文章编号 1674-2915(2012)05-0464-06

Raman gain grating in an ultracold atomic medium

KUANG Shang-qi

(*State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanic and Physics, Chinese Academy of Sciences, Changchun* 130033, *China*)

* *Corresponding author, E-mail: physicskuang@sina.com*

Abstract: This paper demonstrates theoretically that a Raman gain grating can be formed in an ultracold atomic medium driven by a standing wave and a probe field. Due to the spatial modulation of active Raman gain, the weak probe field propagating along the direction normal to the standing wave can be diffracted into the first-order direction effectively, and the zero-order diffracted beam is also amplified. Under manipulation by a microwave field, the first-order diffraction efficiency can be improved to be higher than that of electromagnetically induced phase grating. This system can be used as a highly efficient switch for an all-optical network.

Key words: ultracold atomic medium; active Raman gain; diffraction grating; atomic coherence; first-order diffraction efficiency

超冷原子中的拉曼增益光栅

匡尚奇

(中国科学院 长春光学精密机械与物理研究所 应用光学国家重点实验室,吉林 长春 130033)

摘要:为提高光栅的衍射效率,提出了基于主动拉曼效应的超冷原子光栅系统。理论研究表明:通过拉曼增益的空间周期性调节,可有效地将沿垂直光栅方向传播的弱探测光衍射到一级方向,同时零级衍射光将被放大。当系统中引进微波场的原子相干效应时,可以进一步提高光栅的一级衍射效率。在一定的条件下,拉曼增益光栅的一级衍射效率可高于电磁诱导相位光栅的一级衍射效率。该系统可作为高效光开关用于全光网络。

关 键 词:超冷原子;主动拉曼增益;衍射光栅;原子相干;一级衍射效率

中图分类号:O431.2; O436.1 **文献标识码**:A doi:10.3788/CO.20120505.0464

收稿日期:2012-06-22;**修订日期**:2012-08-20

基金项目:国家自然科学基金资助项目(No. 61178020)

1 Introduction

Recently, an Electromagnetically Induced Grating (EIG) formed by replacing the travelling wave in Electromagnetically Induced Transparency (EIT) with a standing field was theoretically proposed[1], and later the proposed scheme was realized in the experiment[2]. EIG is a kind of amplitude grating based on the spatial modulation of probe absorption, thus its first-order diffraction efficiency can not be very high. In order to increase the first-order diffraction efficiency, an Electromagnetically Induced Phase Grating (EIPG) induced by the spatial modulation of the giant Kerr nonlinearity was demonstrated[3]. EIPG is a phase grating which nearly eliminates the probe absorption, and then its first-order diffraction efficiency can be equal to the efficiency of an ideal sinusoidal phase grating. Meanwhile, the effects of microwave modulation[4] or spontaneous generated coherence[5] were also considered in EIG, and improved diffraction efficiency in the first-order direction was achieved. Comparing with the EIT-based schemes where the probe field operates in the absorption mode, the probe field in the schemes based on Active Raman Gain (ARG) operates in a stimulated Raman emission mode, and the related studies have become a research focus of interest[6-9]. It was demonstrated that the ARG-based schemes can be used to realize the superluminal[6] or subluminal light propagation[7]. Most recently, a large cross phase modulation based on the manipulation of ARG has also been achieved[8-9]. Owing to the probe gain of ARG, the proposes based on ARG have several advantages in comparison with the proposes based on EIT.

Recently, we have demonstrated a kind of gain-phase grating induced by the pumping and standing fields[10]. In this paper, we theoretically demonstrate a Raman gain grating (RGG) in the ultracold atoms. This grating can be induced by only one standing field, and the configuration of RGG is easier than that of the gain-phase grating. Under the action of a microwave field, the first-order diffraction efficiency of the RGG can be improved to be higher than that of EIPG. This kind of gain grating which eliminates the loss of the probe field has the potential to be an all-optical switching in the optical networking.

2 Atomic model and equations

The atomic model under consideration is illustrated in Fig. 1(a), which can be described by a four-level configuration of ^{87}Rb atoms. A weak probe field with a Rabi frequency g interacts with the transition $|3\rangle - |2\rangle$, and the standing and microwave fields connect the transitions $|3\rangle - |1\rangle$ and $|2\rangle - |4\rangle$, respectively. Here γ is the spontaneous emission of the corresponding transition, and the transitions $|1\rangle - |2\rangle$ and $|1\rangle - |4\rangle$ are electric dipole forbidden. The Rabi frequencies of the standing and microwave fields are Ω_s and Ω_m, respectively; for simplicity, we take all the Rabi frequencies as real.

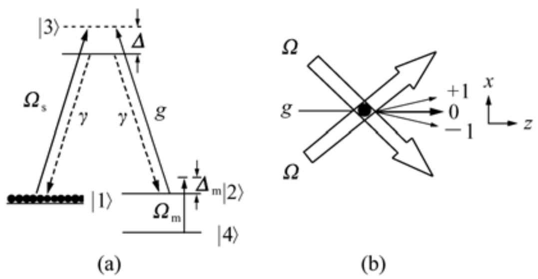

Fig. 1 (a) Level diagram of the four-level atomic system, and the possible levels correspond to the D_1 line of ^{87}Rb: $|1\rangle = |F=2, m_F=-2\rangle$, $|2\rangle = |F=2, m_F=0\rangle$, $|3\rangle = |F'=1, m_F=-1\rangle$, $|4\rangle = |F=1, m_F=0\rangle$. (b) Beam configurations of the standing field and the probe field with respect to an ultracold atomic gas.

According to the process of ARG, the probe field and the standing field have the same detuning Δ, and the detuning of the microwave field is Δ_m. As shown in Fig. 1(b), the standing field in the x direction is formed by the overlap of two travelling waves, and the weak probe field propagates along the z direction. Therefore, the Rabi frequency of the standing field can be written as $\Omega_s(x) = \Omega\sin(\pi x/\Lambda)$, where Λ is the spatial frequency of the standing field.

In the framework of the semiclassical theory, using the dipole approximation and the rotating wave approximation, we obtain the Hamiltonian H_I of the atomic system in the interaction picture:

$$H_I = -\hbar(\Delta|3\rangle\langle 3| + \Delta_m|4\rangle\langle 4| + g|3\rangle\langle 2| + \Omega_s|3\rangle\langle 1| + \Omega_m|4\rangle\langle 2| + H.c.)\ . \quad (1)$$

In the model of ARG, the detuning of the standing field is large and the probe field is weak, thus the majority of atoms populates at the level $|1\rangle$ ($\rho_{11}\approx 1$), and other levels have no atoms. Including the relaxation terms, the equations of motion for the density matrix of the atomic system are:

$$\begin{aligned}
\dot\rho_{13} &= -i\Gamma_{13}\rho_{13} - i\Omega_s - ig\rho_{12}\\
\dot\rho_{32} &= \Gamma_{32}\rho_{32} - i\Omega_m\rho_{34} + i\Omega_s\rho_{12}\\
\dot\rho_{12} &= -\gamma_{12}\rho_{12} - ig\rho_{13} - i\Omega_m\rho_{14} + i\Omega_s\rho_{32}\\
\dot\rho_{34} &= -\Gamma_{34}\rho_{34} - i\Omega_m\rho_{32} + i\Omega_s\rho_{14} + ig\rho_{24}\\
\dot\rho_{24} &= -i\Delta_m\rho_{24} + ig\rho_{34}\\
\dot\rho_{14} &= -\Gamma_{14}\rho_{14} - i\Omega_m\rho_{12} + i\Omega_s\rho_{34}
\end{aligned}\ ,\quad (2)$$

where $\Gamma_{13}=\Delta - i\gamma$, $\Gamma_{32}=i\Delta-\gamma$, $\Gamma_{34}=-i(\Delta-\Delta_m)+\gamma$, $\Gamma_{14}=i\Delta_m+\gamma_{14}$, and γ_{12} and γ_{14} are the dephasing rates of the corresponding transitions due to the atomic collisions. We solve this density-matrix and derive the first-order steady state solution of the element ρ_{32} as

$$\frac{\rho_{32}}{g} = \frac{\Omega_s^2(M+\Gamma_{34}\Gamma_{14})/\Gamma_{13}}{(M+\Gamma_{34}\Gamma_{14})(\gamma_{12}\Gamma_{32}-M)+\Omega_m^2(\Gamma_{34}+\gamma_{12})(\Gamma_{32}-\Gamma_{14})}\ , \quad (3)$$

where $M=\Omega_s^2-\Omega_m^2$. From Eq. (3), the linear susceptibility χ of the probe field induced by the standing field and the microwave field is:

$$\chi = 3\gamma\pi\mathcal{N}\frac{\rho_{32}}{g}\ , \quad (4)$$

here $\mathcal{N} = N_0(\lambda/2\pi)^3$ is the scaled average atomic density, where N_0 and λ present the atomic density and the probe wavelength.

We suppose the length of the ultracold atomic gas experienced by the probe field in the z direction is L, which is given in the unit of $\zeta=\lambda/6\pi^2\mathcal{N}$. In the slowly envelope approximation, the propagation of probe field induced by the atomic polarization can be described by the Maxwell's equation as:

$$\frac{\partial g}{\partial z} = (-\alpha + i\beta)g\ , \quad (5)$$

where $\alpha=(2\pi/\lambda)\mathrm{Im}[\chi]$ and $\beta=(2\pi/\lambda)\mathrm{Re}[\chi]$ are the absorption and dispersion coefficients of the probe field. From Eq. (5), the transmission function of the probe field at $z=L$ can be written as:

$$T(x) = e^{-\alpha(x)L}e^{i\beta(x)L}. \quad (6)$$

Considering the probe field as a plane wave, we obtain the Fraunhofer diffraction pattern of the probe field by the Fourier transform of the transmission function $T(x)$. Following the results in ref. [1], the distribution of the diffraction intensity is:

$$I(\theta) = |E(\theta)|^2\frac{\sin^2(N\pi\Lambda\sin\theta/\lambda)}{N^2\sin^2(\pi\Lambda\sin\theta/\lambda)}\ , \quad (7)$$

where N is the number of spatial periods of the grating illuminated by the probe field, and θ is the angle between the direction of the diffracted beam and the z direction. In Eq. (7), the Fraunhofer diffraction of a single space period is:

$$E(\theta) = \int_0^1 T(x)\exp(-i2\pi\Lambda x\sin\theta/\lambda)\,dx\ . \quad (8)$$

The n-order diffraction intensity of the grating is determined by Eq. (7), and $\sin\theta = n\lambda/\Lambda$, thus the first-order diffraction intensity can be expressed as:

$$I(\theta_1) = |E(\theta_1)|^2 = \left|\int_0^1 T(x)\exp(-2i\pi x)\,dx\right|^2. \quad (9)$$

3 Results and discussion

Using $2\gamma/2\pi = 5.75$ MHz and $\gamma_{14}/2\pi = \gamma_{12}/2\pi = 1$ kHz, we display the amplitude of the transmission function as a function of x in Fig. 2(a). It is seen that the probe field is amplified, and the probe gain changes periodically in space. The reason is that the stimulated Raman gain induced by the standing field leads to an amplification of the probe field, and the periodic intensity pattern of the standing field make the probe gain alter in a period. Because the spatial modulation of the probe gain, a RGG is formed, and one can obtain the corresponding diffraction patterns as a function of $\sin\theta$ for $\Lambda/\lambda = 4$ and $N = 5$ in Fig. 2(b). An investigation of Fig. 2(b) shows that the diffracted beam in the zero-order direction is amplified, and the first-order diffraction efficiency is about 15%. The lower inset in Fig. 2(b) demonstrates the corresponding diffraction patterns when the amplitude modulation is ignored($\alpha(x)L = 0$), and it is seen that only the zero-order diffraction is visible, which proves that the first-order diffracted beam attributes to the gain grating. Therefore, the RGG is a kind of amplitude grating. Under the action of a microwave field($\Omega_m \neq 0$), the probe gain and the first-order diffraction intensity are increased as shown in Fig. 2(a) and Fig. 2(b), respectively. It is found that the first-order diffraction efficiency of the RGG can be higher than the efficiency of EIG, and first-order diffraction efficiency of the RGG modulated by a microwave field is comparable with the efficiency of EIPG.

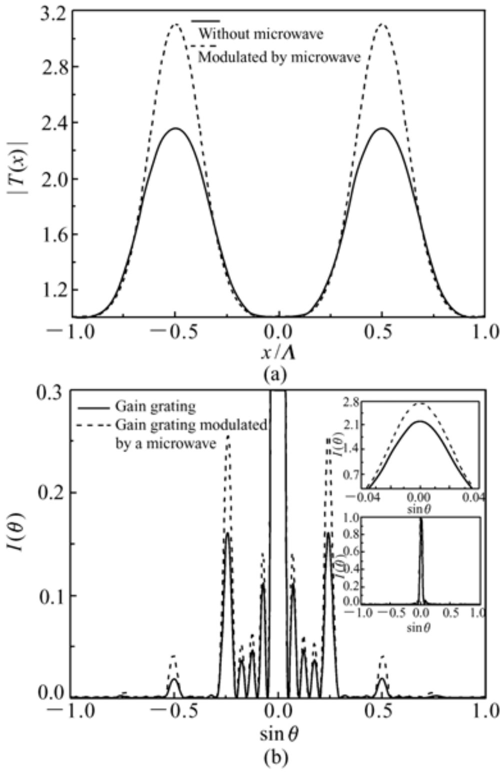

Fig. 2 (a) Amplitude of the transmission function $T(x)$ as a function of x within two space periods when $\Omega_m = 0$, $\Delta_m = 0$ (black solid line) and $\Omega_m = 0.1\gamma$, $\Delta_m = 55\gamma$ (red dash line). Here other parameters for the both cases are $\Delta = 50\gamma$, $\Omega = 0.1\gamma$, and $L = 100\zeta$. (b) Diffraction patterns as a function of $\sin\theta$ for the corresponding transmission functions in (a). The upper inset shows the residual parts of the corresponding diffraction patterns, and the lower inset displays the corresponding diffraction patterns when the amplitude modulations are ignored($\alpha(x)L = 0$).

Since ARG requires that most atoms populate at the level $|1\rangle$, we ensure that the detuning of standing field is much larger than its Rabi frequency. In this case, the first-order diffraction intensities of the RGG and the RGG modulated by a microwave are given as a function of the detuning or Rabi frequency of the standing field in Fig. 3. Fig. 3 shows that no matter in the RGG or in the RGG modulated by a microwave field, the first-order diffraction intensity increases as the intensity of the standing field increases, while the diffraction intensity decreases as the detuning of the standing field increases. These relations can be understood that a standing field with a larger intensity or a smaller detuning can induce a larger probe gain in the grating, and then more energy can be diffracted in the first-order direction.

Fig. 4(a) displays the first-order diffraction in-

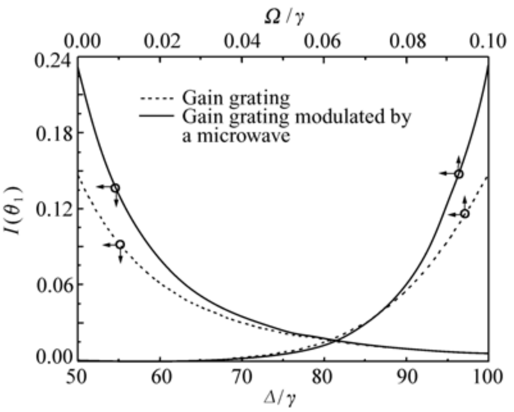

Fig. 3 First-order diffraction intensities of the RGG and the RGG modulated by a microwave field as a function of the detuning of the standing field when $\Omega = 0.1\gamma$ and the Rabi frequency of the standing field when $\Delta = 50\gamma$, respectively. Here $\sin\theta_1 = 0.25$ and other parameters are the same as in Fig. 2(a).

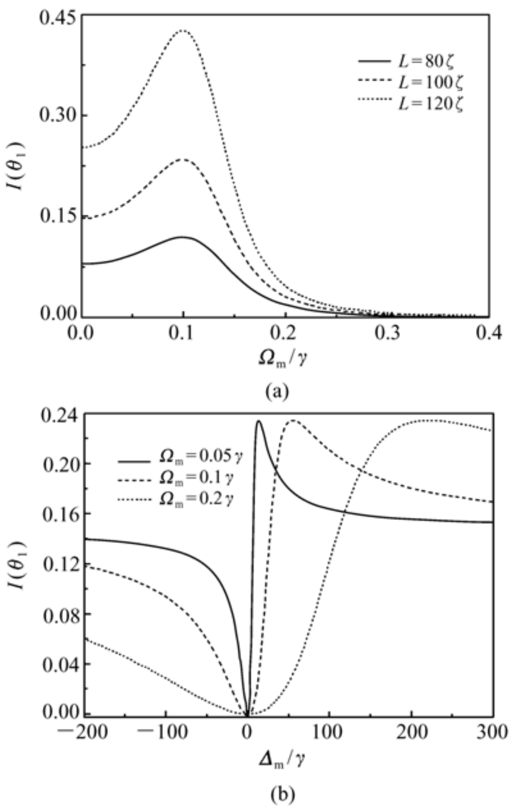

Fig. 4 (a) Diffraction intensity in the first-order direction as a function of the intensity of the microwave field for different interaction lengths. (b) First-order diffraction intensity as a function of the detuning of the microwave field for different intensities of the microwave. In both cases, $\theta_1 = 0.25$ and other parameters are the same as in Fig. 2(a).

tensity as a function of the intensity of the microwave field for different interaction lengths and $\Delta_m = 55\gamma$. It is found that the first-order diffraction intensity increases as the interaction length increases, and at $L = 120\zeta$, for a Rabi frequency of the standing field as 0.1γ, the diffraction efficiency can reach about 43%. In order to confirm the weak field approximation of the probe field in our calculations, the longest interaction length we chosen is $L = 120\zeta$, which leads to an amplification of the probe amplitude by a factor of four. In Fig. 4(b), for different microwave intensities, we demonstrate the dependence of the first-order diffraction intensity on the detuning of the microwave field. From Fig. 4(a) and Fig. 4(b), one can find that there are optimum parameters of the microwave field, proving that there is a largest gain modulation of the probe field in the system. Because the standing field creates an ac Stark shift of the state $|3\rangle$, the probe field has a frequency shift, and the largest frequency shift for a certain detuning is $\Delta_s = -\Omega^2/\Delta$[11]. Meanwhile, the microwave field induces an ac Stark shift of the state $|2\rangle$, and the corresponding frequency shift of the probe field is $\Delta_m = -\Omega_m^2/\Delta_m$. As a result, the largest gain modulation happens when the frequency shift of the probe field induced by the microwave field offsets the largest frequency shift of the probe field created by the standing field ($\Delta_s + \Delta_m \approx 0$). After investigating the optimum parameters of the microwave field in Fig. 4, we find that there is a good agreement in this relation. Although the RGG modulated by the microwave is a kind of amplitude grating, its first-order diffraction efficiency can be higher than the efficiency of an ideal sinusoidal phase grating. Therefore, the RGG or RGG modulated by a microwave has a great potential to be utilized as an all-optical switching in the optical networking.

4 Conclusion

In summary, it is theoretically proposed that a RGG based on spatial modulation of ARG can be formed in ultracold atoms. Owing to the spatially periodic modulation of the probe gain, the diffracted beam in the zero-order direction is amplified, and the first-order diffraction efficiency is higher than that of EIG. Under the action of a microwave field, the diffraction efficiency in the first-order direction is higher than that of EIPG. Therefore, this kind of grating has a great potential to be an all-optical switching in the optical networking.

参考文献:

[1] LING H Y, LI Y Q LI, XIAO M. Electromagnetically induced grating: homogeneously broadened medium[J]. *Phys. Rev. A*, 1998, 57: 1338-1344.

[2] MITSNAGA M, IMOTO N. Observation of an electromagnetically induced grating in cold sodium atoms[J]. *Phys. Rev. A*, 1999, 59: 4773-4776.

[3] de ARAUJO L E E. Electromagnetically induced phase grating[J]. *Opt. Lett.*, 2010, 35: 977-979.

[4] XIAO Z H, SHIN S G, KIM K. An electromagnetically induced grating by microwave modulation[J]. *J. Phys. B*, 2010, 43: 161004.

[5] WAN R G, KOU J, JIANG L, *et al.*. Electromagnetically induced grating via enhanced nonlinear modulation by spontaneously generated coherence[J]. *Phys. Rev. A*, 2011, 83: 033824.

[6] WANG L J, KUZMICH A. DOGARIU A. Gain-assisted superluminal light propagation[J]. *Nature*, 2000, 406: 277-279.

[7] JIANG K J, DENG L. Ultraslow propagation of an optical pulse in a three-state active Raman gain medium[J]. *Phys. Rev. A*, 2006, 74: 041803(R).

[8] DENG L, PAYNE M G. Gain-assisted large and rapidly responding Kerr effect using a rroom-temperature active Raman gain medium[J]. *Phys. Rev. Lett.*, 2007, 98: 253902.

[9] JIANG K J, DENG L, HAGLEY E W, *et al.*. Fast-responding nonlinear phase shifter using a signal-wave gain medium [J]. *Phys. Rev. A*, 2008, 77: 045804.

[10] KUANG S Q, JIN C S, LI C. Gain-phase grating based on spatial modulation of active Raman gain in cold atoms[J]. *Phys. Rev. A*, 2011, 84: 033831.

[11] SCULLY M O, ZUBAIRY M S. *Quantum Optics*[M]. Cambridge: Cambridge University Press, 1997.

作者简介: KUANG Shang-qi(1981—), Associate researcher, Ph. D., Changchun Institute of Optics, Fine Mechanic and Physics, Chinese Academy of Sciences, China. His research interests include quantum optics and optical thin film.
E-mail: physicskuang@sina.com