An analysis of As_2S_3 chirped fiber grating formed by two-photon absorption effect

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When femtosecond laser pulses interfere with chirped femtosecond laser pulses in As_2S_3 fiber, a chirped fiber grating is formed. An analytical expression is given to describe the chirped grating, and its Bragg reflectivity is calculated. Because of the high photosensitive effect of As_2S_3 material, the chirped fiber grating has a wide Bragg reflective spectrum and high reflectivity by choosing proper parameters. This indicates that the chirped fiber grating can be used as a stretcher in the femtosecond chirped pulse amplification (CPA) system.

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Since the invention of the CPA technology[1,2], the peak power of the femtosecond laser pulses has been boosted to multi-terawatt level (1 TW=10^{12} W)[3−5]. The major part of the CPA system is the stretcher and compressor, which have big volume and are sensitive to the environment. The alignment of them is also critical. Researchers have been trying to develop a compact, reliable, and cost-effective CPA system. Chirped fiber gratings have been used in CPA of femtosecond fiber lasers[6]. The weak pulse energy and narrow spectral bandwidth in such lasers allow the same chirped fiber gratings to act as both stretcher and compressor by reversing the direction of the propagation. Chirped fiber gratings have a potential application in all-solid state CPA systems as stretcher, but not as compressor, for they cannot bear the high peak power of the amplified pulses. One possible material for making a chirped fiber grating which can record a large time stretching is As_2S_3 fiber. Because of the high photosensitivity of As_2S_3 material, it has many applications, such as nonlinear optical device[7] and optical waveguide[8]. By exposure to continuous wave laser between 488 and 633 nm[9,10], the As_2S_3 material can be used to make holographic grating and waveguide in As_2S_3 thin film. The similar situation has been discussed by exposure to picosecond laser at 780 nm[11].

In this paper, we point out that the As_2S_3 chirped fiber grating is suitable as stretcher in a CPA system. With the two-photon absorption effect, the interferential pattern will record a chirped grating. The characteristic of the chirped fiber grating is studied. Through choosing proper parameters, the Bragg reflective spectrum of the grating is very wide. Thus the chirped fiber grating can bear a large stretching femtosecond pulse.

A chirped femtosecond laser pulse traveling in x direction interferes with another femtosecond laser pulse traveling in the opposite direction in As_2S_3 fiber. The electronic fields of the two pulses at time t are

$$P_1 = E_1(t - x/v), \tag{1}$$

$$P_2 = E_2(t + x/v), \tag{2}$$

where

$$E_1(t) = E_{01}\exp\left(-\frac{t^2}{2T_1^2}\right)\cos\left(\omega_0 t + \frac{at^2}{T_1^2}\right), \tag{3}$$

$$E_2(t) = E_{02}\exp\left(-\frac{t^2}{2T_0^2}\right)\cos(\omega_0 t), \tag{4}$$

$$T_1 = T_0\sqrt{1+4a^2}, \tag{5}$$

$$v = c/n. \tag{6}$$

The corresponding complex expressions are

$$\widetilde{E}_1(t) = E_{01}\exp\left(-\frac{t^2}{2T_1^2}\right)\exp\left[i\left(\omega_0 t + \frac{at^2}{T_1^2}\right)\right], \tag{7}$$

$$\widetilde{E}_2(t) = E_{02}\exp\left(-\frac{t^2}{2T_0^2}\right)\exp(i\omega_0 t), \tag{8}$$

where ω_0 is the central circle frequency of femtosecond laser pulse, T_0 is the half width of time duration at $1/e$ maximum intensity, E_{01} and E_{02} are amplitudes of electronic fields, and a is chirped coefficient. The system is positive chirped in case $a > 0$, otherwise it is negative. The complex expression of total electronic field in As_2S_3 fiber and its intensity are

$$\widetilde{P} = \widetilde{E}_1(t - x/v) + \widetilde{E}_2(t + x/v), \tag{9}$$

$$I = \widetilde{P}\widetilde{P}^*. \tag{10}$$

Because As_2S_3 material posses two-photon absorption effect under illumination of 800 nm femtosecond laser pulse[11], the refractive index change can be written as

$$\Delta n = c_1 \int_{-\infty}^{\infty} I^2 \mathrm{d}t. \tag{11}$$

Under the following assumptions: (1) the change of the refractive index in the DC component is very small comparing with the refractive index ($n = 2.6$) of As_2S_3 fiber;

(2) the chirped system has $|a| \gg 1$; (3) $E_{02} \gg E_{01}$; (4) the maximum change of the refractive index change is 0.01[10] through exposure; (5) the spatial frequency far from Bragg reflective condition is omitted, and the refractive index $n(x)$ is simplified as

$$n(x) = n + \Delta_0 \exp\left(-\frac{6x^2}{(4+9a^2)v^2T_0^2}\right)\cos\alpha_4, \quad (12)$$

where $\Delta_0 = 0.01, n = 2.6, \alpha_4 = \frac{2x}{v}\omega_0 - \frac{9ax^2}{(4+9a^2)v^2T_0^2} - \frac{\phi}{2}, \phi = \arctan\left(\frac{a}{2+6a^2}\right)$. Equation (12) represents a linear chirped fiber grating whose amplitude of refractive index is adjustable. We define L_0 as the width of the grating at $1/e$ the maximum refractive index change. Under the condition $|a| \gg 1$, we get $L_0 = \sqrt{6}|a|vT_0$. In application the grating length L satisfies $L \leq L_0$. The spatial period of the chirped grating is $\Lambda(x) = 2\pi/K_4(x)$. From Eq. (12) we have

$$K_4(x) = \frac{2\omega_0}{v} - \frac{9ax}{(4+9a^2)v^2T_0^2}. \quad (13)$$

$\Lambda(x)$ can be simplified as

$$\Lambda(x) = \frac{\lambda_0}{2n} + \frac{\lambda_0^2}{8\pi T_0^2 ac^2}x, \quad (14)$$

where $c = 3 \times 10^8$ m/s, $\lambda_0 = 800$ nm.

The grating represented by Eq. (12) is not uniform. We use Rouard's method[12] to calculate its Bragg reflectivity. The Rouard's method is its recursive techniques. The fundamental step in these techniques is the replacement of a thin-film layer by an effective complex reflectivity. A chirped fiber grating with length l is divided into M parts, as shown in Fig. 1, where each part is regarded as an uniform fiber grating and its reflective coefficient r_i ($i = 1, 2, \cdots, M$) can be calculated by coupled-mode theory[13]. The distances between ρ_j and ρ_{j+1} effective interfaces are $d_{j,j+1}$ ($j = 1, 2, \cdots, M-1$).

Under the vertical illumination, the recursive process is

$$\rho_1 = \frac{r_2 + r_1\exp(-i2\Delta_1)}{1 + r_1r_2\exp(-i2\Delta_1)},$$

$$\Delta_1 = \frac{2\pi}{\lambda}nd_{1,2},$$

where λ is the wavelength, n is the refractive index,

$$\rho_2 = \frac{r_3 + \rho_1\exp(-i2\Delta_2)}{1 + \rho_1r_3\exp(-i2\Delta_2)},$$

$$\Delta_2 = \frac{2\pi}{\lambda}nd_{2,3};$$

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$$\rho_{M-1} = \frac{r_M + \rho_{M-2}\exp(-i2\Delta_{M-1})}{1 + r_M\rho_{M-2}\exp(-i2\Delta_{M-1})},$$

$$\Delta_{M-1} = \frac{2\pi}{\lambda}nd_{M-1,M}.$$

Through proper division of a chirped grating with definite length, we can always calculate its reflectivity R by

$$R = |\rho_{M-1}|^2. \quad (15)$$

The numerical results are shown in Figs. 2−5.

If we take the length of the chirped grating as $L = L_0 = \sqrt{6}|a|vT_0$, the spectrum of Bragg reflection will be dependent on T_0 and a. The maximum Bragg reflectivity in Fig. 5 is over 90%. The spectrum width of the chirped fiber grating will be 40−60 nm under the conditions $T_0 \leq 10$ fs and $|a| \leq 1000$. The reason for a wide spectrum of Bragg reflection is that the photosensitivity

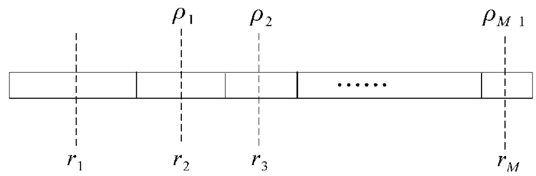

Fig. 1. A diagram to illuminate the application of Rouard's method. The reflective coefficients in M regions are r_1, r_2, $\cdots$, r_M, respectively. The effective interfaces have reflective coefficients ρ_1, ρ_2, $\cdots$, ρ_{M-1}.

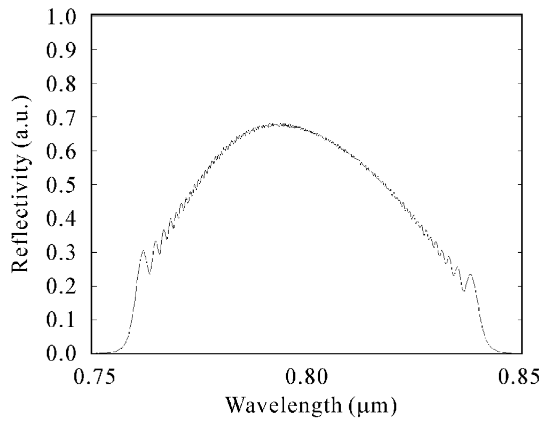

Fig. 2. The reflectivity of As_2S_3 chirped fiber grating with $L = 706.6$ μm, $a = -500$, $T_0 = 5$ fs, $\lambda_0 = 0.8$ μm, $n = 2.6$, $\Delta_0 = 0.01$.

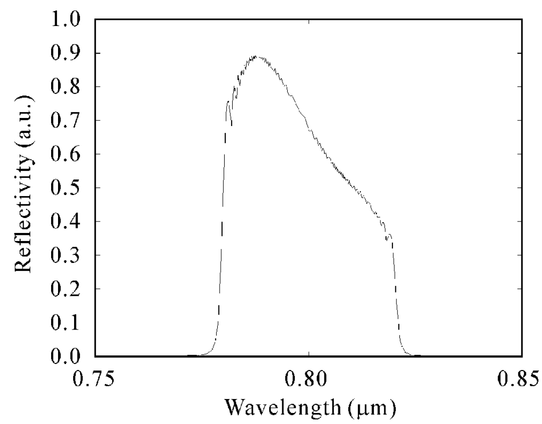

Fig. 3. The reflectivity of As_2S_3 chirped fiber grating with $L = 1413.2$ μm, $a = -500$, $T_0 = 10$ fs, $\lambda_0 = 0.8$ μm, $n = 2.6$, $\Delta_0 = 0.01$.

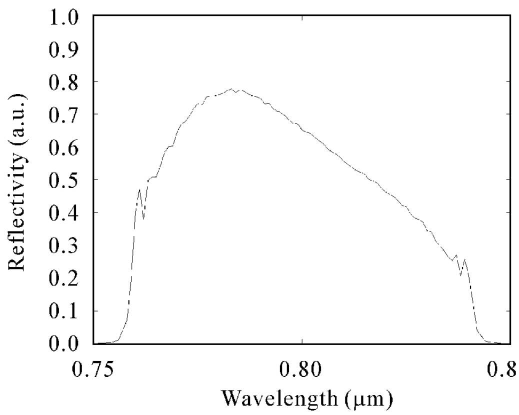

Fig. 4. The reflectivity of As_2S_3 chirped fiber grating with $L = 1413.2$ μm, $a = -1000$, $T_0 = 5$ fs, $\lambda_0 = 0.8$ μm, $n = 2.6$, $\Delta_0 = 0.01$.

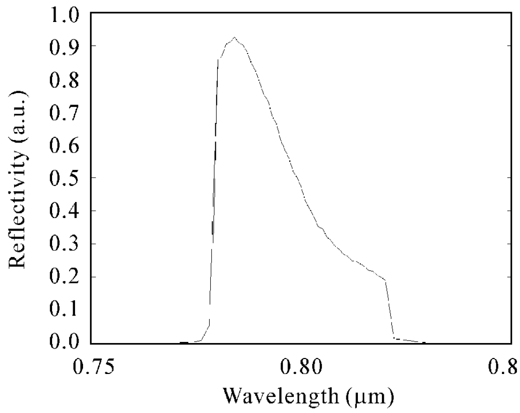

Fig. 5. The reflectivity of As_2S_3 chirped fiber grating with $L = 2826.3$ μm, $a = -1000$, $T_0 = 10$ fs, $\lambda_0 = 0.8$ μm, $n = 2.6$, $\Delta_0 = 0.01$.

of As_2S_3 material is very high. The maximum refractive index change (10^{-2}) of As_2S_3 material is much more than that (10^{-5}) of ordinary communication fiber. The wide Bragg reflective spectrum of a fiber grating is very important for some applications. For example the stretcher of the CPA of a solid femtosecond laser needs a wide spectrum. If the chirped fiber grating is used as the stretcher of a CPA system, both the volume and the cost of the stretcher will be greatly reduced.

The photosensitivity and two-photon absorption effects are two important features of As_2S_3 material under 800 nm femtosecond laser pulse illumination. A chirped grating is formed when a chirped femtosecond laser pulse interferes with another femtosecond laser pulse in As_2S_3 fiber. Usually a chirped grating is made by spatial adjustment. This paper presents that a chirped grating can also be made by temporal adjustment. The width of the incident femtosecond pulse and the chirped coefficient greatly influence the chirped grating's characteristics. By choosing proper parameters the width of the Bragg reflective spectrum of the chirped grating can be very wide. This indicates that the As_2S_3 chirped grating is appropriate to be used as stretcher in an all-solid CPA system.

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