$$

The equivalent decay rates, Rabi frequencies, and detunings of the dressed system of Fig. 2(b) are then

$$\Gamma_{2d} = \Gamma_3 \sin^2\theta, \qquad \Gamma_{3d} = \Gamma_3 \cos^2\theta,$$
$$\Omega_{12d} = -\Omega_{13}\sin\theta, \qquad \Omega_{13d} = \Omega_{13}\cos\theta,$$
$$\Delta\omega_{2d} = \omega_2 - \frac{\delta}{2} + \omega_c - \omega_1 - \omega_p,$$
$$\Delta\omega_{3d} = \omega_3 + \frac{\delta}{2} - \omega_1 - \omega_p,$$
$$\delta = \frac{\Delta\omega_c(1 - \cos 2\theta)}{\cos 2\theta}. \tag{1b}$$

To obtain the absorption profile of the probe beam,

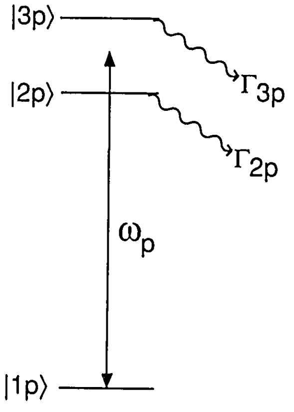

Fig. 1. Prototype system for inversion-free lasers. Γ_{2p} and Γ_{3p} are the decay rates, to the same continuum, of prototype states $|2p\rangle$ and $|3p\rangle$.

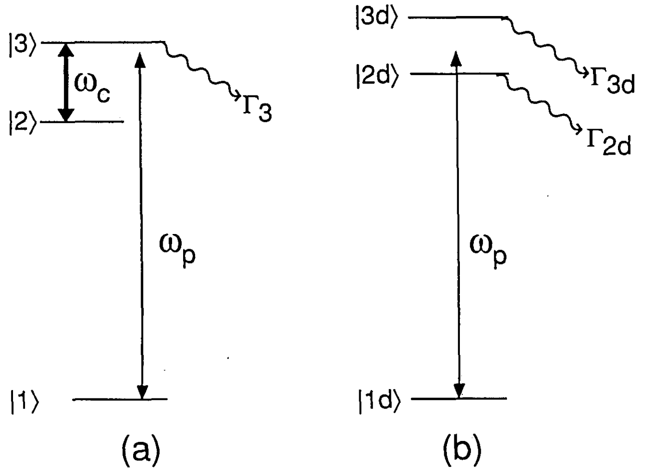

Fig. 2. Energy-level diagrams of the electromagnetic field coupled systems: (a) the bare-state system and (b) the equivalent dressed-state system. ω_c is the frequency of the coupling field, ω_p is the frequency of the probe, and Γ_3 is the decay rate to an arbitrary continuum.

the quantities in Eqs. (1b) are substituted into Eq. (3) of Ref. 1, which gives the absorption of a state $|1p\rangle$ atom of the prototype system. The result of this substitution is

$$W_{ab} = \frac{4\Omega_{13}{}^2(\Delta\omega_p - \Delta\omega_c)^2\Gamma_3}{[\Delta\omega_c{}^2 \sec^2 2\theta - (2\Delta\omega_p - \Delta\omega_c)^2]^2 + 4\Gamma_3{}^2(\Delta\omega_p - \Delta\omega_c)^2} . \tag{2}$$

We note the zero in absorption when $\Delta\omega_p = \Delta\omega_c$, or, equivalently, when $\omega_2 + \omega_c = \omega_p + \omega_1$. It should be noted here, as in Ref. 1, that this equation neglects the transient response of state $|1\rangle$ atoms. The assumption is that atoms will remain in state $|1\rangle$ for a time that is long compared with that of the transient, which is effectively over in approximately one decay time. It is shown in Ref. 4 that when operating at the zero of the interference profile this transient absorption is the only absorption and, as discussed below, in some cases should not be neglected.

The procedure for obtaining the emission profile of the probe beam when a state $|2\rangle$ atom is excited is similar, although somewhat algebraically complicated. The reason is that excitation of bare state $|2\rangle$ results in a superposition excitation of the dressed system. The emission formulas of Ref. 1 must therefore be generalized to allow for simultaneous excitation of states $|2p\rangle$ and $|3p\rangle$ before the substitutions from Eqs. (1b) are made. Carrying out this procedure, the time-averaged stimulated transition rate of a bare state $|2\rangle$ atom may be written as

$$W_e = \Gamma\left\{\frac{\Omega_{13}{}^2\Delta\omega_c{}^2 \tan^2 2\theta}{[\Delta\omega_c{}^2 \sec^2 2\theta - (2\Delta\omega_p - \Delta\omega_c)^2]^2 + 4\Gamma_3{}^2(\Delta\omega_p - \Delta\omega_c)^2}\right\} , \tag{3}$$

where $\Gamma = \Delta\omega_c{}^2\Gamma_3 \tan^2 2\theta/[(4 + 2\tan^2 2\theta)\Delta\omega_c{}^2 + \Gamma_3{}^2]$.

As in Ref. 1, the time-averaged stimulated transition rate is defined as the probability that an atom that at $t = 0$ is in state $|2\rangle$ has made a transition to state $|1\rangle$ as $t \rightarrow \infty$ multiplied by the decay rate Γ of the coupled $|2\rangle$–$|3\rangle$ system. For a small Ω_{23}, Γ approaches zero. As Ω_{23} becomes large, Γ approaches $\Gamma_3/2$. For an ensemble of atoms with a constant excitation rate into state $|2\rangle$, the rate of change of the population of state $|1\rangle$ is equal to W_e times the sum of the populations of states $|2\rangle$ and $|3\rangle$.

Figure 3 shows the absorption and emission transition rates of Eqs. (2) and (3) as a function of the detuning (normalized to Γ_3) of the probe frequency. These transition rates are normalized to the peak (absorption or emission) transition rate of the bare $|3\rangle$–$|1\rangle$ system. We have taken the coupling field to be on resonance with the bare $|2\rangle$–$|3\rangle$ transition and have let $\Omega_{23} = 0.5\Gamma_3$. We note an emission transition rate equal to approximately 0.6 of that of the uncoupled $|3\rangle$–$|1\rangle$ Lorentzian transition and an accompanying absorption rate, at this same probe frequency, of zero.

The above derivation has neglected both dephasing collisions and Doppler broadening. Numerical research shows that the results remain reasonably valid when the lifetime decay rate substantially exceeds the dephasing rate and when Ω_{23} exceeds the Doppler width. It is particularly important that dephasing collisions in the bare $|1\rangle$–$|3\rangle$ and $|2\rangle$–$|3\rangle$ channels do not destroy the zero in absorption. Only $|1\rangle$–$|2\rangle$ dephasing is important. This is to be contrasted with the prototype system, where dephasing collisions in the $|1p\rangle$–$|2p\rangle$ and $|1p\rangle$–$|3p\rangle$ channels may be a hindrance to applications. For our formulas to remain valid, it is also required that Γ_3 be large compared with the (natural) decay rate of state $|2\rangle$.

Excitation of an ensemble of atoms will proceed by rates into each of the states. In this regard we note that it is only excitation of state $|2\rangle$ that leads to the results of Eq. (3). Excitation of state $|3\rangle$ produces an emission that is identical to the absorption of a state $|1\rangle$ atom.

We note another feature of this system: As the strength of the coupling field Ω_{23} is reduced, for $\Delta\omega_c = \Delta\omega_p$, the stimulated transition rate remains unchanged. (This occurs since the spacing of the dressed states is reduced.) However, the lifetime $1/\Gamma$ [Eq. (3)] increases indefinitely. Therefore, for a given rate of excitation, the population and therefore the total gain increase and may be much larger than if this same excitation rate were applied to state $|3\rangle$. (The singularity at the zero coupling field is removed by including a decay rate for state $|2\rangle$.)

Although we have arrived at the above results from the point of view of Refs. 1 and 2, i.e., two interfering paths to the continuum in absorption, and constructive interference in emission, others have proceeded differently and have obtained results that lead in the direction of this research. Mollow[5] has examined a system in which two lower states are strongly coupled by an electromagnetic field and has found different absorption and emission profiles, with in some cases a zero in emission rather than in absorption. Gray *et al.*[6] have used two laser beams to couple two hyperfine

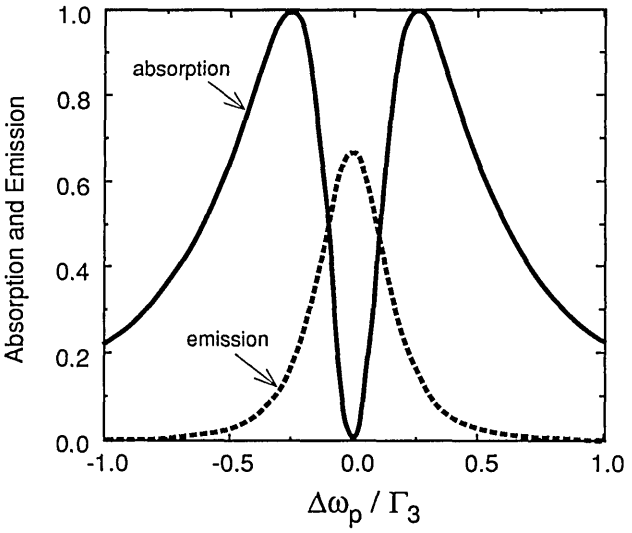

Fig. 3. Emission and absorption transition rates [Eqs. (2) and (3)] normalized to the transition rate of the uncoupled $|1\rangle$–$|3\rangle$ system. The drive strength $\Omega_{23} = 0.5\Gamma_3$, and $\omega_c = \omega_3 - \omega_2$.

ground states of Na to a single *p* state and have experimentally observed an interference hole similar to that of Fig. 3. Radmore and Knight[7] have shown population trapping in strongly coupled systems. We also note the recent suggestion of Scully and Zhu[8] for coupling two lower states with a strong field. Their suggestion does not involve lifetime broadening and is different in concept from that described here. (For example, it requires phase matching of the pertinent fields, while the suggestion of this Letter does not.)

We turn next to an important question: To what extent will the results presented here remain valid if the lifetime broadening of state $|3\rangle$ results from spontaneous Einstein A decay to state $|1\rangle$? If they are valid, it may be possible to obtain lasing, without the need for a population inversion, on the $2p$–$1s$ transition of helium and heliumlike ions. This could be accomplished by coupling the $2s$ and $2p$ states by a strong laser field. The difficulty arises as a result of the transient absorption of ground-state atoms, which, as noted above, is not included in Eq. (2). Spontaneous emission from state $|3\rangle$ atoms invokes this transient and leads to an additional absorption loss.[4]

We have developed a density-matrix approach[9] that includes spontaneous emission. We find that such heliumlike systems exhibit gain when pumped for a time that is short compared with their radiative decay time, or, equivalently, when the pump rate itself increases with time at sufficient slope. These results generally agree with the conclusion of Refs. 1 and 4, which requires that the rate into the upper state exceed that into the lower state, whereas in this case the rate into the lower state is provided by the spontaneous emission from state $|3\rangle$.

We expect that the results of this Letter will be of importance in regions of the electromagnetic spectrum where lifetime decay rates exceed collisional widths. This almost always occurs for Auger broadened states and often occurs for radiatively broadened transitions that have wavelengths less than approximately 10 nm.

The authors thank Jinx Cooper and John Macklin for helpful discussions. The research described here was supported by the U.S. Office of Naval Research, the U.S. Army Research Office, the U.S. Air Force Office of Scientific Research, and the Strategic Defense Initiative Organization.

Note added in proof: We have realized that different emission and absorption profiles, with a zero in absorption, will be obtained even when the collisional and inhomogeneous broadening of state $|3\rangle$ exceed its lifetime broadening.

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