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The influence of nonparaxiality on the spectral behavior in Young's experiment illuminated by partially coherent light*

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Starting from the Rayleigh–Sommerfeld diffraction integral, this paper studies the spectral behavior in Young's experiment illuminated by nonparaxial partially coherent light and compares with the paraxial case, where the influence of nonparaxiality of partially coherent light on the spectral shifts and spectral switches is stressed. It is shown that there is a spectral shift in the nonparaxial case relative to the paraxial one and the critical position changes, at which the spectral switch occurs. The ratio of the waist width to the central wavelength w_0/λ_0 and relative spatial correlation length Δ affect the spectral difference. The smaller w_0/λ_0 is, the larger the difference between the nonparaxial and paraxial results appears. The effect of relative spatial correlation length Δ is relatively small.

Keywords: nonparaxial beams, Young's experiment, spectral shift and spectral switch, partially coherent light

PACC: 4260H, 0765

1. Introduction

Much interest has been exhibited recently in the spectral behavior of partially coherent light on propagation. Extensive theoretical and experimental studies of the spectral changes including spectral shifts and spectral switches have been made.[1−12] It was shown that the spectral switch of partially coherent light belongs to a new effect in singular optics[5] and is both diffraction-induced and correlation-induced.[5−8] On the other hand, it is well known that Young's interference experiment is one of the most important experiments in optics and still remains a source of novel physical insights.[13−19] Up to now, several new effects have already been predicted or observed. For example, a vector mode analysis has been proposed by Gori, Santarsiero and Borghi.[16] Based on the unified theory of coherence and polarization,[20] the spectra, coherence and degree of polarization in Young's interference pattern formed by stochastic electromagnetic beams have been analyzed by Li, Lee and Wolf,[17] Chen and Pu.[19] The spectral shifts and spectral switches of partially coherent polychromatic light in Young's interference experiment were predicted theoretically in references [3] and [4] and confirmed experimentally in reference [10]. Up to now, most works have been restricted to the framework of the paraxial approximation. However, for beams with a large divergence angle and/or with width comparable to the wavelength, the paraxial theory is no longer valid.[21,22] Therefore, it is of interest to ask what will happen if the slits in Young's interference experiment are illuminated by nonparaxial partially coherent polychromatic light. The purpose of this paper is to study how the beam nonparaxiality affects the spectral behavior in Young's experiment. Based on the Rayleigh–Sommerfeld diffraction integral, the theoretical considerations are presented in Section 2. Numerical calculation results are given in Section 3, where the influence of nonparaxiality on the spectral shifts and spectral switches in Young's experiment is stressed and illustrated. Finally, Section 4 summarizes the main results obtained in this paper.

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2. Theoretical model

As shown in Fig.1 in Young's experimental set-up an opaque screen A at the plane $z = 0$ contains two identical slits at points P_1 and P_2, and the inner and outer distances of the two slits are $2b$ and $2a$, respectively. The observation screen B is located at the z plane. Assuming that screen A is illuminated by partially coherent light, a typical example of which is the Gaussian Schell-model source, whose cross-spectral density function is

$$W^{(0)}(x_1, y_1, x_2, y_2, \omega) = S^{(0)}(\omega) \exp\left[-\left(\frac{x_1^2 + x_2^2}{w_0^2} + \frac{y_1^2 + y_2^2}{w_0^2}\right)\right] \times \exp\left[-\left(\frac{(x_1 - x_2)^2}{2\sigma^2(\omega)} + \frac{(y_1 - y_2)^2}{2\sigma^2(\omega)}\right)\right], \quad (1)$$

where ω is the frequency, $S^{(0)}(\omega)$ is the original spectrum, ω_0 and $\sigma(\omega)$ denote the waist width and spatial correlation length of the source at the plane $z = 0$, (x_1, y_1), (x_2, y_2) are transverse coordinates of points P_1 and P_2, respectively.

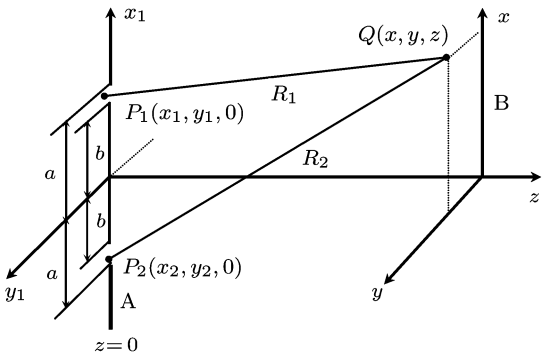


Fig.1. Notation relating to Young's experiment.

Young's interference experiment can be treated as a two-slit diffraction phenomenon.[23] Without invoking the paraxial approximation, we start from the propagation law of cross-spectral density obtained from the Rayleigh diffraction integral,[24] the spectrum for point $Q(x, y, z)$ at the observation screen is expressed as

$$S(x, y, z, \omega) = \left(\frac{k}{2\pi}\right)^2 \int_\Lambda \int_\Lambda \int_\Lambda \int_\Lambda W^{(0)}(x_1, y_1, x_2, y_2, \omega) \times \frac{\cos\theta_1 \cos\theta_2}{R_1 R_2} \exp[\mathrm{i}\, k(R_2 - R_1)] \mathrm{d}x_1 \mathrm{d}y_1 \mathrm{d}x_2 \mathrm{d}y_2, \quad (2)$$

where $k = \omega/c$ is the wavenumber, the integration is made with respect to the two slits and

$$R_j = \sqrt{(x - x_j)^2 + (y - y_j)^2 + z^2} \quad (j = 1, 2 \text{ unless otherwise stated}), \quad (3)$$

$$\cos\theta_j = z/R_j. \quad (4)$$

Equation (2) is valid if $1/R_1 \ll k$, $1/R_2 \ll k$.[24]

The expansion of R_j into a series yields[22]

$$R_j \approx r + \frac{x_j^2 + y_j^2 - 2(x_j x + y_j y)}{2r}, \quad (5)$$

where $r = \sqrt{x^2 + y^2 + z^2}$, and the original spectrum $S^{(0)}(\omega)$ is assumed to be Gaussian with bandwidth σ, i.e.,

$$S^{(0)}(\omega) = \exp\left[-\frac{(\omega - \omega_0)^2}{2\sigma^2}\right]. \quad (6)$$

The spatial correlation length $\sigma(\omega)$ is written as

$$\sigma(\omega) = \sigma_0 \frac{\omega_0}{\omega}, \quad (7)$$

where σ_0 is the spatial correlation length at the central frequency ω_0. Therefore, the beam obeys the scaling law.[1]

Replacing R_j in the exponential term of Eq.(2) by Eq.(5), and that in other terms by r, substituting Eq.(1) into Eq.(2), and letting y=0, after tedious but straightforward integral calculations, we obtain the spectrum $S(u, 0, z, \omega)$ in the x direction at observation screen B, which is given by

$$S(u, 0, z, \omega) = \exp\left[-\frac{(\omega - \omega_0)^2}{2\sigma^2}\right] M(u, 0, z, \omega), \quad (8)$$

where

$$M(u,0,z,\omega)=M_x(u,z,\omega)M_y(0,z,\omega),\quad \text{(spectral modifier)} \tag{9}$$

$$M_x(u,z,\omega)=\frac{1}{2\sqrt{\pi F}}\frac{zz_0}{r^2}\frac{\omega}{\omega_0}\left[\int_{-1}^{-\varepsilon}G(u,z,\omega)\mathrm{d}u_1+\int_{\varepsilon}^{1}G(u,z,\omega)\mathrm{d}u_1\right], \tag{10}$$

$$M_y(0,z,\omega)=\frac{zz_0}{r^2}\frac{\omega}{\omega_0}\frac{1}{\sqrt{FF^*-\omega^4/4\Delta^4\omega_0^4}}, \tag{11}$$

$$\begin{aligned}G(u,z,\omega)=\exp\left[u_1(Hu-F^*u_1)+\frac{(u_1\omega^2-Hu\Delta^2\omega_0^2)^2}{4F\Delta^4\omega_0^4}\right]\Bigg\{&\mathrm{erf}\left[\frac{-u_1\omega^2/\omega_0^2+(2F+Hu)\Delta^2}{2\sqrt{F}\Delta^2}\right]\\&-\mathrm{erf}\left[\frac{-u_1\omega^2/\omega_0^2+(-2F+Hu)\Delta^2}{2\sqrt{F}\Delta^2}\right]+\mathrm{erf}\left[\frac{-u_1\omega^2/\omega_0^2+(Hu-2F\varepsilon)\Delta^2}{2\sqrt{F}\Delta^2}\right]\\&-\mathrm{erf}\left[\frac{-u_1\omega^2/\omega_0^2+(Hu+2F\varepsilon)\Delta^2}{2\sqrt{F}\Delta^2}\right]\Bigg\},\end{aligned} \tag{12}$$

$$F=\frac{z_0}{\lambda_0\pi}\frac{1}{(w_0/\lambda_0)^2}+\frac{1}{2\Delta^2}\left(\frac{\omega}{\omega_0}\right)^2-\frac{H}{2}, \tag{13}$$

$$H=\frac{2\,\mathrm{i}\,z_0}{r}\frac{\omega}{\omega_0}, \tag{14}$$

$$z_0=\pi\frac{a^2}{\lambda_0}, \tag{15}$$

$$\varepsilon=b/a,\quad (0\le\varepsilon<1)\quad \text{(slit parameter)}, \tag{16}$$

$$\Delta=\sigma_0/a,\quad \text{(relative spatial correlation length)}, \tag{17}$$

$$u=x/a,\quad u_1=x_1/a\quad \text{(relative coordinates in the } x \text{ direction)}, \tag{18}$$

in which erf(•) stands for the error function, λ_0 denotes the central wavelength corresponding to the central frequency ω_0 of the original spectrum. Equation (8) indicates that the spectrum in the x direction at observation screen B can be expressed in terms of a product of the original spectrum $S^{(0)}(\omega)$ and spectral modifier $M(u,\,0,\,z,\,\omega)$. $M(u,\,0,\,z,\,\omega)$ describes how the slit diffraction modifies the original spectrum $S^{(0)}(\,\omega)$ and depends mainly on the waist width to the central wavelength w_0/λ_0, relative spatial correlation length Δ, slit parameter ε, and coordinates u, z at the observation point Q.

From Eq.(8) the intensity turns out to be

$$I(u,0,z)=\int_0^{+\infty}S(u,0,z,\omega)\mathrm{d}\omega. \tag{19}$$

Making use of the paraxial approximation

$$R_j\approx z+\frac{x_j'^2+y_j'^2-2(x_j'x+y_j'y)}{2z}, \tag{20}$$

we get the spectrum in the x direction at observation screen B

$$S_p(u,0,z,\omega)=\exp\left[-\frac{(\omega-\omega_0)^2}{2\sigma^2}\right]M_p(u,0,z,\omega), \tag{21}$$

where

$$M_p(u,0,z,\omega)=M_{px}(u,z,\omega)M_{py}(0,z,\omega)\quad \text{(spectral modifier)} \tag{22}$$

$M_{px}\ (u,z,\omega)$ and $M_{py}\ (0,z,\omega)$ are the results of $M_x\ (u,z,\omega)$ and $M_y(0,z,\omega)$ in Eq.(9) by letting $r=z$, and the intensity in the paraxial approximation is written as

$$I_p(u,0,z)=\int_0^{+\infty}S_p(u,0,z,\omega)\mathrm{d}\omega. \tag{23}$$

Furthermore, for the two-dimensional case (x, z), by letting $w_0\to\infty$ and $u=0$, equation (21) becomes

$$S_p(0,z,\omega)=\frac{ak\sigma_0\omega_0}{2\pi z}\exp\left[-\frac{(\omega-\omega_0)^2}{2\sigma^2}\right]\left[\int_{-1}^{-\varepsilon}G_p(0,z,\omega)\mathrm{d}u_1+\int_{\varepsilon}^{1}G_p(0,z,\omega)\mathrm{d}u_1\right], \tag{24}$$

where

$$G_p(0,z,\omega)=\sqrt{\frac{\pi cz}{2\omega(cz\omega-\mathrm{i}\,\sigma_0^2\omega_0^2)}}\exp\left[-\frac{a^2u_1^2\sigma_0^2\omega\omega_0^2}{2c^2z^2\omega-2\,\mathrm{i}\,cz\sigma_0^2\omega_0^2}\right]\left\{\mathrm{erf}\left[\frac{a\sqrt{\omega}(cz\omega(1+u_1)-\mathrm{i}\,\sigma_0^2\omega_0^2)}{\sqrt{2cz}\sigma_0\omega_0\sqrt{cz\omega-\mathrm{i}\,\sigma_0^2\omega_0^2}}\right]\right.$$
$$-\mathrm{erf}\left[\frac{a\sqrt{\omega}(cz\omega(-1+u_1)+\mathrm{i}\,\sigma_0^2\omega_0^2)}{\sqrt{2cz}\sigma_0\omega_0\sqrt{cz\omega-\mathrm{i}\,\sigma_0^2\omega_0^2}}\right]-\mathrm{erf}\left[\frac{a\sqrt{\omega}(cz\omega(u_1+\varepsilon)-\mathrm{i}\,\varepsilon\sigma_0^2\omega_0^2)}{\sqrt{2cz}\sigma_0\omega_0\sqrt{cz\omega-\mathrm{i}\,\sigma_0^2\omega_0^2}}\right]$$
$$\left.+\mathrm{erf}\left[\frac{a\sqrt{\omega}(cz\omega(u_1-\varepsilon)+\mathrm{i}\,\varepsilon\sigma_0^2\omega_0^2)}{\sqrt{2cz}\sigma_0\omega_0\sqrt{cz\omega-\mathrm{i}\,\sigma_0^2\omega_0^2}}\right]\right\}. \tag{25}$$

Equation (24) is the on-axis spectrum at the observation screen if two slits in Young's experiment are illuminated by a two-dimensional Schell-model beam, and is consistent with Eq.(5) in reference [3] provided that the original Gaussian spectrum in Eq.(24) is replaced by the Lorentzian spectrum.

3. Numerical calculation results and comparision

To compare the difference between the nonparaxial and paraxial results and to illustrate the influence of nonparaxiality of partially coherent light on the spectral shifts and spectral switches, numerical calculations were performed by using Eqs. (8), (19), (21) and (23), and typical results are compiled in Figs.2–5 and Table 1. In our calculations the calculation parameters $\omega_0 = 3.2\times10^{15}$ s^{-1}, $\sigma = 0.6\times10^{15}$ s^{-1}, $\varepsilon = 0.3$ and $z = 4z_0$ are fixed.

Figures 2(a) and 2(b) give normalized intensity distributions in the x direction at observation screen B for different values of the ratio of the waist-width to the central wavelength w_0/λ_0 and relative spatial correlation length Δ, respectively, a close look at the vicinity of intensity minima is depicted together. Figures 2(a) and 2(b) indicate that the beam nonparaxiality gives rise to a shift of the position of intensity minimum from $u_{p\min}$ (the paraxial result) to $u_{\min}$ (the nonparaxial result), $\Delta u_{\min} = u_{\min} - u_{p\min}$ compiled in Table 1 is dependent on w_0/λ_0 and Δ, and increases with decreasing w_0/λ_0 and Δ, because the decrease of w_0/λ_0 and Δ results in an increase of the beam nonparaxiality,[22] but Δ plays a minor role, e.g., for w_0/λ_0=1.5 and $\Delta \geq 3$, $\Delta u_{\min} = 0.0404$ does not decrease with increasing Δ.

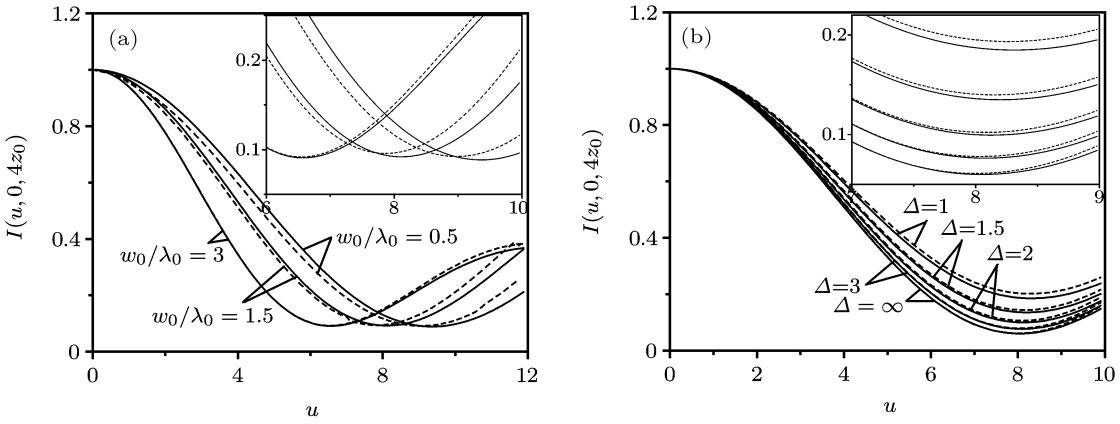


Fig.2. Normalized intensity distributions $I(u, 0, 4z_0)$,"—" by using equation (19),"- - -" by using Eq.(23). (a) $\Delta = 2$, $w_0/\lambda_0 = 0.5$, 1.5 and 3; (b) $w_0/\lambda_0 = 1.5$, $\Delta = 1$, 1.5, 2, 3 and ∞.

The normalized spectra $S(\omega)$ at u=8.0300, 8.0938, 8.1170 and 8.1311 are shown in Figs.3(a)–3(d) respectively, the calculation parameters are w_0/λ_0=1.5 and Δ=2. From figures 3(a)–(d) we see that a noticeable discrepancy between the nonparaxial and paraxial results appears, for example, there is a spectral blue shift in

accordance with Eq.(8) relative to the spectrum in accordance with Eq.(21) at $u = 8.0300$ in Fig.3(a). The spectrum is red-shifted according to Eq.(8) relative to the original spectrum, whereas the spectral switch takes place according to Eq.(21) at $u_{pc} = 8.0938$ near $u_{p\min} = 8.0672$ in Fig.3(b). The spectrum is red- and blue-shifted relative to the original spectrum, according to Eqs.(8) and (21) in Fig.3(c), respectively. The spectral switch takes place at $u_c = 8.1311$ near $u_{\min} = 8.1104$ in Fig.3(d) if the beam nonparaxiality is taken into consideration, whereas the spectrum is blue-shifted relative to the original spectrum in the paraxial approximation.

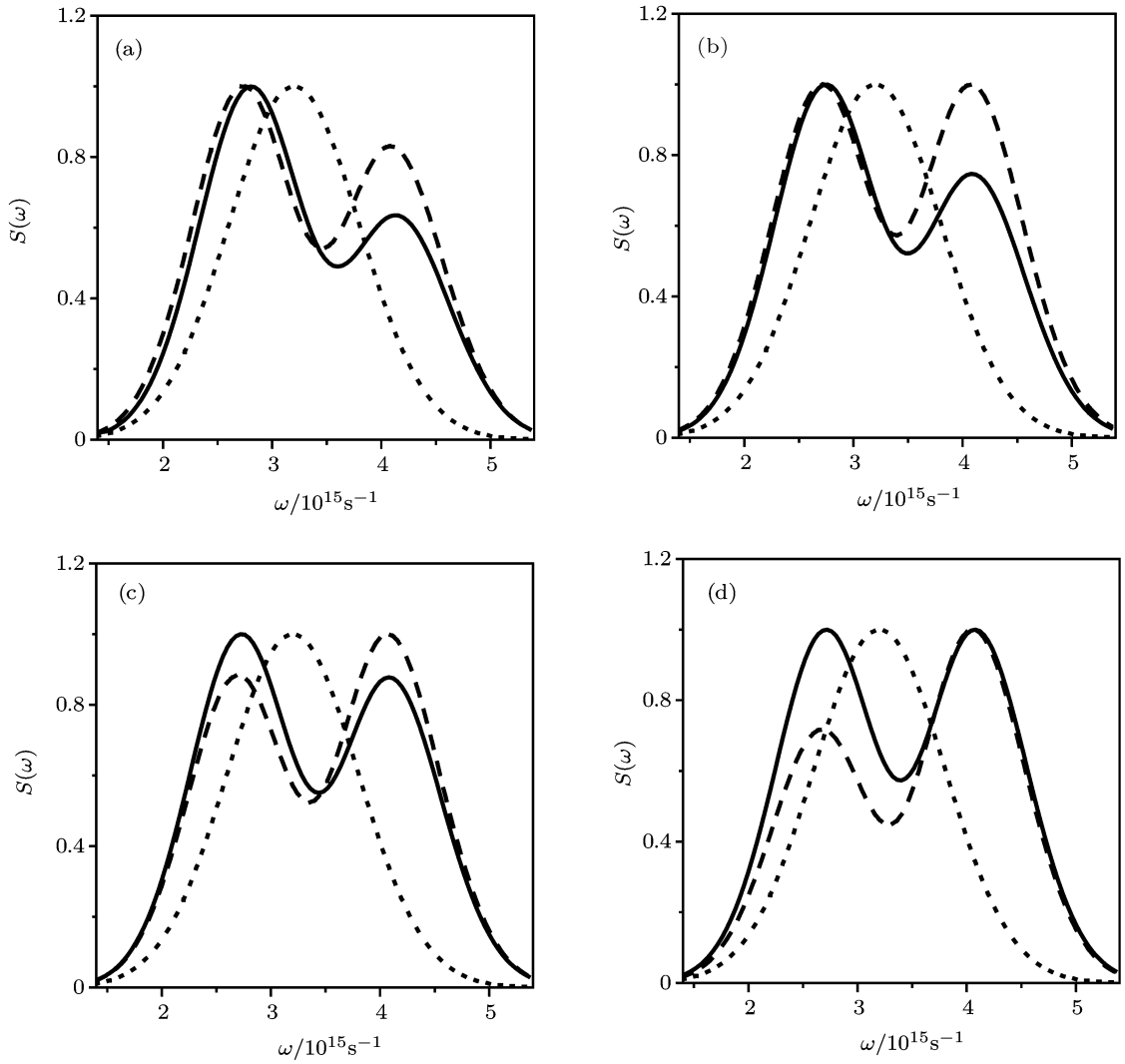


Fig.3. Normalized spectra $S(\omega)$, "—" by using Eq.(8),"- - -" by using Eq.(21), "...." original spectrum. (a) $u = 8.0300$; (b) $u = 8.0938$; (c) $u = 8.1170$; (d) $u = 8.1311$.

Table 1. (a) Positions of intensity minima in Fig.2(a).

w_0/λ_0	0.5	1.5	3
$u_{\min}$	9.3656	8.1104	6.5738
$u_{p\min}$	9.2884	8.0672	6.5492
$\Delta u_{\min}$	0.0772	0.0432	0.0246

Table 1. (b) Positions of intensity minima in Fig.2(b).

Δ	1	1.5	2	3	∞
$u_{\min}$	8.3074	8.1620	8.1104	8.0562	8.0458
$u_{p\,\min}$	8.2530	8.1156	8.0672	8.0158	8.0054
$\Delta u_{\min}$	0.0544	0.0464	0.0432	0.0404	0.0404

The relative spectral shift is defined as

$$\frac{\delta\omega}{\omega_0} = \frac{\omega_{\max} - \omega_0}{\omega_0}, \tag{26}$$

where $\omega_{\max}$ is the frequency corresponding to the spectral maximum. The raito $\delta\omega/\omega_0$ versus the relative coordinate u is plotted in Figs.4(a) and 4(b) for different values of w_0/λ_0 and Δ, respectively. As can be seen, there exists a difference $\Delta u_c = u_c - u_{pc}$ of the critical position between the nonparaxial and paraxial results. The smaller the value of w_0/λ_0 is, the larger the difference $u_c - u_{pc}$ appears, for

example, for $\Delta = 2$, w_0/λ_0=0.5, 1.5 and 3, we have $\Delta u_c = 0.0774$, 0.0379 and 0.0096 in Fig.4(a). Only under a certain condition, e.g., for $\Delta = 2$, $w_0/\lambda_0 \geq 3$, the nonparaxial results are in agreement with the paraxial ones. However, Δu_c nearly remains unchanged as Δ increases, for example, for $w_0/\lambda_0 = 1.5$, $\Delta = 1.5$, 2, 3 and ∞, we have $\Delta u_c = 0.0392$, 0.0377, 0.0365 and 0.0356, respectively, in Fig.4(b). It means that the effect of spatial correlation on the position of the spectral switch is relatively small.

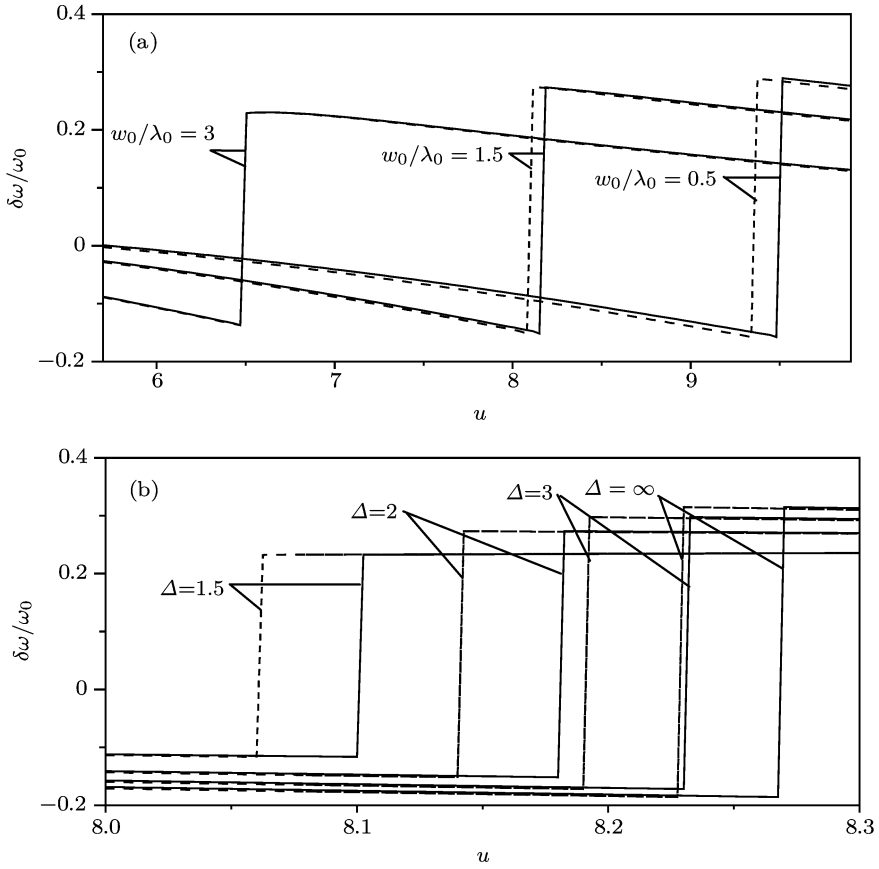


Fig.4. Relative spectral shifts $\delta\omega/\omega_0$ versus the relative coordinate u, "—" by using Eq.(8), "- - -" by using Eq.(21). (a) $\Delta = 2$, $w_0/\lambda_0 = 0.5$, 1.5 and 3; (b) $w_0/\lambda_0 = 1.5$, $\Delta = 1.5$, 2, 3 and ∞.

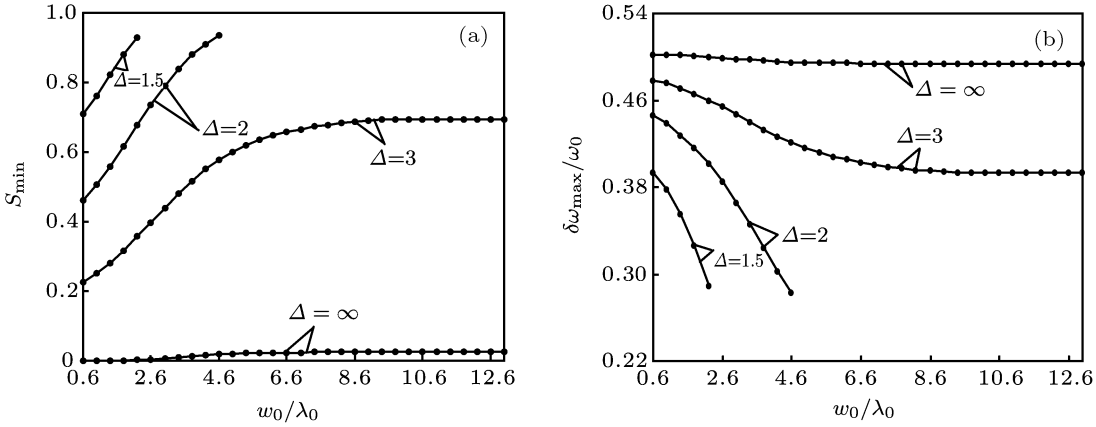


Fig.5. (a) Normalized spectrum minima $S_{\min}$ and (b) relative spectral transition $\delta\omega_{\max}/\omega_0$ versus the ratio of the waist width to the central wavelength w_0/λ_0 for different values of the relative spatial correlation length Δ.

It is known that there are three parameters characterizing spectral switches,[9] they are the critical position u_c at which the spectral switch takes place, the minimum value $S_{\min}$ of the spectrum at the spectral switch and

the relative spectral transition $\delta\omega_{\max}/\omega_0$ defined as

$$\frac{\delta\omega_{\max}}{\omega_0} = \frac{|\omega_{\max,2} - \omega_{\max,1}|}{\omega_0}, \tag{27}$$

where $\omega_{\max,1}$, $\omega_{\max,2}$ are the frequencies corresponding to two equal spectral maxima at the spectral switch, respectively. The normalized spectral minima $S_{\min}$ and relative spectral transition $\delta\omega_{\max}/\omega_0$ as a function of w_0/λ_0 for different values of Δ are depicted in Figs.5(a) and 5(b), which indicate that the effect of nonparaxiality on $S_{\min}$ and $\delta\omega_{\max}/\omega_0$ is negligible because the results in the use of Eq.(8) are consistent with those in the use of Eq.(21) for small values of w_0/λ_0.

4. Concluding remarks

In this paper, based on the generalized Rayleigh–Sommerfeld diffraction integral, we have studied the spectral shifts and spectral switches in Young's experiment illuminated by nonparaxial partially coherent light and compared with the paraxial results. The main physical results obtained in this paper are that the position of intensity minimum calculated by the generalized Rayleigh–Sommerfeld diffraction integral does not coincide with that in the paraxial approximation, which results in a spectral difference between the nonparaxial and paraxial results. The spectrum in the nonparaxial case relative to the paraxial one is shifted and the critical position changes at which the spectral switch takes place. The ratio of the waist width to the central wavelength w_0/λ_0 and relative spatial correlation length Δ affect the spectral difference. The smaller the ratio of the waist width to the central wavelength w_0/λ_0 is, the larger the difference between the nonparaxial and paraxial results appears, and the effect of spatial correlation is relatively small. Only under a certain condition, e.g., for $\Delta = 2$, $w_0/\lambda_0 \geq 3$, the nonparaxial results are consistent with paraxial ones. Therefore, in studying the spectral behavior in Young's experiment illuminated by partially coherent light with width comparable to the wavelength, the effect of beam nonparaxiality has to be taken into consideration. Otherwise, as shown e.g., in Figs.3 and 4(b), the apparent discrepancies will take place.

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