Research Article

Journal of
Environmental
Nanotechnology

Tightly Focusing Properties of Radially Polarized Double Ring Shaped Beam through a Uniaxial Birefringent Crystal

R. Murugesan[1], D. Thiruarul[2], K.B. Rajesh[2*]
1Department of Electronics, Erode Arts and Science College, Erode, TN, India
2Department of Physics, Chikkana Government Arts College, Tiruppur, TN, India
Received: 18.12.2018 Accepted: 02.03.2018 Published: 30-06-2018
*bbsivakumarbb@gmail.com

ABSTRACT

Using vectorial diffraction theory for small birefringence, the properties of a radially polarised Double ring-shaped beam closely oriented through a uniaxial birefringent crystal is computed. Increase the birefringence value [Δn] to adjust the intensity distribution of focal structure in the focal area around the longitudinal axis, and change the pupil to beam ratio[β] to separate the focal position. Also, by changing the pupil to beam ratio, a single focal spot can be broken into two.

Keywords: Radially Polarized Double Ring Shaped Beam; Uniaxial Birefringent Crystal.

1. INTRODUCTION

Tight focusing of the laser beam has attracted much attention because of its much smaller focus spot and strong longitudinal component (Urbach and Pereira, 2008; Dorn *et al.* 2003; Yan *et al.* 2011). In a range of microscopes and spectroscopes, tightly focused light beams can improve imaging precision and boost the concentrated electric field at the nanometer scale. Tightly focused light beams have wide potential applications in optical data storage, optical trapping, and microscopy (Zhang *et al.* 2008; Youngworth and Brown, 2000; Lerman and Levy, 2007; Walker and Milster, 2001; Helseth, 2001). The longitudinal field component at the focal point of a radially polarized beam (RPB) is larger than that of any other focused field (Urbach and Pereira, 2008). In 2003, direct detection and characterization of this sharp longitudinal field by an experimental demonstration was reported (Dorn *et al.* 2003). Tightly focused radially polarized beam has many attractive applications such as particle acceleration (Romea and Kimura, 1990), fluorescent (Novotny *et al.* 2003), second harmonic generation (Yew and Sheppard, 2007), Raman spectroscopy (Hayazawa *et al.* 2004), optical trapping (Zhan, 2004) material processing (Niziev and Nesterov, 1999) and particle acceleration (Tidwell *et al.* 1993), optical data storage (Xiangping *et al.* 2007), applications in high-resolution microscopy (Cheng *et al.* 2011), surface plasmon excitation (Zhan, 2006), particles accelerating (Varin and Piche, 2002) and in material processing (Meier *et al.* 2007). Normally the focusing beam was assumed to be a single-ring-shaped beam, which is often referred to as a radially polarized TEM01* (R-TEM01 *) mode beam (Dorn *et al.* 2003; Youngworth and Brown, 2000; Quabis *et al.* 2000). On the other hand, a double-ring-shaped beam was experimentally observed as a higher-order radially polarized mode (R-TEM11*) directly from a laser cavity (Moser *et al.* 2005). By disruptive interaction between the inner and outer rings with a pi phase change, radially polarised mode(R-TEM11*) beams will effectively decrease the spot size (Kozawa and Sato, 2006; 2007). Recently modulating the focal patterns using double ring-shaped beam is a topic of great interest, and many works are reported (Nie *et al.* 2014; Rajesh *et al.* 2011; Tian and Pu, 2014; Lalithambigai *et al.* 2013; Zhang *et al.* 2009; 2010). Many optical components, including waveplates, compensators, polarizer, and so on, make use of the birefringent effect of uniaxial crystals to realize their functions. Thus, it is of practical significance to study the propagation dynamics of light beams in uniaxial crystals. The properties of light beams propagating in birefringent materials have attracted many researchers' interest for years (Fleck and Feit, 1983; Stallinga, 2001; Ciattoni *et al.* 2002; Avendano-Alejo and Rosete-Aguilar, 2006). Ciattoni et al have been studying the propagation of a paraxial optical beam along the optical axis of a uniaxial crystal in a series of papers (Ciattoni *et al.* 2002; 2003; 2001a; 2001b; 2001c; 2002a; 2002b; 2002c; 2002d; Provenziani *et al.* 2002; Ciattoni *et al.* 2002; 2003). Stamnes et al presented consistent numerical and experimental results for focusing two/three-dimensional electromagnetic waves into uniaxial crystal (Jain *et al.* 2009; Stamnes and Jiang, 1998; Jiang and Stamnes, 2000). The propagation of various kinds of laser beams in uniaxial crystals parallel and orthogonal to the optical axis has been reported (Lu and Luo, 2004; Deng *et al.* 2008; Tang, 2009; Li *et al.* 2010; 2011; Zhou *et al.* 2012; Deng *et al.* 2007; Liu and Zhou, 2008; 2009a; 2009b; 2009c; Du and Zhao, 2010; Zhang and Cai, 2011; Li and Chen, 2012; Zhou *et al.* 2013; Deng *et al.* 2013; Shen *et al.* 2014; Zhang and Cai, 2011). The tight focusing of radially, azimuthally and circularly polarized laser beams through a uniaxial crystal associated with focal shift have received a lot of attention because of the theoretical and experimental interest (Zhang *et al.* 2008; Yonezawa *et al.* 2008; Rao and Wang, 2008). In this paper, based on the theoretical model of Ref. (Zhang *et al.* 2008; Rao and Wang, 2008), We use a uniaxial birefringent crystal to expand the study of tight focusing properties of radially polarised double ring-shaped beams. It is shown that the intensity distribution of focal structure in the focal region can be shift along the longitudinal axis by increasing the birefringence value [Δn], and splitting of focal spot can be obtained by changing the pupil to beam ratio[β].

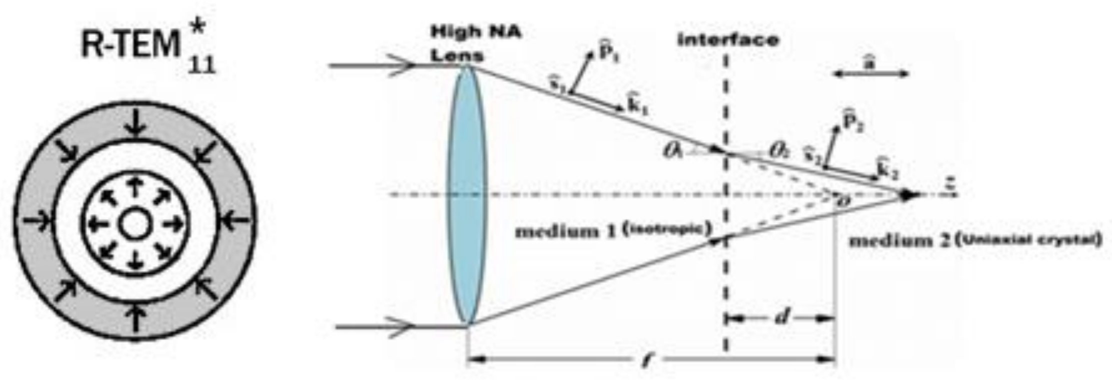

Fig. 1: Scheme of the optical system.

The schematic diagram of the focusing system is shown in Figure 1. It is thought that the radially polarised double ring-shaped beams concentrate from medium 1 through medium 2 (see Fig. 1). Medium 1 is isotropic, while medium 2 is a uniaxial birefringent with a symmetrical axis that runs parallel to the optical axis. Here *d* is the probe depth which is the distance between the interface and geometrical focus (Torok *et al.* 1995). $\hat{k}_1$ and $\hat{k}_2$ are the wave vectors in medium 1 and medium 2 with $\hat{s}_1$ $\hat{p}_1$ and $\hat{s}_2$ $\hat{p}_2$ are the corresponding polarization vectors in a parallel and perpendicular direction to the plane of incidence. Based on vectorial Debye theory (Gu, 2000), Cartesian components of the electric field vector in the focal region can be expressed as

$$E_{tot} = E_x(r,\psi,z) + E_y(r,\psi,z) + E_z(r,\psi,z) \rightarrow 1$$

Where

$$E_x(r,\psi,z) = \frac{-iE_o}{\pi}\int_0^{\alpha}\int_0^{2\pi} \sin\theta_1\sqrt{\cos\theta_1}P(\theta_1)$$

$$\exp[ik_2 z\cos\theta_2 + ik_1 r\sin\theta_1\cos(\psi-\phi)]$$

$$[t_p\cos\theta_2\cos\phi\exp[ik_o(W+\Delta W)]]\exp(-i\phi)d\phi d\theta_1 \rightarrow 2$$

$$E_y(r,\psi,z) = \frac{-iE_o}{\pi}\int_0^{\alpha}\int_0^{2\pi} \sin\theta_1\sqrt{\cos\theta_1}P(\theta_1)$$

$$\exp[ik_2 z\cos\theta_2 + ik_1 r\sin\theta_1\cos(\psi-\phi)]$$

$$[t_p\cos\theta_2\sin\phi\exp[ik_o(W+\Delta W)]]\exp(-i\phi)d\phi d\theta_1 \rightarrow 3$$

and

$$E_z(r,\psi,z) = \frac{-iE_o}{\pi}\int_0^{\alpha}\int_0^{2\pi} \sin\theta_1\sqrt{\cos\theta_1}P(\theta_1)$$

$$\exp[ik_2 z\cos\theta_2 + ik_1 r\sin\theta_1\cos(\psi-\phi)]$$

$$[-t_p\sin\theta_2\exp[ik_o(W+\Delta W)]]\exp(-i\phi)d\phi d\theta_1 \rightarrow 4$$

Here E_o is a constant related to the focal length and the wavelength, $\alpha = \sin^{-1}(NA)$ is the maximal angle determined by the NA of the objective; t_p is the amplitude transmission coefficient for parallel polarization state, which is given by the Fresnel equations (Born and Wolf, 1999)

$$t_p = \frac{2\sin\theta_2\cos\theta_1}{\sin(\theta_1+\theta_2)\cos(\theta_1-\theta_2)} \rightarrow 5$$

$W_p = W + \Delta W$ and $W_s = W$ are the aberration functions of p- and s-polarizations respectively. Here *W* is the aberration function caused by the mismatch of the refractive indices medium 1 and medium 2, where ΔW is the phase difference between the ordinary and extraordinary modes in the uniaxial birefringent medium 2. *W* and ΔW are expressed as (Stallinga, 2001).

$$W = kd(n_2 \cos\theta_2 - n_1 \cos\theta_1) \rightarrow 6$$

$$\Delta W = k(d+z)\Delta n \sin^2\theta_2 / \cos\theta_2 \rightarrow 7$$

Where $k = 2\pi/\lambda$ is the wavenumber in vacuum and d is the distance between the interface and the geometric focus; Where $\Delta n = n_e - n_0$ represents the difference between the refractive indices of ordinary and extraordinary modes in the medium 2, which is the so-called birefringence (the ordinary and extraordinary refractive indices are n_0 and, n_e respectively, and $n_0 = n_2$). It is assumed that the focusing lens is corrected for aberrations introduced by an anisotropic cover layer of thickness d and refractive index $n_2 = n_0$

As a result, $W_s = W = 0$ $W_p = \Delta W$.

Here is the pupil function of the incident double ring-shaped LG (1, 1) beam and is given by (Kozawa and Sato, 2006)

$$P(\theta_1) = \frac{\beta_O^2 \sin(\theta)}{\sin^2\alpha} \exp\left(-\frac{\beta_O^2 \sin^2(\theta)}{\sin^2\alpha}\right) L_p^1\left(2\frac{\beta_O^2 \sin^2(\theta)}{\sin^2\alpha}\right) \rightarrow 8$$

Where β , is the ratio of the pupil radius to the incident beam radius in front of the focusing lens and L_p^1 is the generalized Laguerre polynomial. Note that it β should be greater than 1 because the outer ring of the R-TEM11* beam will be completely truncated by the pupil if $\beta \le 1$. The focal properties are evaluated numerically for the incident radially polarized double ring-shaped beam by solving the above equations using the parameters NA = 0.85, n_1 = 1, n_2 = 1.5, λ = 400 nm, d = 100 μm.

2. RESULT & DISCUSSION

Fig. 2(a-d) shows the intensity distribution in the x-z plane for the incident double ring-shaped beam with β =1.1 and different axial birefringent value (Δn). Fig. 2(e-h) shows the corresponding axial intensity distribution, and Fig. 2(i-l)shows the lateral intensity distribution calculated at the point of maximum axial intensity. It is observed from Fig2(a)and their corresponding radial and axial intensity distribution that the generated focal segment for $\beta = 1.1$ and $\Delta n = 0$ is a focal spot having FWHM of 0.79 λ and focal depth of 4.48 λ. However, we observed that increasing the axial birefringence to Δn to 5,10,10^{-3} and shifts the focal segment in the axial direction and the corresponding on axial maximum is found to located at z=1.8 λ,3.7 λ,5.5 λ respectively. We also noted that increasing the axial birefringence does not change the focal structure but generates only the axial shifting in the positive z-axis.

Table 1. Showing the FWHM, depth of focus and focal shift for different Δn and for β=1.1.

Beam Parameter $\beta = 1.1$			
Birefringence $\Delta n(10^{-3})$	**Spot size** (λ)	**Depth of Focusing** (λ)	**Position of Maximum Intensity Shifted** (λ)
0	0.79	4.48	0
5	0.79	4.48	1.8
10	0.79	4.48	3.7
15	0.79	4.48	5.5

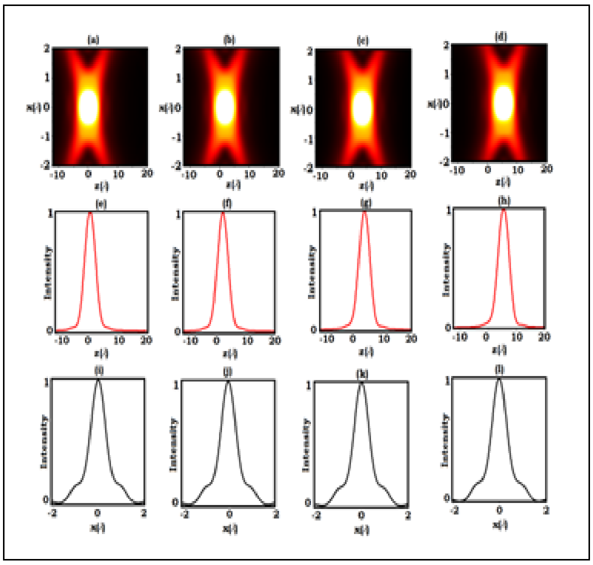

Fig. 2: (a-d) 3D Intensity distribution in the x-z plane corresponding to β = 1.1 and for Δn = 0, 5, 10, 15. (e-h) are the corresponding axial intensity distribution. (i-l) are the intensity distribution in the transverse direction measured at the point of maximum axial intensity.

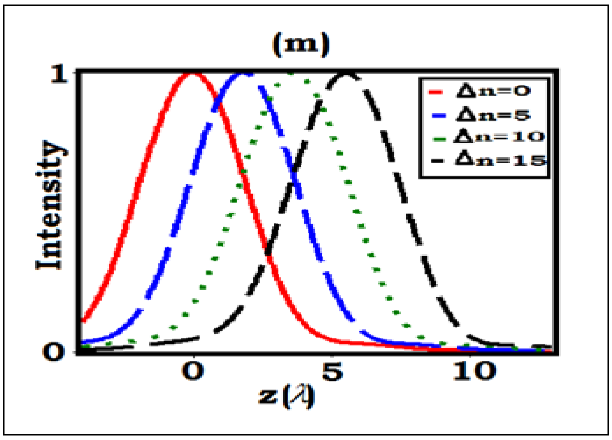

Fig. 3(m): shows focal shift in the 2D on axial intensity distribution corresponding to different Δn values.

Table 1 shows the FWHM, depth of focus, and maximum position on axial intensity obtained for different values of axial birefringence. To produce a focal shift profile, one may insert a physical mask such as a cosine wave plate in the pupil plane of the objective (Prabakaran *et al.* 2013; Li *et al.* 2010; Gao *et al.* 2016; 2009; Yun *et al.* 2010; Yan *et al.* 2011). However, the presence of a cosine wave plate or phase filter makes some applications more difficult or even impossible. To avoid these drawbacks here, we suggest a simple method of modulating the axial birefringence to the incident radially polarized double ring-shaped beam.

Fig. (3) shows the same as Fig. (2) but for β =1.5. It is noted from Fig. 3(a) and their corresponding axial and transverse intensity distribution in the absence of axial birefringence. Increasing β to 1.5 generates an axially split focal segment, each having FWHM of 0.74 λ and focal depth of 2.80 λ. We observed that these spots are axially separated by a distance of (5.4)λ.

Table 2. Showing the FWHM, depth of focus and focal shift for different Δn and for β=1.5.

Beam Parameter $\beta = 1.5$			
Birefringence $\Delta n(10^{-3})$	**FWHM** (λ)	**DOF** (λ)	**Focal Shift** (λ)
0	0.74	2.80	2.70
5	0.74	2.80	4.50
10	0.74	2.80	6.40
15	0.74	2.80	8.30

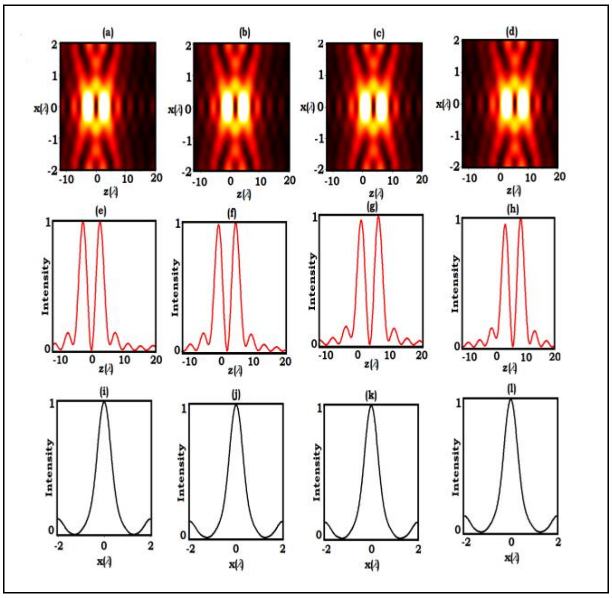

Fig. 3: (a-d) 3D Intensity distribution in the x-z plane corresponding to β =1.5 and for Δn = 0, 5, 10, 15. (e-h) are the corresponding 2D intensity measured in the axial direction. (i-l) are the 2D intensity distribution in the transverse direction.

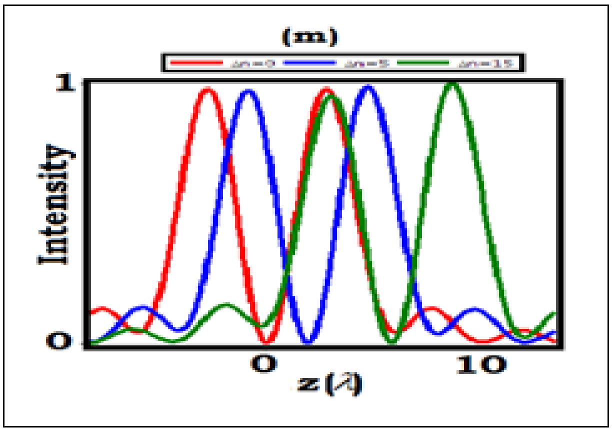

Fig. 3(m): shows focal shift in the 2D on axial intensity distribution corresponding to different Δn values.

It is observed from Fig. 3(b-d) and their corresponding transverse and axial intensity distribution plots that increasing axial birefringence shifts the generated focal segment in the positive axial direction without modulating the focal structure. Such a focal structure is useful in trapping and shifting two industrial particles (Gao *et al.* 2009; Qiufang Zhan *et al.* 2009). Hence it is noted that by properly manipulating the axial birefringence and pupil to beam ratio of the double ring-shaped beam, one can generate single and axially split focal spots and can shift axially.

3. CONCLUSION

Using vectorial diffraction theory for small birefringence, the properties of a radially polarised Double ring-shaped beam tightly oriented through a uniaxial birefringent crystal were analyzed. Increase the birefringence value [Δn] to modify the intensity distribution of focal structure in the focal area around the longitudinal axis, and change the pupil to beam ratio [β] to separate the focal position. Even, by changing the pupil to beam ratio [β], a single focal spot can be broken into two.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCE

Avendaño-Alejo, M. and Rosete-Aguilar, M., Optical path difference in a plane-parallel uniaxial plate, *J. Opt. Soc. Am. A.*, 23(4), 926-932(2006). https://doi.org/10.1364/JOSAA.23.000926

Born, M., Wolf, E.: Principles of Optics 7th edn.(1999). (Cambridge: Cambridge University Press).

Cheng, Gonçalves, J. T., Golshani, P., Arisaka, K. and Portera-Cailliau, C., Simultaneous two-photon calcium imaging at different depths with spatiotemporal multiplexing, *Nat. Methods*., 8(2), 139–142(2011). https://doi.org/10.1038/nmeth.1552

Ciattoni, A., Crosignani, B. and Di Porto, P., Vectorial theory of propagation in uniaxially anisotropic media, *J. Opt. Soc. Am. A*., 18(7), 1656-1661(2001a). https://doi.org/10.1364/JOSAA.18.001656

Ciattoni, A., Cincotti, G. and Palma, C., Ordinary and extraordinary beams characterization in uniaxially anisotropic crystals, *Opt. Commun*., 195(1-4), 55-61(2001b). https://doi.org/10.1016/S0030-4018(01)01335-9

Cincotti, G., Ciattoni, A. and Palma, C., Hermite–Gauss Beams in Uniaxially Anisotropic Crystals, *IEEE J. Quantum Electron*., 37, 1517(2001c).

Ciattoni, A., Ciattoni, G. and Palma, C., Propagation of cylindrically symmetric *fields* in uniaxial crystals, *J. Opt. Soc. Am. A*., 19, 792-796(2002). https://doi.org/10.1364/JOSAA.19.000792

Cincotti, G., Ciattoni, A. and Palma, C., Laguerre–Gauss and Bessel–Gauss beams in uniaxial crystals, *J. Opt. Soc. Am. A*., 19(8), 1680-1688(2002a). https://doi.org/10.1364/JOSAA.19.001680

Ciattoni, A., Cincotti, G. and Palma, C., Nonparaxial description of reflection and transmission at the interface between an isotropic medium *and* a uniaxial crystal, *J. Opt. Soc. Am.*, A19(7), 1422-1431(2002b). https://doi.org/10.1364/JOSAA.19.001422

Ciattoni, A., Cincotti, G., Palma, C. and Weber, H., Energy exchange between the Cartesian components of a paraxial beam in a uniaxial crystal, *J. Opt. Soc. Am. A*., 19(9), 1894-1900(2002c). https://doi.org/10.1364/JOSAA.19.001894

Cincotti, G., Ciattoni, A. and Palma, C., Propagation-invariant beams in uniaxial *crystals*, *J. Mod. Opt.*, 49(13),2267-2272(2002d). https://doi.org/10.1080/09500340210133153

Ciattoni, A., Cincotti, D., Provenziani, C. and Palma, C., Paraxial propagation along the optical axis of a uniaxial medium, *Phys. Rev*., E66(3 pt 2B), 036614-1(2002). https://doi.org/10.1103/PhysRevE.66.036614

Ciattoni, A., Cincotti, G. and Palma, C., Circularly polarized beams and vortex generation in uniaxial media, *J. Opt. Soc. Am. A*., 20(1), 163-171(2003). https://doi.org/10.1364/JOSAA.20.000163

Ciattoni, G., Ciattoni, A. and Sapia, C., Radially and azimuthally polarized vortices in uniaxial crystals, *Opt. Commun*., 220, 33-40(2003). https://doi.org/10.1016/S0030-4018(03)01372-5

Deng, D., Chen, C., Zhao, X. and Li, H., Propagation of an Airy vortex beam in uniaxial crystals, *Appl. Phys. B.*, 110(3), 433-436(2013). https://doi.org/10.1007/s00340-012-5273-5

Deng, D., Shen, J., Tian, Y., Shao, J. and Fan, Z., Propagation properties of beams generated by Gaussian mirror resonator in uniaxial crystals, *Optik(Stuttgart)*., 118(11), 547–551(2007). https://doi.org/10.1016/j.ijleo.2006.05.006

Deng, D., Yu, H., Xu, S., Shao, J. and Fan, Z., Propagation and polarization properties of hollow Gaussian beams in uniaxial crystals, *Opt. Commun*., 281(2), 202–209(2008). https://doi.org/10.1016/j.optcom.2007.09.038

Dorn, R., Quabis, S. and Leuchs, G., Sharper Focus for a Radially Polarized Light Beam, *Phys. Rev. Lett*., 91, 233901 (2003). https://doi.org/10.1103/PhysRevLett.91.233901

Du, X. and Zhao, D., Propagation of uniformly polarized stochastic electromagnetic beams in uniaxial crystals, *J. Electromagn. Waves Appl*., 24(7), 971-981(2010). https://doi.org/10.1163/156939310791285182

Fleck, J. A. Jr. and Feit, M. D., Beam propagation in uniaxial anisotropic media, *J. Opt. Soc. Am*., 73(7), 920-926(1983). https://doi.org/10.1364/JOSA.73.000920

Gao, P., Tian, S., Weng, X., Guo, H.: Dynamically shifting the focal spot with tunable pupil filters, *J. Mod. Opt*., 63(16), 1558-1563(2016). https://doi.org/10.1080/09500340.2016.1162334

Gao, X. M., Gao, M. Y., Hu, S., Guo, H. M., Wang, J. and Zhuang, S.L., Focal shift of radially polarized Bessel-modulated Gaussian beam by phase shifting, *Nat. Science*., 1(3), 229-233(2009). https://doi.org/10.4236/ns.2009.13031

Gao, X., Hu, S., Gu, H. and Wang, J., Focal shift of three-portion concentric piecewise cylindrical vector beam, *Optik.* 120(11), 519-523(2009). https://doi.org/10.1016/j.ijleo.2007.11.011

Gu, M., Advanced Optical Imaging Theory. (2000)(Berlin: Springer). https://doi.org/10.1007/978-3-540-48471-4

Hayazawa, N., Saito, Y. S. and Kawata, S., Detection and characterization of longitudinal field for tip-enhanced Raman spectroscopy, *Appl. Phys. Lett*., 85, 6239–6241(2004). https://doi.org/10.1063/1.1839646

Helseth, L. E., Focusing of atoms with strongly confined light potentials, *Opt. Commun*. 212, 343–352(2002). https://doi.org/10.1016/S0030-4018(02)01998-3

Jain, M., Lotsberg, J. K., Stamnes, J. J., Frette, O., Velauthapillai, D., Jiang, D. and Zhao, X., Numerical and experimental results for focusing of three-dimensional electromagnetic waves into uniaxial crystals, *J. Opt. Soc. Am. A Opt. Image Sci. Vis.*, 26(3), 691–698(2009). https://doi.org/10.1364/JOSAA.26.000691

Jiang, D. and Stamnes, J. J., Numerical and experimental results for focusing of two-dimensional waves in uniaxial crystals, *Opt. Commun*., 174(5-6), 321–334(2000). https://doi.org/10.1016/S0030-4018(99)00671-9

Kozawa, Y. and Sato, S., Focusing property of a double-ring shaped radially polarized beam, *Opt. Lett.*, 31(6), 820–822(2006). https://doi.org/10.1364/OL.31.000820

Kozawa, Y. and Sato, S., Sharper focal spot formed by higher-order radially polarized laser beams, *J. Opt. Soc. Am. A*., 24(6), 1793-98(2007). https://doi.org/10.1364/JOSAA.24.001793

Lalithambigai, K., Saraswathi, R. C., Anbarasan, P. M., Rajesh, K. B. and Jaroszewicz, Z., Generation of Multiple Focal Hole Segments Using Double-Ring Shaped Azimuthally Polarized Beam, *J. At. Mol. Phy.*, 451715(2013). https://doi.org/10.1155/2013/451715

Lerman, G. M. and Levy, U., Tight focusing of spatially variant vector optical fields with elliptical symmetry of linear polarization, *Opt. Lett*., 32, 2194–2196(2007). https://doi.org/10.1364/AO.48.001288

Li, J. and Chen, Y., Propagation of confluent hypergeometric beam through uniaxial crystals orthogonal to the optical axis, *Opt. Laser Technol*., 44(5), 1603-1610(2012). https://doi.org/10.1016/j.optlastec.2011.11.041

Li, J., Chen, Y., Xin, Y. and Xu, S., Propagation of higher-order cosh-Gaussian beams in uniaxial crystals orthogonal to the optical axis, *Eur. Phys. J*., D57(3), 419–425 (2010). https://doi.org/10.1140/epjd/e2010-00068-9 R

Li, J., Gao, X., Zhuang, S., Huang, C.: Focal shift and focusing properties generation by radial cosine phase masks, *Optik*, 121(9), 821-825(2010). https://doi.org/10.1016/j.ijleo.2008.09.030

Liu, D. and Zhou, Z., Propagation properties of anomalous hollow beam in uniaxial crystals orthogonal to the optical axis, *Opt. Laser Technol*., 41(7), 877–884 (2009a). https://doi.org/10.1016/j.optlastec.2009.02.008

Liu, D. and Zhou, Z., Propagation of partially coherent flat-topped beams in uniaxial crystals orthogonal to the optical axis, *J. Opt. Soc. Am. A*., 26(4), 924-930(2009b). https://doi.org/10.1364/JOSAA.26.000924

Liu, D. and Zhou, Z., Propagation of partially polarized, partially coherent beams in uniaxial crystals orthogonal to the optical axis, *Eur. Phys. J*., D54, 95-101(2009c). https://doi.org/10.1140/epjd/e2009-00166-9

Liu, D. and Zhou, Z., Various dark hollow beams propagating in uniaxial crystals orthogonal to the optical axis, *J. Opt. A, Pure Appl. Opt*., 10(9), 095005(2008). https://doi.org/10.1088/1464-4258/10/9/095005

Lü, B. and Luo, S., Propagation properties of three-dimensional flatted Gaussian beams in uniaxially anisotropic crystals, *Opt. Laser Technol*., 36(1), 51-56(2004). https://doi.org/10.1016/S0030-3992(03)00132-4

Meier, M., Romano, V. and Feurer, T., Material processing with pulsed radially and azimuthally polarized laser radiation, *Appl. Phys. A*., 86(3), 329–334(2007). https://doi.org/10.1007/s00339-006-3784-9

Moser, T., Glur, H., Romano, V., Pigeon, F., Parriaux, O., Ahmed, M. A. and Graf, T., Polarization-selective grating mirrors used in the generation of radial polarization, *Appl. Phys. B.*, 80(6), 707-713(2005). https://doi.org/10.1007/s00340-005-1794-5

Nie, Z., Li, Z., Shi, G., Zhang, X., Wang, Y. and Song, Y., Generation of a sub-wavelength focal spot with a long transversally polarized optical needle using a double-ring-shaped azimuthally polarized beam, *Opt. Lasers Eng*., 59, 93-97(2014). https://doi.org/10.1016/j.optlaseng.2014.03.006

Niziev, V. G. and Nesterov, A. V., Influence of beam polarization on laser cutting efficiency, *J. Phys. D*., 32(13), 1455–1461(1999). https://doi.org/10.1088/0022-3727/32/13/304

Novotny, L., Beversluis, M. R., Youngworth, K. S. and Brown, T. G., Continuum generation from single gold nanostructures through near-field mediated intraband transitions, *Phys. Rev. B*., 68(11), 115433(2003). https://doi.org/10.1103/PhysRevB.68.115433

Prabakaran, K., Rajesh, K. B., Pillai, T. V. S., Chandrasekaran, R., Jaroszewicz, Z., Focal shift in radially polarized beam with high NA lens axicon by using radial cosine phase wavefront, *Opt. Quant. Electron.*, 45(6), 563-570(2013). https://doi.org/10.1007/s11082-013-9670-8

Provenziani, D., Ciattoni, A., Cincotti, G. and Palma, C., Diffraction by elliptic and circular apertures in uniaxially anisotropic crystals: theory and experiment, *J. Opt. A. Pure Appl. Opt*., 4(4), 424(2002). https://doi.org/10.1088/1464-4258/4/4/310

Qiufang Zhan, Jinsong Li , Xiumin Gao, Alterable focal shift of concentric piecewise cylindrical vector beam, *Proc. of SPIE, 7497*, 74970X-1(2009).
https://doi.org/10.1117/12.832338

Quabis, S., Dorn, R., Eberler, M., Glöcke, O. and Leuchs, G., Focusing light to a tighter spot, *Opt. Commun.*, 179, 01–07(2000).
https://doi.org/10.1007/s00339-006-3784-9

Rajesh, K. B., Veerabagu Suresh, N., Anbarasan, P. M., Gokulakrishnan, K. and Mahadevan, G., Tight focusing of double ring shaped radially polarized beam with high NA lens axicon, *Opt. Laser Tech.*, 43(7), 1037-1040(2011).
https://doi.org/10.1016/j.optlastec.2010.11.009

Rao, L. Z., Wang, Z. C., and Zheng, X. X., Tightly Focusing of Circularly Polarized Vortex Beams through a Uniaxial Birefringent Crystal, *Chin. Phys. Lett.*, 25(9), 3223-3226(2008).

Romea, R. D. and Kimura, W. D., Modeling of inverse Cerenkov laser acceleration with axicon laser-beam focusing, *Phys. Rev. D.*, 42(5), 1807–1818(1990).
https://doi.org/10.1103/PhysRevD.42.1807 ·

Shen, Y., Liu, L., Zhao, C., Yuan, Y. and Cai, Y., Second-order moments of an electromagnetic Gaussian Schell-model beam in a uniaxial crystal, *J. Opt. Soc. Am. A.*, 31(2), 238-245(2014).
https://doi.org/10.1364/JOSAA.31.000238

Stallinga, S., Axial birefringence in high-numerical-aperture optical systems and the light distribution close to focus, *J. Opt. Soc. Am. A.*, 18(11), 2846-2859(2001).
https://doi.org/10.1364/JOSAA.18.002846

Stamnes, J. J. and Jiang, D., Focusing of electromagnetic waves into a uniaxial crystal, *Opt. Commun.*, 150(1-6), 251–262(1998).
https://doi.org/10.1016/S0030-4018(98)00055-8

Tang, B., Hermite-cosine-Gaussian beams propagating in uniaxial crystals orthogonal to the optical axis, *J. Opt. Soc. Am. A.*, 26(12), 2480–2487(2009).
https://doi.org/10.1364/JOSAA.26.002480

Tian, B. and Pu, J., Tight focusing of a double-ring-shaped, azimuthally polarized beam, *Opt. Lett.*, 36(11), 2014-2016(2011).
https://doi.org/10.1364/OL.36.002014

Tidwell, S. C., Kim, G. H. and Kimura, W. D., Efficient radially polarized laser beam generation with a double interferometer, *Appl. Opt.*, 32(27), 5222–5229(1993).
https://doi.org/10.1364/AO.32.005222

Torok, P., Varga, P., Laczik, Z. and Booker, G. R., Electromagnetic diffraction of light focused through a planar interface between materials of mismatched refractive indices: an integral representation, *J. Opt. Soc. Am. A.*, 12(2), 325-332(1995).
https://doi.org/10.1364/JOSAA.12.000325

Urbach, H. P. and Pereira, S. F., Field in Focus with a Maximum Longitudinal Electric Component, *Phys. Rev. Lett.*, 100(12), 123904(2008).
https://doi.org/10.1103/PhysRevLett.100.123904

Varin, C. and Piche, M., Acceleration of ultra-relativistic electrons using high-intensity TMo1 laser beams, *Appl. Phys. B.*, 74(S1), S83–S88(2002).
https://doi.org/10.1007/s00340-002-0906-8

Walker, E. P. and Milster, T. D., Beam shaping for optical data storage, *Proc. SPIE 4443*, 73–92(2001).

Xiangping Li, James W. M. Chon, Shuhui Wu, Richard A. Evans and Min Gu, Rewritable polarization-encoded multilayer data storage in a 2,5-dimethyl-4-(p-nitrophenylazo)anisole doped polymer, *Opt. Lett.*, 32(3), 277-279(2007).
https://doi.org/10.1364/OL.32.000277

Yan, S., Yao, B. and Rupp, R., Shifting the spherical focus of a 4Pi focusing system, *Opt. Express.*, 19(2), 673-678(2011).
https://doi.org/10.1364/OE.19.000673

Yan, S., Yao, B., Rupp, R.: Shifting the spherical focus of a 4Pi focusing system, *Opt. Express.*, 19(2), 673-678(2011).
https://doi.org/10.1364/OE.19.000673

Yew, E. and Sheppard, C., Second-harmonic generation microscopy with tightly focused linearly and radially polarized beams, *Opt. Commun.*, 275(2), 453–457(2007).
https://doi.org/10.1016/j.optcom.2007.03.065

Yonezawa, K., Kozawa, Y. and Sato, S., Focusing of radially and azimuthally polarized beams through a uniaxial crystal, *J. Opt. Soc. Am. A.*, 25(2), 469-472(2008).
https://doi.org/10.1364/JOSAA.25.000469

Youngworth, K. S. and Brown, T. G., Focusing of high numerical aperture cylindrical vector beams, *Opt. Express.*, 7, 77–87(2000).
https://doi.org/10.1364/OE.7.000077

Yun, M., Liang, W., Kong, W., Gao, X., Zhu, H., Liang, J.: Transverse super-resolution and focal shift with rotational tunable phase mask, *Opt. Commun.*, 283(10), 2079-2083(2010).
https://doi.org/10.1016/j.optcom.2010.01.039

Zhan, Q., Evanescent Bessel beam generation via surface plasmon resonance excitation by a radially polarized beam, *Opt. Lett.*, 31(11), 1726–1728(2006).
https://doi.org/10.1364/OL.31.001726

Zhan, Q., Trapping metallic Rayleigh particles with radial polarization, *Opt. Express.*, 12(15), 3377–3382(2004).
https://doi.org/10.1364/OPEX.12.003377

Zhang, L. and Cai, Y., Evolution properties of a twisted Gaussian Schell-model beam in a uniaxial crystal, *J. Mod. Opt.*, 58(14), 1224-1232(2011).
https://doi.org/10.1080/09500340.2011.599503

Zhang, L. and Cai, Y., Statistical properties of a Nonparaxial Gaussian Schell-model beam in a uniaxial crystal, *Opt. Express.*, 19(14), 13312-13325(2011).
https://doi.org/10.1364/OE.19.013312

Zhang, Y., Suyama, T. and Ding, B., Longer axial trap distance and larger radial trap stiffness using a double-ring radially polarized beam, *Opt. Lett*., 35(8), 1281-1283(2010).
https://doi.org/10.1364/OL.35.001281

Zhang, Y., Xu, X. and Okuno, Y., Theoretical study of optical recording with a solid immersion lens illuminated by focused double-ring-shaped radially-polarized beam, *Opt. Commun*., 282(23), 4481–4485(2009).
https://doi.org/10.1016/j.optcom.2009.08.031

Zhang, Z., Pu, J. and Wang, X., Focusing of partially coherent Bessel–Gaussian beams through a high numerical-aperture objective, *Opt. Lett*., 33(1), 49–51(2008).
https://doi.org/10.1364/OL.33.000049

Zhang, Z., Pu, J. and Wang, X., Tight focusing of radially and azimuthally polarized vortex beams through a uniaxial birefringent crystal, *Appl. Opt*., 47(12), 1963-1967(2008).
https://doi.org/10.1364/AO.47.001963

Zhou, G., Chen, R. and Chu, X., Propagation of Airy beams in uniaxial crystals orthogonal to the optical axis, *Opt. Express*., 20(3), 2196-2205(2012).
https://doi.org/10.1364/OE.20.002196

Zhou, Y., Wang, X., Dai, C., Chu, X. and Zhou, G., Nonparaxial analysis in the propagation of a cylindrical vector Laguerre-Gaussian beam in a uniaxial crystal orthogonal to the optical axis, *Opt. Commun.*, 305, 113-125(2013).
https://doi.org/10.1016/j.optcom.2013.04.074