Tight focus of light using a micropolarizer and a microlens

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Using a binary microlens of diameter 14 µm and focal length 532 nm (NA = 0.997) in resist, we focus a 633-nm laser beam into a near-circular focal spot with dimensions 0.35×0.02λ and 0.38×0.02λ (λ is incident wavelength) at full-width of half-maximum intensity. The incident light is a mixture of linearly and radially polarized beams generated by reflecting a linearly polarized Gaussian beam at a 100 µm x 100 µm four-sector subwavelength diffractive optical microelement with a gold coating. The focusing of a linearly polarized laser beam (the other conditions being the same) is found to produce an elliptical focal spot measuring (0.40±0.02)λ and (0.56±0.02)λ. In both cases, the area of the focal spots is 0.105λ². This is the first implementation of subwavelength focusing of light using a pair of microoptical elements (a binary microlens and a micropolarizer). © 2012 Optical Society of America

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1. Introduction

The manipulation of polarization states of laser light and generation of a prescribed intensity distribution in a given plane by means of subwavelength diffraction gratings was first proposed in Ref. [1]. Subwavelength diffraction gratings were utilized to convert the laser light polarization in Refs. [2-7]. When a linearly polarized light is incident on such a grating, the magnitude of polarization rotation depends on the angle between the incident polarization vector and the direction of the grating lines/grooves. Refs. [2-7] describe gratings operating in transmission and manufactured from a variety of materials for the IR wavelength range. In particular, GaAs gratings for a wavelength of 10.6 µm were utilized in Refs. [2-5]. For the grating polarizer, the etch depth was 2.5 µm. A GaAs grating operating at a wavelength of 1.06 µm and characterized by a 240-nm period and 470-nm etch depth was discussed in Ref. [6]. In Ref. [7] an azimuthally polarized laser beam was generated using a subwavelength grating with birefringence properties at 1.55 µm. The structure was composed of alternating SiO₂ and SiN layers of the overall height 8 µm. It presents a challenging task to manufacture a subwavelength grating in transmission for the visible range due to high aspect ratio (of about 5). Considering this, a reflection four-sector binary grating in a gold film of period 400 nm and depth 110 nm was utilized in Ref. [8] to generate a radially polarized light of wavelength 633 nm. The present authors have reported [9-11] experiments on tightly focusing a linearly polarized laser beam by means of microoptic components. In Ref. [9], the focusing was realized with a binary microlens with a circular grating of period 800 nm (NA = 0.67). In Ref. [10], a binary microlens of focus f = 0.532 µm, diameter 14 µm, and micrelief depth 510 nm was utilized. Using a scanning near-field optical microscope (SNOM), we studied the propagation of a linearly polarized Gaussian beam of wavelength λ = 532 nm through the microlens. A focal spot of size at full-width at half-maximum intensity FWHM = (0.44±0.02)λ was experimentally obtained. By replacing the 532-nm incident wavelength with λ = 633 nm, we managed to obtain [11] a tighter focal spot of size FWHM = (0.40±0.02)λ using the same microlens.

Publications concerned with the subwavelength focusing of radially and azimuthally polarized laser beams have also been widely known [12-15]. Focal spots of size FWHM = 0.43λ (NA = 0.95) [12, 14], FWHM = 0.30λ (NA = 1.4) [13] have been obtained in the numerical and physical experiments. In Ref. [13], the above-mentioned resolution was experimentally attained in recording of 3Tbit of data on a conventional optical disk. In this work, a 633-nm laser beam was focused using a binary microlens of diameter 14 µm and focus 532 nm (NA = 0.997) fabricated in resist. The beam composed of a mixture of linearly and radially polarized beams, generated by reflection of a linearly polarized Gaussian beam from a gold-coated four-sector subwavelength binary diffractive optical microelement (micropolarizer) of size 100x100 µm, was focused near the microlens surface into a near-circular focal spot measuring...
The measurement of the focal spot was conducted with a 20-nm step using a SNOM with a metal cantilever shaped as a hollow pyramid tip with a 70° vertex angle and a 100-nm pinhole. Such a cantilever is 3 times more sensitive to the transverse electric field component than to the longitudinal field component [16].

2. Reflection binary micropolarizer
A gold layer of thickness 160-180 nm was deposited on a glass substrate by electron beam evaporation. Then, the golden layer was coated with a layer of electron beam resist (ZEON ZEP520A), and the pattern of the four-sector grating polarizer projected into the resist using a 30-KV electron beam. The sample was then developed in xylene to dissolve resist fragments that had been exposed to the electron beam. The pattern of the grating polarizer was then transferred into the gold layer using by sputtering with an Argon plasma.

Figure 1a depicts a SEM image of the grating polarizer central fragment. Note that the overall size of the polarizer is 100x100 µm, and the fill factor was equal to 0.5. The quality of the micropolarizer was superior to that of Ref. [8].

When the linearly polarized white light is reflected at the micropolarizer under study (Fig. 1a) just two of the four sections of the polarizer appear as bright (or dark) in the image plane (Fig. 1b) if observed through the polarizer rotated by +45 or -45 degrees relative to the incident light polarization plane. From Fig. 1b, the light reflected at each micropolarizer section is seen to be devoid of circular symmetry, whereas the average intensities across two diagonal squares are seen to be different.
diagonals (as in Fig. 2b,c). When the output polarizer is rotated by +45° and -45°, the resulting beam is a mixture of linearly and radially polarized beams.

![Image](image1.png)

**Fig. 3** Far-field intensity patterns for the laser light (633 nm) reflected at the micropolarizer (Fig. 1): (a) without an output polarizer, with a polarizer rotated by (b) 45° and (c) -45°.

### 3. Binary microlens in a resist

A high quality binary microlens [10, 11] was fabricated in ZEP520A resist (refractive index $n = 1.52$) by electron beam lithography. Figure 4 depicts a SEM image of the microlens: mirorelief depth 510 nm, diameter 14 µm, outermost zone 0.5λ = 266 nm. The microlens is composed of 12 rings and a central disk.

![Image](image2.png)

**Fig. 4.** SEM image of the microlens with a 18000x magnification.

The radii of the microlens rings were calculated using the familiar formula $r_m = (m \lambda f + m^2 \lambda^2 / 4)^{1/2}$, where $f = \lambda = 532$ nm is the focal length and $m$ is the radius number. The microlens has NA = 0.997. When the microlens in Fig. 4 is illuminated by a linearly polarized Gaussian beam of wavelength 633 nm and radius approximately equal to that of the microlens (7 µm), the focal spot is formed nearer than it is suggested by the calculations (532 nm), being found 230 nm away from the microlens, as shown in Ref. [11]. Using the FDTD method [11], the numerically calculated minimal and maximal dimensions of the focal spot were shown to equal $\text{FWHM}_{\text{min}} = (0.40 \pm 0.02) \lambda$ and $\text{FWHM}_{\text{max}} = (0.87 \pm 0.02) \lambda$. In the meantime, the minimal and maximal dimensions of the focal spot experimentally measured with a SNOM were $\text{FWHM}_{\text{min}} = (0.40 \pm 0.02) \lambda$ and $\text{FWHM}_{\text{max}} = (0.60 \pm 0.02) \lambda$.

### 4. Simulation

Using the FDTD-method, the focusing of a radially polarized TEM$_{01}$ mode of wavelength $\lambda = 633$ nm and mode parameter $R = 10\lambda$ by means of a microlens of focal length 532 nm intended to operate at a wavelength of 532 nm was simulated. In Fig. 5 is (a) the intensity profile in the focal point is shown and (b) the expected experimental profile that would be measured using a SNOM with a pyramid metal cantilever [16]. In Fig. 5a, the focal spot size is $\text{FWHM} = 0.37\lambda$.

![Image](image3.png)

**Fig. 5.** (a) Intensity profile in the focus near the microlens surface when focusing the $\text{R-TEM}_{01}$ mode with the parameter $R = 10\lambda$ and (b) the same NSOM-aided pattern 3 times less sensitive to the longitudinal component.

Figure 5 suggests that should there be a perfect radially polarized binary-microlens-aided focus (Fig. 4), the SNOM image of the focal spot would appear as a circle (Fig. 5b) of size FWHM = 0.47λ. That is to say that the image of a tight focus of a perfect radially polarized beam obtained with a SNOM with a hollow metal pyramid tip will be larger than the real spot. In the case under study, instead of the real size of FWHM = 0.37λ the SNOM image is supposed to be of size FWHM = 0.47λ.
However, the four-sector micropolarizer in Fig. 1a generates a mixed linearly and radially polarized beam [8]. Below, we simulate in which way this type of beam will be focused by the microlens of Fig. 4 and in which way the focal spot is to be imaged by the SNOM. Figure 6 shows the intensity pattern generated 200 µm apart from the micropolarizer of Fig. 1a, with the arrows showing the polarization directions.

![Fig. 6. Numerically modeled intensity pattern |E|^2 200 µm apart from the micropolarizer of Fig. 1a. The frame size is (5x5)µm.](image)

Figure 7 shows the intensity profiles in the focus of the microlens in Fig. 4 along the (a) X and (b) Y axes.

![Fig. 7. FDTD method: Intensity profiles of the electric field components in the focus of the microlens in Fig. 4 on the Y-axis. The longitudinal intensity E_z has been decreased by a factor of 3.](image)

In Section 5, we show that a mixed, linearly and radially polarized beam from the micropolarizer of Fig. 1a can be focused by means of the microlens of Fig. 4 into a near-circular focal spot, which is tighter than that reported in Ref. [11].

5. Experimental focusing of a mixed linear-radially polarized beam with a binary microlens

The experiment studied the tight focusing of an optical beam reflected from a micropolarizer (Fig. 1a) that had converted the linear polarization into the radial one. The experimental optical setup is shown in Fig. 9.
The light from a He-Ne laser (λ = 633 nm) was focused with an objective O₁ onto a four-sector micropolarizer (Fig. 1a), which converted the linear polarization into the mixed, linear-radial one. The polarizers P₁ and P₂ served the double purpose of verifying that the light incident on the micropolarizer was linearly polarized and attenuating the light power. After reflecting at the micropolarizer, the beam was focused onto the bottom of the microlens of Fig. 4 of focal length 532 nm, producing a subwavelength focal spot after passing it. The intensity pattern of the focal spot was measured with a SNOM Ntegra Spectra (NT-MDT) (shown in a dashed line rectangle in Fig. 9). Figure 10a illustrates a SNOM-aided intensity pattern, with the minimal and maximal size of the focal spot measuring FWHM\textsubscript{max} = (0.38±0.02)λ (Fig.10b) and FWHM\textsubscript{min} = (0.35±0.02)λ (Fig.10c). The simulation results for this case are shown in Fig. 10 (black curve): with the focal spot measuring FWHM\textsubscript{max} = (0.40±0.02)λ (Fig.10b) and FWHM\textsubscript{min} = (0.36±0.02)λ (Fig.10c). Thus, the discrepancy between the experiment and simulation falls within the RMS error 2%. In the focal spot, the side-lobes of the diffraction pattern amount to 30% of the major intensity peak (Fig. 10c). Thus, one can infer that a high-NA binary microlens (Fig.4) operates as a binary axicon, generating a focal spot with the intensity profile described by the squared zero-order Bessel function. For a Bessel beam, the diffraction limit is known to equal FWHM = 0.36λ.

To evaluate the effect of the micropolarizer, the substrate containing the micropolarizer was shifted in the transverse direction to allow the light to be reflected at the relief-free golden surface. This resulted in a microlens-aided focal spot of dimensions FWHM\textsubscript{max} = (0.50±0.02)λ and FWHM\textsubscript{min} = (0.40±0.02)λ. Thus, when focusing a linearly polarized beam, the resulting focal spot was found to be more elliptical

\[ S_{\text{linear}} = \frac{\pi(FWHM_{\text{min}} FWHM_{\text{max}})}{4} = 0.157\lambda^2 \]
\[ S_{\text{radial}} = \frac{\pi(FWHM_{\text{min}} FWHM_{\text{max}})}{4} = 0.105\lambda^2 \]
Conclusion

Using a binary microlens of diameter 14 μm and focal length 532 nm (NA = 0.997) we have focused a 633-nm laser beam into a near-circular focal spot with dimensions (0.35±0.02)λ and (0.38±0.02)λ at full-width of half-maximum intensity. The incident light is a mixture of linearly and radially polarized beams generated by reflecting a linearly polarized Gaussian beam at a gold 100 µm x 100 µm four-sector subwavelength diffractive optical microelement, with the sector gratings of period 400 nm and microrelief depth 110 nm. The focusing of a linearly polarized laser beam (other conditions being the same) has been found to produce an elliptical focal spot measuring (0.40±0.02)λ and (0.50±0.02)λ. In both cases, the area of the focal spots is 0.105λ². The subwavelength focusing of light using a pair of micropolaric elements (a binary microlens and a micropolarizer) has been implemented for the first time. It is notable that recently [17] a focal spot of size 0.25λ has been attained by focusing an azimuthally polarized first-order vortex beam by means of a conventional immersion microlens with NA = 1.4. By reducing this focal spot and the one reported in this work, equal to 0.35λ, to the same NA, we obtain the same-size focal spots, namely,

FWHM=0.25λ=0.25λ*1.4/NA=0.35λ/NA,
FWHM=0.35λ*0.997/NA=0.35λ/NA.

From formulae above it follows that immersion microlens (fig. 4) gives the same result as in [17].

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