Available online at www.sciencedirect.com
SCIENCE @ DIRECT®
ELSEVIER
Optik 117 (2006) 388–392
Optik Optics
www.elsevier.de/ijleo

Influence of the chirp on the intensity distributions of an apertured pulse

Runwu Peng[a,b,*], Yunxia Ye[b,c], Zhixiang Tang[b], Shuangchun Wen[a], Dianyuan Fan[b]

[a]School of Computer and Communication, Hunan University, Changsha 410082, China
[b]Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, P.O. Box 800-211, Shanghai 201800, China
[c]Mechanical Engineering College, Jiangsu University, Zhenjiang 212013, China

Received 4 July 2005; accepted 3 November 2005

Abstract

Starting from the Huygens–Fresnel diffraction integral and the Fourier transform, the propagation expression of a chirped pulse passing through a hard-edged aperture is derived. Using the obtained expression, the intensity distributions of the pulse with different chirp in the near and far fields are analyzed in detail. Due to the modulation of the aperture, many intensity peaks emerge in the intensity distributions of the chirped pulse in the near field. However, the amplitudes of the intensity peaks decrease on increasing the chirp, which results in the smoothing effect in the intensity distributions. The beam smoothing brought by increasing the chirp is explained physically. Also, it is found that the radius of the intensity distribution of the chirped pulse decreases when the chirp increases in the far field.

Keywords: Chirped pulse; Broadband; Beam smoothing

1. Introduction

All real optical systems have finite aperture, with some sort of boundaries or edges. Due to the modulation of the aperture, nonuniform intensity is generated when a laser pulse passes through a hard-edged aperture. The nonuniform intensity is a disadvantage for the applications of laser. For example, nonuniform intensity imprints itself on the target causing surface damage, which can "seed" the Rayleigh–Taylor fluid instability, and enhances the ignition energy in inertial confinement fusion [1,2], and self-focusing is generated because of the phenomenon [3], which may damage the laser media and limit the laser outpower. Thus, ways to improve the beam uniformity by smoothing the intensity distributions of laser pulse has became an interesting topic and has been the subject of many investigations in the last decades [4–16]. To achieve beam smoothing, some techniques have been studied, such as using soft-edged aperture [4], adopting multiple spatial filters [5], converting a coherent wave to a random-phased wave [6], and using a lens array [7]. In addition, the technique of smoothing by spectral dispersion (SSD) of the laser pulse was developed by Skupsky et al. [8]. Following the study, much work was undertaken to develop this technique [9–15] and it evolved into three-dimensional SSD [14]. The applications of the methods investigated in the previous works are effective in improving the beam uniformity and they have been applied extensively, especially the SSD [10].

The beam uniformity can also be improved by increasing the bandwidth of the laser pulse [16]. When

*Corresponding author. Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, P.O. Box 800-211, Shanghai 201800, China. Tel.: +86 21 69918809.

E-mail addresses: pengrunwu@siom.ac.cn, pengrunwu@163.com (R. Peng).

0030-4026/$ - see front matter
doi:10.1016/j.ijleo.2005.11.003

the broadband laser pulse is adopted in the highpower laser system, the uniform illumination of the targets is improved in the highpower laser driver and some benefits are generated for laser system itself. For example, the diffraction and the interference effects are eliminated, optical noise is weakened, and self-focusing decreases, which results in the increase of the laser outpower. However, the laser pulse investigated in Ref. [16] is transform-limited pulse and the increase of the bandwidth is achieved by decreasing the pulse duration. Generally, the broadband laser pulse is generated by broadening the femtosecond or piecosecond pulse to nanosecond pulse in the highpower laser system, and thus the pulse takes big chirp, in which the chirp parameter reaches 10^3–10^4 and even bigger. To know and utilize such big-chirped pulse better, it is necessary to study the properties of the pulse.

In this paper, influence of the chirp on the time-integrated intensity distributions of the pulse passing through a hard-edged aperture is studied. Firstly, we derived the propagation expression of a chirped pulse passing through a hard-edged aperture. Then the time-integrated intensity distributions in the near and far fields are analyzed by numerical calculations. The results show that the time-integrated intensity distributions can be smoothed to a certain degree in the near field and the radius of the time-integrated intensity decreases in the far field when the chirp increases. Finally, a brief summary of the results and further extension conclude the paper.

2. Intensity distribution of an apertured chirped pulse

Starting from the Helmholtz equation and using the Green's theorem and the Kirchhoff's boundary conditions, we can obtain the scalar Fresnel–Kirchhoff diffraction integral. When the distance between the examined plane and the aperture is greater than the half-width of the aperture and the length of examined section, the Fresnel–Kirchhoff diffraction integral is deduced to Huygens–Fresnel diffraction integral [17,18]. Thus, when a chirped pulse passes through a hard-edged aperture, we obtain the field in the frequency domain in terms of the Huygens–Fresnel diffraction integral as

$$\tilde{E}(x,z,\omega) = \left(\frac{\mathrm{i}}{\lambda z}\right)^{1/2} \exp(-\mathrm{i}kz) \int_{-a}^{a} \tilde{E}_0(x_0,0,\omega) \times \exp\left[-\frac{\mathrm{i}k}{2z}(x_0-x)^2\right] \mathrm{d}x_0, \quad (1)$$

where $k=\omega/c$ is wave number, a is half-width of the hard-edged aperture, and

$$\tilde{E}_0(x_0,0,\omega) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{\infty} E_0(x_0,0,t)\exp(-\mathrm{i}\omega t)\,\mathrm{d}t \quad (2)$$

is field of the incident pulse in the frequency domain and $E_0(x_0,0,t)$ is field of the incident pulse in the time domain. Assuming that the space and time field of the initial pulse can be separated, $E_0(x_0,0,t)$ can be written as

$$E_0(x_0,0,t) = E_0(x_0,0)f(t), \quad (3)$$

where $f(t)$ is the field distribution at $x=z=0$ in time domain. Thus, we obtained

$$\tilde{E}_0(x_0,0,\omega) = E_0(x_0,0)\tilde{f}(\omega), \quad (4)$$

where

$$\tilde{f}(\omega) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{\infty} f(t)\exp(-\mathrm{i}\omega t)\,\mathrm{d}t. \quad (5)$$

The field of any point behind the hard-edged aperture in time domain is derived from inverse Fourier transform of Eq. (1) as

$$E(x,z,t) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{\infty} \tilde{E}(x,z,\omega)\exp(\mathrm{i}\omega t)\,\mathrm{d}\omega. \quad (6)$$

Consider the pulse with spatial form of spherical wave

$$E_0(x_0,0) = \exp\left(-\frac{\mathrm{i}k}{2R}x_0^2\right), \quad (7)$$

where R is the curvature radius of the spherical wave and the complex constant A_0 is omitted. Assume that temporal form of the pulse is a chirped Gaussian shape whose field at $z=0$ is in the form

$$f(t) = \exp\left(-a_g^2\frac{t^2}{T_P^2}\right)\exp\left[\mathrm{i}(\omega_0 t - Ct^2)\right], \quad (8)$$

where $a_g = (2\ln 2)^{1/2}$, T_P is pulse duration (full-width at half-maximum, FWHM),ω_0 is the carrier frequency, C is the chirp parameter, and the initial phase φ is omitted. By substituting Eq. (8) into (5), spectrum $\tilde{f}(\omega)$ at $z=0$ is expressed as

$$\tilde{f}(\omega) = \left[\frac{\pi T_P^2}{a_g^2(1+\mathrm{i}C)}\right]^{1/2} \exp\left[-\frac{T_P^2(\omega-\omega_0)^2}{4a_g^2(1+\mathrm{i}C)}\right]. \quad (9)$$

The integral calculation of Eq. (1) yields

$$\tilde{E}(x,z,\omega) = \left[\frac{R}{4(z+R)}\right]^{1/2} \exp(-\mathrm{i}kz)\exp\left[-\frac{\mathrm{i}kx^2}{2(z+R)}\right] \times[\mathrm{erf}(\chi_+)+\mathrm{erf}(\chi_-)]\tilde{f}(\omega), \quad (10)$$

where

$$\chi_+ = \left[\frac{\mathrm{i}k(z+R)}{2zR}\right]^{1/2}\left(a+\frac{Rx}{z+R}\right), \quad (11)$$

$$\chi_- = \left[\frac{\mathrm{i}k(z+R)}{2zR}\right]^{1/2}\left(a-\frac{Rx}{z+R}\right) \quad (12)$$

and

$$\operatorname{erf}(y) = \frac{2}{\pi^{1/2}} \int_0^y \exp(-x^2)\,\mathrm{d}x \tag{13}$$

is error function. Thus, the field distribution in time domain is given by

$$E(x,z,t) = \left[\frac{R}{8\pi(z+R)}\right]^{1/2} \int_{-\infty}^{\infty} [\operatorname{erf}(\chi_+) + \operatorname{erf}(\chi_-)] \times \tilde{f}(\omega) \exp(\mathrm{i}\omega\tau')\,\mathrm{d}\omega, \tag{14}$$

where

$$\tau' = \tau - \frac{x^2}{2c(z+R)} \tag{15}$$

and $\tau = t - z/c$ is local time. The intensity distribution of the pulse is derived from Eq. (14) as

$$I(x,z,t) = \frac{R}{8\pi(z+R)} \left| \int_{-\infty}^{\infty} [\operatorname{erf}(\chi_+) + \operatorname{erf}(\chi_-)] \tilde{f}(\omega) \times \exp(\mathrm{i}\omega\tau')\,\mathrm{d}\omega \right|^2. \tag{16}$$

In the highpower laser system, the time-integrated intensity (energy density) of the laser pulse was paid more attention, which is obtained as

$$I_{\text{Time-integrated}}(x,z) = \int_{-T_P}^{T_P} I(x,z,t)\,\mathrm{d}t. \tag{17}$$

3. Influence of the chirp on the time-integrated intensity distributions

When the chirp parameter C is given in the chirped pulse, the width of the spectrum can be obtained relatively from

$$\Delta\omega = \frac{2a_g^2(1+C^2)^{1/2}}{T_P} \tag{18}$$

and thus the bandwidth $\Delta\lambda$ is also obtained relatively. In fact, the influence of the chirp on the intensity is the influence of the spectrum broadened by the frequency chirp. The chirp parameters in the following calculation are $C = 100$, 5000, and 10 000, and thus $\Delta\lambda$ are 0.2 nm, 10 nm, and 20 nm, relatively, where the calculation parameters are $\lambda_0 = 800$ nm and $T_P = 0.47$ ns, and $a = 1$ mm additionally. The time-integrated intensity distributions at $z = 5$ mm are given in Fig. 1. It can be seen that many intensity peaks are generated because of the modulation of the hard-edged aperture and the amplitude of the peaks in the intensity distribution of the pulse with $C = 100$ is the greatest in the pulse with $C = 100$, 5000, and 10 000. The amplitude of the peaks of the pulse with $C = 5000$ and 10 000 decreases in the radius of 0.7 mm obviously and the intensity uniformity of them are improved. Especially, the beam smoothing is achieved in the pulse with $C = 10\,000$ in the radius. However, many peaks with large amplitude still exist at the edge of the intensity distributions and the amplitudes have no significant changes. They can be eliminated when soft aperture is utilized in the optical systems [4].

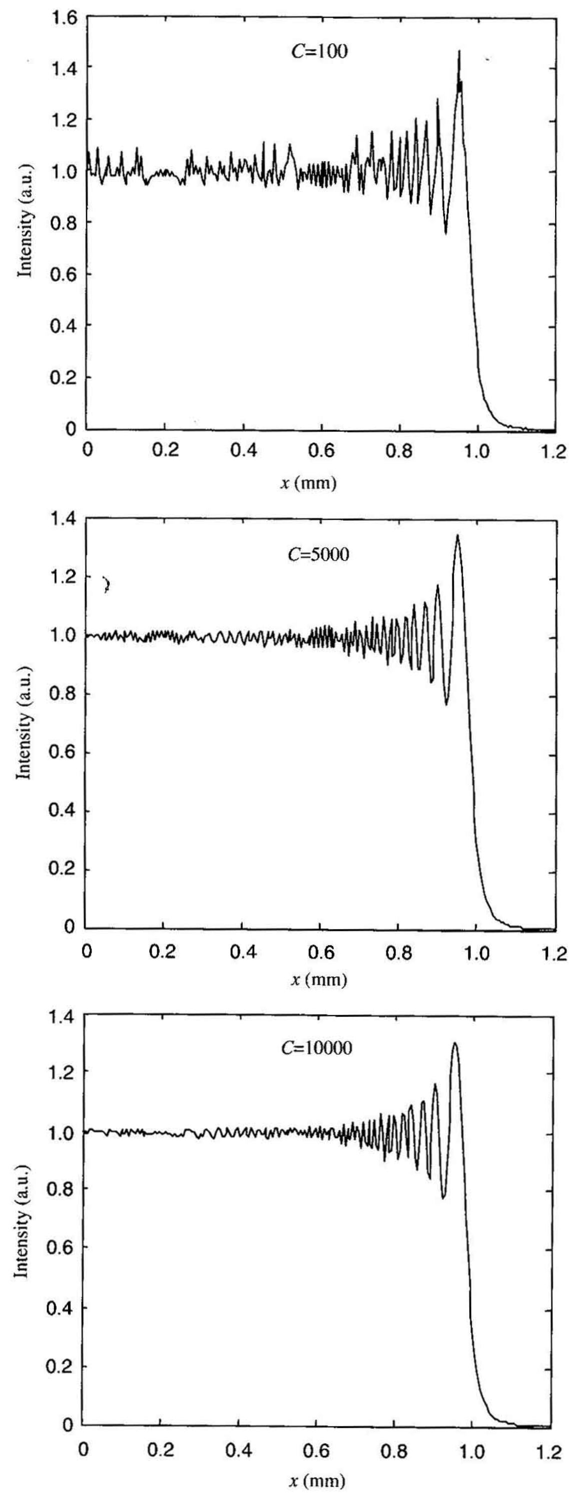

Fig. 1. Time-integrated intensity distributions ($z = 5$ mm).

Physically, the beam smoothing is brought by increasing the chirp results from different extents of diffraction of each frequency component. We know that the diffraction patterns are determined by Fresnel number $F = a^2/\lambda z$, and there exist different Fresnel numbers and thus different diffraction patterns are generated for each frequency component at a determined point. The different diffraction patterns of the frequency components differ from one another in spatial distribution and the intensity peaks of some fill in the intensity valleys of others when the diffraction patterns of all frequency components are overlapped, so that the intensity is smoothed. Fig. 2 gives the intensity distributions of waves with wavelengths 798 and 802 nm and their overlapped intensity distributions at $z = 5$ mm. The intensity peaks and the intensity valleys of the two waves are staggered one another in the region depicted in the figure, so that the peaks fill in the valleys, which results in the smoothing of the overlapped intensity. The bigger the chirp, the larger the bandwidth and the more phenomenon that the peaks fill in the valleys is generated, and thus the better the smoothing effect is achieved.

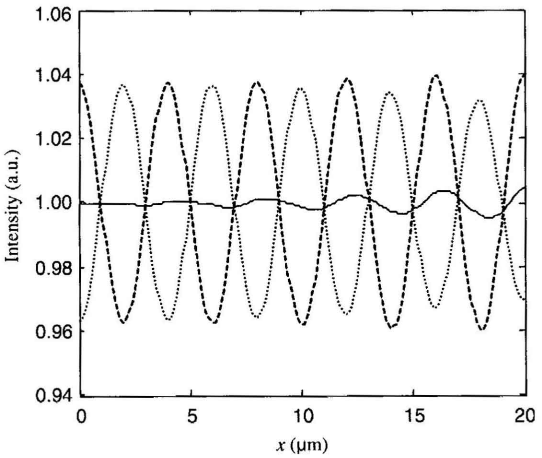

Fig. 2. Intensity distributions of waves with wavelengths 798 and 802 nm and their overlapped intensity distributions ($z = 5$ mm). The solid line is the overlapped intensity distribution, the dashed line is the intensity distribution of wave with wavelength 798 nm, the dotted line is the intensity distribution of wave with wavelength 802 nm.

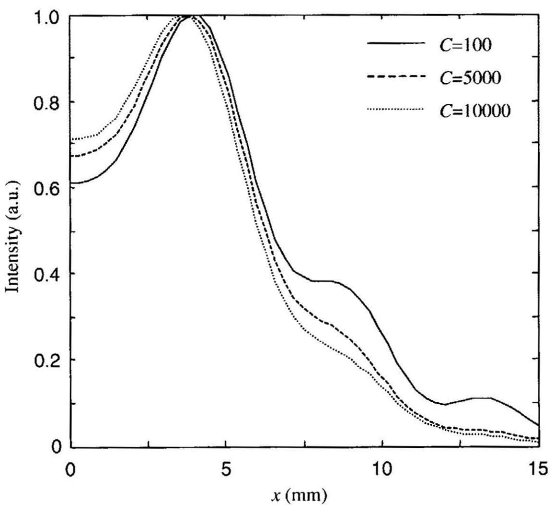

Fig. 3. Time-integrated intensity distributions ($z = 10$ m).

The time-integrated intensity distributions at $z = 10$ m are depicted in Fig. 3, from which it can be seen that there is no intensity peaks generated in the intensity distributions in the far field. The intensity on the z-axis ($x = 0$) increases as the chirp increases. The figure also indicates that the radius of the far-field intensity decreases with increasing the chirp, as well as the transform-limited pulse [16].

4. Conclusions

Influence of the chirp on the time-integrated intensity distributions is analyzed in detail by using the propagation expression of the chirped pulse passing through a hard-edged aperture. Increasing the chirp in the chirped pulse results in increasing the bandwidth of the pulse, which brings a benefit of improving the time-integrated intensity uniformity in the practical applications. The physical reason for beam smoothing is that different diffraction patterns are generated because of the different extents of diffraction of each frequency component and the intensity peaks of some fill in the intensity valleys of others when the diffraction patterns of all frequency components are overlapped.

In the design of highpower laser driver, the bandwidth of the laser pulse already reaches 20 nm at present. The beam smoothing can be achieved to a certain degree in the pulse with bandwidth 20 nm, but the smoothing effect is not good enough in the laser applications. Due to limitation of some factors, it is very difficult to increase the bandwidth in such highpower laser systems further. To obtain more uniform intensity in highpower laser system, it is necessary to combine the other method with the broadband laser pulse. For example, when a dispersive wedge is adopted in the broadband laser pulse, the different diffraction patterns generated by the frequency components will stagger an appropriate distance, which is of more advantage to the fill of the intensity peaks in the intensity valleys, so that better smoothing effect would be achieved. It is a subject worthy of study.

Acknowledgements

This work is partially supported by the National Natural Science Foundation of China (Grant Nos.

10576012 and 60538010), the National High Technology Research and Development Program of China (Grant No. 2004AA84ts12), and the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20040532005).

References

[1] K.A. Bruecker, S. Jorna, Laser-driven fusion, Rev. Mod. Phys. 46 (1974) 325–367.
[2] S. Skupsky, K. Lee, Uniformity of energy deposition for laser driven fusion, J. Appl. Phys. 54 (1983) 3662–3671.
[3] P.L. Kelly, Self-focusing of optical beams, Phys. Rev. Lett. 15 (1965) 1005–1008.
[4] V.R. Cositich, B.C. Johnson, Apertures to shape high-power beams, Laser Focus 10 (1974) 43–46.
[5] J.T. Hunt, P.A. Renard, W.W. Simmons, Improved performance of fusion lasers using the imaging properties of multiple spatial filters, Appl. Opt. 16 (1977) 779–782.
[6] Y. Kato, K. Mima, N. Miyanaga, S. Arinaga, Y. Kitagawa, M. Nakatsuka, C. Yamanaka, Random phasing of high-power lasers for uniform target acceleration and plasma-instability suppression, Phys. Rev. Lett. 53 (1984) 1057–1060.
[7] X.M. Deng, X.C. Liang, Z.Z. Chen, W.Y. Yu, R.Y. Ma, Uniform illumination of large targets using a lens array, Appl. Opt. 25 (1986) 377–381.
[8] S. Skupsky, R.W. Short, T. Kessler, R.S. Craxton, S. Letzring, J.M. Soures, Improved laser-beam uniformity using the angular dispersion of frequency-modulated light, J. Appl. Phys. 66 (1989) 3456–3462.
[9] H. Nakano, K. Tsubakimoto, N. Miyanaga, M. Nakatsuka, T. Kanabe, H. Azechi, T. Jitsuno, S. Nakai, Spectrally dispersed amplified spontaneous emission for improving irradiation uniformity into high power Nd:glass laser system, J. Appl. Phys. 73 (1993) 2122–2130.
[10] Two-dimensional SSD on OMEGA, LLE Rev. 69 (1996) 1–10.
[11] J.E. Rothenberg, Comparison of beam-smoothing methods for direct-drive inertial confinement fusion, J. Opt. Soc. Am. B 14 (1997) 1664–1671.
[12] H.A. Rose, S. Ghosal, Effect of smoothing by spectral dispersion on flow induced laser beam deflection: the random phase modulation scheme, Phys. Plasmas 5 (1998) 775–781.
[13] Q.F. Tan, Q.S. He, Y.B. Yan, G.F. Jin, D.Y. Xu, Spatial-frequency spectrum analysis of the performance of diffractive optical element for beam smoothing, Optik 113 (2002) 163–166.
[14] G. Miyaji, N. Miyanaga, S. Urushihara, K. Suzuki, S. Matsuoka, M. Nakatsuka, A. Morimoto, T. Kobayashi, Three-directional spectral dispersion for smoothing of a laser irradiance profile, Opt. Lett. 27 (2002) 725–727.
[15] Q.F. Tan, Y.B. Yan, G.F. Jin, Application of spatial-frequency spectrum method on diffractive optical element for beam smoothing, Optik 115 (2004) 370–374.
[16] R.W. Peng, Y.X. Ye, Z.X. Tang, D.Y. Fan, Transverse intensity distributions of broadband laser modulated by a hard-edged aperture, J. Opt. Soc. Am. A 22 (2005) 1903–1908.
[17] M. Born, E. Wolf, Principles of Optics, seventh ed., Cambridge University, Cambridge, 1999.
[18] F. Lytle, An introduction to diffraction. Part I: The near field, Appl. Spectrosc. 53 (1999) 212A–226A.