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Effect of Phase Modulation on Electromagnetically Induced Grating in a Five-Level M-Type Atomic System *

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We theoretically investigate the phenomena of electromagnetically induced grating in an M-type five-level atomic system. It is found that a weak field can be effectively diffracted into high-order directions using a standing wave coupling field, and different depths of the phase modulation can disperse the diffraction light into different orders. When the phase modulation depth is approximated to the orders of π, 2π and 3π, the first-, second- and third-order diffraction intensity reach the maximum, respectively. Thus we can take advantage of the phase modulation to control the probe light dispersing into the required high orders.

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Electromagnetically induced grating (EIG), proposed first by Ling *et al.*,[1] is another interesting and important phenomenon based on electromagnetically induced transparency (EIT).[2–5] Replacing the travelling field in an EIT-system with a standing wave field, the weak probe field can travel through the media without any absorption in the segment of antinodes, while it is absorbed completely in the segment of nodes. The atomic medium then is reconstructed to be a periodic grating in the direction of the standing wave field propagation, which can redistribute the energy of the diffraction field in different orders. Since EIG was put forward, it has attracted lots of attention due to its potential applications for atomic/molecular velocimetry,[6] all-optical switching and routing,[7] realization of optical bistability,[8,9] developing a background-free technique,[10] tracing the appearance of CPT,[11] surface solitons,[12] Talbot effect,[13–18] beam splitting and fanning[19] and shaping a biphoton spectrum,[20] and so on. Till now, the EIG effect has been realized theoretically in the Λ-type,[1] Ξ-type,[11] N-type,[21] Y-type,[22] double dark state[23] atomic and semiconductor quantum well[24] systems, and has been observed in cold[6,10] and hot atomic[7,25] samples experimentally. Furthermore, schemes based on nonlinear modulation,[26,27] microwave modulation,[23] static magnetic field,[28] spontaneously generated coherence (SGC)[29,30] and Raman gain[31–33] were also proposed to enhance the efficiency of EIG. In 2014, we proposed a scheme for two-dimensional electromagnetically induced cross-grating (EICG) based on EIT in a four-level tripod-type atomic system.[34] Then, the two-dimensional EICG was also generalized to different systems.[35–37]

However, to the best of our knowledge, the other similar work about EIG only showed that the phase modulation can disperse more light into the high-order directions, but the relationship between the phase modulation depth and the diffraction grades is not specifically researched. Thus in this study, we examine the diffractive properties of an M-type five-level medium by using a standing wave coupling field and research the relationship between the phase modulation depth and the diffraction grades. We find that the first-order diffraction intensity in our system is stronger than the one in the Λ-type three-level medium. At the same time, the first-, second- and third-order diffraction intensities are mainly determined by the phase modulation. When the phase modulation is approximated to the order of π, the energy of the probe light can be dispersed into the first-order direction; when the phase modulation is approximated to the order of 2π, it can be dispersed into the second-order direction; and this is the case for the third-order diffraction. Thus we can control the probe light dispersed into different high-order diffraction directions by the phase modulation and prove theoretically that EIG can be used to effectively control light. The results may be used to develop novel photonic devices used in quantum information processing, quantum networking and optical imaging.

We assume that the medium consists of cold vapor atoms placed in a magneto-optical trap (MOT), and the effect of the Doppler broadening is ignored. A five-level atomic system driven into the M-configuration by four monochromatic laser fields is considered as

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shown in Fig. 1(a). A weak probe field with Rabi frequency $\Omega_{\rm p}$ couples the transition $|1\rangle \leftrightarrow |2\rangle$. Three strong coupling fields with Rabi frequencies $\Omega_{\rm c1}$, $\Omega_{\rm c2}$ and $\Omega_{\rm c3}$ drive the transitions $|3\rangle \leftrightarrow |2\rangle$, $|3\rangle \leftrightarrow |4\rangle$ and $|5\rangle \leftrightarrow |4\rangle$, respectively.

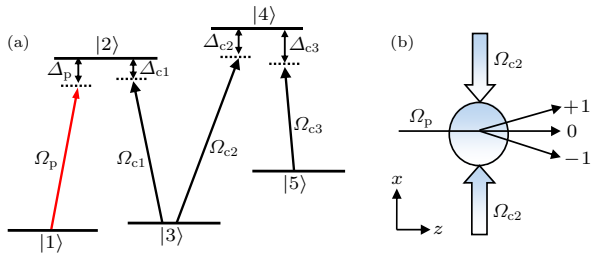

Fig. 1. (a) Schematic diagram of a five-level M-type atomic system. (b) Sketch of a prototype.

Under the rotating-wave approximation and the electric-dipole approximation, we obtain the related density-matrix equations

$$
\begin{aligned}
\dot\rho_{11} =& -i\Omega_{\rm p}\rho_{12} + i\Omega_{\rm p}\rho_{21} + \Gamma_{21}\rho_{22},\\
\dot\rho_{12} =& -(\gamma_{12} - i\Delta_{\rm p})\rho_{12} - i\Omega_{\rm p}(\rho_{22} - \rho_{11})\\
& - i\Omega_{\rm c1}\rho_{13},\\
\dot\rho_{13} =& -[\gamma_{13} - i(\Delta_{\rm p} - \Delta_{\rm c1})]\rho_{13} + i\Omega_{\rm p}\rho_{23}\\
& - i\Omega_{\rm c1}\rho_{12} - i\Omega_{\rm c2}\rho_{14},\\
\dot\rho_{14} =& -[\gamma_{14} - i(\Delta_{\rm p} - \Delta_{\rm c1} + \Delta_{\rm c2})]\rho_{14}\\
& + i\Omega_{\rm p}\rho_{24} - i\Omega_{\rm c2}\rho_{13} - i\Omega_{\rm c3}\rho_{15},\\
\dot\rho_{15} =& -[\gamma_{15} - i(\Delta_{\rm p} - \Delta_{\rm c1} + \Delta_{\rm c2} - \Delta_{\rm c3})]\rho_{15}\\
& + i\Omega_{\rm p}\rho_{25} - i\Omega_{\rm c3}\rho_{14},\\
\dot\rho_{22} =& i\Omega_{\rm p}\rho_{12} - i\Omega_{\rm p}\rho_{21} + i\Omega_{\rm c1}\rho_{32} - i\Omega_{\rm c1}\rho_{23}\\
& - (\Gamma_{21} + \Gamma_{23})\rho_{22},\\
\dot\rho_{23} =& -(\gamma_{23} + i\Delta_{\rm c1})\rho_{23} + i\Omega_{\rm c1}(\rho_{33} - \rho_{22})\\
& + i\Omega_{\rm p}\rho_{13} - i\Omega_{\rm c2}\rho_{24},\\
\dot\rho_{24} =& -[\gamma_{24} + i(\Delta_{\rm c1} - \Delta_{\rm c2})]\rho_{24} + i\Omega_{\rm p}\rho_{14}\\
& + i\Omega_{\rm c1}\rho_{34} - i\Omega_{\rm c2}\rho_{23} - i\Omega_{\rm c3}\rho_{25},\\
\dot\rho_{25} =& -[\gamma_{25} + i(\Delta_{\rm c1} - \Delta_{\rm c2} + \Delta_{\rm c3})]\rho_{25}\\
& + i\Omega_{\rm p}\rho_{15} + i\Omega_{\rm c1}\rho_{35} - i\Omega_{\rm c3}\rho_{24},\\
\dot\rho_{33} =& i\Omega_{\rm c1}\rho_{23} - i\Omega_{\rm c1}\rho_{32} + i\Omega_{\rm c2}\rho_{43}\\
& - i\Omega_{\rm c2}\rho_{34} + \Gamma_{21}\rho_{22} + \Gamma_{43}\rho_{44},\\
\dot\rho_{34} =& -(\gamma_{34} - i\Delta_{\rm c2})\rho_{34} + i\Omega_{\rm c1}\rho_{24} - i\Omega_{\rm c3}\rho_{35}\\
& + i\Omega_{\rm c2}(\rho_{44} - \rho_{33}),\\
\dot\rho_{35} =& -[\gamma_{35} - i(\Delta_{\rm c2} - \Delta_{\rm c3})]\rho_{35} - i\Omega_{\rm c3}\rho_{34}\\
& + i\Omega_{\rm c2}\rho_{25} - i\Omega_{\rm c2}\rho_{45},\\
\dot\rho_{44} =& i\Omega_{\rm c3}\rho_{54} - i\Omega_{\rm c3}\rho_{45} - i\Omega_{\rm c2}\rho_{43}\\
& + i\Omega_{\rm c2}\rho_{34} - (\Gamma_{43} + \Gamma_{45})\rho_{44},\\
\dot\rho_{45} =& -(\gamma_{45} + i\Delta_{\rm c3})\rho_{45} + i\Omega_{\rm c2}\rho_{35}\\
& + i\Omega_{\rm c3}(\rho_{55} - \rho_{44}),
\end{aligned}
\tag{1}
$$

where $\Delta_{\rm p}$, $\Delta_{\rm c1}$, $\Delta_{\rm c2}$ and $\Delta_{\rm c3}$ are the frequency detunings of probe field, three coupling fields, respectively. In Eq. (1), Γ_{ij} is the population decay rate from level $|i\rangle$ to $|j\rangle$, and γ_{ij} is the coherence dephasing rate. To be more specific, we have $\gamma_{ij} = (\Gamma_i + \Gamma_j)/2$, with the spontaneous decay rates $\Gamma_i = \sum_m \Gamma_{im}$, and $\Gamma_j = \sum_n \Gamma_{jn}$. The spontaneous decay rates Γ_1, Γ_3 of the ground levels $|1\rangle$, $|3\rangle$ are ignored for the simple calculation.

To obtain a relatively simple expression, we ignore the spontaneous decay rates Γ_4, Γ_5 of the excited states $|4\rangle$, $|5\rangle$ in our calculations, which is reasonable as long as Γ_4 and Γ_5 are considerably smaller than Γ_2. By taking the levels $|^1S_0, F = 1/2, m_F = -1/2\rangle$, $|^1P_1, F = 1/2, m_F = -1/2\rangle$, $|^1S_0, F = 1/2, m_F = 1/2\rangle$, $|^3P_1, F = 3/2, m_F = -1/2\rangle$ and $|^3P_0, F = 1/2, m_F = 1/2\rangle$ in a ^{171}Yb atom as $|1\rangle$, $|2\rangle$, $|3\rangle$, $|4\rangle$ and $|5\rangle$,[38] we can realize this case easily. The spontaneous decay rate of level $|2\rangle$ ($\Gamma_2 = 28.0\,$MHz) is much larger than that of $|4\rangle$ ($\Gamma_4 \sim 182.0\,$kHz) and $|5\rangle$ ($\Gamma_5 \sim 44\,$mHz) in such an atom, thus the latter ones could be safely ignored. Assuming that the system is initially in its ground state $|1\rangle$ (i.e., $\rho_{11}(0) = 1$) and $\Delta_{\rm c1} = \Delta_{\rm c2} = \Delta_{\rm c3} = 0$, the steady-state linear susceptibility $\chi_{\rm p}$ can be expressed as

$$\chi_{\rm p} = \frac{N_0|\mu_{21}|^2}{\varepsilon_0\hbar}\chi, \tag{2a}$$

where N_0 is the atomic density, and μ_{21} is the dipole matrix element between the states $|2\rangle$ and $|1\rangle$, and χ can be written as

$$
\begin{aligned}
\chi =& i\Delta_{\rm p}/\{\Delta_{\rm p}(\gamma_{12} + i\Delta_{\rm p})\\
& - i\Omega_{\rm c1}^2/[1 + \Omega_{\rm c2}^2/(\Omega_{\rm c3}^2 - \Delta_{\rm p}^2)]\}.
\end{aligned}
\tag{2b}
$$

Under the slowly varying envelope approximation and in the steady state regime, the propagation of the probe field is described by Maxwell's equation[1,31]

$$\frac{\partial E_{\rm p}}{\partial z} = i\frac{\pi}{\varepsilon_0\lambda_{\rm p}}P_{\rm p}, \tag{3a}$$

where $\lambda_{\rm p}$ is the wavelength of the probe field, $P_{\rm p}$ is the polarization of the medium, and $P_{\rm p} = \varepsilon_0\chi_{\rm p}E_{\rm p}$. Equation (3a) can be rewritten as

$$\frac{\partial E_{\rm p}}{\partial z'} = i\gamma_{12}\chi E_{\rm p}, \tag{3b}$$

where $z' = \pi N_0|\mu_{21}|^2/(\varepsilon_0\hbar\lambda_{\rm p}\gamma_{12})z$, z' can be made dimensionless by setting $z_0 = (\varepsilon_0\hbar\lambda_{\rm p}\gamma_{12})/(\pi N_0|\mu_{21}|^2)$ as the unit for z. By solving Eq. (3b), the transmission function for an interaction length L of the medium can be obtained,

$$T(x) = \exp(-{\rm Im}[\chi]\gamma_{12}L + i\Phi), \tag{4}$$

where $\Phi = {\rm Re}[\chi]\gamma_{12}L$ is the transmission function's phase. When the second coupling field is in the form of a standing wave, which is produced as shown in Fig. 1(b), its Rabi frequency can be expressed as $\Omega_{\rm c2} = \Omega_2\sin(\pi x/\Lambda_{cx})$ with Λ_{cx} being the spatial period of the standing wave. Based on the Fourier trans-

formation of $T(x)$ and the Fraunhofer diffraction theory, we obtain the Fraunhofer diffraction intensity represented by

$$I_{\rm p}(\theta) = |F(\theta)|^2 \frac{\sin^2(N\pi\Lambda_{cx}\sin\theta/\lambda_{\rm p})}{N^2\sin^2(\pi\Lambda_{cx}\sin\theta/\lambda_{\rm p})}, \quad (5)$$

where

$$F(\theta) = \int_0^1 T(x)\exp(-i2\pi x\Lambda_{cx}\sin\theta/\lambda_{\rm p})dx. \quad (6)$$

with θ being the diffraction angle of the probe field with respect to the z-direction, and N the number of space period for the grating. The n-order diffraction efficiency is determined by the grating equation, i.e., $\sin\theta = n\lambda_{\rm p}/\Lambda_{cx}$. Hence, the first-order diffraction intensity can be expressed as $I_{\rm p}(\theta_1) = |F(\theta_1)|^2 = |\int_0^1 T(x)\exp(-i2\pi x)dx|^2$.

In the following we implement the numerical calculations, and discuss the main results on the diffraction properties of electromagnetically induced grating in the proposed M-type five-level atomic system. To present the results in a unitless form, we choose γ_{12} as the unit for all the Rabi frequencies, probe frequency detuning.

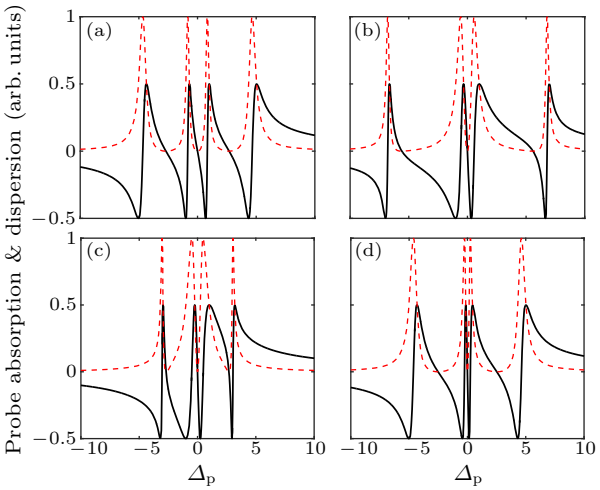

Fig. 2. (Color online) Probe absorption (red dashed line) and dispersion (black solid line) in arbitrary units: (a) $\Omega_{c1} = 3.9$, $\Omega_{c2} = 2.5$, $\Omega_{c3} = 1$; (b) $\Omega_{c1} = 3.9$, $\Omega_{c2} = 5.5$, $\Omega_{c3} = 1$; (c) $\Omega_{c1} = 1.5$, $\Omega_{c2} = 2.5$, $\Omega_{c3} = 1$; and (d) $\Omega_{c1} = 3.9$, $\Omega_{c2} = 2.5$, $\Omega_{c3} = 0.3$.

Since the susceptibility of the medium plays a crucial role in EIG, first in Fig. 2 we introduce the probe absorption and dispersion as a function of the probe detuning for different Rabi frequencies of three coupling fields. From Fig. 2, we observe three EIT windows, and the middle EIT window is very narrow compared with those in both sides. Clearly, these unusual features in the EIT profile arise from a more complicated interference effect.[39] From Eq. (2), we can find that the M-type five-level atomic system is simplified to a Λ-type three-level atomic one in the absence of the coupling fields Ω_{c2} and Ω_{c3}. In comparison with the Λ-type three-level atomic system,[2] there are three EIT windows in the M-type five-level atomic system, and the width of the middle EIT window is related to the Rabi frequencies of the three coupling fields. From Figs. 2(a) and 2(b), the width of the middle EIT window becomes narrower with increasing Ω_{c2}. However, it becomes broader with increasing Ω_{c1} and Ω_{c3} (see from Figs. 2(a), 2(c) and 2(d)).

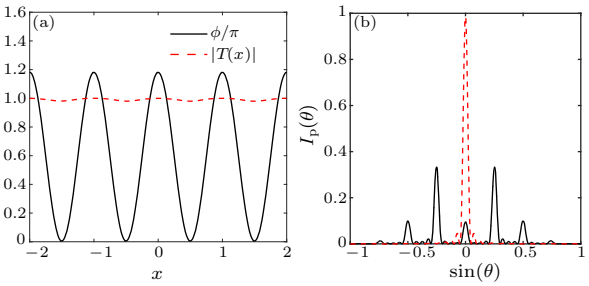

Fig. 3. (a) The amplitude $|T(x)|$ (red dotted line) and phase Φ/π (black solid line) of the transmission function as a function of x. (b) The normalized Frauhofer diffraction intensity with (black solid line) and without (red dotted line) the phase modulation as a function of $\sin(\theta)$. The parameters are $\Omega_{c1} = 3.9$, $\Omega_{c2} = 2.5$, $\Omega_{c3} = 1$, $\Delta_{\rm p} = 0.01$, $\Lambda_{cx}/\lambda_{\rm p} = 4$, $N = 5$, and $L = 900z_0$.

We have plotted the amplitude $|T(x)|$ and the phase Φ/π of the transmission function as a function of x in Fig. 3(a). We can see a small periodic amplitude modulation across the light profile of the probe field, where the transmissivity of the transmission function is close to 100%. At the same time, a large phase modulation of the transmission function is observed, where the depth of the phase modulation is approximately of the order of π. This indicates that the atomic medium possesses a large phase modulation ability with a low energy loss. To illustrate the role of the phase modulation, we plot the diffraction pattern with and without the phase modulation in Fig. 3(b). It shows that the amount of light in the first order is dramatically increased with the phase modulation, and the first-order diffraction intensity at $\sin\theta = \pm 0.25$ is about 33%, which is greater than the one in the Λ-type three-level atomic system.[1] This is because the dispersion of the middle EIT window in the M-type five-level atomic system is larger than the one in the Λ-type three-level atomic system, which leads to the larger phase modulation.

We hope that an atomic medium is transparent to the probe field, and can induce a large phase modulation to disperse more light into the high-order directions. Figures 4(a) and 4(b) show the amplitude $|T(x)|$ and the phase Φ/π of the transmission function as a function of x for different Rabi frequencies of the standing wave coupling field Ω_2. With the increase of Ω_2, the amplitude modulation depth slightly increases, and the minimum transmissivity is still greater than 90% as shown in Fig. 4(a), while

the phase modulation depth significantly increases as shown in Fig. 4(b). With increasing the depth of the phase modulation, the energy of diffraction light in the first order is gradually transferred to the second- and third-order directions. When $\Omega_2 = 3.2$, the phase modulation depth is approximately of the order of 2π (see Fig. 4(b)). At this time, the second-order diffraction intensity at $\sin\theta = \pm 0.5$ has the maximum value, which reaches 23% (see Fig. 4(c)). From Figs. 2(a) and 2(b), the width of the middle EIT window becomes narrower with increasing Ω_2, resulting in the decrease of the minimum transmissivity, while the dispersion of the middle EIT window becomes larger, which leads to the larger phase modulation. Thus the second-order diffraction intensity reaches the maximum at $\Omega_2 = 3.2$, where the phase modulation depth is approximately of the order of 2π. When Ω_2 is further increased, more energy of the diffraction light transfers to the third-second direction. As shown in Fig. 4(d), the third-order diffraction intensity at $\sin\theta = \pm 0.75$ reaches the maximum at $\Omega_2 = 3.8$, where the corresponding phase modulation is approximately of the order of 3π (see Fig. 4(b)). As a result, we obtain that different depths of the phase modulation can disperse the diffraction light into the different orders. When the phase modulation depth is of the order of π, the energy of the diffraction light is mainly dispersed into the first-order direction; when the phase modulation depth is of the order of 2π, it is mainly dispersed into the second-order direction; and this is also the case for the third-order diffraction.

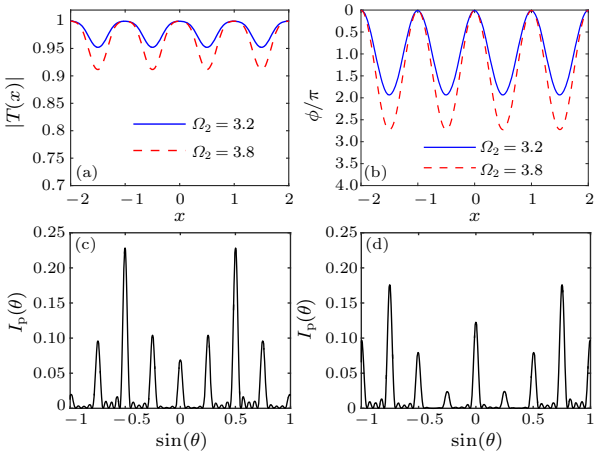

Fig. 4. (a) The amplitude $|T(x)|$ and (b) the phase Φ/π of the transmission function as a function of x for different Ω_2. The normalized diffraction intensity $I_{\rm p}$ (θ) as a function of $\sin(\theta)$ for (c) $\Omega_2 = 3.2$, and (d) $\Omega_2 = 3.8$. The other parameters are the same as those in Fig. 3.

As is known to all, in the M-type five-level atomic system, there are numerous adjustable parameters, such as the probe detuning and the Rabi frequencies of the other two coupling fields. However, no matter how these parameters change, the energy of the diffraction light is dispersed into the corresponding high-order directions as long as the phase modulation depth is of different orders of π. Let us take the probe detuning $\Delta_{\rm p}$ as an example. Keeping the other parameters to be constant, Figs. 5(a) and 5(b) describe the amplitude $|T(x)|$ and the phase Φ/π of the transmission function as a function of x for different probe detunings $\Delta_{\rm p}$. It shows that, with the increase of $\Delta_{\rm p}$, which is still within the middle EIT window (see Fig. 2(a)), the amplitude modulation and the phase modulation are similar to the case of Ω_2. At $\Delta_{\rm p} = 0.016$, the phase modulation depth is approximately of the order of 2π, the energy of diffraction light in the first order transfers to the second order as shown in Fig. 5(c). At $\Delta_{\rm p} = 0.022$, the phase modulation depth is of the order of 3π, the energy of the diffraction light is mainly dispersed into the third-order direction as shown in Fig. 5(d). Therefore, we obtain that the transfer of diffraction light from the center maximum to different high-order directions is mainly accomplished by different depths of the phase modulation.

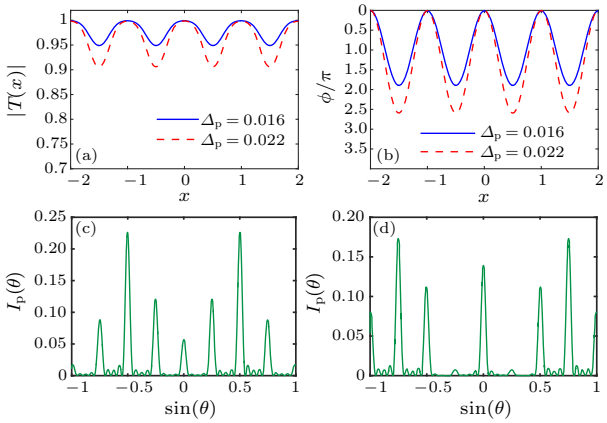

Fig. 5. (a) The amplitude $|T(x)|$ and (b) the phase Φ/π of the transmission function versus x for different $\Delta_{\rm p}$. (c) The normalized diffraction intensity $I_{\rm p}$ (θ) as a function of $\sin(\theta)$ for (c) $\Delta_{\rm p} = 0.016$, and (d) $\Delta_{\rm p} = 0.022$. The other parameters are the same as those in Fig. 3.

In conclusion, we have investigated the electromagnetically induced grating in an M-type five-level system. It is shown that the first-order diffraction intensity in the M-type five-level atomic system is greater than the one in the Λ-type three-level atomic system, and the sensitive phase modulation can control the diffractive properties of the grating. When the phase modulation is of the orders of π, 2π and 3π, the energy of the probe light can be dispersed into the first-, second- and third-order directions, respectively. Thus we can take advantage of the phase modulation to control the probe light dispersing in diffraction high orders.

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