Coherent Control of Spontaneous Emission near a Photonic Band Edge: A Single-Atom Optical Memory Device

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We demonstrate coherent control of spontaneous emission from a three-level atom with one resonant frequency near the edge of a photonic band gap. As a result of quantum interference and photon localization, spontaneous emission can be totally suppressed or strongly enhanced depending on the relative phase between the control and pump laser fields. The fractionalized steady state inversion of the atom depends sensitively on the initial conditions, suggesting the possibility of a phase-sensitive, optical memory device on the atomic scale. [S0031-9007(97)04879-5]

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Photon localization is a fundamental effect predicted [1] to occur in certain strongly scattering dielectric microstructures. The realization of this effect has been facilitated by the prediction [2,3] and development [4–7] of photonic band gap (PBG) materials. These are lossless materials which exhibit a range of frequencies for which electromagnetic wave propagation is classically forbidden. In addition to strong localization of light [3] at the classical level, these systems lead to the suppression of spontaneous emission [2,8] and the formation of photon-atom bound states [9]. Near a photonic band edge, spontaneous emission [2,8] and the formation of photon-classical level, these systems lead to the suppression of spontaneous emission dynamics is anomalous [10] and leads to a fractionalized steady-state inversion [8,10,11] for a single atom. Nonexponential spontaneous emission depends on the externally prescribed initial conditions, suggesting the possibility of a phase-sensitive, optical memory device on the atomic scale. As a result, such a system may be relevant for a single-atom, phase-sensitive, optical memory device.

The model we consider consists of a three-level atom with two upper levels [3] and [2] and a ground state [1] (Fig. 1). The level [3] is coupled by radiation modes to the ground level [1], and the resonant transition frequency $\omega_{31}$ is assumed to be equal to the band edge frequency $\omega_e$ of a photonic band gap [9–11,14]. The transition between the two upper levels [3] and [2] is driven by a resonant ($\omega_c = \omega_{32}$) control laser field. The Hamiltonian of the system in the interaction picture has the form,

$$H = i\hbar\Omega (e^{i\phi}\sigma_{23} - e^{-i\phi}\sigma_{32}) + \sum_\lambda \hbar\Delta_\lambda a_\lambda^\dagger a_\lambda + i\hbar \sum_\lambda g_\lambda (a_\lambda^\dagger \sigma_{13} - \sigma_{31} a_\lambda).$$

(1)

Here $\sigma_{ij} = |i\rangle \langle j| (i, j = 1, 2, 3)$ are the atomic operators, $a_\lambda$ and $a_\lambda^\dagger$ are the radiation field annihilation and creation operators, $\Omega$ is the resonant Rabi frequency, $\phi_c$ is the phase of the control laser beam which depends on its optical path, and $\Delta_\lambda = \omega_\lambda - \omega_{31}$ is the detuning of the radiation mode frequency $\omega_\lambda$ from the atomic resonant frequency $\omega_{31}$. In the final term of (1), $g_\lambda = (\omega_{31}d_{31}/\hbar)(\hbar/2\epsilon_0\omega_A V_0)^{1/2}e_{k}\cdot u_d$ is the atom-radiation field coupling, where $d_{31}$ and $u_d$ are the magnitude and unit vector of the atomic dipole moment of the transition $|3\rangle \rightarrow |1\rangle$, $V_0$ is the quantization volume, $e_k \equiv e_{k,\sigma}$.