Far-Field Optical Hyperlens Magnifying Sub-Diffraction-Limited Objects

Zhaowei Liu,* Hyesog Lee,* Yi Xiong, Cheng Sun, Xiang Zhang†

The diffraction limit of light, which is caused by the loss of evanescent waves in the far field that carry high spatial frequency information, limits the resolution of optical lenses to the order of the wavelength of light used to image the object. Projecting a sub-diffraction-limited image into the far field would require recovery of the evanescent waves. A metamaterials-based superlens offers that possibility (*1*). Although slablike superlenses have demonstrated sub-diffraction-limited resolution (*1*–*4*) imaging in the near field, magnification of subwavelength features into the far field has not been possible. It was proposed that a magnifying superlens could be constructed by using cylindrical metamaterials (*5*, *6*). Recent theoretical studies on an optical hyperlens and a metamaterial crystal superlens have proposed the use of an anisotropic medium with a hyperbolic dispersion such that ordinary evanescent waves propagate along the radial direction of the layered metamaterial (*7*–*9*). Microscopically, the large spatial frequency waves propagate through coupled surface plasmon excitations between the metallic layers (*10*, *11*).

We demonstrate a magnifying optical hyperlens consisting of a curved periodic stack of Ag (35 nm) and Al_2O_3 (35 nm) deposited on a half-cylindrical cavity fabricated on a quartz substrate (Fig. 1A). Sub-diffraction-limited objects were inscribed into a 50-nm-thick chrome layer located at the inner surface (air side). The anisotropic metamaterial was designed so that the radial and tangential permittivities have different signs. Upon illumination, the scattered evanescent field from the object enters the anisotropic medium and propagates along the radial direction. Because of the conservation of angular momentum, the tangential wave vectors are progressively compressed as the waves travel outward, resulting in a magnified image at the outer boundary of the hyperlens (*7*). Once the magnified feature is larger than the diffraction limit, it can then be imaged with a conventional optical microscope. We calculated the electromagnetic field in a metamaterials hyperlens by using the actual metal loss (Fig. 1A).

In our experiment, the object imaged with the hyperlens was a pair of 35-nm-wide lines spaced 150 nm apart (Fig. 1B). The magnified image (350-nm spacing) can be clearly resolved with an optical microscope [numerical aperture (NA) = 1.4], thus demonstrating magnification and projection of a sub-diffraction-limited image into the far field. In a control experiment, the line pair object was imaged without the hyperlens. The line pair could not be resolved because of the diffraction limit (λ/NA = 260 nm) (Fig. 1, B and C). Because the hyperlens supports the propagation of a very broad spectrum of wave vectors, it can magnify arbitrary objects with sub-diffraction-limited resolution. The recorded image of the letters "ON" shows the fine features of the object (Fig. 1D). The subdiffraction resolution of 130 nm was achieved (fig. S1). Although this work deals with the cylindrical hyperlens, it should be possible to design a spherical hyperlens that can magnify in three dimensions. Unlike near-field optical microscopy that uses a tip to scan the object, our optical hyperlens magnifies a sub-diffraction-limited image and projects it into the far field.

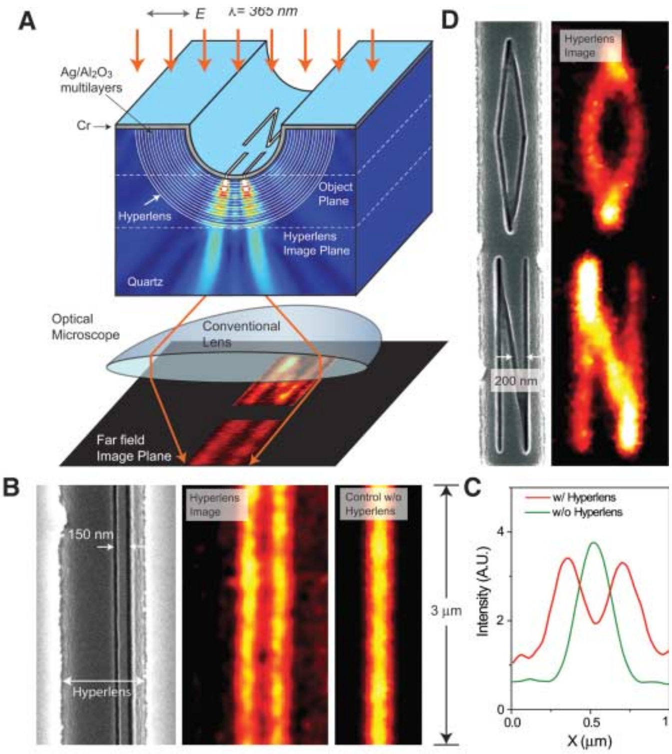

Fig. 1. Magnifying optical hyperlens. (**A**) Schematic of hyperlens and numerical simulation of imaging of sub-diffraction-limited objects. (**B**) Hyperlens imaging of line pair object with line width of 35 nm and spacing of 150 nm. From left to right, scanning electron microscope image of the line pair object fabricated near the inner side of the hyperlens, magnified hyperlens image showing that the 150-nm-spaced line pair object can be clearly resolved, and the resulting diffraction-limited image from a control experiment without the hyperlens. (**C**) The averaged cross section of hyperlens image of the line pair object with 150-nm spacing (red), whereas a diffraction-limited image obtained in the control experiment (green). A.U., arbitrary units. (**D**) An arbitrary object "ON" imaged with subdiffraction resolution. Line width of the object is about 40 nm. The hyperlens is made of 16 layers of Ag/Al_2O_3.

This experiment demonstrates the capability of a hyperlens for sub-diffraction-limited imaging. The hyperlens magnifies the object by transforming the scattered evanescent waves into propagating waves in the anisotropic medium, projecting a high-resolution image into the far field. The optical hyperlens opens up exciting possibilities in applications, such as real-time biomolecular imaging and nanolithography.

References and Notes

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Supporting Online Material

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Materials and Methods
Fig. S1

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5130 Etcheverry Hall, NSF Nanoscale Science and Engineering Center (NSEC), University of California, Berkeley, CA 94720–1740, USA.

*These authors contributed equally to this work.

†To whom correspondence should be addressed. E-mail: xiang@berkeley.edu