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Diffraction properties of ultrashort pulsed beams with arbitrary temporal profiles by a volume holographic grating

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Abstract

In this paper, the diffraction properties of an ultrashort optical pulse with arbitrary profiles in time diffracted by a volume holographic grating are investigated using the modified Kogelnik coupled-wave theory. Simple analytical expressions for the spectrum and spatial profiles of the transmitted and diffracted beams are obtained. The dependences of the diffraction bandwidth, the Bragg selectivity bandwidth and the total diffraction efficiency of the volume grating on the temporal profiles of the input ultrashort pulse are investigated. For three different temporal profiles, numerical results of diffraction properties are given. It is shown that the temporal shapes of the input pulsed beams have been found to be an important factor in the analyses of the propagation characteristics.

Keywords: Diffraction optics; Coupled-wave theory; Volume holographic grating; Ultrashort pulsed beam

1. Introduction

The ultrashort pulsed beam (UPB) has many promising applications in fields such as optical communication, signal and imaging processing. Because of its abundant spectrum and high bandwidth, the diffraction properties of volume holographic gratings (VHG) under illumination by ultrashort pulsed beams will be different from that of the monochromatic continuous wave. As a result, it has been paid increasingly much attention in recent years [1–5]. Consequently, the combination of volume holographic elements such as volume grating and ultrashort pulses will have enormous potential and novel applications in many practical fields.

In this paper, the diffraction properties of the UPB with arbitrary profiles in time diffracted by a VHG are investigated using the modified Kogelnik coupled-wave theory. Simple analytical expressions for the spectrum and spatial profiles of the transmitted and diffracted beams are obtained. The temporal intensity and spectral intensity distribution of the diffracted beam are calculated. The diffraction bandwidth, the Bragg selectivity bandwidth and the total diffraction efficiency are also analyzed. Numerical results are also illustrated for several different temporal profiles.

2. Modified coupled-wave analysis

As shown in Fig. 1, we consider an ultrashort pulsed beam incident on a VHG, which is characterized by a refractive index in the modulated region ($0 \leqslant z \leqslant d$) of the

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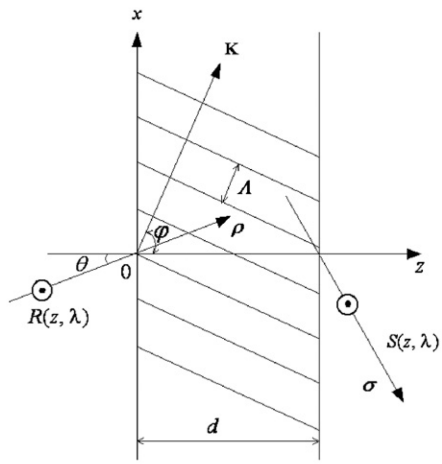

Fig. 1. Configuration and coordinate system of a thick planar grating.

form

$$n = n_0 + n_1 \cos(Kx) \quad n_1 \ll n_0 \tag{1}$$

where n_0 is the refractive index of the grating region, n_1 is the amplitude of index modulation and K is the grating vector oriented perpendicular to the fringe planes with the length $K = 2\pi/\Lambda$, where Λ is the period of the grating. d is the thickness of grating and φ is the slant angle. It is also assumed to extend infinitely in the x–y plane and to be bounded by two identical homogenous media with refractive indices equal to that of the grating. The UPB with TE polarization illuminates the grating at an angle θ that corresponds to the Bragg angle of central wavelength λ_0. It is assumed to be a pulse with an arbitrary temporal shape. Its electric field can be expressed as

$$E_0(r, t) = \exp(-i\omega_0 t)F(t) \tag{2}$$

where $\omega_0 = 2\pi c/\lambda_0$ is the centre frequency and $F(t)$ represents the temporal envelopes of the input UPB. The three different temporal profiles $F(t)$ and their corresponding Fourier spectral profiles $G(\omega)$ are listed in Table 1.

The diffraction grating operates in the two-wave Bragg regime including small deviations from the Bragg case and neglecting the phase curvature of the readout pulse. Only the transmitted beam $R(z, \lambda)\exp(-i\boldsymbol{\rho}\cdot\boldsymbol{r})$ and diffracted beam $S(z, \lambda)\exp(-i\boldsymbol{\delta}\cdot\boldsymbol{r})$ are present, where $R(z, \lambda)$ and $S(z, \lambda)$ are, respectively, the scalar amplitudes of the transmitted and diffracted beam in the grating, and $\boldsymbol{\rho}$ and $\boldsymbol{\delta}$ are their propagation vectors, connected to the grating vector by the relation $\delta = \rho - K$.

Considering lossless VHG, we take Kogelnik's [6,8] coupled-wave theory of volume holography,

$$c_R R' + i\kappa(\lambda)S = 0$$
$$c_S S' + i\vartheta(\lambda)S + i\kappa(\lambda)S = 0 \tag{3}$$

Table 1. The UPB's temporal profiles $F(t)$ and their corresponding Fourier spectral profiles.

Temporal envelope	$F(t)$	$G(\omega)$	C_B
Gauss	$e^{-(t/\tau_G)^2}$	$e^{-(\omega\tau_G/2)^2}$	0.441
Sech	$\mathrm{Sech}(t/\tau_s)$	$\mathrm{Sech}(\pi\omega\tau_s/2)$	0.315
Lorentz	$[1+(t/\tau_L)^2]^{-1}$	$e^{-\lvert\omega\rvert\tau_L}$	0.142

where the primes indicate differentiation with respect to z, and $c_R = \cos\theta$, $c_S = \cos\theta - K\cos\varphi/\beta$, $\beta = 2\pi n(\lambda)/\lambda$, $\vartheta(\lambda) = K\cos(\varphi-\theta) - K^2\lambda/4\pi n(\lambda)$, $\kappa(\lambda) = \pi n_1/\lambda$ is the coupling coefficient. Here, $n(\lambda)$ is the average refractive index of the medium at wavelength λ and can be given by Sellmeier's formulary [7]. n_1 is the modulation amplitude of the refractive index of the medium. For transmission VHG, where $c_S > 0$, the boundary conditions are $S(0,\lambda) = 0$ and $R(0,\lambda) = G(\lambda)$.Then solving the coupled-wave Eq. (3), we arrive at the results for the amplitude distributions of $S(d,\lambda)$ and $R(d,\lambda)$:

$$S(d,\lambda) = -iu_0(\lambda)\sqrt{\frac{c_R}{c_S}}\exp(\xi)\frac{\sin(\upsilon^2-\xi^2)^{1/2}}{(1-\xi^2/\upsilon^2)^{1/2}}$$
$$R(d,\lambda) = u_0(\lambda)\exp(\xi)\left[-\frac{\xi\sin(\upsilon^2-\xi^2)^{1/2}}{(\upsilon^2-\xi^2)^{1/2}} + \cos(\upsilon^2-\xi^2)^{1/2}\right] \tag{4}$$

where $\upsilon = \kappa(\lambda)d/\sqrt{c_S c_R}$ and $\xi = -i\vartheta d/2c_S$. So the corresponding intensities of the diffraction and transmission light in temporal domain are $I_S(d, \lambda) = |S(d, \lambda)|^2$ and $I_R(d, \lambda) = |R(d, \lambda)|^2$, respectively.

3. Numerical analysis and discussion

3.1. The spectral bandwidth of the VHG

Due to the Bragg diffraction condition of the VHG, the diffraction efficiencies for different components of wavelength λ within the spectrum of an UPB are extremely different, and the maximum one is for the centre wavelength λ_0. Using a similar method as in Ref. [4], we then obtain a wavelength range $2\Delta\lambda_{1/2}$, beyond which the diffraction efficiency will drop below 50% of its maximum value. Then $\Delta\lambda_G = 2\Delta\lambda_{1/2}$. It is the maximum spectral bandwidth of the diffraction light for the input UPB with different spectral bandwidths. For the lossless and unslanted case of VHG, $\Delta\lambda_G$ can be obtained approximately with Ref. [8]:

$$\Delta\lambda_G = \frac{4\bar{\xi}\cos\theta\Lambda^2}{\pi d C} \tag{5}$$