Magnifying Sub-diffraction-limited Objects by an Optical Metamaterials Hyperlens

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Abstract: We experimentally demonstrate the first optical hyperlens made by metal/dielectric metamaterial which is able to magnify sub-diffraction-limited objects. Hyperlens opens up new possibilities for optical nano-imaging in the far-field.

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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]. 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 opposite signs of its effective permittivities in the radial and the tangential directions demonstrating a hyperbolic dispersion. Upon the light illumination, scattered evanescent field from the object enters the anisotropic medium and become propagating along the radial direction. Due to the conservation of angular momentum, the tangential wave vectors are progressively compressed when the waves travel outwards, resulting in a magnified image at the outer boundary of the hyperlens. Once the magnified features become larger than the diffraction limit, it can be imaged by conventional optics such as an optical microscope at the far-field. In Fig. 1 we show the calculated electromagnetic field distribution in and after the metamaterial hyperlens using the actual material properties. Obviously, the image is magnified.

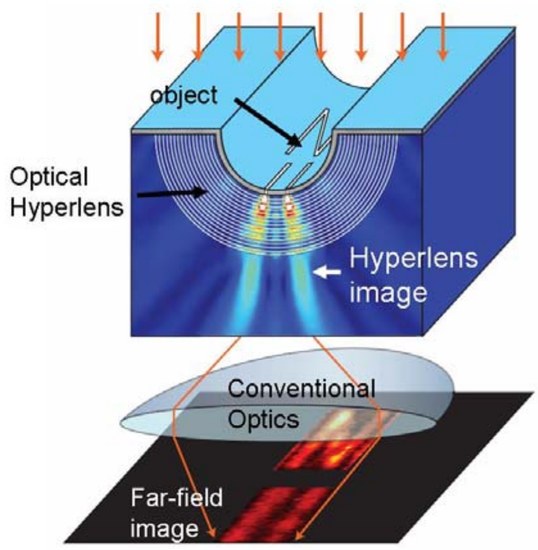

Figure 1. Schematic of an optical hyperlens for sub-diffraction-limited imaging in the far-field. The optical hyperlens is made by a metal/dielectrics multilayer metamaterial. The sub-diffraction-limited object can be magnified into a diffraction limited image by the hyperlens and then interfaced with conventional optics to the far-field.

In our experiment, an object of a 35 nm wide line pair with 150 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). This demonstrates that the hypelens is capable of magnifying (the magnification is about 2.3 in this case) and projecting a sub-diffraction-limited image to the far-field. In the control experiment, the same line pair object is imaged without the hypelens. The line pair could not be resolved due to the diffraction limit (λ/NA =260 nm) (Fig. 2c). Because the hyperlens supports the transformation of very broad spectrum of wave vectors, it can magnify arbitrary objects with sub-diffraction-limited resolution. As an example, the image of the nanometer scale letters “ON” shows the fine features of the object with the sub-diffraction resolution of 200 nm (Fig. 2d, e). Though this work deals with the cylindrical hypelens, it is possible to design a spherical hyperlens that can magnify sub-diffraction-limited object in three dimensions. Unlike near field optical microscope that uses a sharp tip to scan the object, optical hyperlens magnifies and projects a sub-diffraction-limited image.

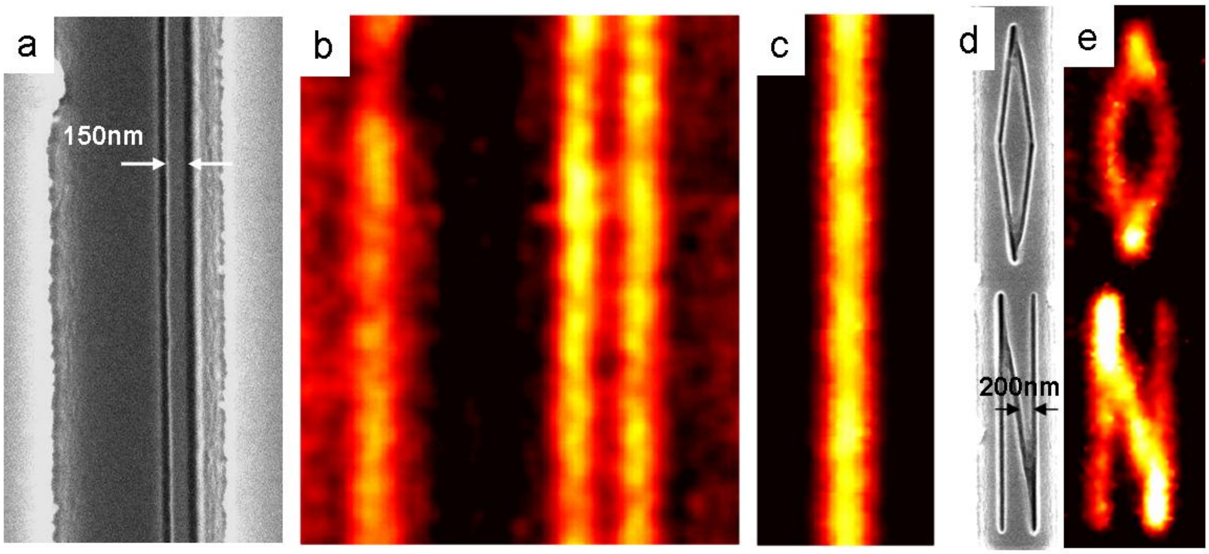

Figure 2. (a), (b), and (c) Hyperlens imaging of a line pair object with line width of 35 nm and spacing of 150nm. (a) SEM image of line pair object fabricated in the inner side of the hyperlens. (b) The hyperlens image shows the 150nm spaced object can be clearly resolved in the far-field. (c) Control optical image using conventional optical microscope with N. A. =1.4 can not resolve the line pair object. Another example with an arbitrary object "ON" imaged by (d) SEM and by (e) hyperlens. The line width of the "ON" object is about 40nm. The hyperlens is made of 16 layers of Ag/Al_2O_3.

To summarize, this experiment demonstrates 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 an anisotropic metamaterial, projecting a high resolution image at the far-field. The optical hyperlens opens up new possibilities for optical nano-imaging and may lead to numerous applications such as real time bio-molecular imaging and nano-lithography.

References

1. J. B. Pendry, Phys. Rev. Lett. 85, 3966 (2000).
2. N. Fang, H. Lee, C. Sun and X. Zhang, Science 308, 534 (2005).
3. D. O. S. Melville, R. J. Blaikie, Opt. Exp. 14, 2127 (2005).
4. T. Tauber, D. Korobkin, Y. Urzhumov, G. Shvets, R. Hillenbrand, Science 313, 1595 (2006).
5. Z. Jacob, L. V. Alekseyev, and E. Narimanov,, Opt. Exp. 14, 8247 (2006)
6. A. Salandrino, N. Engheta, Phys. Rev. B 74, 075103 (2006).
7. Z. Liu, H. Lee, Y. Xiong, C. Sun, and X. Zhang, to appear in Science (2007).