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Smoothing effect in the broadband laser through a dispersive wedge

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Abstract

The propagation expression of a broadband laser passing through a dispersive wedge is derived on the basis of the Huygens–Fresnel diffraction integral. Smoothing effects caused by the phase perturbation of the dispersive wedge on the intensity profiles are investigated in detail. The phase perturbation of the dispersive wedge induces a relative transverse position shift between the diffraction patterns of different frequency components. The relative transverse position shift is of great benefit to the fill of the intensity peaks of some patterns in the valleys of others when these patterns are overlapped and thus the smoothing effect is achieved.

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Keywords: Smoothing effect; Dispersive wedge; Broadband laser; Phase perturbation

1. Introduction

Due to the requirements for the laser beam uniformity in many practical applications, to eliminate large intensity modulation, which results in some disadvantages, such as self-focusing in high power laser systems [1,2], to improve the beam uniformity has been an interesting subject for a long time [3–10]. In the research of improving the beam uniformity, methods, such as using soft aperture [3], multiple spatial filters [4], random phase wave [5], lens array [6] and smoothing by spectral dispersive (SSD) technique [7] have been studied in detail. These methods are effective to improve the beam uniformity and thus have been applied in some practical applications. For example, the SSD technique is well used in the OMEGA system [10]. As pointed in Refs. [11,12], beam smoothing is also achieved by using a broadband laser, in which each frequency component generates a different diffraction pattern and the overlapping of all of the patterns results in the beam smoothing. However, the results in Refs. [11,12] indicated that the smoothing effect is not good enough because the bandwidth of laser beam is not broad sufficiently in high power systems. If a dispersive wedge is used to obtain a different transverse position shift for each diffraction pattern, the beam may be better smoothed.

In this paper, the smoothing effect of a broadband laser passing through a dispersive wedge is studied. Firstly, the field of the broadband laser passing through a dispersive wedge is derived. Then, smoothing effect brought by the phase perturbation of the dispersive wedge on the intensity distributions are investigated and the results demonstrate that better smoothing effect is achieved in comparison with that in Refs. [11,12]. In conclusion, the main results obtained in this paper and further extension are mentioned finally.

2. Theoretical analyses

Consider a laser beam passes through a rectangular hard-edged aperture with half radius a followed by a dispersive

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wedge and a sketch map of the experimental setup is shown in Fig. 1. The wedge generates a phase perturbation to the laser beam [13]. From the Huygens–Fresnel diffraction integral, the field of each frequency component can be written as [14]

$$E(x,z,\omega) = \frac{\exp(\mathrm{i}kL)}{(\mathrm{i}\lambda L)^{1/2}} \int_{-a}^{a} E_0(x,0,\omega) \times \exp\left[\frac{\mathrm{i}k}{2L}(x_0-x)^2 + \mathrm{i}\varphi(\lambda,\theta)\right] \mathrm{d}x_0, \tag{1}$$

where $E_0(x_0,0,\omega)$ is the incident field and $k = 2\pi/\lambda$ is the wave number. $\varphi(\lambda,\theta)$ is a phase perturbation generated by the dispersive wedge and is given by

$$\varphi(\lambda,\theta) = k[n(\lambda)-1]\left(\frac{d_1+d_2}{2} - x_0\theta\right). \tag{2}$$

Assume that the dispersive wedge is made of the fused silica, whose refractive index is given by [15]

$$n^2(\lambda) = 1 + \sum_{i=1}^{3} \frac{B_i}{1-\lambda_i^2/\lambda^2}, \tag{3}$$

where $B_1 = 0.6961663$, $B_2 = 0.4079426$, $B_3 = 0.8974794$, $\lambda_1 = 0.0684043$ μm, $\lambda_2 = 0.1162414$ μm and $\lambda_3 = 9.896161$ μm. In addition, d_1 and d_2 are widths of upside and underside of the dispersive wedge, respectively, θ is the wedge angle of the dispersive wedge and the propagation distance is expressed as

$$L = \frac{z}{\sqrt{1-\sin^2 D}}, \tag{4}$$

where

$$D = -\theta[n(\lambda)-1] \tag{5}$$

is the deflection angle when laser beam passes through the dispersive wedge and the negative sign means the direction of the deflection angle is clockwise. When $\theta = 0$, D also equals zero and $L = z$, thus Eq. (1) is reduced to the general Huygens–Fresnel diffraction integral.

Assuming the spatial and spectral field of the initial pulse can be separated, i.e.

$$E_0(x_0,0,\omega) = E_0(x_0,0)S(\omega). \tag{6}$$

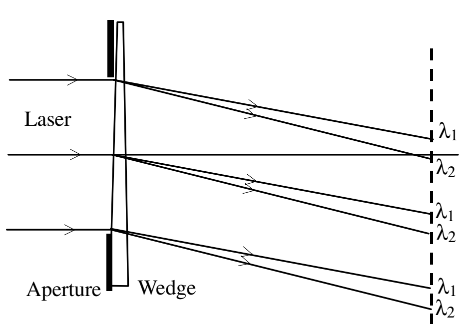

Fig. 1. The sketch map of a laser beam passing through a hard-edged aperture and a dispersive wedge.

Consider the incident spatial field $E_0(x_0, 0)$ is a rectangular shape as

$$E_0(x_0,0) = \begin{cases} 1 & |x_0| \leqslant a, \\ 0 & |x_0| > a. \end{cases} \tag{7}$$

The integral calculation of Eq. (1) yields

$$E(x,z,\omega) = -\frac{\exp(\mathrm{i}kz)}{2} \exp\left(\frac{\mathrm{i}k}{2}[n(\lambda)-1] \times \left\{d_1+d_2-2x\theta - z[n(\lambda)-1]\theta^2\right\}\right) \times [\mathrm{erf}(\chi_+) + \mathrm{erf}(\chi_-)]S(\omega), \tag{8}$$

where

$$\chi_\pm = \mathrm{i}\left(\frac{\mathrm{i}k}{2z}\right)^{1/2} (a \pm \{x + z[n(\lambda)-1]\theta\}), \tag{9}$$

and

$$\mathrm{erf}(y) = \frac{2}{\pi^{1/2}} \int_0^y \exp(-x^2)\mathrm{d}x, \tag{10}$$

is error function. Also, to make easier our evaluations, we suppose that the incident spectral profile is a rectangular shape as

$$S(\omega) = \begin{cases} 1 & |\lambda| \leqslant \lambda_0 - \Delta\lambda/2, \\ 0 & |\lambda| > \lambda_0 + \Delta\lambda/2, \end{cases} \tag{11}$$

where λ_0 is central wavelength and $\Delta\lambda$ is bandwidth of the laser. A qualitatively similar results would be obtained with more sophisticated models. Thus, the field of the broadband laser is given by

$$E(x,z) = \frac{1}{\Delta\lambda} \int_{\lambda_0-\Delta\lambda/2}^{\lambda_0+\Delta\lambda/2} E(x,z,\omega)\mathrm{d}\lambda, \tag{12}$$

Then, the intensity is obtained as

$$I(x,z) = |E(x,z)|^2. \tag{13}$$

3. Numerical results

The calculation parameters are $a = 10$ mm and $\lambda_0 = 800$ nm in the following calculations. Fig. 2 shows the transverse intensity profiles of laser beams with bandwidths 0, 20, 100 nm when $\theta = 0.1$ and the Fresnel number $F = a^2/\lambda z = 12.5$, where the central wavelength is adopted in calculating F. We can see from the figure that lots of peaks are generated and intensity is highly non-uniform when the incident beam is monochromatic wave and the amplitude of the peaks decreases somewhat when the bandwidth is 20 nm. Further, as the bandwidth increases to 100 nm, the amplitude of the peaks decreases distinctly and the beam uniformity is improved. Thus, it is concluded that the broader the bandwidth, the better the beam uniformity.

Transverse intensity profiles of laser beam with bandwidth 20 nm when $\theta = 0.2$ and 0.5 and $F = 12.5$ are

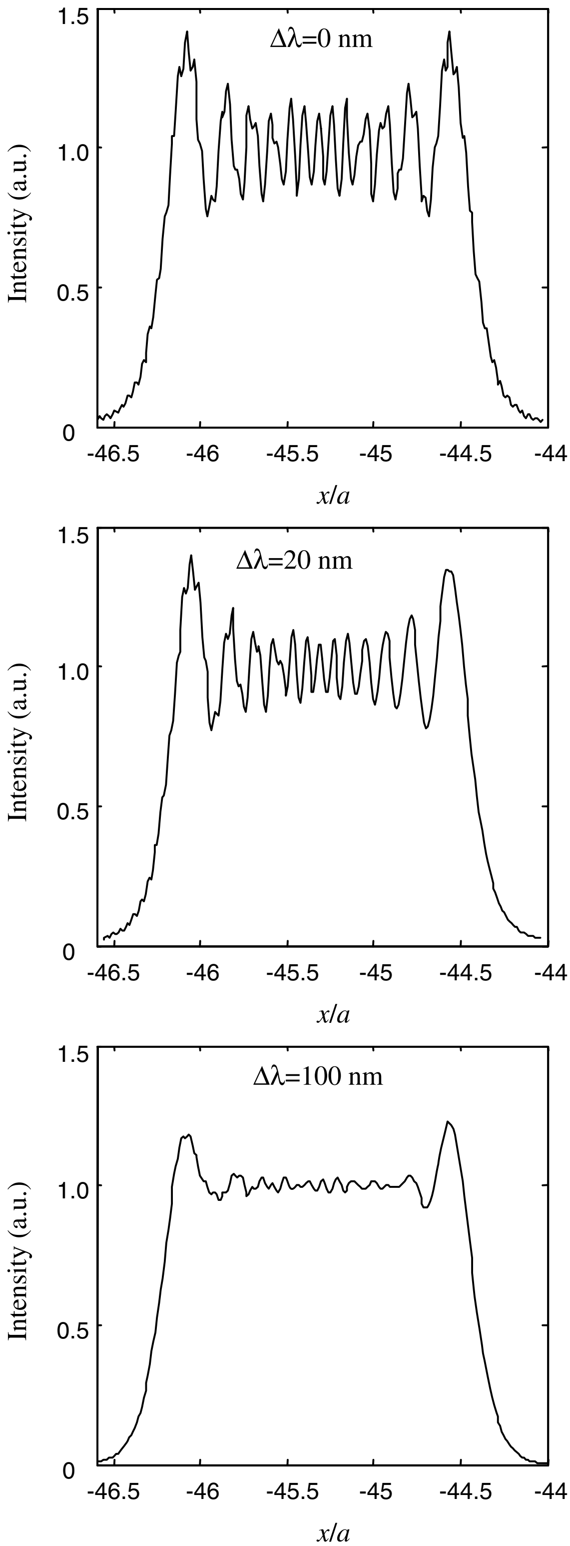

Fig. 2. Transverse intensity profiles of laser beams with bandwidths 0, 20, 100 nm when $\theta = 0.1$ and $F = 12.5$.

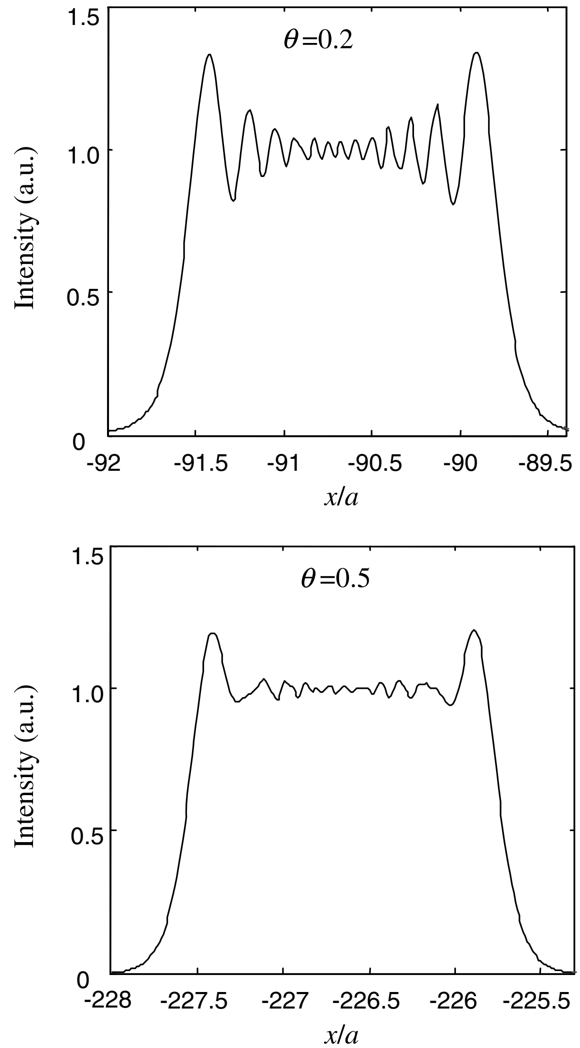

Fig. 3. Transverse intensity profiles of laser beam with bandwidth 20 nm when $\theta = 0.2$ and 0.5 and $F = 12.5$.

depicted in Fig. 3, from which it is known that when $\theta = 0.2$ the amplitude of the peaks in the central region is smaller than that of $\theta = 0.1$ obviously, and when $\theta = 0.5$ the profile has a satisfying shape and the beam uniformity is well improved except two peaks at the edge of the profile.

By comparison of the profiles of the laser beam with bandwidth 20 nm when $\theta = 0.1$, 0.2 and 0.5, it is found that the beam uniformity is better improved with a larger wedge angle of the dispersive wedge.

Fig. 4 gives the side lobes of the diffraction patterns of laser beams with bandwidths 0, 4, 10, 20 nm when $\theta = 0.1$ and $F = 0.25$. It is well known that the diffraction pattern of the monochromatic wave in the far field appears as a series of concentric bright and dark rings around a central disk called the Airy disk. It can be seen from Fig. 4 that the amplitude of the bright rings decrease as the bandwidth increases. The bright rings are eliminated when the bandwidth is 20 nm, and thus only the Airy disk is presented in the intensity profile and the side lobes of the diffraction patterns are smoothed.

4. Discussion

In principle, the smoothing effect is caused by that a different transverse position shift of the diffraction pattern of each frequency component is generated due to the phase

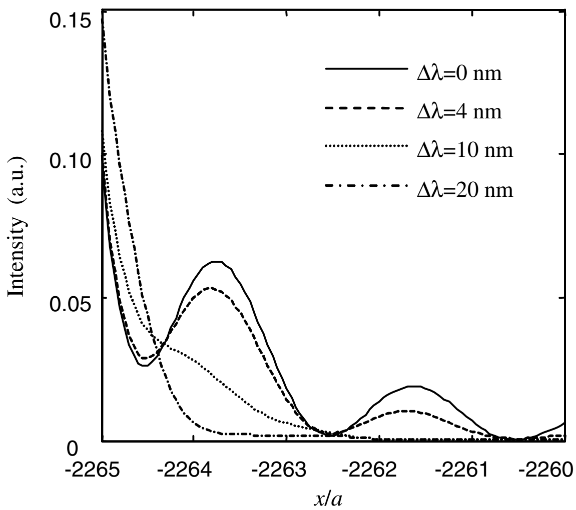

Fig. 4. Side lobes of the diffraction patterns of laser beams with bandwidths 0, 4, 10, 20 nm when $\theta = 0.1$ and $F = 0.25$.

perturbation of the dispersive wedge and the intensity peaks of some patterns fill in the intensity valleys of others when the patterns are overlapped. Because of different refractive index of each frequency component in the dispersive wedge, diffraction pattern of each frequency component generates a different transverse position shift, which is given by

$$\Delta x = -L\theta[n(\lambda) - 1]. \tag{14}$$

Therefore, a relative transverse position shift is originated between diffraction patterns of different frequency components, which is deduced as

$$\Delta x_{\lambda_2-\lambda_1} = -L\theta[n(\lambda_2) - n(\lambda_1)]. \tag{15}$$

The relative transverse position shift between these patterns is of advantage to the fill of the intensity peaks of some patterns in the valleys of others in the overlapping of the patterns. From Eq. (15) it is known that the larger the wedge angle of the dispersive wedge and the broader the bandwidth, the larger the relative transverse position shift of the pattern is generated and thus the better smoothing effect is achieved. Also, it is seen that the relative transverse position shift $|\Delta x_{\lambda_2-\lambda_1}|$ increases as the propagation distance increases, thus the phenomenon in Fig. 4 that well effect on the side lobes of the patterns can be achieved in the far field even with small bandwidth and small wedge angle of the dispersive wedge can be explained.

We supposed that the incident spatial field is rectangular shape in above numerical calculations and analyses. When the incident spatial field is spherical wave, which is in the form of

$$E_0(x_0, 0) = \exp\left(\frac{\mathrm{i}k}{2R}x_0^2\right), \tag{16}$$

where R is the radius of the wave curvature of the spherical wave and the complex constant A_0 is omitted, the integral calculation of Eq. (1) yields

$$\begin{aligned}E(x,z,\omega) = &-\frac{1}{2}\left(\frac{R}{z+R}\right)^{1/2}\exp\left[\frac{\mathrm{i}k}{2z}(x^2+(d_1+d_2)z[n(\lambda)-1]\right.\\ &\left.-\frac{R}{z+R}\{x+z[n(\lambda)-1]\theta\}^2)\right]\\ &\times\exp(\mathrm{i}kz)[\mathrm{erf}(\chi_+)+\mathrm{erf}(\chi_-)]S(\omega),\end{aligned} \tag{17}$$

where

$$\chi_{\pm} = \mathrm{i}\left[\frac{\mathrm{i}k(z+R)}{2zR}\right]^{1/2}\left(a \pm \frac{R}{z+R}\{x+z[n(\lambda)-1]\theta\}\right). \tag{18}$$

Similarly, the field can also be derived when the incident spatial field is Gaussian shape. Similar results would be obtained when the smoothing effects of the dispersive wedge on intensity profiles are analyzed in those cases.

SSD technique in Ref. [7] smoothes the laser beam in time by overlapping many copies of diffraction patterns, each shifts in space, so that the intensity peaks of some patterns fill in the intensity valleys of others when averaged in time. The smoothing effect in Refs. [11,12] results from that all frequency components generate different diffraction patterns, which differ from each other in spatial distribution, and the peaks of some patterns fill in the valleys of others when these patterns are overlapped. In this paper, using the phase perturbation of the dispersive wedge, besides differ from each other in spatial distribution, the diffraction pattern of each frequency component obtains a different transverse position shift additionally, which is more beneficial to the fill of the peaks in the valleys in the overlapping of the patterns than in Refs. [11,12], thus better smoothing effect is achieved.

In addition, the dispersive wedge has been used in two-dimensional (2D) SSD technique on the OMEGA system [10], but its effect differs somewhat from that in our paper. The main effect of the wedge in 2D SSD technique is to separate the laser beam into two orthogonal polarizations ("o" and "e") and two speckle patterns produced on target are spatially displaced, thus doubling the number of independent speckle patterns. The effect of the wedge in our paper is to separate all frequency components and a significant relative position shift between diffraction patterns of them are generated because of broad bandwidth and large angle of the wedge.

5. Conclusions

The smoothing effects brought by the phase perturbation of the dispersive wedge on the intensity profiles are investigated in this paper. A different transverse position shift of diffraction pattern of each frequency component is generated due to the phase perturbation of the dispersive wedge and thus well smoothing effect is achieved. In the far field, the smoothing effects are mainly realized on the side lobes of the patterns and well smoothing effect is achieved even with small wedge angle and small bandwidth. In the near field, however, large wedge angle or broad bandwidth is necessary if well smoothing effect is desired. Even then, the intensity profile in the near field is not good enough because two visible peaks still exist at the edge of the profile. As pointed by the previous works, the high frequency components in the diffraction pattern can be eliminated by using the spatial filters, so that the pattern can be well smoothed [4]. Thus, to obtain better smoothing effect, further study of the combination of these methods seems to be necessary.

Acknowledgements

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