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RESEARCH ARTICLE

INFLUENCE OF ANISOTROPIC TURBULENT PLASMA ON THE PARTIALLY COHERENT FOUR-PETAL GAUSSIAN VORTEX BEAMS

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Abstract

Based on the extended Huygens-Fresnel principle, the analytical expressions for partially coherent four-petal Gaussian (FPG) vortex beams propagating in turbulent plasma are obtained, the influence of the turbulent plasma parameters on beam profile and coherence of the beams is discussed in detail using numerical examples. It is found that a four-petal Gaussian-shaped intensity distribution will eventually transform into a Gaussian distribution after propagating in turbulent plasma. Meanwhile, turbulent plasma parameters will also influence the coherence characterizations of the beams.

Keywords: Partially coherent, Four-petal Gaussian vortex beams, Anisotropic turbulent plasma.

1-Introduction

Hypersonic turbulence (due to turbulence in the flow about a high-speed flight vehicle) is an important factor in understanding optical propagation and optical communication [1]. In fact, when the aircraft or spacecraft pierces the Earth's atmosphere with exceedingly high speed (hypersonic), the gas environment surrounding a hypersonic aircraft will rub with an aircraft body and causes a hypersonic plasma sheath surrounding an aircraft. The presence of anisotropic turbulent plasma sheaths around the vehicles can have a strong influence on the communication characteristics between the vehicles and radars. It can be perturb the communication and in some circumstances may lead to a disconnection [2, 3].

In 2005, four-petal Gaussian beams are first introduced [4]. The new beams have four equal petals at the source plane. The four-petal Gaussian beams may find potential applications in micro-optics, optical communications, beam splitting techniques, etc. With the development of laser optics, a new laser beam called four-petal Gaussian vortex beams has been introduced, where the wave-front phase of four-petal Gaussian vortex beams can modulate the beam profile and carry the orbital angular momentum by the passage of a four-petal Gaussian vortex beam through a spiral phase plate. This beam has potential application in the fields of optical micro-manipulation, nonlinear optics, etc. . Since then, the evolution properties of four-petal Gaussian vortex beams have been widely studied [5, 6, 7, 8].

However, to the best of our knowledge, the intensity distribution and coherence properties of partially coherent four-petal Gaussian vortex beams propagating in turbulent plasma have not been studied and reported. In this work, we studied the influence of turbulent plasma on beam profile and coherence of partially coherent four-petal Gaussian vortex beams using numerical examples.

2- Theoretical Model

In the Cartesian coordinate system, the z-axis is taken to be the propagation axis. The general four-petal Gaussian vortex beam in the source plane z=0 takes the form [8]:

$$E(x',y',0)=\left(\frac{x'y'}{w_0^2}\right)^{2n}\exp\left[-\frac{x'^2+y'^2}{w_0^2}\right][x' +i\,sgn(l)\,y']^{|l|}, \qquad (1)$$

where n denotes the order of the four-petal Gaussian beams, $sgn(.)$ is specifies the sign function ,l is the topological charge of the spiral phase plane and w_0 is the waist width of the Gaussian beam. Figure 1 shows the normalized intensity distribution of the four-petal Gaussian vortex beam for different values of n, when $n=0$, Eq.(1) will reduce to electric field of ordinary fundamental Gaussian beam.

The cross-spectral density of a partially coherent vortex beam at the source plane is defined as a two-point correlation function, i.e. [9]:

$$W(\mathbf{r}_1', \mathbf{r}_2', 0) = \langle E(\mathbf{r}_1', 0) E^*(\mathbf{r}_2', 0)\rangle = A(\mathbf{r}_1') A(\mathbf{r}_2') g(\mathbf{r}_1' - \mathbf{r}_2'), \quad (2)$$

Here, $E(\mathbf{r}_i', 0)$ electric field of a fully coherent optical vortex beam and $\mathbf{r}_i'$ is the position vectors at the source plane, $i = 1,2$. The angular brackets $\langle \ \rangle$ denote an ensemble average, while the asterisk $*$ denotes the complex conjugate, $A(\mathbf{r}_i')$ represents the amplitude and $g(\mathbf{r}_1' - \mathbf{r}_2')$ denotes the correlation function between two points $\mathbf{r}_1'$ and $\mathbf{r}_2'$ which can be written as [9] :

$$g(\mathbf{r}_1' - \mathbf{r}_2') = \exp\left[-\frac{(\mathbf{r}_1' - \mathbf{r}_2')^2}{2\sigma^2}\right], \quad (3)$$

where σ denotes the spatial coherence length. Then the cross-spectral density of a partially coherent four-petal Gaussian vortex beams at the source plane $z = 0$ is written as:

$$W(\mathbf{r}_1', \mathbf{r}_2', 0) = \left(\frac{x_1' \ y_1'}{w_0^2}\right)^{2n} \left(\frac{x_2' \ y_2'}{w_0^2}\right)^{2n} \exp\left[-\frac{\mathbf{r}_1'^2 + \mathbf{r}_2'^2}{w_0^2}\right] [x_1' + i \, sgn(l) y_1']^{|l|} \times [x_2' - i \, sgn(l) \, y_2']^{|l|} \exp\left[-\frac{(\mathbf{r}_1' - \mathbf{r}_2')^2}{2\sigma^2}\right] \quad (4)$$

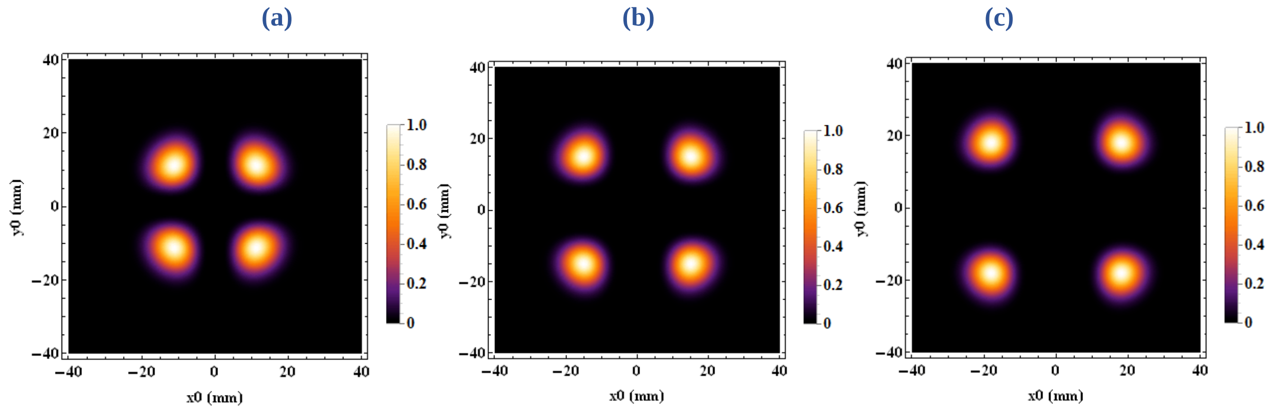


Fig. 1 : Normalized intensity distribution at the source plane before beam passing through anisotropic turbulent plasma for different values of the order of the four-petal beams (a) $n = 1$,(b) $n = 2$, (c) $n = 3$.

By using the extended Huygens-Fresnel integral formula, the cross-spectral density of the partially coherent four-petal Gaussian vortex beams in anisotropic turbulent plasma can be expressed as [10]:

$$W_{out}(\boldsymbol{r}_1, \boldsymbol{r}_2, z) = \left(\frac{k}{2\pi z}\right)^2 \iint W_{in}(\boldsymbol{r}_1', \boldsymbol{r}_2', 0) \exp\left\{-\frac{ik}{2z}[(\boldsymbol{r}_1 - \boldsymbol{r}_1')^2 - (\boldsymbol{r}_2 - \boldsymbol{r}_2')^2]\right\} \times \langle \exp \ [\psi^*(\boldsymbol{r}_1', \boldsymbol{r}_1, z) + \psi(\boldsymbol{r}_2', \boldsymbol{r}_2, z)]\rangle \, d^2\boldsymbol{r}_1' \, d^2\boldsymbol{r}_2', \quad (5)$$

where $k = 2\pi/\lambda$ is the wave number, in which λ is the incident wave length, z is the beam propagation distance, ψ is the random part of the complex phase of a spherical wave propagating through anisotropic turbulent plasma. Over the ensemble of the statistical realization of the random medium, we can written [11] :

$$\langle \exp[\psi^*(\mathbf{r}_1', \boldsymbol{r}_1, z) + \psi(\mathbf{r}_2', \boldsymbol{r}_2, z)]\rangle = \exp\{-4\pi^2 k^2 z \int_0^1 \int_0^\infty [1 - J_0(\kappa|(1-\xi)(\boldsymbol{r}_2 - \boldsymbol{r}_1) + \xi(\boldsymbol{r}_2' - \boldsymbol{r}_1')|)] \ \Phi_n(\kappa) \, \kappa d\kappa d\xi\} \simeq \exp\{-D(z)[(\boldsymbol{r}_1 - \boldsymbol{r}_2)^2 + (\boldsymbol{r}_1 - \boldsymbol{r}_2)(\mathbf{r}_1' - \mathbf{r}_2') + (\mathbf{r}_1' - \mathbf{r}_2')^2]\} \ . \quad (6)$$

where J_0 is the zero-order Bessel function and $D(z) = \frac{1}{\rho_0^2(z)}$, $\rho_0(z)$ is the coherence length of a sphererical wave propagation in anisotropic turbulent plasma, which given by [12]:

$$D(z) = \frac{32\,\pi^3\, k^2 z\, a_1 \langle n_1^2\rangle L_0^2\, (m_1 - 1)}{3} \frac{(\xi_x^2 + \xi_y^2)}{\xi_x^3\, \xi_y^3} \left(\frac{1}{100 L_0^2}\right)^4 \times U\left(4{,}5 - m_1, \frac{1}{100 L_0^2\, \kappa_0}\right) \Gamma(4)\,, \quad (7)$$

where $\langle n_1^2\rangle$ is the variance of the refractive-index fluctuation, m_1 is a constant $m_1 = 4 - d$, with d is the fractal dimension of the anisotropic turbulent plasma, L_0 is the outer scale of anisotropic turbulent plasma, $U(a, b, z)$ is the confluent hypergeometric function of the second kind and $\Gamma(.)$ is the Gamma function. Here, a_1 is a fitting parameter, which can be expressed as $a_1 = 475\,(\kappa_0)^{2m_1}$ where $\kappa_0 = (2\pi/l_0)^{m_1 - 0.7}$, in which l_0 represents the inner scale of anisotropic turbulent plasma. The relation between L_0 and l_0 is given by $L_0/l_0 = R_e^{\frac{3}{4}}$ where R_e represents the Reynolds number [13]. For the fully developed turbulence in the mixing layer, $R_e = 5 \times 10^5$, $d = 2.6$, and thus $m_1 = 1.4$. The outer scale $L_0 = 0.1m$, then the inner scale $l_0 = 5.3 \times 10^{-6} m$.

Now, substituting Eqs.(4) and (6) into Eq.(5), and using the following expression [14, 15]:

$$(x+iy)^n=\sum_{t=0}^{n}\frac{n!}{t!\,(n-t)!}x^{n-t}(iy)^t, \tag{8}$$

$$\int_{-\infty}^{\infty}x^n\exp(-px^2+2qx)dx = n!\sqrt{\frac{\pi}{p}}\left(\frac{q}{p}\right)^n\exp\left(\frac{q^2}{p}\right)\sum_{k=0}^{[n/2]}\frac{1}{k!\,(n-2k)!}\left(\frac{p}{4q^2}\right)^k, \tag{9}$$

$$H_n(x)=\sum_{k=0}^{[n/2]}\frac{(-1)^k n!}{k!\,(n-2k)!}(2x)^{n-2k}, \tag{10}$$

The integration in the Eq. (5) can be evaluated, and finally we obtain the cross spectral density for partially coherent four-petal Gaussian vortex beams propagating through turbulent plasma :

$$\begin{aligned}
W_{out}(\boldsymbol{r}_1,\boldsymbol{r}_2,z) &= \left(\frac{k}{2\pi z}\right)^2\left(\frac{1}{w_0^2}\right)^{4n}\exp\left[-\frac{ik}{2z}(x_1^2+y_1^2)+\frac{ik}{2z}(x_2^2+y_2^2)\right]\\
&\times \exp[-D(z)(x_1-x_2)^2-D(z)(y_1-y_2)^2]\sum_{t=0}^{l}\frac{i^t\,l!}{t!\,(l-t)!}\sum_{s=0}^{l}\frac{(-i)^s\,l!}{s!\,(l-s)!}\\
&\times \left\{(2n+l-t)!\sqrt{\frac{\pi}{a}}\left(\frac{1}{a}\right)^{2n+l-t}\exp\left\{\frac{1}{a}\left[\frac{ik}{2z}x_1-\frac{D(z)}{2}(x_1-x_2)\right]^2\right\}\right.\\
&\times \sum_{d_1=0}^{\frac{2n+l-t}{2}}\frac{1}{d_1!\,(2n+l-t-2d_1)!}\left(\frac{a}{4}\right)^{d_1}\sum_{t_1=0}^{2n+l-t-2d_1}\frac{(2n+l-t-2d_1)!}{t_1!\,(2n+l-t-2d_1-t_1)!}\\
&\times \left(\frac{1}{\sigma^2}+D(z)\right)^{t_1}\left[\frac{ik}{2z}x_1-\frac{D(z)}{2}(x_1-x_2)\right]^{2n+l-t-2d_1-t_1}2^{-2n-l+s-t_1}\\
&\times \left. i^{2n+l-s+t_1}\exp\left(\frac{c_1^2}{b}\right)\sqrt{\frac{\pi}{b}}\left(\frac{1}{\sqrt{b}}\right)^{2n+l-s+t_1}H_{2n+l-s+t_1}\left(-i\frac{c_1}{\sqrt{b}}\right)\right\}\\
&\times \left\{(2n+t)!\sqrt{\frac{\pi}{a}}\left(\frac{1}{a}\right)^{2n+t}\exp\left\{\frac{1}{a}\left[\frac{ik}{2z}y_1-\frac{D(z)}{2}(y_1-y_2)\right]^2\right\}\right.\\
&\times \sum_{d_2=0}^{\frac{2n+t}{2}}\frac{1}{d_2!\,(2n+t-2d_2)!}\left(\frac{a}{4}\right)^{d_2}\sum_{t_2=0}^{2n+t-2d_2}\frac{(2n+t-2d_2)!}{t_2!\,(2n+t-2d_2-t_2)!}\\
&\times \left[\frac{ik}{2z}y_1-\frac{D(z)}{2}(y_1-y_2)\right]^{2n+t-2d_2-t_2}\left(\frac{1}{\sigma^2}+D(z)\right)^{t_2}\\
&\times \left. 2^{2n-s-t_2}i^{2n+s+t_2}\exp\left(\frac{c_2^2}{b}\right)\sqrt{\frac{\pi}{b}}\left(\frac{1}{\sqrt{b}}\right)^{2n+s+t_2}H_{2n+s+t_2}\left(-i\frac{c_2}{\sqrt{b}}\right)\right\}.
\end{aligned} \tag{11}$$

Where:

$$a=\frac{1}{w_0^2}+\frac{1}{2\sigma^2}+\frac{ik}{2z}+D(z), \tag{12}$$

$$b=\frac{1}{w_0^2}+\frac{1}{2\sigma^2}-\frac{ik}{2z}+D(z)-\frac{1}{a}\left[\frac{1}{2\sigma^2}+D(z)\right]^2, \tag{13}$$

$$c_1=\frac{1}{a}\left[\frac{ik}{2z}x_1-\frac{D(z)}{2}(x_1-x_2)\right]\left(\frac{1}{2\sigma^2}+D(z)\right)-\frac{ik}{2z}x_2+\frac{D(z)}{2}(x_1-x_2), \tag{14}$$

$$c_2=\frac{1}{a}\left[\frac{ik}{2z}y_1-\frac{D(z)}{2}(y_1-y_2)\right]\left(\frac{1}{2\sigma^2}+D(z)\right)-\frac{ik}{2z}y_2+\frac{D(z)}{2}(y_1-y_2), \tag{15}$$

Since the optical intensity of the partially coherent light is given by [9]:

$$I(\boldsymbol{r},z)=W(\boldsymbol{r},\boldsymbol{r},z) \tag{16}$$

, and the spectral degree of coherence for a partially coherent four-petal Gaussian vortex beams at a pair of field points $\boldsymbol{r}_1=(x_1,y_1)$ and $\boldsymbol{r}_2=(x_2,y_2)$ can be written as [16]:

$$\mu(\boldsymbol{r}_1,\boldsymbol{r}_2,z)=\frac{W(\boldsymbol{r}_1,\boldsymbol{r}_2,z)}{\sqrt{W(\boldsymbol{r}_1,\boldsymbol{r}_1,z)W(\boldsymbol{r}_2,\boldsymbol{r}_2,z)}} \tag{17}$$

3- Numerical results and discussion

In this section, we will study the effect of the anisotropic turbulent plasma on the intensity distribution and coherence properties of partially coherent four-petal Gaussian vortex beams using numerical examples. The parameters of the beam and anisotropic turbulent plasma are chosen as (unless the other values of parameters are specified in the caption): the order of the four-petal Gaussian beams $n=1$, the topological charge $l=1$, the beam width $w_0=1cm$, the wave length $\lambda=1550nm$, the correlation length $\sigma=1mm$, the outer scale $L_0=0.1m$, the inner scale $l_0=5\times10^{-6}m$, we use refractive index fluctuation variance of $\langle n_1^2\rangle=0.73\times10^{-20}$ and anisotropy parameters $\xi_x=2$, $\xi_y=1$ [12].

Figures 2-4 give the normalized intensity of partially coherent four-petal Gaussian vortex beams propagating in turbulent plasma for the different turbulent plasma parameters (anisotropy parameter ξ_x, outer scale L_0 and refractive index fluctuation variance $\langle n_1^2\rangle$) at the propagation distance $z=1$ m. The normalized intensity of partially coherent FPG beams propagating through turbulent plasma for different values of anisotropy parameter ξ_x and outer scale L_0 are shown in Figs. 2-3, respectively. As can see from these figures, when the anisotropy parameter ξ_x and outer scale L_0 are large, the distribution of the intensity keeps initial four-petal profile as shown in figure 2(c) and figure 3(c). With decreasing ξ_x and L_0, the beam is gradually spread, and the shape of the beam will lose their initial four-petal profile. While Figure 4 shows the normalized intensity of partially coherent FPG vortex beams propagating through turbulent plasma for the different refractive index fluctuation variance $\langle n_1^2\rangle$. It can be found that partially coherent FPG vortex beams in turbulent plasma with higher refractive index fluctuation variance $\langle n_1^2\rangle$ will lose their initial four-petal profile rapidly.

(a) **(b)** **(c)**

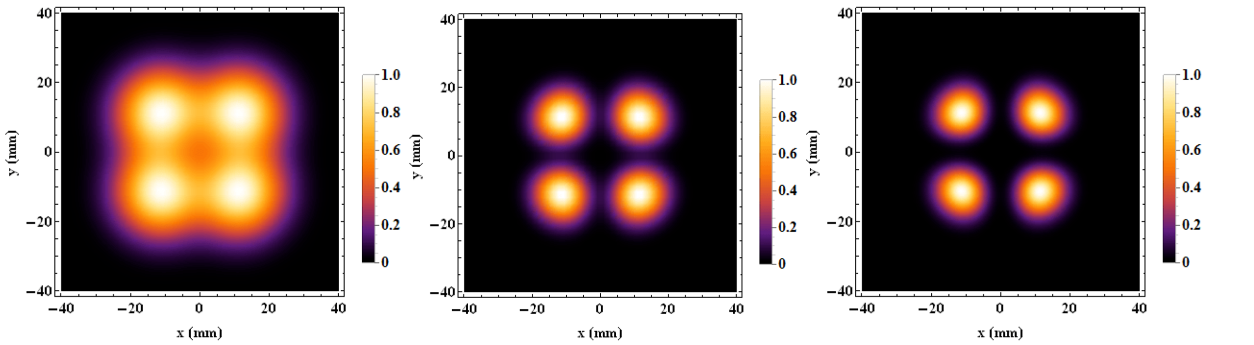


Fig. 2 : Normalized intensity of the partially coherent four-petal Gaussian vortex beams in anisotropic turbulent plasma for different values of the anisotropy parameter (a) $\xi_x = \xi_y = 1$,(b) $\xi_x = 3$, $\xi_y = 1$,(c) $\xi_x = 6$, $\xi_y = 1$, $(z = 1\text{m})$.

(a) **(b)** **(c)**

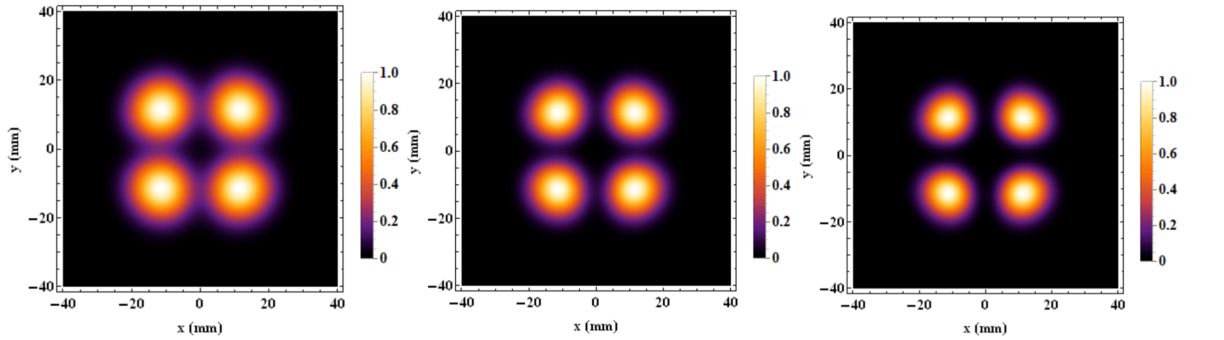


Fig. 3 : Normalized intensity of the partially coherent four-petal Gaussian vortex beams in anisotropic turbulent plasma for different values of the outer scale (a) $L_0 = 0.1$ m, (b) $L_0 = 0.2$ m, (c) $L_0 = 0.4$ m, $(z = 1$ m).

(a) **(b)** **(c)**

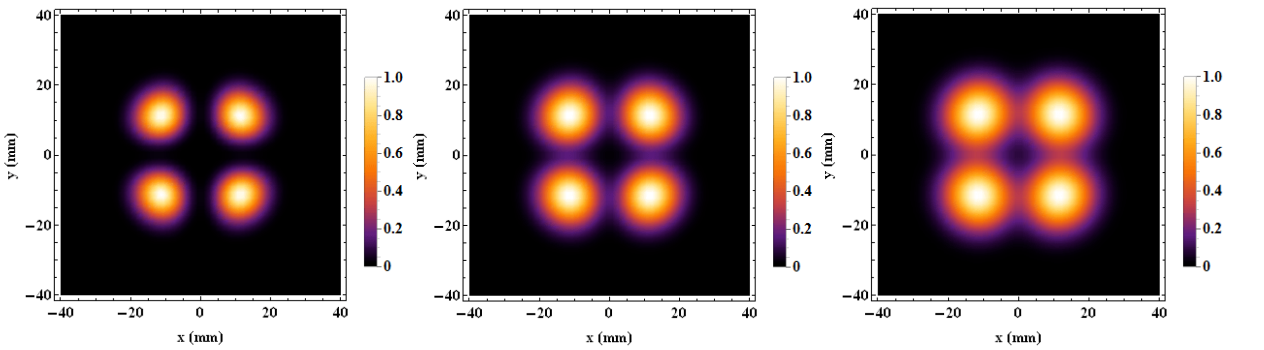


Fig. 4 : Normalized intensity of the partially coherent four-petal Gaussian vortex beams in anisotropic turbulent plasma for different values of refractive index fluctuation variance (a) $\langle n_1^2 \rangle = 0.2 \times 10^{-20}$, (b) $\langle n_1^2 \rangle = 0.6 \times 10^{-20}$, (c) $\langle n_1^2 \rangle = 1 \times 10^{-20}$, $(z = 1\text{m})$.

Figure 5 shows the evolution of the intensity distribution of partially coherent FPG vortex beams propagating in turbulent plasma. From this figure, we can see that the beam will keep its initial four-petal profiles in the near field propagation (Fig. 5(a)), that it will lose its four-petal profiles and become a flat-topped-like beam with increasing propagation distance (Fig. 5(b)), and that it will evolve into a Gauss-like beam in the far-field (Fig. 5(c)) due to the influence of coherence length and plasma turbulence.

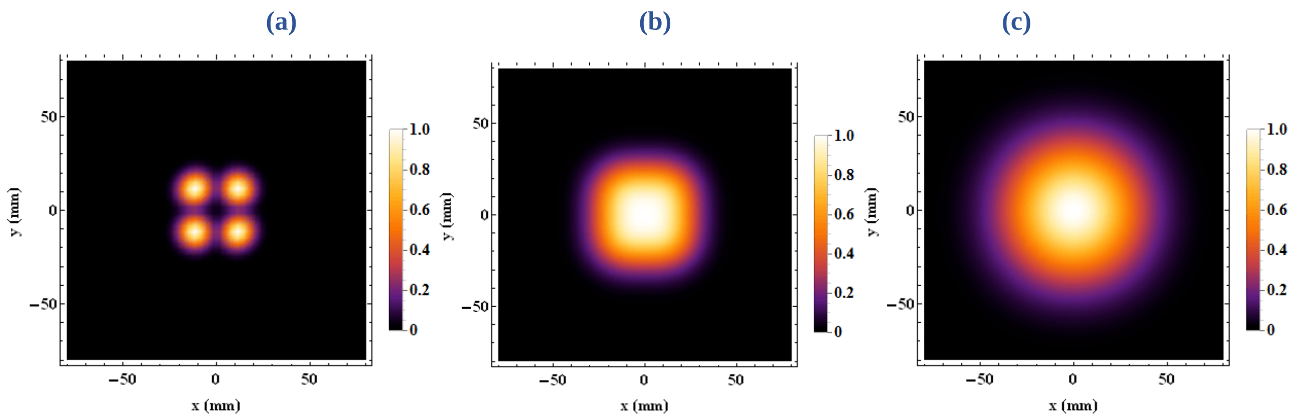
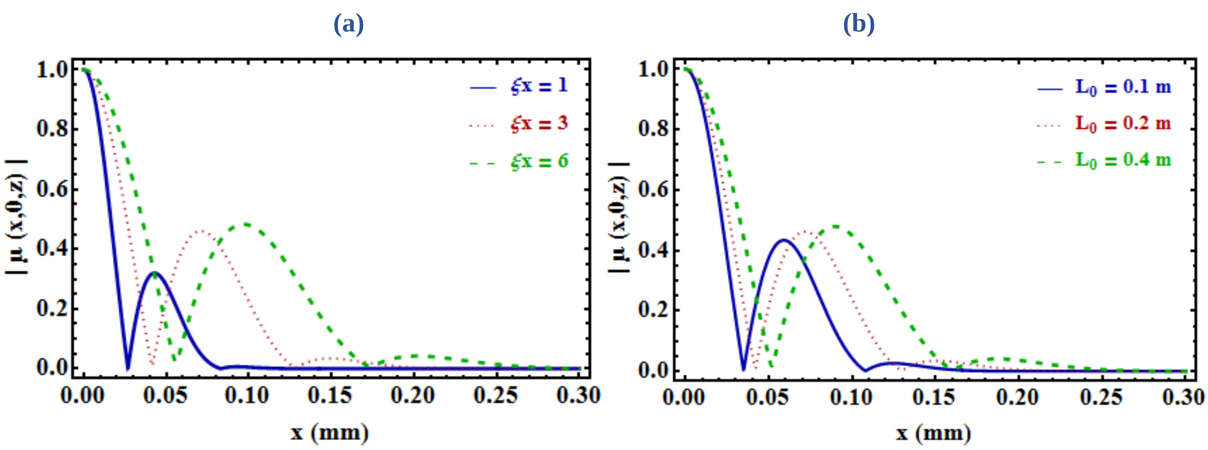


Fig. 5 : Normalized intensity of the partially coherent four-petal Gaussian vortex beams in anisotropic turbulent plasma for different values of propagation distances (a) $z = 1\ m$, (b) $z = 2\ m$, (c) $z = 3\ m$.

The spectral degrees of coherence $|\mu(x, 0, z)|$ along the x-axis of the partially coherent four-petal Gaussian vortex beams propagating in a turbulent plasma for the different turbulence parameters (anisotropy parameter ξ_x, outer scale L_0 and refractive index fluctuation variance $\langle n_1^2 \rangle$) and propagation distances z are investigated in Fig.6. In this numerical calculation, the point (x_2, y_2) is chosen as $(0,0)$. It can be seen from Fig.6(a-d), the spectral degree of coherence of FPG beams has an oscillatory behavior and exists zero points. The influence of anisotropy parameter ξ_x on the spectral degree of coherence is shown in Fig.6(a). It is shown that with the increases in the distance from the source, the spectral degree of coherence decreases from unity firstly and then oscillates around zero. It is also found that the turbulent plasma with the smallest anisotropy parameter will become the least coherent. Figure 6(b) is plotted to illustrate the variation of the spectral degree of coherence against outer scale L_0. It is found that after propagating for a certain distance, the turbulent plasma with the smallest outer scale will become the least coherent. Figure 6(c) illustrates the behavior of the degree of coherence for refractive index fluctuation variance $\langle n_1^2 \rangle$. One sees that the degree of coherence alters significantly with the change in $\langle n_1^2 \rangle$ for turbulent plasma. For the large value of $\langle n_1^2 \rangle$, the faster the degree of coherence decays. Finally, Fig.6(d) is plotted to show how the spectral degree of coherence changes with the increasing propagation distance in turbulent plasma. We find that as the beam propagates, the coherence of the beam becomes better, what is more, the oscillation of the degree of coherence becomes weaker due to the beam has a larger beam spot.



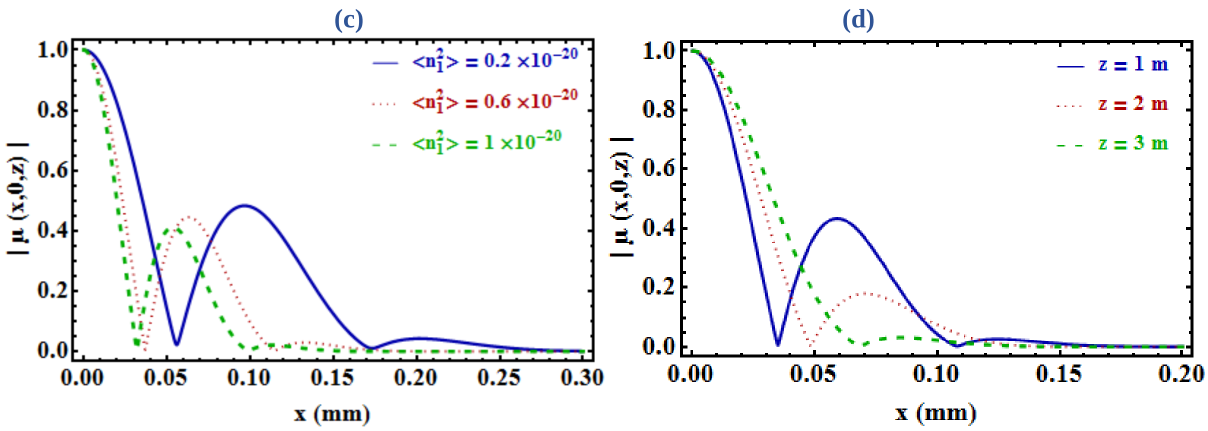


Fig. 6 : The spectral degree of coherence $|\mu(x,0,z)|$ of the partially coherent FPG vortex beams in anisotropic turbulent plasma for different values of (a) anisotropy parameter ξ_x ,(b) outer scale L_0, (c) refractive index fluctuation variance $\langle n_1^2 \rangle$, (d) propagation distances z.

4- Conclusions

In this paper, the analytical formula for the cross-spectral density of partially coherent four-petal Gaussian vortex beams through turbulent plasma is derived. The results show that beam will lose its initial four-petal profile rapidly with decreasing turbulent plasma parameters anisotropy parameter ξ_x and outer scale L_0 or increasing refractive index fluctuation variance $\langle n_1^2 \rangle$. We found that partially coherent four-petal Gaussian vortex beams can keep their initial four-petal profile in the short propagation distance, and the beam will evolve into the Gauss-like beam in the far-field due to the influence of turbulent plasma. The influences of turbulent plasma parameters on the coherence properties of partially coherent FPG vortex beams have been illustrated, it is found that the degree of coherence has an oscillatory behavior will decrease as the distance between two points increases, and decrease slower at the larger propagation distance, and it may disappear for small anisotropy parameter ξ_x and outer scale L_0 or for large refractive index fluctuation variance $\langle n_1^2 \rangle$. It is to be noted that these results may be useful for optical communications.

*Disclosures

the authors declare no conflicts in interest

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مقالة بحثية

تأثير البلازما المضطربة المتباينة الخواص على حزم ملتوية جاوسية رباعية البتلات ومترابطة جزئيا

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المُلخّص

استنادًا إلى مبدأ فرينل-هيجنز الممتد ، تم الحصول على التعبيرات التحليلية لحزم ملتوية جاوسية رباعية البتلات (FPG) مترابطة جزئيًا تنتشر في بلازما مضطربة، وتم مناقشة تأثير بارامترات البلازما المضطربة على المظهر الجانبي للحزم وترابط الحزم بالتفصيل باستخدام الأمثلة العددية. لقد وجد أن توزيع الشدة على شكل جاوسي رباعي البتلات سيتحول في النهاية إلى توزيع جاوسي بعد الانتشار في البلازما المضطربة. وفي الوقت نفسه، ستؤثر بارامترات البلازما المضطربة أيضًا على خصائص ترابط الحزم.

الكلمات المفتاحية: الترابط الجزئي، حزم ملتوية جاوسية رباعية البتلات، بلازما مضطربة متباينة الخواص.

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