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Partial etch phase (PEP) optical elements for high-volume applications

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ABSTRACT

Using binary etch and sub-wavelength DUV photolithography, we have designed and fabricated a variety of flat optical devices (lenses, vortex phase plates, vortex plus lens, and diffusers) useful in telecommunications and other areas. The devices provide the precision and low cost associated with modern semi-conductor manufacturing and offer unique functional performance. Since the design method involves selective binary removal of substrate material we designate derivative devices partial etch phase (PEP) devices. Design principles and fabricated device performance are described.

Keywords: Diffractive optical element, meta-materials, sub-wavelength, effective refractive index, vortex lens, vortex plate, flat lens, DUV lithography

1. INTRODUCTION

Diffractive optical elements have a long history. Here we focus specifically on phase-based, thin, transmissive devices [1-4]. In a typical transmissive phase device an input beam is transformed on passage through the device to an output beam whose phase is shifted in a spatially-dependent, device-determined manner relative to the input beam. Difficulties in producing optimal diffractive optical elements include the need for very fine surface structuring combined with the need to produce multiple transmissive phase levels. Historically, spatial resolution has been limited to multiples of the operative wavelength and in this regime, producing multiple phase levels typically requires multilevel or gray scale material removal typically through wet or dry etch. With super-lambda spatial resolution, the transmissive phase is determined by the thickness of the optical material through which light propagates. Over the years, semiconductor fabrication technology has improved to the point where detailed surface structuring at the sub-wavelength scale has become possible and, via DUV lithography and reactive ion etch, consistent with high volume, low cost production. As we demonstrate here and others have recently shown, once sub-wavelength surface structuring is available, it is possible to achieve multi-level or even continuous phase variation through an exclusively binary etch process. Design of such structures can be straight forward. As described in more detail below, one may simply divide the active surface involved into sub-wavelength spatial bins, assign each bin a phase based on the optical phase shift appropriate to desired overall device function, and etch a percentage of the surface area of each sub-wavelength bin proportional to the phase shift desired. The etch is binary to a depth that provides, for example, one wavelength difference in optical path length when fully unetched vs etched. Owning to the subwavelength character of the spatial bins, the net transmissive phase shift produced varies, to first approximation, to the percentage area of the spatial bin etched. With a one wavelength thick etch layer of refractive index n=2, one has available (lithographic resolution permitting), a full 2π range of phase values available for design implementation. Deviations from simple etch area – phase shift proportionality can be calibrated via fabrication and test.

2. DEVICES

A number of devices have been designed and fabricated using the PEP approach to controlling transmitted phase. In all cases discussed here, the devices are designed to operate at λ=850 nm wavelength. Phase plates comprise a layer of SiN (refractive index near 2) deposited on a glass or fused silica substrate. In the binary etch process employed, the etch is typically configured to reach the bottom of the SiN layer. The thickness of the SiN layer, d, is chosen to give the minimum and maximum phase shift desired (no removal to full removal). A surficial high index layer is not necessary and etch directly into the substrate is possible. In such cases d is the simply the etch depth. The phase plate surface is

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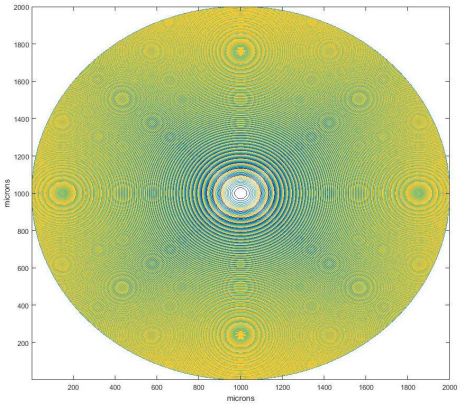
divided into 2D square spatial bins arranged in a lattice. Bins are 0.5 microns on a side. Bins are sufficiently sub-wavelength so that no diffracted signals arise from the array of bins themselves. Each bin is assigned a phase shift necessary to transform a design input beam into a design output beam. As the devices affect only phase, the input and output fields should have continuous amplitude for maximal output efficiency. The phase of each bin is controlled via etching a fraction of its area, σ, such that $\sigma\varphi_0$, where $\varphi_0 = 2\pi(n-1)d/\lambda$ is the geometrical optical phase difference of fully etched and unetched surface areas, equals the desired bin phase shift. It is assumed that the etched areas are unfilled. Ultimately, empirical calibration of phase shift versus σ is used to refine the design. In early devices discussed here, σ, was rounded to a discrete set of values, typically 4 or 5. More recent devices, not discussed here utilize a continuous variation in σ. Fabrication utilizes standard DUV photolithography and reactive ion etch. The spatial resolution of the DUV stepper employed is approximately 200-250 nm depending on resist and exposure parameters.

2.1 PEP focusing lens



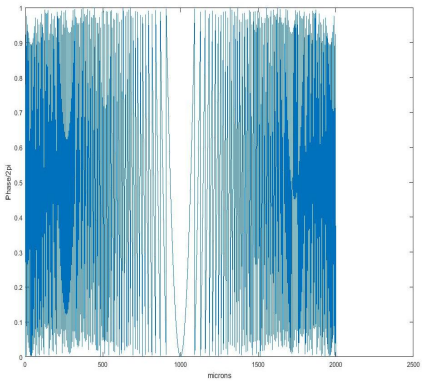
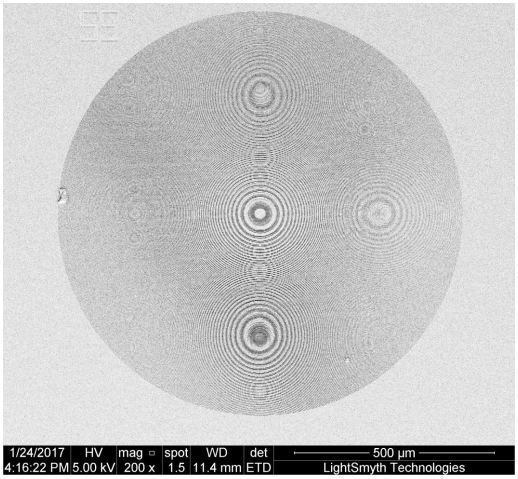


Figure 1a (left) shows the two-dimensional phase distribution of a 2-mm diameter, 5-mm focal length lens. Figure 1b (right) shows the phase change, mod(2π), along a diameter of the same lens. These values are calculated to provide optimal infinite conjugate focusing performance.



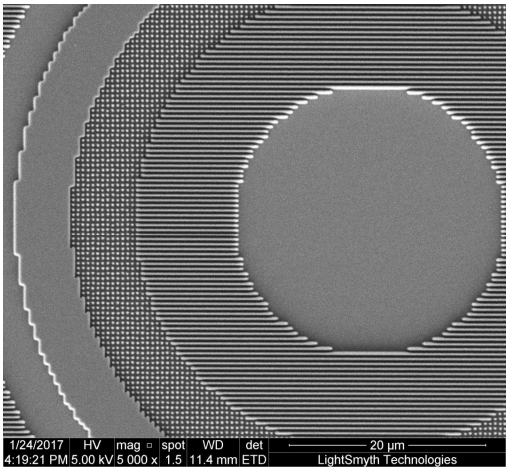


Figure 2a (left) shows an SEM photograph of a fabricated 1-mm diameter, 5-mm focal length lens. Figure 2b (right) shows a higher magnification SEM photograph of the lens shown in Figure 2a. The target-like structures in Figure 2a (other than the center one) are moiré patterns involving the device structure and the SEM photo pixels. They are not real. In Figure 2b, detailed binary etch patterns are shown. Four different etch patterns provide four phase levels. The phase depth of the etch was $\varphi_0=2\pi\times(1.25)$, i.e. $(n-1)d=1.25\ \lambda$. Thus unetched regions have a quarter wave, mod(2π), phase difference relative to fully etched regions. The dots and lines provide 0.5 and 0.75 times 2π phase shifts relative to fully etched regions. Individual dots demark separate design bins 0.5 microns on a side.

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Figure 1a shows the phase change distribution required of a 2-mm diameter focusing phase plate optimized for infinite conjugate ratio with a focal length of 5 mm. Figure 1b, shows the phase distribution (modulo 2π) of the same lens along a lens diameter. Figure 2a shows a low magnification SEM of a fabricated 1-mm diameter and 5-mm focal length PEP lens. Bullseye structure other at the center of the lens are moiré patterns resulting from the device structure and photo pixilation. The moiré patterns are not physical. Figure 2b shows a higher magnification SEM of the center of the same lens. The four different etch regions used to represent that phase variation are clearly visible. If the central region defined as providing a 2π relative phase shift, the next three rings are designed to be $(.75, .5, .25)\times 2\pi$, respectively. Subsequent rings repeat the pattern.

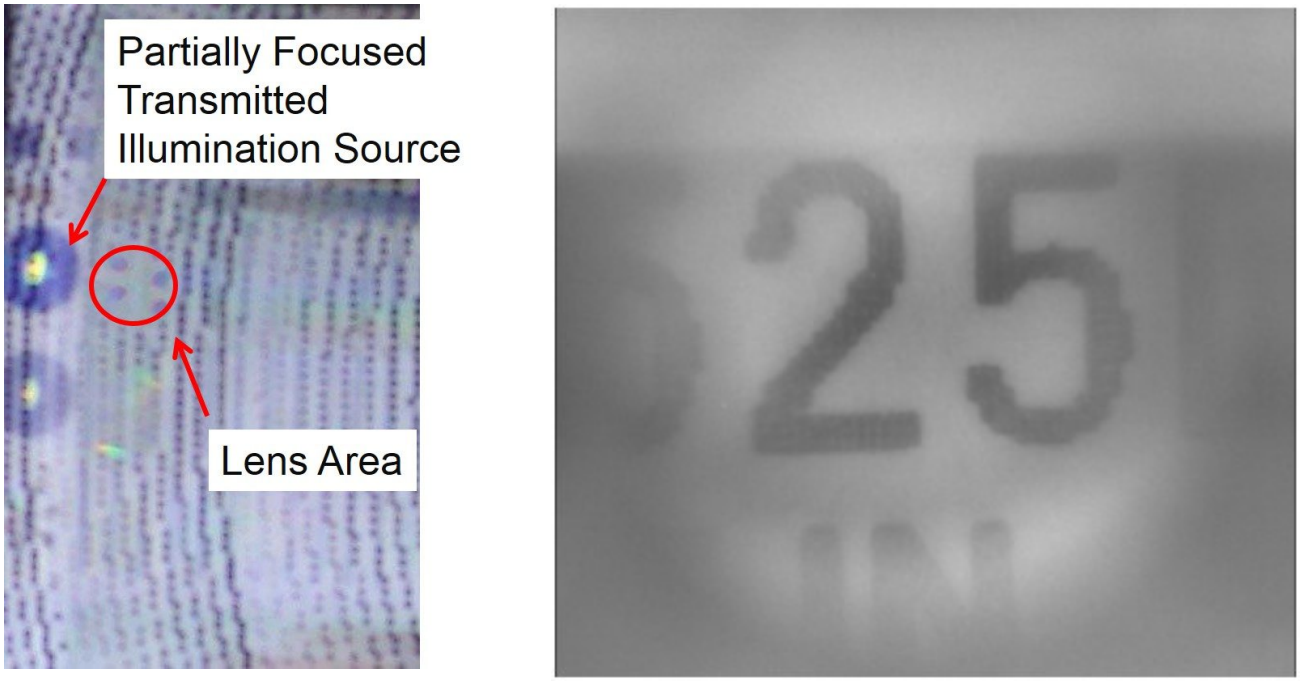

Figure 3a (left) shows PEP lens etched on glass positioned above a printout of its radial phase distribution. The PEP lens surrounded by a solid circle as indicated. Figure 3b (right) shows an image magnified by the same lens.

In Figure 3, we examine imaging and focusing properties of a PEP lens. In Figure 3a, a glass wafer containing a PEP lens (circled region) is positioned above a printed dot pattern. The wafer is positon less than a focal length above the pattern and thus acts as a magnifier. Note the enlarged spots seen through the lens. Note that the original pattern is not seen through the lens area indicating relatively high lens efficiency. To the left and slightly above the PEP lens, we see a partially focused imaged of the light used to illuminate the picture which passed through the lens at an angle. Notice the darkness of the shadow, which also speaks to the lens efficiency. In Figure 3b, we show another magnified image produced by the PEP lens. In both cases, illumination was white light (tungsten). Notice the lack of obvious chromaticity even though the devices were specifically designed for 850 nm.

2.2 PEP vortex plate

A vortex plate comprises a cylindrical device wherein the phase shift imparted on a transmitted beam varies linearly with azimuthal angle, where azimuthal angle refers to rotation about the device surface normal. Typically, the imparted phase will vary from 0 to $m2\pi$, where m is an integer and is referred to as the vortex order, as the azimuthal angle varies from 0 to 2π. A vortex plate may be implemented as a spiral thickness ramp with a thickness discontinuity. It may also be implemented as a PEP device where surface etch area as a function of azimuthal angle is used to introduce required phase shifts. In Figure 4a, we show SEM image of a PEP vortex plate of 8th order. There are four different phase levels, each subjected to a different etch pattern including fully etched and not etched at all. The set of four phase levels, repeated 8 times azimuthally produces the 8th order vortex behavior. Figure 4b, shows a higher magnification SEM image of the PEP vortex plate center wherein the different etch patterns can be seen. Figure 4c, depicts an image produced by placing the vortex plate in a two beam interferometer so as to transform transmitted phase variation into

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intensity variation. The intensity is color coded. The variation of transmitted phase between pie-shaped etch regions is apparent.

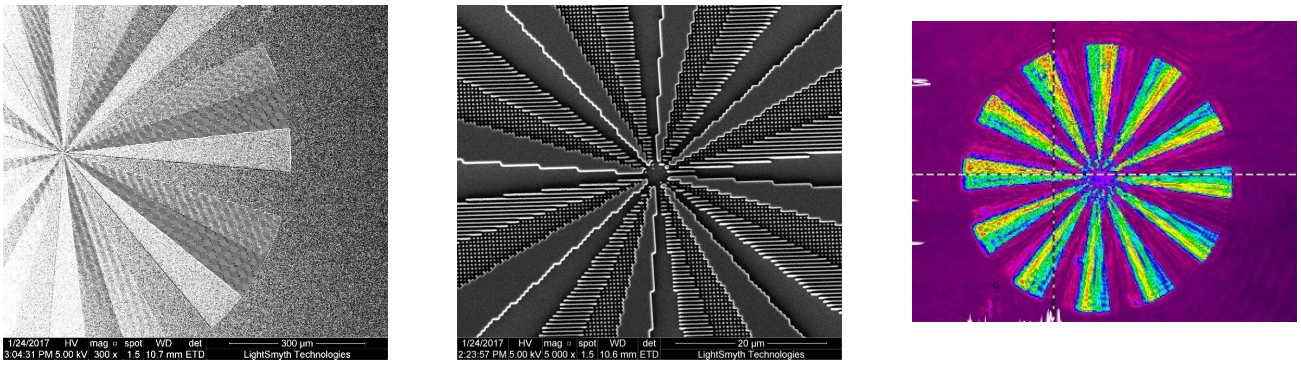

Figure 4 (left) Low magnification SEM of PEP vortex plate, (center) Higher magnification of PEP vortex plate around its center, (right) transmitted phases of PEP vortex plate transformed to color coded intensity variations in a two-beam interferometer.

In Figure 5, we display the far-field intensity distribution produced a collimated beam through the 8th order vortex plate shown in Figure 4.

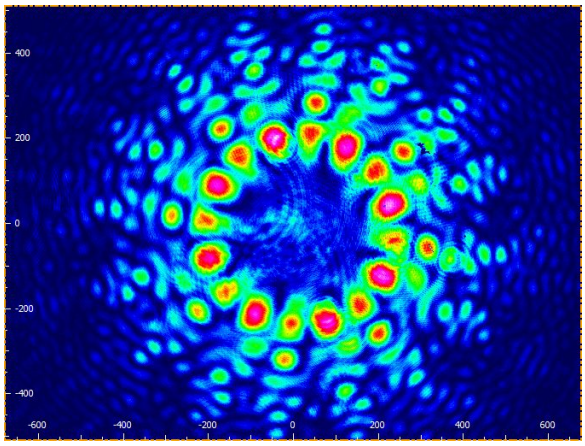

Figure 5, far-field intensity distribution from PEP 8th order vortex plate.

It will be noted that the pattern in Figure 5 comprises a ring of dots rather than a continuous ring expected with a linear and continuous azimuthal phase ramp. Simulations reveal that the appearance of dots is related not to the 4-level phase scheme employed, but to errors in the phase shifts experimentally realized for each level. In Figure 6, far-field intensity distributions are calculated for the case of a device produced with etch regions displaying the correct phase shift values (left) and for the case in which level specific phase shift errors on the order of several percent are introduced (right). It can be seen in Figure 6 (left) that the vortex realized with discrete but correct phase levels forms a smooth ring pattern whereas in Figure 6 (right) shows the discrete peaks reminiscent of the observed pattern of Figure 5. It is to be noted that Figure 6 uses 5 discrete phase levels whereas the device measured had 4 discrete phase levels. Breakdown of the smooth ring into spots occurs for a variety of phase levels if the phase levels are not fabricated correctly. It should be noted that the device characterized here did not have the benefit of etch area calibration which can be utilized to fabricate etch levels with proper phase shift levels and produce smooth ring output. It should be also noted that the peaked nature of the ring does not imply that the characteristic vortex angular momentum properties are not present.

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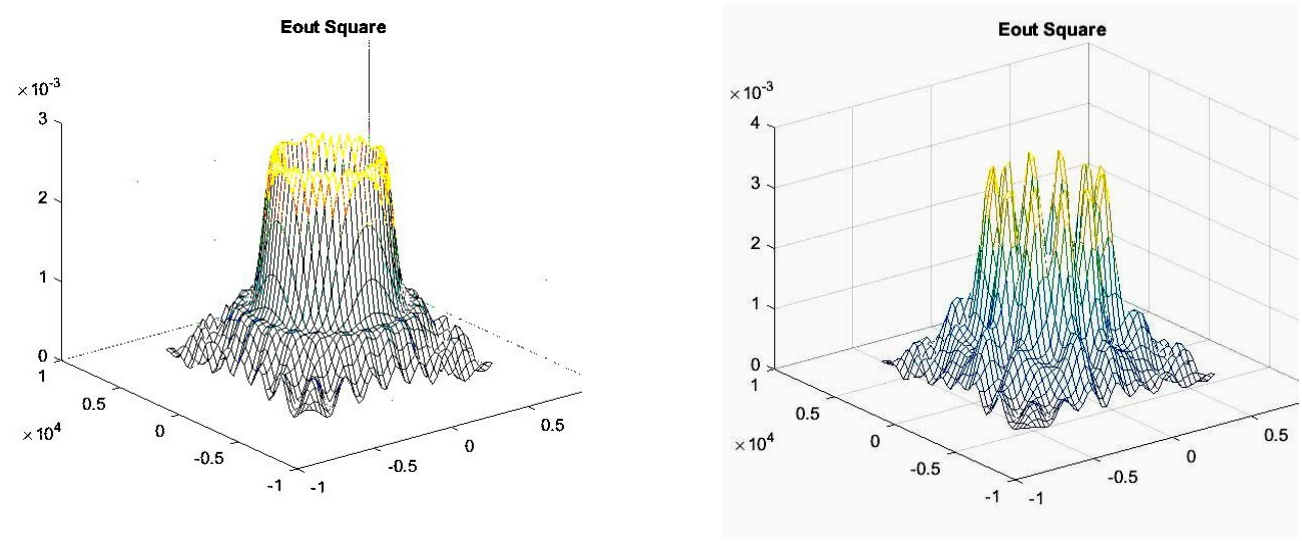

Figure 6 (left) far-field intensity pattern of a 5-phase level 6th order vortex plate with levels having design phase shift levels; (right) same as (left) expect phase levels are given small errors.

2.3 Vortex and lens function in a single PEP phase transformation

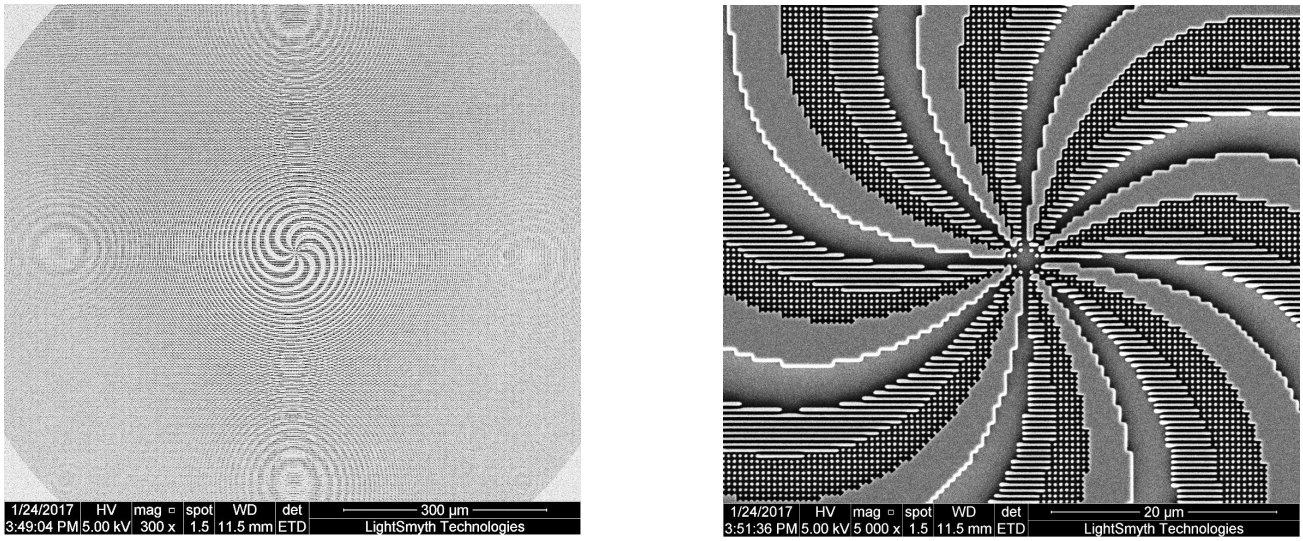

Figure 7. (left) low magnification SEM image of a PEP phase plate combining both vortex and focusing function. (right) higher magnification SEM showing spiral center of the lens-vortex PEP device. Circular structures (left) comprise moirés patterns and are not real.

Multiple optical functions can be combined on a single PEP phase transforming plate**.** This can be done simply by taking calculated phase transfer functions for say focusing, splitting, making a vortex, beam shaping, etc. and adding them together and finally defining a PEP surface whose phase shifts equal (modulo 2π) the phase shifts of the summed phase transfer functions. We have demonstrated this by designing and fabricating a PEP phase plate whose single etched surface both focuses and applies a vortex function. The fabricated lens-vortex PEP device is shown in Figure 7. Four discrete phase (etch patterns) are used. The vortex order is eight. With both lens and vortex function incorporated, the classic vortex ring intensity distribution occurs in the focal plane of the device as would be needed for example to couple

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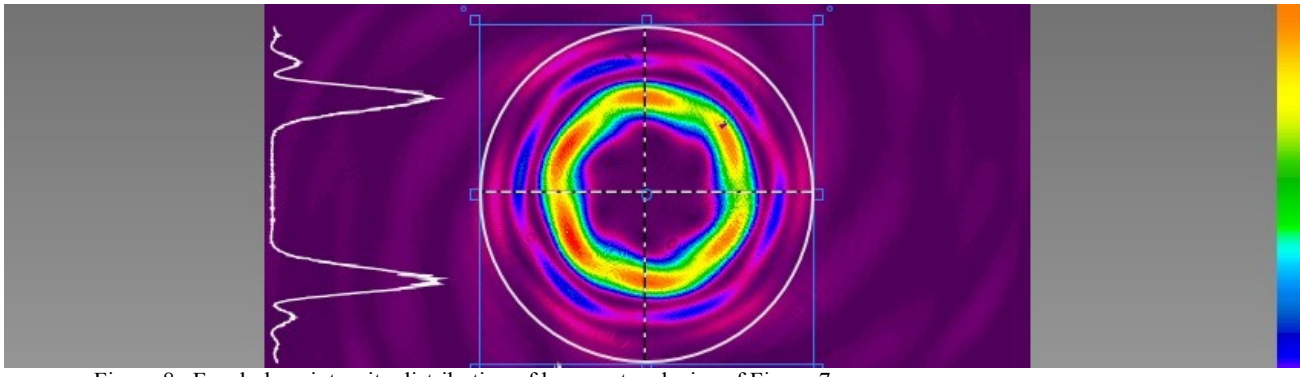

Figure 8. Focal plane intensity distribution of lens-vortex device of Figure 7.

the vortex beam into a fiber. In Figure 8, we show the transmitted intensity distribution as a function of positon in the focal plane of the lens-vortex device.

It can be seen that the ring produced is smoother than produced with the vortex plate device of Figures 4 and 5 even though phase errors of the levels is expected to be similar.

2.4 Phase Calibration

The fabricated devices described above were based on theoretical modelling of transmitted phase shift dependence on surface etch pattern. However, it is to be noted that fabricated etch patterns typically deviate somewhat from designs. Etch sidewalls and etch bias are difficult to predict a priori and can, in fact, vary dependent on the local etch pattern within a device. Accordingly, improved performance can be expected by empirically calibrating transmitted phase

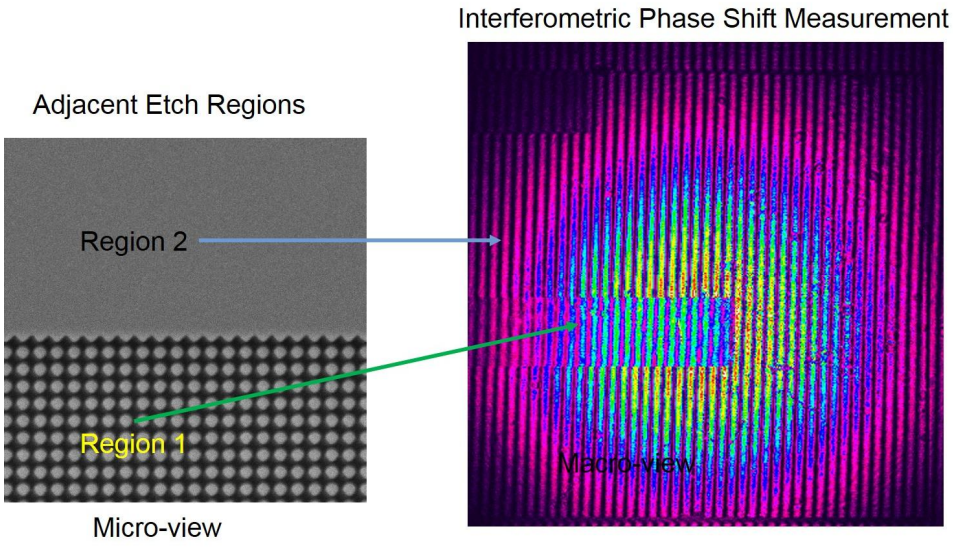

Figure 9 (left) SEM image of abutting etch patterns, (right) interferometric measurement of the relative transmitted phase shift of the regions.

shifts. Figure 9 (left) shows a boundary between a partially etched region and an etched region. The etched posts are on a 500 nm grid. Figure 9 (right) is taken on a much larger macroscopic scale using a two beam interferometer to convert regional transmitted phase shifts into a shifting of lines within the two-beam interference pattern. The precise transmitted phase achieved in fabrication can be measured and designs modified to achieve required phase shifts. Subsequent fabrication work will take advantage of calibration measurements.

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3. CONCLUSIONS

As available fabrication technology evolves, opportunities for new device classes arises. Partial etch phase (PEP) devices utilize high resolution, sub-wavelength lithography and binary etch to create transmissive phase plates with essentially arbitrary phase-space mapping. The devices can be implemented with a finite number of bin etch patterns providing discrete phase values, or with suitable lithographic resolution, continuous phase mapping (modulo 2π). Binary etch is economical and reproducible. Single layer devices with superimposed phase transfer functions providing, for example, vortex and focusing action have been demonstrated as well as single function devices providing either vortex or focusing.

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