Generation of a localized hollow laser beam using crossed nonlinear optical crystals

Zhizhang Wang [a], Chunxi Wang [a], Chunying Pei [a], Yaling Yin [a], Yong Xia [a,b,*], Jianping Yin [a]

[a] State Key Laboratory of Precise Spectroscopy, School of Physics and Materials Science, East China Normal University, Shanghai 200062, People's Republic of China
[b] Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, People's Republic of China

ABSTRACT

A nonlinear optical approach to generate a localized hollow laser beam and its array using crossed nonlinear ZnSe crystals is proposed. We calculate the intensity distributions of the hollow beam and its propagating properties in free space, and study the dependences of the dark spot size of the hollow beam on the incident beam waist radius and the crystal length. Our studies show that the longitudinal size of the hollow beam can be reduced by ~660 times than that generated by a single nonlinear crystal. Such laser beam with a dark hollow region and a large intensity gradient can be used to trap cold neutral atoms, molecules and microscopic particles.

1. Introduction

A localized hollow laser beam (LHB) is a kind of laser beam consisting of a dark central region that is fully surrounded by regions of high intensity [1]. Since the LHB has a three-dimension (3D) closed dark hollow region and a large intensity gradient, it can be used to trap microscopic particles and neutral atoms. So, the LHB has many important and extensive applications in modern optics and atomic (or molecular) optics [2–6]. In particular, the intensity gradient near the focal point of a LHB may be used to efficiently cool neutral atoms by LHB-induced Sisyphus cooling [7].

LHBs have been generated by a number of approaches, e.g. holograms [8], conical refraction [9–12], uniaxial crystal [13], interferometer [14], photon sieve [15], optical fiber [16], polarized light [17], focusing multi-ring hollow Gaussian beam [18], to form a desirable hollow axial structure. The concept of a LHB has also been recently extended to plasmonic structures [19,20], the plasmonic bottle beam could be used to optically sort particles by trapping those with a specific size. Nowadays, nonlinear optical methods have been proposed to generate non-diffraction beams [21–23]. Many self-action effects have been thoroughly investigated, including self-phase modulation [24], self-focusing [25–27] and self-bending [28–30]. Our approach is motivated by the self-bending (SB) effect of ZnSe nonlinear material. ZnSe is a kind of materials with large nonlinear refractive index, and it can induce the SB effect for the incident laser beam, which can be transformed to the hollow beam distribution at the optimal position by the nonlinear medium.

In this paper, we propose a scheme – using crossed ZnSe nonlinear crystals – to generate a LHB and its array, and validate this scheme theoretically. The intensity distributions of the LHB in different cases of the symmetric parameters are calculated. The ratio of the longitudinal size of LHB can be tuned by altering the relative position of two crystals. As well, the aspect ratio of the LHB is calculated to study the shape of the beam. The LHB array formed by more nonlinear ZnSe crystals is also discussed.

2. Principle description

The schematic setup to generate a LHB is shown in Fig. 1. Two orthogonal incident Gaussian laser beams (GBs) propagate along the x and z direction, respectively. The GB_1 (or GB_2) is collimated by the lenses L_1(or L_2) and then passes through a nonlinear dielectric material ZnSe crystal C_1 (or C_2). Due to the nonlinearity of the ZnSe crystals, the phases of two GBs will be modulated. In each optical path, a hollow beam can be generated after the nonlinear crystal C_1 (or C_2). Two beams are modulated by two crystals, and then superimposed to form a LHB. Such a LHB has a 3D closed hollow region, and the longitudinal size of the hollow beam is much smaller than that generated by a single nonlinear crystal [31].

In theory, the refractive index n of the ZnSe crystal can be described by the relationship

$$n = n_0 + n_2|U|^2 \tag{1}$$
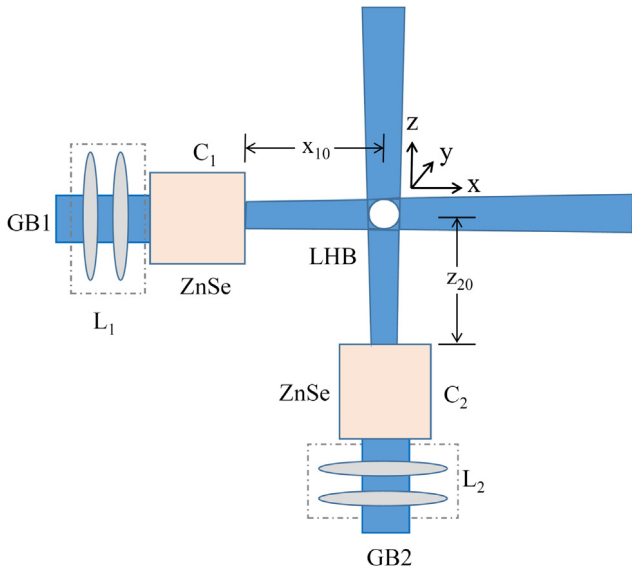
Fig. 1. Schematic diagram to generate a LHB. GB_1 and GB_2 are incident laser beams, L_1 and L_2 are collimated lenses, C_1 and C_2 are nonlinear dielectric material ZnSe crystals, respectively.

Where n_0 and n_2 are the linear and nonlinear refractive indexes, respectively, U is the complex amplitude of the light field.

We set L as the length of the nonlinear ZnSe crystal along the propagating direction and set the center of the superposition of two crossed beams as the coordinate origin. The 2D complex amplitude $U(y_1, z_1, -(L + x_{10}))$ of the incident well-collimated GB_1 can be described by

$$U(y_1, z_1, -(L + x_{10})) = U_0(y_1, z_1) \exp(i\varphi_0(y_1, z_1, -(L + x_{10}))) \quad (2)$$

where x_{10} is the initial position of the crystal C_1 and $U_0(y_1, z_1)$ can be expressed as

$$U_0(y_1, z_1) = U_m \exp(-\frac{y_1^2 + z_1^2}{w^2}) \quad (3)$$

where U_m is the light field complex amplitude, which depends on both the waist radius and power of the incident GB_1. The complex amplitude $U_1(y_1, z_1, -x_{10})$ of the light field at the output face of the nonlinear ZnSe crystal C_1 can be given by

$$U_1(y_1, z_1, -x_{10}) = U(y_1, z_1, -(L + x_{10}))$$
$$\times \exp\left[i\left(\varphi_0(y_1, z_1, -x_{10}) + n(y_1, z_1)kL\right)\right] \quad (4)$$

According to the Huygens–Fresnel diffraction theory, the light field complex amplitude $U_1(x, y, z)$ in the propagating position x after the nonlinear ZnSe crystal C_1 can be written as

$$U_1(x, y, z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{\exp(ik(x - x_{10}))}{i\lambda(x - x_{10})}$$
$$\exp\left(ik\frac{(z - z_1)^2 + (y - y_1)^2}{2(x - x_{10})}\right) \quad (5)$$
$$U_1(y_1, z_1, -x_{10})\, dy_1 dz_1,$$

Based on the analysis above, the corresponding light field complex amplitude $U_2(x, y, z)$ reshaped by C_2 in the transverse at propagation position z in free space can be written as

$$U_2(x, y, z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{\exp(ik(z - z_{20}))}{i\lambda(z - z_{20})}$$
$$\exp\left(ik\frac{(x - x_2)^2 + (y - y_2)^2}{2(z - z_{20})}\right) \quad (6)$$
$$U_2(x_2, y_2, -z_{20})\, dx_2 dy_2$$

where z_{20} is the initial position of the crystal C_2 and $U_2(x_2, y_2, -z_{20})$ can be expressed as

$$U_2(x_2, y_2, -z_{20}) = U(x_2, y_2, -(L + z_{20})) \exp\left[i\left(\varphi_0(x_2, y_2, -z_{20})\right.\right.$$
$$\left.\left. + n(x_2, y_2)kL\right)\right] \quad (7)$$

As a result, the intensity $I(x, y, z)$ of the light between two crystals is represented as the superposition of corresponding intensity of light $U_1(x, y, z)$ after crystal C_1 and light $U_2(x, y, z)$ after crystal C_2. It can be written as

$$I(x, y, z) = |U_1(x, y, z)|^2 + |U_2(x, y, z)|^2 \quad (8)$$

3. Results and Discussions

To study the propagation characteristics of the LHB in free space, we define the special parameter, the dark spot size (DSS) as the full width at half maximum (FWHM) of the radial-intensity distribution inside the notch of the LHB [3]. Based on the theoretical analyses above, the intensity distributions of the LHB moving the relative position between two nonlinear ZnSe crystals can be calculated by using Eqs. (2)–(8). In the numerical calculation, the waist radius of the two incident GBs is taken as $w_1 = w_2 = 300$ μm, the light field complex amplitude is $U_m = 3.3 \times 10^4 \sqrt{W}/m$ and the wavelength is $\lambda = 447.6$ nm - experimentally from a dye laser. With these light parameters, the significant nonlinear effect of the ZnSe crystal can be excited. For the ZnSe crystal, the length is $L = 450$ μm, n_0 is 2.8 and n_2 is 6.1×10^{-13} m^2/W. According to the calculated results in Ref. [31], an optimal hollow beam can be obtained at a distance $z_{optimal} = 0.62$ m away from the ZnSe crystal under these parameters, the beam is kept to be a ring beam and to be hollow at the beam center for a long distance with ~0.8 m in the propagating direction, which looks like a hollow ellipsoid with a large elliptical ratio. From our calculation, the intensity distributions of the superposed light beam after crystal C_2 at the different z position and at $x_{10} = x_{optimal} = -0.62$ m are shown in Fig. 2. The left and center columns are the 1D intensity distributions along the x and z direction, respectively, the right column is 2D intensity distributions in xz plane. In Fig. 2, the position of the crystal C_1 is fixed while the position of the crystal C_2 moves along the z direction. The superposed light field appears as a pipe in the z direction where the position of the crystal C_2 is $z_{20} = -0.2$ m (as shown in Fig. 2(m)).

As the position of the crystal C_2 approaches the optimal position $z_{20} = z_{optimal} = -0.62$ m gradually, the light intensity in the x and z direction will have the same hollow profile distributions (as shown in Fig. 2(d), (j)). At the position of the crystal $C_2 z_{20} = x_{10} = -0.62$ m, an optimal 3D closed LHB is formed — it is nearly square (as shown in Fig. 2(p)), and the DSS_z (1.2 mm) of this LHB is much less than DSS_z (0.8 m) that generated by a single ZnSe crystal. So the ratio of the longitudinal size of LHB can be easily changed by altering the relative position of two crystals. The smaller the longitudinal size is, the higher the intensity gradient of the LHB is, so the blue-detuned LHB can be used to trap and cool neutral atoms by intensity-gradient induced Sisyphus cooling. When the position of the crystal C_2 is larger than 0.62 m, the light beam gradually displays a profile with a non-zero central intensity and larger size, and the superposed light beam looks like a pipe in the x direction (as shown in Fig. 2(r)). In this case, the superposed light beam is dominated by the light beam after C_1.

As a result, we study the relationship of the LHB size with the waist radius of the incident GB and the length of the nonlinear ZnSe crystal. Firstly, we assume that two waist radiuses of both GBs are the same, i.e., $w_1 = w_2$. When the positions of the two crystals C_1 and C_2 are fixed at $x_{10} = z_{20} = -0.62$ m, an optimal closed LHB can be obtained. Fig. 3 shows the 2D intensity distributions of the LHBs under the different waist radius of incident GBs. It is evident that all the LHBs are nearly square in xoz plane and the DSS is gradually increasing while increasing the waist radius w. The detailed information about each LHB's size — DSS at x (or z) direction is concluded in Fig. 4. The DSS is linearly related