Subwavelength Focusing of Light with a Slanted-Nanoaperture-Array Metal Lens

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Refraction of light at media interface forms an essential basis in imaging and beam-shaping optics. The ability to bend an incident beam into an arbitrary direction (including the negative-angle direction) would open up the possibility to develop optical components that can provide imaging functions surpassing the limits of conventional refractive optics, e.g., full-angle imaging and super-resolution imaging. In this work we have investigated the radiation pattern of nanoaperture transmission as a new degree of freedom in shaping transmission wavefronts for negative angles with well-suppressed background transmission. By employing a vertical dipole concept of nanoaperture transmission (Fig. 1) we demonstrate negative-angle refraction and subwavelength focusing (FWHM, 0.3λ) of light with a slanted-nanoaperture-array metal lens.

By forming a vertically-oriented nanoslit aperture on a metal film, the aperture radiation pattern becomes highly tilt-oriented to one side. An array of such vertical-dipole nanoslits is designed such that the transmitted radiations constructively interfere only to the direction of tilted radiation pattern, which corresponds to a desired negative-angle refraction direction. This vertical-dipole nanoslit structure was fabricated on quartz substrate by focused-ion-beam etching followed by angle deposition of metal. The transmission radiation pattern was then measured by scanning an NSOM probe in the near to far field region (Fig. 2).

For a beam focusing function the nanoslit array is designed such the nanoslit transmissions orient to a common focal point at far field and constructively interfere there (Fig. 3). Note that the resolution in imaging (i.e, a minimum spot size in focusing) is determined by the maximum transverse wave-vector available at the focal plane. In conventional lenses the glancing transmission components are of relatively minor intensity, and therefore the wave components that can reach a focal point with large transverse wave-vectors are severely limited, resulting in poor resolution. By contrast, we demonstrate that a slanted nanoaperture array can produce a sharp focus (0.3λ) at a single location in far-fields, even with use of a relatively small number of apertures (Fig. 3). This is because each nanoaperture funnels incident light into narrowly defined directions and allows glancing angle transmission through apertures, which carries maximum transverse wave-vectors.

[1] M. Kim, Y. S. Jung, Y. Xi, and H. K. Kim, Appl. Phys. Lett. 107, 101107 (2015).

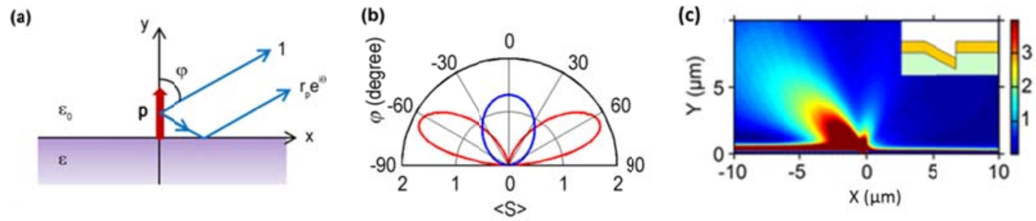

Figure 1: (a) A vertical dipole placed on metal surface. (b) Radiation patterns: a vertical dipole (red) and a horizontal dipole (blue). (c) The radiation pattern of nanoaperture transmission through a slanted (tilted vertical dipole) nanoslit formed in a metal film (FDTD simulation).

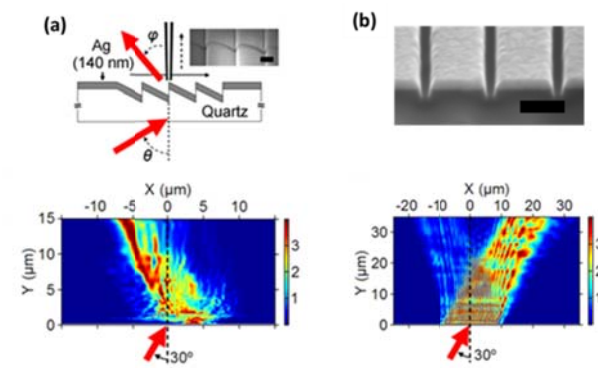

Figure 2: Transmission of light through nanoslit arrays fabricated by FIB and angle deposition: NSOM scan image measured at 633nm wavelength (TM polarized). (a) A vertical-dipole nanoslit array demonstrates negative-angle refraction with well-suppressed zero-order transmission. (b) A conventional, horizontal-dipole nanoslit array demonstrates zero-order transmission as a dominant mode.

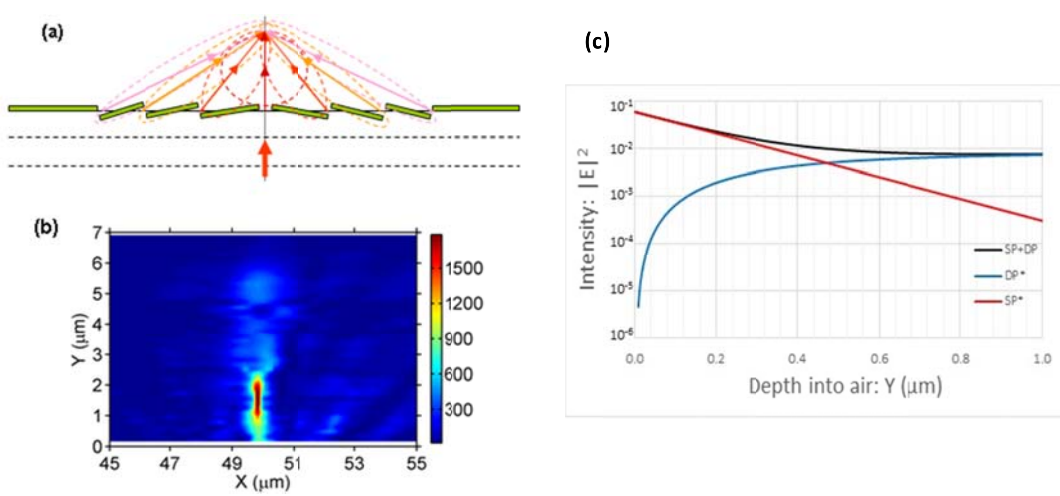

Figure 3: (a) Schematic of a slanted-nanoslit-array metal lens. (b) NSOM scan image of a beam focusing profile measured at 633nm wavelength. The laser beam is sharply focused at 1.4μm distance with a FWHM beam diameter of 0.3λ. (c) Distribution of vertical dipole field (DP) and surface plasmon field (SP) around the focal plane.