Vol 14 No 1, January 2005
1009-1963/2005/14(01)/0128-05

Chinese Physics

© 2005 Chin. Phys. Soc.
and IOP Publishing Ltd

Propagation of partially polarized Gaussian Schell-model beams through aligned and misaligned optical systems*

Ge Di(戈 迪), Cai Yang-Jian(蔡阳健), and Lin Qiang(林 强)†

Institute of Optics, Department of Physics, Zhejiang University, Hangzhou 310027, China

(Received 20 May 2004; revised manuscript received 25 August 2004)

By use of a tensor method, the transform formulae for the beam coherence-polarization matrix of the partially polarized Gaussian Schell-model (GSM) beams through aligned and misaligned optical systems are derived. As an example, the propagation properties of the partially polarized GSM beam passing through a misaligned thin lens are illustrated numerically and discussed in detail. The derived formulae provide a convenient way to study the propagation properties of the partially polarized GSM beams through aligned and misaligned optical systems.

Keywords: partially polarized beam, physical optics, optical coherence
PACC: 4210N, 4225, 4225K

1. Introduction

The Collins formula has been widely used to treat the propagation and transformation of beams passing through paraxial optical systems.[1,2] It has been extended to axially nonsymmetrical optical systems by using tensor algebra and a tensor $ABCD$ law for treating the propagation of elliptical Gaussian beams in a spatial domain was derived. [3] The Collins formula has also been extended to misaligned optical systems, and the generalized diffraction integral formulae for misaligned optical systems were developed.[4] Recently, the generalized diffraction integral formulae for partially coherent beams were derived, and the propagation properties of the partially coherent Gaussian Schell-model (GSM) beam through aligned and misaligned optical systems were studied in detail.[5−7]

On the other hand, increasing attention has been devoted toward the light beams generated by sources that are both partially coherent and partially polarized due to their importance in coherence theory and practical applications.[8−10] In particular, a new type of source called partially polarized GSM source has been recently introduced by Gori *et al.*[11−12] The propagation of the partially polarized GSM beams has been studied through the formalism based on the beam coherence-polarization (BCP) matrix.[13−15] Recently, by use of a new tensor method, the fractional Fourier transform for partially coherent GSM beams and partially polarized GSM beams was studied.[16−18]

In this paper, for the more general case, we are going to study the propagation of a partially polarized GSM beam through aligned and misaligned optical systems by use of the tensor method. The analytical transform formulae were derived. By use of the derived formulae, the propagation properties of the partially polarized GSM beam were illustrated numerically.

2. Propagation of partially polarized GSM beams through aligned and misaligned optical systems

A partially polarized GSM beam is characterized by the BCP matrix,[11] by using the tensor method, we can express the BCP matrix of the partially polarized GSM beam in a tensor form as follows:[5,18]

*Project supported by the National Natural Science Foundation of China (Grant No 10334050).
†Corresponding author. E-mail: qlin@zju.edu.cn

$$\hat{\Gamma}_0(\tilde{\boldsymbol{r}}) = \begin{pmatrix} \Gamma_{0xx}(\tilde{\boldsymbol{r}}) & \Gamma_{0xy}(\tilde{\boldsymbol{r}}) \\ \Gamma_{0yx}(\tilde{\boldsymbol{r}}) & \Gamma_{0yy}(\tilde{\boldsymbol{r}}) \end{pmatrix} = \begin{pmatrix} I_{0xx}\exp\left[-\frac{\mathrm{i}k}{2}\tilde{\boldsymbol{r}}^{\mathrm{T}}\boldsymbol{M}_{0xx}^{-1}\tilde{\boldsymbol{r}}\right] & I_{0xy}\exp\left[-\frac{\mathrm{i}k}{2}\tilde{\boldsymbol{r}}^{\mathrm{T}}\boldsymbol{M}_{0xy}^{-1}\tilde{\boldsymbol{r}}\right] \\ I_{0yx}\exp\left[-\frac{\mathrm{i}k}{2}\tilde{\boldsymbol{r}}^{\mathrm{T}}\boldsymbol{M}_{0yx}^{-1}\tilde{\boldsymbol{r}}\right] & I_{0yy}\exp\left[-\frac{\mathrm{i}k}{2}\tilde{\boldsymbol{r}}^{\mathrm{T}}\boldsymbol{M}_{0yy}^{-1}\tilde{\boldsymbol{r}}\right] \end{pmatrix}, \quad (1)$$

where $I_{0\alpha\beta}$ is a constant intensity factor. I_{0xx} and I_{0yy} have to be real, positive quantities, while I_{0xy} and I_{0yx} may be complex. They satisfy the relation $I_{0xy} = I_{0yx}^{*}$. $\tilde{\boldsymbol{r}}^{\mathrm{T}} = (\boldsymbol{r}_1^{\mathrm{T}} \ \ \boldsymbol{r}_2^{\mathrm{T}}) = (x_1\ y_1\ x_2\ y_2)$, $\boldsymbol{M}_{0\alpha\beta}^{-1}$ is a 4×4 transpose symmetric matrix called "partially coherent complex curvature tensor" given by

$$\boldsymbol{M}_{0\alpha\beta}^{-1} = \begin{pmatrix} \left(-\frac{\mathrm{i}}{2k}(\sigma_{I0\alpha\beta}^2)^{-1} - \frac{\mathrm{i}}{k}(\sigma_{g0\alpha\beta}^2)^{-1}\right)\boldsymbol{I} & \left(\frac{\mathrm{i}}{k}(\sigma_{g0\alpha\beta}^2)^{-1}\right)\boldsymbol{I} \\ \left(\frac{\mathrm{i}}{k}(\sigma_{g0\alpha\beta}^2)^{-1}\right)\boldsymbol{I} & \left(-\frac{\mathrm{i}}{2k}(\sigma_{I0\alpha\beta}^2)^{-1} - \frac{\mathrm{i}}{k}(\sigma_{g0\alpha\beta}^2)^{-1}\right)\boldsymbol{I} \end{pmatrix}. \quad (2)$$

$\sigma_{I0\alpha\beta}^2$ and $\sigma_{g0\alpha\beta}^2$ are the transverse spot width and transverse coherence width respectively. $\boldsymbol{I}$ is a 2×2 identity matrix.

Applying the propagation formula of the partially coherent GSM beam through an aligned optical system,[5] we can obtain the propagation formula for the BCP matrix of the partially polarized GSM beam through the aligned optical system as follows:

$$\hat{\Gamma}_p(\tilde{\boldsymbol{u}}) = \begin{pmatrix} \Gamma_{pxx}(\tilde{\boldsymbol{u}}) & \Gamma_{pxy}(\tilde{\boldsymbol{u}}) \\ \Gamma_{pyx}(\tilde{\boldsymbol{u}}) & \Gamma_{pyy}(\tilde{\boldsymbol{u}}) \end{pmatrix}$$

$$= \begin{pmatrix} I_{0xx}\left[\det(\bar{\boldsymbol{A}} + \bar{\boldsymbol{B}}M_{0xx}^{-1})\right]^{-\frac{1}{2}}\exp\left[-\frac{\mathrm{i}k}{2}\tilde{\boldsymbol{u}}^{\mathrm{T}}\boldsymbol{M}_{pxx}^{-1}\tilde{\boldsymbol{u}}\right] & I_{0xy}\left[\det(\bar{\boldsymbol{A}} + \bar{\boldsymbol{B}}M_{0xy}^{-1})\right]^{-\frac{1}{2}}\exp\left[-\frac{\mathrm{i}k}{2}\tilde{\boldsymbol{u}}^{\mathrm{T}}\boldsymbol{M}_{pxy}^{-1}\tilde{\boldsymbol{u}}\right] \\ I_{0yx}\left[\det(\bar{\boldsymbol{A}} + \bar{\boldsymbol{B}}M_{0yx}^{-1})\right]^{-\frac{1}{2}}\exp\left[-\frac{\mathrm{i}k}{2}\tilde{\boldsymbol{u}}^{\mathrm{T}}\boldsymbol{M}_{pyx}^{-1}\tilde{\boldsymbol{u}}\right] & I_{0yy}\left[\det(\bar{\boldsymbol{A}} + \bar{\boldsymbol{B}}M_{0yy}^{-1})\right]^{-\frac{1}{2}}\exp\left[-\frac{\mathrm{i}k}{2}\tilde{\boldsymbol{u}}^{\mathrm{T}}\boldsymbol{M}_{pyy}^{-1}\tilde{\boldsymbol{u}}\right] \end{pmatrix}, \quad (3)$$

where $\boldsymbol{M}_{0\alpha\beta}^{-1}$ and $\boldsymbol{M}_{p\alpha\beta}^{-1}$ are the partially coherent complex curvature tensors in the input plane and output plane respectively. They satisfy the following relation:

$$\boldsymbol{M}_{p\alpha\beta}^{-1} = \left(\bar{\boldsymbol{C}} + \bar{\boldsymbol{D}}M_{0\alpha\beta}^{-1}\right)\left(\bar{\boldsymbol{A}} + \bar{\boldsymbol{B}}M_{0\alpha\beta}^{-1}\right)^{-1}, \quad (4)$$

where $\bar{\boldsymbol{A}}$, $\bar{\boldsymbol{B}}$, $\bar{\boldsymbol{C}}$ and $\bar{\boldsymbol{D}}$ are defined as follows:

$$\bar{\boldsymbol{A}} = \begin{pmatrix} \boldsymbol{A} & 0 \\ 0 & \boldsymbol{A} \end{pmatrix}, \quad \bar{\boldsymbol{B}} = \begin{pmatrix} \boldsymbol{B} & 0 \\ 0 & -\boldsymbol{B} \end{pmatrix}, \quad (5)$$

$$\bar{\boldsymbol{C}} = \begin{pmatrix} \boldsymbol{C} & 0 \\ 0 & -\boldsymbol{C} \end{pmatrix}, \quad \bar{\boldsymbol{D}} = \begin{pmatrix} \boldsymbol{D} & 0 \\ 0 & \boldsymbol{D} \end{pmatrix},$$

and $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ are sub-matrices of the aligned optical system. Equations (3) and (4) are the analytical transform formulae for the BCP matrix of the partially polarized GSM beam passing through an aligned optical system.

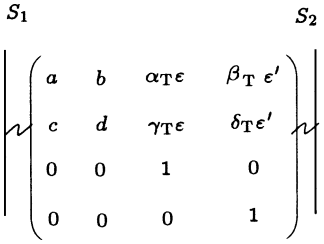


Fig.1. A misaligned optical system.

Now we study the propagation of the partially polarized GSM beams through a paraxial misaligned optical system. Let us consider a misaligned optical system with multi-element as shown in Fig.1. The misaligned optical system can be characterized by a 4×4 augmented matrix. S_1 and S_2 represent the input and output reference planes, respectively. The generalized diffraction integral formula for the partially coherent beam through misaligned optical systems is given by[7]

$$\begin{aligned}\Gamma(\tilde{\boldsymbol{u}}) =& \frac{1}{\lambda^2[\det(\bar{\boldsymbol{B}})]^{1/2}} \iint \Gamma_0(\tilde{\boldsymbol{r}}) \\ & \times \exp\Big[-\frac{\mathrm{i}\pi}{\lambda}(\tilde{\boldsymbol{r}}^{\mathrm{T}}\bar{\boldsymbol{B}}^{-1}\tilde{\boldsymbol{A}}\tilde{\boldsymbol{r}} - 2\tilde{\boldsymbol{r}}^{\mathrm{T}}\bar{\boldsymbol{B}}^{-1}\tilde{\boldsymbol{u}} \\ & + \tilde{\boldsymbol{u}}^{\mathrm{T}}\tilde{\boldsymbol{D}}\bar{B}^{-1}\tilde{\boldsymbol{u}})\Big] \\ & \times \exp\Big[-\frac{\mathrm{i}\pi}{\lambda}(\tilde{\boldsymbol{r}}^{\mathrm{T}}\bar{\boldsymbol{B}}^{-1}\tilde{\boldsymbol{e}}_f + \tilde{\boldsymbol{\rho}}^{\mathrm{T}}\bar{\boldsymbol{B}}^{-1}\tilde{\boldsymbol{g}}_h)\Big]\mathrm{d}\tilde{\boldsymbol{r}}, \end{aligned} \tag{6}$$

where $\tilde{\boldsymbol{e}}_f^{\mathrm{T}} = (\boldsymbol{e}_f^{\mathrm{T}}\ \boldsymbol{e}_f^{\mathrm{T}}) = (e\ f\ e\ f)$, $\boldsymbol{g}_h^{\mathrm{T}} = (\boldsymbol{g}_h^{\mathrm{T}}\ \boldsymbol{g}_h^{\mathrm{T}}) = (g\ h\ g\ h)$. The parameters e, f, g and h take the following forms:

$$e = 2(\alpha_{\mathrm{T}}\varepsilon_x + \beta_{\mathrm{T}}\varepsilon'_x), \tag{7}$$

$$f = 2(\alpha_{\mathrm{T}}\varepsilon_y + \beta_{\mathrm{T}}\varepsilon'_y), \tag{8}$$

$$g = 2(b\gamma_{\mathrm{T}} - \mathrm{d}\alpha_{\mathrm{T}})\varepsilon_x + 2(b\delta_{\mathrm{T}} - \mathrm{d}\beta_{\mathrm{T}})\varepsilon'_x, \tag{9}$$

$$h = 2(b\gamma_{\mathrm{T}} - \mathrm{d}\alpha_{\mathrm{T}})\varepsilon_y + 2(b\delta_{\mathrm{T}} - \mathrm{d}\beta_{\mathrm{T}})\varepsilon'_y, \tag{10}$$

where ε_x,ε'_x, ε_y and ε'_y denote the two-dimensional misalignment parameters: ε_x and ε_y are the displacement elements in the x and y directions respectively, while ε'_x and ε'_y are the tilting angles of the elements in the x and y directions respectively. α_{T}, β_{T}, γ_{T} and δ_{T} represent the misaligned matrix elements determined by

$$\alpha_{\mathrm{T}} = 1 - a, \quad \beta_{\mathrm{T}} = l - b, \quad \gamma_{\mathrm{T}} = -c, \quad \delta_{\mathrm{T}} = \pm 1 - d. \tag{11}$$

$\bar{\boldsymbol{A}}, \bar{\boldsymbol{B}}, \bar{\boldsymbol{C}}$ and $\bar{\boldsymbol{D}}$ are defined as shown in Eq.(5).

Applying the propagation formula of the partially coherent GSM beam through a misaligned optical system,[7] we can obtain the propagation formula for the BCP matrix of the partially polarized GSM beam through the misaligned optical system as follows:

$$\hat{\Gamma}_p(\tilde{\boldsymbol{u}}) = \begin{pmatrix} \Gamma_{pxx}(\tilde{\boldsymbol{u}}) & \Gamma_{pxy}(\tilde{\boldsymbol{u}}) \\ \Gamma_{pyx}(\tilde{\boldsymbol{u}}) & \Gamma_{pyy}(\tilde{\boldsymbol{u}}) \end{pmatrix}. \tag{12}$$

where

$$\begin{aligned}\Gamma_{p\alpha\beta}(\tilde{\boldsymbol{u}}) =& \frac{I_{0\alpha\beta}}{[\det(\bar{\boldsymbol{A}} + \bar{\boldsymbol{B}}\boldsymbol{M}_{0\alpha\beta}^{-1})]^{1/2}} \\ & \times \exp\Big(-\frac{\mathrm{i}k}{2}\tilde{\boldsymbol{u}}^{\mathrm{T}}\boldsymbol{M}_{p\alpha\beta}^{-1}\tilde{\boldsymbol{u}} - \frac{\mathrm{i}k}{2}\tilde{\boldsymbol{u}}^{\mathrm{T}}\bar{\boldsymbol{B}}^{-1}\bar{\boldsymbol{g}}_h \\ & - \frac{\mathrm{i}k}{2}\tilde{\boldsymbol{u}}^{\mathrm{T}}\tilde{\boldsymbol{B}}^{-1\mathrm{T}}(\bar{\boldsymbol{A}} + \bar{\boldsymbol{B}}\boldsymbol{M}_{0\alpha\beta}^{-1})^{-1}\bar{\boldsymbol{e}}_f\Big) \\ & \times \exp\Big[\frac{\mathrm{i}k}{8}\bar{\boldsymbol{e}}_f^{\mathrm{T}}\bar{\boldsymbol{B}}^{-1\mathrm{T}}(\bar{\boldsymbol{A}} + \bar{\boldsymbol{B}}\boldsymbol{M}_{0\alpha\beta}^{-1})\bar{\boldsymbol{e}}_f\Big], \end{aligned} \tag{13}$$

where $\boldsymbol{M}_{p\alpha\beta}^{-1}$ is related with $\boldsymbol{M}_{0\alpha\beta}^{-1}$ as shown in Eq.(4). Equations (3), (4), (12) and (13) provide a convenient way to study the propagation properties of the partially polarized GSM beams through a complex optical system.

3. Numerical example

In this section, we are going to study the propagation properties of the partially polarized GSM beams through a misaligned optical system by use of the derived formulae in the above section.

The degree of polarization of the partially polarized GSM beam is defined as[11−12]

$$P(\boldsymbol{u}) = \sqrt{1 - \frac{4\det\{\hat{\Gamma}_p(\boldsymbol{u},\boldsymbol{u})\}}{(\mathrm{Tr}\{\hat{\Gamma}_p(\boldsymbol{u},\boldsymbol{u})\})^2}}. \tag{14}$$

The equivalent cross-spectral density in the FRT plane can be expressed as

$$\begin{aligned}\Gamma_{peq}(\boldsymbol{u}_1,\boldsymbol{u}_2) =& \Gamma_{pxx}(\boldsymbol{u}_1,\boldsymbol{u}_2) + \Gamma_{pyy}(\boldsymbol{u}_1,\boldsymbol{u}_2) \\ =& \mathrm{Tr}\{\hat{\Gamma}_p(\boldsymbol{u}_1,\boldsymbol{u}_2)\}, \end{aligned} \tag{15}$$

and the corresponding optical intensity at a typical point $\boldsymbol{u}$ will be given by

$$I(\boldsymbol{u}) = \Gamma_{peq}(\boldsymbol{u},\boldsymbol{u}). \tag{16}$$

Let us consider a partially polarized GSM beam propagating through a misaligned optical system consisting of a misaligned thin lens as shown in Fig.2. The displacements and angle misalignments of the thin lens with respect to the optical axis of the system are $\varepsilon_x, \varepsilon_y = \varepsilon_{x'} = \varepsilon_{y'} = 0$ respectively. The thin lens is located at $z = z_1$ and the exit plane is located at z. The ray transfer matrices of the optical system between the source plane and the exit plane take the following forms:

$$\boldsymbol{A} = \begin{pmatrix} 1 - (z - z_1)/f & 0 \\ 0 & 1 - (z - z_1)/f \end{pmatrix},$$

$$\boldsymbol{B} = \begin{pmatrix} z - z_1(z - z_1)/f & 0 \\ 0 & z - z_1(z - z_1)/f \end{pmatrix},$$

$$\boldsymbol{C} = \begin{pmatrix} -1/f & 0 \\ 0 & -1/f \end{pmatrix},$$

$$\boldsymbol{D} = \begin{pmatrix} 1 - z_1/f & 0 \\ 0 & 1 - z_1/f \end{pmatrix}. \tag{17}$$

Then the misalignment parameters α_{T}, β_{T}, γ_{T} and δ_{T} take the following forms:

$$\alpha_{\mathrm{T}} = \frac{z - z_1}{f}, \quad \beta_{\mathrm{T}} = \frac{z_1(z - z_1)}{f},$$

$$\gamma_{\mathrm{T}} = \frac{1}{f}, \quad \delta_{\mathrm{T}} = \frac{z_1}{f}, \tag{18}$$

and the corresponding e, f, g and h take the forms

$$e = 2\frac{(z - z_1)\varepsilon_x}{f}, \quad f = 0,$$

$$g = \frac{2z_1\varepsilon_x}{f}, \quad h = 0. \tag{19}$$

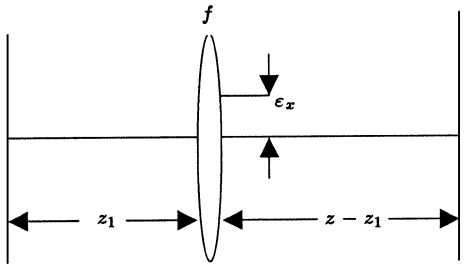


Fig.2. An optical system with a misaligned thin lens.

Applying the above equations, we can conveniently study the propagation properties of the partially polarized GSM beam passing through a misaligned thin lens. Figure 3 shows the evolution of polarization degree of the partially polarized GSM beam through the misaligned thin lens in a spatial domain in certain planes. The parameters used in calculation are λ=632.8nm, ε_x=0.5mm, f=15mm, z_1=20mm, $\sigma_{I0xx} = \sigma_{I0yy} = \sigma_{I0xy} = \sigma_{I0yx} = 1$mm, $\sigma_{g0xx} = \sigma_{g0yy} = 0.1$mm, $\sigma_{g0xy} = \sigma_{g0yx} = 0.2$mm, $I_{0xx} = I_{0yy} = 0.5$, and $I_{0xy} = I_{0yx} = 0.1$. For comparison, the polarization degree of the partially polarized GSM beam in the input plane is also shown in Fig.3. As can be seen from Fig.3, the polarization distribution at the input plane is uniform for all the points in the transversal section of the beam with the same value 0.2. After its passing through a misaligned thin lens, the beam has the degree of polarization distribution across the transversal section of the beam different from point to point in the output plane. The peak position polarization distribution is not located on the axis because of the effect of the misaligned thin lens. It is clear from Fig.3 that the degree of polarization distribution is also closely related to the initial spatial coherence of the beam. With the increase of the initial spatial coherence of the partially polarized beam, the degree of polarization of the points near the peak position increases, but the degree of polarization of the points far from the peak position decreases.

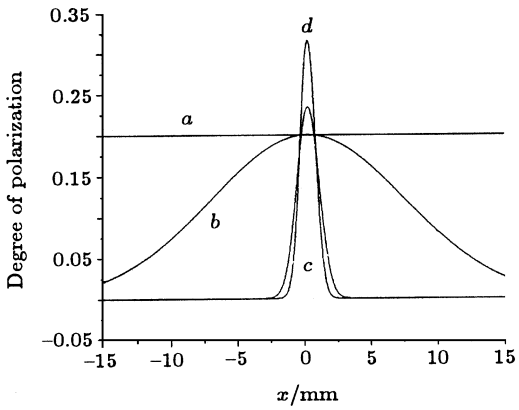


Fig.3. Polarization degree of a partially polarized GSM beam as a function of variable x after its passing through a misaligned thin lens with different initial spatial coherence widths at z=30mm. Curve a: input plane, curve b: $\sigma_{g0xx} = \sigma_{g0yy} = 0.005$mm, $\sigma_{g0xy} = \sigma_{g0yx} = 0.01$mm, curve c: $\sigma_{g0xy} = \sigma_{g0yx} = 0.01$mm, $\sigma_{g0xy} = \sigma_{g0yx} = 0.02$mm, curve d: $\sigma_{g0xy} = \sigma_{g0yx} = 0.1$mm, $\sigma_{g0xy} = \sigma_{g0yx} = 0.2$mm.

Figure 4 shows the normalized intensity profile of a partially polarized GSM beam with different initial spatial coherence widths after its passing through a misaligned thin lens at z = 30mm for y = 0. The parameters used in the calculation take the same values as those in Fig.3. From Fig.4, we can find that the partially polarized GSM beam becomes a decentred beam. Calculations show that the peak position of the intensity profile moves continuously in propagation. It is clear from Fig.4 that the beam spot width of a partially polarized GSM beam is also related to the initial coherence of the beam. With the increase of the initial spatial coherence of the partially polarized beam, the peak value of the intensity profile increases and the beam spot width decreases, which means the beam with higher coherence is easy to focus relatively.

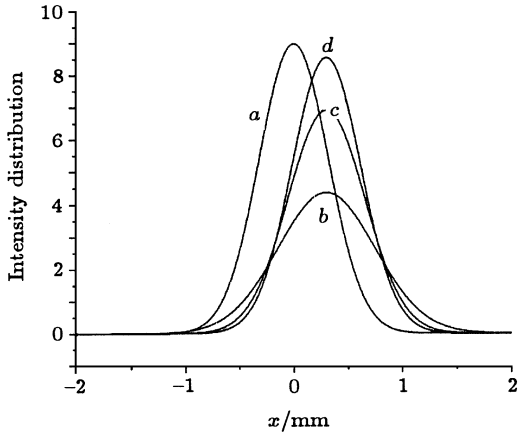


Fig.4. The intensity profile of a partially polarized GSM beam with different initial spatial coherence widths after its passing through a misaligned thin lens at z=30mm for y=0. Curve a: input plane, curve b: $\sigma_{g0xx} = \sigma_{g0yy} = 0.005$mm, $\sigma_{g0xy} = \sigma_{g0yx} = 0.01$mm, curve c: $\sigma_{g0xy} = \sigma_{g0yx} = 0.01$mm, $\sigma_{g0xy} = \sigma_{g0yx} = 0.02$mm, curve d: $\sigma_{g0xy} = \sigma_{g0yx} = 0.1$mm, $\sigma_{g0xy} = \sigma_{g0yx} = 0.2$mm.

4. Conclusions

Based on the generalized diffraction integral formulae for a partially coherent beam passing through aligned and misaligned optical systems, the analytical transform formulae for partially polarized GSM beams through aligned and misaligned optical systems are derived by use of the tensor method. Using the derived formulae, the propagation properties of a partially polarized GSM beam passing through a misaligned thin lens are illustrated numerically. The results show that the misaligned thin lens and the initial coherence of the beam have strong influences on the polarization and intensity properties of the partially polarized GSM beams. Our method provides a convenient way to treat the propagation of the partially polarized GSM beams through aligned and misaligned optical systems.

References

[1] Collins S A 1970 *J. Opt. Soc. Am.* **60** 1168
[2] Belafhal A and Dalil-Essakali L 2001 *Opt. Commun.* **177** 181
[3] Lin Q, Wang S, Alda J and Bernabeu E 1990 *Optik* **85** 67
[4] Wang S and Ronchi L 1988 *Principles and Design of Optical Array* In: Wolf E, Progress in Optics, vol. 25 (Amsterdam: Elsevier Science BV) p279
[5] Lin Q and Cai Y 2002 *Opt. Lett.* **27** 216
[6] Cai Y and Lin Q 2003 *Opt. Commun.* **215** 239
[7] Cai Y and Lin Q 2002 *Opt. Commun.* **211** 1
[8] James D F V 1994 *J. Opt. Soc. Am.* A **11** 1641
[9] James D F V 1994 *Opt. Commun.* **109** 209
[10] Martinez-Herrero R, Mejias P M and Movilla J M 1997 *Opt. Lett.* **22** 206
[11] Gori F 1998 *Opt. Lett.* **23** 241
[12] Gori F, Santarsiero M, Piquero G, Borghi R, Mondello A and Simon R 2001 *J. Opt.* A: *Pure. Appl. Opt.* **3** 1
[13] Piquero G, Gori F, Romanini P, Santarsiero M and Borghi R 2002 *Opt. Commun.* **208** 9
[14] Piquero G, Borghi R and Santarsiero M 2001 *J. Opt. Soc. Am.* A **18** 1399
[15] Agrawal G P and Wolf E 2000 *J. Opt. Soc. Am.* A **17** 2019
[16] Lin Q and Cai Y 2002 *Opt. Lett.* **27** 2036
[17] Cai Y and Lin Q 2004 *Chin. Phys.* **13** 1025
[18] Cai Y, Ge D and Lin Q 2003 *J. Opt.* A: *Pure Appl. Opt.* **5** 1