



Nonlinear optical investigation of Gaussian laser beam propagating in a dye-doped nematic liquid crystal

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ABSTRACT

The laser beam shape and variation of the curvature radius of the wavefront have been simulated when the Gaussian laser beam passes through a dye-doped nematics liquid crystal. The effect of different dyes is investigated in the wavefront distortion as well as the beam shape due to its quality factor. We have reported the dependency of the curvature radius of the wavefront to the nonlinearity of the sample. Also we have obtained the beam shape of three dyes doped nematic liquid crystal as a nonlinear optical material compared with the experimental results.

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1. Introduction

Liquid crystals are mesophases between crystalline solids and isotropic liquids. Recently, the nonlinear effects of azo-dye-doped liquid crystals (ADDLCs), such as photorefractive effect [1–3] and degenerate four-wave mixing [4], have attracted much interest due to their applications in optical devices such as liquid crystal displays which are used in electronic watches, calculators, laptop and desktop computers.

In linear optical processes the physical properties of the liquid crystal, such as molecular structure, individual or collective molecular orientation, temperature, density, and population of electronic levels are not affected by the optical fields. However the direction, amplitude, intensity, and phase of the optical fields are affected in a unidirectional way. Liquid crystals are optically highly nonlinear materials and their physical properties i.e. temperature, molecular orientation, density and electronic structure can be easily perturbed by applied optical field [5–9]. Since liquid crystalline molecules are anisotropic hence a polarized light from a laser source can induce an alignment or order in the isotropic phase, or realign the molecules in the ordered phase.

The optical properties of liquid crystals can be controlled by external applied DC or low-frequency fields; which gives rise to a variety of electro-optical effects which are widely used in many electro-optical display and image-processing applications.

There are several methods for nonlinear characterization of materials such as z-scan which is a powerful technique to obtain both the sign and magnitude of the complex nonlinear refractive index of some optical materials. This technique is based on the principle that spatial variations of the incident intensity distribution can photoinduce a lens in the nonlinear material which affects the posterior propagation of the beam and intensity changes at the far-field.

During developing the z-scan technique [10,11], many improvements and modifications have been suggested due to its sensitivity and simplicity such as eclipsing [12], top hat beams [13], two colours [14] and reflection [15]. Detailed analysis of the parameters affecting the z-scan measurements was reported by Chapple et al. [16]. In this investigation, a Gaussian beam incident to a thin Kerr nonlinear sample was considered to obtain simple analytical formulas relating the z-scan curve obtained from the on-axis intensity at the far-field. Gaussian decomposition method has been used to analyze the characteristics of the z-scan curves for thin samples with small or large nonlinear phase shifts.

In this paper, we focus on nonlinear properties of dye-doped liquid crystal. Also, we have studied the laser beam propagation in a thin nonlinear material (dye-doped liquid crystal) and compared with experimental data. Furthermore, the radius of curvature of the wavefront was calculated and it is found that convergent (divergent) Gaussian beam passing through a self-focusing sample, the radius of curvature of the wavefront becomes larger (smaller).

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2. Theoretical approach

A plane wave and a spherical wave represent two opposite extremes of angular and spatial confinement. Waves including wavefront normals which make small angles with the z -axis are called paraxial waves and they must satisfy the paraxial Helmholtz equation [17].

An important solution of the mentioned equation which exhibits the characteristics of an optical beam is a wave called the Gaussian beam. The electric field of a TEM₀₀ Gaussian beam with beam waist radius w_0 travelling in the z direction can be written as

$$E_{in}(r, z) = A_0 \frac{W_0}{W(z)} \exp\left(-\frac{\rho^2}{W^2(z)}\right) \exp\left(-ikz - ik\frac{\rho^2}{2R(z)} + i\zeta(z)\right) \quad (1)$$

$$W(z) = W_0 \left[1 + \left(\frac{z}{z_0}\right)^2\right]^{1/2} \quad (2)$$

$$R(z) = z \left[1 + \left(\frac{z_0}{z}\right)^2\right] \quad (3)$$

where I_0 , $W(z)$, $R(z)$ and z_0 are respectively the irradiance at beam waist of the Gaussian beam, the beam radius at z , the radius of curvature of the wavefront at z and the diffraction length of the beam respectively and $\zeta(z) = \tan^{-1} \frac{z}{z_0}$, $W_0 = \left(\frac{\lambda z_0}{\pi}\right)^{1/2}$.

In this study, first of all some of Gaussian beam parameters such as intensity, beam radius and curvature radius are introduced.

Within any transverse plane, the beam intensity assumes its peak value on the beam axis, and drops by the factor $1/e^2$ at the radial distance $\rho = W(z)$. Since 86% of the power is carried within a circle of radius $W(z)$, we regard $W(z)$ as the beam radius. The phase of the Gaussian beam could be calculated from Eq. (1). It is given by

$$\varphi(\rho, z) = kz - \zeta(z) + \frac{k\rho^2}{2R(z)}. \quad (4)$$

On the beam axis ($\rho = 0$) the phase

$$\varphi(\rho, z) = kz - \zeta(z). \quad (5)$$

The first term of Eq. (4), kz , is the phase of a plane wave and the second represents a phase retardation $E(z)$ given which ranges from $-\pi/2$ at $z = -\infty$ to $+\pi/2$ at $z = \infty$. This phase retardation corresponds to an excess delay of the wavefront in comparison with a plane wave or a spherical wave. The total accumulated excess retardation as the wave travels from $z = -\infty$ to $z = \infty$ is π . The last term is responsible for wavefront bending. It represents the deviation of the phase at off-axis points in a given transverse plane from that at the axial point. Because the variations of $\tan^{-1}(z/z_0)$ and $R(z)$ are slow, the constant phase surfaces satisfy the following equation:

$$z + \frac{r^2}{2R(z)} = \left(m + \frac{\zeta(z)}{2\pi}\right) \times \lambda \approx \text{constant}. \quad (6)$$

This is the equation of a paraboloidal surface of curvature radius R ; where $R(z)$ is the radius of curvature of the wavefront at position z on the beam axis. The radius of curvature $R(z)$ is infinite at $z = 0$, corresponding to plane wavefronts. It decreases to a minimum value of $2z_0$ at $z = z_0$. The radius of curvature subsequently increases with further increase of z until $R(z) = z$ for $z \gg z_0$. The wavefront is then approximately the same as that of a spherical wave. For negative z the wavefronts follow an identical pattern, except for a change in sign.

If the Gaussian beam passes through a thin third-order nonlinear optical sample with nonlinear refraction c (MKS) located at z , the phase shift of the Gaussian beam is given by:

$$\Delta\varphi_0(z, r) = \frac{\Delta\varphi_0}{1 + \left(\frac{z}{z_0}\right)^2} e^{-\frac{2r^2}{w^2(z)}} \quad (7)$$

where $\Delta\varphi_0 = k\gamma I_0 L_{eff} = k\Delta n I_0$ and $L_{eff} = \frac{(1 - e^{-\alpha L})}{\alpha}$. The electric field at the exit plane of the sample is obtained [10], and the far-field at a vertical plane in the far-field is given by:

$$E(r, z) = E_{in}(z, r) e^{-\alpha L/2} \sum_{m=0}^{\infty} \frac{[i\Delta\varphi_0(z)]^m}{m!} \frac{w_{m0}}{w_m} \exp\left(-\frac{r^2}{w_m^2} - \frac{ikr^2}{2R_m} + i\theta_m\right) \quad (8)$$

where the term $E_{in}(r=0, z)$ is the input electric field of the incident Gaussian beam at the sample plane. Defining d as the propagation distance in free space from the sample to the plane of the far-field and $g = 1 + d/R(z)$, the remaining parameters in Eq. (8) are expressed as:

$$\begin{aligned} w_{m0}^2 &= \frac{w^2(z)}{2m+1} \\ d_m &= \frac{kw_{m0}^2}{2} \\ w_m^2 &= w_{m0}^2 \left[g^2 + \frac{d^2}{d_m^2} \right] \\ R_m &= d \left[1 - \frac{g}{g^2 + \frac{d^2}{d_m^2}} \right]^{-1} \\ \theta_m &= \tan^{-1} \left[\frac{d/d_m}{g} \right]. \end{aligned} \quad (9)$$

The electric field of the beam is now a summation of some subbeams having individually own wavefront curvature radius at position z . The parameter $W(z)$ guides us to stimulate the beam profile before and after transmitting the beam from the sample.

3. Discussion and experimental approach

We used three azo-dyes (Sudan black b, Sudan III and Sudan IV) doped to a nematic liquid crystal (w1680) which their nonlinear optical properties have been investigated in recent works [18,19]. Sudan dyes were obtained from Merck and used as the guest. A nematic mixture of w1680 was synthesized in the Institute of Chemistry of the Military Technical Academy, Warsaw, Poland, and used as the host. The dyes are dissolved in a nematic liquid crystal with 1% concentration. The guest–host cell was made by sandwiching the solutions between two optical glass plates ($2 \times 1.2 \text{ cm}^2$). The homeotropic orientation of the guest and host molecules was achieved by depositing of a thin layer of lecithin on the clean glass surfaces and mylar film ($12.5 \mu\text{m}$) was used as the spacer. The plates were sealed together by epoxy resin glue. The liquid crystal cells were

Table 1
Nonlinear parameters of samples.

Doped material	Laser intensity I_0 (W/cm ²)	Rayleigh range (cm)	n_2 (cm ² /W)
Sudan black b	641	0.31	1.01×10^{-6}
Sudan III	794	3.12	2.1×10^{-6}
Sudan IV	1440	3.12	8.04×10^{-6}

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