Creation of a narrow Bessel-like laser beam using a nematic liquid crystal

Antti Hakola, Andriy Shevchenko, Scott C. Buchter, and Matti Kaivola

Department of Engineering Physics and Mathematics, Helsinki University of Technology, P. O. Box 4100, FI-02015 TKK, Finland

Nelson V. Tabiryan

BEAM Engineering for Advanced Measurements Company, 686 Formosa Avenue, Winter Park, Florida 32789

Received July 13, 2005; revised September 26, 2005; accepted October 11, 2005; posted October 13, 2005 (Doc. ID 63394)

We present a simple and efficient method to convert a Gaussian laser beam into a Bessel-like beam with a long and narrow focal line by using a nematic liquid crystal with a high third-order nonlinearity. © 2006 Optical Society of America

OCIS codes: 160.3710, 260.5950, 350.5500.

1. INTRODUCTION

A large number of applications in physics, chemistry, biology, and engineering would greatly benefit from a laser beam that had a sharp focus but, simultaneously, a negligible spreading due to diffraction. Examples of such applications include laser drilling and writing,[1,2] trapping and guiding of microparticles or nanoparticles and neutral atoms,[3–6] precise alignment and metrology techniques,[7,8] and high-resolution three-dimensional imaging.[9] The usability of conventional, focused laser beams for these purposes is limited owing to diffraction; an optical field focused to a small spot quickly diverges. The Rayleigh range of, e.g., an ideal Gaussian beam with a waist radius of 5 μm is only 160 μm for the wavelength of 500 nm.

The beam divergence can be reduced by converting the Gaussian laser beam into a Bessel-like beam, which has a nearly propagation-invariant intensity profile within a long distance of propagation. Typically, this is realized by using an axicon-based optical system,[8,10–14] by inserting a narrow ring-shaped aperture in front of a positive lens,[15–17] or by applying a two-element diffractive system.[18] Certain approximate Bessel modes can also be generated directly in a laser resonator, as demonstrated in Refs. 19–23. Axicons are perhaps the most widely used elements in the realization of Bessel-type laser beams, but their use has some drawbacks. For example, to obtain a narrow and long focal line, the axicon has to be combined with an annular aperture or an apodizing transmittance mask[24] that inevitably blocks a significant part of the incident light. Furthermore, the quality of the focal line is sensitive to alignment and, in the case of diffractive axicons, to fabrication errors.[25,26] Bessel-like beams created inside a laser resonator, for their part, are difficult to make narrow at the laser output, and focusing of such a beam does not result in a long depth of focus.

In this work, we investigate the possibility to create a long and narrow focal line by using self-phase modulation of a Gaussian laser beam in a thin layer of a nematic liquid crystal that exhibits a high third-order nonlinearity.[27] We show that when a Gaussian beam undergoes self-focusing in such a crystal, the self-focal region can have Bessel-like field characteristics. The width of the central intensity maximum, for example, can be as small as a few micrometers over a propagation distance of more than 1 mm. The paper is organized as follows. In Section 2 we present a simple theoretical basis for the creation of Bessel-like self-focused fields. Section 3 describes experimental demonstration of the phenomenon, and Section 4 summarizes the results.

2. THEORY

A focused laser beam that passes through a ring-shaped aperture has a Bessel-like field distribution within a long distance near the focus.[17] A Gaussian beam self-focused in a thin liquid crystal, on the other hand, behaves as if it was formed by a converging hollow beam with an increasing thickness of its ring.[27] This converging beam is similar to the field behind the ring aperture and, depending on the beam parameters, it could show a reduced divergence in its focus. We present a theoretical description of this field in the frame of the Fresnel diffraction theory.

A self-focused Gaussian laser beam is assumed to be normally incident on the liquid-crystal cell and have a perfect axial symmetry. In the case of a thin cell, the intensity distribution behind the liquid crystal can be considered to be the same as at its input. Then, the complex amplitude of the field, $U(z,r)$, as a function of distance z from the crystal and a distance r from the beam axis is obtained by using the Fresnel diffraction integral in cylindrical coordinates

$$U(z,r) = \frac{2\pi}{\lambda z}\int_0^\infty U(0,\rho)\rho \exp\left(j\frac{\pi\rho^2}{\lambda z}\right)J_0\left(\frac{2\pi r\rho}{\lambda z}\right)\mathrm{d}\rho. \quad (1)$$

Here ρ denotes the radial coordinate at the crystal output, λ is the laser wavelength, and J_0 is the zeroth-order

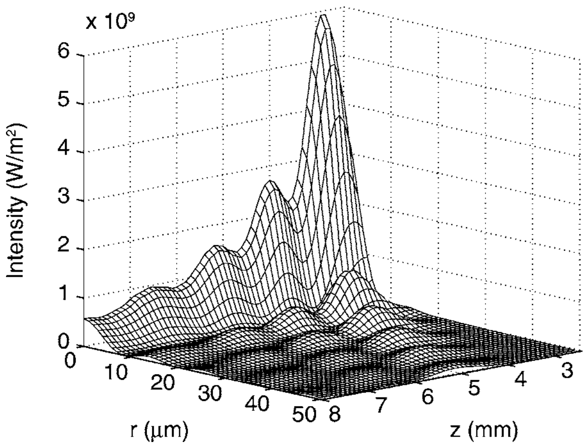

Fig. 1. Intensity distribution $I(r,z)$ of the simulated self-focused field; z and r denote the axial and radial coordinates, respectively.

Bessel function of the first kind. The field $U(0,\rho)$ is described by

$$U(0,\rho) = \sqrt{I_p}\exp\left[-\frac{\rho^2}{W_{\mathrm{LC}}^2} + j\phi(\rho)\right], \qquad (2)$$

where I_p is the peak intensity and W_{LC} is the $1/e^2$ beam radius. The nonlinear phase $\phi(\rho)$ due to self-phase modulation is described by

$$\phi(\rho) = \frac{2\pi}{\lambda} L n_2 I_p \exp\left(-\frac{2\rho^2}{W_{\mathrm{LC}}^2}\right), \qquad (3)$$

where L is the thickness and n_2 is the nonlinear refractive-index coefficient of the liquid crystal. If the crystal is not located exactly at the waist of the incident beam, then an additional phase factor, $\exp(j\pi\rho^2/\lambda R_{\mathrm{LC}})$, where R_{LC} is the radius of the wavefront curvature, must be inserted into Eq. (2). In practice, the phase distribution has a more complicated dependence on the parameters I_p, W_{LC}, n_2, and L, but this model still gives a qualitatively accurate description of the beam behavior upon propagation.[28–30] It is also worth noting that in general the radius in the nonlinear phase distribution [Eq. (3)] can be different from that of the incident beam owing to the spatially nonlocal response of the liquid crystal.[31]

Figure 1 shows the intensity profile of the self-focused field $I(z,r)=|U(z,r)|^2$ calculated for the particularly chosen parameter values of $\lambda=532$ nm, $W_{\mathrm{LC}}=220$ μm, $R_{\mathrm{LC}}=-39$ mm, $L=100$ μm, $n_2=3\times10^{-5}$ cm^2/W, and $I_p=1.7\times10^7$ W/m^2. These values were used in one of our experiments, the results of which are presented in Section 3. The ranges $z>2.5$ mm and $r<50$ μm satisfy well the Fresnel approximation. The profile has a major peak at $z\approx2.8$ mm. At that point the field intensity reaches a value of 6×10^9 W/m, and the width of the central maximum is as small as $W_{\mathrm{SF}}\approx5$ μm. In the absence of the liquid crystal, a beam waist radius of approximately 30 μm would be obtained at $z=38$ mm; this is an interesting detail of how the nonlinear lens shapes the incoming beam. When the beam propagates an additional 4.5 mm, the peak intensity drops by a factor of 10, whereas the width of the central peak remains essentially unchanged. It is tempting to compare these results with a Gaussian beam focused to the same waist. At a distance of 4.5 mm from the focal plane, the beam radius would increase to $W_G\approx150$ μm, and the peak intensity of the beam would drop by 10^3 times, i.e., 2 orders of magnitude faster than the intensity of the calculated self-focused beam. From Eqs. (2) and (3) one can see that, close to the center ($\rho\approx0$), the intensity distribution behind the crystal resembles that of a Gaussian beam focused with a positive lens. When the beam propagates, this central part interferes with the rest of the beam, producing a long and narrow focal line. Thus, mathematically, the self-focused field is different from a diffraction-free Bessel field produced, e.g., by an axicon. According to Eq. (3), the action of the liquid crystal can be mathematically treated by dividing the self-focusing region into a collection of narrow ring axicons whose angles depend on the radial distance from the beam axis. Each of these axicons has its own propagation-invariant range. As a result, the beam looks Bessel-like within a long range, whereas upon propagation it slowly spreads in contrast to a beam from a single axicon.

3. EXPERIMENT

To experimentally verify the results obtained in Section 2, we used the setup shown in Fig. 2. As the laser source we used a frequency-doubled, diode-pumped Nd:YVO_4 laser (Spectra Physics Millenia Xs) operating at $\lambda=532$ nm. The beam waist radius at the laser output is $W_0=1150$ μm. The beam is focused with a lens L_1 that has a focal length of 200 mm, and the liquid crystal, LC, is placed at a distance of 162 mm from it. This yields the incident-beam radius W_{LC} of 220 μm and the radius of the wavefront curvature R_{LC} of −39 mm. The crystal is displaced from the beam waist in order to obtain the desired W_{LC} by using a single lens with a reasonably short focal length. In this case, the spatial phase modulation due to the convergence of the beam does not disturb the strong phase modulation induced by self-focusing. The liquid crystal is a 100 μm thick homeotropically oriented nematic crystal with a nonlinear refractive index coefficient n_2 larger than 10^{-5} cm^2/W.[32] The intensity profiles after the crystal are imaged with a lens L_2 onto a CCD camera (BeamStar FX 50, 640×480 pixels, pixel dimensions 9.9 μm×9.9 μm). In our experiments, the lens L_2 was a 20× microscope objective with an effective focal length of 8.5 mm. The distance between the camera and the back face of the objective was fixed to 160 mm. The corresponding magnification of the system is $M=21.2$. Several neutral-density attenuators were inserted into the beam path between the objective and the camera.

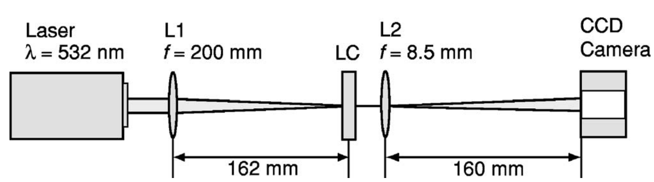

Fig. 2. Schematic illustration of the experimental setup. The beam from a cw laser is focused with a lens L_1 into the liquid crystal LC. The resulting self-focused beam is imaged with another lens, L_2, to a CCD camera which is located at a fixed distance from the lens.

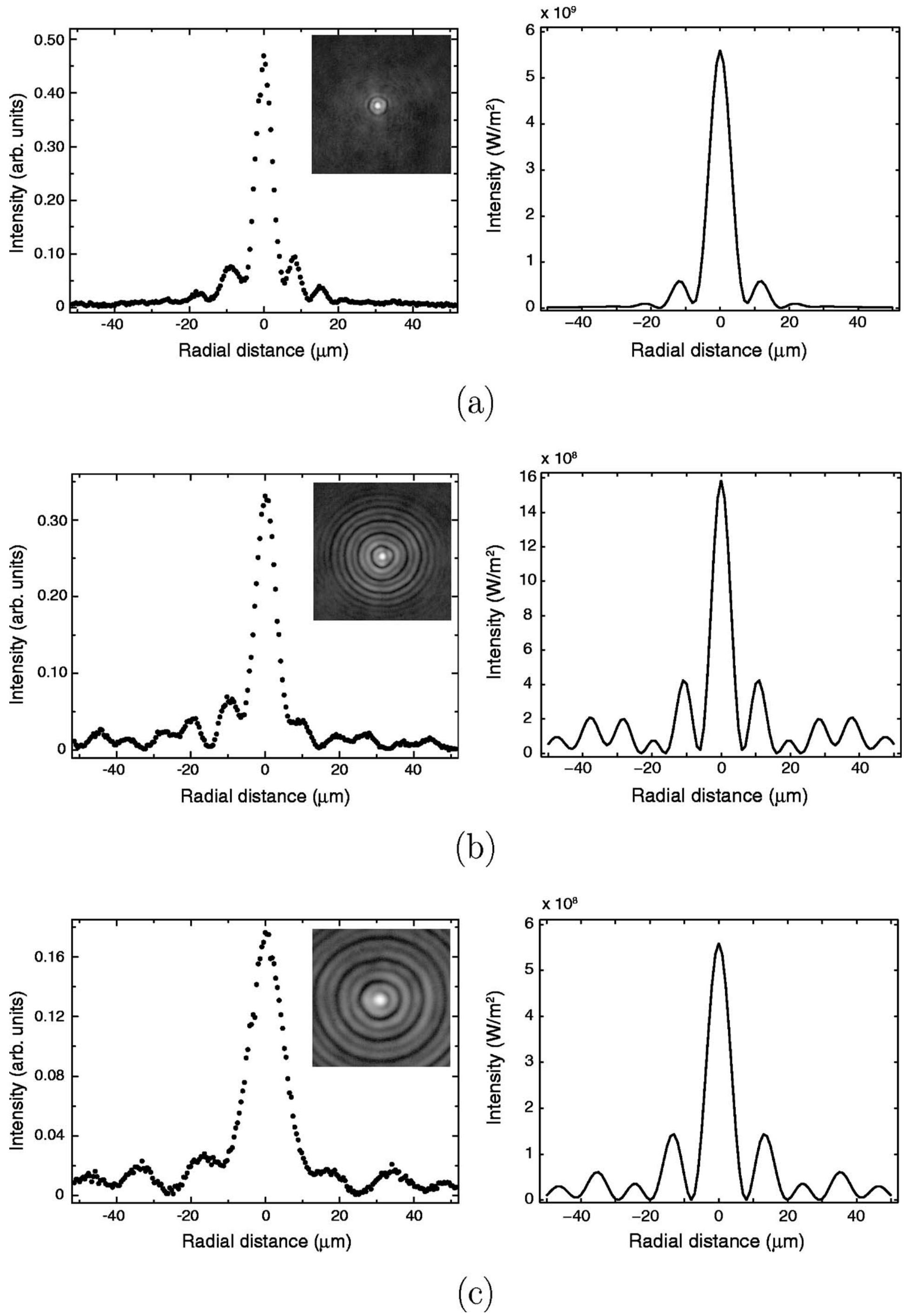

Fig. 3. Measured (left column) and simulated (right column) intensity profiles of the self-focused laser beam. The profiles in (b) and (c) are measured at distances of 1.5 mm and 4.5 mm, respectively, from the location corresponding to (a) along the beam axis. The two-dimensional CCD images of the beam are shown in the insets.

The laser beam power was selected to be 1.3 W, which resulted in a peak intensity of 1.7×10^7 W/m^2 at the crystal input. This intensity is well above the self-focusing threshold, which at normal incidence has the value $I_{\mathrm{th}} \approx 1.0 \times 10^7$ W/m^2.[33] The response time of the liquid crystal is inversely proportional to the squared value of its thickness. In our experiments, it was of the order of minutes, and to accelerate the transition process, we first increased the laser power to 2–2.5 W. One should note that by using a different crystal, it is possible to reduce the threshold power down to ~10 mW. When the diffraction rings started to form,[30,32] we decreased the power to the desired level and allowed the system to stabilize. Then, a sequence of images of the self-focused beam was taken by translating the imaging system (lens + CCD camera) along the optical axis at 500-μm steps. Three such images, scaled by the magnification $M=21.2$, are shown on the left column of Fig. 3. The profile illustrated in Fig. 3(a) is taken at a location close to the point where the beam intensity reaches its maximum, and the profiles in

Figs. 3(b) and 3(c) are measured at distances of 1.5 and 4.5 mm, respectively, from this point. The right column shows the corresponding theoretical profiles obtained from Eq. (1) by using the same parameter values as in this experiment. In other words, they are the cross sections of the profile shown in Fig. 1. The two-dimensional CCD images in the insets of Fig. 3 illustrate the ring patterns of the transverse intensity distribution of the beam.

The measured self-focused beam clearly exhibits a Bessel-like beam behavior. The $1/e^2$ radius of its central peak is nearly constant over a distance of at least 1.5 mm. In Fig. 3(a), the radius is equal to 4.8 μm, and in Figs. 3(b) and 3(c) the radii are 5.8 μm and 9.8 μm, respectively. The spreading of the beam upon propagation is very slow compared with what it would be for a Gaussian beam; the radius of a Gaussian beam with a waist radius of 4.8 μm would be almost 160 μm at a 4.5-mm distance from the waist. Compared with the simulated self-focused beam, the observed beam has a somewhat larger divergence. Also, the shapes of the simulated and measured beam profiles show some differences. Most clearly this can be noticed from the doubled-ring patterns in the two-dimensional beam profiles. The experimental curves for the measured beam are not perfectly symmetric. Possible reasons for this are a misalignment of the setup or a slightly asymmetric incident-beam spot. Furthermore, the self-focused beam has a high peak intensity and a small divergence such that even a tiny back reflection from the microscope objective may locally distort the refractive-index profile in the crystal. Nevertheless, the propagation characteristics of the beam are still qualitatively well described by our approximate model. Both theory and the experiments reveal that longer self-focal lines are obtained with larger incident-beam radii. At a fixed incident-beam radius, the larger the laser power, the narrower but shorter the focal line is. We also note that for p-polarized light, the onset power for self-focusing depends on the tilt angle of the crystal; when the crystal is tilted from its original position, the self-focusing threshold intensity is decreased. Thus the width and length of the self-focused beam, as well as the required peak intensity, can be adjusted to the desired values.

4. CONCLUSIONS

We have demonstrated the possibility to create laser beams with a long and narrow focal line using a homeotropically oriented nematic liquid crystal. The method is based on the self-phase modulation of a Gaussian beam in a thin liquid-crystal cell. We modeled the field behind the crystal by applying the Fresnel diffraction theory and showed that the self-focused beam can have a very small divergence compared to a Gaussian beam with the same waist. These predictions were experimentally confirmed by generating a self-focused beam with its central-peak width of 5 μm remaining nearly unchanged over a distance of more than 1 mm. The measured profiles matched well with the simulated ones although the beam divergence was somewhat larger than expected. The method we presented here is an attractive alternative to other techniques for producing laser beams with a long and narrow focal line. It is simple and efficient, since only a single lens and a liquid crystal are needed to produce beams with adjustable dimensions and peak intensities. The power loss of this beam-shaping technique is essentially zero, and there are no strong restrictions to the incident beam size, the phase profile, or the wavelength used. Therefore this technique can certainly find practical applications.

ACKNOWLEDGMENTS

The work of A. Hakola was supported by the Ministry of Education, Finland, under the Graduate School on Modern Optics and Photonics. The authors acknowledge Finnish Academy of Science and Letters, Vilho, Yrjö, and Kalle Väisälä Foundation, Tekniikan edistämissäätiö, and Academy of Finland for financial support.

A. Hakola is the corresponding author and can be reached via e-mail at antti.hakola@tkk.fi.

REFERENCES

1. M. Rioux, R. Tremblay, and P.-A. Belanger, “Linear, annular, and radial focusing with axicons and applications to laser machining,” Appl. Opt. **17**, 1532–1536 (1978).
2. R. B. Charters, B. Luther-Davies, and F. Ladouceur, “Improved performance of laser written channel waveguides using a TEM_{01}^{*} beam,” IEEE Photonics Technol. Lett. **11**, 1617–1619 (1999).
3. J. Arlt, V. Garces-Chavez, W. Sibbett, and K. Dholakia, “Optical micromanipulation using a Bessel light beam,” Opt. Commun. **197**, 239–245 (2001).
4. M. Lei and B. Yao, “Characteristics of beam profile of Gaussian beam passing through an axicon,” Opt. Commun. **239**, 367–372 (2004).
5. J. Arlt, T. Hitomi, and K. Dholakia, “Atom guiding along Laguerre-Gaussian and Bessel light beams,” Appl. Phys. B **71**, 549–554 (2000).
6. M. Florjanczyk and R. Tremblay, “Guiding of atoms in a travelling-wave laser trap formed by the axicon,” Opt. Commun. **73**, 448–450 (1989).
7. G. Bickel, G. Häusler, and M. Maul, “Triangulation with expanded range of depth,” Opt. Eng. (Bellingham) **24**, 975–977 (1985).
8. Z. Jaroszewicz, V. Climent, V. Duran, J. Lancis, A. Kolodziejczyk, A. Burvall, and A. T. Friberg, “Programmable axicon for variable inclination of the focal segment,” J. Mod. Opt. **51**, 2185–2190 (2004).
9. G. Hausler and W. Heskel, “Light sectioning with large depth and high resolution,” Appl. Opt. **27**, 5165–5169 (1988).
10. J. H. McLeod, “The axicon: a new type of optical element,” J. Opt. Soc. Am. **44**, 592–597 (1954).
11. J. H. McLeod, “Axicons and their uses,” J. Opt. Soc. Am. **50**, 166–169 (1960).
12. J. Turunen, A. Vasara, and A. T. Friberg, “Holographic generation of diffraction-free beams,” Appl. Opt. **27**, 3959–3962 (1988).
13. A. Vasara, J. Turunen, and A. T. Friberg, “Realization of general nondiffracting beams with computer-generated holograms,” J. Opt. Soc. Am. A **6**, 1748–1754 (1989).
14. J. Arlt and K. Dholakia, “Generation of high-order Bessel beams by use of an axicon,” Opt. Commun. **177**, 297–301 (2000).
15. J. Durnin, “Exact solutions for nondiffracting beams. I. The scalar theory,” J. Opt. Soc. Am. A **4**, 651–654 (1987).
16. J. Durnin, J. J. Miceli Jr., and J. H. Eberly, “Diffraction-free beams,” Phys. Rev. Lett. **58**, 1499–1501 (1987).
17. C. J. R. Sheppard and A. Choudhury, “Annular pupils, radial polarization, and superresolution,” Appl. Opt. **43**, 4322–4327 (2004).
18. P. Pääkkönen, J. Simonen, M. Honkanen, and J. Turunen,

"Two-element diffractive systems for generation of Bessel fields," J. Mod. Opt. **49**, 1943–1953 (2002).
19. A. N. Khilo, E. G. Katranji and A. A. Ryzhevich, "Axicon-based Bessel resonator: analytical description and environment," J. Opt. Soc. Am. A **18**, 1986–1992 (2001).
20. K. Uehara and H. Kikuchi, "Generation of nearly diffraction-free laser beams," Appl. Phys. B Lasers Opt. **48**, 125–129 (1989).
21. T. Erdogan, O. King, G. W. Wicks, D. G. Hall, E. Anderson, and M. J. Rooks, "Circularly-symmetric operation of a concentric-circle-grating, surface-emitting, AlGaAs/GaAs quantum-well semiconductor laser," Appl. Phys. Lett. **60**, 1921–1923 (1992).
22. P. Pääkkönen and J. Turunen, "Resonators with Bessel–Gauss modes," Opt. Commun. **156**, 359–366 (1998).
23. A. Hakola, S. C. Buchter, T. Kajava, H. Elfström, J. Simonen, P. Pääkkönen, and J. Turunen, "Bessel–Gauss output beam from a diode-pumped Nd:YAG laser," Opt. Commun. **238**, 335–340 (2004).
24. S. Yu Popov and A. T. Friberg, "Apodization of generalized axicons to produce uniform axial line images," Pure Appl. Opt. **7**, 537–548 (1998).
25. S. Yu Popov, A. T. Friberg, M. Honkanen, J. Lautanen, J. Turunen, and B. Schnabel, "Apodized annular-aperture diffractive axicons fabricated by continuous-path-control electron beam lithography," Opt. Commun. **154**, 359–367 (1998).
26. I. Kallioniemi, J. Saarinen, K. Blomstedt, and J. Turunen, "Polygon approximation of the fringes of diffractive elements," Appl. Opt. **36**, 7217–7223 (1997).
27. A. Shevchenko, S. C. Buchter, N. V. Tabiryan, and M. Kaivola, "Creation of a hollow laser beam using self-phase modulation in a nematic liquid crystal," Opt. Commun. **232**, 77–82 (2004).
28. J. J. Wu, S. H. Chen, J. Y. Fan, and G. S. Ong, "Propagation of a Gaussian-profile laser beam in nematic liquid crystals and the structure of its nonlinear diffraction rings," J. Opt. Soc. Am. B **7**, 1147–1157 (1990).
29. I. C. Khoo, J. Y. Hou, T. H. Liu, P. Y. Yan, R. R. Michael, and G. M. Finn, "Transverse self-phase modulation and bistability in the transmission of a laser beam through a nonlinear thin film," J. Opt. Soc. Am. B **4**, 886–891 (1987).
30. M. A. Bolshtyansky, N. V. Tabiryan, B. Ya. Zeldovich, "BRIEFING: beam reconstruction by iteration of an electromagnetic field with an induced nonlinearity gauge," Opt. Lett. **22**, 22–24 (1997).
31. A. L. Murazyan, N. V. Tabiryan, T. Vogeler, and T. Tschudi, "Non-resonant optical limiting due to self-induced multiwave interference," Optik **101**, 145–148 (1996).
32. N. V. Tabiryan, B. Ya. Zel'dovich, and A. V. Sukhov, "Orientational optical nonlinearity of liquid crystals," Mol. Cryst. Liq. Cryst. Sci. Technol. Sect. A **136**, 139 (1986).
33. A. Shevchenko, S. C. Buchter, N. V. Tabiryan, and M. Kaivola, "Self-focusing in a nematic liquid crystal for measurements of wavefront distortions," Opt. Commun. **232**, 439–442 (2004).