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Plasmon-induced phase grating via nonlinear modulation

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ABSTRACT

By studying the linear and nonlinear properties of four-level quantum system near plasmonic nanostructure (PS), it is realized that the diffraction efficiency of weak probe light can be controlled by plasmon induced linear and nonlinear modulation. We investigated that due to presence of plasmonic nanostructure, the giant Kerr nonlinearity with vanishing linear and nonlinear absorption can be obtained. In this case, a weak probe light can be diffracted to the higher-order direction due to modulation of nonlinear susceptibility.

1. Introduction

The interaction between light and matter leads to many well known phenomenon in nonlinear and quantum optics [1–9]. In this case, the Kerr nonlinearity which corresponds to the third-order nonlinearity has essential role for observation of these phenomenon [10–14]. It is known that the giant Kerr nonlinearity with reduced absorption is desirable in various optical systems. To reaching these advantages coherent electromagnetically induced transparency (EIT) technique have been suggested for reducing the linear absorption [4]. The giant Kerr nonlinearity with vanishing linear absorption has been observed in various media [15–20]. The most of proposals on the giant Kerr nonlinearity have been studied on multi-level atomic systems with at least two coupling laser fields or other crucial conditions [17,21–24]. However, it is show that the quantum interference can also be created via plasmonic nanostructures which is located near to the quantum system, and named as plasmon induced quantum interference [25]. This type of quantum interference in multi-level atomic systems can leads to many interesting phenomena such as slow light propagation [26], controlling the spontaneous emission [27] and others [16,28–37]. In this article, we will discuss the impact of plasmon induced quantum interference on the third-order cross nonlinear interacted between the probe and coupling laser fields in a four-level quantum system. For a closed distance between quantum system and plasmonic nanostructure, the quantum interference between two spontaneous emission channels can be enhanced. Therefore, the enhanced nonlinear refraction in EIT condition can be possible due to presence of plasmonic nanostructure near the quantum systems. Moreover, by using the standing-wave intensity pattern of coupling field, the medium acts as an absorption or phase grating due to changing in absorption or refractive index of probe light. In this case, the probe light can be diffracted into high-order direction which is known as electromagnetically induced grating (EIG) [38]. Many schemes have been suggested for the preparation of EIG based on different mechanisms [39–49]. For example Cheng et al. [46], studied the EIG in the two-level quantum dot system at the presence of excitons–phonon interactions. In this article, we propose a new model for studying the features of grating based on nonlinear modulation of four-level quantum system due to presence of plasmon nanostructure. The enhanced Kerr nonlinearity of a two-level atom placed in the near of plasmonic nanostructure has been reported due to quenching of both radiative and non-radiative spontaneous emission paths for frequencies near the surface plasmon resonances [30]. In our proposed model, the quantum system interacts with probe and standing-wave laser fields. By using the density matrix method, we calculated the linear and nonlinear susceptibilities. We show that in the presence of plasmonic nanostructure, the giant Kerr nonlinearity with probe light amplification can be obtained. Moreover, the diffraction patterns of the probe light in the presence of plasmonic nanostructure have also been studied. We realized that a weak probe light can be diffracted into the high-order directions due to absorptive and nonlinear modulation.

The paper is organized as follows. In next section, we present the proposed model and discuss the properties of linear and nonlinear susceptibilities. We show that the plasmonic nanostructure can enhance the nonlinearity of the medium with optimized of probe absorption. And then, we study the diffraction efficiency of grating in different conditions. At the end, we present the conclusion of paper.

2. Model and equations

The double-ladder type four-level quantum system which located in vacuum at distance d from the surface of the plasmonic nanostructure

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(PS) is displayed in Fig. 1(a). The quantum system interacts with a weak probe and strong coupling fields. The weak probe light couples the ground level $|1\rangle$ to two upper closely levels $|2\rangle$ and $|3\rangle$ with Rabi-frequencies $\Omega_{p1} = E_p.\wp_{21}/2\hbar$ and $\Omega_{p2} = E_p.\wp_{31}/2\hbar$. Moreover, the states $|2\rangle$ and $|3\rangle$ are coupled to the upper level $|4\rangle$ by a strong coupling field with Rabi-frequencies $\Omega_{c1} = E_c.\wp_{24}/2\hbar$ and $\Omega_{c2} = E_c.\wp_{34}/2\hbar$, respectively. The parameter $\wp_{ij}$ shows the electric-dipole moment for transition $|i\rangle \leftrightarrow |j\rangle$. We suppose that $\wp_{31}/\wp_{21} = \alpha$ and $\wp_{34}/\wp_{24} = \beta$, therefore, we have $\Omega_{p1} = \Omega_{p2}/\alpha = \Omega_p$ and $\Omega_{c1} = \Omega_{c2}/\beta = \Omega_c$. The interaction between quantum system and vacuum leads to spontaneous emission from state $|4\rangle$ which is denoted by γ', while the interaction between quantum system and surface Plasmon bands of the PS is displayed with γ. Under the rotating wave approximation, the density matrix equations of motions can be given as follows:

$$\frac{\partial\rho_{31}}{\partial t} = -(\gamma + i(\Delta_p + \delta))\rho_{31} + i\Omega_{c1}\rho_{41} - i\Omega_{p1}(\rho_{33} - \rho_{11}) - i\Omega_{p2}\rho_{32} - \eta\rho_{21}$$
$$\frac{\partial\rho_{21}}{\partial t} = -(\gamma + i(\Delta_p - \delta))\rho_{21} + i\Omega_{c2}\rho_{41} - i\Omega_{p1}\rho_{23} + i\Omega_{p2}(\rho_{11} - \rho_{22}) - \eta\rho_{31}$$
$$\frac{\partial\rho_{41}}{\partial t} = -(\gamma' + i(\delta - \Delta_p))\rho_{41} + i\Omega_{c1}\rho_{31} + i\Omega_{c2}\rho_{21} - i\Omega_{p1}\rho_{43} + i\Omega_{p2}\rho_{42}$$
$$\frac{\partial\rho_{42}}{\partial t} = -[(\gamma + \gamma') - i\Delta_c]\rho_{42} + i\Omega_{c2}(\rho_{22} - \rho_{44}) + i\Omega_{c1}\rho_{32} - i\Omega_{p2}\rho_{41} - \eta\rho_{43}$$
$$\frac{\partial\rho_{43}}{\partial t} = -[(\gamma + \gamma') - i\Delta_c]\rho_{43} + i\Omega_{c1}(\rho_{33} - \rho_{44}) + i\Omega_{c2}\rho_{23} - i\Omega_{p1}\rho_{41} - \eta\rho_{42}$$
$$\frac{\partial\rho_{32}}{\partial t} = -[\gamma + 2i\delta]\rho_{32} + i\Omega_{c1}\rho_{42} - i\Omega_{c2}\rho_{34} + i\Omega_{p1}\rho_{12} - i\Omega_{p2}\rho_{31} - \eta(\rho_{33} + \rho_{22})$$
$$\frac{\partial\rho_{33}}{\partial t} = i\Omega_{p1}(\rho_{13} - \rho_{31}) + i\Omega_{c1}(\rho_{43} - \rho_{34}) + \gamma'\rho_{44} - \gamma\rho_{33} - \eta(\rho_{23} + \rho_{32})$$
$$\frac{\partial\rho_{22}}{\partial t} = i\Omega_{p2}(\rho_{12} - \rho_{21}) + i\Omega_{c2}(\rho_{42} - \rho_{24}) + \gamma'\rho_{44} - \gamma\rho_{22} - \eta(\rho_{23} + \rho_{32})$$
$$\frac{\partial\rho_{44}}{\partial t} = i\Omega_{c2}(\rho_{24} - \rho_{42}) + i\Omega_{c1}(\rho_{34} - \rho_{43}) - 2\gamma'\rho_{44} \quad (1)$$

where $\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44} = 1$ and $\rho_{ij} = \rho^*_{ji}$. The parameter η is the coupling coefficient between levels $|2\rangle$ and $|3\rangle$ denotes the appearance of quantum interference. The parameters $\Delta_p = (\omega_{21} + \omega_{31})/2 - \omega_p$ and $\Delta_c = (\omega_{42} + \omega_{43})/2 - \omega_c$ are the detunings of the probe and coupling fields. The values of parameters γ and η are obtained via [37]:

$$\gamma = \frac{\mu_0\wp^2\bar{\omega}^2}{2\hbar}\mathrm{Im}[G_\perp(r,r;\bar{\omega}) + G_\parallel(r,r;\bar{\omega})] = \frac{1}{2}(\Gamma_\perp + \Gamma_\parallel),$$
$$\eta = \frac{\mu_0\wp^2\bar{\omega}^2}{2\hbar}\mathrm{Im}[G_\perp(r,r;\bar{\omega}) - G_\parallel(r,r;\bar{\omega})] = \frac{1}{2}(\Gamma_\perp - \Gamma_\parallel) \quad (2)$$

where $G(r,r;\bar{\omega})$ is the dyadic electromagnetic Green's tensor, r denotes the position of the quantum system and μ_0 is permeability of vacuum and $\bar{\omega} = (\omega_2 + \omega_3)/2 - \omega_1$. The symbol $\perp(\parallel)$ shows the dipole oriented normal-along the z axis (parallel-along the x axis) to the surface of the PS. In the case of $\Gamma_\perp = \Gamma_\parallel$ (the quantum system is placed in vacuum) leads to $\eta = 0$ which means there is no quantum interference appears in the system. In our proposed structure the PS is a 2D array of touching metal-coated silica nanospheres which presented in Fig. 1. The dielectric function can be given as:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\tau)} \quad (3)$$

Parameter ω_p shows the bulk plasma frequency and τ refers to the relaxation time of the conduction-band electrons of the metal. By considering the $\hbar\omega_p \simeq 3.8$ eV, corresponds to the silver the lattice constant of the square lattice is $a = 104$ nm and the sphere radius $S = 52$ nm with core radius $S_c = 36.4$ nm can be obtained. From ref, we can obtain the values of $\Gamma_\perp$ and $\Gamma_\parallel$ for the different distance d.

3. Part A: Linear and nonlinear susceptibility

In the following, we will drive the linear and nonlinear susceptibility of the four-level quantum system via Eq. (1). Due to relation $\varepsilon_0\chi_p E_p = 2N(\wp_{21}\rho_{21} + \wp_{31}\rho_{31})$, one can find the cross-Kerr nonlinearity between the coupling and probe lights, after expanding the probe susceptibility χ_p into the second order of Ω_c as follows:

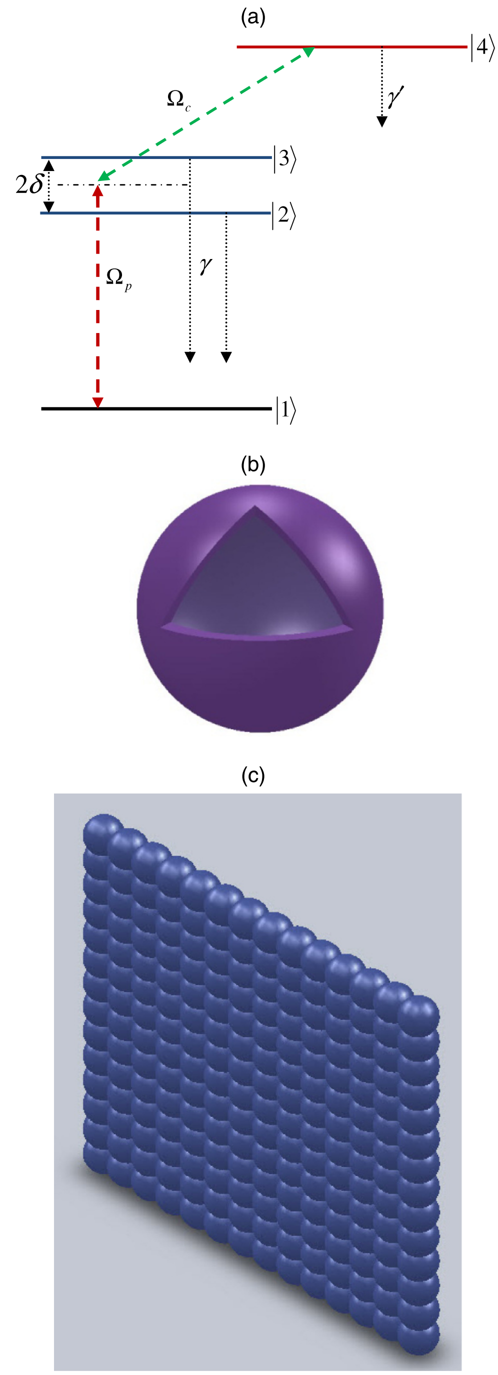

Fig. 1. (a) Four-level quantum system which interacted with a probe and standing coupling fields. (b) Metal-coated dielectric nanospheres and (c) two-dimensional array of nanospheres.

$$\chi_p = \frac{N\wp_{21}^2}{\varepsilon_0\hbar}[\chi^{(1)} + \chi^{(3)}\Omega_c^2] \quad (4)$$

where $\chi^{(1)}$ and $\chi^{(3)}$ refer to the linear and nonlinear parts of susceptibility and are given in Box I.

We now, discuss the features of linear and nonlinear susceptibility of four-level quantum system in the presence of PS. The parameter of plasmonic nanostructure is taken as $\varepsilon = 2.1, \tau^{-1} = 0.1\omega_p$. In our