Tight focusing of circularly polarized light beam for the fabrication of NEMS

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Abstract-We investigate the focused properties of circularly polarized beam by a high NA lens axicon based on vector diffraction theory. The Circularly polarized femtosecond laser vortex pulses ablate material differently depending on the handedness of light.This effect offers an additional degree of freedom to control the shape and size of laser-machined structures on a sub-wavelength scale.

Keywords: Depth of Focus(DOF),Laugerre Gaussian Beams(LG),Left Circularly Polarized Light(LHCP),Right Circularly Polarized light(RHCP),Numerical Aperture(NA)

1 INTRODUCTION

Focused femtosecond laser vortex pulses are routinely used to micromachine or change the properties of different materials.By focusing the pulses very tightly and by simultaneously keeping the light intensity in the focal region near the optical breakdown threshold the structural changes can be spatially localized to 10's of nanometers[1].So far,this combined approach has been used in high density optical recording [2],fabrication of 3-D nano fluidic channels [3],single cell surgery [4],and synthesis of novel material phases using linearly polarized Laugerre Gaussian (LG) beams.

In this paper,we investigate the vectorial nature of tightly focused femtosecond laser vortex pulses.Specifically,we demonstrate that the circularly polarized vortex pulses of the opposite handedness,but with an identical intensity distribution at the entrance pupil of the focusing optics can produce ablation features which dramatically change in shape and size.

2 THEORY

In our experiment, we ablate Silicon in air either by using fixed spot radiation or by moving the sample perpendicular to the laser beam propagation Z.The ablation is performed on the basis of spin and orbital angular momentum of the pulses,which are defined by the handedness of circular polarization σ and the sign of m respectively were either parallel or anti-parallel.According to the theory [15],these two situations correspond to quite different focal intensity distributions in the regime of tight focusing.

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A schematic diagram of the suggested method is shown in Fig-1.The analysis was performed on the basis of Richards and Wolf's vectorial diffraction method widely used for high NA focusing systems at arbitrary incident polarization. The complex amplitudes of the longitudinal(E_z) and transverse electric field components(Ep) can be written as

$$E_p^+ = 2\pi i\{A_1 \exp(i\varphi)\sigma^+ + A_4 \exp(3i\varphi)\sigma^+\} \tag{1}$$
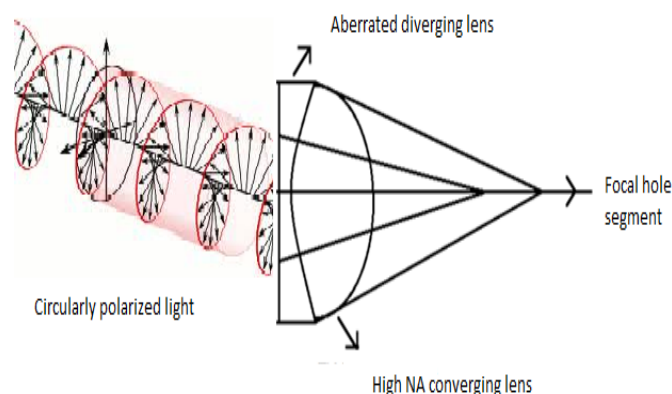
$$E_Z = 4\pi A_2 \exp(2i\varphi) E_z \tag{2}$$

Figure 1:Focusing of circularly polarized light using lens axicon

For the left handed circularly(σ=1) polarized Laguerre Gaussian beam and as:

$$E_p^- = 2\pi i\{A_1 \exp(i\varphi)\sigma^- + A_5 \exp(-i\varphi)\sigma^+\} \tag{3}$$

$$E_z = -4\pi A_3 e_z \tag{4}$$

For the right handed circularly(σ=-1) polarized Laguerre Gaussian beam,where:

$$A_1 = -i\frac{A}{\lambda}\int_0^\alpha GabT(\theta)J_1(krsin\theta)\exp(-ikzcos\theta)\,sin\theta d\theta \tag{5}$$

$$A_2 = -i\frac{A}{\lambda}\int_0^\alpha GaT(\theta)J_2(kr\,sin\theta)\exp(-ikz\,cos\theta)\,sin^2\theta\,d\theta \quad (6)$$

$$A_3 = -i\frac{A}{\lambda}\int_0^\alpha GaT(\theta)J_0(kr\,sin\theta)\exp(-ikz\,cos\theta)\,sin^2\theta d\theta \quad (7)$$

$$A_4 = -i\frac{A}{\lambda}\int_0^\alpha GacT(\theta)J_3(kr\,sin\theta)\exp(-ikz\,cos\theta)\,sin\theta d\theta \quad (8)$$

$$A_5 = i\frac{A}{\lambda}\int_0^\alpha GacT(\theta)J_1(kr\,sin\theta)\exp(-ikz\,c\,os\theta)sin\theta d\theta \quad (9)$$

$\sigma^{\pm}$ are the unit vectors in the circular basis.

$$a=\sqrt{cos\theta} \quad (10)$$

$$b=1+cos\theta \quad (11)$$

$$c=1-cos\theta, \quad (12)$$

$$G=\sqrt{2}\gamma A_0\left(\frac{sin\theta}{sin\alpha}\right)exp\left(\frac{-\gamma^2 sin^2\theta}{sin^2\alpha}\right) \quad (13)$$

Where G is the function of the incident beam, A_0 is the amplitude at the peak of intensity,A is the coefficient that depends upon the optical parameters of the system, k=$\frac{2\pi}{\lambda}$ is the wave number of light in vacuum,r is the radial distance from the z-axis,φ and θ are the angular coordinates of r, J_n is the Bessel function of the first kind of order n, the truncation parameter $\gamma=\frac{R}{\omega}$ is the ratio of the entrance pupil aperture radius R and the beam size parameter ω, and α=arcsin(NA).In our experiments, α=1.12,R=2mm and ω=1.8mm.The integrals were calculated only for the central wa
velength of the femtosecond laser radiation which has a FWHM spectral bandwidth of ~5nm.This approximation is valid as the influence of light polychromaticity on the intrafocal intensity distribution becomes noticeable only for very short ($\square$10fs) broadband laser pulses.
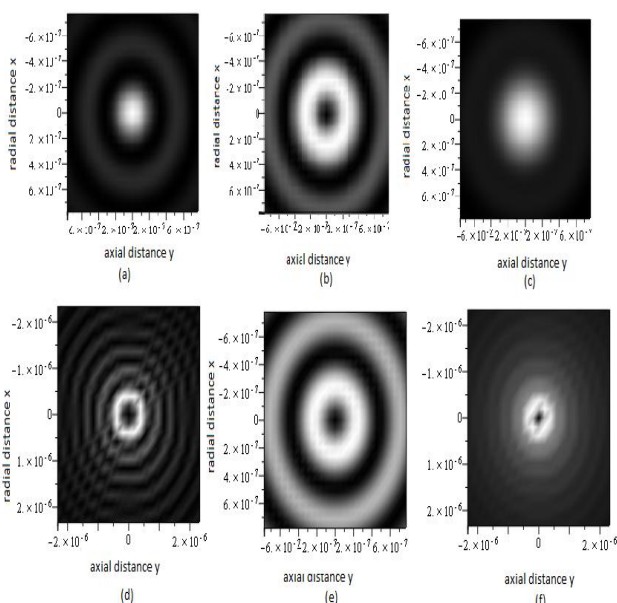
3 RESULTS

We perform the integration of Eq. (1) numerically using parameters λ =1, NA=0.6 and β=1.2 as in [9].For simplicity, we assume that the refractive index n = 1 and A = 1.

The intensity distribution of the lens axicon is evaluated by by the function T(θ), where T(θ) is the non-paraxial transmittance function of the thin aberrated diverging lens.

$$T(\theta) = \exp\left(Ik\left(\frac{\psi sin\theta}{sin\alpha}\right)^4 + \left(\frac{1}{2f}\left(\frac{sin\theta}{sin\alpha}\right)^2\right)\right) \quad (14)$$

Where ψ is the aberration coefficient. In our calculation,we take f=18.4mm and $\psi = 6.67 \times 10^{-5}$mm^{-3}.

We observed that the increase in the NA results in the decrease of the DOF.The proposed high NA lens axicon system generates sub wavelength super long dark channel without any annular truncation.

Fig-2 Intensity distribution of the focused field near focus for the circularly polarized beam focused by high NA lens axicon. The other parameters are β=2 and NA =0.9 (a,d)Intensity distribution produced by the transverse components of right and left circularly polarized light.(b,e)Intensity distribution produced by longitudinal component right and left circularly polarized light.(c,f)Total intensity distribution of right and left circularly polarized light

Since such a long uniform sub wavelength focal hole segment is generated without any annular aperture, the intensity of the focal hole segment also remains very high.

4 CONCLUSION

The intensity distributions of circularly polarized beam that has a double-ring-shaped transverse mode pattern tightly focused by high NA lens axicon were calculated based on vector diffraction theory. It is observed that the distribution of the electric field near the focus varied drastically with the degree of truncation of the incident beam by a pupil. This effect offers an additional degree of freedom to control the shape and size of laser-machined structures on a sub-wavelength scale.

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