Optical Hyperlens Imaging with Resolution Go Beyond the Conventional Diffraction Limit

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Abstract: We experimentally demonstrate a new optical imaging technique based on an optical hyperlens made by metal/dielectric metamaterial. The hyperlens can magnify sub-diffraction -limited objects into far field thus opens up new possibilities for optical nano-imaging.

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The diffractive nature of light limits the resolution of the optical microscope to the order of half wavelength. This so called diffraction limit arises from the missing evanescent wave components at the far-field that carry high spatial frequency information of the object. A slab of silver superlens shows sub-diffraction-limited resolution of $\lambda/6$ utilizing an evanescent wave enhancement mechanism [1-4], however it does not magnify the sub-wavelength features and the fine resolution image is restricted in the near field. Recently, theories of optical hyperlens [5] and metamaterial crystal superlens [6] using anisotropic medium have been proposed. Such devices have interesting hyperbolic dispersion such that ordinary evanescent waves become propagating along radial direction of the layered metamaterials. This provides a possibility to realize sub-diffraction limited imaging in the far-field.

For the first time, we experimentally demonstrated such a magnifying hyperlens [7, 8]. The optical hyperlens consists of curved multilayer of Ag (35 nm)/Al_2O_3 (35 nm) deposited on a half-cylindrical cavity fabricated on quartz substrate (Fig 1). Sub-diffraction-limited objects are inscribed into a 50 nm thick chrome layer located at the inner surface (air side). The anisotropic metamaterial is designed to have sign effective permittivity in the radial direction and negative effective permittivity in the tangential directions, demonstrating a hyperbolic dispersion relationship. Upon the light illumination, scattered evanescent field from the object enters the anisotropic medium and become propagating along the radial direction. As the angular momentum has to be conserved, the tangential wave vectors are progressively compressed when the waves travel outwards, resulting in a magnified image at the outer boundary of the hyperlens. If the magnified features go beyond the diffraction limit, they can be imaged by conventional optics such as an optical microscope at the far-field. In Fig. 1 (a) we show the calculated electromagnetic field distribution in and after the metamaterial hyperlens using the actual material properties. Obviously, the image is magnified.

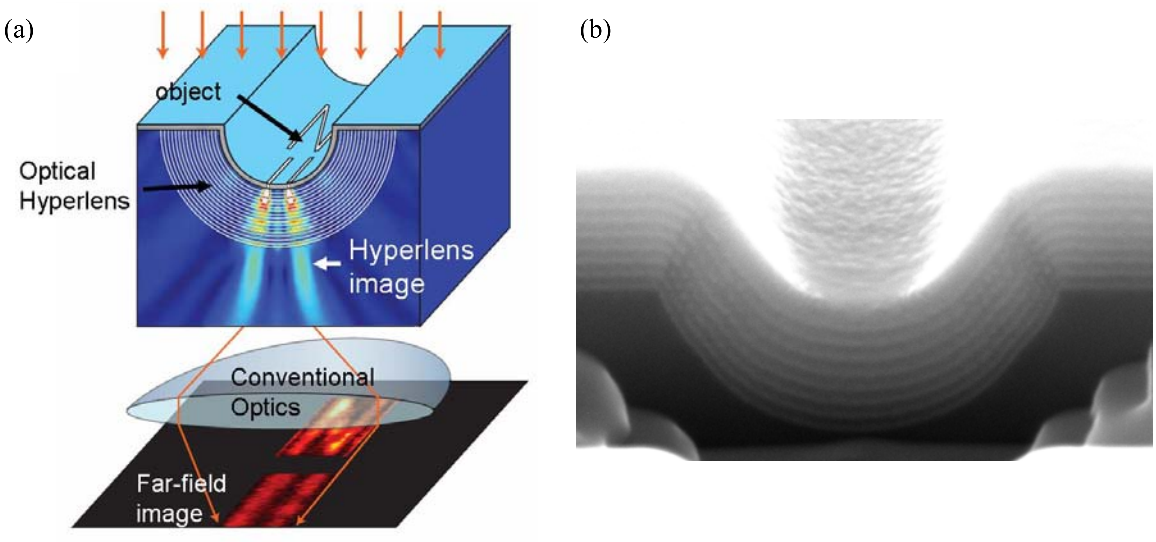

Figure 1. (a) Schematic of an optical hyperlens for far-field imaging beyond the diffraction limit. The sub-diffraction-limited object can be magnified into a diffraction limited image by the hyperlens and then interfaced with conventional optics to the far-field. The optical hyperlens is made by 16 layers of silver /Al_2O_3 multilayer. (b) A cross-sectional SEM image of a hyperlens.

In our experiment, an object of a 35 nm wide line pair with 130 nm spacing (see SEM image in Fig. 2a) is imaged through the hyperlens using a mercury lamp i-line illuminator (λ=365nm). The magnified image taken by a classical optical microscope (NA=1.4) clearly resolves the object with sub-diffraction-limited resolution (Fig. 2b). The hyperlens provides additional 2.3 time magnification and directly projects a sub-diffraction-limited image to the far-field. In the control experiment, the same object is imaged without the hypelens. Obviously, the line pair could not be resolved due to the diffraction limit (λ/NA =260 nm) (Fig. 2c, blue curve). Because the hyperlens supports the transformation of very broad spectrum of wave vectors, it can magnify arbitrary objects with sub-diffraction-limited resolution. The current cylindrical hypelens only provides magnification along one direction according to the geometry. However, the same principle can be applied to a spherical geometry that can magnify sub-diffraction-limited object in two dimensions. Unlike near field optical microscope that uses a sharp tip to scan an object, optical hyperlens magnifies and projects a sub-diffraction-limited image directly into far field.

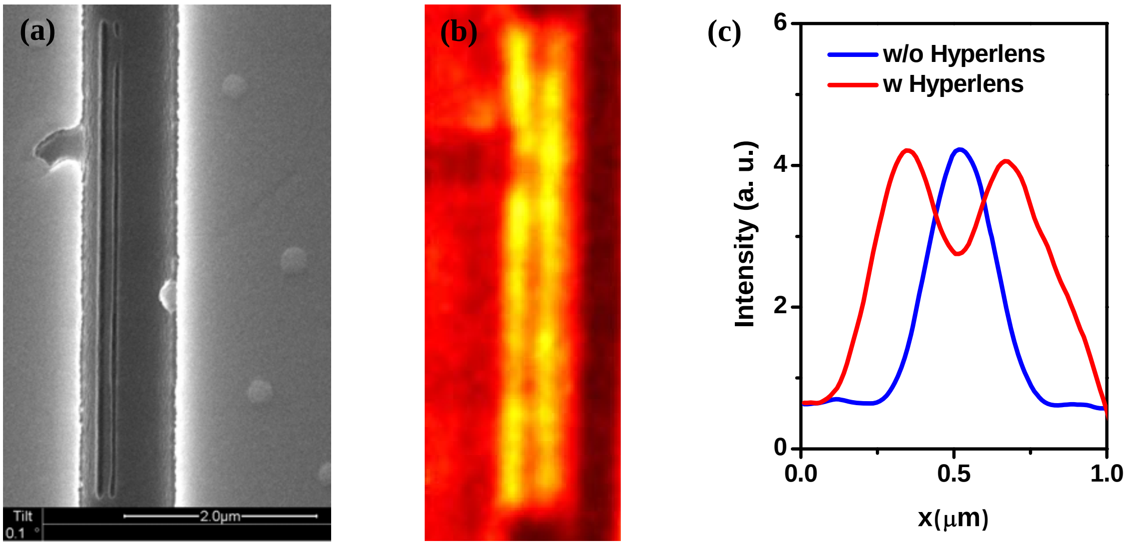

Figure 2. Hyperlens imaging of a line pair object with line width of 35 nm and spacing of 130nm. (a) SEM image of a line pair object fabricated in the inner side of the hyperlens. (b) The hyperlens image shows the 130nm spaced object can be clearly resolved in the far-field. (c) Comparison of the optical image with and without the hyperlens. The control optical image using conventional optical microscope with N. A. =1.4 can not resolve the line pair object.

In summary, we experimentally demonstrated the first optical hyperlens for sub-diffraction-limited imaging in the far-field. The device magnifies the objects by transforming the originally evanescent waves into the propagation waves in a highly anisotropic metamaterial, projecting a high resolution image at the far-field. The optical hyperlens opens up new possibilities for optical imaging at deep subwavelength nanometer scale.

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