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Anomalous spectral behaviour of diffracted chirped Gaussian pulses in the near field*

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By using the Fourier transform method, analytical expressions for the axial power spectrum and near-field intensity in the spacetime domain of chirped Gaussian pulses diffracted at an aperture are derived, which permit us to study changes in spectral and temporal profiles of the chirped Gaussian pulses both analytically and numerically. Detailed numerical results and physical analysis show that spectral anomalies take place in the neighbourhood of certain critical distances, and the shifting of maximum and splitting of temporal intensity profiles appear. In particular, for ultrashort chirped pulses, there exists also spectral switch. Besides the truncation parameter, the chirp parameter and pulse duration affect the behaviour of spectral switches.

Keywords: spectral anomaly, spectral switch, chirped Gaussian pulse, aperture diffraction
PACC: 0765, 4225F, 4280W

1. Introduction

Much interest has been exhibited recently in the structure of wave fields in the neighbourhood of phase singularities, and thus a new branch of physical optics, referred to as singular optics, has been developed.[1] Very recently, the work in singular optics has been extended from monochromatic waves to spatially fully and partially coherent polychromatic light beams diffracted at an aperture.[2−8] It was found that the spectrum of spatially fully or partially coherent beams passing through an aperture changes remarkably at positions close to certain critical distances, where the intensity has a zero or minimum value. The spectrum is redshifted on one side of the critical distances, and blueshifted on the other side, and is split into two lines at the critical distances. The theoretically predicted anomalous spectral behaviour has been confirmed by experiment.[9,10] Particular attention has been paid to the rapidly advanced ultrashort light pulses.[11−16] However, most of the studies in spectral anomalies have been focused on the light beams, only a few papers have dealt with the diffraction and spectral changes of ultrashort pulses.[17,18] This paper studies the anomalous spectral behaviour of diffracted chirped Gaussian pulses in the near field. In Sec.2, based on the Fourier transform method, analytical expressions for axial power spectrum and the near-field intensity in the spacetime domain of chirped Gaussian pulses diffracted at an aperture are derived. Detailed numerical results and physical interpretations are presented in Sec.3. A brief summary of the main results concludes this paper.

2. Basic equations

Suppose that in the spacetime domain an ultrashort Gaussian pulse of the form [13]

$$E(\boldsymbol{r}', 0, t) = \exp\left(-\frac{\boldsymbol{r}'^2}{w_0^2}\right) A(t) \tag{1}$$

is incident upon a circular aperture of radius a in the plane z=0, where $E(\boldsymbol{r}', 0, t)$ and $A(t)$ denote the initial field and temporal profile of the pulse, respectively, w_0 is the waist width, which is assumed to be independent of the frequency ω,[14] $\boldsymbol{r}' = x'\boldsymbol{i} + y'\boldsymbol{j}$ is the transversal position vector in the plane z=0, and $\boldsymbol{i}$ and $\boldsymbol{j}$ stand for the unit vectors in the x and y directions, respectively.

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By the Fourier transform, the field in the space–frequency domain is expressed as

$$E(\boldsymbol{r}',0,\omega) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} E(\boldsymbol{r}',0,t)\exp(\mathrm{i}\omega t)\,\mathrm{d}t = \exp\left(-\frac{\boldsymbol{r}'^2}{w_0^2}\right) f(\omega), \quad (2)$$

where the original Fourier spectrum of the pulse reads as

$$f(\omega) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} A(t)\exp(\mathrm{i}\omega t)\,\mathrm{d}t. \quad (3)$$

Within the framework of the paraxial approximation, the propagation of the field in Eq.(2) is characterized by the Huygens–Fresnel diffraction integral of the form

$$E(\boldsymbol{r},z,\omega) = \frac{\mathrm{i}}{\lambda z}\exp(-\mathrm{i}kz)\int_S E(\boldsymbol{r}',0,\omega) \times \exp\left\{-\frac{\mathrm{i}k}{2z}\left[\boldsymbol{r}'^2+\boldsymbol{r}^2-2\boldsymbol{r}'\cdot\boldsymbol{r}\right]\right\}\mathrm{d}\boldsymbol{r}', \quad (4)$$

where k is the wavenumber related to the wavelength λ by $k = 2\pi/\lambda$. The integration is made with respect to the aperture plane S.

The inverse Fourier transform of Eq.(4) leads to the field $E(\boldsymbol{r},z,t)$ in the spacetime domain

$$E(\boldsymbol{r},z,t) = \int_{-\infty}^{\infty} E(\boldsymbol{r},z,\omega)\exp(-\mathrm{i}\omega t)\,\mathrm{d}\omega. \quad (5)$$

Assume that the incident pulse is a chirped Gaussian one, thus $A(t)$ takes the form [13]

$$A(t) = \exp\left[-\frac{(1+\mathrm{i}C)t^2}{2T^2}\right]\exp(-\mathrm{i}\omega_0 t), \quad (6)$$

where T denotes the pulse duration, ω_0 is the central frequency, and C is the chirp parameter, C=0 corresponding to the chirped-free one. Substituting Eq.(6) into Eq.(2), straightforward integral calculations deliver

$$E(\boldsymbol{r}',0,\omega) = \exp\left(-\frac{\boldsymbol{r}'^2}{w_0^2}\right) f(\omega) = \sqrt{\frac{T^2(1-\mathrm{i}C)}{1+C^2}}\exp\left[-\frac{T^2(1-\mathrm{i}C)}{2(1+C^2)}(\omega-\omega_0)^2\right] \times \exp\left(-\frac{\boldsymbol{r}'^2}{w_0^2}\right). \quad (7)$$

Thus, the power spectrum (i.e. the spectral intensity) of the incident pulse is given by

$$I^{(0)}(\omega) = |f(\omega)|^2 = \frac{T^2\sqrt{1+C^2}}{1+C^2}\exp\left[-\frac{T^2}{1+C^2}(\omega-\omega_0)^2\right], \quad (8)$$

which depends on the pulse duration T and chirp parameter C.

Substituting from Eq.(7) into Eq.(4) yields

$$E(\boldsymbol{r},z,\omega) = \frac{\mathrm{i}}{\lambda z}\exp(-\mathrm{i}kz)\int_S \sqrt{\frac{T^2(1-\mathrm{i}C)}{1+C^2}} \times \exp\left[-\frac{T^2(1-\mathrm{i}C)}{2(1+C^2)}(\omega-\omega_0)^2\right] \times \exp\left(-\frac{\boldsymbol{r}'^2}{w_0^2}\right) \times \exp\left\{-\frac{\mathrm{i}k}{2z}\left[\boldsymbol{r}'^2+\boldsymbol{r}^2-2\boldsymbol{r}'\cdot\boldsymbol{r}\right]\right\}\mathrm{d}\boldsymbol{r}'. \quad (9)$$

From Eq.(9) the axial field ($\boldsymbol{r}$=0) at the z plane turns out to be

$$E(0,z,\omega) = \mathrm{i}\exp(-\mathrm{i}kz)\sqrt{\frac{T^2(1-\mathrm{i}C)}{1+C^2}} \times \exp\left[-\frac{T^2(1-\mathrm{i}C)}{2(1+C^2)}(\omega-\omega_0)^2\right] \times \frac{T_0\omega}{\mathrm{i}T_0\omega+2z/z_0} \times \left[1-\exp(-\delta^2)\exp\left(-\mathrm{i}\frac{\delta^2 T_0\omega}{2z/z_0}\right)\right], \quad (10)$$

where

$$\delta = \frac{a}{w_0}, \quad \text{(truncation parameter)}. \quad (11)$$

The axial power spectrum obtained from Eq.(10) is

$$I(0,z,\omega) = |E(0,z,\omega)|^2 = I^{(0)}(\omega)M(0,z,\omega), \quad (12)$$

where

$$M(0,z,\omega) = \frac{T_0^2\omega^2}{T_0^2\omega^2+4(z/z_0)^2} \times \left[1+\exp(-2\delta^2) - 2\exp(-\delta^2)\cos\left(\frac{\delta^2 T_0\omega}{2z/z_0}\right)\right] \quad (13)$$

is called the spectral modifier [2] describing how the aperture diffraction modifies the original spectrum. $z_0 = w_0^2/\lambda_0$, and $T_0 = 2\pi/\omega_0$ is the pulse period corresponding to the central frequency ω_0, or equivalently, to the central wavelength λ_0.

Substituting Eq.(10) into Eq.(5) leads to the axial field in the spacetime domain

$$E(0,z,t)=\int_{-\infty}^{\infty}\mathrm{i}\exp(-\mathrm{i}kz)\sqrt{\frac{T^2(1-\mathrm{i}C)}{1+C^2}}\times\exp\left[-\frac{T^2(1-\mathrm{i}C)}{2(1+C^2)}(\omega-\omega_0)^2\right]\times\frac{T_0\omega}{\mathrm{i}T_0\omega+2z/z_0}\times\left[1-\exp(-\delta^2)\exp\left(-\mathrm{i}\frac{\delta^2T_0\omega}{2z/z_0}\right)\right]\times\exp(-\mathrm{i}\omega t)\,\mathrm{d}\omega, \tag{14}$$

which can be rewritten as

$$E(0,z,t')=\int_{-\infty}^{\infty}\mathrm{i}\sqrt{\frac{T^2(1-\mathrm{i}C)}{1+C^2}}\times\exp\left[-\frac{T^2(1-\mathrm{i}C)}{2(1+C^2)}(\omega-\omega_0)^2\right]\times\frac{T_0\omega}{\mathrm{i}T_0\omega+2z/z_0}\left[1-\exp(-\delta^2)\exp\left(-\mathrm{i}\frac{\delta^2T_0\omega}{2z/z_0}\right)\right]\times\exp(-\mathrm{i}\omega t')\,\mathrm{d}\omega, \tag{15}$$

where $t'=t+z/c$ denotes the local time. For the near field the slowly varying term $\dfrac{T_0\omega}{\mathrm{i}T_0\omega+2z/z_0}$ in the integrand can be neglected. Therefore, the straightforward integral of Eq.(15) yields

$$E(0,z,t')\approx\mathrm{i}\sqrt{2\pi T}\left(\exp\left[-\frac{t'}{2T^2}\left(t'+\mathrm{i}Ct'+2\mathrm{i}\omega_0T^2\right)\right]-\exp(-\delta^2)\exp\left\{-\frac{t'+\delta^2T_0/(2z/z_0)}{2T^2}\times\left[\left(t'+\frac{\delta^2T_0}{2z/z_0}\right)(1+\mathrm{i}C)+2\mathrm{i}\omega_0T^2\right]\right\}\right), \tag{16}$$

and the axial spacetime intensity is given by

$$I(0,z,t')=|E(0,z,t')|^2\approx2\pi T\left\{\exp\left(-\frac{t'^2}{T^2}\right)+\exp\left[-2\delta^2-\frac{1}{T^2}\left(t'+\frac{\delta^2T_0}{2z/z_0}\right)^2\right]-2\exp\left[-\delta^2-\frac{t'^2}{2T^2}-\frac{1}{2T^2}\left(t'+\frac{\delta^2T_0}{2z/z_0}\right)^2\right]\times\cos\left[\frac{\delta^2T_0}{2z/z_0}\left(\omega_0+\frac{t'C}{T^2}+\frac{C}{2T^2}\frac{\delta^2T_0}{2z/z_0}\right)\right]\right\}. \tag{17}$$

Equations (12) and (17) are the basic analytical results obtained in this paper, which describe the changes in the axial power spectrum and spacetime intensity of diffracted chirped Gaussian pulses in the near field. It follows from Eqs.(12) and (13) that the axial power spectrum of diffracted chirped Gaussian pulses is dependent on the original power spectrum $I^{(0)}(\omega)$ and spectral modifier $M(0,z,\omega)$. The axial spectrum and spacetime intensity in the near field mainly depend on the truncation parameter δ, chirp parameter C and pulse duration T.

3. Numerical calculation results and physical interpretations

3.1. Axial power spectrum

Equations (12) and (13) indicate that axial spectral behaviour of diffracted chirped Gaussian pulses depend on the modification of the original power spectrum $I^{(0)}(\omega)$ by the spectral modifier $M(0,z,\omega)$, which is a product of two parts, namely the slowly varying part $\dfrac{T_0^2\omega^2}{T_0^2\omega^2+4(z/z_0)^2}$, and the fast varying one $\left[1+\exp\left(-2\delta^2\right)-2\exp\left(-\delta^2\right)\cos\left(\dfrac{\delta^2T_0\omega}{2z/z_0}\right)\right]$, so that the extremum of $M(0,z,\omega)$ is determined by the fast varying part. $M(0,z,\omega)$ takes its maximum when

$$\omega_0=\omega_{\max}=2(2m+1)\pi(z/z_0)/(\delta^2T_0), \tag{18a}$$

namely

$$z/z_0=\frac{\delta^2}{2m+1}; \tag{18b}$$

and it reaches its minimum when

$$\omega_0=\omega_{\min}=2(2m+2)\pi(z/z_0)/(\delta^2T_0), \tag{19a}$$

i.e.

$$z/z_0=\frac{\delta^2}{2m+2}, \tag{19b}$$

where $m=0,1,2,\ldots$.

According to the position z/z_0, or the position of the central frequency ω_0 on the $M(0,z,\omega)$ curve, there are four cases of interest:

(A) If

$$\frac{\delta^2}{2m+2}<z/z_0<\frac{\delta^2}{2m+1}, \tag{20a}$$

i.e.

$$2(2m+1)\pi(z/z_0)/(\delta^2T_0)<\omega_0<2(2m+2)\pi(z/z_0)/(\delta^2T_0), \tag{20b}$$

the central frequency ω_0 is located at the position of the $M(0,z,\omega)$ curve with negative slope. As a consequence, the maximum of the power spectrum $I(0,z,\omega)$ in Eq.(12) moves toward the left-hand side of ω_0, and the spectrum is redshifted. Figure 1 shows the normalized power spectrum $I(\omega) = I(0,z,\omega)/I_{\max}(0,z,\omega)$ of chirped Gaussian pulses at the positions (a) z/z_0=0.427 (m=0), (b) z/z_0=0.183 (m=1) and (c) z/z_0=0.116 (m=2), satisfying inequality (20); $I_{\max}(0,z,\omega)$ is the maximum power spectrum. The parameters for calculation are T=3fs, λ_0=800nm, δ=0.8, and C=0, 1, 3. As can be seen, the red shift appears for chirped-free (C=0) and chirped (C=1, 3) Gaussian pulses, and increases with increasing chirp parameter C (absolute value). For example, the red shift of the central frequency ω_0 is equal to $\Delta=\omega_{\max}-\omega_0$=–0.079fs^{-1}, –0.142fs^{-1} and –0.393fs^{-1} in Fig.1(a) for C=0, 1, 3, respectively. In addition, the spectrum is split into more than two parts, as shown in Fig.1(b) for C=3, and in Fig.1(c) for C=1, and 3, respectively.

(B) If

$$\frac{\delta^2}{2m+3} < z/z_0 < \frac{\delta^2}{2m+2}, \tag{21a}$$

i.e.

$$2(2m+2)\pi(z/z_0)/(\delta^2 T_0) < \omega_0 < 2(2m+3)\pi(z/z_0)/(\delta^2 T_0), \tag{21b}$$

then ω_0 is located at the position of the $M(0,z,\omega)$ curve with positive slope; therefore, the maximum of the power spectrum moves toward the right-hand side of ω_0, and the blue shift occurs. The normalized power spectrum $I(\omega)$ of chirped Gaussian pulses at the positions (a) z/z_0=0.256 (m=0), (b) z/z_0=0.142 (m=1) and (c) z/z_0=0.099 (m=2), satisfying inequality (21),

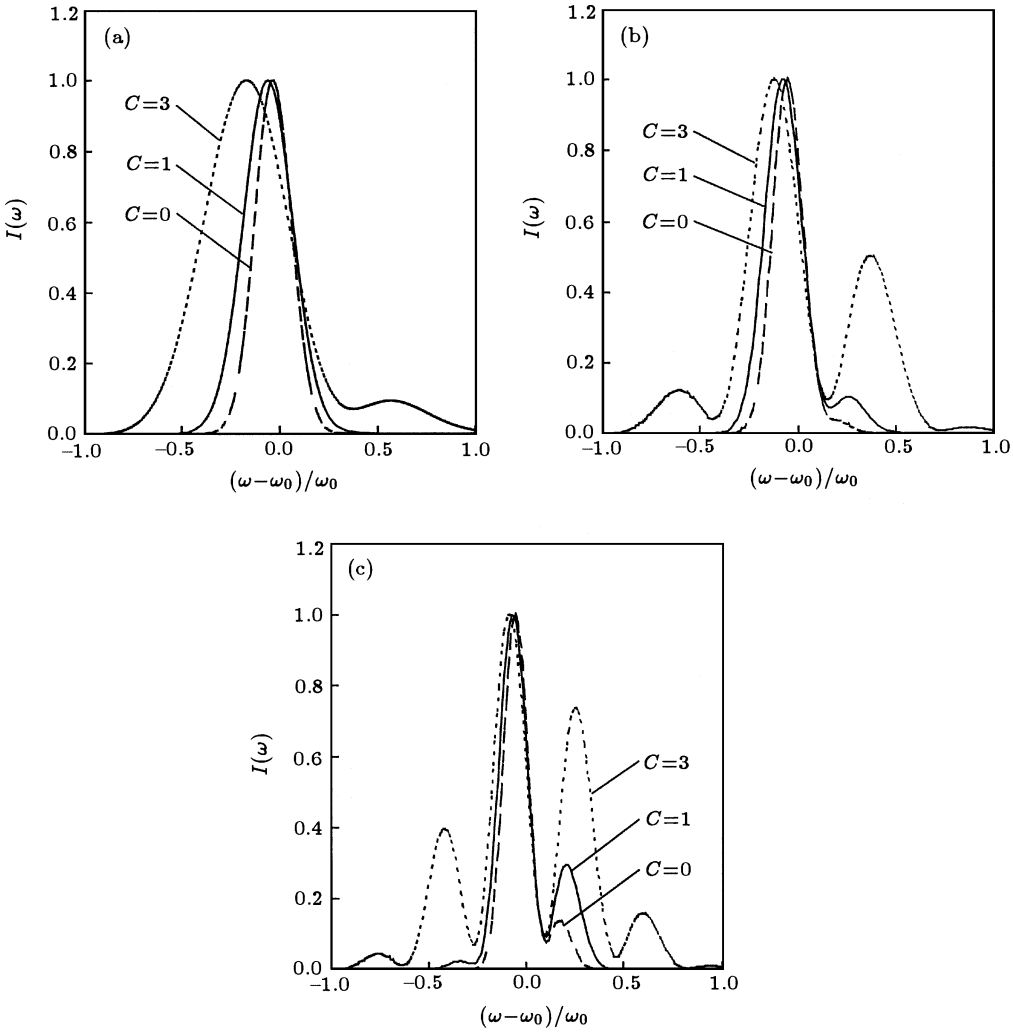


Fig.1. Normalized power spectrum $I(\omega)$ of chirped Gaussian pulses for different values of C=0, 1 and 3. (a) z/z_0=0.427 (m=0); (b) z/z_0=0.183 (m=1); (c) z/z_0=0.116 (m=2). The calculation parameters are T=3fs, λ_0=800nm and δ=0.8.

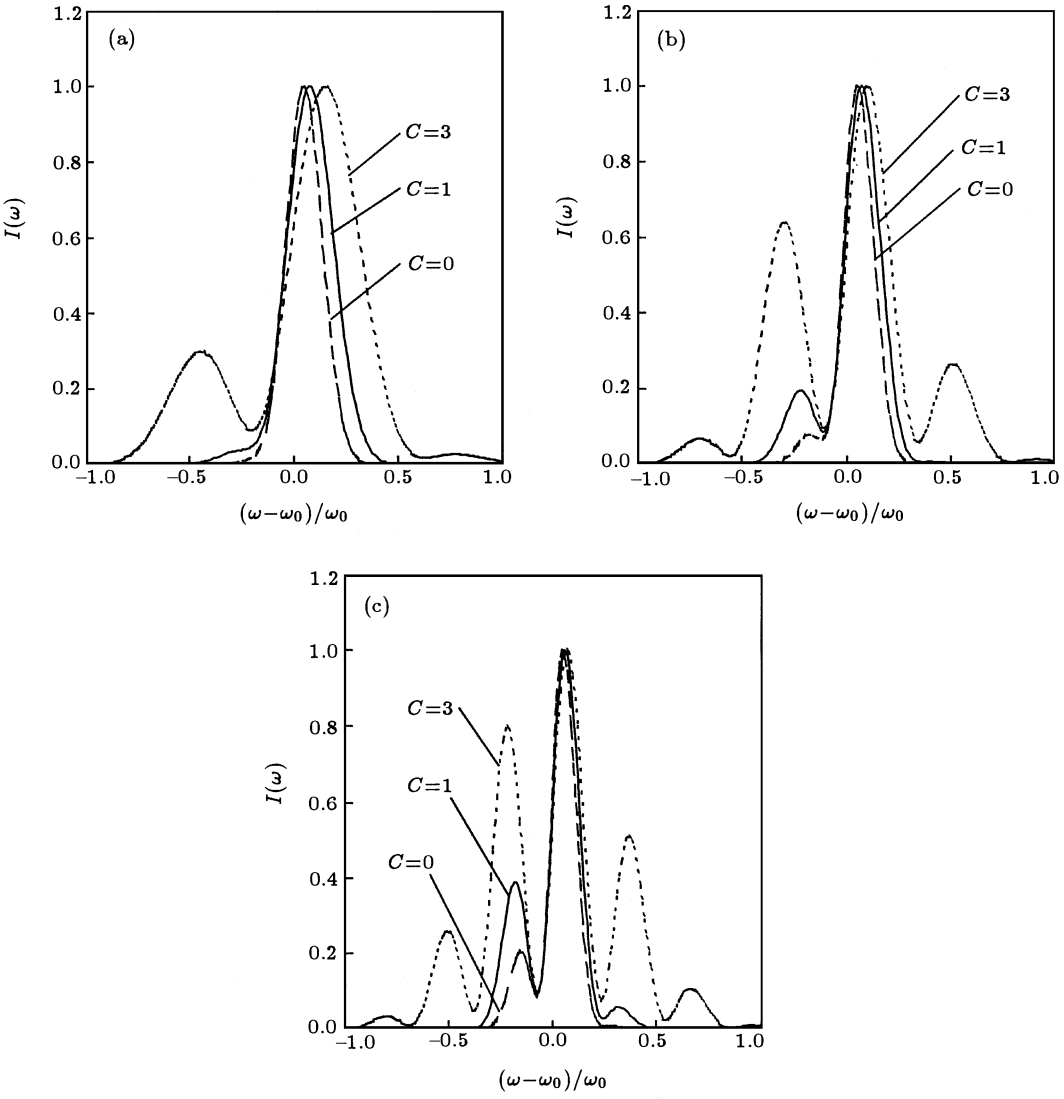


Fig.2. Normalized power spectrum $I(\omega)$ of chirped Gaussian pulses for different values of C=0, 1 and 3. (a) z/z_0=0.256 (m=0); (b) z/z_0=0.142 (m=1); (c) z/z_0=0.099 (m=2). The other calculation parameters are as in Fig.1.

is plotted in Fig.2, the other calculation parameters are the same as those in Fig.1. The blue shift, for example, in Fig.2(a) is found to be $\Delta=\omega_{max}-\omega_0$=0.111fs^{-1}, 0.176fs^{-1} and 0.347fs^{-1} for C=0, 1, 3, respectively, thus the larger chirp parameter C results in a larger blue shift. Similar to the case (A), there is a spectral splitting, and more than two parts are also seen in Fig.2.

(C) If

$$z/z_0 = \frac{\delta^2}{2m+1}, \tag{22a}$$

i.e.

$$\omega_0 = 2(2m+1)\pi(z/z_0)/(\delta^2 T_0), \tag{22b}$$

ω_0 is positioned at the maximum of the $M(0,z,\omega)$ curve, thus the maximum of the power spectrum does not shift, as shown in Fig.3, where (a) z/z_0=0.64 (m=0), (b) z/z_0=0.213 (m=1) and (c) z/z_0=0.128 (m=2), satisfying Eq.(22). It is seen that the spectrum is broadening and split into more than two parts with increasing chirp parameter C.

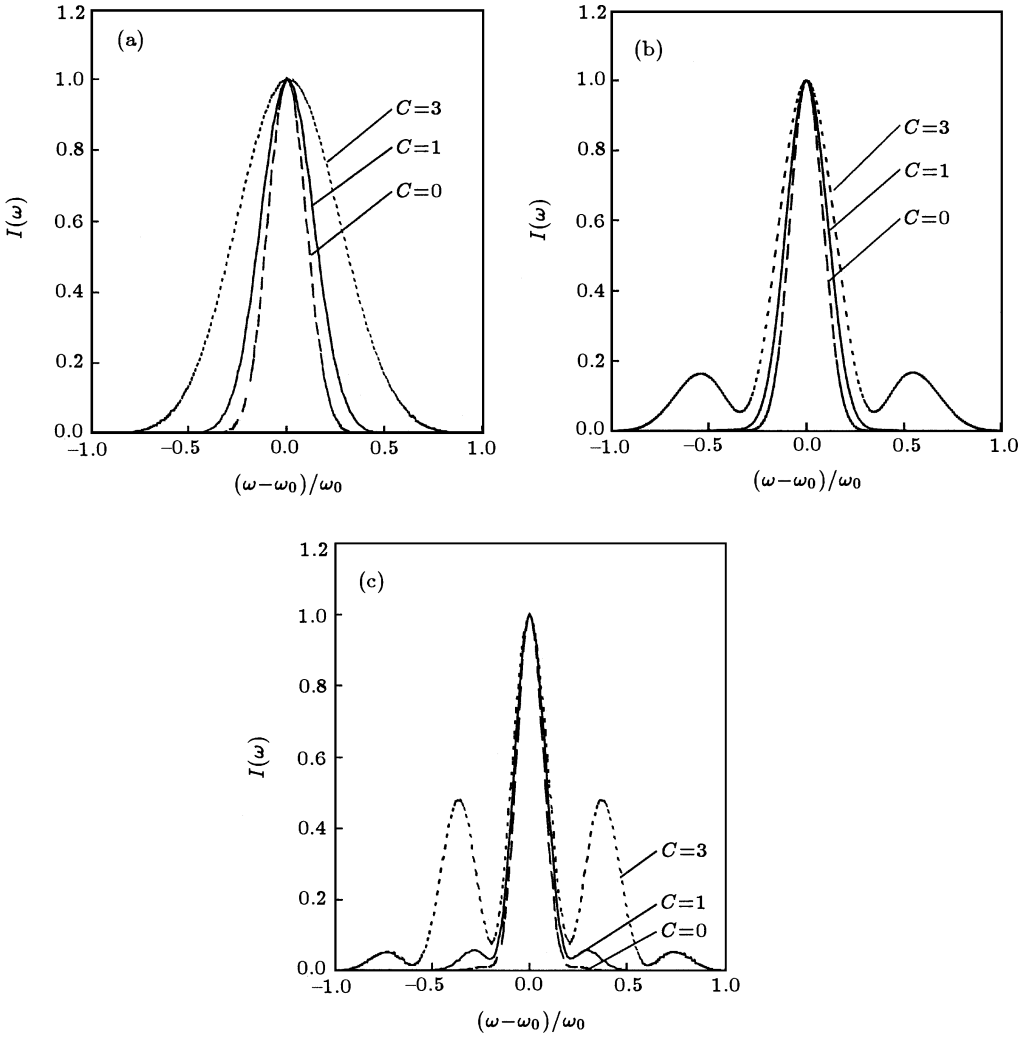


Fig.3. Normalized power spectrum $I(\omega)$ of chirped Gaussian pulses for different values of C=0, 1 and 3. (a) z/z_0=0.64 (m=0); (b) z/z_0=0.213 (m=1); (c) z/z_0=0.128 (m=2). The other calculation parameters are the same as those in Fig.1.

(D) If

$$z/z_0 = \frac{\delta^2}{2m+2}, \tag{23a}$$

i.e.

$$\omega_0 = 2(2m+2)\pi(z/z_0)/(\delta^2 T_0), \tag{23b}$$

then ω_0 is positioned at the minimum of the $M(0,z,\omega)$ curve. As a result, there exists a central dip. Numerical examples are depicted in Fig.4 at (a) z/z_0=0.32 (m=0), (b) z/z_0=0.16 (m=1) and (c) z/z_0=0.107 (m=2), satisfying Eq.(23). From Fig.4 we see that the spectrum is split into two or more than two parts with a central dip, depending on the chirp parameter C. The central dip and spectral width (FWHM) increases as the chirp parameter C increases.

From the above analysis it follows readily that there exist certain critical distances z/z_0 satisfying Eq.(22) or (23). The drastic spectral changes in the chirped Gaussian pulses take place in the neighbourhood of those critical distances z/z_0. This means that the spectrum is redshifted on one side of z/z_0 (see Fig.1), blueshifted on the other side (see Fig.2), and, in particular, split into two lines with equal height (see Fig.4). The latter is sometimes referred to as a spectral switch, which is shown to be a new effect in singular optics.[5] As compared with polychromatic light beams,[2–8] the truncation parameter δ, chirp parameter C and pulse duration T affect the spectral switch of chirped Gaussian pulses. Figures 5 and 6 give the normalized power spectrum $I(\omega)$ for different values of δ and T, respectively. It is shown that the central dip and spectral width increase with decreasing δ and T, as the spectral switch of chirped Gaussian pulses occurs.

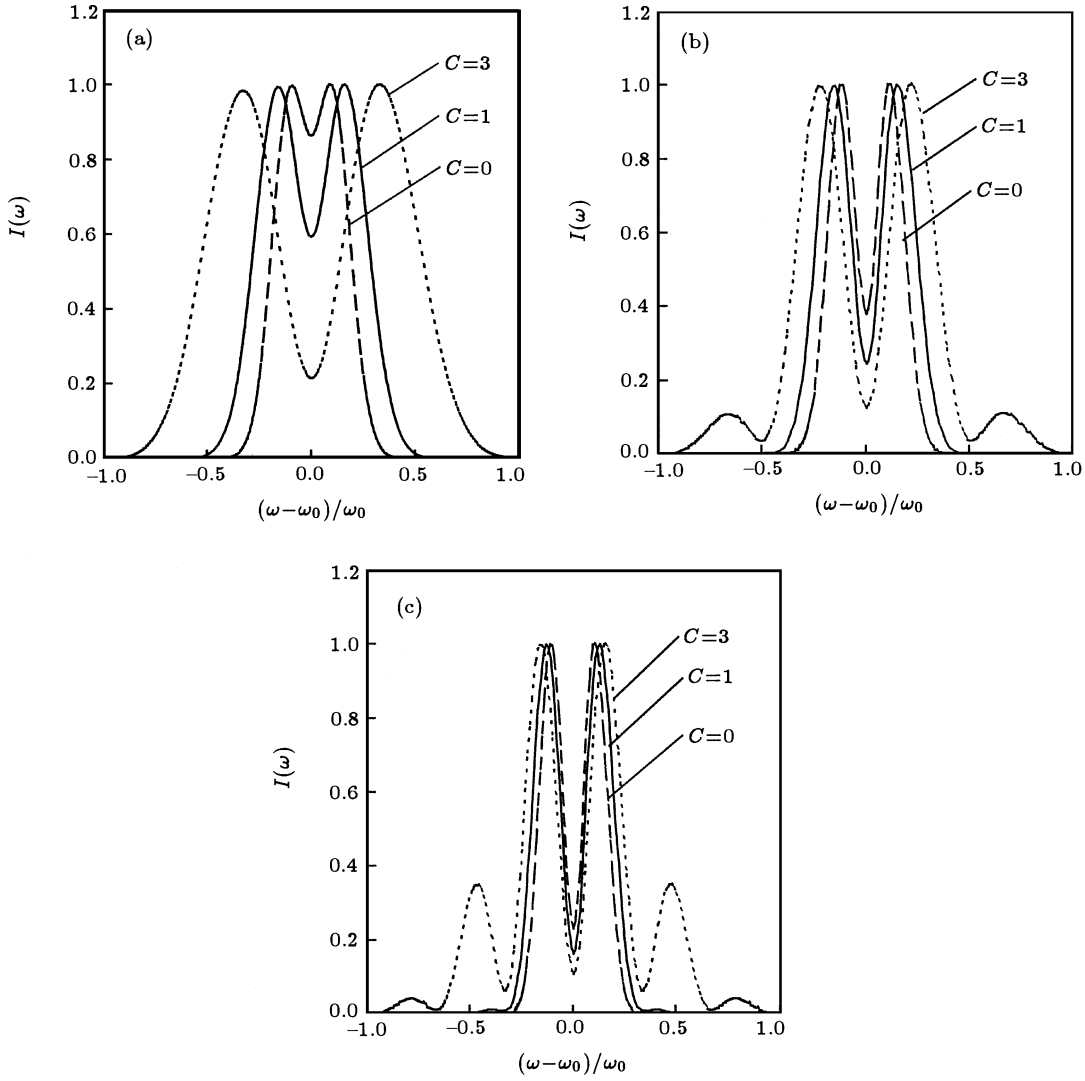


Fig.4. Normalized power spectrum $I(\omega)$ of chirped Gaussian pulses for different values of C=0, 1 and 3. (a) z/z_0=0.32 (m=0); (b) z/z_0=0.16 (m=1); (c) z/z_0=0.107 (m=2). The other calculation parameters are the same as those in Fig.1.

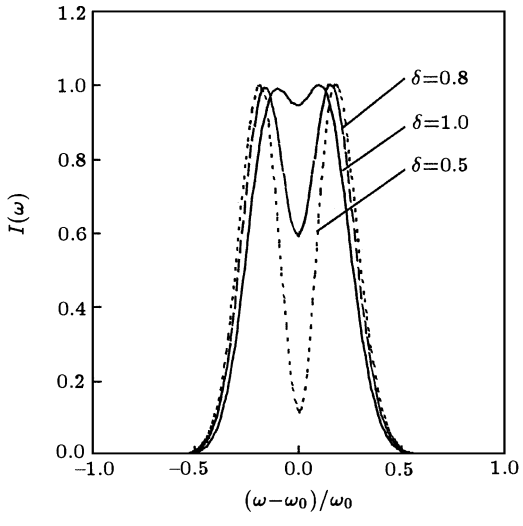


Fig.5. Normalized power spectrum $I(\omega)$ of chirped Gaussian pulses for different values of δ=0.5, 0.8 and 1. The calculation parameters are C=1, T=3fs, λ_0=800nm and z/z_0=0.125, 0.32 and 0.5, corresponding to δ=0.5, 0.8 and 1 (m=0).

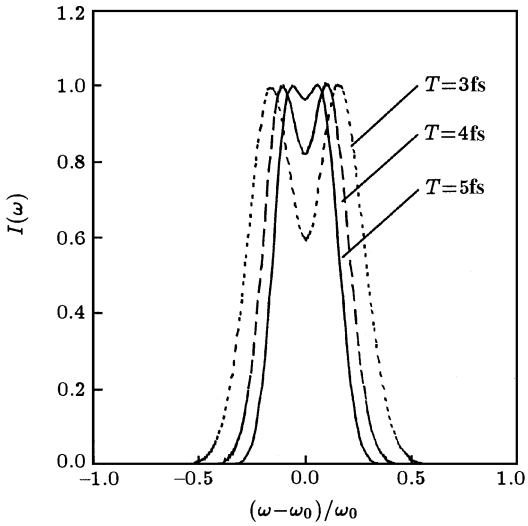


Fig.6. Normalized power spectrum $I(\omega)$ of chirped Gaussian pulses for different values of T=3fs, 4fs and 5fs. The calculation parameters are C=1, δ=0.8, λ_0=800nm and z/z_0=0.32 (m=0).

3.2. Axial intensity distribution in the space-time domain

To confirm the validity of Eq.(17), numerical calculations for the temporal intensity distribution were performed using Eqs.(15) and (17). Some examples are shown in Figs.7(a)–(c), where the normalized temporal intensity distribution $I(t') = I(0,z,t')/I_{\max}(0,z,t')$ at the position z/z_0=0.4 of chirped Gaussian pulses for different values of C=0, 1 and 3 are plotted against normalized local time t'/T. It is seen that the results in the use of Eqs.(15) and (17) find a good consistency in the near field.

Equation (17) indicates that the axial temporal intensity distribution $I(0,z,t')$ is affected by the function of $\cos\left[\frac{\delta^2 T_0}{2z/z_0}\left(\omega_0 + \frac{t'C}{T^2} + \frac{C}{2T^2}\frac{\delta^2 T_0}{2z/z_0}\right)\right]$; the modification of the axial intensity increases with increasing chirp parameter C and decreasing z/z_0, as shown in Fig.8, where the normalized temporal intensity distributions of chirped Gaussian pulses at z/z_0=0.213 and 0.16 are given in Figs.8(a) and (b), respectively. As can be seen, there are additionally the shifting of maximum and splitting of temporal intensity profiles.

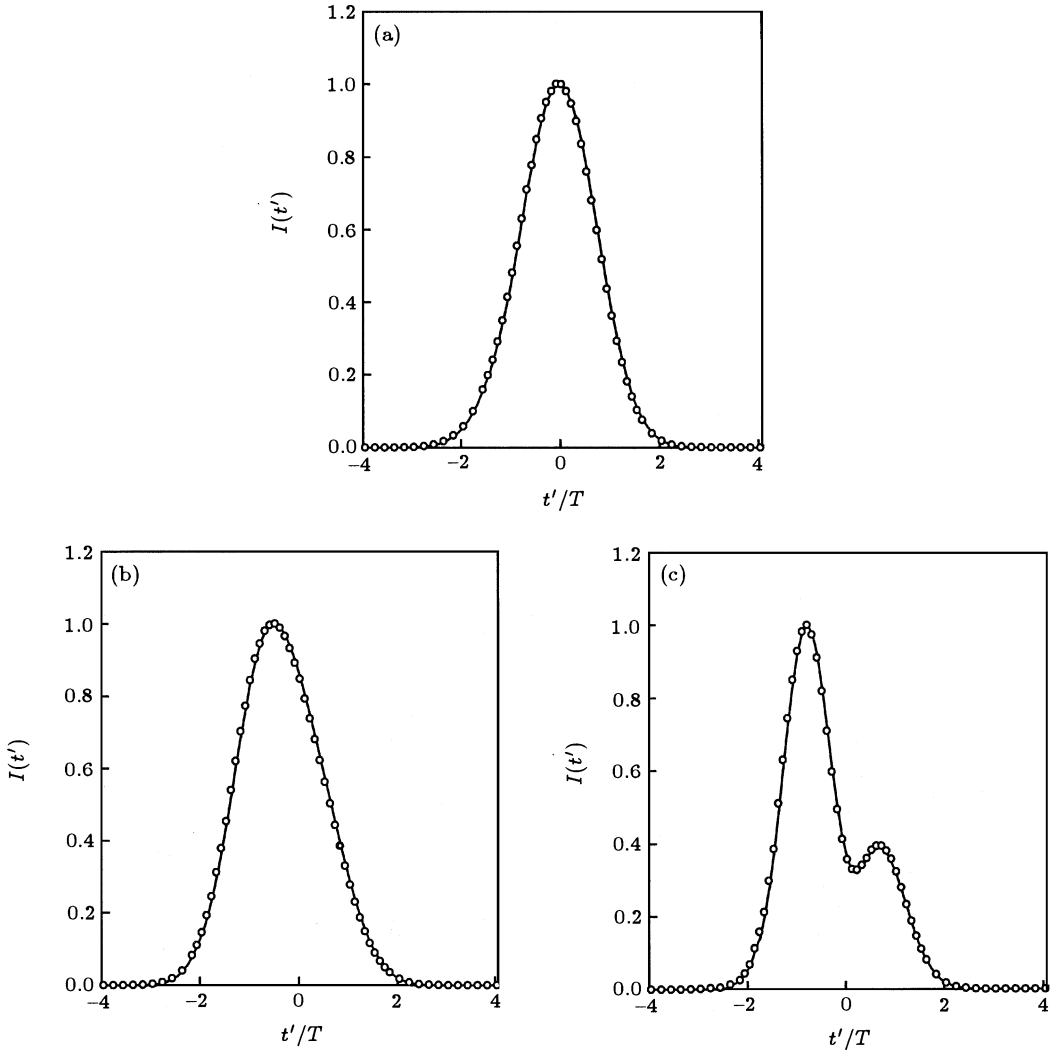


Fig.7. Normalized temporal intensity distribution $I(t') = I(0,z,t')/I_{\max}(0,z,t')$ at z/z_0=0.4 of chirped Gaussian pulses. (a) C=0; (b) C=1; (c) C=3. The other calculation parameters are the same as those in Fig.1. 'o o o' by using Eq.(15), '—' by using Eq.(17).

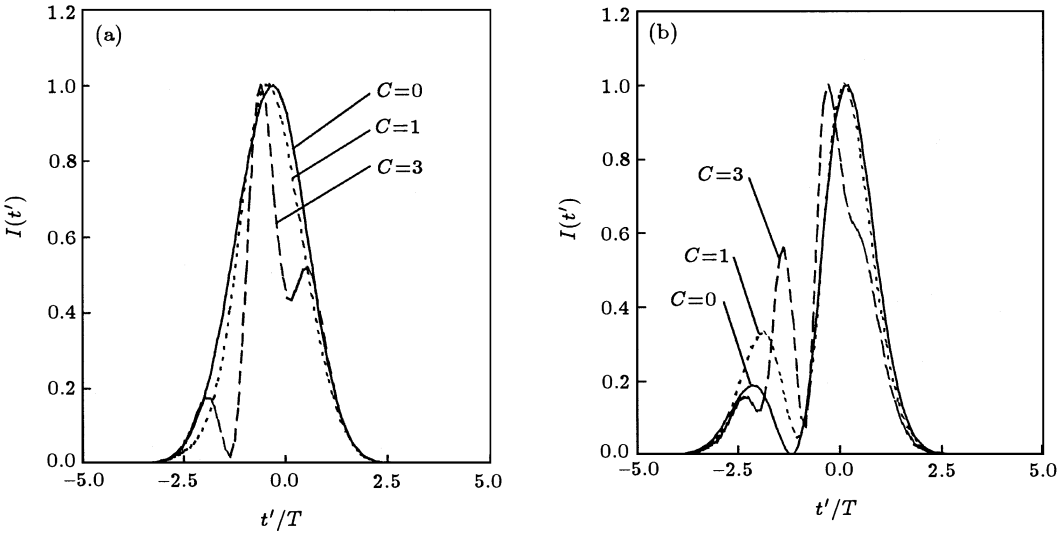


Fig.8. Normalized temporal intensity distribution $I(t')$ of chirped Gaussian pulses for different values of C=0, 1 and 3. (a) z/z_0=0.213; (b) z/z_0=0.16. The other calculation parameters are as in Fig.1.

4. Conclusions

In this study analytical expressions for the axial power spectrum and near-field intensity in the space-time domain of chirped Gaussian pulses diffracted at an aperture have been derived. Detailed numerical examples have been given to illustrate the anomalous spectral behaviour of diffracted chirped Gaussian pulses in the near field. The spectrum may be redshifted, blueshifted and split into two or more than two parts, depending upon the axial position of z/z_0, or equivalently, upon the position of central frequency ω_0 on the $M(0, z, \omega)$ curve. Specifically, the spectral switch may take place for diffracted chirped pulses. Besides the truncation parameter δ, the chirp parameter C and pulse duration T affect the behaviour of spectral switches for ultrashort chirped pulses. The central dip and spectral width increase with decreasing δ, T and increasing C. Finally, it is worth mentioning that the spectral switch of ultrashort pulses provides a useful tool, capable of performing 'rapid switching' both in the spectral and temporal regions, and has some potential applications in optical interconnects and communications, etc.[19,20] However, several key techniques must be solved, as pointed out in Ref.[8], before finding its practical applications.

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