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Abstract. A type of configuration with four identical chirped volume Bragg gratings (CVBGs) in parallel combination was proposed to improve dispersion, and the maximum group delay of nanoseconds can be reached at an oblique incidence. The diffraction properties of CVBGs at oblique incidence were simulated with the transfer matrix method. The performance of this configuration on dispersion, including group delay dispersion and cubic dispersion, was well studied with detailed numerical simulation. With optimization of the CVBG structural parameters, including the grating thickness, spatial chirp rate, and refractive index modulation, the configuration can be applied in large dispersion applications. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.54.5.056105]

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1 Introduction

The dispersive element plays an important role in a chirp pulse amplification (CPA) system,¹ which has been widely used in high-peak-power ultrashort lasers. In petawatt high-energy laser facilities, diffraction grating pairs have been employed as the dispersion elements to stretch the laser pulse, avoid laser-induced damage to the laser media, and increase the light extraction efficiency. However, due to the low laser-induced threshold of diffraction gratings, the aperture of the gratings is required to be as large as 1 m × 1 m to reduce the power density.² In addition, the distance between the gratings has to be several meters to obtain enough group delay dispersion (GDD). Therefore, a dispersion element with a high laser-induced damage threshold and large dispersion is drawing much attention in high-power and large-dispersion applications.

In the last decade, chirped volume Bragg gratings (CVBGs) fabricated in photo-thermo-refractive (PTR) glass³ have attracted growing interest in ultrashort laser systems due to the high laser-induced damage threshold⁴ and large dispersion.⁵ In 2005, Liao et al.³ used a 10-mm long CVBG to stretch a 1-ps pulse to a 100-ps duration, and compressed the stretched pulse back with the same CVBG. Thereafter, a variety of studies on CPA systems with CVBGs in PTR glass were reported.⁵⁻⁸ Due to the diffraction properties,⁹ the stretching or compression ratio of CVBGs is related to the grating thickness. For the chirped pulses with a certain bandwidth, a thick CVBG will result in a large stretching or compression ratio. To compress a pulse from nanoseconds to picoseconds, a CVBG with a thickness of about 100 mm is required.¹⁰ However, the thickness of common CVBGs is only about several centimeters.¹¹ An alternative solution is to use multiple CVBGs in combination to achieve a larger dispersion. In the scheme of a series combination, CVBGs

have different structural parameters, such as the grating thickness, grating period, and refractive index modulation. Each CVBG diffracts beams with wavelengths in different and adjacent bandwidths. A large bandwidth, therefore, can be obtained.¹² However, a disadvantage of the series combination is that the distance between two adjacent CVBGs may result in temporal waveform clipping of the compressed pulses. What is more, angular alignment is also required to avoid divergence of the beams diffracted by different CVBGs.

To solve these problems, obtain higher dispersion and optimize the pulse stretching and compression, a configuration of four identical CVBGs in parallel combination is proposed in this paper. In the parallel combination configuration, each CVBG can diffract all wavelength components of the incident beam, and the stretching or compression ratio will increase as the total length of the CVBGs increases. That is, the number of CVBGs increasing. With oblique incidence and in good alignment, the output beam has no spatial chirp and the propagation direction is in the incident direction. With the transfer matrix method¹³ and ray tracing method,¹⁴ the dependence between the GDD and the cubic dispersion (CD) with CVBG parameters of thickness, spatial chirped rate (SCR), and refractive index modulation are investigated.

2 Diffraction Properties of Chirped Volume Bragg Gratings at Oblique Incidence

The diffraction efficiency and spectral phase of the CVBG working at oblique incidence were simulated with the classical transfer matrix method. The transfer matrix method had been well studied and successfully used to study the diffraction properties of CVBGs working at normal incidence in our early work.¹³ The CVBG in simulation here has a grating thickness of 3 cm and an SCR of 0.67 nm/cm, and the central grating period of the CVBG is 351 nm. The amplitude of the refractive index modulation was well chosen to obtain 100% diffraction efficiency. In the numerical simulation with the transfer matrix method, the CVBG was divided

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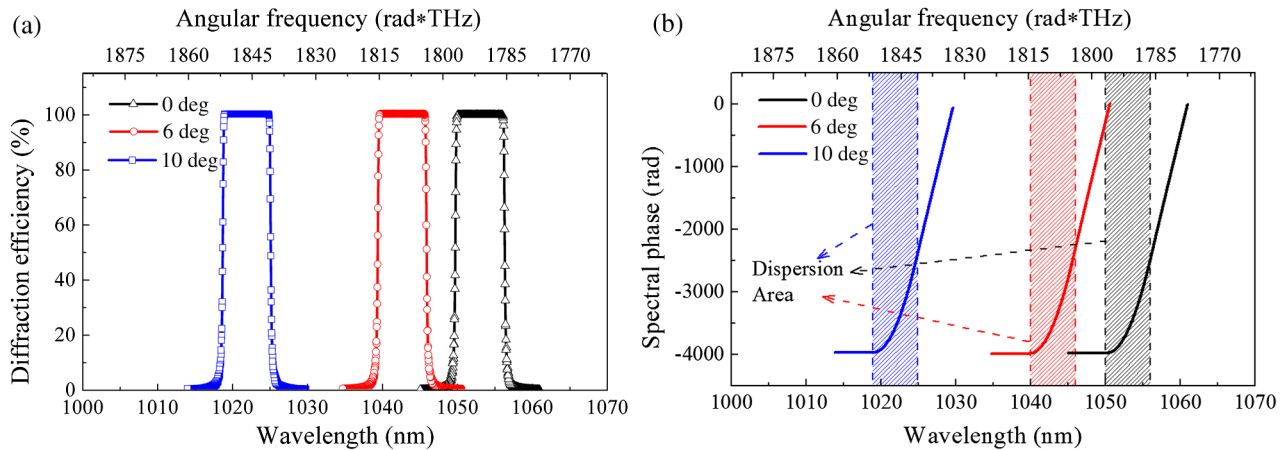


Fig. 1 Diffraction properties of chirped volume Bragg gratings (CVBGs) at different incident angles: (a) diffraction efficiency and (b) spectral phase.

into multiple uniform slabs in which the light beam propagation can be easily characterized with a transfer matrix. Each grating period of the CVBG was divided equally into 30 slabs.

Working at normal incidence, the diffraction efficiency and spectral phase of the CVBG are plotted in Fig. 1 with black lines. The central Bragg wavelength is 1053 nm and the bandwidth is 6 nm. For the incident beams with wavelengths outside the bandwidth, the diffraction efficiency decreases sharply. The spectral phase outside the CVBG bandwidth is constant or linear with respect to the angular frequency, and the dispersion area of the CVBG is limited within the bandwidth. Inside the dispersion area, the spectral phase can be well fitted with a quadratic polynomial which may be used in dispersion compensation applications.

With the incident angle increasing from zero, as indicated in Fig. 1, the bandwidth and dispersion area move toward a shorter wavelength since the Bragg-matching condition is met at a shorter wavelength. According to the Bragg-matching condition,¹⁵ the central Bragg wavelength of the CVBG varies along with the incident angle

$$\lambda_0 = 2\Lambda_0 \sqrt{n^2 - \sin^2 \theta}, \quad (1)$$

where Λ_0 is the central grating period of the CVBG, n (about 1.49) is the refractive index of the PTR glass, and θ is the incident angle in air. With the SCR of the CVBG, the bandwidth can be obtained

$$B = 2\Delta\Lambda \cdot \sqrt{n^2 - \sin^2 \theta} = 2SCR \cdot d \cdot \sqrt{n^2 - \sin^2 \theta}, \quad (2)$$

where $\Delta\Lambda$ is the value of the grating period variation along the CVBG thickness direction and d is the grating thickness of the CVBG.

3 Configuration of Chirped Volume Bragg Gratings in Parallel Combination

For a single CVBG with thickness d , the maximum time delay (MTD) over the bandwidth of the CVBG can be obtained with an approximate expression

$$\text{MTD} \approx \frac{2n^2 d}{c\sqrt{n^2 - \sin^2 \theta}}, \quad (3)$$

where c is the light speed in vacuum. The thickness of single CVBG is limited by grating fabrication. CVBG with the thickness of less than 40 mm is now available, which provides an MTD of about 400 ps. In larger dispersion applications, such as nanosecond CPA systems, an MTD of several nanoseconds may be required to stretch the pulse, increase the light extraction efficiency and obtain a high output energy. To increase the dispersion, CVBGs can be combined to avoid a further increase in the grating thickness. CVBGs in series combination, as shown in Fig. 2(a), can improve the dispersion and obtain the required MTD. However, the distance between the combined CVBGs may result in slipping in the temporal waveform of compressed pulses.

Differing from the CVBGs in a series combination, CVBGs in parallel combination can improve the dispersion in a low-cost and compact way, as shown in Fig. 2(b). The CVBGs in parallel combination have the same structural parameters, such as the grating thickness, the grating period, and the amplitude of the refractive index modulation. Working at oblique incidence, no other optics is required to avoid overlapping between the incident beam and the diffracted beam from the same grating. However, the configuration will result in spatial chirp, and the aperture of the diffracted beam from the CVBGs will expand horizontally. As shown in Fig. 2(b), for a well-collimated beam with no spatial chirp incident onto CVBG-I, the diffracted beam expands due to the oblique incidence. After being stretched or compressed by CVBG-II, the horizontal diameter of the beam doubles. As the number of CVBGs in parallel combination increases, the horizontal aperture of the output beam expands monotonically. CVBGs with a larger aperture will be required to diffract beams efficiently. What is more, this spatial chirp must be compensated to make the beam operation easy and efficient.

In order to get rid of the spatial chirp resulting from the oblique incidence, a configuration with four CVBGs in parallel combination was proposed here, as shown in Fig. 2(c). The last two CVBGs (CVBG-III and CVBG-IV) will totally compensate the spatial chirp that results from the first two CVBGs (CVBG-I and CVBG-II). The configuration with four CVBGs in parallel combination will not change the beam propagation direction when the CVBGs are aligned well enough, and it can be used as a plug and play device. The maximum horizontal beam aperture occurs in the space between CVBG-II and CVBG-III. The aperture of CVBG-II

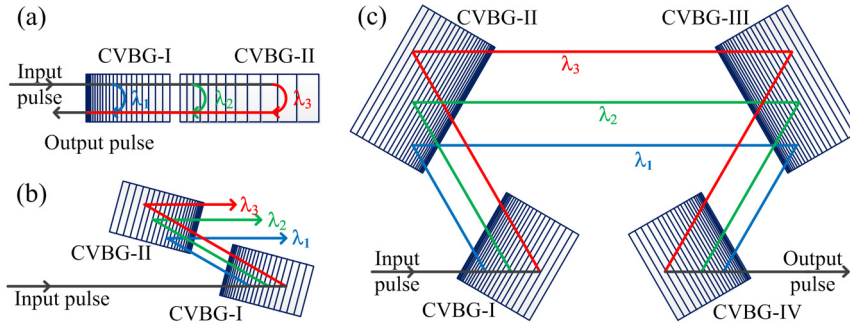


Fig. 2 Different combinations of CVBGs: (a) series combination, (b) parallel combination, and (c) four CVBGs in parallel combination.

and CVBG-III shall be larger than CVBG-I and CVBG-IV to efficiently diffract the expanded beam.

The configuration with four CVBGs in parallel combination has two kinds of MTD: (a) the MTD from the four CVBGs and (b) the MTD induced by the structure. The MTD from the CVBGs originates from different diffraction depths in CVBGs, while the latter is due to different optical paths in air. As indicated in Fig. 2(c), the sign of the structure-induced MTD is always opposite to that of the MTD from the four CVBGs. Along with the increase in the incident angle, the structure-induced MTD increases and the dispersion of the configuration with four CVBGs in parallel combination decreases. As shown in Fig. 3, the ratio between the structure-induced MTD and the MTD from the four CVBGs increases as the incident angle increases, and the ratio reaches the maximum value of 23% when the incident angle is 45 deg. In order to avoid a decrease in the dispersion, the incident angle shall be chosen to be below 6 deg, and the ratio is less than 1%.

4 Dispersion of Four Chirped Volume Bragg Gratings in Parallel Combination

As indicated in the Bragg-matching condition, beams with different wavelengths will be diffracted at different depths in the CVBG, which is related to the dispersion of a CVBG.

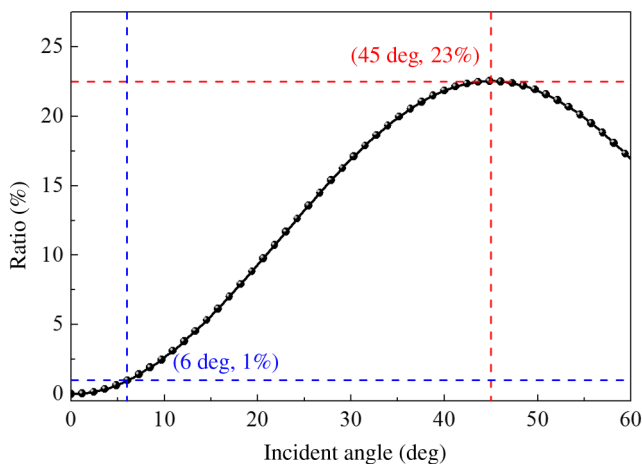


Fig. 3 Ratio between the structure-induced MTD and the MTD from four CVBGs.

The dispersion of the configuration with four CVBGs in parallel combination, however, consists of the dispersion in gratings and the dispersion out of the gratings, as shown in Fig. 2(c). With the transfer matrix method, the dispersion resulting from the four CVBGs can be obtained. The dispersion out of the gratings can be easily calculated with the ray tracing method. In order to characterize the dispersion of the configuration, GDD and CD were employed here. GDD and CD are the coefficients of the quadratic and cubic terms in a Taylor expansion of the spectral phase, ϕ , which is expanded about the pulse center angular frequency, ω_0 , corresponding to λ_0

$$\text{GDD} = \left. \frac{d^2\phi}{d\omega^2} \right|_{\omega_0}, \tag{4}$$

$$\text{CD} = \left. \frac{d^3\phi}{d\omega^3} \right|_{\omega_0}. \tag{5}$$

To obtain the GDD and CD of the configuration, the spectral phase was first calculated by a wave propagating between input and output ends of the configuration based on the transfer matrix method and the ray tracing method. In addition to the incident angle, the effects of SCR, grating thickness, and refractive index modulation on GDD and CD were studied to understand the dispersion of the configuration.

Figure 4 shows the variation of GDD and CD with the grating thickness and the amplitude of the refractive index modulation. The SCR is 0.67 nm/cm. At small amplitudes of the refractive index modulation, such as 100 ppm, the GDD and CD of the configuration are almost constant as the grating thickness increases, as shown in Fig. 4. As the amplitude of the refractive index modulation increases, the GDD and CD show closer relationships with the grating thickness. When the grating thickness is large enough, however, the GDD and CD converge to constants, 120 ps² and 0 ps³, respectively. Compared with the GDD, the CD shows a closer relationship with the amplitude of the refractive index modulation. Decreasing the refractive index modulation will apparently decrease the CD, which is consistent with the results obtained in the previous studies.¹⁶ As indicated in Ref. 9, the product of the grating thickness and the amplitude of refractive index modulation should be large enough to obtain a high diffraction efficiency for the CVBGs. Thus, increasing the grating thickness will be even better than

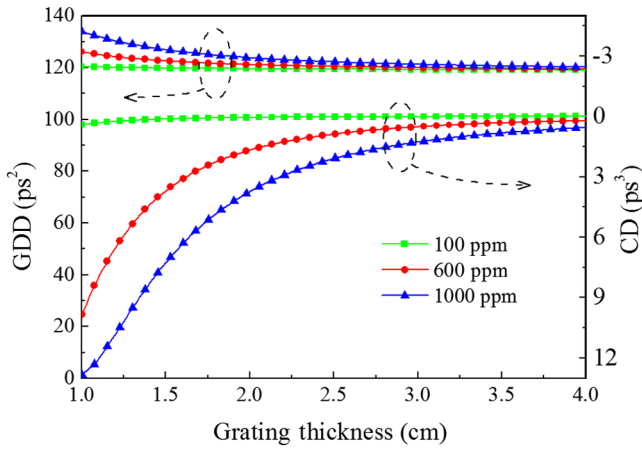


Fig. 4 Dispersion of the configuration versus the grating thickness at different amplitudes of refractive index modulation (ppm: 10^{-6}).

enlarging the amplitude of the refractive index modulation if one is considering the CD suppression.

With the SCR increasing, the GDD and CD of the configuration show a monotonous decrease, as shown in Fig. 5. The grating thickness of a CVBG is 3 cm. Comparing Figs. 5(a) and 5(b) show that GDD is almost unaffected by the incident angle or the refractive index modulation. Thus,

the SCR of the four CVBGs can be obtained directly with the required GDD in a certain application. As indicated in Fig. 5(a), the CD also shows no relationship with the incident angle. The incident angle affects nothing in the optimization of the GDD and CD. The CD decreases sharply as the SCR increases to 1 nm/cm, and then it converges to a limit of 0 ps^3 . When the SCR is larger than 1 nm/cm, the CDs of the configuration at different refractive index modulations are of the same value. It seems that due to the small amplitude of the refractive index modulation (≤ 1000 ppm), increasing the refractive index modulation will not strengthen the Fabry–Perot (FP) resonance effect in a CVBG or result in a noticeable CD. When the SCR is less than 1 nm/cm, the noticeable CD at a large refractive index modulation may be caused by linear-chirp distortion. The bandwidth of CVBGs may deviate from Eq. (2) in this case. It is clear that much additional work is required before a complete understanding of the CD can be obtained.

With the results obtained from Figs. 4 and 5, a general understanding of the dispersion of the configuration can be reached, which will be beneficial for the configuration optimization in large dispersion applications. The GDD shows a close relationship to the SCR, and does not change along with the grating thickness, the refractive index modulation, or the incident angle. Thus, the SCR of CVBGs can be

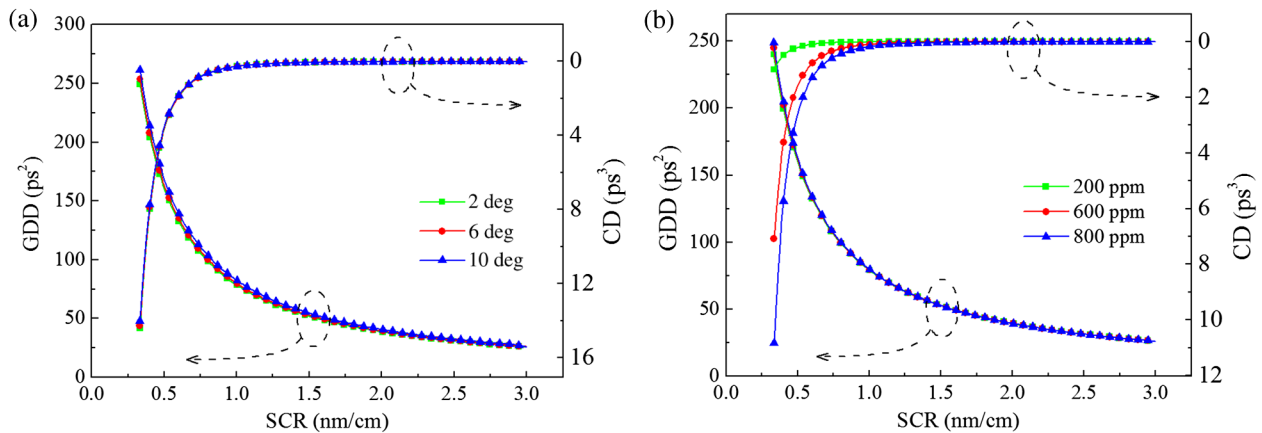


Fig. 5 Dispersion of the configuration versus SCR at different (a) incident angles and (b) amplitudes of refractive index modulation.

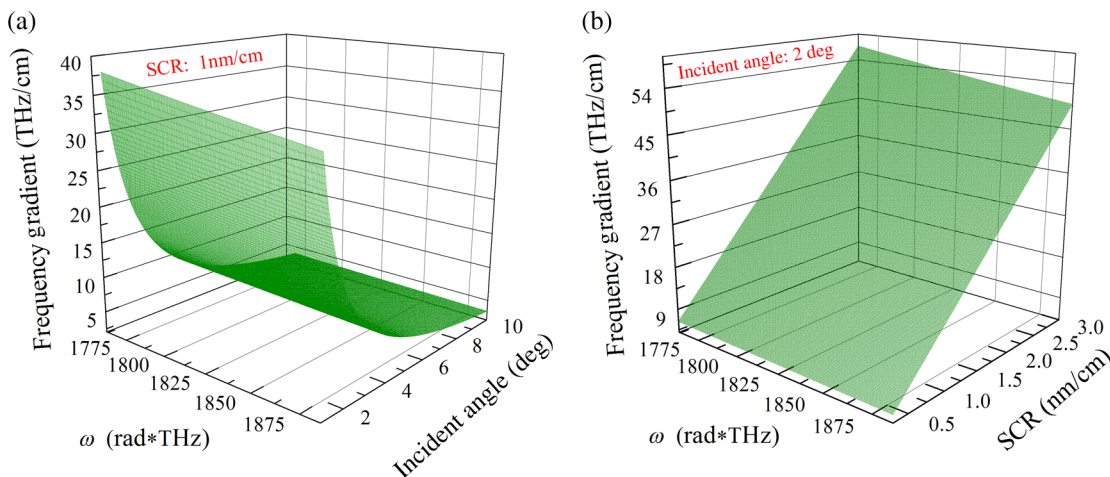


Fig. 6 Frequency gradient versus (a) the incident angle and (b) SCR.

determined first in a certain application. To reduce the CD, a large grating thickness will be helpful. Increasing the grating thickness will also be beneficial for a high diffraction efficiency. In addition, the pulse spatial chirp resulting from the oblique incidence can be compensated completely when the four CVBGs are well aligned. Since the maximum spatial chirp occurs in the space between CVBG-II and CVBG-III, the aperture of the two CVBGs should be large enough to avoid beam clipping in space. In order to characterize the maximum spatial chirp inside the configuration, a frequency gradient¹⁷ is used

$$FG \equiv \frac{\Delta f}{\Delta x} \approx \frac{c}{\lambda_0^2} \cdot \frac{SCR \cdot (n^2 - \sin^2 \theta)}{\sin \theta \cdot \cos \theta}, \quad (6)$$

where Δf is the bandwidth of the pulse beam and Δx is the horizontal aperture increment of the pulse beam after CVBG-II and before CVBG-III. The approximation expression in the right-hand side of Eq. (6) was obtained when assuming that the chirp of CVBGs is linear and the higher-order (≥ 3) dispersion is ignored. When the spatial chirp grows, the FG decreases and a large CVBG aperture is required. As shown in Fig. 6(a), the FG decreases sharply as the incident angle initially increases, and when the incident angle is more than 5 deg, the rate of change decreases. Figure 6(b) shows that the frequency gradient increases linearly as the SCR increases. Since the incident angle is free to design in the optimization of the GDD and CD, decreasing the incident angle is more practical in order to obtain a large FG.

5 Conclusions

Prior work has documented the effectiveness of CVBGs as dispersive elements in CPA systems to stretch femtosecond pulses to picosecond or compress picosecond pulses to femtosecond. However, the thickness of the CVBGs used in these studies has been limited due to the fabrication system, and stretching pulses to nanosecond duration or compressing nanosecond pulses to picosecond with a single CVBG may not be practical. In this study, a configuration with four identical CVBGs in parallel combination was proposed to solve this problem. The CVBGs work at oblique incidence and no other optics is required to avoid overlapping between the incident beam and output beam. With the transfer matrix method and the ray tracing method, the GDD and CD of this configuration were studied to benefit the dispersion design with an optimization of CVBG structural parameters, including grating thickness, SCR, central grating period, and refractive of index modulation. These investigations broaden the applications of CVBGs, and nanosecond CPA systems are available with the configuration as a dispersive element. In addition, the configuration proposed here will not result in spatial chirp, and the propagation direction of the output beam will be in the incident direction when the four CVBGs are well aligned.

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