Radially polarized beam restructuring based on Stokes-vector measurement and interferometry

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Abstract: With rapid development of optical manipulation technology, it became urgent to measure and reconstruct the radially polarized beam (RPB). Utilizing a set of quartz rotators, the RPB was prepared firstly. In consideration of optical quality assessment, due to the direct connection with longitudinal component at the focal region, the parameter of polarization orientation and power deviation have been brought up and measured. A method to reconstruct the vector-structure of RPB was designed and implemented. Results show that the normalized amplitude deviation was 0.054 8 and polarization deviation is 0.004 4. Furthermore, by the interferometer, the phase distribution of the RPB has been achieved, and the average phase difference was 1.471 between neighboring sections. Finally, by processing the data of polarization and phase information, the vector-field of the RPB have been successfully reconstructed, the topological charge was 3, which paves the way for accurate quantum manipulation and measurement.

Key words: radially polarized beams; Stokes vector; interferometer; optical field reconstructing

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基于 Stokes 矢量测量与干涉法的径向偏振光束重建

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摘 要:随着光学操控技术的迅速发展,测量与重建径向偏振光束(RPB)成为迫切任务之一。利用一套石英旋光片组合,首先产生了 RPB。借助计算机控制的 CCD,对 RPB 的斯托克斯矢量场分布进行了测量,并获得其偏振态分布。结果表明:所产生的 RPB 归一化功率偏差为 0.054 8,偏振偏差为 0.004 4。利用干涉仪,获得了 RPB 的相位分布,相邻断面间平均相位差为 1.471。最后,通过偏振和相位信息的数据处理,成功重建了 RPB 的矢量场分布,并发现其拓扑荷在 3 左右。这些结论为实现精密量子调控与测量铺平了道路。

关键词: 径向偏振光束; 斯托克斯矢量; 干涉仪; 光场重建

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0 Introduction

Radially polarized beams (RPBs) are one of the most important cylindrical vector beams. In the past few years, due to its special property and promising utility, radially polarized beams have attracted great interest recently in many fields. [1-6,7-13] Due to its symmetric distribution of the polarization, the radially polarized beams have several unique focal properties under high numerical aperture focus; focal spot is much more smaller than uniformly polarized beam, which could break through the diffraction limitation. [2,6]And the focal region contains prominent longitudinal electric component, which have been applied in optical tweezers[2] and the manipulation of quantum system. In the past few years, numerous schemes have been proposed for RPBs generation and manipulation. Generally, the methods of RPB generation could be categorized into two groups: the passive methods and the initiative methods. The former focus on transform the uniformly polarized beam into RPB, and the latter could directly produce the RPB due to its special intra-cavity design. While as further development and extensive application proceed, the measurement of the optical field of RPBs has gradually become an urgent issue. Hayazawa et al. firstly characterized the longitudinal field of the RPBs focus using a tip-enhanced near-field microscope based on localized surface plasmon polaritons. However, most of the reports focus on measuring the longitudinal field of RPBs, while few researches have been done on measuring and restructuring the vector-field of the RPBs.

In this paper, we have measured the Stokes vector of the RPB generated by employment of a set of quartz rotators, and obtained its polarization orientation distribution assisted with CCD. Then the interferometry experiment has been carried out to achieve the phase distribution of the RPB. Finally, by processing the data of polarization and phase information, we successfully restructure the vector-field of the RPB.

1 Principle of measuring and restructuring

For any vector optical beam, by measuring the Stokes vector distribution, one can acquire the distribution of electric amplitude, degree of polarization, and the shape parameter of polarization ellipse and polarization orientation accordingly. Generally, it takes four measuring value to pinpoint stokes vector, either by split the amplitude or rotate the polarize devices, but if the polarization of the light source is strictly linear, two independent value could determine stokes vector. The phase distribution is crucially important for any kind of cylindrical vector beam. In the measurement the phase distribution of vectorial optical beams such as the RPBs, the most suitable method is the interferometry, that is, interfering the RPB with a phase-known laser beam, there is a small include angle between two mirrors, and extract the phase distribution from the interferential pattern. Choosing a region as zero-phase reference, by measuring the pattern shift distance x from the reference point and the fringe spacing d, the phase difference can be obtained by[14]:

$$\varphi=\frac{2\pi d}{x_0} \tag{1}$$

Furthermore, how to evaluate the RPBs is an open question. One important feature of radially polarized beam is the prominent longitudinal electrical component at the focal region, under high numerical aperture focus condition. The direct assessment methods are of the longitudinal electrical component, are complex and inconvenient. According to Wolf-Richard method[13], the optical field distribution could be obtained by diffractional integral of the sphere with a focal length radius.

$$\vec{E}(r,\phi,z)=\frac{-i\kappa}{2\pi}\iint_{\Omega}\vec{\alpha}(\theta,\phi)\exp(-i\vec{s}\cdot\vec{r})\mathrm{d}\Omega=$$

$$\frac{-i\kappa}{2\pi}\int_0^{\alpha}\mathrm{d}\theta\int_0^{2\pi}\vec{\alpha}(\theta,\phi)\exp(-i\vec{s}\cdot\vec{r})\sin\theta\mathrm{d}\Omega \tag{2}$$

Obviously, the purity and the amplitude of the longitudinal component rely on the symmetry of the electric vector structure on the pupil. Thus, by measuring the degree of symmetry, the quality of the focal field could be obtained. We denote ξ_α as the amplitude deviation from its average along a loop with α radius of 1, which is given by:

$$\xi_\alpha=\frac{1}{2\pi l}\oint\left(\frac{P(\theta,r)}{\overline{P}}-1\right)^2 \mathrm{d}\theta \tag{3}$$

Similarly, we define the polarization deviation:

$$\xi_P=\frac{1}{2\pi l}\oint(\phi(\theta,r)-\overline{\phi})^2 \mathrm{d}\theta \tag{4}$$

The range of ξ_α and ξ_p are both from 0-1, value 0 indicates the ideal RPB, which could generates the maximum and purest longitudinal component, 1 indicates the opposite, in this case, the angularly polarized beam. The amplitude deviation and polarization deviation have been measured in the following experiment.

2 Experimental demonstration

The inve stigated RPB is generated by a set of quartz optical rotators, polarizers, and collimators as shown in Fig.1(a), Fig.1(b) is the photograph of the setup.

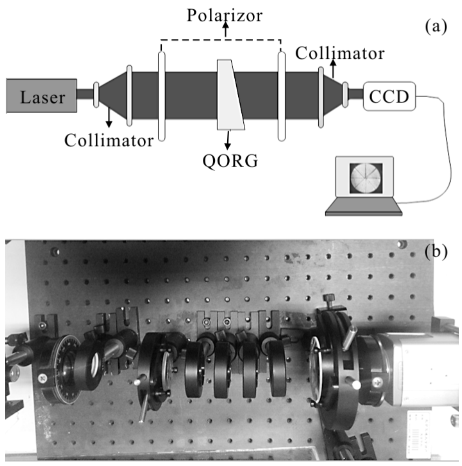

Fig.1 (a) experimental setup for Stokes vector and polarization measurements (b) photograph of the setup

The semiconducor laser emits coherent beam with wave- length at 633 nm, which goes through the collimator and a polarizer, then come vertically into the Quartz optical rotator group (QORG). The QORG is composed of eight equal fan- shaped sections, the thickness of the rotator increase by sections, and rotation angles increase in sequence by 22.5°, thus convert the linearly polarized laser beam to RPB. Finally, the generated RPB has been analyzed by a rotatable linear polarizer and CCD. Figure 2 shows some of the recorded results. Figure2 (a1), (b1), (c1)

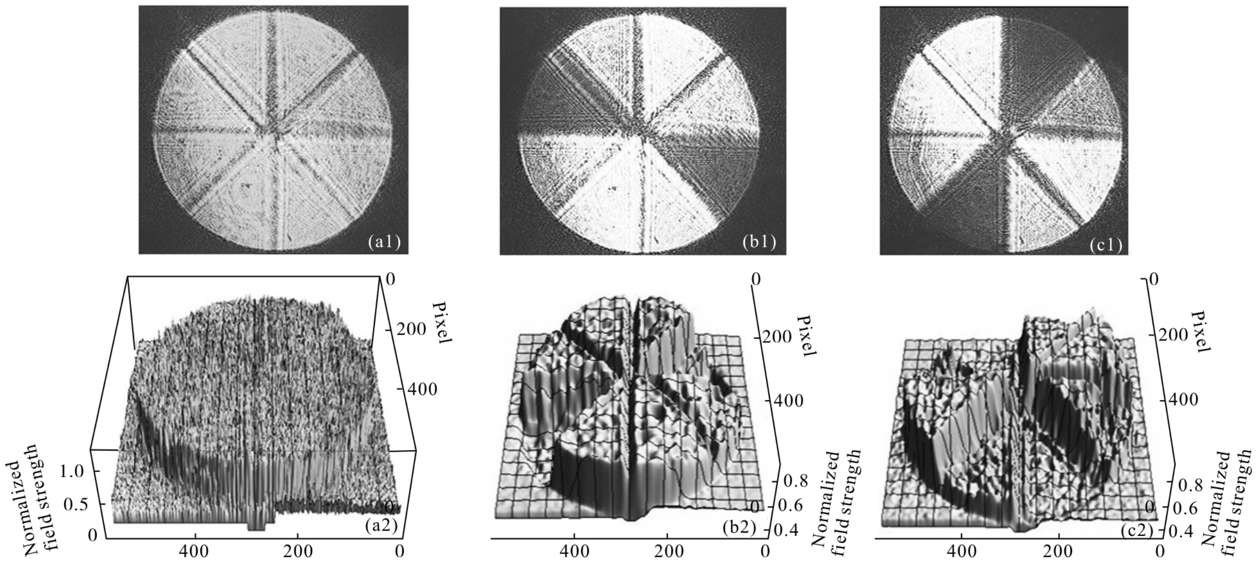

Fig.2 Fig.2(a1), (b1), (c1) and optical field distributions Fig.2(a2), (b2), (c2) for the RPBs by inserting no polarizor, horizontal, and vertical polarizor

and optical field distributions Fig.2(a2), (b2), (c2) for the RPBs by inserting no polarizor, horizontal, and vertical polarizor inserting no polarizer, horizontal, and vertical polarizer.

Filtered by two vertical polarizer respectively; the distribution of x component and y component in the form of a 566×566 matrix has been obtained. Since the RPB is completely polarized, the stokes vector distribution has been calculated as the function of E_x and E_y

$$\begin{pmatrix} E_x^2+E_y^2 \\ E_x^2-E_y^2 \\ 2E_x^2E_y^2\cos\delta \\ 2E_x^2E_y^2\sin\delta \end{pmatrix} \quad (5)$$

Thus, each pixel related to one stokes vector, the stokes vectors distribution has been obtained in the form of a 566×566×4 matrix. We obtain the polarization orientation and the polarization orientation distribution as shown in Fig.3(a). The theoretical distribution has been calculated based on the characteristic parameter of the quartz rotators and the laser, shown in Fig.3(b), known from the contrast that the result consist with the calculation.

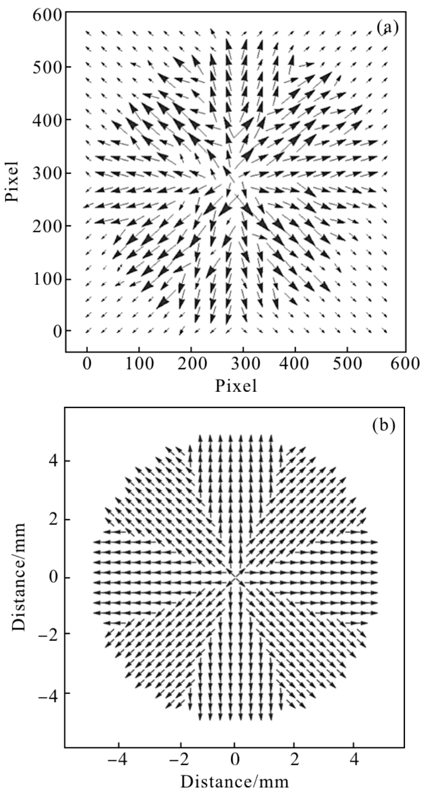

Fig.3 Measured (a) and theoretical (b) results of polarization orientation distribution

Based on above results and according to Eqs.(4) and (5), we calculate the deviation of amplitude and polarization orientation distribution. Results show that the normalized ξ_a is around 0.054 8 while ξ_P is about 0.004 4, which is rather a small definite. Next step, for the phase distribution measurement, the Mach-Zehnder(MZ) interference system has been established as schematically shown in Fig.4(a). Figure 4(b) shows the photograph of the setup.

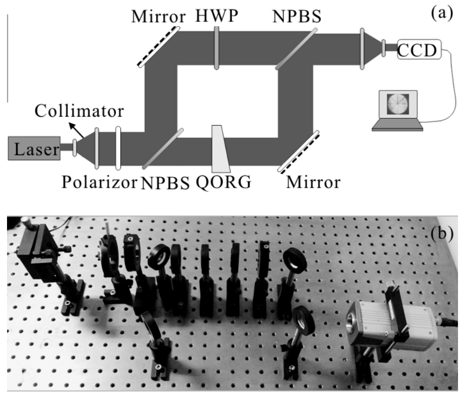

Fig.4 (a) Mach-Zehnder interference system for phase measurement, and (b) photograph of experimental setup

In the MZ interferometer, one arm carries the RPB, which would interfere with the uniformly polarized Gaussian beam in another arm as reference. Considering that there is a non-interference region caused by polarization verticality between the RPB and reference beam, a half-wave plate (HWP) was added to change the polarization state of reference beam so as to scan the entire field of the RPB. In order to eliminate any unnecessary polarization drifting, the non-polarized beam splitters (NPBS) have been employed for beam splitting and coupling. The interference pattern was recorded by CCD, shown in Fig.5. For beam that phase gradually change by location, the phase distribution could been obtained by analyze the pattern intensity distribution, In our case, the transverse plane of beam has been divided into

8 section, and inside each section the phase is uniform, we analyzed shift distance of interference patterns section by section. Each pattern shift has been extracted from the curves that are fitted to interference patterns, which is shown in Fig.6. According to Eq.(2), we calculated the phase difference between every neighboring section, and the results show that every section has a phase difference of 1.471 refer to the previous one.

Fig.5 Interference pattern of RPB and polarized Gaussian beam

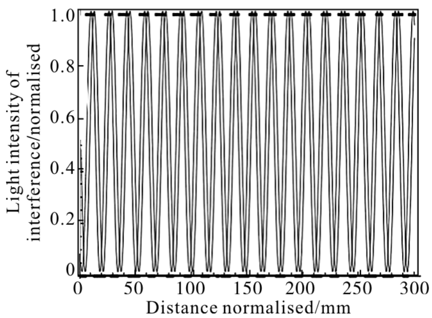

Fig.6 Interference pattern difference, from which the phase difference has been extracted

Taking into account the pow er distribution, polarize orientation, and phase distribution, we reconstruct the generated RPB based on Eqs.(1) and (5) assisted with the software Mathematica. The result is shown in Fig.7 (a). For the contrast, we calculated the theoretical reconstruct result based on the polarize orientation of the input laser beam, the rotate angle and phase delay of the rotator, given by provider and tested. Each section of rotators group provides different rotate angle, related to the thickness of the rotator, and thus has different phase delay, using the parameters of the rotators, the theoretical phase and polarize orientation has obtained. The theoretical result shown in Fig.7 (b). The result of polarized orientation distribution was obtained similarly.

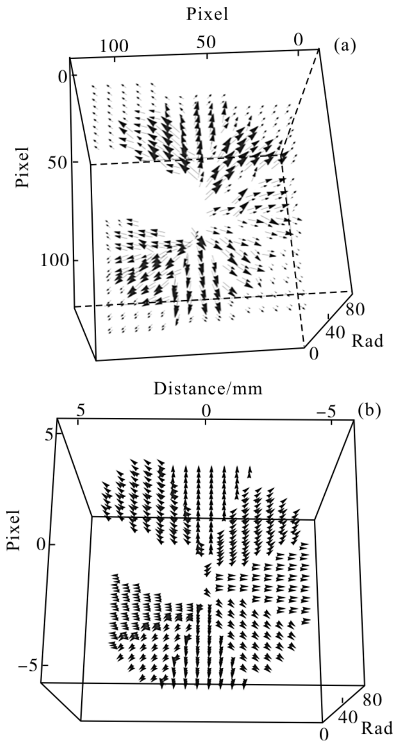

Fig.7 Reconstructed RPB (a) and contrast with the theoretical result (b)

3 Conclusion

In summ ary, the RPB has been generated by using a set of quartz rotators, and its Stokes vector has been measured based on a CCD, while the polarization distribution obtained as well, which shows the normalized power deviation and polarization deviation are ~0.054 8 and ~0.004 4 respectively. Compared to the other generation methods, such as intro-cavity methods and special wave plate, rotators group is a convenient and reliable alternative, qualified for applications such as optical tweezer and laser manufacture. Compared to directly measure the longitudinal component, the amplitude deviation and polarization deviation bring a insight of the focal region without expensive and complex experiments, so this assessment methods has a potential for industrial application for monitoring RPB quality. By the interferometry experiment, the phase distribution of the RPB has been obtained. Result shows that the measurement consists with theoretical calculation, and the average phase difference is 1.471 between neighboring sections. Eventually we restructure well the vector-field of the RPB by processing the data of polarization and phase information. Compare to the standard phase measurement, our methods is targeted on RPB and APB, so the experiments have been simplified, and the results pave the way for accurate quantum manipulation and measurement.

References:

[1] Yan Shubin, Zhao Yu, Yang Dechao, et al. Optical tweezers based on near-field optical theory [J]. ***Infrared and Laser Engineering***, 2015, 44(3): 1034-1041. (in Chinese)

[2] Xiao Yun, Zhang Yunhai, Wang Zhen, et al. Effect of incident laser on resolution of LSCM [J]. ***Optics and Precision Engineering***, 2014, 22(1): 31-38. (in Chinese)

[3] Zhu Yanying, Yao Wenying, Li Yuntao, et al. Experiment of vertex beam generated by method of computer generated holography [J]. ***Infrared and Laser Engineering***, 2014, 43 (12): 3907-3911. (in Chinese)

[4] Ke Xizheng, Guo Xinlong. Orbital angular momentum research of high order Bessel Gaussian beam in a slant atmosphere turbulence [J]. ***Infrared and Laser Engineering***, 2015, 44(12): 3744-3749. (in Chinese)

[5] Wei Tongda, Zhang Yunhai, Tang Yuguo, et al. Effect of polarization, phase and amplitude on depletion focus spot in STED [J]. ***Optics and Precision Engineering***, 2014, 22(5): 1157-1164. (in Chinese)

[6] Yang Hong, Huang Yuanhui, Gong Changmei, et al. Advances on techniques of breaking diffraction limitation using scattering medium [J]. ***Chinese Optics***, 2014, 7(1): 1-25. (in Chinese)

[7] Dorn R, Quabis S, Leuchs G. Sharper focus for a radially polarized light beam [J]. ***Phys Rev Lett***, 2003, 91(23): 233901.

[8] Liu J L, Sheng Z M, Zheng J. Electron acceleration by tightly focused radially polarized few-cycle laser pulses [J]. ***Chin Phys B***, 2012, 21(2): 024101.

[9] Zhang M Q, Wang J, Tian Q. Experimental research on the longitudinal field generated by a tightly focused beam [J]. ***Chin Phys B***, 2013, 22(4): 044202.

[10] Wang R M, Wang X P, Wu Z K, et al. Multi-component optical azimuthons of four-wave mixing [J]. ***Chin Phys B***, 2014, 23(5): 054209.

[11] Zhou Z H, Zhu L Q. Multiple optical trapping based on high-order axially symmetric polarized beams [J]. ***Chin Phys B***, 2015, 24(2): 028704.

[12] Hayazawa N, Saito Y, Kawata S. Detection and characterization of longitudinal field for tip-enhanced Raman spectroscopy [J]. ***Appl Phys Lett***, 2004, 85(25): 6239.

[13] Richards B, Wolf E. Proceedings of the Royal Society of London mathematical [J]. ***Physical and Engineering Sciences***, 1959, 253-358.

[14] Ghadyani Z, Vartiainen I, Harder I, et al. Concentric ring metal grating for generating radially polarized light [J]. ***Appl Opt***, 2011, 50(16): 2451-2457.