做科研，非一朝一夕

买器材，应速战速决

Newport数千种优质产品当日发货，更多惊喜尽在PhotonSpeed™光速购！
An analysis of As$_2$S$_3$ chirped fiber grating formed by two-photon absorption effect

Huaisheng Wang (王淮生), Zhigang Zhang (张志刚),
Lu Chai (柴 鹏), and Qingyue Wang (王清月)

Ultrafast Laser Laboratory, School of Precision Instruments and Optoelectronics Engineering, Tianjin University,
Key Laboratory of Optoelectronic Information Technical Science, EMC, Tianjin 300072

Received December 31, 2002

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$_2$S$_3$ fiber. Because of the high photosensitivity of As$_2$S$_3$ 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$_2$S$_3$ material can be used to make holographic grating and waveguide in As$_2$S$_3$ 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$_2$S$_3$ 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$_2$S$_3$ fiber. The electronic fields of the two pulses at time $t$ are

$$ P_1 = E_1(t - x/v), $$
$$ P_2 = E_2(t + x/v), $$

where

$$ E_1(t) = E_{01} \exp \left(-\frac{t^2}{2T_1^2}\right) \cos \left(\omega_0 t + \frac{at^2}{T_1^2}\right), $$
$$ E_2(t) = E_{02} \exp \left(-\frac{t^2}{2T_0^2}\right) \cos(\omega_0 t), $$

$$ T_1 = T_0 \sqrt{1 + 4a^2}, $$
$$ v = c/n. $$

The corresponding complex expressions are

$$ \tilde{E}_1(t) = E_{01} \exp \left(-\frac{t^2}{2T_1^2}\right) \exp \left[i \left(\omega_0 t + \frac{at^2}{T_1^2}\right)\right], $$
$$ \tilde{E}_2(t) = E_{02} \exp \left(-\frac{t^2}{2T_0^2}\right) \exp(i\omega_0 t), $$

where $\omega_0$ 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$_2$S$_3$ fiber and its intensity are

$$ \tilde{P} = \tilde{E}_1(t - x/v) + \tilde{E}_2(t + x/v), $$
$$ I = \tilde{P} \tilde{P}^*. $$

Because As$_2$S$_3$ material possesses two-photon absorption effect under illumination of 800 nm femtosecond laser pulse$^{[11]}$, the refractive index change can be written as

$$ \Delta n = c_1 \int_{-\infty}^{\infty} i^2 dt. $$

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$_2$S$_3$ 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\cite{10} through exposure; (5) the spatial frequency far from Bragg reflective condition is omitted, and the refractive index $n(x)$ is simplified as

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

where $\Delta_0 = 0.01$, $n = 2.6$, $\alpha_4 = \frac{2\pi}{\lambda} \omega_0 - \frac{9a^2}{(4+9a^2)v^2 T_0^2}$, $\frac{9a}{2} \phi = \arctan \left( \frac{2}{3+4a^2} \right)$. 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 $L_0 = \sqrt{6} |a| v T_0$. 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

$$K_4(x) = \frac{2a_0}{v} - \frac{9a^2}{(4+9a^2)v^2 T_0^2}.$$

$\Lambda(x)$ can be simplified as

$$\Lambda(x) = \frac{\lambda_0}{2\pi} + \frac{\lambda_0^2}{8\pi T_0^2 a^2} x,$$

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\cite{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\cite{13}. The distances between $\rho_j$ and $\rho_{j+1}$ effective interfaces are $d_{j,j+1}$ ($j = 1, 2, \cdots, M - 1$).

Under the vertical illumination, the recursive process is

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

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

where $\lambda$ is the wavelength, $n$ is the refractive index,

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

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

$$\cdots$$

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

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

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

$$R = |\rho_{M-1}|^2.$$

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

If we take the length of the chirped grating as $L = L_0 = \sqrt{6} |a| v T_0$, 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. 4. The reflectivity of As$_2$S$_3$ chirped fiber grating with $L = 1413.2 \mu m$, $a = -1000$, $T_0 = 5$ fs, $\lambda_0 = 0.8 \mu m$, $n = 2.6$, $\Delta_0 = 0.01$.

Fig. 5. The reflectivity of As$_2$S$_3$ chirped fiber grating with $L = 2826.3 \mu m$, $a = -1000$, $T_0 = 10$ fs, $\lambda_0 = 0.8 \mu m$, $n = 2.6$, $\Delta_0 = 0.01$.

of As$_2$S$_3$ material is very high. The maximum refractive index change ($10^{-2}$) of As$_2$S$_3$ 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$_2$S$_3$ 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$_2$S$_3$ 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$_2$S$_3$ chirped grating is appropriate to be used as stretcher in an all-solid CPA system.

The authors acknowledge the support of the National Key Basic Research Special Foundation of China (No. G1999075201-2), the National Natural Science Foundation of China (No. 60178007), and the Science Foundation of China for Post Ph. D (2002032163). H. Wang’s e-mail address is wanghs11@eyou.com.

References