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Vectorial structural properties of truncated beam generated by Gaussian mirror resonator in the near field

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ABSTRACT

Internal vectorial structure of the beam generated by the Gaussian mirror resonator (GMR) diffracted through a hard-edged aperture are evaluated in the near-field. Based on the vectorial angular spectrum representation of electromagnetic fields and the paraxial approximation, TE and TM terms of intensity distributions of the beam in the near field are derived in analytical forms, respectively. Numerical results reveal that the behaviors of TE and TM terms not only depend on the parameters of mirror resonators but also relate to the truncated parameter of the aperture. It is also shown that the distributions of TE and TM terms would not keep detached from each other because of the unorthogonality of their vectorial structures in the near field.

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1. Introduction

As is well known from numerous reports, optical resonators with mirrors of the Gaussian reflective profile have gained substantial interests in the production of high power laser beams. It is shown that eigenmodes of optical resonators with Gaussian classical reflective mirrors can be expanded into terms of freely propagating TEM_{00} fundamental modes [1]. The discriminations inducing by the misalignment of Gaussian reflective mirrors of optical resonators have been evaluated in analytical forms [2]. Since then, many achievements have been made concentrated on the excitation of large-sized TEM_{00} modes by the operation of specific optical resonators. For instance, the output beam with a near-Gaussian intensity distribution had been obtained in experiments by means of a novel apoditic filter [3]. Subsequently, it has been verified through experiments that the Gaussian modes with large sections can be produced in Cassegrain resonators by the usage of Gaussian reflective convex couplers [4]. The characteristics of Gaussian beams while transmitting through complementary reflective couplers show advantages of more brightness in on-axis intensity distributions together with lower misalignment sensitivity [5]. Based on the Huygens-Fresnel principle, the propagation and focusing properties of the beam generated by the Gaussian mirror resonators (GMR) are studied numerically [6,7]. Propagation properties of such a beam which passes through a paraxial optical system are investigated by means of the generalized Collins formula [8–10]. Explicit expressions for properties of the beam which propagates through a hard-edged circular aperture are formulated with the help of the scalar diffraction theory [11]. The propagation factor of the beam is derived by the second-order moments and the corresponding numerical results are shown in modulations with respect to various parameters [12]. Analytical propagation equations of the beam which transmits through uniaxial crystals are derived based on the paraxial vectorial theory of beams in uniaxially anisotropic medium [13]. Furthermore, through the expansion of the hard-edged-aperture function into a finite sum of complex Gaussian terms, propagation properties of the beam which passes through a truncated Fractional Fourier transform (FFT) optical system are studied in modulations with respect to resonator parameters [14]. Very recently, a report shows that the bell-shaped, flat-topped and angular Gaussian beam profiles can be separately generalized in Q-switched Nd:YAG laser by the modification of magnifications of the Gaussian mirror resonator [15]. Generally speaking, the output beam generated by the GMR occasionally is truncated by an obstruction or limited by finite radius of emitter sources; therefore the effect of the truncation should be further considered. Besides, as we all know, the TE and TM terms of a vectorial beam would remain orthogonal to each other in the far field. However, the property cannot hold true for the following two cases, i.e. the evaluation close to sources or in the near field. The near field corresponds to the situation that the on-axis propagation distance is only larger than a few wavelengths. In this case the TE and TM terms of the whole beam would not remain detached from each other. In this paper, the vectorial structure of the truncated beam generated by the GMR in the near field is

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revealed. Analytical expressions are derived for the TE and TM terms of the beam evaluated in the near field by means of the vectorial angular spectrum representation of electromagnetic fields and the paraxial approximation. Furthermore, relations of TE and TM terms of intensity distributions varying with respect to resonator parameters are also revealed. The corresponding results indicate that the TE and TM terms of the beam in the near field cannot remain orthogonal to each other due to the presence of a cross-light intensity among the internal vectorial structure of the beam.

2. Intensity distributions for TE and TM terms of beams in the near field

The electric field of the beam generated by the Gaussian mirror resonator through a hard-edged aperture can be given by the expression [11,14]

$$E(r',0)=A\exp\left(-\frac{r'^2}{\omega_0^2}+ik\frac{r'^2}{2R_0}\right)\left[1-K\exp\left(-2\beta^2\frac{r'^2}{\omega_0^2}\right)\right]^{1/2}circ(r'), \tag{1}$$

where A denotes the amplitude of a conventional Gaussian beam, $k=2\pi/\lambda$ is the wave number, ω_0 is the Gaussian waist width, K represents the on-axis reflectance of the mirror, $\beta=\omega_0/\omega_c$, ω_c is named as the mirror spot size where the reflectance of mirrors reduce to $1/e^2$ of its peak value. R_0 is the so-called wavefront curvature of the incident beam. When the reflectance of mirrors tends to the zero mean, i.e. $K\to 0$, Eq. (1) converts into the expression for truncated Gaussian beams. $circ(r')$ is the so-called *circ* function which represents a hard-edged aperture with radius R located at the initial plane $z=0$

$$circ(r')=\begin{cases}1, & r'\le R,\\ 0, & r'>R.\end{cases} \tag{2}$$

Eq. (2) can be further expanded into a finite sum of complex Gaussian terms [16,17]

$$circ(r')=\sum_{h=1}^{N}A_h\exp\left(-\frac{B_h r'^2}{R^2}\right), \tag{3}$$

where N is the number of complex Gaussian terms, A_h, B_h are the coefficients of which the values can be indexed in Table 1 of Refs. [16,17]. Due to the convergence property of the exponential function in Eq. (3), $N=10$ is large enough to provide high accuracy in numerical calculations. By performing binomial expansions to the factor $[1-K\exp(-2\beta^2(r'^2/\omega_0^2))]^{1/2}$, Eq. (1) can be alternatively rewritten as

$$E(r',0)=\sum_{m=0}^{\infty}A_m\exp\left(-\frac{r'^2}{q_m}\right)circ(r'), \tag{4}$$

with

$$A_m=\alpha_m A,\quad \alpha_0=1,\quad \alpha_1=-K/2,$$
$$\alpha_m=\frac{(2m-3)(2m-5)\cdots(3)\cdot(1)}{m!},\quad (m\ge 2), \tag{5}$$

$$\frac{1}{q_m}=\frac{1}{(\omega_0)_m^2}+i\frac{k}{2R_0},\quad (\omega_0)_m=\frac{\omega_0}{(2m\beta^2+1)^{1/2}},\quad (m\ge 2), \tag{6}$$

Furthermore, it is further assumed that the wavefront of incident beams locates at the plane of Gaussian mirrors, i.e. $R_0\to\infty$ should be satisfied in Eq. (6). Eqs. (4)–(6) deliver the message that the complex electric field of beams generated by the GMR can be obtained by the superposition of finite Gaussian fields each with different amplitude and waist width.

By means of the vectorial angular spectrum representation of electromagnetic fields, the propagating electric field of a beam with linear polarization along the x-axis can be given in the cylindrical coordinate system [18–22]

$$\mathbf{E}(r,\varphi,z)=\int_0^{\infty}\int_0^{2\pi}A_x(b,\theta)\left(\hat{\mathbf{e}}_x-\frac{b\cos\theta}{m}\hat{\mathbf{e}}_z\right)\exp\{ik[rb\cos(\theta-\varphi)+mz]\}b\,db\,d\theta, \tag{7}$$

where $m=\sqrt{1-b^2}$, $r=(x^2+y^2)^{1/2}$ denotes the position vector located at the output plane z. $A_x(b,\theta)$ is the component of the vectorial angular spectrum along the x-axis, which can be expressed by the Fourier transform of the initial electric field component

$$A_x(b,\theta)=\frac{1}{\lambda^2}\int_0^{\infty}\int_0^{2\pi}E_x(r',\alpha,0)\exp[-ikr'b\cos(\alpha-\theta)]r'\,dr'\,d\alpha, \tag{8}$$

θ, φ and α denote the azimuthal angles with regard to the coordinate systems (r,φ,z), $(b,\theta,0)$ and $(r',\alpha,0)$, respectively. $\hat{\mathbf{e}}_x$ and $\hat{\mathbf{e}}_z$ separately denotes the unit vectors along the x and z axis. The inequation $b<1$ corresponds to the case of homogeneous plane waves; while $b>1$ is in agreement with evanescent waves. Furthermore, in order to obtain the electric fields for the TE and TM terms of the vectorial beam, three unit vectors $\hat{\mathbf{e}}_1$,$\hat{\mathbf{e}}_2$ and $\hat{\mathbf{s}}$ which make up of a mutually perpendicular right-handed system are defined [23–32]

$$\hat{\mathbf{s}}\times\hat{\mathbf{e}}_1=\hat{\mathbf{e}}_2,\quad \hat{\mathbf{e}}_1\times\hat{\mathbf{e}}_2=\hat{\mathbf{s}},\quad \hat{\mathbf{e}}_2\times\hat{\mathbf{s}}=\hat{\mathbf{e}}_1, \tag{9}$$

with

$$\hat{\mathbf{e}}_1=\sin\theta\cdot\hat{\mathbf{e}}_x-\cos\theta\cdot\hat{\mathbf{e}}_y,\quad \hat{\mathbf{e}}_2=m\cos\theta\cdot\hat{\mathbf{e}}_x+m\sin\theta\cdot\hat{\mathbf{e}}_y-b\hat{\mathbf{e}}_z, \tag{10}$$

$$\hat{\mathbf{s}}=b\cos\theta\hat{\mathbf{e}}_x+b\sin\theta\cdot\hat{\mathbf{e}}_y+m\hat{\mathbf{e}}_z, \tag{11}$$

Correspondingly, the propagating electric field of a beam in the cylindrical coordinate system can be expressed as a sum of TE and TM terms

$$\mathbf{E}(r,\varphi,z)=\mathbf{E}_{TE}(r,\varphi,z)+\mathbf{E}_{TM}(r,\varphi,z), \tag{12}$$

with $\boldsymbol{E}_{TE}(r,\varphi,z)$ and $\boldsymbol{E}_{TM}(r,\varphi,z)$ separately being given by

$$\begin{aligned}\mathbf{E}_{TE}(r,\varphi,z)&=\int_0^{\infty}\int_0^{2\pi}\left[A_x(b,\theta)\left(\hat{\mathbf{e}}_x-\frac{b\cos\theta}{m}\hat{\mathbf{e}}_z\right)\cdot\hat{\mathbf{e}}_1\right]\hat{\mathbf{e}}_1\exp\{ik[rb\cos(\theta-\varphi)+mz]\}b\,db\,d\theta\\&=\int_0^{\infty}\int_0^{2\pi}A_x(b,\theta)(\sin^2\theta\cdot\hat{\mathbf{e}}_x-\sin\theta\cos\theta\cdot\hat{\mathbf{e}}_y)\exp\{ik[rb\cos(\theta-\varphi)+mz]\}b\,db\,d\theta,\end{aligned} \tag{13}$$

$$\begin{aligned}\mathbf{E}_{TM}(r,\varphi,z)&=\int_0^{\infty}\int_0^{2\pi}\left[A_x(b,\theta)\left(\hat{\mathbf{e}}_x-\frac{b\cos\theta}{m}\hat{\mathbf{e}}_z\right)\cdot\hat{\mathbf{e}}_2\right]\times\hat{\mathbf{e}}_2\exp\{ik[rb\cos(\theta-\varphi)+mz]\}b\,db\,d\theta\\&=\int_0^{\infty}\int_0^{2\pi}A_x(b,\theta)\left(\cos^2\theta\cdot\hat{\mathbf{e}}_x+\sin\theta\cos\theta\cdot\hat{\mathbf{e}}_y-\frac{b\cos\theta}{m}\hat{\mathbf{e}}_z\right)\times\exp\{ik[rb\cos(\theta-\varphi)+mz]\}b\,db\,d\theta,\end{aligned} \tag{14}$$

By substituting Eqs. (4)–(6) into Eq. (8) and performing the Fourier transform, the vectorial angular spectrum component yields the following analytical form:

$$A_x(b,\theta)=\sum_{m=0}^{\infty}\sum_{h=1}^{N}\frac{A_mA_h}{\frac{2m\beta^2+1}{\omega_0^2}+\frac{B_h}{R^2}}\exp\left[-\frac{k^2}{4\left(\frac{2m\beta^2+1}{\omega_0^2}+\frac{B_h}{R^2}\right)}b^2\right], \tag{15}$$

subsequently, substituting Eq. (15) into Eqs. (13) and (14), respectively, and utilizing the integral formula [33]

$$J_n(krb)=\frac{1}{2\pi}\int_0^{2\pi}\exp\left[ikrb\cos(\theta-\varphi)+in\left(\theta-\varphi-\frac{\pi}{2}\right)\right]d\theta. \tag{16}$$

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