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Propagation of flat-topped beams

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Abstract

The propagation of flat-topped beams passing through paraxial *ABCD* optical system is investigated based on the propagation formulas of Gaussian beam. The focal shift of focused coherent flat-topped beam is also studied in detail. Analytical expressions of the M^2 factor and the far-field intensity distribution for flat-topped beams are derived on the basis of second-order moments.
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1. Introduction

In many applications, such as optical processing and inertial confinement fusion, light beam is required that has flat-topped profiles and can propagate with limited distortion of its uniformity. A flat-topped beam can be obtained by refractive [1,2] and reflective anamorphic [3] optical systems. Several theoretical models have been put forward to describe light beam with flat-topped profiles. Flattened Gaussian beams proposed by Gori is a typical model [4]. The propagation of coherent and partially coherent flattened Gaussian beams in free space and through *ABCD* optical system has been studied analytically [5–7] by expanding the flattened Gaussian beams as a finite sum of Laguerre–Gauss modes [4] or Hermite–Gauss modes [5]. A closed-form propagation expression of flattened Gaussian beams is also obtained on the basis of generalized Huygens–Fresnel diffraction integral, in which the flattened Gaussian beams are regarded as a whole beam [8]. The analytical properties of flattened Gaussian beam make it an alternative to the super-Gauss beam, where numerical techniques are required even when evaluating the propagation in free space [9].

More recently, another model of flat-topped beam expressed in terms of a finite series of lowest-order Gaussian modes with different parameters is also proposed [10]. The flattened Gaussian beams with an elliptical flat-topped profile have been studied in detail based on this model [11]. An extension from fully coherent flat-topped beams to partially coherent flat-topped beams is straightforward [12]. In the present paper, we investigate the propagation of flat-topped beams through paraxial *ABCD* optical system. The focal shift of flat-topped beams is also studied. Furthermore, analytical expressions of far-field intensity distribution and M^2 factor for flat-topped beams are obtained.

2. The axial intensity distribution

Let us consider a flat-topped beam whose field distribution can be expressed as a finite series of Gaussian modes with different parameters and is characterized by [10]

$$E_N(r,0)=\sum_{n=1}^{N}\frac{(-1)^{n-1}}{N}\binom{N}{n}\exp\left[-\frac{r^2}{w_n^2(0)}\right],\tag{1}$$

where N is the beam order, $\binom{N}{n}$ represents a binomial coefficient, w_0 is the beam waist size of Gaussian beam and $w_n^2(0)=w_0^2/n$. Fig. 1 shows the normalized intensity distribution of the flat-topped light beams as a function of r/w_0 with different beam order N. As shown by Fig. 1, the degree of flatness increases with an increase of the beam order N. The propagation of flat-topped beams through a

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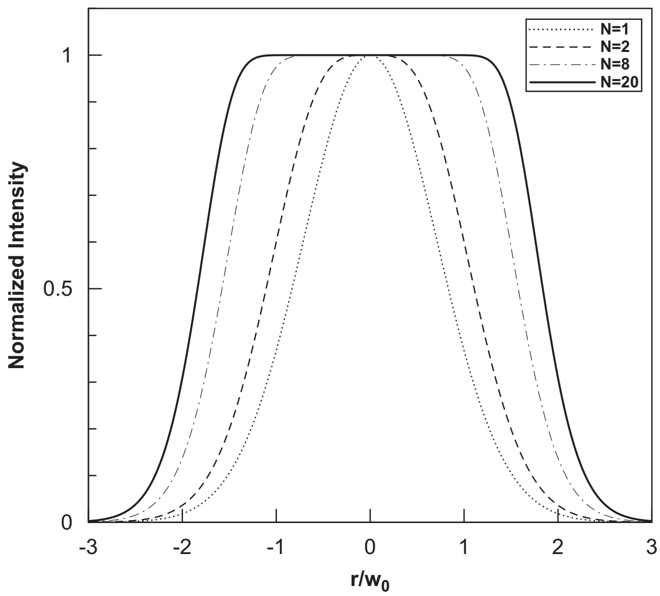

Fig. 1. Normalized intensity distribution of the flat-topped light beams as a function of r/w_0 with different beam order N at $z=0$ plane based on Eq. (1).

paraxial optical system parameterized by transfer matrix $\begin{pmatrix} A & B \\ C & D \end{pmatrix}$ can be solved by the well-known propagation formulas of Gaussian beams [7,13], A, B, C, D being the matrix elements of the optical system. Therefore, the propagation equation of flat-topped beams at a distance z is given by

$$E_N(r,z) = \sum_{n=1}^{N} \frac{(-1)^{n-1}}{N} \begin{pmatrix} N \\ n \end{pmatrix} \frac{w_n(0)}{w_n(z)} \exp\left[-\frac{r^2}{w_n(z)^2}\right] \times \exp\left\{ i\left[\frac{kr^2}{2R_n(z)} + kz - \Phi_n\right]\right\}, \tag{2}$$

where k is the wave number, w_n, R_n and Φ_n are given by

$$w_n(z) = Aw_n(0)\sqrt{1+F^2}, \tag{3a}$$

$$R_n(z) = AB\frac{1+F^{-2}}{1+BC[1+F^{-2}]}, \tag{3b}$$

$$\Phi_n(z) = \arctan F, \tag{3c}$$

where $F = \lambda B / A\pi w_n^2(0)$.

For the case of a flat-topped beam diffracted by a thin lens located at the $z=0$ plane, the corresponding matrix can be written as [14]

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & z \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} = \begin{pmatrix} -\Delta z & f(1+\Delta z) \\ -1/f & 1 \end{pmatrix}, \tag{4}$$

and

$$\Delta z = \frac{z-f}{f}, \tag{5}$$

where z is the propagation distance and f is the focal length of the lens. Taking into account Eqs. (2) and (4), the on-axis intensity distribution of flat-topped beam passing through a lens can be expressed as

$$I_N(0,\Delta z) = \left| \sum_{n=1}^{N} \frac{(-1)^n}{N} \begin{pmatrix} N \\ n \end{pmatrix} \frac{1}{\Delta z \sqrt{1 + \left[\frac{2n(1+\Delta z)}{\Delta z N_F}\right]^2}} \times \exp\left\{ i \arctan\left[\frac{2n(1+\Delta z)}{\Delta z N_F}\right]\right\} \right|^2, \tag{6}$$

where

$$N_F = \frac{kw_0^2}{f} \tag{7}$$

coincides with 2π times the Fresnel number [15].

To characterize the behavior of the axial intensity distribution of flat-topped beams, we give some numerical results. In Figs. 2 and 3, we plot the axial intensity distribution of flat-topped beams as a function of Δz with different N_F when the beam order N is fixed at 10 and with different beam order N when N_F is fixed at 4. It is seen from Figs. 2 and 3 that the point of the absolute maximum axis intensity is always located at a distance from geometric focus and closer to the lens. This effect is named as focal shift [16]. Fig. 2 indicates that the distance between the point of absolute maximum intensity and the geometric focus decreases as the N_F increases. In the limited cases, when the N_F is big enough, the distance will become zero. That is to say, the focal shift can occur only if the Fresnel number is of the order of unity or smaller [16,17]. Fig. 3 shows that the distance between the point of maximum intensity and geometric focus is maximum when the beam order N is 1 and decreases as the beam order N increases. In other words, the fundamental Gaussian beam experiences more "focal shift" than the flat-topped beams.

3. Far-field intensity distribution and M^2 factor

An important property of optical beams is the beam propagation factor M^2 factor defined as [18]

$$M^2 = 2\pi\sigma_0\sigma_\infty, \tag{8}$$

where σ_0 and σ_∞ are the second-order moments associated with the intensity distributions at the waist plane and in the far field. M^2 factor specifies the far-field divergence properties of the light beam for a fixed beam waist width [13]. The M^2 factor defined in the sense of second-order moments through paraxial first-order $ABCD$ optical systems remains invariant upon propagation. M^2 factor is always not less than 1 and equals to 1 for the case of Gaussian beam [12]. According to the second-moment

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