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飞秒径向偏振光紧聚焦实验

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摘　要:以飞秒激光器为光源,搭建记录测量聚焦光斑的光学实验系统,研究飞秒径向偏振光紧聚焦特性.数值模拟表明当物镜数值孔径为 0.9,波长为 750 nm 时,线偏振光和径向偏振光焦斑的最小半高全宽分别是 1.3 μm 和 1.0 μm.实验中,使用全息干板作为记录介质,记录和测量微小的聚焦光斑,并通过精密电动平移台实现几十纳米量级步长的移动,获得精确焦平面处的聚焦光斑.测量结果表明,线偏振光和径向偏振光焦斑的最小半高全宽分别是 4.6 μm 和 2.9 μm.在高数值孔径聚焦条件下,径向偏振光可以获得比线偏振光更细锐的聚焦光斑.

关键词:径向偏振光;紧聚焦;实验研究;高数值孔径

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Experimental Research on Tight Focus of Femtosecond Radially Polarized Light

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Abstract: The tight focusing properties of the femtosecond radially polarized light was analyzed on experimental setup, which including a femtosecond laser source and focal spot recording setup. According to the numerical simulation, in the case of being focused with the objective lens of NA=0.9, the linearly polarized light with the wavelength of 750 nm can get its smallest focal spot with FWHM of 1.3 μm, while that of the radially polarized light is 1.0 μm. The holographic plates were used as the recording media to record and measure the tiny focal spots, which were placed on a electric power-driven precise translation stage with precision of tens of nonameters so as to obtain the exactly minimum focal spots for the measurements by precise step-scan. The measurement result indicated that the radially polarized light can achieve sharper and tinier focal spots than the lineraly polarized light when with high NA focussing lens, whose FWHMs are 4.6 μm and 2.9 μm respectively for the same cases as the somulations.

Key words: Radially polarized light; Tight focus; Experimental research; High numerical aperture

OCIS Codes: 260.1960; 320.7090; 160.2100; 090.2890; 080.3620

0 Introduction

With perfect polarization distribution of axial symmetry[1-2], the radially polarized light has various distinction compared with the linearly polarized light and the circularly polarized light especially when being

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converged by high NA objective lens[3], such as smaller focal spots as well as perfect 3D focused light field distribution[4]. Recently, the radially polarized light has been utilized for many fields, such as guiding and capturing particles, particle acceleration, improving the resolution of the microscope, metal cutting, improving the optical storage density and so on[5-6]. The optical near field analysis indicates that, it is much sharper than that of the linearly polarized light and the circularly polarized light[7]. Besides, the longitudinal magnitude of the radially polarized light′s focal field is much stronger than that of the linearly and circularly polarized light[8]. The further research of the focal properties is significant for deeper and broader applications of the radially polarized light.

Up to day, most researches of the focal properties of the radially polarized light are of theoretical simulations and numerical calculations[9], rarely focusing on the experimental research. Really, as the focal properties of the radially polarized light are usually determined by the practical properties of the lens and the beams, and the size of focal spot is much smaller than the pixel size of the camera, the tight focus of radially polarized light is hard to be achieved perfectly. We try various effective experimental ways to perform the experimental study of the radially polarized light′s tight focus. The holographic plates are used to record and measure the size of the tiny focal spots exactly. According to the experiments the Full Width at Half Maximum (FWHM) of the radially polarized light′s focal spot is 2.9 μm for focusing lens with NA=0.9, while it is 4.6 μm for the linearly polarized light.

1 Numerical simulations

When focused by high NA lens, the apodization and phase contrast domino effect of light ray will not be ignored, while those domino effects will be ignored in the case of paraxial approximation, whose numerical aperture is less than 0.7[10]. The linearly polarized light and the radially polarized light are selected for the analysis.

According to Richards-Wolf′s theory[11], the two kinds of polarized lights′ complex amplitude distribution of electric field on the focal plane can be deduced. If the incident laser beam is a linearly polarized beam oscillating along x-axis direction, its complex amplitude distribution is

$$E^y(r_p,\varphi_p)=-\mathrm{i}AI_2\sin 2\varphi_p X-\mathrm{i}A(I_0-I_2\cos 2\varphi_p)Y-2AI_1\sin\varphi_p Z \tag{1}$$

In the formula above, A is a constant, and I_0, I_1 and I_2 contain amplitude factor $f(\theta)$ as following

$$I_0=\int_0^\alpha f(\theta)\sqrt{\cos\theta}\sin\theta(1+\cos\theta)\mathrm{J}_0(kr_p\sin\theta)\mathrm{d}\theta \tag{2}$$

$$I_1=\int_0^\alpha f(\theta)\sqrt{\cos\theta}\sin^2\theta(1+\cos\theta)\mathrm{J}_1(kr_p\sin\theta)\mathrm{d}\theta \tag{3}$$

$$I_2=\int_0^\alpha f(\theta)\sqrt{\cos\theta}\sin\theta(1-\cos\theta)\mathrm{J}_2(kr_p\sin\theta)\mathrm{d}\theta \tag{4}$$

Among the formulas, $f(\theta)=\exp\left(-\frac{\sigma^2}{\sin^2\alpha}\cdot\sin^2\theta\right)$, $\sigma=R_0/w_0$, R_0 is the radius of the lens, w_0 is the waist radius of light, and α is the largest bending angle of the light axis and the bending light, which changes with different NA.

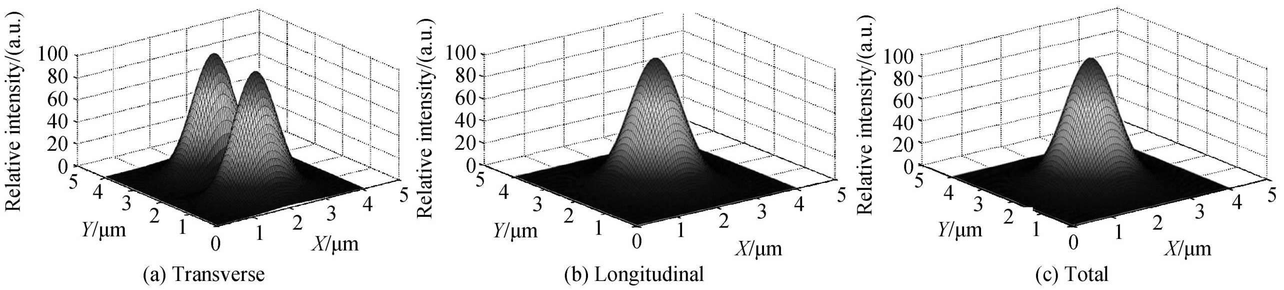

Fig. 1 The light field intensity distribution on the focal plane of x-directioned linearly polarized beam

For the radially polarized light beam

$$E^r(r_p,\varphi_p)=2A\Gamma_1\cos\varphi_p X+2A\Gamma_1\sin 2\varphi_p Y+\mathrm{i}2A\Gamma_0 Z \tag{5}$$

Thereinto,

$$\Gamma_0=\int_0^\alpha f(\theta)\sqrt{\cos\theta}\sin^2\theta\mathrm{J}_0(kr_p\sin\theta)\mathrm{d}\theta \tag{6}$$

$$\Gamma_1=\int_0^\alpha f(\theta)\sqrt{\cos^3\theta}\sin\theta\mathrm{J}_1(kr_p\sin\theta)\mathrm{d}\theta \tag{7}$$

In the numerical simulations, lens′ NA is set to 0.9, and the wavelength is set to $\lambda=750$ nm as the same for the experiments. According to the numerical simulation results, the differences between the light field intensity distribution on the focal plane of the two kinds of polarized lights are remarkable. For example, for the linearly polarized light, the transverse components are of double-peak structure and symmetrical about x axis and y axis, while for the radially polarized light, the transverse components are of ring structure without central light field intensity. Furthermore, the longitudinal light field intensity of the radially polarized light is more sharply concentrated at the center to achieve tight focal spots for high NA lens focusing.

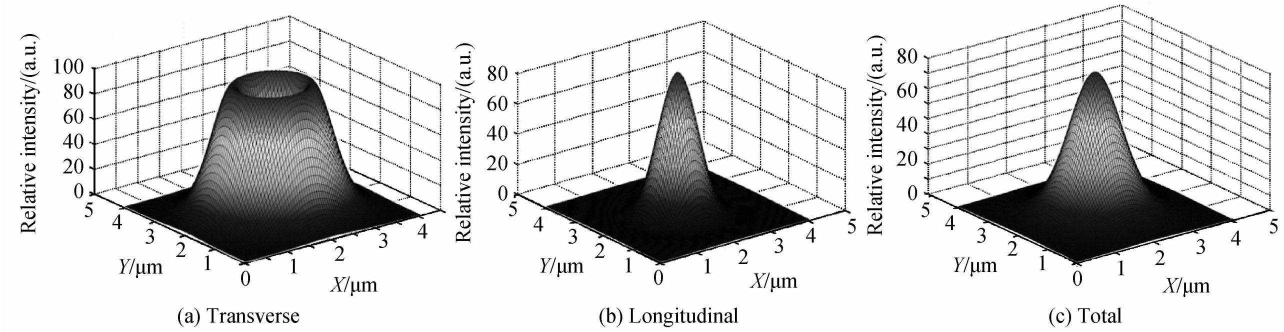

Fig. 2 The light field intensity distribution on the focal plane of radially polarized beam

The focal light intensities along x axis for the linearly polarized light and the radially polarized light are shown in Fig. 3. The FWHM of the linearly polarized light and the radially polarized light is 1.3 μm and 1.0 μm respectively.

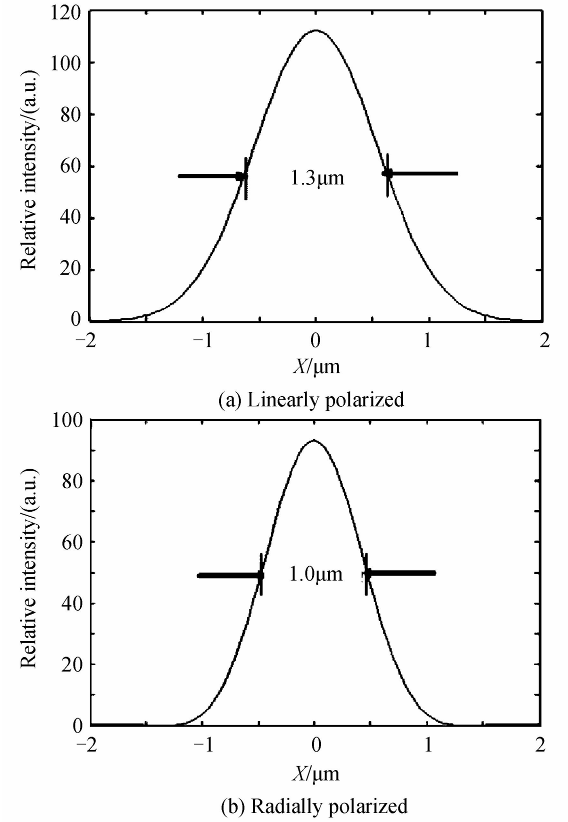

Fig. 3 Light intensity distribution along X-axis of focal spots

2 Experimental setup for recording focal spots

The experimental setup for recording focal spots is shown in Fig. 4, in which the input beams are provided by a Spectra-Physics MaiTai HP femtosecond laser. The monolithic converter is used to produce the radially polarized pulses, whose conversion efficiency is larger than 65%. A high NA objective lens is used to produce focal spots. According to the simulations, as the pixel pitch of up-to-date digital camera is bigger than the FWHM of the focal spots, the fine holographic plates are used for recording the focal spots, which can record much finer pictures than the digital cameras[12]. The recording plates are placed on an electric controlled fine stage-a piezoelectric ceramic electric platform, which can move precisely in two dimensions by 30nm per step. With the fine stage, the spots for various z positions around the focal point can be recorded so as to find the minimum spots, which can be considered as the focal spots. The recorded spots will be measured by an optical microscope.

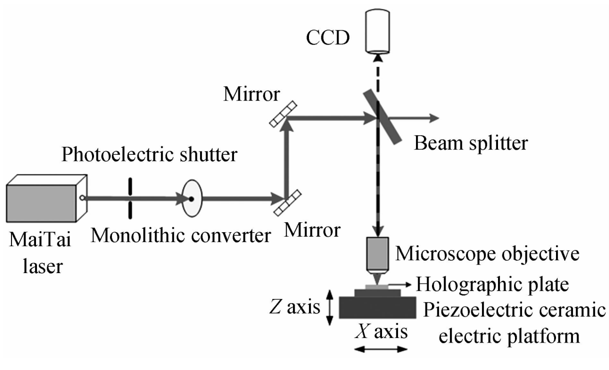

Fig. 4 The experimental setup for recording focal spots

In order to record the focal spots permanently, the holographic plates are used for the experiments. The experimental results are shown in Fig. 5 and Fig. 6, in which the 1st-16th in (a) and (b) respectively represent the spots recorded under different numerical values of the z axis of the motolized stage, from 500 nm to 2 000 nm, and the latter one is 100nm larger than the one before it.

The 10th spot in (a) and the 6th spot in (b) are tiniest, which are respectively the focal spot of the linearly polarized light and the radially polarized light. It can be intuitively found that, when NA=0.65, the focal spot of radially polarized light is smaller than that

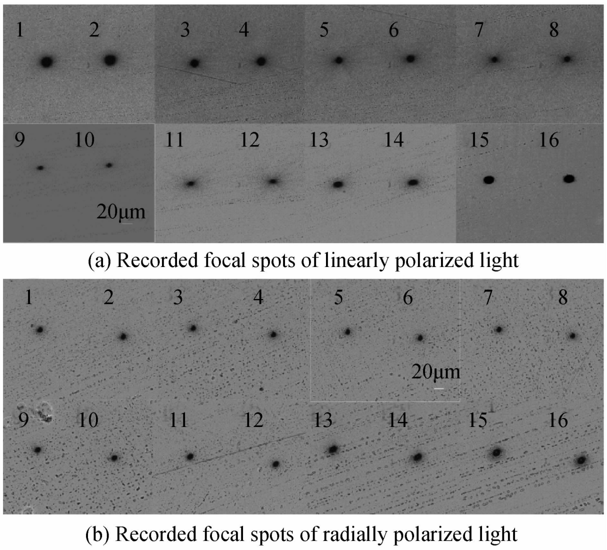

Fig. 5　The recorded focal spots recorded by the holographic plates (NA=0.65)

of linearly polarized light, and its shape is circular, while the shape of linearly polarized light's focal spot is almost elliptic.

The 8th spot in (a) and the 10th spot in (b) are tiniest, which are respectively the focal spot of the linearly polarized light and radially polarized light. Obviously, the experimental results of NA=0.9 get a similar trend as NA=0.65.

3　Results and discussions

The measured intensity curves and the corresponding fitting curves are shown below, in which

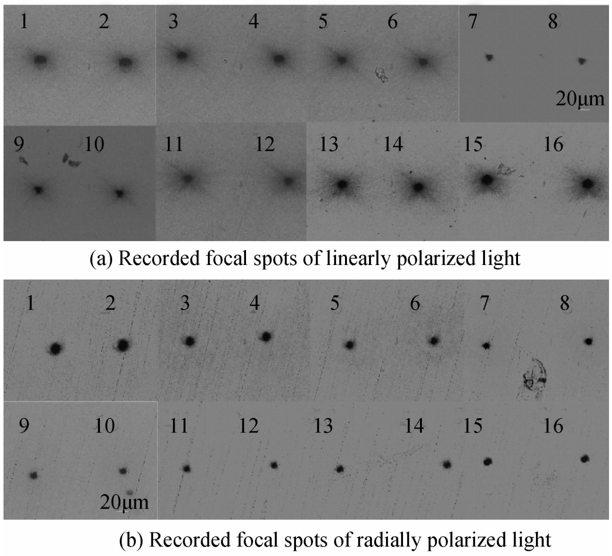

Fig. 6　The recorded focal spots recorded by the holographic plates (NA=0.9)

the fitting cures are following the Gaussian function.

The measured intensity curves and the corresponding fitting curves of the linearly polarized light and the radially polarized light are shown in Fig. 7 and 8. A ccording to the spot sizes in x and y axis, the shape of the radially polarized light's focal spot is much more circular than that of the linearly polarized light's focal spot, getting the same conclusion as the numerical simulation. The size of FWHM of the linearly polarized light's focal spot is about 5.8 μm, and the radially polarized light's focal spot is about 3.6 μm.

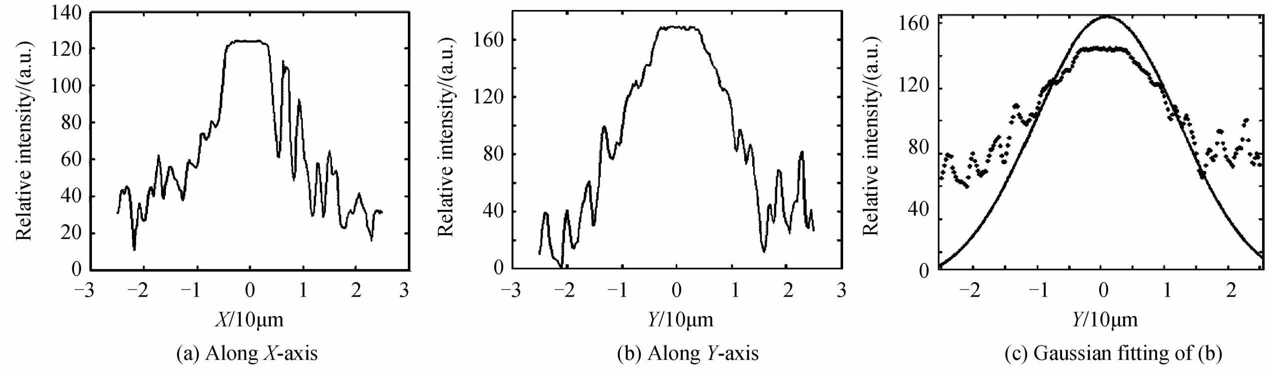

Fig. 7　The intensity curves of the focal spot of linearly polarized light (NA=0.65)

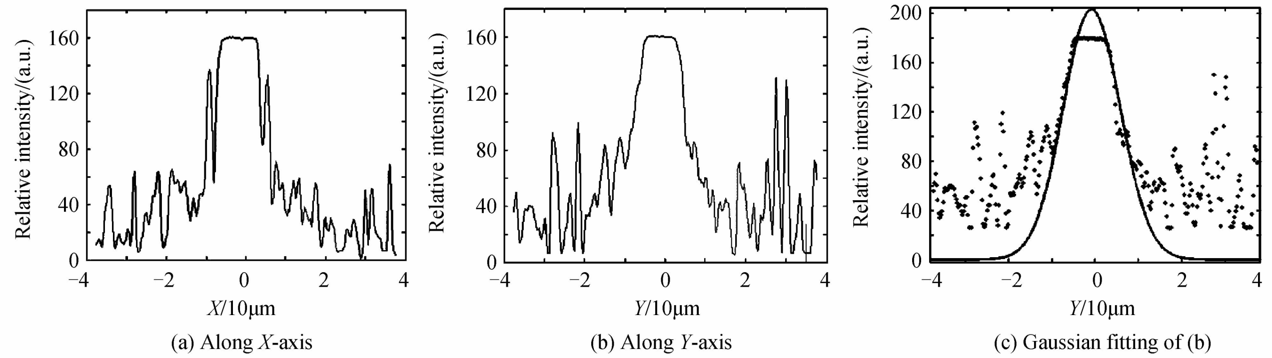

Fig. 8　The intensity curves of the focal spot of radially polarized light (NA=0.65)

Fig. 9 and 10 show the measured intensity curves and the corresponding fitting curves of the linearly polarized light and the radially polarized light for NA= 0.9. The size of the FWHM of linearly polarized light′s focal spot is about 4.6 μm, and that of radially polarized light′s focal spot is about 2.9 μm.

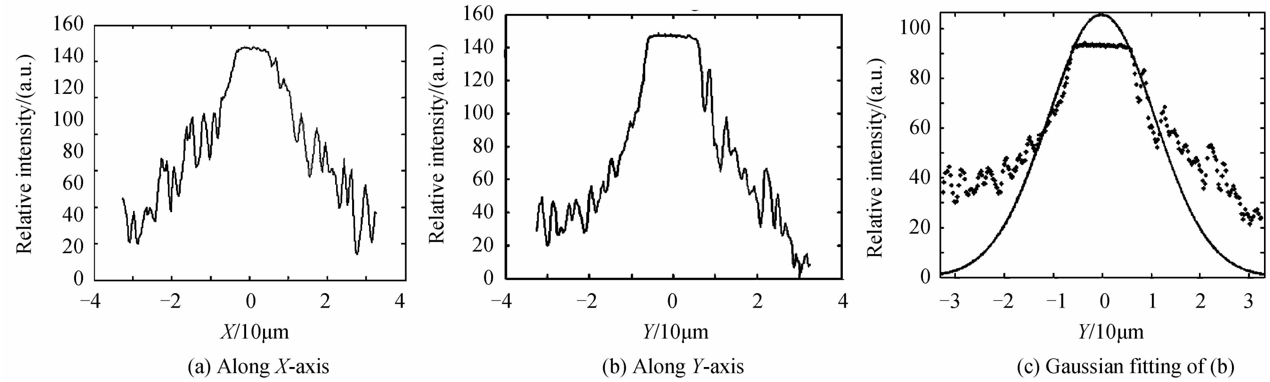

Fig. 9 The intensity curves of the focal spot of linearly polarized ligh (NA=0.9)

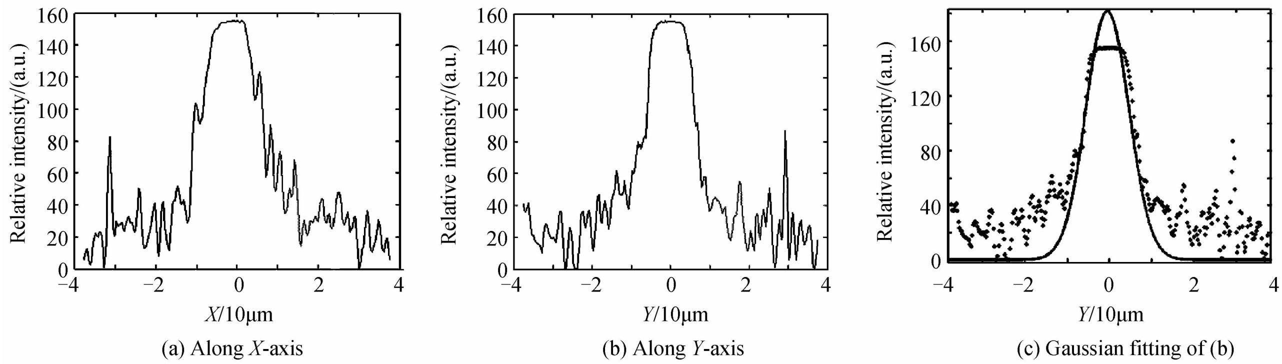

Fig. 10 The intensity curves of the focal spot of radially polarized ligh (NA=0.9)

Obviously, when NA becomes larger, the focal spot size will get smaller, and the focal spot of radially polarized light will get much sharper than that of the linearly polarized light. However, as the limit of the experimental conditions, the focal spots are larger than that of the simulations. Anyway, the trend which the experimental results indicate is coincide with the simulation, which confirm that the focal spot properties trend of various polarized light can be predicted by the simulations.

4 Conclusions

The focusing of the femtosecond radially polarized light and the linearly polarized light are analyzed by experimental measurements. The experimental results confirm that the shape of the radially polarized light′s focal spot is much more circular than that of the linearly polarized light′s focal spot. When NA of the focusing lens becomes larger, the focal spots of the radially polarized light will get sharper than that of the linearly polarized light. Although the experimental results are somewhat different from the numerical simulation results, the trend of the experimental measurements is coincide with the simulation, which confirm that the focal spot properties trend of various polarized light can be predicted by the simulations.

In order to obtain fine measurement results, the proper exposure time and light intensity for the focusing should be controlled well, and the thickness of the holographic plates should be improved, which will make the recording spots present the real focal spots so as to obtain the real properties of the tight-focus spots of the radially polarized pulses. Anyway, the analysis results will provide useful information for the design of laser-induced particle acceleration.

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