Far-field Metamaterial Superlens

Guanghui Yuan,1\* Katrine Rogers,2 Edward T. F. Rogers,3,4 and Nikolay I. Zheludev1,3

1Centre for Disruptive Photonic Technologies, TPI, SPMS, Nanyang Technological University, Nanyang Link 21, 637371, Singapore

*2School of Mathematics and Statistics, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK*

3Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Southampton, United Kingdom

*4Instiute for Life Sciences, University of Southampton, Southampton, United Kingdom*

Author e-mail address: \*[ghyuan@ntu.edu.sg](mailto:ghyuan@ntu.edu.sg)

**Abstract:** We demonstrate a radically new type of metamaterial ‘super-lens’ that exploits the phenomenon of super-oscillations, giving a smallest hotspot size of 0.33λ and effective numerical aperture as high as 1.52 in air.

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The next disruptive step in nanoscale imaging since the invention of the acclaimed stimulated emission depletion and single-molecule microscopies will be the development of a far-field super-resolution label-free technique. In this work, using the phenomenon of super-oscillations, we propose and demonstrate a new type of far-field metamaterial ‘superlens’ which beats the Abbe-Rayleigh diffraction limit without engaging the evanescent wave contributions. Hotspots as small as 0.33λ corresponding to an effective numerical aperture of 1.52 are resolutely confirmed in air, compared with a conventional lens with the same diameter and focal distance giving diffraction limited hotspot size of 0.55λ.

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Figure 1. Schematics to design the metamaterial ‘superlens’. Typical features of two-dimensional super-oscillatory focus beyond the diffraction limit: a mainlobe surrounded by halo rings. FWHM: full width at half maximum; FOV: field of view defined as the diameter where the sideband intensity is less than 25% of the central hotspot.

Super-resolution optical imaging began with scanning near-field optical microscopy (SNOM) [1] that registers the evanescent field of the object. Providing unprecedented nanoscale level of resolution, near-field techniques have one very important limitation: the object has to be in nanoscale proximity of the near-field probe. This forbids imaging inside cells, for instance. A number of other techniques that target recovery and registration of the evanescent field have been suggested, most notably the Veselago-Pendry “super-lens” that using a slab of negative index metamaterial to recover evanescent waves of the object into the image plane [2]. However, implementation of these techniques faces substantial technological challenges.

Far-field super-resolution imaging is also possible with light diffracted on a precisely tailored mask that forms in the far-field extremely rapid local variations of electromagnetic fields, known as optical super-oscillations where band-limited functions can locally oscillate much faster than their highest Fourier components of their spectra within finite intervals. This phenomenon was explained by M. V. Berry that in the Wigner representations the local Fourier transform can have both positive and negative values, which causes subtle cancellations in the Fourier integration over all of the function [3]. Experimental observation of the phenomenon was firstly demonstrated on diffraction of coherent light on the quasi-crystal array of nanoholes in a metal screen [4] and its potential for super-resolution imaging without evanescent fields was soon recognized [5].

Here we propose, fabricate and characterize a radically new type of metamaterial ‘super-lens’ that for the first time allows full control of intensities and phases of the scattered waves and – in principle – can create a hotspot of arbitrary small size and shape. It is a planar array containing thousands discrete sub-wavelength plasmonic metamolecules set in cylindrical symmetry. Here individual metamolecule has scattering characteristics tailored in such a way that their array creates a large number of interfering waves converging into a super-oscillatory focus with size that is considerably smaller than that allowed by the Abbe-Rayleigh limit.

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Figure 2. (a) SEM image of a metamaterial ‘superlens’. (b) Theoretical and experimental focusing behaviour of different metamaterial ‘superlens’ for a combination of FWHM=0.56λ, 0.44λ, 0.39λ, 0.33λ, 0.28λ and FOV=1.0λ and 1.6λ.

To design the metamaterial ‘super-lens’ (see Fig. 1) we first constructed the desired super-oscillatory focus using band-limited functions so that it can be formed by the interference of free-space waves. We then defined the planar amplitude and phase mask necessary to create such waves diffracted on it forming the focus by multiple-wave interference. Finally we defined the metamaterial with a discrete array of sub-wavelength plasmonic metamolecules with individual scattering characteristics matching the local amplitude and phase profiles of the mask.

The super-oscillatory masks were fabricated by focused ion beam milling into a 100-nm thickness gold film deposited on glass substrate. An exemplified metamaterial ‘superlens’ is given in Fig. 2(a). Their focusing performance is characterized by a customized dual-mode microscope and the diffraction patterns at different propagation distances are captured by a high-resolution camera. The patterns in the focal plane are summarized in Fig. 2(b), which show excellent agreement with simulation. Free-space lenses with yet unattainable effective numerical aperture as high as 1.52 and foci ranging from 0.56λ to 0.28λ in size are experimentally demonstrated.

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