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Effect of astigmatism on spectral switches of partially coherent beams*

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A detailed study of the spectrum of partially coherent beams diffracted at an astigmatic aperture lens is performed. Considerable attention is paid to the effect of astigmatism on spectral switches of polychromatic Gaussian Schell-model beams. It is shown that the spectral switch can also take place in the vicinity of intensity minimum in a geometrical focal plane for the astigmatic case, but the astigmatism of the lens and the spatial correlation of the beam affect the critical position u_c, spectral minimum S_{min}, and transition height Δ of spectral switches.

Keywords: modern optics, spectral switch, astigmatic lens, aperture, polychromatic Gaussian Schell-model (GSM) beam

PACC: 4255, 4200

1. Introduction

In 1999 Pu and his collaborators found theoretically[1] that when a partially coherent beam was diffracted at an aperture, remarkable spectral changes took place close to certain critical positions. The spectra are redshifted on one side of their positions, blueshifted on the other side, and split into two lines at their critical positions. The phenomenon is referred to as a spectral switch. Since then an extensive study of spectral changes and spectral switches has been made theoretically[1–7] and confirmed experimentally.[8–10] In 2002 Foley and Wolf pointed out that the phenomenon of spectral switches belonged to the domain of a rapidly developing new field of modern optics known as singular optics.[11] The physical interpretation of spectral switches of spatially fully and partially coherent, polychromatic beams is given in Refs.[6] and [11]. As yet, the main attention has been focused on spectral changes and spectral switches for the aberration-free case. However, the experiment demonstrated[10] that there existed discrepancies between the theory and experiment, which can be attributed to phase aberrations in the optical system. The purpose of the present paper is to study the effect of astigmatism of an aperture lens on spectral switches of partially coherent beams. In Section 2 the polychromatic Gaussian Schell-model (GSM) beam is taken in a typical example of partially coherent beams, an expression for the spectrum of polychromatic GSM beams in passage through an astigmatic aperture lens is derived and analysed on the basis of the propagation law of partially coherent beams. Section 3 presents numerical calculations and discussions. Finally, The main results obtained in this paper are summarized in Section 4.

2. Theoretical formulation

Assume that a polychromatic GSM beam is incident upon an astigmatic lens with an rectangular aperture in the z=0 plane. The cross-spectral density function of the GSM beam reads as[12]

$$\begin{aligned} &W^{(0)}(x'_1, y'_1, x'_2, y'_2, 0, \omega) \\ =&S^{(0)}(\omega)\exp\left[-\left(\frac{x'^2_1+x'^2_2}{w_0^2}+\frac{y'^2_1+y'^2_2}{w_0^2}\right)\right] \\ &\times\exp\left[-\left(\frac{(x'_1-x'_2)^2}{2\sigma_u^2}+\frac{(y'_1-y'_2)^2}{2\sigma_u^2}\right)\right], \quad (1) \end{aligned}$$

where w_0 and σ_u denote the waist width and spatial correlation length of the GSM beam, respectively.

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$(x'_1, y'_1), (x'_2, y'_2)$ are transversal coordinates of two points in the z=0 plane, $S^{(0)}(\omega)$ stands for the original spectrum, and ω is the frequency.

According to the propagation law of partially coherent beams,[1,12] the spectrum of GSM beams in passage through the astigmatic aperture lens reads as

$$S(x,y,z,\omega) = \left(\frac{k}{2\pi B}\right)^2 \int_{-a}^{a}\int_{-a}^{a}\int_{-a}^{a}\int_{-a}^{a} W^{(0)}(x'_1, y'_1, x'_2, y'_2, 0, \omega)\exp\{\mathrm{i}kC_6[(x'^2_1 - x'^2_2) - (y'^2_1 - y'^2_2)]\}$$
$$\times \exp\left\{-\frac{\mathrm{i}k}{2B}[A((x'^2_1 + y'^2_1) - (x'^2_2 + y'^2_2)) - 2x(x'_1 - x'_2) - 2y(y'_1 - y'_2)]\right\}\mathrm{d}x'_1\mathrm{d}y'_1\mathrm{d}x'_2\mathrm{d}y'_2, \quad (2)$$

where k is the wave number, a is the half width of the aperture, and the $ABCD$ matrix is expressed as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 - z/f & z \\ -1/f & 1 \end{bmatrix} \quad (3)$$

with f being the focal length of the lens. In Eq.(2) the astigmatism of the lens is characterized by a term

$$\exp\{\mathrm{i}kC_6[(x'^2_1 - x'^2_2) - (y'^2_1 - y'^2_2)]\}, \quad (4)$$

where C_6 is the astigmatic coefficient.[13]

Substituting Eqs.(1) and (3) into Eq.(2), tedious integral calculations lead to

$$S(u, v, \Delta z, \omega) = S^{(0)}(\omega)M(u, v, \Delta z, \omega), \quad (5)$$

where

$$M(u, v, \Delta z, \omega) = M(u, \Delta z, \omega)M(v, \Delta z, \omega), \quad \text{(spectral modifier)}, \quad (6)$$

$$M(u, \Delta z, \omega) = \frac{N}{1+\Delta z}\frac{\omega}{\omega_0}\frac{\sqrt{\pi}}{2\mathrm{i}\sqrt{Q_1^*}}\int_{-\delta}^{\delta}\exp\left\{2\mathrm{i}Huu_1 + Q_1u_1^2 + \frac{[2Hu - \mathrm{i}u_1(\beta^2-1)/\beta^2]^2}{4Q_1^*}\right\}$$
$$\times\left\{\mathrm{erf}\left[\frac{2Hu - u_1(\beta^2-1)\mathrm{i}/\beta^2 + 2Q_1^*\delta\mathrm{i}}{2\sqrt{Q_1^*}}\right] - \mathrm{erf}\left[\frac{2Hu - u_1(\beta^2-1)\mathrm{i}/\beta^2 - 2Q_1^*\delta\mathrm{i}}{2\sqrt{Q_1^*}}\right]\right\}\mathrm{d}u_1,$$
(spectral modifier in the x direction), (7)

$$M(v, \Delta z, \omega) = \frac{N}{1+\Delta z}\frac{\omega}{\omega_0}\frac{\sqrt{\pi}}{2\mathrm{i}\sqrt{Q_2^*}}\int_{-\delta}^{\delta}\exp\left\{2\mathrm{i}Hvv_1 + Q_2v_1^2 + \frac{[2Hv - \mathrm{i}v_1(\beta^2-1)/\beta^2]^2}{4Q_2^*}\right\}$$
$$\times\left\{\mathrm{erf}\left[\frac{2Hv - v_1(\beta^2-1)\mathrm{i}/\beta^2 + 2Q_2^*\delta\mathrm{i}}{2\sqrt{Q_2^*}}\right] - \mathrm{erf}\left[\frac{2Hv - v_1(\beta^2-1)\mathrm{i}/\beta^2 - 2Q_2^*\delta\mathrm{i}}{2\sqrt{Q_2^*}}\right]\right\}\mathrm{d}v_1,$$
(spectral modifier in the y direction), (8)

$$N = w_0^2/(\lambda_0 f), \quad \text{(Fresnel number)}, \quad (9)$$

$$\delta = a/w_0 \quad \text{(truncation parameter)}, \quad (10)$$

$$\beta = \left[1 + \left(\frac{w_0}{\sigma_u}\right)^2\right]^{-1/2} \quad \text{(spatial correlation parameter)}, \quad (11)$$

$$\Delta z = (z - f)/f \quad \text{(relative propagation distance)}, \quad (12)$$

$$u = x/w_0, \quad u_1 = x'_1/w_0, \quad \text{(relative transversal coordinate in the } x \text{ direction)}, \quad (13)$$

$$v = y/w_0, \quad v_1 = y'_1/w_0, \quad \text{(relative transversal coordinate in the } y \text{ direction)}, \quad (14)$$

$$H = \pi N\omega/[(1+\Delta z)\omega_0], \quad (15)$$

$$Q_1 = -1 + (\beta^2-1)/2\beta^2 + \mathrm{i}(2\pi N f C_6\omega/\omega_0 + H\Delta z), \quad (16)$$

$$Q_2 = -1 + (\beta^2-1)/2\beta^2 - \mathrm{i}(2\pi N f C_6\omega/\omega_0 - H\Delta z), \quad (17)$$

λ_0 and ω_0 denote the central wavelength and central frequency of the original spectrum $S^{(0)}(\omega)$, respectively, Q_i^* is the conjugate of $Q_i(i$=1,2), erf is the error function. Equations (5)–(8) provide the spectrum $S(u,v,\Delta z,\omega)$ of polychromatic GSM beams passing through an astigmatic aperture lens. $S(u,v,\Delta z,\omega)$ is expressed as a product of the original spectrum $S^{(0)}(\omega)$ and spectral modifier $M(u,v,\Delta z,\omega)$. $M(u,v,$

Δz, ω) describes how the diffraction at the aperture modifies $S^{(0)}(\omega)$, in which the effect of astigmatism of the lens on the spectrum is included.

Suppose that the original spectrum $S^{(0)}(\omega)$ has a Gaussian form

$$S^{(0)}(\omega) = \exp\left[- \frac{(\omega - \omega_0)^2}{2\sigma_0^2}\right] \tag{18}$$

with σ_0 being the bandwidth. The substitution of Eq.(18) into Eq.(5) yields

$$S(u, v, \Delta z, \omega) = \exp\left[- \frac{(\omega - \omega_0)^2}{2\sigma_0^2}\right] M(u, v, \Delta z, \omega). \tag{19}$$

Equations (7), (8) and (19) imply that the spectrum $S(u,v, \Delta z, \omega)$ is dependent on the truncation parameter δ, spatial correlation β, bandwidth σ_0, Fresnel number N, and position parameters u, v and Δz, as well as the astigmatic coefficient C_6 in general.

Inserting Δz=0 into Eq.(19), we obtain the spectrum in the geometrical focal plane. For simplicity, only the spectrum in the x direction (v=0) is considered, which is given by

$$S(u, 0, 0, \omega) = \exp\left[- \frac{(\omega - \omega_0)^2}{2\sigma_0^2}\right] M(u, 0, 0, \omega), \tag{20}$$

where

$$\begin{aligned} M(u,0,0,\omega) =& \left(N\frac{\omega}{\omega_0}\right)^2 \frac{\pi}{4\sqrt{Q_1^* Q_2^*}} \int_{-\delta}^{\delta} \exp\left\{ 2\mathrm{i}uu_1\pi N\omega/\omega_0 + Q_1 u_1^2 + \frac{[2u\pi N\omega/\omega_0 - \mathrm{i}u_1(\beta^2-1)/\beta^2]^2}{4Q_1^*}\right\} \\ &\times \left\{ \mathrm{erf}\left[\frac{2u\pi N\omega/\omega_0 - u_1(\beta^2-1)\mathrm{i}/\beta^2 + 2Q_1^*\delta\mathrm{i}}{2\sqrt{Q_1^*}}\right] \right. \\ &\left. - \mathrm{erf}\left[\frac{2u\pi N\omega/\omega_0 - u_1(\beta^2-1)\mathrm{i}/\beta^2 - 2Q_1^*\delta\mathrm{i}}{2\sqrt{Q_1^*}}\right]\right\} \mathrm{d}u_1 \\ &\times \int_{-\delta}^{\delta} \exp\left\{ \left[Q_2 - \frac{(\beta^2-1)^2/\beta^4}{4Q_2^*}\right] v_1^2 \right\} \left\{ \mathrm{erf}\left[\frac{v_1(\beta^2-1)\mathrm{i}/\beta^2 - 2Q_2^*\delta\mathrm{i}}{2\sqrt{Q_2^*}}\right] \right. \\ &\left. - \mathrm{erf}\left[\frac{v_1(\beta^2-1)\mathrm{i}/\beta^2 + 2Q_2^*\delta\mathrm{i}}{2\sqrt{Q_2^*}}\right]\right\} \mathrm{d}v_1 \end{aligned} \tag{21}$$

and

$$Q_1 = -1 + (\beta^2-1)/2\beta^2 + \mathrm{i}2\pi N f C_6(\omega/\omega_0), \tag{22}$$

$$Q_2 = -1 + (\beta^2-1)/2\beta^2 - \mathrm{i}2\pi N f C_6(\omega/\omega_0). \tag{23}$$

The spectrum for the aberration-free case is readily obtained from Eq.(19) by letting C_6=0. In particular, the spectral modifier $M(u,v, \Delta z, \omega)$ in the geometrical focal plane of the aberration-free lens is expressed as

$$\begin{aligned} M(u,0,0,\omega) =& \left(N\frac{\omega}{\omega_0}\right)^2 \frac{\pi\beta^2}{2\mathrm{i}(1+\beta^2)} \int_{-\delta}^{\delta} \exp\left[- \frac{2(N^2\pi^2u^2\beta^2\omega^2 + 2\mathrm{i}N\pi uu_1\beta^2\omega\omega_0 + u_1^2\omega_0^2}{(1+\beta^2)\omega_0^2}\right] \\ &\times \left\{ \mathrm{erf}\left[\frac{-2N\pi u\beta^2\omega + (1-\beta^2)u_1\omega_0\mathrm{i} + (1+\beta^2)\delta\omega_0\mathrm{i}}{\sqrt{2(1+\beta^2)}\beta\omega_0}\right] \right. \\ &\left. - \mathrm{erf}\left[\frac{-2N\pi u\beta^2\omega + (1-\beta^2)u_1\omega_0\mathrm{i} - (1+\beta^2)\delta\omega_0\mathrm{i}}{\sqrt{2(1+\beta^2)}\beta\omega_0}\right]\right\} \mathrm{d}u_1 \\ &\times \int_{-\delta}^{\delta} \exp\left[- \frac{2v_1^2}{1+\beta^2}\right] \left\{ \mathrm{erf}\left[\frac{(-1+\beta^2)v_1 - (1+\beta^2)\delta}{\sqrt{2(1+\beta^2)}\beta}\right] - \mathrm{erf}\left[\frac{(-1+\beta^2)v_1 + (1+\beta^2)\delta}{\sqrt{2(1+\beta^2)}\beta}\right]\right\} \mathrm{d}v_1. \end{aligned} \tag{24}$$

The total intensity in the z plane is

$$I(u, v, \Delta z) = \int_0^{\infty} S(u, v, \Delta z, \omega)\mathrm{d}\omega. \tag{25}$$

The normalized intensity distribution $I(u) = I(u,0,0)/I_{\max}(u,0,0)$ ($I_{max}(u,0,0)$—maximum intensity) in the x direction in the geometrical focal plane can be calculated from Eqs.(20), (21) and (25). Numerical examples are given in Fig.1, where the calculation parameters are ω_0=10^{15} s^{-1}, σ_0=0.2×10^{15}s^{-1}, w_0=10^{-3}m, δ=0.4, f=200×10^{-3}m, and (a) β=0.85, (b) β=0.9, (c) β=1. The corresponding intensity parameters are compiled in Table 1(a), (b) and (c).

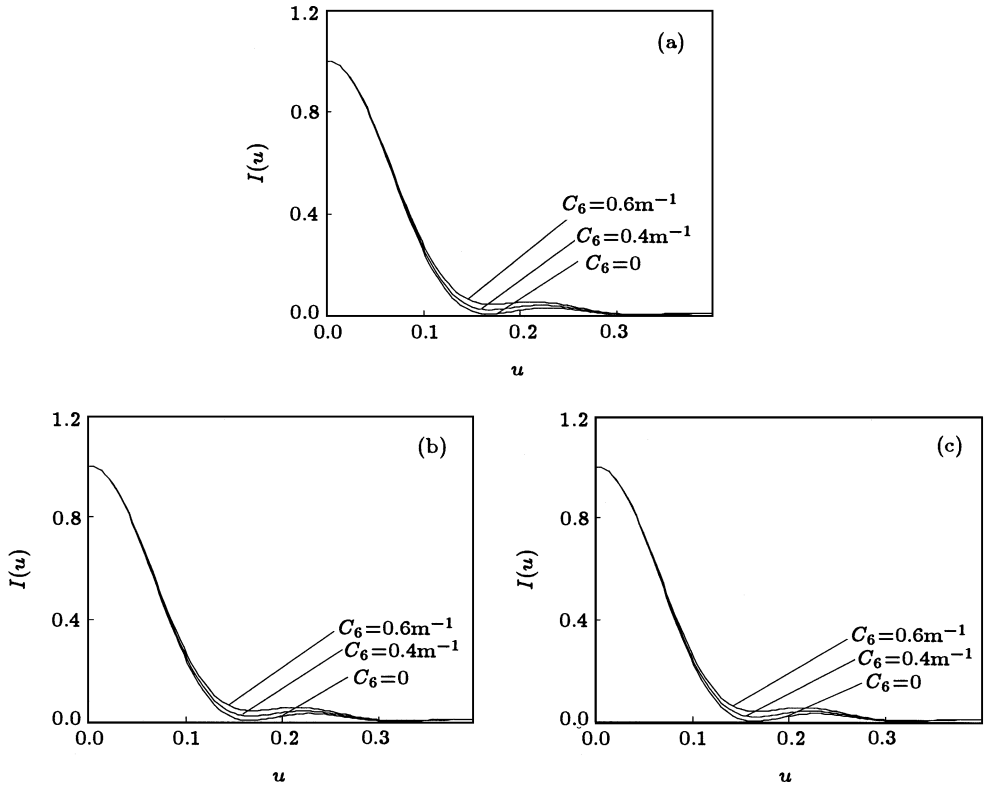


Fig.1. Normalized intensity distributions $I(u)$ in the x direction in the geometrical focal plane of a polychromatic GSM beam passing through an astigmatic aperture lens. The calculation parameters are seen in the text. (a) β=0.85, (b) β=0.9 and (c) β=1.

Table 1. Intensity parameters relating to Fig.1.(a) β=0.85, (b) β=0.9 and (c) β=1.

a

C_6/m^{-1}	0	0.4	0.6
u_0	0.1661, 0.3192	0.1672, 0.3197	0.1691, 0.3206
$I_{\min}$	0.0087, 0.0040	0.0252, 0.0053	0.0464, 0.0072

b

C_6/m^{-1}	0	0.4	0.6
u_0	0.1648, 0.3181	0.1656, 0.3189	0.1674, 0.3198
$I_{\min}$	0.0069, 0.0037	0.0235, 0.0049	0.0448, 0.0068

c

C_6/m^{-1}	0	0.4	0.6
u_0	0.1626, 0.3171	0.1635, 0.3177	0.1648, 0.3184
$I_{\min}$	0.0039, 0.0031	0.0206, 0.0043	0.0420, 0.0061

As can be seen, the intensity distribution depends on the correlation parameter β and astigmatic coefficient C_6. In the region $0 \leq u \leq 0.4$, there are two minima, for example at positions u_0=0.1656 and 0.3189 for β=0.9 and C_6=0.4m^{-1}, the normalized intensity minima $I_{\min}(u_0)$=0.0235 and 0.0049, whereas the calculations showed that in the aberration-free case of C_6 =0, the two intensity minima are located at u_0=0.1648 and 0.3181 for β=0.9. Moreover, the intensity minimum $I_{\min}$ and its position u_0 increase with increasing C_6 and decreasing β.

3. Numerical calculations and discussions

To illustrate the effect of astigmatism on the spectral behaviour in the geometrical focal plane of polychromatic GSM beams diffracted at an astigmatic aperture lens, numerical calculations were performed using Eqs.(20), (21) and (24). Figure 2 gives normalized spectra $S(\omega)=S(u,0,0,\omega)/S_{\max}(u,0,0,\omega)$ ($S_{\max}(u,0,0,\omega)$—spectral maximum) of a polychromatic GSM beam with β=0.9 in passage through an aperture lens. The other calculation parameters are the same as those in Fig.1 (unless otherwise stated). It is seen that, as compared with the aberration-free case, the spectral changes take place. For example, for the case of C_6=0.4m^{-1} (solid curves), the spectrum is redshifted at u=0.3152 in Fig.2(a) and blueshifted at u=0.3174, 0.3178 in Figs.2(c) and (d). The spectrum is split into two lines with equal height at u=0.3169 in Fig.2(b),where the spectral switch appears,[1] whereas by contrast with the aberration-free case of C_6=0 (dashed curves), the spectral switch takes place at u=0.3174 in Fig.2(c). It is noted that the critical position where the spectral switches take place, is located in the neighbourhood of the normalized intensity minima u_0=0.3181 and 0.3189 for C_6=0 and 0.4m^{-1}, respectively.

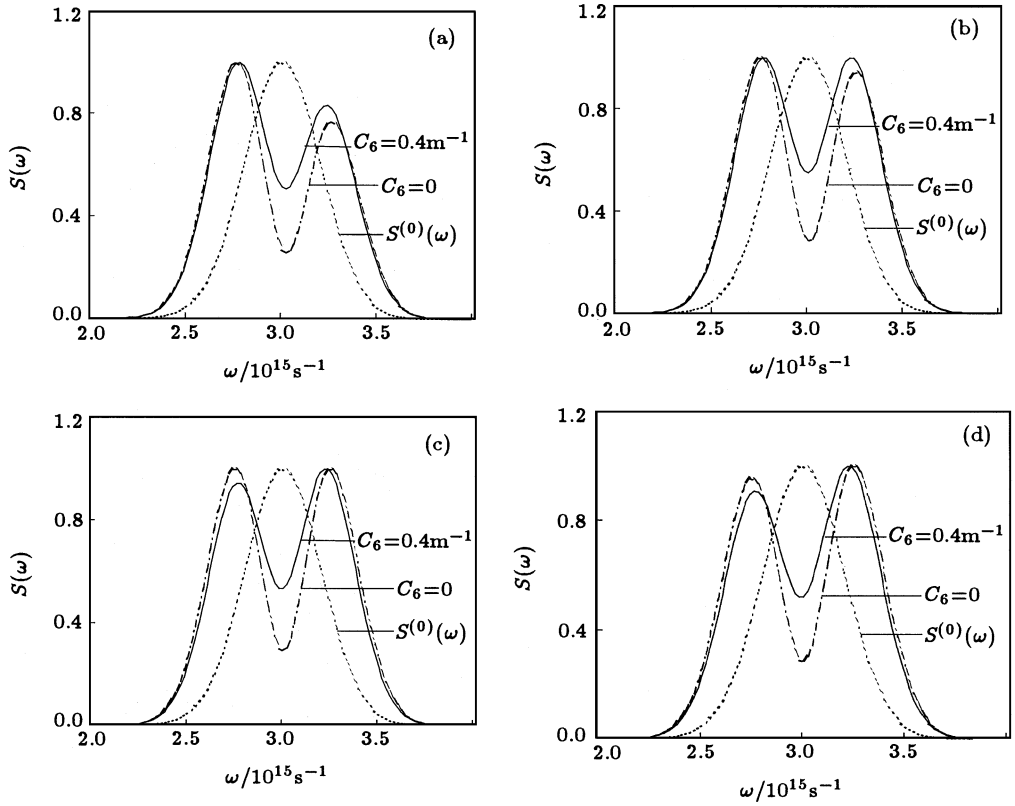


Fig.2. Normalized spectra S (ω) in the geometrical focal plane of a polychromatic GSM beam passing through an astigmatic aperture lens for different values of C_6=0 and 0.4m^{-1}. (a) u=0.3152, (b) u=0.3169, (c) u=0.3174, (d) u=0.3178.

The critical positions u_c of the first- and second-order spectral switches versus astigmatic coefficient C_6 are plotted in Fig.3 for different values of β=0.85, β=0.9 and β=1, where the first- and second-order spectral switches are numbered in accordance with their critical positions referred to the z axis. From Fig.3 we see that, the first- and second-order spectral switches occur within the ranges $0\leq C_6 \leq 0.1\text{m}^{-1}$ and $0\leq C_6 \leq 0.8\text{m}^{-1}$ for β=0.85, $0\leq C_6 \leq 0.2\text{m}^{-1}$ and $0\leq C_6 \leq 0.925\text{m}^{-1}$ for β=0.9, $0\leq C_6 \leq 0.25\text{m}^{-1}$ and $0\leq C_6 \leq 0.95\text{m}^{-1}$ for β=1, respectively. The critical positions of the first-and second-order spectral switches appear in the neighbourhood of the intensity minima and move toward the z axis with increasing C_6 and β, and their ranges increase as β increases. The first- and second-order spectral switches vanish as C_6 is larger than a certain value, e.g. as C_6 >0.1m^{-1} for β=0.85, C_6 >0.2m^{-1} for β=0.9,C_6 >0.25m^{-1} for β=1 in Fig.3(a) and C_6 >0.8m^{-1} for β=0.85, C_6 > 0.925m^{-1} for β=0.9, C_6 > 0.95m^{-1} for β=1 in Fig.3(b), respectively.

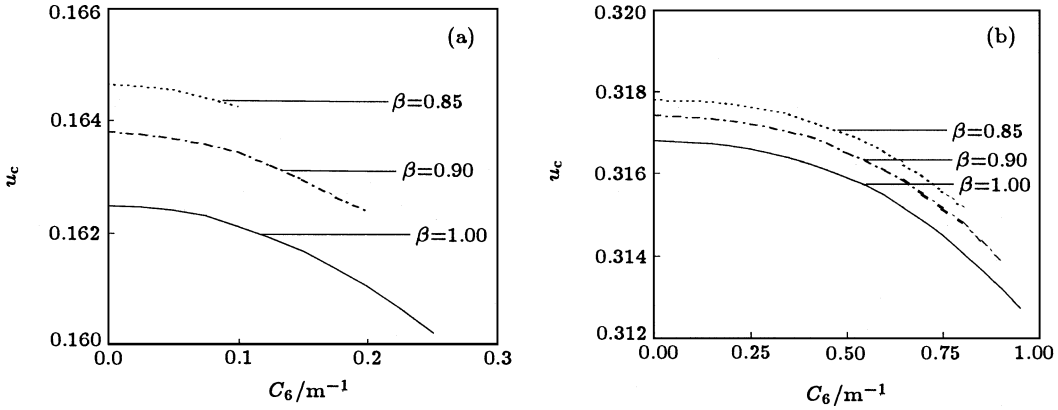


Fig.3. Critical positions u_c versus astigmatic coefficient C_6 for different values of β=0.85, β=0.9 and β=1 (a) the first-order spectral switch, (b)the second-order spectral switch.

The normalized spectra S (ω) at the critical positions of the second-order spectral switch for different values of C_6=0,0.4m^{-1} and 0.6m^{-1} are depicted in Fig.4(a) β=0.85, (b) β=0.9 and (c) β=1, and the corresponding spectral parameters are summarized in Tables 2(a), (b) and (c).

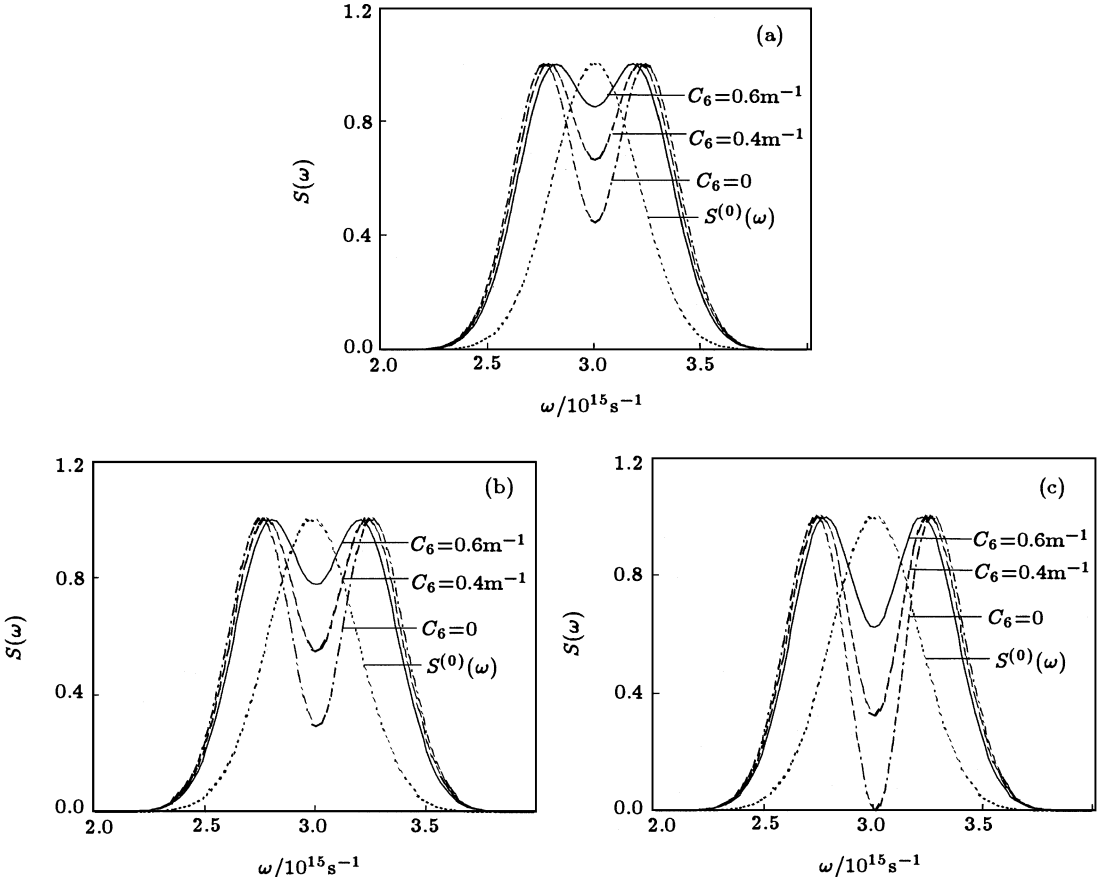


Fig.4. Normalized spectra S (ω) at the critical positions of the second-order spectral switch for different values of C_6=0, 0.4m^{-1} and 0.6m^{-1}. (a) β=0.85, (b) β=0.9 and (c) β=1.

Table 2. Spectral parameters relating to Fig.4. (a) β=0.85, (b) β=0.9 and (c) β=1.

(a)

C_6/m^{-1}	0	0.4	0.6
u_c	0.3178	0.3173	0.3165
$\omega_{max}/10^{15}$s^{-1}	2.7608, 3.2384	2.7824, 3.2280	2.8144, 3.1800
$\delta\omega/\omega_0$	–0.0797, 0.0795	–0.0725, 0.0715	–0.0619, 0.0600
S_{min}	0.4440	0.6643	0.8497
Δ	0.1592	0.1440	0.1219

(b)

C_6/m^{-1}	0	0.4	0.6
u_c	0.3174	0.3168	0.3161
$\omega_{max}/10^{15}$s^{-1}	2.7488, 3.2496	2.7688, 3.2280	2.7984, 3.1968
$\delta\omega/\omega_0$	–0.0837, 0.0832	–0.0771, 0.0760	–0.0672, 0.0656
S_{min}	0.2905	0.5494	0.7765
Δ	0.1669	0.1531	0.1328

(c)

C_6/m^{-1}	0	0.4	0.6
u_c	0.3168	0.3162	0.3155
$\omega_{max}/10^{15}\mathrm{s}^{-1}$	2.7328, 3.2664	2.7504, 3.2464	2.7760, 3.2192
$\delta\omega/\omega_0$	–0.0891, 0.0888	–0.0832, 0.0821	–0.0747, 0.0731
S_{min}	0.0000	0.3252	0.6238
Δ	0.1779	0.1653	0.1478

The relative spectral shift $\delta\omega/\omega_0$ is defined as $\delta\omega/\omega_0=(\omega_{max}\text{-}\omega_0)/\ \omega_0$, where ω_{max} denotes the frequency at which the spectrum reaches its maximum, the transition height Δ equals the relative spectral shift between two maxima (absolute value), and S_{min} is the spectral minimum. The relative spectral shifts $\delta\omega/\omega_0$ versus relative transversal coordinate u for different values of C_6=0,0.4m^{-1}, 0.6m^{-1} and β=0.9 are given in Fig.5. From Figs.4, 5 and Table 2 it follows that C_6 and β affect the behaviour of spectral switches, namely, the transition height Δ increases with decreasing C_6 and increasing β. The spectrum minimum S_{min} decreases with decreasing C_6 and increasing β. Specifically, S_{min}=0 for the case of C_6=0 and β=1. Additionally, the critical position u_c shifts toward the z axis as C_6 and β increase, which is in agreement with Fig.3.

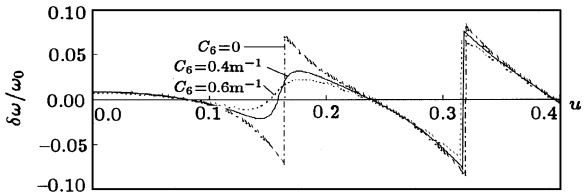


Fig.5. Relative spectral shifts $\delta\omega/\omega_0$ versus relative transversal coordinate u for different values of C_6=0, 0.4m^{-1} and 0.6m^{-1}.

4. Concluding remarks

In this paper a detailed study of the spectral behaviour of polychromatic GSM beams passing through an astigmatic aperture lens has been presented. Generally, the spectrum depends on the truncation parameter δ, spatial correlation β, bandwidth σ_0, Fresnel number N, position parameters u, v, Δz, and astigmatic coefficient C_6. As compared with the previous work,[1–8] considerable attention has been paid to the effect of astigmatism on spectral switches in the geometrical focal plane of polychromatic GSM beams diffracted at an astigmatic aperture lens. It has been found that spectral switch takes place in the neighbourhood of intensity minimum for both cases of C_6=0 and $C_6 \neq$0, but the critical position u_c moves toward the z axis as C_6 and β increase, and the spectral switch disappears when C_6 is larger than a certain value. The transition height Δ increases with decreasing C_6 and increasing β. The spectral minimum S_{min} decreases as C_6 decreases and β increases. Usually, $S_{min} \neq$0, only for the spatially fully coherent and aberration-free case the spectrum minimum S_{min} is equal to zero. The results obtained in this paper are useful for understanding some discrepancies between the experimentally measured spectral switches and numerical calculations without consideration of aberrations.[10] To make a further comparison between the theory and experiment of spectral switches, the beam type, source spectrum and phase aberrations in optical systems used in the theoretical model have to be consistent with those used in the experiment, thus a quantitative correspondence between the theoretical results and experimental observations would be expected. Finally, we would like to mention that apart from C_6 and β, the truncation parameter δ and bandwidth σ_0 affect the spectral switch. In particular, the aperture diffraction plays a dominant role in inducing spectral switches of partially coherent beams. The relevant discussions can be found, for example, in Refs.[5], [6] and [11].

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