Holey metallic lens for light focusing

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Abstract: It is experimentally demonstrated that subwavelength holes milled in a metallic film as a set of concentric circular rings can focus linearly polarized light in the visible range.
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An incident plane wave can be focused if the transmitted phase front is modified to be concave. This can be achieved by making a convex dielectric lens or by introducing a graded index in a planar dielectric slab. Recently, a set of plasmonic nano-antennas have been used to make planar and thin focusing devices [1, 2]. Nano-apertures can be used to control phase front as well. The simplest structure is an array of nanoslits milled in a metallic film [3, 4]. In short, those devices take advantage of the waveguide modes of light propagating through slits with different widths. In our recent work, it was shown experimentally that an array of nanoslits can be polarization-selective [5]. The device either focuses or diverges linearly polarized light depending on the incident polarization. The same device becomes an intensity-tunable lens if the nanoslits are filled with liquid crystals [6]. Since those devices have a one-dimensional structure, they are comparable to cylindrical lenses. One feature of such one-dimensional lenses is their strong polarization dependence.

A straightforward way to convert a one-dimensional lens into a two-dimensional lens is to mill concentric nano-rings in a metallic film. However, this idea does not work for linearly polarized light because the linearly polarized light will excite plasmonic modes as well as photonic modes depending on the orientation of the E-field relative to a nano-ring slit [7]. In order to avoid this issue, each concentric ring was discretized into holes. This structure was used to experimentally demonstrate that a set of concentric circular rings of nano-scale holes milled in a metallic film focuses light with arbitrary orientation of its linear polarization.

A hole in a metallic film can be considered as a finite-length cylindrical waveguide cladded by metal. The lowest propagating mode is the hybrid HE_{11} mode [8]. In Fig. 1, the simulated output phase of 531-nm linearly polarized light propagating through a 380-nm long cylindrical waveguide made of gold is shown. The light was incident from the glass substrate side and the hole was filled with a polymer which also forms a 200-nm thick film on top of the gold film. The calculations were done using a three dimensional spatial harmonic analysis method [9]. As shown in Fig. 1(a), the relative phase becomes larger as the hole radius becomes larger. Hence, by placing the holes with the largest radius in the center and gradually decreasing the radius of the holes in the set of concentric rings, the output light from the device can be concentrated into a tight focal spot.

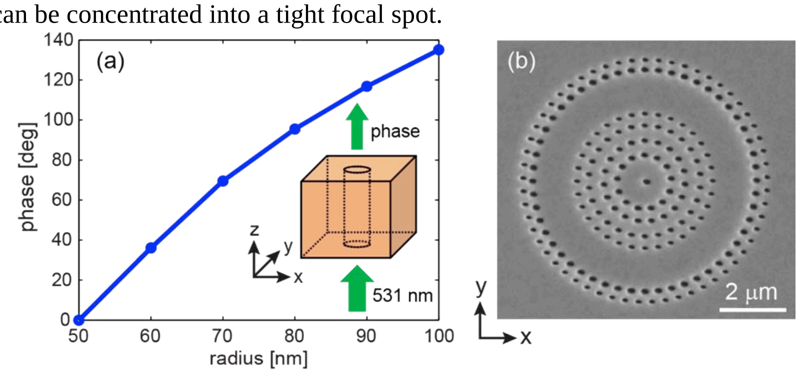

Fig. 1 (a) Numerically evaluated relative phase for linearly polarized 531-nm plane waves transmitted through a variable-radius hole in a 380-nm thick gold film in far field. (b) SEM image of the holey lens.

Computing light propagation within a volume of a few tens of micrometers requires a huge computational resource. Instead, a simple analytical model was developed based on the three dimensional Green function to estimate the focusing performance of the device. Using the reciprocity principle, a dipole point source was located which emitted light with a free-space wavelength λ_0 at the desired focal point F(0, 0, f) of the system, where f is the focal length. The phase at the sample surface $\phi(x, y, 0)$ relative to the origin O(0, 0, 0) is retrieved by taking the argument of the Green function. To model the transmission profile, a phase of $-\phi(x, y, 0)$ was assigned to each dipolar source and located at the discrete positions on the sample's metallic surface where the holes would exist. The array of phase-shifted dipoles was then used to calculate the total intensity of the focused beam.

In experiment, a 380-nm thick gold film was deposited on a glass substrate using an electron beam evaporator and a set of holes was milled using the focused ion beam. The SEM image of the sample is shown in Fig. 1(b). Then, PMMA was spin coated onto the sample which filled the holes and left a 200-nm thick layer on top of the gold film. The measurements were carried out with an optical microscope system where the sample was illuminated from the substrate side by a linearly polarized 531-nm laser source. The transmitted light was collected by a CCD camera. The details of the experimental procedure are explained elsewhere [5].

In Fig. 2, the experimental results when illuminated by two orthogonal linear polarizations are compared with the intensity plot obtained from the analytical method. The incident electric fields in Figs. 2(a) and 2(b) are along the x-axis and the y-axis, respectively. Figure 2(c) was obtained for $f = 10$ μm and $\lambda_0 = 531$-nm where the locations of the dipolar sources correspond to the center positions of the holes in Fig. 1(b). From Figs. 2(a) and 2(b), it can be seen that the device is independent of the incident linear polarizations since both plot show focusing at $z = 10$ μm. The analytical plot shown in Fig. 2(c) captures the major features of Figs. 2(a) and 2(b). Analogous to the fact that the analytical model that was previously developed for one dimensional lenses works for nanoslit lenses [5], this computationally inexpensive model is a powerful tool for optimizing the two dimensional holey metallic lenses as well.

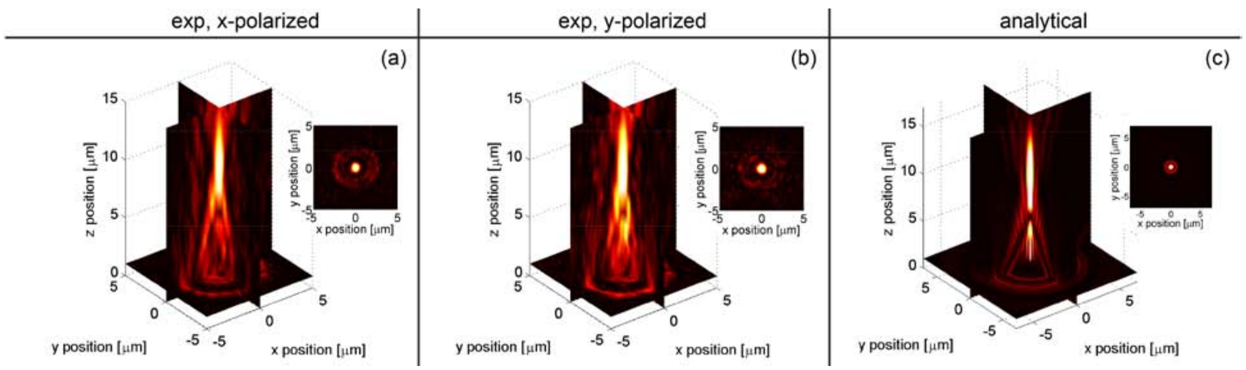

Fig. 2 Pseudo-color intensity maps from the measurements (in x-polarized light (a) and in y-polarized light) and the analytical model at 531 nm(c). The color scale is normalized to its maximum intensity. The inset shows the beam cross section at the focal point ($z = 10$ μm).

To summarize, a metallic focusing device consisting of a set of nano-holes which form concentric rings was designed, fabricated, and tested. The focusing property of the holey lens does not depend on the incident polarization angle. The device is planar and its thickness is subwavelength, it can be easily integrated with a chip or placed at the end of optical fiber.

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