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Diffraction study of volume holographic gratings in dispersive photorefractive material for femtosecond pulse readout

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Abstract

Based on the modified Kogelnik diffraction efficiency equation, the diffraction intensity spectrum and the total diffraction efficiency of volume gratings in photorefractive media are studied systematically. Taking photorefractive InP:Fe crystal as an example, the effect of the grating parameters and the pulse width on the diffraction properties are presented, in particular under the influence of crystal material dispersion. Under the combined effects, the diffraction pulse profiles and the total diffraction efficiency are shown. Also, the diffraction properties with and without crystal material dispersion are compared. These studies indicate that the properties of the diffraction beams can be controlled by the holographic grating parameters; this property can be used for pulse shaping applications.

Keywords: Femtosecond pulse; Diffraction intensity spectrum; Diffraction efficiency; Material dispersion

1. Introduction

Because of the wavelength and angular selectivity, volume gratings, especially the photorefractive volume gratings (PVGs) have been widely used in pulse shaping applications for manipulating laser output pulses to achieve desired functional waveforms [1–7]. The former discussions are based on the coupled wave theory of Kogelnik [8], which is a widely acceptable theory in studying volume grating diffraction. However, we should remember in mind that the Kogelnik theory is from the plane wave discussion. In deduction, the effect of the material dispersion on diffraction is neglected, it is reasonable in plane wave analysis because there has been only one frequency component involved; but in pulsed beam diffraction, the dispersion cannot be neglected because of the large bandwidth of pulse beam, where each frequency component corresponds to a specific refractive index in the material, which will affect the diffraction greatly. In Ref. [1], the authors commenced that the grating dispersion has been included in their discussion, but what they included is the difference of the refractive indices between ordinary and extraordinary beams, not among all frequencies in the pulse beam. Moreover, we find when studying the diffraction intensity spectrum and diffraction efficiency, the diffraction efficiency equation deduced from the coupled wave theory of Kogelnik can be used directly after redefining some parameters. Therefore in this paper, based on the modified diffraction efficiency equation of Kogelnik, we systematically investigate the diffraction properties of PVGs under femtosecond pulse illumination on condition of including the dispersion effect of the material. Taking photorefractive InP:Fe crystal as an example, we show the influence of the grating

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parameters, pulse width and material dispersion on the diffracted pulsed beams and the total diffraction efficiency. Although the analysis can be applied to many types of volume gratings, we limit our discussion to the case of unslanted transmission PVG and a Gaussian femtosecond pulse.

In Section 2, the modified diffraction efficiency equation used to analyze the diffraction of PVGs in dispersion material is derived, from which expressions of the diffraction intensity spectrum and total diffraction efficiency are given. The effect of the grating parameters, pulse width and material dispersion on the diffraction properties are discussed in Section 3.

2. Modified diffraction efficiency equation, diffraction intensity spectrum and total diffraction efficiency

Our discussion is based on the diagram shown in Fig. 1. The unslanted PVG is written by two coherent waves 1 and 2 with the same wavelength λ_w and incident angle θ_w. The grating has the form of $\Delta n = \Delta n_0 \cos(Kx)$, where Δn_0 is the maximum refractive index change induced by photorefractive effect, $K = 2\pi/\Lambda$ is the grating wave number, with the grating period $\Lambda = \lambda_w/(2\sin\theta_w)$. After the writing process, a femtosecond laser pulse $\mathbf{E_r}$ with a central wavelength λ_{r0} incidents on the recorded grating at Bragg angle θ_r (the angle inside the crystal is $\theta'_r(\omega)$), and the diffraction is detected with the spectrum analyzer or detector.

The incident femtosecond pulse is a Gaussian wave packet in the time domain,

$$E_r(t) = \exp\left(-\mathrm{i}\omega_{r0}t - \frac{t^2}{T^2}\right) \tag{1}$$

where ω_{r0} is the central angular frequency corresponding to the central wavelength λ_{r0}. Parameter T is related to the full width at half maximum (FWHM) $\Delta\tau$ by $T = \Delta\tau/2\sqrt{\ln 2}$.

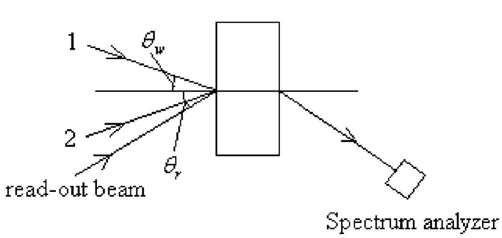

Fig. 1. Setup for investigating the diffraction of femtosecond pulse from PVG. 1 and 2 are cw waves to write an unslanted PVG, then a femtosecond pulse with a central wavelength λ_{r0} and Bragg angle θ_r readout the recorded grating, and the diffractions are detected by a spectrum analyzer.

The Fourier transform of $E_r(t)$ is

$$E_r(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} E_r(t)\exp(\mathrm{i}\omega t)\,\mathrm{d}t = \frac{T}{2\sqrt{\pi}}\exp\left[-\frac{T^2(\omega-\omega_{r0})^2}{4}\right] \tag{2}$$

The existence of inverse Fourier transform means that the femtosecond pulse beam can be assumed as a superposition of plane waves with different frequency and weight. The weight is determined by Eq. (2).

If the readout light is a monochromatic plane wave, the diffraction efficiency is governed by [8]

$$\eta = \frac{[\sin(v^2+\xi^2)^{1/2}]^2}{(1+\xi^2/v^2)} \tag{3a}$$

where $v = \pi\Delta n_0 d/\lambda(c_R c_S)^{1/2}$, $\xi = \vartheta d/2c_S$, c_R and c_S are obliquity factors, ϑ is the dephasing measure, and d is the grating thickness.

If the readout beam is pulse beam, parameters v and ξ are frequency dependent, so is η. In the following, we will deduce the frequency-dependent η.

Due to the material dispersion, the frequency components in the femtosecond pulse will be separated according to the Snell refraction law $\sin\theta_r = n(\omega)\sin\theta'_r(\omega)$. Accordingly, the obliquity factors are changed to frequency-dependent $c_R = c_S = \cos\theta'_r(\omega)$, and also v,

$$v(\omega) = \frac{\omega\Delta n_0 d}{2c\cos\theta'_r(\omega)} \tag{3b}$$

As the central wavelength component of the incident pulse satisfies the Bragg diffraction condition, we have $2\Lambda n(\omega_0)\sin\theta'_{r0} = \lambda_{r0}$, the dephasing measure can be newly defined as $\vartheta(\omega) = K^2c/2n(\omega)(1/\omega_0 - 1/\omega)$, and thus

$$\xi(\omega) = \frac{\pi^2 dc}{\Lambda^2 n(\omega)\cos\theta'_r(\omega)}\left(\frac{1}{\omega_0} - \frac{1}{\omega}\right) \tag{3c}$$

where c is the velocity of light in free space, $n(\omega)$ is the refractive index of the crystal to frequency ω. In InP:Fe crystal, the frequency-dependent refractive index of the material at room temperature is given by [2]

$$n^2(\omega) = A + \frac{B(2\pi c)^2}{(2\pi c)^2 - \omega^2 C^2 \times 10^{-20}} \tag{4}$$

where $A = 7.225$, $B = 2.316$, $C^2 = 0.3922\times 10^8$.

By substituting Eqs. (3b) and (3c) in (3a), expression for the diffraction efficiency spectrum of the PVG is obtained

$$\eta(\omega) = \left(\frac{\Delta n_{r0}\omega d}{2c\cos\theta'_r(\omega)}\right)^2 \times \sin c^2$$
$$\left\{\frac{d}{\cos\theta'_r(\omega)}\left\{\left(\frac{\Delta n_{r0}\omega}{2c}\right)^2\right.\right.$$