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An electromagnetically induced grating by microwave modulation

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Abstract

We study the phenomenon of an electromagnetically induced phase grating in a double-dark state system of \(^{87}\text{Rb}\) atoms, the two closely placed lower fold levels of which are coupled by a weak microwave field. Owing to the existence of the weak microwave field, the efficiency of the phase grating is strikingly improved, and an efficiency of approximately 33% can be achieved. Under the action of the weak standing wave field, the high efficiency of the phase grating can be maintained by modulating the strength and detuning of the weak microwave field, increasing the strength of the standing wave field.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Electromagnetically induced transparency (EIT) is the most fundamental of many novel effects of atomic coherence and has been extensively developed both theoretically and experimentally. The essence of EIT is that the resonant absorption disappears and the medium becomes effectively transparent for the probe field under the action of a strong coherent field on a linked transition [1–3]. The technique of manipulating atomic-optical response by EIT has been successfully applied in various fields, which include slow light, stopped light and light storage [4–8], quantum information [9–12], and nonlinear optics [13–15]. Recently, another interesting and important phenomenon, i.e. an electromagnetically induced grating (EIG) [16–19] based on EIT, has received great attention owing to its potential applications such as being a background-free technique [17], tracing the appearance of CPT [18], diffracting and switching a quantized probe field [19], etc.

It is well known that atomic coherence can also occur by the process of spontaneous emission, wherein atoms decay spontaneously from a single excited state to two closely placed lower levels or from two closely excited levels to a single ground level. This kind of coherence is called spontaneously generated coherence (SGC) [20]. The existence of SGC, however, needs to simultaneously satisfy two conditions, which are that two closely placed levels are near degenerate and the corresponding atomic dipole moments are non-orthogonal in free space. Unfortunately, finding such a real atomic system is very difficult. In order to overcome these difficulties, the two closely placed lower levels may be coupled by a microwave field instead of SGC.

In the present communication, a microwave-coupled four-level atomic system with a twofold level [21–23] is considered. As [21, 22] pointed out, the existence of the microwave field leads to two distinct dark resonances, and the atomic response can be manipulated efficiently. The transparency and high dispersion can be simultaneously achieved by modulating the microwave field, i.e. coherent perturbation on a double-dark line. By analyzing, it is seen that, in such an atomic system, the diffraction efficiency of the electromagnetically induced phase grating increases dramatically due to the existence of the weak microwave field. To maintain the high efficiency of the phase grating under the action of the weak standing wave field, tuning the strength and detuning of the microwave field, increasing the strength of the standing wave field, the efficiency of the phase grating is improved. This kind of atomic system is very appropriate for the investigation of the phenomenon of EIG since the strength and detuning of the microwave field can be controlled readily.
2. Theory

Figure 1(a) illustrates a four-level configuration of $^8$Rb atoms. A probe beam with Rabi frequency $\Omega_p(=\mu_3 E_p/2\hbar)$ and wavelength $\lambda$ drives the transition $|F = 2, m = 1\rangle \leftrightarrow |F = 2, m = 2\rangle$; the transition $|F = 2, m = 1\rangle \leftrightarrow |F = 2, m = 0\rangle$ is driven by a coupling field with Rabi frequency $\Omega_c(=\mu_1 E_c/2\hbar)$; a microwave field with Rabi frequency $\Omega_m(=\mu_4 E_m/2\hbar)$ is applied to the transition $|F = 2, m = 0\rangle \leftrightarrow |F = 1, m = 0\rangle$; the detunings of the probe, coupling and microwave field are given by $\Delta_p(=\omega_p - \omega_{13})$, $\Delta_c(=\omega_c - \omega_{12})$ and $\Delta_m(=\omega_m - \omega_{24})$, where $\omega_{13}$, $\omega_{24}$ and $\omega_{12}$ are the corresponding atomic transition frequencies, while $\omega_p$, $\omega_c$ and $\omega_m$ are the frequencies of the corresponding optical fields.

In the rotating-wave approximation, the density-matrix equation is obtained:

\[ \dot{\rho}_{11} = -(\gamma_1 + \gamma_2)\rho_{11} - i\Omega_p(\rho_{13} - \rho_{31}) - i\Omega_c(\rho_{12} - \rho_{21}) \]
\[ \dot{\rho}_{22} = \gamma_1 \rho_{11} - i\Omega_m(\rho_{24} - \rho_{42}) - i\Omega_c(\rho_{21} - \rho_{12}) \]
\[ \dot{\rho}_{33} = \gamma_2 \rho_{11} + i\Omega_p(\rho_{13} - \rho_{31}) \]
\[ \dot{\rho}_{12} = -(\gamma_1 - i\Delta_c)\rho_{12} + i\Omega_p(\rho_{21} - \rho_{12}) - i\Omega_m\rho_{14} \]
\[ \dot{\rho}_{13} = -(\gamma_1 - i\Delta_p)\rho_{13} + i\Omega_p(\rho_{31} - \rho_{13}) + i\Omega_m\rho_{14} \]
\[ \dot{\rho}_{23} = -(\gamma_2 - i\Delta_c)\rho_{23} + i\Omega_p(\rho_{32} - \rho_{23}) + i\Omega_m\rho_{24} \]
\[ \dot{\rho}_{34} = -(\gamma_2 - i\Delta_m)\rho_{34} + i\Omega_p(\rho_{42} - \rho_{34}) + i\Omega_m\rho_{32} \]
\[ \dot{\rho}_{41} + \rho_{22} + \rho_{33} + \rho_{44} = 1, \quad \rho_{ij} = \rho_{ji}^* \quad (i \neq j) \]

where $\gamma_1$ and $\gamma_2$ are from level $|1\rangle$ to levels $|2\rangle$ and $|3\rangle$, respectively. In the limit of the weak probe field, by solving the above density-matrix equation with initial conditions

\[ \rho_{33}^{(0)} = 1, \quad \rho_{11}^{(0)} = \rho_{22}^{(0)} = \rho_{44}^{(0)} = 0, \quad \rho_{ij}^{(0)} = 0 \quad (i \neq j) \]

we obtain

\[ \dot{\rho}_{13} = -(\gamma_1 - i\Delta_c)\rho_{13} + i\Omega_p + i\Omega_c\rho_{23} \]
\[ \dot{\rho}_{23} = -(\gamma_2 - i\Delta_c)\rho_{23} + i\Omega_p + i\Omega_c\rho_{13} + i\Omega_m\rho_{14} \]
\[ \dot{\rho}_{34} = -(\gamma_4 - i\Delta_c - \Delta_m)\rho_{34} + i\Omega_m\rho_{23} \]

Therefore, in the steady-state case, we get for the probe field

\[ \rho_{13} = i\Omega_p F_{13|/\Omega_m|^2 + \Gamma_3\Gamma_4} + \gamma_3 \Gamma_3 \gamma_3 \Gamma_4 \]
\[ \Gamma_1 = (\gamma_1 - i\Delta_p) \]
\[ \Gamma_2 = (\gamma_2 - i\Delta_c) \]
\[ \Gamma_3 = (\gamma_3 - i\Delta_c) \]
\[ \Gamma_4 = (\gamma_4 - i\Delta_p) \]

The induced polarization of the probe field is $P(\omega_p) = e_p^x(\omega_p) E_p = N\mu_3 P(\omega_p)$; thus, the real and imaginary parts of the steady-state probe susceptibility are given by the following equations:

\[ R_e^x = -K(DB + AD)/(B^2 + A^2) \]
\[ I_c^x = K(DB - AC)/(B^2 + A^2) \]

where

\[ K = N\mu_3^2/2\hbar \]

The dynamic response of the probe field in the medium is described by Maxwell’s wave equation, which in the slowly varying envelope approximation and the steady-state regime is reduced to $\partial E_p/\partial z = i(\pi/\lambda \epsilon_0) p(\omega_p) - \partial E_p/\partial z' = \{-\text{Im}[x] + i\text{Re}[x]\} E_p$, where $z' = (N\mu_3^2/4\hbar \epsilon_0) k_pz$ with $k_p = 2\pi/\lambda_s$, $(N\mu_3^2/4\hbar \epsilon_0) k_p$ is treated as the unit for $z$. When the coupling field is in the form of a standing wave along the $x$-direction (see figure 1(b)), the coupling Rabi frequency can be expressed as $\Omega_c = \Omega_0 \sin(\pi x/L_{\text{eff}})$ [16]. $L_{\text{eff}}$ is the spatial frequency of the standing wave. The coherent decay rate $\gamma_{ij}$ is given as $\gamma_{ij} = \Gamma/2$, $\gamma_{23} = \gamma_3 = 4.002\Gamma$, in which $\Gamma = 2\pi \times 5.9 $ MHz is the spontaneous decay rate of the excited state $|5P_{3/2}\rangle$ [23]. Then, the normalized transmission function for the interaction length $L$ of the atomic sample is written as $T(L) = e^{-\text{Im}[x] L} e^{\text{Re}[x] L}$ [16]. The transmission function $T(x)$ depends on the localization of the atom and EIT. By Fourier transformation of $T(x)$, the Fraunhofer or far-field diffraction pattern.
equation can be obtained [16]:

$$I_p(\theta) = \frac{1}{\Lambda_{ce}} \int_0^1 T(x) \exp(-i2\pi x \cdot \sin(\theta) R) \, dx,$$

where \( R = \Lambda_{ce}/\lambda \), the angle \( \theta \) is the diffraction angle of the probe field with respect to the \( z \)-direction and the parameter \( M \) is a constant factor, which is defined as the spatial width of the probe beam. The \( n \)-order diffraction intensity is determined by equation (2), and \( n = R \sin(\theta) \). When \( \sin(\theta) = \lambda/\Lambda_{ce} \), we obtain the first-order diffraction intensity of the grating, which is expressed as

$$I_p(\theta) = |\Omega_p^1(\theta)|^2.$$  

Here, \( \Omega_p^1(\theta) = \int_0^1 T(x) \exp(-i2\pi x \cdot \sin(\theta) R) \, dx \). Note, in this communication, \( \Lambda_{ce} \) is treated as the unit for \( x \).

3. Results and discussion

The diffraction patterns of the amplitude and phase modulation as a function of \( \sin(\theta) \) are displayed in figure 2. It is seen that, in the pure amplitude modulation, the zero-order diffraction intensity is very strong, the light is gathered mainly at the end, and the available light is very fractional for the first order and high order owing to the absence of phase modulation (Re(\(\gamma\)) = 0, thus \( T(x) = e^{-i\text{Im}(\gamma)x} \)); however, in the process of phase modulation, the first-order diffraction intensity is enhanced dramatically and the zero-order diffraction intensity becomes weak. The transfer of light from zero-order to first-order diffraction is realized; the phase modulation causes much light to be dispersed into the first-order component. We compare the diffraction patterns of phase modulation with and without the microwave field, as shown in figure 3. It is found that the existence of the microwave field greatly improves the diffraction efficiency of the phase grating and the first-order diffraction intensity is increased. As pointed out by Lukin et al [22], in such a system a large refractive index without absorption can be created by proper tuning of the microwave field, i.e. coherent perturbation on double-dark lines. Thus for the atomic response, the dispersion enhanced by the interacting dark resonances can be much larger than that generated in a single dark-resonance system. To this end, adjusting the strength and detuning of the microwave field can affect the diffraction efficiency of the phase grating.

The first-order diffraction intensity \( I_p(\theta) \) as a function of \( \Omega_m \) with and without the detuning \( \Delta_m \) is given in figure 4. The diffraction efficiency of the phase grating considering the detuning \( \Delta_m \) is much larger than that without the detuning \( \Delta_m \). We see that considering the detuning \( \Delta_m \) leads to an increase of the first-order diffraction intensity, and a diffraction efficiency of 33% is obtained at \( \Omega_m \approx 3.5 \text{ MHz} \) for fixed \( \Delta_p \) and \( \Omega \); at the same time, the corresponding strength of the microwave field is very weak. Choosing properly the detuning and strength of the microwave field is very important to improve the diffraction efficiency of the phase grating. Figure 5 illustrates the first-order diffraction intensity \( I_p(\theta) \) as a function of \( \Omega_m \) at various \( \Omega \). The first-order diffraction intensity of the phase grating increases with the increase of the
increase of the detuning of system, the two distinct EIT windows vary over the
standing wave field. The result shows that the applied coupling field is the weak
microwave field intensity when with different
Figure 6. Other parameters are as follows:
\[ \Omega = \Gamma, \gamma = 0.002\Gamma, \Delta_c = 0, \Delta_m = \Gamma, \Delta_p = 0.9\Gamma, L = 300. \]

coupling field and microwave field intensity when \( \Omega \leq \Gamma \); in contrast, the diffraction efficiency is very slow when \( \Omega > \Gamma \). The result shows that the applied coupling field is the weak standing wave field.

The first-order diffraction intensity as a function of the detuning \( \Delta_m \) with different \( \Omega \) is plotted in figure 6. It is found that increasing the strength of the coupling field and the detuning \( \Delta_m \), the first-order diffraction intensity of the phase grating increases and can reach approximately 33% at \( \Omega = 0.5\Gamma \) and \( \Omega = 0.8\Gamma \); however, the diffraction intensity becomes markedly weak when \( \Omega = 1.2\Gamma \). The other observed phenomenon is that there appear two different peak values at different detunings \( \Delta_m \) for a certain \( \Omega \); then, as Niu and her co-workers pointed out [21], in this kind of system, the two distinct EIT windows vary over the increase of the detuning \( \Delta_m \): increasing the detuning \( \Delta_m \), one EIT window accompanying high dispersion becomes narrow, and the other EIT window accompanying the decrease of dispersion becomes broadened. The first-order diffraction efficiency depends on the width and the position of the EIT windows.

4. Conclusions

In conclusion, we have investigated the phenomenon of the electromagnetically induced phase grating in a double-dark state atomic system. The result shows that the diffraction efficiency of the phase grating is effectively improved owing to the existence of a weak microwave field and can be controlled by modulating the strength and detuning of the microwave field; the first-order diffraction intensity of the phase grating is increased remarkably by making a slightly detuning \( \Delta_m \), and the diffraction efficiency can reach 33%; in order to achieve a high diffraction efficiency, both the weak standing wave and weak microwave field should be applied; properly enhancing the strength of the weak standing wave field for the various \( \Delta_m \), two different peak values for first-order diffraction are observed; the reason is that the width and the position of the EIT window are changed with a variation of the detuning \( \Delta_m \). Such a system is very appropriate for the investigation of the phenomenon of EIG since the strength and detuning of the microwave field can be conveniently controlled.

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References