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Theory of polarizing beam splitter based on pendulum effect in volume holographic grating

Hongru Jiang, Xiaona Yan*, Xiaoyan Wang, Yuanyuan Chen, Ye Dai, Xihua Yang, Guohong Ma

Lab. of Ultrafast Photonics, Department of Physics, Shanghai University, Shanghai 200444, China

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ABSTRACT

A Polarizing beam splitter (PBS) based on pendulum effect in volume holographic grating (VBG) is proposed. Using the modified coupled-wave equations of Kogelnik, expressions of transmitted and diffracted intensities are derived when a polarized femtosecond pulse incidents on a VHG. Simulation results show that the intensities of the transmitted and diffracted pulses are periodic oscillation and exchange along the propagation depth, and this property is pendulum effect. Period of the pendulum effect is sensitive to polarization state of the incident pulse. By suitably using this property, it is possible to realize a PBS where the incident TE polarization outputs in transmitted direction of the VHG and TM component outputs in diffracted direction.

1. Introduction

Dynamical Bragg diffraction in the Laue scheme originates from multiple wave scattering in a spatially periodic structure and leads to a number of specific effects, such as Borrmann effect [1], pendulum effect [2], spatial beam splitting [3], etc. These phenomena were originally studied by Elward in the case of x-ray propagating in perfect crystal [4]. Later, reviews of the theory and experiment of dynamical diffraction of X-ray by crystal were given by Batterman and Cole [5].

Pendulum effect is a periodic transfer of beam energy between transmitted and diffracted waves existing in a period structure and under Bragg conditions in the Laue diffraction. In 1969, Shull observed pendulum interference fringes in the interaction of neutron beam with silicon crystal and used the pendulum period to determine the atomic scattering amplitude [2]. The pendulum effect was also predicted and observed in second-order Bragg scattering of matter waves [6] or atomic wave [7] from a standing light waves. In recent years, optical pendulum effect has been predicted and observed in linear 1D photonic crystal [8–10]. In VHG, Calvo observed pendulum effect of angular selectivity in a photopolymerizable glass grating with high refractive index modulation [11]. Later, based on the coupled wave equations of Kogelnik [12], Yan theoretically studied the periodic energy oscillation and pulse splitting in VHG under femtosecond pulse readout [13]. Pendulum effect is of special interest in realizing all-optical switch [14], negative refraction [15], selective stretching and compressing of femtosecond [16], Second harmonic generator [17] and PBS [18].

PBS is an essential optical element that can be used to separate TE- and TM-polarizations, and has attracted much attentation [19–21]. In this paper, based on the coupled wave equations of Kogelnik, we further study the diffraction of

* Corresponding author.
E-mail address: xnyan@staff.shu.edu.cn (X. Yan).

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a polarized femtosecond pulse from a VHG, then use the interference effect to explain pendulum effect, at last we use polarization sensitivity of the pendulum period to realize a PBS.

2. Theoretical model of diffraction of a polarized femtosecond pulse from VHG

The transmitted VHG is a static unslanted phase grating, which is characterized by a refractive index distribution of the form

$$n = n_0 + \Delta n \cos(Kx) \tag{1}$$

where n_0 is the background refractive index of the grating material; Δn is the refractive index modulation; grating vector $\boldsymbol{K}$ is parallel to axis x with grating wavenumber $K = 2\pi/\Lambda$, grating period $\Lambda = \lambda_0/(2\sin\theta_0)$, λ_0 and θ_0 are the Bragg wavelength and angle of the VHG.

A polarized femtosecond pulse incidents on the VHG at Bragg angle, the expression of which is

$$E_r(t) = \hat{e}_r \exp(-i\omega_0 t - \frac{t^2}{T^2}) \tag{2}$$

Where $\hat{e}_r$ represents the unit polarization vector of incident pulse, $\omega_0 = 2\pi c/\lambda_0$ is the central angular frequency of the incident pulse, λ_0 is the central wavelength. Parameter T is related to full width at half maximum (FWHM) $\Delta\tau$ of incident pulse by $T = \Delta\tau/\sqrt{2\ln 2}$.

Applying Fourier transform on Eq. (2), the incident femtosecond pulse is expanded as a series of spectral components, each represents a plane monochromatic wave, complex field amplitude of each monochromatic wave is given by

$$E_{\mathrm{r}}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} E_r(t)\exp(i\omega t)dt = \frac{T}{2\sqrt{\pi}}\exp[-\frac{T^2(\omega-\omega_0)^2}{4}] \tag{3}$$

Due to the couple of the incident wave with the VHG, the total field in the VHG is

$$E(\omega, z) = \hat{e}_t E_t(\omega, z)\exp(-i\vec{\rho}\cdot\vec{r}) + \hat{e}_d E_d(\omega, z)\exp(-i\vec{\sigma}\cdot\vec{r}) \tag{4}$$

Where $\hat{e}_t$, $\hat{e}_d$ represent the unit polarization vectors of transmission and diffraction, respectively; $E_t(\omega,z)$, $E_d(\omega,z)$ and $\boldsymbol{\rho}$, $\boldsymbol{\sigma}$ are complex spectral amplitudes and propagating vectors of the transmitted and diffracted waves, respectively. The propagating vectors connect to the grating vector $\boldsymbol{K}$ by the relation $\vec{\sigma} = \vec{\rho} - K$.

Substituting Eqs. (1) and (4) into wave equation $\nabla^2 E + k^2 E = 0 (k = 2\pi n/\lambda)$, considering slowly varying envelop approximation and ignoring terms that are quadratic in refractive index change, the modified Kogelnik's coupled-wave equations can be acquired

$$\begin{aligned} \cos\theta'_r \frac{dE_t(\omega, z)}{dz} &= -i\kappa C E_d(\omega, z), \\ \cos\theta'_r \frac{dE_t(\omega, z)}{dz} - i\frac{2\pi c K^2}{4\pi n_0}(\frac{1}{\omega} - \frac{1}{\omega_0})E_d(\omega, z) &= -i\kappa C E_t(\omega, z) \end{aligned} \tag{5}$$

Where C represents polarization factor, with $C = \hat{e}_t \cdot \hat{e}_d = 1$ for TE polarization and $C = \hat{e}_t \cdot \hat{e}_d = \cos(2\theta_r')$ for TM-polarization; coupling coefficient $\kappa = \omega \cdot \Delta n/2c$, ω is the angular frequency of the spectral component included in the incident pulse; c is the speed of light in vacuum; θ_r' is the incident angle inside the VHG.

Solving Eq. (5), complex spectral fields of the diffracted and transmitted waves are obtained,

$$E_d(\omega, z) = -i\nu \cdot \exp(i\xi) \cdot \frac{\sin\sqrt{\nu^2 + \xi^2}}{\sqrt{\nu^2 + \xi^2}} \cdot E_r(\omega) \tag{6}$$

$$E_t(\omega, z) = \exp(i\xi) \times (\cos\sqrt{\nu^2 + \xi^2} - i\xi\frac{\sin\sqrt{\nu^2 + \xi^2}}{\sqrt{\nu^2 + \xi^2}}) \times E_r(\omega) \tag{7}$$

Where $\nu = \frac{C\omega\Delta nz}{2c\cos\theta'_r}$ determines the maximum diffraction efficiency when the readout spectral component satisfies Bragg condition of the VHG. $\xi = \frac{\pi^2 cz}{\Lambda^2 n_0 \cos\theta'_r}(\frac{1}{\omega} - \frac{1}{\omega_0})$ represents the deviation from the Bragg condition, which is caused by the spectral components with frequency different from central frequency ω_0.

Diffraction efficiency spectrum of the VHG is defined as the intensity spectrum of the diffraction to that of the incident, and the expression is

$$\eta(\omega, z) = \frac{\sin^2\sqrt{\nu^2 + \xi^2}}{1 + \frac{\xi^2}{\nu^2}} \tag{8}$$