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Chirped pulse distortion in stratified volume reflection gratings

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ABSTRACT

The problem of chirped pulse light Bragg diffraction by stratified volume reflection gratings is considered using characteristic matrix method. The spectral profiles of the transmitted and diffracted chirped pulses have been presented. Using these expressions the calculations of the diffracted spectra and diffraction efficiency have been made in the wide range of initial parameters of incident chirped pulse and the stratified volume reflection gratings. Variously shaped spectral distortions have been revealed and discussed based on these calculations.

1. Introduction

Diffraction of the periodically layered structures such as volume gratings, liquid crystals and one-dimensional photonic crystals have been intensively studied because of their many potential applications in optical communication and information processing [1,2]. Especially, volume holographic grating (VHG) is of wide interest in many applications because of their properties of high diffraction efficiency, excellent wavelength selectivity and angular selectivity. Lately it has received wide attention as a class of novel diffraction elements, in which multiple layers of VHG are separated by optically homogeneous intermediate layers. Many device applications based on multilayer volume gratings such as wavelength division multiplexer, optical interconnects, and optical filters have been demonstrated experimentally [3–5]. Chirped pulse laser is widely used in many fields such as strong field laser physics, ultrafast imaging, and laser spectroscopy because of its abundant frequency spectrum [6]. McMullen et al. [7] have analyzed the chirped pulse transmitted through a strong dispersive grating pair that indicated the pulse laser distorted greatly. Chuang et al. [8] have shown both theoretically and experimentally that the chirped pulse transmission and amplify characteristics based on Maxwell equation and population inversion. Research on the diffraction of chirped pulse laser has the important significance. Therefore, to design a periodically layered device for some specific applications, a precise knowledge on the spectral response of the periodically layered structure is necessary.

In this paper, we investigated the diffraction characteristics of chirped laser pulse by periodically layered structure, stratified volume reflection gratings. The spectral profiles of the transmitted and diffracted chirped pulses have been presented. Using these expressions the calculations of the diffracted spectra and diffraction efficiency have been made in the wide range of initial parameters of incident chirped pulses and stratified volume reflection gratings. Variously shaped spectral distortions have been revealed and discussed based on these calculations. The analysis of this paper will be valuable for the accurate design novel optical devices based on stratified volume reflection gratings.

2. Modified coupled wave theory for chirped laser pulse

2.1. The structure of stratified volume reflection gratings

Fig. 1 shows the structure of the stratified volume reflection gratings, in which N discrete volume reflection gratings are interleaved with $N-1$ optically homogeneous buffer layers. The thickness of the volume reflection grating layers and the buffer layers are T_i ($i=1, 2, \ldots, N$) and gaps d_i ($i=1, 2, \ldots, N-1$), respectively. The averaged refractive indices for both the grating layers and the buffer layers are set to n_0. The refractive index modulation amplitude for the grating layers is n_1. K is the grating vector with grating slant angle φ and magnitude $K=2\pi/\Lambda$, Λ is grating spacing. $n=n_0+n_1\cos(\boldsymbol{K}\cdot\boldsymbol{r})$, $n_1 \ll n_0$. Therefore the refractive index distribution of the grating layers can be expressed as:

The incident pulse can be expressed as

$$u_0(t) = \exp[-t^2/T^2]\exp[i(\omega_0 t + Ct^2/T^2)]. \tag{1}$$

where ω_0 is the center frequency of the chirped pulse, C is the chirped parameter, $T = \Delta\tau/\sqrt{2\ln 2}$ and $\Delta\tau$ is the full width at half

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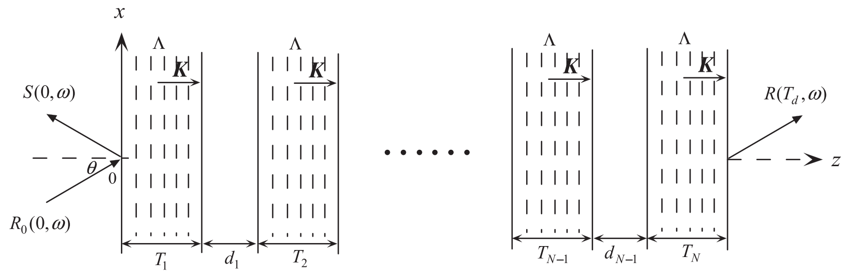

Fig. 1. The structure of the stratified volume reflection gratings.

maximum (FWHM) of the chirped pulse temporal intensity. The spectral expression of Eq. (1) can be given by

$$U_0(\omega) = \sqrt{\frac{\pi}{1-iC}}T\exp\left\{-\frac{T^2(\omega-\omega_0)^2}{4(1-iC)}\right\}. \quad (2)$$

2.2. Derivation of the diffracted spectra

Supposing a linear chirped Gaussian pulse $u_0(t)$ is incident onto the stratified volume reflection gratings at $z = 0$. The wave equation describing the light propagation in volume grating is given by [9],

$$\frac{\partial^2 E(z,\omega)}{\partial z^2} + \frac{\omega^2 n^2}{c^2}E(z,\omega) = 0. \quad (3)$$

Based on Kogelnik's coupled wave theory, In Bragg diffraction regime, only the transmitted and diffracted beams are present. The electric field in the ith-layers of grating region can be expressed as,

$$\boldsymbol{E}(z,\omega) = \boldsymbol{R}_i(z,\omega)\exp(-j\boldsymbol{k}_r\cdot\boldsymbol{r}) + S_i(z,\omega)\exp(-j\boldsymbol{k}_s\cdot\boldsymbol{r}). \quad (4)$$

where $R_i(z,\omega)$ and $S_i(z,\omega)$ are the complex amplitudes of the transmitted and diffracted pulse beams in the ith-layer grating, $\boldsymbol{k}_r$ and $\boldsymbol{k}_s$ is the propagation vectors of the incident beam and the diffracted beam. The phase-matching condition for diffraction process is given by $\boldsymbol{k}_s = \boldsymbol{k}_r - \boldsymbol{K}$.

Substituting Eq. (4) into the wave equation Eq. (3), we can get the transmitted and diffracted beams on the right-hand boundary of the ith layer R_{ir} and S_{ir} are connected with the amplitudes of these beams on the left-hand boundary R_{il} and S_{il} by the following matrix equation [10],

$$\begin{bmatrix} R_{ir} \\ S_{ir} \end{bmatrix} = \begin{bmatrix} m_{i11} & m_{i12} \\ m_{i21} & m_{i22} \end{bmatrix} \times \begin{bmatrix} R_{il} \\ S_{il} \end{bmatrix}, \quad (5)$$

where $m_{i11} = \left[\cosh(VT_i) + j\frac{\xi}{V}\sinh(VT_i)\right]\exp(-j\xi T_i)$, $m_{i12} = -j\frac{\gamma}{V}\sqrt{\frac{C_S}{C_R}}\sinh(VT_i)\exp(-j\xi T_i)$, $m_{i21} = -j\frac{\gamma}{V}\sqrt{\frac{C_R}{C_S}}\sinh(VT_i)\exp(-j\xi T_i)$, $m_{i22} = \left[\cosh(VT_i) - j\frac{\xi}{V}\sinh(VT_i)\right]\exp(-j\xi T_i)$, $c_R = \cos\theta$, $c_S = -\cos\theta$, $V = \left(-\xi^2 - \frac{\kappa^2}{C_R C_S}\right)^{1/2}$, $\kappa = \pi n_1/\lambda$ is the coupling constant, and $\xi = \vartheta/2c_S$ is off-Bragg parameter and $\vartheta = \frac{K^2}{4\pi}\left(\frac{\lambda_0}{n(\omega_0)} - \frac{\lambda}{n(\omega)}\right)$.

At the boundary between the ith buffer layer and the $i+1$ layer grating, we can also find the following matrix equation,

$$\begin{bmatrix} R_{(i+1)l} \\ S_{(i+1)l} \end{bmatrix} = [D_i] \times \begin{bmatrix} R_{il} \\ S_{il} \end{bmatrix}, \quad (6)$$

where $[D_i] = \begin{bmatrix} 1 & 0 \\ 0 & \exp\left(-j\frac{\vartheta d_i}{C_S}\right) \end{bmatrix}$ is the transmission function of the ith buffer layer.

For a system of stratified volume reflection gratings, on the input surface ($z = 0$), there are diffracted beam $S(0,\omega)$ and the input pulse $R_0(0,\omega) = U_0(\omega)$. At the output boundary, the amplitudes of the initial diffracted beam $S_0(T_d,\omega) = 0$ and transmitted beam $R(T_d,\omega)$ satisfy the following matrix equation:

$$\begin{bmatrix} R(T_d,\omega) \\ S_0(T_d,\omega) \end{bmatrix} = [M_C] \times \begin{bmatrix} R_0(0,\omega) \\ S(0,\omega) \end{bmatrix}. \quad (7)$$

where $T_d = \sum_{i=1}^{N}(T_i + d_i)$ and $[M_C] = M_N D_{N-1} M_{N-1} \ldots D_i M_i \ldots D_1 M_1$ are respectively the total thickness and the optical transmission function of the system, M_i and D_i can be obtained in Eqs. (5) and (6).

The intensity distributions of the transmitted and diffracted pulsed beams and the diffraction efficiency can be given by, $I_R(T_d,\omega) = |R(T_d,\omega)|^2$,

$$I_S(0,\omega) = |S(0,\omega)|^2, \quad (8)$$

$$\eta = \frac{|C_S|}{C_R}\frac{\int I_S(0,\omega)d\omega}{\int I_R(0,\omega)d\omega + \int I_S(0,\omega)d\omega}. \quad (9)$$

Eqs. (7)–(9) provide a precise prediction of the charateristics of the diffracted spectra of the stratified volume reflection gratings. In the following section, we will discuss these charateristics in detail.

3. Characteristics of the diffracted spectra of stratified volume reflection gratings

To study the characteristics of the diffracted spectra and to understand the effects of the buffer layers on the diffracted spectra, let us consider the simplest stratified volume reflection gratings with $N = 2$, where a buffer layer is sandwiched between two volume reflection gratings. In simulation, we assume that the central wavelength of the readout chirped pulse is $\lambda_0 = 1.06\,\mu$m and the average refractive index of the stratified volume reflection gratings is $n_0 = 2.25$.

Fig. 2 shows the normalized intensity distributions of the diffraction pulse with different initial parameters of the incident linear chirped pulse, (a) chirped parameter $C = 5, 10, 20$, (b) pulse duration $\Delta\tau = 50$ fs, 150 fs, 300 fs. In the simulation, the structure parameters for the 2-layer volume reflection gratings are $n_1 = 8\times10^{-5}$, $\Lambda = 3\,\mu$m, $T_1 = T_2 = 0.25$ mm and $d_1 = 0.2$ mm. It is shown that the normalized spectral distributions change greatly with increasing chirped parameter and the intensities of side lobe increase. When the pulse duration $\Delta\tau$ increases, the distortion of the pulse envelope is clearly decreased and the side peaks are becoming smaller and smaller. The reason is that the grating can pass more frequencies from the initial pulse spectrum at large $\Delta\tau$. The grating bandwidth $\Delta\lambda_G$ is larger than the incident bandwidth $\Delta\lambda_{in}$ of the chirped pulse. Thus, when the grating is fixed, the spectral profile of diffracted pulse is influenced greatly by the shape of an incident chirped pulse, such as linear chirped parameter C and pulse duration $\Delta\tau$.