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Diffraction of an ultrashort pulsed beam with arbitrary polarization state from a volume holographic grating in $LiNbO_3$ crystals*

Wang Chun-Hua(王春花)†, Liu Li-Ren(刘立人), Yan Ai-Min(闫爱民), Zhou Yu(周 煜), Liu De-An(刘德安), and Hu Zhi-Juan(胡志娟)

Information Laboratory, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, *China*

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Based on a modified coupled wave theory of Kogelnik, we have studied the diffraction of an ultrashort pulsed beam with an arbitrary polarization state from a volume holographic grating in photorefractive $LiNbO_3$ crystals. The results indicate that the diffracted intensity distributions in the spectral and temporal domains and the diffraction efficiency of the grating are both changed by the polarization state and spectral bandwidth of the input pulsed beam. A method is given of choosing the grating parameters and input conditions to obtain a large variation range of the spectral bandwidth of the diffracted pulsed beam with an appropriate diffraction efficiency. Our study presents a possibility of using a volume holographic grating recorded in anisotropic materials to shape a broadband ultrashort pulsed beam by modulating its polarization state.

Keywords: diffraction optics, coupled wave theory, volume holographic grating, ultrashort pulsed beam

PACC: 4240D, 4240E, 4225F, 4225J

1. Introduction

The technique to generate ultrashort pulsed beams (UPBs) has made much progress in recent years,[1] which has extended the bandwidth of optical communications and signal processing. It is of great importance to control the laser output pulses at will to achieve functional waveforms with large bandwidths that can be utilized in a variety of applications. Many methods have been reported.[2−5] For an optical pulse with a duration of longer than 1 ns, it can be directly shaped in a temporal domain with an electro-optic device by means of the Kerr effect. For the even shorter pulses, the above method is difficult to utilize, but another technique can be used for shaping them in the Fourier domain, where the optical frequency components of the UPB are spatially dispersed by a dispersive element, then modified by a filter, and recombined by an identical dispersive element to form the temporal output with a shaped waveform. Among many filtering masks for the UPBs, volume holographic gratings (VHGs) are most interesting because of their flexibility and the possibility of using them to implement dynamic processing.[6−12] Ding *et al*[8] have shown both theoretically and experimentally that in the frequency domain it is possible to achieve a large enough diffraction bandwidth of VHG for the bandwidth of 100 fs pulses mainly by increasing the grating period and decreasing the grating thickness. Recently Teng[9] has studied the dispersion effect in the crystal. However, as a matter of fact, most of the materials used for VHG are optically anisotropic, such as photorefractive $LiNbO_3$ crystals. The refractive index and the corresponding index modulation in these materials will change with the variation of the polarization state of the readout beam. And, the application of VHGs to signal transmission in optical fibre communications is just the case where the polarization state of the readout pulsed beam of the VHG changes arbitrarily because fibres are subjected to stress and temperature changing with their surroundings. Therefore, the polarization-dependent diffraction properties of VHGs for the UPB readout should be taken into considera-

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†E-mail: yzchwang@hotmail.com

tion. However, it is worth to mention that few studies of the problem have been carried out up to now. Therefore in this paper, we investigate the properties of an input UPB with an arbitrary linear polarization state diffracted by a VHG in the anisotropic crystals, and also discuss the effects of the bandwidth of the input UPB on the diffraction properties. Here, we restrict our discussion to the case of an unslanted transmission grating in a photorefractive $LiNbO_3$ crystal, and assume that the input UPB is of Gaussian shape in time.

In Section 2, the modified coupled wave theory of Kogelnik[13] is derived, and expressions of the spectral and temporal distributions of the diffracted intensity and the diffraction efficiency of the VHG are obtained. Numerical analyses of the polarization-dependent diffraction properties, with the spectral bandwidth of the input UPB changing, are given in Section 3. Based on these studies, we show the possibility of shaping a broadband UPB through the adjustment of its polarization state. A summary and suggestions are given in the last section.

2. Modified coupled wave analysis

As shown in Fig.1, a VHG is recorded in an anisotropic photorefractive $LiNbO_3$ crystal. The crystal's optical axis coincides with the x-axis. The grating vector $\boldsymbol{K}$ is perpendicular to the fringe planes and parallel to the crystal's optical axis. And $\boldsymbol{K}$ has a length of $K = 2\pi/\Lambda$, where Λ is the grating period. The parameter d is the grating thickness. A UPB with a field amplitude $u_0(t)$ in the temporal domain enters the interior of the $LiNbO_3$ crystal at an angle θ. We assume that it is polarized with a normalized polarization vector $\boldsymbol{e}_\mathrm{r}$, where $\boldsymbol{e}_\mathrm{r}$ is independent of z. We then have $\boldsymbol{e}_\mathrm{r} = \sin\varphi\,\boldsymbol{e}_\mathrm{ro} + \cos\varphi\,\boldsymbol{e}_\mathrm{re}$, where φ is defined as the polarization angle included between $\boldsymbol{e}_\mathrm{r}$ and the incidence plane. $\boldsymbol{e}_\mathrm{ro}$ and $\boldsymbol{e}_\mathrm{re}$ are normalized polarization vectors that are perpendicular and parallel to the plane of incidence, respectively. Then in the spectral domain, the amplitude of the input UPB $u_0(\lambda)$, which is obtained by performing the Fourier transform of $u_0(t)$, is the superposition of the ordinary component (o- component) $R_\mathrm{o}(0,\lambda) = u_0(\lambda)\sin\varphi$ and the extraordinary component (e- component) $R_\mathrm{e}(0,\lambda) = u_0(\lambda)\cos\varphi$ in the crystal. $R_i(0,\lambda)$ (i = o or e) is diffracted by the VHG as shown in Fig.1.

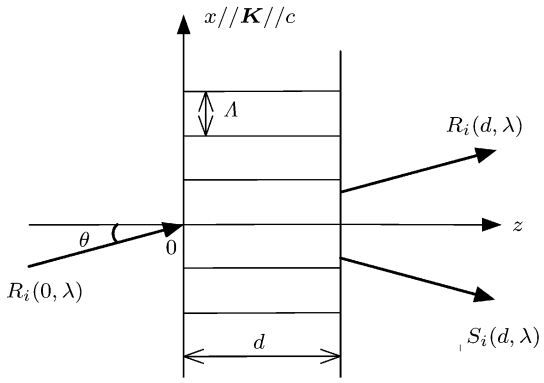


Fig.1. Model of a volume holographic grating illuminated by the o- or e- beam component of an ultrashort pulsed beam with an arbitrary linear polarization state.

As an example, we suppose that the UPB is of a Gaussian shape in time, so the temporal amplitude of the input pulse can be generally expressed as

$$u_0(t) = \exp\Big(\mathrm{i}\omega_0 t - \frac{t^2}{T^2}\Big), \tag{1}$$

where $\omega_0 = 2\pi c/\lambda_0$ is the central frequency, and c is the light velocity in free space. Also, the parameter T is related to the temporal full width at half-maximum (TFWHM) of $|u_0(t)|^2$, denoted as $\Delta\tau_{\mathrm{in\,p}}$, by the relation: $T = \Delta\tau_{\mathrm{in\,p}}/\sqrt{2\ln 2}$. The Fourier transform of Eq.(1) gives its distribution in the spectral domain as fellows:

$$u_0(\lambda) = \sqrt{\pi}T\exp\Big\{-\Big[\pi Tc\Big(\frac{1}{\lambda} - \frac{1}{\lambda_0}\Big)\Big]^2\Big\}. \tag{2}$$

Then the spectral full width at half-maximum (SFWHM) of $I_0(\lambda) = |u_0(\lambda)|^2$ is given by $\Delta\lambda_{\mathrm{in\,p}} = 0.441\lambda_0^2/c\Delta\tau_{\mathrm{in\,p}}$.

We assume that the two recording beams of the VHG in the $LiNbO_3$ crystal are ordinarily polarized, and the space-charge field E_{sc} produced by the linear photorefractive effects in the process of transport of photo-induced charges in the crystal (diffusion, drift, photovoltaic effect *et al*) is parallel to $\boldsymbol{K}$. There is no anisotropic Bragg diffraction due to zero effective electro–optic coefficient.[14] And for the o and e components of the input UPB, the amplitudes of the spatial modulation of the refractive indices $n_{1\mathrm{o}}$ and $n_{1\mathrm{e}}$ are, respectively,

$$n_{1\mathrm{o}} = -n_\mathrm{o}^3(\lambda_0)\gamma_{13}E_{\mathrm{sc}}/2\,, \tag{3}$$

$$n_{1e}=-\frac{[-\gamma_{13}n_o^4(\lambda_0)\sin^2\theta+\gamma_{33}n_{e0}^4(\lambda_0)\cos^2\theta]E_{sc}}{2n_e(\lambda_0)}, \quad (4)$$

where $\gamma_{13}=8.6\times10^{-12}$ mV^{-1} and $\gamma_{33}=3.08\times10^{-11}$ mV^{-1} are the electro–optic coefficients, $n_o(\lambda_0)$ and $n_e(\lambda_0)$ are values of the average ordinary and extraordinary refractive indices $n_o(\lambda)$ and $n_e(\lambda)$ when $\lambda=\lambda_0$, respectively, and

$$n_e(\lambda_0)=\frac{n_o(\lambda_0)n_{e0}(\lambda_0)}{\sqrt{n_o^2(\lambda_0)\cos^2\theta+n_{e0}^2(\lambda_0)\sin^2\theta}},$$

where $n_o(\lambda_0)$ and $n_{e0}(\lambda_0)$ can be obtained by Sellmeier's formulae.[15]

For the VHG, it is sufficient to consider that only the transmitted beam $R_i(z,\lambda)\boldsymbol{e}_{ri}$ and the diffracted beam $S_i(z,\lambda)\boldsymbol{e}_{si}$ are present in the grating,[13] where $i=$o or e. $\boldsymbol{e}_{so}$ and $\boldsymbol{e}_{se}$ are independent of z, and they are normalized polarization vectors perpendicular and parallel to the plane of incidence, respectively. Then the modified coupled wave equations for each wavelength component within the spectrum of the UPB are

$$\begin{aligned}&\cos\theta R_i'+\alpha(\lambda)R_i=-\mathrm{j}\kappa_i(\lambda)(\boldsymbol{e}_{ri}\cdot\boldsymbol{e}_{si})S_i,\\&\cos\theta S_i'+[\alpha(\lambda)+\mathrm{i}\vartheta_i(\lambda)]S_i=-\mathrm{j}\kappa_i(\lambda)(\boldsymbol{e}_{ri}\cdot\boldsymbol{e}_{si})R_i,\end{aligned} \quad (5)$$

where $i=$ o or e, the primes denote the differentiation with respect to z,

$$\begin{aligned}\alpha(\lambda)&=\mu c\sigma(\lambda)/2n_i(\lambda),\\\vartheta_i(\lambda)&=K\cos\theta-K^2\lambda/4\pi n_i(\lambda),\\\kappa_i(\lambda)&=\pi n_{1i}/\lambda-\mu c\sigma_i/8n_i(\lambda),\end{aligned}$$

$\sigma(\lambda)$ is the average conductivity, and σ_1 is the amplitude of the spatial modulation of the conductivity. Referring to the grating geometry in Fig.1, we have $\boldsymbol{e}_{ro}\cdot\boldsymbol{e}_{so}=1$ and $\boldsymbol{e}_{re}\cdot\boldsymbol{e}_{se}=\cos(2\theta)$. Here θ is assumed to be the Bragg angle of the VHG for the central wavelength component within the spectrum of $R_o(0,\lambda)$. Owing to the average birefringence of the crystal, there inevitably exists a small deviation between θ and the Bragg angle for the central wavelength component within the spectrum of $R_e(0,\lambda)$. But in our analysis, we assume that $\cos\theta$ remains near unity. Then the deviation is very small, and the energy coupling between $R_e(0,\lambda)$ and $S_e(z,\lambda)$ is stronger than that between $R_o(0,\lambda)$ and $S_o(z,\lambda)$ according to the relation $n_{1e}>n_{1o}$ obtained from Eqs.(3) and (4) in $LiNbO_3$ crystal. So we neglect the small deviation here.

A Taylor series expansion of ϑ yields the following expression that is correct to the first order in the deviation of $\Delta\lambda=\lambda-\lambda_0$: $\vartheta_i=-\Delta\lambda\pi N_i^{-1}/\Lambda^2$, where

$$N_i^{-1}=[\lambda/n_i(\lambda)]'|_{\lambda=\lambda_0}. \quad (6)$$

The prime $'$ denotes differentiation with respect to λ. If the dispersion effect in the crystal is neglected, we have $N_i^{-1}=1/n_i(\lambda_0)$.

In the spectral domain, the boundary condition of Eq.(5) are $R_o(0,\lambda)=u_0(\lambda)\sin\varphi$, $S_o(0,\lambda)=0$ and $R_e(0,\lambda)=u_0(\lambda)\cos\varphi$, $S_e(0,\lambda)=0$. By solving Eq.(5), we arrive at the result for the amplitude distribution of the diffracted pulsed beam at the output of the VHG as follows:

$$\begin{aligned}S_i(d,\lambda)=&-\mathrm{j}R_i(0,\lambda)\exp(-\alpha d/\cos\theta)\\&\times\exp(\mathrm{j}\xi_i)\frac{\sin(\upsilon_i^2+\xi_i^2)^{1/2}}{(1+\xi_i^2/\upsilon_i^2)^{1/2}},\end{aligned} \quad (7)$$

where

$$\begin{aligned}\upsilon_i&=\kappa_i(\boldsymbol{e}_{ri}\cdot\boldsymbol{e}_{si})d/\cos\theta,\\\xi_i&=-\vartheta_i d/2\cos\theta.\end{aligned} \quad (8)$$

For a lossless grating, $\sigma(\lambda)=0$ and $\sigma_1=0$, and we obtain $\kappa_i(\lambda)=\pi n_{1i}/\lambda$. According to Eq.(7), the intensity distributions of the diffracted pulsed beam in the spectral and temporal domains, respectively, are

$$I_S(d,\lambda)=\sum_i|S_i(d,\lambda)|^2, \quad (9)$$

$$I_s(d,t)=\sum_i|s_i(d,t)|^2, \quad (10)$$

where $s_i(d,t)$ is obtained by performing the Fourier transform of $S_i(d,\lambda)$ in Eq.(7) with respect to frequency $\omega=2\pi c/\lambda$. The diffraction efficiency of the VHG is defined as

$$\eta=\frac{\int I_S(d,\omega)\mathrm{d}\omega}{\int I_0(\omega)\mathrm{d}\omega}, \quad (11)$$

where $I_S(d,\omega)$ and $I_0(\omega)$ are the intensity distributions of the diffracted and the input pulsed beams in the frequency domain, which can be calculated from $I_S(d,\lambda)$ and $I_0(\lambda)$, respectively.

The SFWHM of the diffracted pulsed beam $\Delta\lambda_{diff}$ may change with the variation of the polarization state of the input UPB. We denote $\Delta\lambda_{diff}$ as $\Delta\lambda_{diff\,e}$ when $\varphi=0$, and as $\Delta\lambda_{diff\,o}$ when $\varphi=\pi/2$. With the increase of the SHWHM of the input UPB $\Delta\lambda_{in\,p}$, $\Delta\lambda_{diff\,i}(i=$ o or e) will reach its maximum value because of the spectral selectivity of the VHG. We regard the maximum value as the corresponding spectral bandwidth of the VHG $\Delta\lambda_{Gi}$, beyond which, the

diffraction efficiency for each wavelength component within the spectrum of the UPB will drop to below 50% of its maximum value, which is for the central wavelength. $\Delta\lambda_{\mathrm{G}i}$ can be obtained by using a similar method to that in Ref.[12]. For the lossless case of VHG, it is approximately expressed as

$$\Delta\lambda_{\mathrm{G}i} = \frac{4\bar{\xi}_i \cos\theta \Lambda^2 N_i(\lambda)}{\pi d}, \tag{12}$$

where $\bar{\xi}_i$ is the average value of ξ_i when the diffraction efficiency for each wavelength component drops to 50% of its maximum value with small changes of υ_i.

From Eq.(12), we see that $\Delta\lambda_{\mathrm{G}i}$ decreases with the increase of the grating thickness d, but increases rapidly with the increase of Λ when θ is very small, and is influenced by the dispersion effect in the crystal.

According to Eq.(9), when φ changes from 0 to $\pi/2$, the variation range of $\Delta\lambda_{\mathrm{diff}}$ will be

$$\Delta\lambda_{\mathrm{rang}} = |\Delta\lambda_{\mathrm{diff\,o}} - \Delta\lambda_{\mathrm{diff\,e}}|. \tag{13}$$

And, $\Delta\lambda_{\mathrm{rang}}$ will reach its maximum value $|\Delta\lambda_{\mathrm{G\,o}} - \Delta\lambda_{\mathrm{G\,e}}|$ with the increase of $\Delta\lambda_{\mathrm{in\,p}}$. Clearly, by modulating the grating parameters and the input condition, an appropriate value of $\Delta\lambda_{\mathrm{rang}}$ can be obtained. With it, it is possible to perform the pulse shaping in the frequency domain by modulating the polarization state of the input UPB.

3. Numerical analysis

For a VHG in a $LiNbO_3$ crystal that is grown from the stoichiometric melt with mole ratio Li/Nb=1.000 at 293 K, the values of $\Delta\lambda_{\mathrm{G}i}$ are tabulated as shown in Table 1, where $\lambda_0 = 1.06$ μm, $d = 1$ mm and $E_{\mathrm{sc}} = 5.0 \times 10^6$ V·m^{-1}.[16] And $\Delta\tau_{\mathrm{G}i}$ denotes the corresponding TFWHM of a UPB with an SFWHM of $\Delta\lambda_{\mathrm{G}i}$ respectively, assuming it to be of transform-limited Gaussian pulse shape. It is clear that $\Delta\lambda_{\mathrm{G}i}$ is larger for the larger values of the grating period Λ, and $\Delta\lambda_{\mathrm{G\,o}} > \Delta\lambda_{\mathrm{G\,e}}$. And, due to the dispersion of the $LiNbO_3$ crystal, $\Delta\lambda_{\mathrm{G}i}$ decreases since we have $N_i(\lambda) < n_i(\lambda_0)$ calculated from Eq.(6). It means that the input UPB is broadened in the temporal domain after being diffracted by the VHG due to the dispersion effect. In addition, according to Table 1, we calculate that $\Delta\lambda_{\mathrm{rang}} = 0.62$ nm when $\Lambda = 1$ μm, and $\Delta\lambda_{\mathrm{rang}} = 8.35$ nm when $\Lambda = 3$ μm, while $\Delta\lambda_{\mathrm{rang}} = 24.47$ nm when $\Lambda = 5$ μm. Obviously, $\Delta\lambda_{\mathrm{rang}}$ is also larger for the larger values of Λ.

Table 1. The variations of $\Delta\lambda_{\mathrm{G}i}$ and $\Delta\tau_{\mathrm{G}i}$ with Λ, where $d = 1$ mm, $E_{\mathrm{sc}} = 5.0 \times 10^6$ V·m^{-1}.

Λ/μm	φ/rad	$\Delta\lambda_{\mathrm{G}i}$/nm	$\Delta\tau_{\mathrm{G}i}$/fs
1	0	3.044	542.5
1	$\pi/2$	3.664	450.8
3	0	25.52	64.71
3	$\pi/2$	33.87	48.77
5	0	70.33	23.49
5	$\pi/2$	94.28	17.52

For the VHG in Table 1 with $\Lambda = 3$ μm, Fig.2 demonstrates the variation of $\Delta\lambda_{\mathrm{diff\,i}}$ as a function of $\Delta\lambda_{\mathrm{in\,p}}$ and $\Delta\tau_{\mathrm{in\,p}}$.

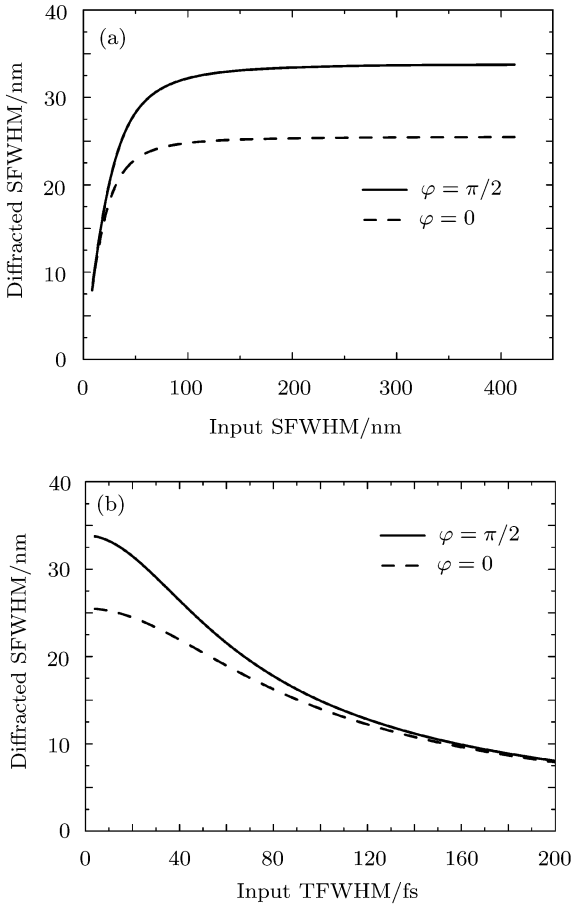


Fig.2. The variations of the diffracted SFWHM $\Delta\lambda_{\mathrm{diff}}$ with (a) the SFWHM $\Delta\lambda_{\mathrm{in\,p}}$ and (b) the TFWHM $\Delta\tau_{\mathrm{in\,p}}$ of the input UPB, $d = 1$ mm, $\Lambda = 3$ μm.

According to Fig.2, $\Delta\lambda_{\mathrm{diff\,o}} > \Delta\lambda_{\mathrm{diff\,e}}$ for the input UPB with larger values of $\Delta\lambda_{\mathrm{in\,p}}$, or with smaller values of $\Delta\tau_{\mathrm{in\,p}}$. And with the increase of $\Delta\lambda_{\mathrm{in\,p}}$ or the decrease of $\Delta\tau_{\mathrm{in\,p}}$, $\Delta\lambda_{\mathrm{diff\,i}}$ is closer to its maximum value $\Delta\lambda_{\mathrm{G}i}$ that is analytically given as 33.87 nm for $\Delta\lambda_{\mathrm{G\,o}}$ and as 25.52 nm for $\Delta\lambda_{\mathrm{G\,e}}$ in Table 1. Correspondingly, $\Delta\lambda_{\mathrm{rang}}$ is close to its maximum value 8.35 nm. So in order to obtain a larger $\Delta\lambda_{\mathrm{rang}}$ to be used

for shaping a pulse, the smaller values of $\Delta\tau_{\mathrm{in\,p}}$ are preferable.

When the polarization state of the input UPB changes, taking the VHG with $\Lambda = 3$ μm in Table 1 for example, Fig.3 shows the variations of the spectral and temporal distributions of the normalized diffraction intensity with the polarization state of the input UPB, provided that the UPB is of Gaussian shape with $\Delta\tau_{\mathrm{in\,p}} = 20$ fs. Figure 3 shows $\Delta\lambda_{\mathrm{diff}}$ increasing with the increase of the polarization angle φ, which leads to the great differences among the corresponding temporal intensity distributions of the diffracted pulsed beam in Fig.3(b). Moreover, the UPBs with smaller polarization angles are distorted more seriously. For other input pulses with $\Delta\lambda_{\mathrm{in\,p}} > \Delta\lambda_{\mathrm{G}i}$ or with $\Delta\tau_{\mathrm{in\,p}} < \Delta\tau_{\mathrm{G}i}$, the change of $\Delta\lambda_{\mathrm{diff}}$ with φ is similar.

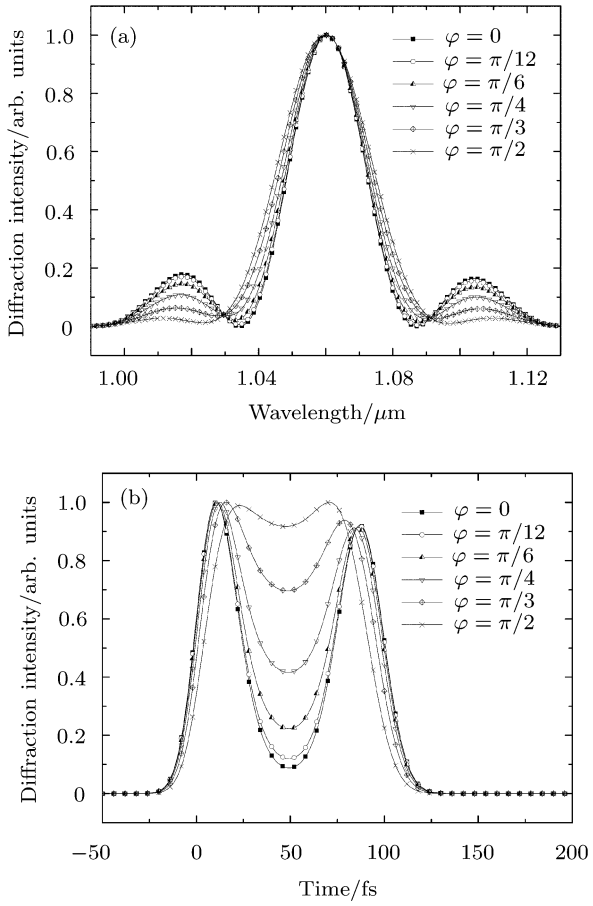


Fig.3. The distributions of the normalized diffraction intensity for the input pulse with polarization angles $\varphi = 0,\ \pi/12,\ \pi/6,\ \pi/4,\ \pi/3,\ \pi/2$, where $d = 1$ mm, $\Lambda = 3$ μm, $\Delta\tau_{\mathrm{in\,p}}$= 20 fs, (a) in the spectral domain, and (b) in the temporal domain.

Given the grating parameters and the TFWHM of the input UPB, the diffraction efficiency of the VHG η defined by Eq.(11) will also vary with the polarization state of the input UPB. In Fig.4, at any given values of $\Delta\tau_{\mathrm{in\,p}}$, η is larger for smaller values of φ, and reaches its maximum value when $\varphi = 0$. The reason is that when $\varphi = 0$, the strongest energy coupling exits between the diffracted and transmitted pulsed beams in the VHG. Also, given the value of φ, η increases with the increase of $\Delta\tau_{\mathrm{in\,p}}$, and is very close to a constant when $\Delta\tau_{\mathrm{in\,p}}$ is so large that the input pulsed beam can be considered as a continuous wave. Although an input UPB with smaller $\Delta\tau_{\mathrm{in\,p}}$ is preferable in application of VHGs to shaping a pulse, the diffraction efficiency is small. Therefore, in order to obtain a large enough variation range $\Delta\lambda_{\mathrm{rang}}$ with an appropriate diffraction efficiency, it is necessary to choose $\Delta\tau_{\mathrm{in\,p}}$ appropriately when a VHG is used to shape a pulse through modulating its polarization state.

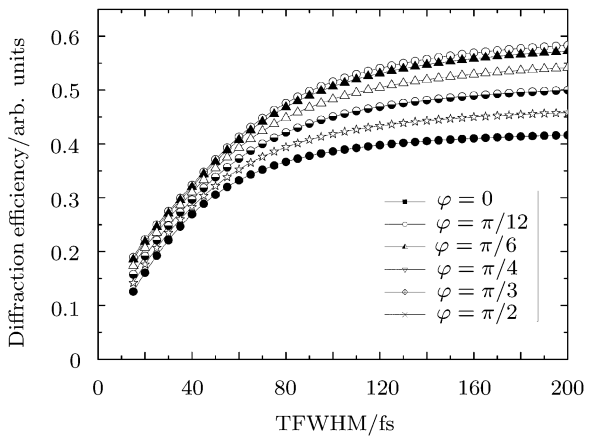


Fig.4. The variation of the diffraction efficiency η with the TFWHM of the input UPB $\Delta\tau_{\mathrm{in\,p}}$, where $d = 1$ mm, $\Lambda = 3$ μm.

4. Conclusions

We have studied the properties of a UPB with an arbitrary polarization state diffracted by a VHG in an anisotropic photorefractive $LiNbO_3$ crystal, where the UPB is of an ultrashort Gaussian-shaped pulsed beam in time and the VHG is an unslanted transmission type. The modified coupled wave theory of Kogelnik combining the dispersion effect in the crystal is used.

The results show that when the polarization angle of the input UPB changes from 0 to $\pi/2$, the SFWHM of the diffracted pulsed beam increases while the diffraction efficiency decreases for the input UPB with larger SFWHM. And, the variation range of the diffracted SFWHM reaches a maximum value with the increase of the input SFWHM, which can be controlled

by the grating parameters and the input conditions. As for a readout pulsed beam with an elliptical polarization state, we can analyse the diffraction properties by using a similar method because it can be represented as a superposition of o wave component and e wave component in the crystal. Our results indicate that the volume holographic grating recorded in anisotropic materials can be used for shaping a UPB in the frequency-domain through modulating the polarization state of the input pulsed beam.

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