Generation of a radially polarized light beam using space-variant subwavelength gratings at 1064 nm

Gilad M. Lerman[1,*] **and Uriel Levy**[1,2]
[1]*Department of Applied Physics, The Benin School of Engineering and Computer Science, The Hebrew University of Jerusalem, Jerusalem, 91904, Israel*
[2] *ulevy@cc.huji.ac.il*
**Corresponding author: gilad.lerman@mail.huji.ac.il*

Received August 11, 2008; accepted September 26, 2008;
posted October 17, 2008 (Doc. ID 100061); published November 20, 2008

The generation of radially polarized beams at a wavelength of 1064 nm by the use of a polarization transformer device consisting of space-variant subwavelength gratings (SGs) is demonstrated experimentally. The SG generates a π phase retardation between the TE and TM polarizations, acting as a half-wave plate, reflecting the polarization vector with respect to the axes of the plate. The polarization transformer is characterized by polarization analysis and by far-field measurements. The characterization results show good agreement with theory. The device is suitable for operation with Nd:YAG lasers; thus it is attractive for biological, optical tweezers, and material processing applications. © 2008 Optical Society of America

OCIS codes: 260.5430, 180.0180, 350.5730.

Radially polarized light beams have been gaining growing attention in the past few years [1–5]. Such beams can be generated using numerous techniques, including, for example, interference of modes, a liquid-crystal polarization converter, and a cylindrical sheet of polarizing film [6–8]. Another approach is using an element consisting of several pieces of half-wave plates oriented such that the incident linear polarization is rotated toward the radial direction [9]. Recently the generation of radially polarized beams using subwavelength gratings (SGs) was demonstrated in the 10.6 [10,11] and 1.55 [12] μm regime. These demonstrations are based on the form birefringence concept, previously demonstrated for various other applications [13–17]. The fabrication of space-variant polarization transformers made of SGs at shorter wavelength is challenging. Yet there is a great benefit in developing such devices. In particular, the realization of such polarization transformers at 1064 nm is desirable, because high-power Nd:YAG lasers used primarily for material processing and biological applications are operating at this wavelength and because both applications are expected to benefit from using radially polarized light [18,19]. In addition, this wavelength falls within the operation window for optical trapping of biological cells and small organisms (750–1200 nm [20]). To support the above mentioned applications, we demonstrate for the first time (to our knowledge) the generation of a radially polarized beam by the use of a space-variant subwavelength periodic element at a wavelength of 1064 nm.

SGs can generate phase retardation between the TE and TM components of the incident beam. By controlling the duty cycle and the depth of these gratings, one can achieve a retardation of π between the two polarizations, thus creating a half-wave plate. By controlling the orientation of the SGs one can rotate the polarization at any coordinate on the beam's cross section into the desired direction, creating an electromagnetic field with any desired space-variant polarization including radial polarization. Radial polarization is defined such that the polarization of light is directed along the $\hat{r}$ axis in a polar coordinate system; i.e., it makes an angle θ with the $\hat{x}$ axis, where θ is the azimuthal coordinate in polar coordinate system. Therefore, assuming incident beam that is linearly polarized along the $\hat{x}$ axis, the k vector of the SGs should be oriented at an angle of $\theta/2$ with respect to the $\hat{x}$ axis, in order to rotate the incident beam into the radial direction. The k vector of the SG is thus described by

$$\vec{k}_g(x,y) = \frac{2\pi}{\Lambda}\left[\cos\left(\frac{\theta(x,y)}{2}\right)\hat{x} + \sin\left(\frac{\theta(x,y)}{2}\right)\hat{y}\right], \quad (1)$$

where Λ is the period of the grating.

To realize a radial polarization converter at 1064 nm we used a GaAs substrate with a refractive index of $n=3.478$ at this wavelength. To avoid diffraction inside the element at normal angle of incidence, the period of the SGs should be kept below λ/n, i.e., 305 nm. It is recommended to further reduce the grating period such that a wider set of incident angles can be used without resulting in internal diffraction; thus we chose the grating period to be 240 nm. We divided our polarization transforming device into discrete segments. The SG in each segment was rotated by a half of a degree with respect to the grating in the adjacent segment. This very fine segmentation results in deviation from the desired polarization direction by a maximum of 1°, with negligible effect on the extinction ratio. This approach is different from the approach that was used in [10,11] where continuous grating lines were realized by spatially modifying the periodicity of the SG along the element. Unfortunately, the requirement for modifying the periodicity indicates that only a specific portion of the aperture can be used for polarization transformation; therefore the conversion efficiency is limited. The gratings patterns were written in an electron-

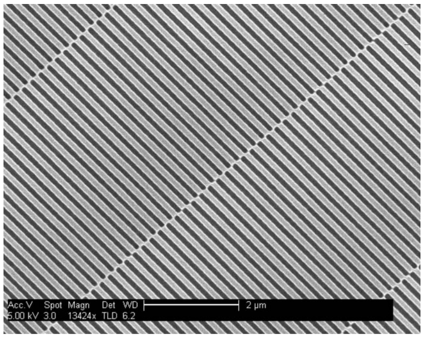

Fig. 1. SEM picture showing the different sections of the element written in the electron-beam resist. The period is 240 nm, and the duty cycle is 50%.

beam resist (ZEP 520A) using an electron-beam tool (Raith e-line) at 20 kV. Owing to the segmentation of the element, the length of the gratings lines near the center of the element is very short (few tens of nanometers), reaching the limits of the electron-beam tool. Therefore we blocked the central portion of the element by depositing 300 nm Ag layer on a 55 μm radius circle. Nevertheless, the radius of the whole device is 500 μm; thus only 1% of the aperture area is opaque. Figure 1 is a scanning electron microscope (SEM) picture showing few segments of the elements written in the electron-beam resist. The pattern was then transferred into the GaAs substrate using a reactive ion etching process. The etching depth and profile for achieving π phase retardation were estimated by the effective medium theory followed by an exact calculation using rigorous coupled-wave analysis (RCWA). It is known that a trapezoidal grating profile can assist in reducing the Fresnel reflection of such SG [21]. Our simulations show that a trapezoid angle of 3°, a long base of 145 nm, and a grating depth of 470 nm should provide π retardation with reflection coefficients of 14.4% and 3.6% for TE and TM polarization, respectively. Owing to fabrication inaccuracy the profile of the fabricated element is slightly different from the designed profile. To evaluate the effect of fabrication inaccuracies we resimulated the obtained structure with RCWA. Based on the simulation results we estimate the polarization inaccuracies to be smaller than 10%. Figure 2(a) shows a microscope picture of the whole element. Figure 2(b) is an SEM picture showing a cross section of the fabricated nanograting. The slightly trapezoid grating profile can be observed.

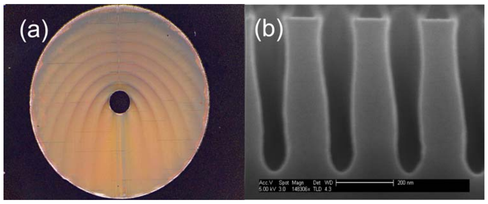

Fig. 2. (Color online) (a) Microscope picture showing the whole element. The diameter of the element is 1 mm. The picture was taken with a 5× objective lens. (b) SEM picture showing a cross section of the grating etched into the GaAs.

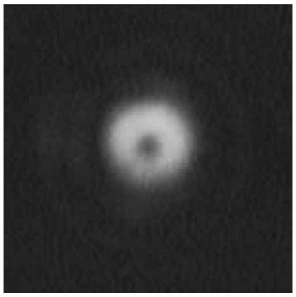

Fig. 3. Far-field intensity distribution of the radially polarized beam.

For qualitative characterization of the polarization transformer device we captured the far-field intensity distribution of the radially polarized light. The device was illuminated by a collimated, linearly polarized (along the horizontal, $\hat{x}$ axis) Nd:YAG laser beam (1064 nm wavelength). The beam was then focused by a lens such that the Fourier transform of the radially polarized light is obtained at the back focal plane of the lens. The obtained Fourier transform was captured by a CCD camera. Figure 3 shows the obtained intensity distribution across the Fourier plane. As expected, a donut-shape mode was obtained.

To quantify the performance of our polarization converter, we placed a linear polarizer (analyzer) behind it to convert the polarization modulation into easily observable intensity modulation. The analyzer was oriented perpendicular to the polarization direction of the incident beam. The image of the resulting intensity distribution was captured by a CCD camera that was placed at the imaging plane of the polarization converter element. Figure 4 shows the obtained intensity distribution. Since the polarization direction is varying across the cross section of the beam, one can see dark and bright zones corresponding to regions where the polarization is perpendicular or parallel to the polarizer axis, respectively. To calculate the intensity versus the azimuthal angle θ (measured anticlockwise from the horizontal axis) we integrated the intensity along the radial coordinate of Fig. 4 for different values of θ. The results are shown in Fig. 5 along side with the theoretical prediction. According to theory [10], the light intensity should vary as $\sin^2(\theta)$. The results fit very well to the theory,

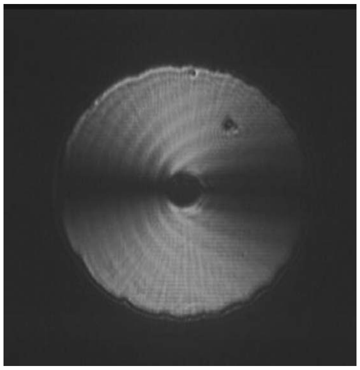

Fig. 4. Intensity distribution of the radially polarized beam after passing through a linear polarizer.

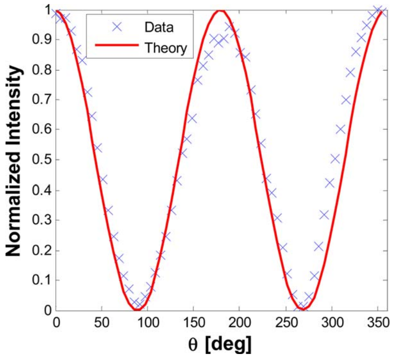

Fig. 5. (Color online) Crosses, normalized intensity after the polarization analyzer versus angle of polarization. The experimental data were obtained by digital integration across the radial coordinate of Fig. 4. Solid curve, theoretical curve.

with an extinction ratio of about 100, indicating a high purity of the produced radially polarized beam. We repeated this process for several orientations of the analyzer, showing similar trend to that shown in Fig. 5, although with lower extinction ratios.

In summary, we demonstrated a polarization transformer device that converts a linearly polarized beam to a radially polarized beam using a subwavelength periodic space variant structure at a wavelength of 1064 nm. The device was characterized using a polarization analyzer and by measuring the far-field distribution of the radially polarized beam. Both measurements were in good agreement with the theoretical prediction. Operating at 1064 nm wavelength, the device is particularly attractive for biological applications, in particular for optical trapping of cells and small organisms. It can also be used for other applications involving tight focusing of light beams and for efficient cutting of metals.

G. M. Lerman acknowledges financial support from the Eshkol fellowship under a doctoral training award. U. Levy acknowledges the Peter Brojde Center for Innovative Engineering and Computer Science for partial support of this research.

References

1. K. S. Youngworth and T. G. Brown, Opt. Express **7**, 77 (2000).
2. Q. Zhan and J. R. Leger, Opt. Express **10**, 324 (2002).
3. M. R. Beversluis, L. Novotny, and S. J. Stranick, Opt. Express **14**, 2650 (2006).
4. E. Descrovi, L. Vaccaro, L. Aeschimann, W. Nakagawa, U. Staufer, and H.-P. Herzig, J. Opt. Soc. Am. A **22**, 1432 (2005).
5. G. M. Lerman and U. Levy, Opt. Express **16**, 4567 (2008).
6. S. C. Tidwell, D. H. Ford, and W. D. Kimura, Appl. Opt. **29**, 2234 (1990).
7. M. Stalder and M. Schadt, Opt. Lett. **21**, 1948 (1996).
8. A. Shoham, R. Vander, and S. G. Lipson, Opt. Lett. **31**, 3405 (2006).
9. R. Dorn, S. Quabis, and G. Leuchs, Phys. Rev. Lett. **91**, 233901 (2003).
10. U. Levy, C.-H. Tsai, L. Pang, and Y. Fainman, Opt. Lett. **29**, 1718 (2004).
11. Z. 'e. Bomzon, G. Biener, V. Kleiner, and E. Hasman, Opt. Lett. **27**, 285 (2002).
12. W. S. Muhammed, A. Mehta, M. Pitchumani, and E. G. Johnson, IEEE Photon. Technol. Lett. **17**, 1441 (2005).
13. J. E. Ford, F. Xu, K. Urquhart, and Y. Fainman, Opt. Lett. **18**, 456 (1993).
14. I. Richter, P. C. Sun, F. Xu, and Y. Fainman, Appl. Opt. **34**, 2421 (1995).
15. R. C. Tyan, P. C. Sun, A. Scherer, and Y. Fainman, Opt. Lett. **21**, 761 (1996).
16. U. Levy, C. H. Tsai, H. C. Kim, and Y. Fainman, Opt. Express **12**, 5345 (2004).
17. N. Davidson, A. A. Friesem, and E. Hasman, Opt. Lett. **17**, 1541 (1992).
18. Q. Zhan and J. R. Leger, Opt. Express **10**, 324 (2002).
19. V. G. Niziev and A. V. Nesterov, J. Phys. D **32**, 1455 (1999).
20. K. C. Neuman and S. M. Block, Rev. Sci. Instrum. **75**, 2787 (2004).
21. D. H. Raguin and G. M. Morris, Appl. Opt. **32**, 1154 (1993).