Effect of bandwidth on the intensities of an apertured laser in the near and far fields

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ABSTRACT

By means of the Huygens-Fresnel diffraction integral, the propagation expression of a laser beam passing through a hard-edged aperture is derived. The effects of the bandwidth on the transverse intensity distributions of the beam in the near and far fields are analyzed. It is found that, in the near field, the beam uniformity is improved with increasing the bandwidth and the broader the spectrum, the smoother the transverse intensity distribution is. Intensity spikes produced by low-frequency diffraction are eliminated in the diffraction patterns and the transverse intensity distribution near axis tends to smooth when the bandwidth increases. The intensity spikes produced by high-frequency diffraction still exist with increasing the bandwidth, but the amplitudes and numbers of them decrease. In the far field, there are only a few differences among the transverse intensity distributions of the beams with different bandwidthes. However, The secondary maximum intensity still presents for the beam with small bandwidth, and it decreases with increasing the bandwidth and is eliminated with large bandwidth.

KEYWORDS: broadband laser, bandwidth, beam smoothing, hard-edged aperture, transverse intensity distribution

1. INTRODUCTION

In recent decades, rapid development of pulsed laser techniques results in the generation of broad-spectrum laser. For example, 3.8-fs pulse with a bandwidth of ~270 THz is produced from adaptive compression of a cashed hollow fiber supercontinuum by Schenkel etc..[1] Such broad-spectrum pulse presents different propagation properties in comparison with monochromatic wave and thus propagation theories of the pulse in free space and dispersive medium have been investigated extensively.[2-6] It is found that, for the broad-spectrum pulse, complex space-time couplings emerge because of different extent of diffraction of each frequency component, which results in pulse broadening, time delay and shifting of frequency. Due to existence of these phenomena, intensity distribution of the pulse also differs from that of monochromatic wave.

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Modulated spatially by a hard-edged aperture, laser beam will present nonuniform intensity distribution. The intensity spikes in nonuniform intensity distribution often results in self-focusing,[7,8] which causes the limitation of laser output power. In addition, nonuniform intensity imprints itself on the target causing surface damage, which can "seed" the Rayleight-Taylor fluid instability, and also enhances the ignition energy in inertial confinement fusion (ICF).[9,10] Therefore, it is an interesting subject that how to improve the uniformity of laser beam and lots of investigations have been involved in it.[11-17] In order to achieve beam smoothing, multiple spatial filters are suggested to be utilized by Hunt etc..[11] Also, a new technique named smoothing by spectral dispersion (SSD) is adopted by Skupsky etc. in University of Rochester.[12] Following them, a lot of works have been devoted to investigating the SSD technique further[12-17] and it is developed into 3D SSD.[16] As pointed in this paper, the beam uniformity is also improved in terms of broad-spectrum lasers. In order to know propagation properties of such broadband pulses and the smoothing effect brought by them detailedly, further investigations should be made and some of the works are done in this paper. Firstly, propagation expression of a laser beam passing through a hard-edged aperture is derived starting from Huygens-Fresnel diffraction integral. Then, the effect of bandwidth on transverse intensity distribution is analyzed. A conclusion obtained in this paper is given finally.

2. FIELDS OF LASER BEAMS PASSING THROUGH A HARD-EDGED APERTURE

Consider a hard-edged rectangular aperture of half width a at z=0. Field of each frequency component of a laser beam passing through the aperture is given by Hugens-Fresnel diffraction integral[18]

$$\widetilde{E}(x,z,\omega)=\sqrt{\frac{i}{\lambda z}}\exp(-ikz)\int_{-a}^{a}\widetilde{E}_0(x_0,0,\omega)\exp\left[-\frac{ik}{2z}(x-x_0)^2\right]dx_0\,, \tag{1}$$

where $k=\omega/c$ is wave number and ω frequency of the beam. Assume that space and time field of the initial pulse can be separated, i.e.

$$\widetilde{E}_0(x_0,0,\omega)=E_0(x,0)\widetilde{S}(\omega)\,, \tag{2}$$

where $\widetilde{S}(\omega)$ denotes the initial spectrum at $x=0$ and $z=0$. By taking $\widetilde{S}(\omega)$ outside the integral, it is obtained

$$\widetilde{E}(x,z,\omega)=\sqrt{\frac{i}{\lambda z}}\exp(-ikz)\widetilde{S}(\omega)\int_{-a}^{a}E_0(x_0,0)\exp\left[-\frac{ik}{2z}(x-x_0)^2\right]dx_0\,. \tag{3}$$

Consider the input field is in the form

$$E_0(x_0,0)=\begin{cases}1 & |x_0|\le a\\ 0 & |x_0|>a\end{cases}. \tag{4}$$

By using error function

$$\mathrm{erf}(y) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-x^2) dx \,, \tag{5}$$

integral calculation of equation (3) yields

$$\widetilde{E}(x,z,\omega) = \frac{1}{2} \exp(-ikz) [\mathrm{erf}(\xi_+) - \mathrm{erf}(\xi_-)] \widetilde{S}(\omega) \,, \tag{6}$$

where

$$\xi_+ = \sqrt{\frac{ik}{2z}} (-x + a) \,, \tag{7}$$

$$\xi_- = \sqrt{\frac{ik}{2z}} (-x - a) \,. \tag{8}$$

The field of the pulse in time domain can be derived from the inverse Fourier transform of equation (6) as

$$E(x,z,t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \widetilde{E}(x,z,\omega) \exp(i\omega t) d\omega \,. \tag{9}$$

Thus, the field is given by

$$E(x,z,t) = \frac{1}{2\sqrt{2\pi}} \int_{-\infty}^{\infty} [\mathrm{erf}(\xi_+) - \mathrm{erf}(\xi_-)] \widetilde{S}(\omega) \exp(i\omega\tau) d\omega \,, \tag{10}$$

where

$$\tau = t - z/c \tag{11}$$

is local time.

Consider $\widetilde{S}(\omega)$ is in the form of Gaussian spectrum. For transform-limited pulse, pulse duration is given by

$$T_p = \frac{2a_g^2}{\omega_0 \gamma} \tag{12}$$

where $\gamma = \Delta\omega/\omega_0$ is bandwidth, $\Delta\omega$ spectrum width (FWHM), ω_0 carrier frequency and $a_g = \sqrt{2\ln 2}$. Hence, the Gaussian spectrum can be written as

$$\widetilde{S}(\omega) = \frac{a_g}{\sqrt{2}\omega_0 \gamma} \exp\left[-\frac{a_g^2 (\omega - \omega_0)^2}{\omega_0^2 \gamma^2} \right]. \tag{13}$$

From equation (10), intensity of the pulse is obtained as

$$I(x,z,t) = \frac{1}{8\pi} \left| \int_{-\infty}^{\infty} [\mathrm{erf}(\xi_+) - \mathrm{erf}(\xi_-)] \widetilde{S}(\omega) \exp(i\omega\tau) d\omega \right|^2 . \tag{14}$$

3. EFFECTS OF THE BANDWIDTH ON TRANSVERSE INTENSITY DISTRIBUTIONS

Transverse intensity distributions of the beams with bandwidthes 0, 0.02, 0.11 and 0.44 at $\tau=0$ and z=10mm are shown in Fig. 1, where the calculation parameters are a=1mm, $\omega_0=1.77\text{fs}^{-1}$. It is seen from the figure that the transverse intensity distribution of monochromatic wave is the most nonuniform one and that of the pulse with bandwidth 0.44 is the most uniform one among all subgraphs, which indicate that the broader the spectrum width, the smoother the transverse intensity distribution is. Especially, intensity spikes produced by low-frequency diffraction are eliminated and the transverse intensity distributions in a certain domain near z-axis (x=0) are perfect smoothing in the beams with bandwidthes 0.02, 0.11 and 0.44. Although the intensity spikes produced by high-frequency diffraction even are not eliminated in the beam with large value bandwidth, the amplitudes and numbers of them decrease with increasing the bandwidth obviously. Hence, it is concluded that the spectrum width is an important parameter affecting the transverse intensity distribution.

For spatial modulation laser, beam uniformity can be compared using a parameter called modulation contrast

$$M=\frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}}. \tag{15}$$

The dependence of modulation contrast of the pulse on the bandwidth at $\tau=0$ and z=10mm is depicted in Fig. 2, from which it is known that the curve decreases monotonically, i.e. modulation contrast decreases as the bandwidth increases. The results indicate that the broader the bandwidth, the better the beam uniformity is. Variation of modulation contrast with the bandwidth is small and the value of it is almost equal to that of the monochromatic wave when $\gamma<0.1$. It changes significantly only for the pulse with certain bandwidth.

Because the maximum and minimum intensities are located at the edge of the patterns generated by high-frequency diffraction, modulation contrast only denotes the effect of spectrum width on these diffraction patterns. In order to know the effect of spectrum width on patterns generated by low-frequency diffraction, the intensity near z-axis (x=0) should be investigated. Assume that

$$\frac{I_x-I_{x=0}}{I_{x=0}}\leqslant 0.005 \tag{16}$$

is regarded as a condition that beam smoothing is achieved. The dependence of the width of beam smoothing on the bandwidth is given in Fig. 3, from which it is seen that the width of beam smoothing increases with increasing the bandwidth. For example, the width of beam smoothing is 0.24 mm for the beam with the bandwidth 0.02 and 0.64 mm with the bandwidth 0.1. It increases rapidly when the bandwidth increases from 0.01 to 0.1 and reaches a constant value of 0.82 mm as $\gamma>0.4$.

Physically, such effects of the spectrum width on intensity are resulted from different extent of diffraction of each frequency component. It is known that beam diffraction is determined by Fresnel number $F=a^2/\lambda z$. There exists only one Fresnel number for a determined point and single diffraction pattern is generated when the input field is monochromatic wave. However, when broad-spectrum pulse incidences, there exist different Fresnel number and different diffraction pattern is generated for each frequency component at the same point. Overlapping of these diffraction patterns of all frequency components results in the beam smoothing.

The time-integrated intensity (energy density) is utmost interesting in lost of applications. Fig. 4 shows time-integrated intensities at z=10mm, which are similar as those of τ =0. The time-averaged intensity studied in Ref. 12 was smoothed in time by overlapping many copies of the pattern, each shifted in space, so that the peaks of some fill in the valleys of others. Intensity in this paper is already smoothed at any time and the reason is given in the previous section. However, the time-integrated intensity is not better than those of any time, which is because that each pattern at any time shifted little in space. Obviously, the origin of achieving beam smoothing in this paper differs that in Ref. 12.

The transverse intensity distributions at τ =0 and z=5m are given in Fig. 5, from which it is seen that there is only a little difference in the intensities of the beams with different bandwidthes. Distributions of all the intensities at central region become to Gaussian shape in the far field and amplitude of the secondary maximum intensity decreases with increasing the bandwidth and it is eliminated for large bandwidth. According to the calculations, the time-integrated intensities is the same as those of τ =0 at the place.

4. CONCLUSIONS

In conclusion, for laser beam modulated by a hard-edged aperture, spatial modulation contrast of broad-spectrum pulse is smaller than that of monochromatic wave and the transverse intensity distribution of it is achieved smoothing within a certain domain in the near field. Beam smoothing for broad-spectrum pulse is mainly presented in improvement of patterns generated by low-frequency diffraction, i.e. the intensity spikes near z-axis are eliminated and the width of beam smoothing increases as the bandwidth increases. Also, the intensity spikes produced by high-frequency diffraction are improved in the aspects of decreasing the amplitudes and numbers of them with increasing the bandwidth. There is only a little difference in the intensities of the beams with different bandwidthes in the far field.

The beam smoothing brought by increasing the bandwidth may provide additional method to improve the beam uniformity. As compared with other methods to achieve beam smoothing studied in the previous works, the method of increasing spectrum width investigated in this paper presents its own advantage that there is no any additional optical instrument required. However, there exist some difficulties, such as limitation of spectrum width of gain medium and low efficiency of frequency multiplication for such pulse, to obtain broad-spectrum pulse with high power. Hence, these technologies also are subjects of current interest and further investigations of theories and applications about the broad-spectrum pulse seem to be necessary.

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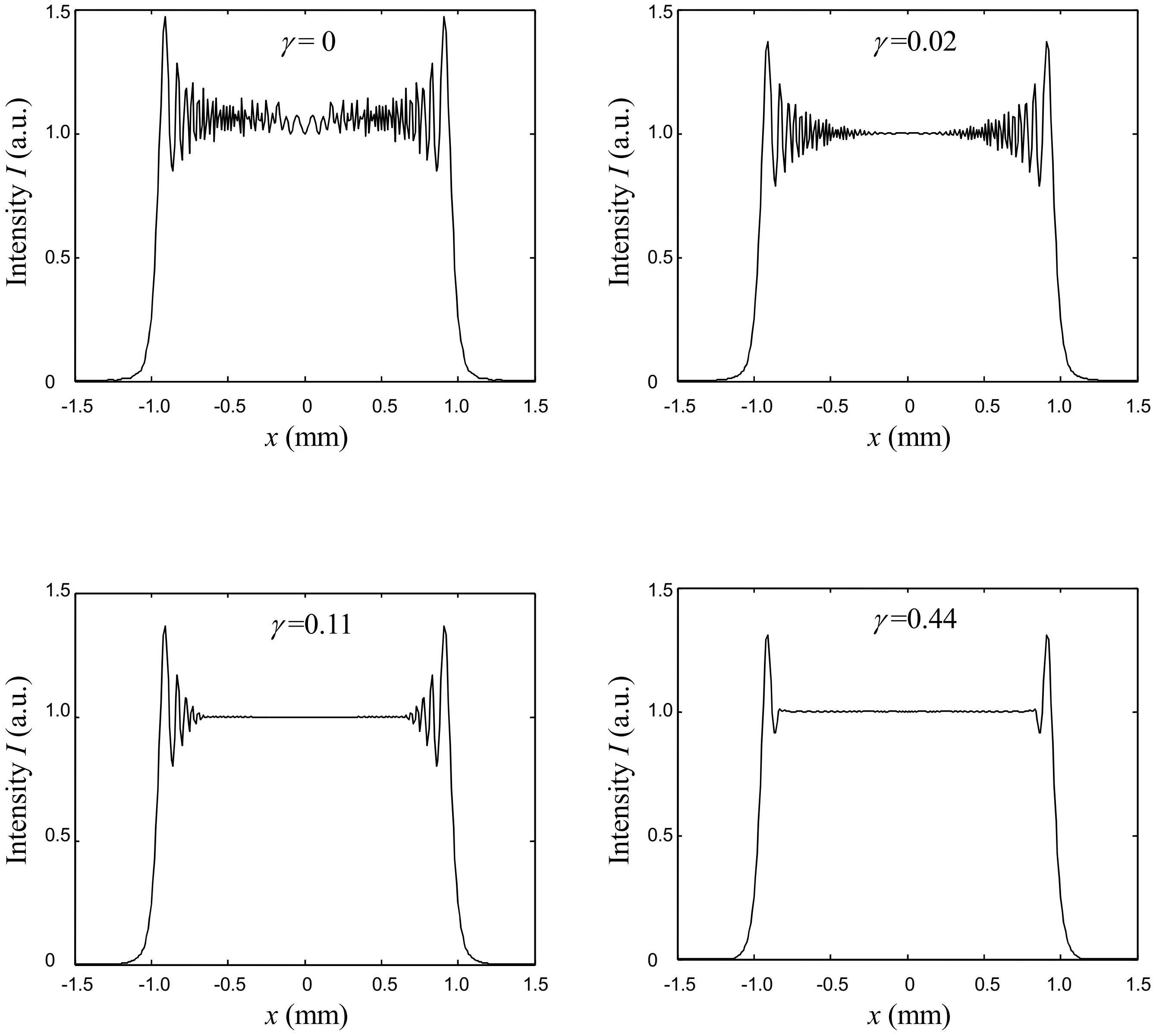

Figure 1. Transverse intensity distributions of the apertured beams with different bandwidthes at τ =0 and z=10mm

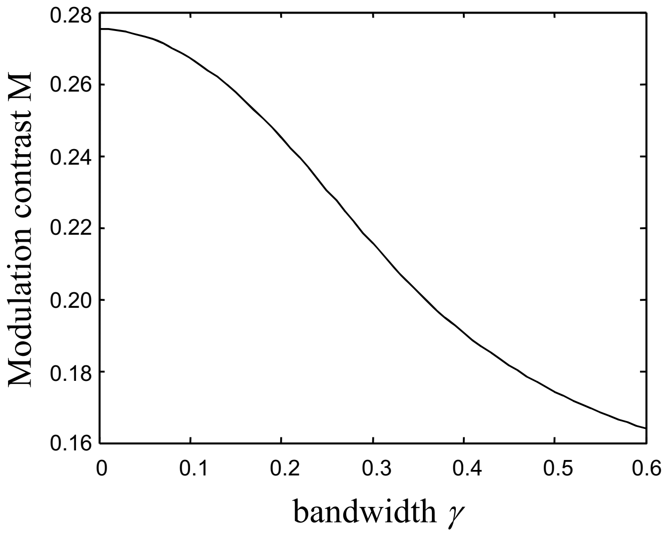

Figure 2. Dependence of the modulation contrast of the aperture beam on the bandwidth

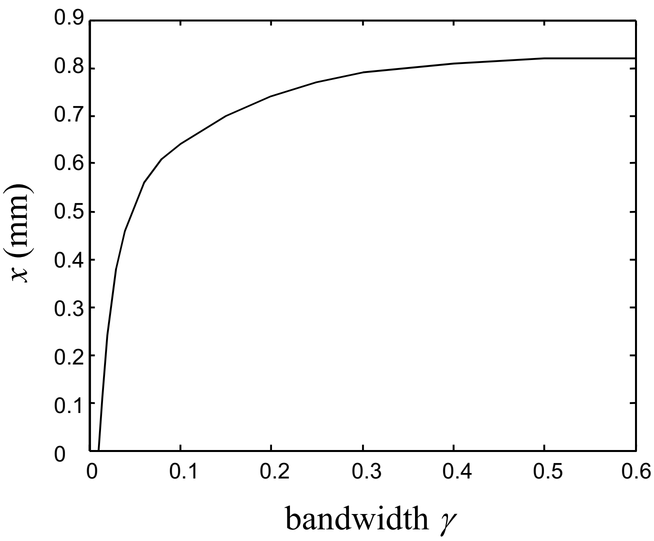

Figure 3. Width of beam smoothing of the apertured beam versus the bandwidth

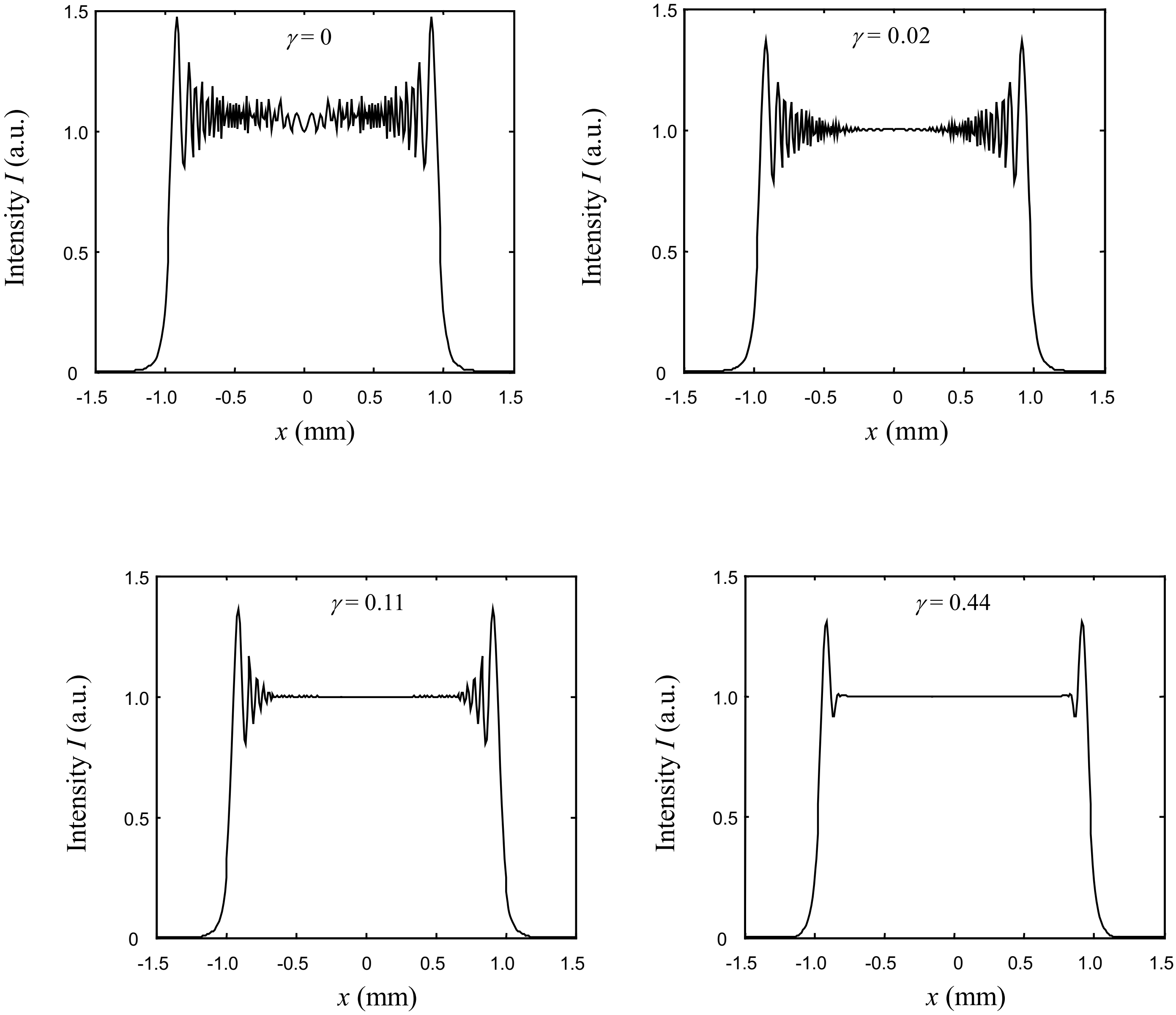

Figure 4. Time-integrated transverse intensity distributions of the apertured beams with different bandwidthes at z=10mm

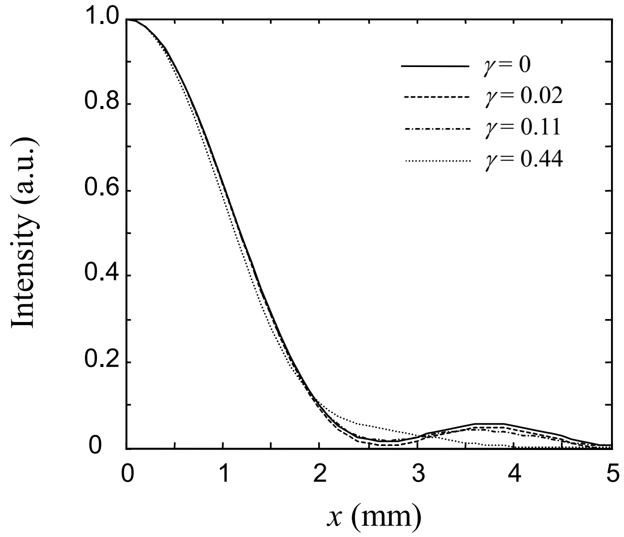

Figure 5. Transverse intensity distributions of the apertured beams with different bandwidthes at τ =0 and z=5m