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Electromagnetically induced grating in a crystal of molecular magnets system

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ABSTRACT

We investigate the response of the molecular system to the magnetic field modulation. Molecular magnets are subjected to a strong standing ac magnetic field and a weak probe magnetic field. The transmission and absorption of the weak probe magnetic field can be changed due to quantum coherence and the spatially modulating of the standing field. And a electromagnetically induced grating is formed in the crystal of molecular magnets via electromagnetically induced transparency (EIT). The diffraction efficiency of the grating can be adjusted efficiently by tuning the intensity of the standing wave field and the single photon detuning.

1. Introduction

A great deal of attention has been paid to the cold atomic medium, semiconductor quantum well nanostructures and molecular magnets, because these systems demonstrate many interesting quantum phenomena [1–14] due to quantum coherence and quantum interference. The optical properties of molecular magnets have attracted considerable attention because they show many interesting phenomena, such as the phonon superradiance and phonon laser effect [15], giant Kerr nonlinear [16] and EIT [17], space–time Rabi oscillations [18] as well as the acoustic waves propagation in molecular magnets [19–22]. Electromagnetically induced grating (EIG) [23] can be formed in an atomic system which is subjected to a strong standing wave and a weak probe field. The transmission and absorption of the weak probe field can be adjusted by the spatial modulation of the strong standing wave field, and the probe field is diffracted into the high-order directions. Due to Fano interference, the diffraction efficiency of the EIG in an asymmetric semiconductor quantum well can be significantly enhanced [24]. Electromagnetically induced phase grating (EIPG) [25] can be generated in an atomic medium based on the giant Kerr nonlinearity via EIT. The diffraction efficiencies can research 30% due to the high transmissivity of the probe field. Due to the phonon-induced coherent population oscillation, EIPG can be formed in a driven two-level quantum dot exciton system [26]. The effect of spontaneous emission on EIPG has been studied [27,28] and the results show that the diffraction efficiency of phase grating and the transmission and reflection of the weak probe field can be changed due to the existence of spontaneously generated coherence (SGC). The gain-phase grating is theoretically proposed in ultracold atomic systems [29] based on the spatial modulation of active Raman gain and they pointed out that the gain-phase grating has larger diffraction efficiencies than EIPG in the high-order directions. The potential applications of EIG have been discussed in atomic systems, such as transient Bragg diffraction [30], all optical switching and routing [31], optical bistability [32] and engineering biphoton wave packets [33].

In this paper, we study the generation of EIG in a crystal of molecular magnets structure, which interacts with a strong standing wave field and a weak probe magnetic field. By suitably adjusting the intensity of coupling field, EIG can be created in this magnetic medium via EIT. And the transmission of the weak probe magnetic field can be increased by adjusting the intensity of standing wave. Besides, the influences of the control field intensity and the single photon detuning on the diffraction efficiency of the grating are also discussed.

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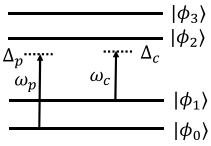

Fig. 1. Two lower doublets of a magnetic molecule. Weak field frequency ω_p is close to the transition frequency between states from $|\phi_0\rangle$ to $|\phi_2\rangle$. Strong field frequency ω_c is close to the transition frequency between states from $|\phi_1\rangle$ to $|\phi_2\rangle$.

2. Model and analytical solution

Let us consider a crystal of noninteracting magnetic molecule (for example, Fe_8 acetate) interacting with a weak probe magnetic field and a strong standing wave field to generate EIG. The noninteracting magnetic molecule is subject to one dc magnetic field and the Hamiltonian of the system can be written as ($\hbar = 1$) [17]

$$\hat{H} = \hat{H}_{tr} - D\hat{S}_z^2 - g\mu_B H_0 \hat{S}_x, \tag{1}$$

where z is the easy anisotropy axis; g is the Landé factor and μ_B is the Bohr magneton; D is the longitudinal anisotropy constant; $\hat{H}_{tr}$ is the operator of the transverse anisotropy energy; H_0 is the dc magnetic field and directed along the x axis; $\hat{S}_x$, $\hat{S}_y$, and $\hat{S}_z$ are the x, y, and z projections of the spin operator, respectively.

Due to the dc magnetic field and the transverse anisotropy, the molecule levels form a series of doublets split. The molecule energy is $E(m) = -D_0 m^2$ in the absence of dc fields and ignoring the transverse anisotropy. m designates the eigenvalues of $\hat{S}_z$ in units of $\hbar$. According the Refs. [34,35], the dc magnetic field H_0 and the transverse anisotropy induce spin tunneling between two states of any doublet and $E(m) = -D_0 m^2 \pm \Delta_E$, Δ_E is small energy due to the transverse anisotropy and dc magnetic field H_0. For Fe_8, $S = 10$. There exist 21 $(2S+1)$ energy levels and 21 state vectors. The split molecule energy levels can be denoted as $\epsilon_0 = E(10), \epsilon_1 = E(-10), \epsilon_2 = E(9), \cdots$ and the corresponding eigenfunctions are $|\phi_\rangle, |\phi_1\rangle, |\phi_2\rangle \cdots$. In our case, we only consider the lowest three energy levels which interact with the weak probe field and the strong coupling field and the corresponding energy levels are shown in Fig. 1. We assume that the weak probe magnetic field drives the transmission from $|\phi_0\rangle$ to $|\phi_2\rangle$ and with the expression

$$H_p(z,t) = \frac{1}{2} H_p e^{-i\omega_p t + ik_p z} + c.c. \tag{2}$$

Here H_p is the magnitude of the probe magnetic field, and $c.c.$ stands for complex conjugate. The standing wave can be formed by two coupling fields which are symmetrically displaced with respect to z. The two coupling magnetic fields have frequency ω_c and the wave vector of the two coupling magnetic fields composed of a z component k_{cz} and an x component k_{cx} or $-k_{cx}$. In the overlap region, the two coupling magnetic fields form a standing wave in the x direction. So the coupling fields can be written as

$$H_c(x,z,t) = \frac{1}{2} H_{c0} \sin(\pi x/\Lambda) e^{-i\omega_c t + ik_{cz} z} + c.c.\,, \tag{3}$$

where H_c is the magnitude of the standing wave field, and Λ is the space period. Λ can be adjusted by varying the angle between the corresponding wave vector k_{cx} and k_{cz} for a fixed k_c satisfying $k_c^2 = k_{cx}^2 + k_{cz}^2$. Under the rotational wave approximation, the interaction Hamiltonian can be written as:

$$H_I = \Delta_c |\phi_2\rangle\langle\phi_2| + (\Delta_p - \Delta_c)|\phi_1\rangle\langle\phi_1| - [\Omega_p |\phi_2\rangle\langle\phi_0| + \Omega_c \sin(\pi x/\Lambda)|\phi_2\rangle\langle\phi_1| + h.c.]\,, \tag{4}$$

where $\Delta_p = \omega_p - \omega_{20}$ and $\Delta_c = \omega_c - \omega_{21}$ are single photon detunings. And the Rabi frequencies $\Omega_{c(p)}$ are defined as $\Omega_c = \frac{1}{2\hbar} g\mu_B H_{c0} \langle\phi_1|S_y|\phi_2\rangle$ and $\Omega_p = \frac{1}{2\hbar} g\mu_B H_p \langle\phi_0|S_x|\phi_2\rangle$. The dynamics of the magnetic molecule can be described by the density matrix equation [36]

$$\begin{aligned} &\frac{d\sigma_{mn}}{dt} + \left(\gamma_{mn} - i\frac{\epsilon_n - \epsilon_m}{\hbar}\right)\sigma_{mn} + \frac{i}{\hbar}[\hat{H}_I, \hat{\sigma}]_{mn} = 0 \quad (m \neq n), \\ &\frac{d\sigma_{nn}}{dt} + \frac{i}{\hbar}[\hat{H}_I, \hat{\sigma}]_{mn} = \sum_{k=0}^{2} (W_{nk}\sigma_{kk} - W_{kn}\sigma_{nn}), \end{aligned} \tag{5}$$

where $m, n = 0, 1, 2$; σ_{mn} is a density matrix element; γ_{mn} is the relaxation constant of the matrix elements σ_{mn}; ϵ_n and ϵ_m are the eigenenergies of the Hamiltonian H. W_{nk} is the rate of the transition from the kth level to the nth one. It should be noticed that $\sigma_{mn} = \sigma_{nm}^*$ and $\gamma_{mn} = \gamma_{nm}$. Under the rotating-wave approximation, we can easily obtain the time dependent density matrix equation as follows

$$\dot{\sigma}_{00} - W_{01}\sigma_{11} - W_{02}\sigma_{22} + (W_{10} + W_{20})\sigma_{00} - i\Omega_p^*\sigma_{20} + i\Omega_p\sigma_{02} = 0, \tag{6a}$$

$$\dot{\sigma}_{11} - W_{10}\sigma_{00} - W_{12}\sigma_{22} + (W_{01} + W_{21})\sigma_{11} - i\Omega_c^* \sin(\pi x/\Lambda)\sigma_{21} + i\Omega_c \sin(\pi x/\Lambda)\sigma_{12} = 0, \tag{6b}$$

$$\dot{\sigma}_{10} + (\gamma_{10} - i(\Delta_c - \Delta_p))\sigma_{10} - i\Omega_c^* \sin(\pi x/\Lambda)\sigma_{20} + i\Omega_p\sigma_{12} = 0, \tag{6c}$$

$$\dot{\sigma}_{20} + (\gamma_{20} + i\Delta_p)\sigma_{02} - i\Omega_p(\sigma_{00} - \sigma_{22}) - i\Omega_c \sin(\pi x/\Lambda)\sigma_{10} = 0, \tag{6d}$$

$$\dot{\sigma}_{21} + (\gamma_{21} + i\Delta_c)\sigma_{12} - i\Omega_p\sigma_{01} - i\Omega_c \sin(\pi x/\Lambda)(\sigma_{11} - \sigma_{22}) = 0. \tag{6e}$$