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FAR-FIELD SUPERLENS Optical Nanoscope

Breaking the diffraction limit for the resolution of conventional optical systems has long been the primary aim of optical imaging. The recently demonstrated far-field optical superlens is paving the way to this elusive goal.

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nvented most probably by Galileo Galilei, named by Giovanni Faber, improved and brought to the attention of biologists by Robert Hooke and Anton van Leeuwenhoek, and perfected by Ernst Abbe, the light microscope revolutionized life sciences and was a key instrument to the advancement of knowledge in many areas. It is perhaps the most important single piece of scientific apparatus in the history of mankind. Even today, nearly 400 years since its invention, the optical microscope remains indispensable, as focused light is the only way to examine living cells non-invasively.

As first demonstrated by Abbe in 1873¹, the resolution of a conventional optical microscope is constrained by the wavelength of light - something which is generally referred to as the 'diffraction limit'. Although information about small (subwavelength) features of the object are present in so-called scattered evanescent waves, these waves decay exponentially with distance and are only detectable in the near field. In the far field, the loss of these evanescent waves and the information that they contain, precludes reconstructing an image of an object with a resolution better than half the incident wavelength.

Although near-field scanning optical microscopy² can detect evanescent fields through an optical probe placed in the direct vicinity of the object, the approach has limitations. The information is collected on a 'point-by-point' basis, which is a slow process and does not allow direct projection of real-time images. Similar issues limit the usefulness of other subwavelength imaging methods, such as those based on nonlinear optics³ and stimulated emission depletion⁴.



Figure 1 The schematics of the FSL. The evanescent waves are enhanced in the metal layer, owing to their resonant coupling to surface plasmons, and then scattered into the propagating band by the subwavelength grating at the top surface. The device provides an improvement on point-to-point imaging techniques, such as near-field scanning optical microscopy, but still requires close proximity between the lens and the object. Reproduced with permission from ref. 8, copyright (2007) ACS.

However, the illusive goal of an optical 'nanoscope' — a device capable of direct imaging of subwavelength structures (as opposed to point-by-point scanning) - was suddenly brought to the realm of device engineering when John Pendry proposed the concept of the 'superlens'5. Such a superlens is capable of enhancing evanescent waves and thus leading to the recovery of the information they carry. This enhancement originates from the resonant coupling of the evanescent waves to surface plasmons, and when the decay of evanescent waves in free space is compensated for, a nearly perfect image can be recovered⁶.

However, this balance between the decay of evanescent waves in free space and the resonant enhancement of surface excitations is also the Achilles heel of the superlens. Any limit on the efficiency of the surface-excitation enhancements (for example, the material losses) severely limits the imaging distance, and the planar superlens appears 'near-sighted'⁷.

To deliver the subwavelength information recovered by the superlens, this information first needs to be imprinted onto the propagating (rather than exponentially decaying) waves. It is this critical ingredient for the creation of a future optical nanoscope that was recently introduced by the researchers from Berkeley in their 'far-field optical superlens'⁸.

The far-field superlens (FSL) proposed in ref. 8, is a slab superlens with periodic corrugations on its outer surface (Fig. 1). The FSL used in the experiments of ref. 8, consists of a 34-nm-thick silver slab surrounded by polymethyl methacrylate, beneath 2 layers of periodic silver corrugations, each with a height of 55 nm and a periodicity of 100 nm (one immediately

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on top of the slab surface, and the other above, shifted by half a period). The evanescent field from the object first couples to the surface plasmons supported by the superlens, resulting in a substantial field enhancement — just as in an 'ordinary' (planar) superlens. However, the enhanced evanescent components are then scattered by the surface corrugations. With the proper design of corrugation period, the enhanced evanescent components can be converted by the surface corrugations into a propagating wave that is able to reach the far field.

To test the performance of their farfield superlens, Zhaowei Liu and colleagues imaged several subwavelength patterns with different geometries - from onedimensional arrays formed by chromium nanowires to pairs of lines. Figure 2a shows an example of a line pair - two lines, each 50 nm wide and separated by a 70-nm gap. As expected, optical imaging with a conventional optical microscope cannot resolve the line pair owing to the diffraction limit (Fig. 2b). Neither can imaging with s-polarized light as it does not couple to surface plasmons in the metal slab, and therefore is not enhanced (Fig. 2c). In contrast, under p-polarization, the evanescent waves from the object are strongly enhanced by the excitation of surface plasmons in the silver superlens, and are subsequently converted into measurable propagating waves in the far field. Combining the evanescent components from p-polarized illumination with the propagating components from s-polarized illumination, the pair of lines of 50 nm width can be clearly imaged (Fig. 2d).

The essentially one-dimensional pattern of surface corrugations in the FSL demonstrated in ref. 8, can only lead to light scattering in one direction. As the scattering on the surface corrugations is critical for the performance of the FSL, Liu and colleagues focused on imaging subwavelength one-dimensional structures. However, as they pointed out, this is not a fundamental problem. With a more complicated (and essentially two-dimensional) pattern of surface corrugations, the scattering of the evanescent to propagating waves can be achieved in all directions.



Figure 2 Far-field imaging of a subwavelength pattern. **a**, Scanning electron microscope image of a pair of nanowires with a 50-nm-wide slit separated by a 70-nm gap. When illuminated by 377-nm-wavelength light, the structure is not resolved by **b**, a conventional microscope or by **c**, the FSL operating under s-polarization. However **d**, using FSL with both p- and s-polarized light clearly resolves the object. The length of the scale bar is 200 nm. Reproduced with permission from ref. 8, copyright (2007) ACS.

Of much greater importance is the other limitation of the FSL: although the image is projected into the far field, the lens itself must be in the near vicinity of the object. But as opposed to scanning point-to-point techniques, such as near-field scanning optical microscopy, the FSL has several critical advantages, especially for applications in biomedical sensing and imaging. Being essentially a projection lens, the FSL does not require a time-consuming scanning process, enables fast and dynamic imaging - especially for biologically related applications - and can operate at low illumination intensities.

With their recent work, Liu and colleagues established an important milestone towards the optical nanoscope:

subwavelength objects can now be optically magnified and projected into the far field. Although the ultimate problem of optical imaging — the difficulties in devising a nanoscope that can operate at a long distance from the object — is not yet fully overcome, Zhaowei Liu and colleagues have brought us a step closer to that goal.

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