Lasers without Inversion: A Closed Lifetime Broadened System

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We show a model laser system which operates by an electromagnetically induced interference. Provided that an inversion condition for the thermal radiation field is satisfied, the system lases without atomic population inversion in steady state. The system is pumped by incoherent radiation on the transition on which lasing occurs.

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Recently, there has been considerable interest in lasers that operate without the need for a population inversion. These systems are based on a quantum interference effect which in atomic systems that are dominantly lifetime broadened creates different emissive and absorptive profiles.[1-11] Two related questions[8,9] have drawn attention: (1) Is there a hidden atomic basis set in which the system is inverted? (2) Must such systems be pumped from an external state which, like Raman lasers, is inverted with regard to the lower laser state?

In this Letter, we address these questions by proposing a model system (Fig. 1), which is closed with regard to the atomic basis set: That is, the lifetime broadening occurs by radiative decay to other states within the same system, and the laser is pumped by incoherent photons from its lower state. This closed system lases without atomic population inversion in steady state, provided that the occupancy of the radiation field modes satisfies an "inversion" condition.

Before proceeding further we note that Kocharovskaya and co-workers[12] and Scully and co-workers[13] have proposed a different class of laser systems which are based on a phase-dependent quantum interference. Such systems do not depend on lifetime broadening and the considerations of this work may not apply.

In the system of Fig. 1, following Imamoğlu and Harris,[7] a strong electromagnetic field of frequency ω_c couples a metastable state $|2\rangle$ to a state $|3\rangle$ which decays radiatively to states $|2\rangle$ and $|1\rangle$. This coupling field creates a pair of dressed states which *a priori* decay to the same final states. The absorption of state $|1\rangle$ atoms as measured by a probe of frequency ω_p will exhibit a destructive interference with a minimum absorption at the frequency $\omega_2+\omega_c-\omega_1$. There are two essential requirements for the system: (i) The spontaneous decay rate from state $|3\rangle$ to state $|2\rangle$ exceeds that from state $|3\rangle$ to state $|1\rangle$, (ii) the average number of thermal photons per mode in the $|1\rangle$-$|3\rangle$ channel exceeds that in the $|2\rangle$-$|3\rangle$ channel.

We have, in part, chosen the system of Fig. 1 since all pumping and decay processes are radiative and therefore the density matrix for the system may be derived without the addition of phenomenological terms. We take the system to be pumped by incoherent radiation which has a different intensity (temperature) on the $|1\rangle$-$|3\rangle$ and on the $|2\rangle$-$|3\rangle$ transitions and which at each transition is spectrally broad as compared to the larger of the decay rate Γ_{32}, detuning $|\omega_2+\omega_c-\omega_3|$, or the Rabi frequency $|\Omega_{23}|$. We assume that the effect of the atoms on the pumping radiation is negligible and that each laser field is represented by a single coherent state. The derivation also assumes the Rabi frequencies to be much smaller than the corresponding laser frequencies. By tracing the global density matrix over the radiation field variables we obtain the equation of motion for the atomic density matrix elements in a frame rotating at the probe frequency ω_p.[14] These equations are the following:

$$\frac{d\rho_{11}}{dt}=\Gamma_{31}\rho_{33}+\tfrac{1}{2}i\Omega_{13}(\rho_{31}-\rho_{13})+R_{13}(\rho_{33}-\rho_{11}), \tag{1a}$$

$$\frac{d\rho_{22}}{dt}=\Gamma_{32}\rho_{33}+\tfrac{1}{2}i\Omega_{23}(\rho_{32}-\rho_{23})+R_{23}(\rho_{33}-\rho_{22}), \tag{1b}$$

$$\frac{d\rho_{33}}{dt}=-(\Gamma_{32}+\Gamma_{31})\rho_{33}+\tfrac{1}{2}i\Omega_{13}(\rho_{13}-\rho_{31})+\tfrac{1}{2}i\Omega_{23}(\rho_{23}-\rho_{32})-R_{23}(\rho_{33}-\rho_{22})-R_{13}(\rho_{33}-\rho_{11}), \tag{1c}$$

$$\frac{d\rho_{12}}{dt}=-(\tfrac{1}{2}\gamma_{21}-i\Delta\omega_{21})\rho_{12}-\tfrac{1}{2}i\Omega_{23}\rho_{13}+\tfrac{1}{2}i\Omega_{13}\rho_{32}, \tag{1d}$$

$$\frac{d\rho_{13}}{dt}=-(\tfrac{1}{2}\gamma_{31}-i\Delta\omega_{31})\rho_{13}+\tfrac{1}{2}i\Omega_{13}(\rho_{33}-\rho_{11})-\tfrac{1}{2}i\Omega_{23}\rho_{12}, \tag{1e}$$

$$\frac{d\rho_{23}}{dt}=-(\tfrac{1}{2}\gamma_{32}-i[\Delta\omega_{31}-\Delta\omega_{21}])\rho_{23}+\tfrac{1}{2}i\Omega_{23}(\rho_{33}-\rho_{22})-\tfrac{1}{2}i\Omega_{13}\rho_{21}, \tag{1f}$$

where

$$\begin{aligned}
\gamma_{21} &= R_{23}+R_{13}\,,\\
\gamma_{31} &= \Gamma_{32}+R_{23}+2R_{13}+\Gamma_{31}\,,\\
\gamma_{32} &= \Gamma_{32}+2R_{23}+R_{13}+\Gamma_{31}\,, \qquad (2)\\
R_{23} &= \Gamma_{32}\{\exp[\hbar(\omega_3-\omega_2)/k_b T_{\text{rad}23}]-1\}^{-1}=\Gamma_{32}\bar{n}_{23}\,,\\
R_{13} &= \Gamma_{31}\{\exp[\hbar(\omega_3-\omega_1)/k_b T_{\text{rad}13}]-1\}^{-1}=\Gamma_{31}\bar{n}_{13}\,.
\end{aligned}$$

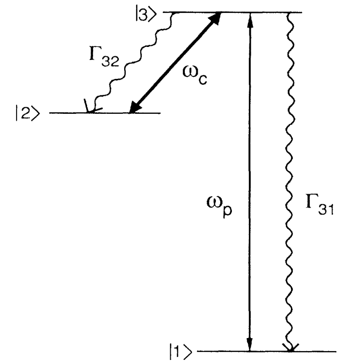

FIG. 1. Model system for lasing without inversion.

Here, Ω_{23} and Ω_{13} are the laser coupling coefficients (Rabi frequencies), $\Delta\omega_{21}=\omega_2+\omega_c-\omega_p-\omega_1$ and $\Delta\omega_{31}=\omega_3-\omega_p-\omega_1$ are the respective detunings, and Γ_{32} and Γ_{31} are the spontaneous emission rates from state $|3\rangle$ to states $|2\rangle$ and $|1\rangle$, respectively. We take $\omega_3>\omega_2>\omega_1$. For atoms in an isotropic environment, the pumping rates R_{13} and R_{23} may be expressed in the form of Eq. (2), where T_{13} and T_{23} are the temperatures of the pumping thermal radiation fields at $\omega_3-\omega_1$ and $\omega_3-\omega_2$. $\bar{n}_{13}$ and $\bar{n}_{23}$ are the average number of thermal photons per mode, at these frequencies.

We seek a steady-state solution and set the derivatives in Eq. (1) equal to zero. The rate of change of the number of probe laser photons in the pumped volume is then

$$\frac{d\langle n_p\rangle}{dt}=-W_{\text{abs}}\rho_{11}+W_{\text{em}}(\rho_{22}+\rho_{33})\,. \qquad (3\text{a})$$

The stimulated absorption and emission rates are

$$W_{\text{abs}}=\frac{\Omega_{13}^2}{|\Delta|^2}[4\Delta\omega_{21}^2\gamma_{31}+\gamma_{21}(\Omega_{23}^2+\gamma_{21}\gamma_{31})]\,, \qquad (3\text{b})$$

$$\begin{aligned}
W_{\text{em}}=\frac{\Omega_{13}^2}{|\Delta|^2}&\frac{1}{(\Gamma_{32}+2R_{23})[\gamma_{32}^2+4(\Delta\omega_{31}-\Delta\omega_{21})^2]+2\Omega_{23}^2\gamma_{32}}\\
&\times(\Omega_{23}^2[\gamma_{32}(\Gamma_{32}+\gamma_{21})(\Omega_{23}^2+\gamma_{21}\gamma_{31})+4\Delta\omega_{21}^2\gamma_{31}(\gamma_{32}-\Gamma_{32})+4\Delta\omega_{31}^2\gamma_{21}\Gamma_{32}+4\Delta\omega_{21}\Delta\omega_{31}\Gamma_{32}(\gamma_{31}-\gamma_{32}-\gamma_{21})]\\
&\quad+R_{23}\{[\gamma_{32}^2+4(\Delta\omega_{31}-\Delta\omega_{21})^2][4\Delta\omega_{21}^2\gamma_{31}+\gamma_{21}(\Omega_{23}^2+\gamma_{21}\gamma_{31})]\})\,, \qquad (3\text{c})
\end{aligned}$$

where

$$|\Delta|^2=(\Omega_{23}^2+\gamma_{21}\gamma_{31}-4\Delta\omega_{21}\Delta\omega_{31})^2+(2\gamma_{21}\Delta\omega_{31}+2\gamma_{31}\Delta\omega_{21})^2 \qquad (3\text{d})$$

and the steady-state populations satisfy

$$\frac{\rho_{22}+\rho_{33}}{\rho_{11}}=\frac{R_{13}}{\Gamma_{31}+R_{13}}\left[\frac{(\Gamma_{32}+2R_{23})[\gamma_{32}^2+4(\Delta\omega_{31}-\Delta\omega_{21})^2]+2\Omega_{23}^2\gamma_{32}}{R_{23}[\gamma_{32}^2+4(\Delta\omega_{31}-\Delta\omega_{21})^2]+\Omega_{23}^2\gamma_{32}}\right]. \qquad (4)$$

We take both the coupling and probe fields to be resonant, i.e., $\Delta\omega_{21}=\Delta\omega_{31}=0$. The necessary and sufficient condition for amplification without population inversion in any atomic basis set is

$$\frac{\Gamma_{32}}{\gamma_{21}}>\frac{\Gamma_{31}}{R_{13}}\frac{\Omega_{23}^2+R_{23}\gamma_{32}}{\Omega_{23}^2}>\frac{\Omega_{23}^2+(\Gamma_{32}+R_{23})\gamma_{32}}{\Omega_{23}^2}\,. \qquad (5)$$

If the first inequality is satisfied then there is net gain $[W_{\text{em}}(\rho_{22}+\rho_{33})>W_{\text{abs}}\rho_{11}]$; if the second is satisfied, there is no population inversion ($\rho_{11}>\rho_{22}+\rho_{33}$). These two inequalities are compatible and they are satisfied by real atomic systems.

For all conditions, observation of gain requires that the spontaneous decay rate from state $|3\rangle$ to state $|2\rangle$ exceed that from state $|3\rangle$ to state $|1\rangle$ ($\Gamma_{32}>\Gamma_{31}$). This condition, which is the essence of this model system, is understood by considering a single atom at a time.[6] Following an excitation such as that caused by a spontaneous decay, an atom experiences a transient loss (gain) before becoming transparent on a time scale given by the inverse decay rate. Atoms which experience a spontaneous decay from state $|3\rangle$ to state $|1\rangle$ invoke this single-atom transient response and produce loss to the probe laser. Atoms which decay to state $|2\rangle$ produce gain. It has been shown previously[6] that the threshold of a laser of this type is determined by the rates into the upper and lower states, and not by the population difference. $\Gamma_{32}>\Gamma_{31}$ guarantees that an atom is more likely to contribute to gain than to loss. When $\Gamma_{32}\gg\Gamma_{31}$, an atom which is initially pumped by incoherent radiation from state $|1\rangle$ to state $|3\rangle$, decays spontaneously to state $|2\rangle$ and is recycled by the coupling field so as to allow many spontaneous excitations of state $|2\rangle$ before decaying back to state $|1\rangle$ and invoking a (single-atom) transient loss.

In order to satisfy Eq. (5) it is also necessary that $R_{13}\Gamma_{32} > \Gamma_{31}R_{23}$, or equivalently $\bar{n}_{13} > \bar{n}_{23}$. This inequality states that the modes of the radiation field with higher energy $(\hbar\omega_3 - \hbar\omega_1)$ have a higher occupancy than the modes with lower energy $(\hbar\omega_3 - \hbar\omega_2)$, if lasing without inversion is to occur. This condition can be thought of as an inversion condition for the radiation field.

We have shown that the steady-state lasing without atomic inversion is possible in a closed atomic system. As the total population in the upper manifold (states $|2\rangle$ and $|3\rangle$) is independent of the basis set that one uses, one may not find an atomic basis in which this system is inverted. For a system that satisfies $\Gamma_{32} > \Gamma_{31}$, the requirement for lasing is an inversion in the radiation field.

In a real system there will also be collisional dephasing, excitation, and deexcitation. Such terms may be added macroscopically to the density matrix; if this is done, then a condition for net gain is that Γ_{32} must exceed the collisional dephasing rate of the $|1\rangle$-$|2\rangle$ transition. The effects of finite laser linewidth can also be incorporated into the density-matrix equations. For lasers that obey the Wiener-Levy phase diffusion statistics, the effect of the linewidth is similar to that of collisional dephasing of the $|1\rangle$-$|2\rangle$ transition.[15]

The laser scheme that we have presented could be realized in practice if, in addition to the already mentioned conditions, the Doppler broadening is kept comparable to the lifetime broadening. As the coupling Rabi frequency must be chosen on the order of the Doppler broadening, large values of the latter quantity give very small gain cross sections. An example for this laser scheme could be found in neutral Sn. Here, we identify the ground state $5s^2 5p^2\,{}^3P_0$ as state $|1\rangle$, $5s^2 5p^2\,{}^1S_0$ as state $|2\rangle$, and $5s^2 5p5d\,{}^1P_1$ as state $|3\rangle$ (Fig. 1).

In summary, this work shows a model three-state laser system which does not require an atomic population inversion, but operates using an inversion in the radiation field. The system is pumped by incoherent radiation at the transition on which lasing occurs. Pumping and decay are radiative and occur within the closed system.

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