LETTERS
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# Subwavelength light focusing using random nanoparticles

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**There has been an escalation in interest in developing methods to control the near field because of its role in subwavelength optics. Many novel ideas have emerged in the field of plasmonics[1], super-resolution optical imaging[2–5] and lithography[6], among others. However, the near field generated in plasmonic metamaterials is fundamentally restricted by their predesigned structure, and super-resolution optical techniques do not directly control the near field. Here, we achieve direct control of the optical near field by shaping the wavefront impinging on turbid media consisting of random nanoparticles. The linear relation between input far field and scattered output near fields allows us to coherently control the near field at arbitrary positions. Direct control of the near field through scattering control offers novel approaches for subwavelength optics and may have direct applications in bio- and nanophotonics.**

Since the invention of the optical lens about 3,000 years ago, the field of optics has not only had an impact in daily life, but also in almost all areas of science and technology, including imaging, medical diagnosis and treatment, communications and manufacturing. With a conventional lens, typically made of transparent refractive materials, one can easily manipulate light with a large degree of freedom. However, it is difficult to control light on the subwavelength scale, where conventional optical components fail due to the inaccessibility of the near-field waves. A major constraint of all techniques operating in the far field is the diffraction limit; indeed, the smallest focus that can be made is ~250 nm for visible light. This is because the information regarding the fine features of an object (or focus) is carried in the evanescent near fields. Inaccessibility to the near fields is unfortunate because there are enormous potentials to be exploited in the subwavelength regime, which is the realm of cells, biomolecules, nanostructures and devices.

The near field, as the terminology implies, is bound to distances comparable to the wavelength of light because of its decaying nature upon propagation. This property restricts direct measurement of the near fields using conventional optics placed at distances much greater than 10λ from the object of interest. It is for the same reason that conventional optics fail in the formation of a subdiffraction-limited focus. For the focus to become arbitrarily smaller, higher-spatial-frequency components of the angular spectrum that are not contained in the propagating far fields must be available. This is only possible when the near fields, which contain information regarding the high spatial frequencies, are efficiently delivered to the target focus, which is impossible using conventional optics.

In optical imaging, super-resolution techniques have been developed that make use of single particle localization[2,5] or artificially limit the fluorescing area to a size smaller than the diffraction limit[3]. These methods produce stunning images by using clever techniques that overcome the diffraction limit by using single-molecule-based localization approaches[2,5] or special illumination patterns[3,4]. Direct control of the near fields to create a sub-diffraction-limited optical focus has not yet been demonstrated using conventional refraction-based optical systems; indeed, it has only been shown using a subwavelength aperture, as in near-field scanning optical microscopy (NSOM)[7], or by developing novel metallic optical elements based on metamaterials. Several techniques based on transformation optics and metamaterials have been proposed to directly probe the near field[8], where the specifically designed metamaterials impose boundary conditions that amplify the evanescent field[9] or magnify and convert the near field into far-field components[10]. Recent related work[11] has demonstrated the active control of plasmonic hotspots, but only the scattered far fields of the extended propagating plasmonic modes were investigated. A disadvantage of techniques that utilize plasmonic metamaterials is that the plane of imaging or where the focus can be placed is fixed by the physical structure. The required precision in design and fabrication is stringent, and the applicable bandwidth is restricted due to its resonant nature. In many cases, the object of interest also has to be imprinted onto the metamaterial itself, which complicates practical applications.

Here, we present a method for the direct and dynamic control of near-field subwavelength optics. Exploiting multiple scattering in random nanoparticles, we demonstrate focusing beyond the diffraction limit by controlling the far-field wavefront. In analogy with recent work in microwaves[12], we use elastic light scattering from a highly turbid medium to efficiently convert propagating far-field components into near-field wave vectors. During propagation through turbid media, each scattering event effectively scrambles an incident wave vector **k** into multiple output **k** values that contain both far- and near-field components. The scattering events accumulate in an unbiased avalanche, which results in a random distribution of **k** at the output surface of the scattering medium. The random scrambling of the phases of each **k** results in granular speckles, where the smallest size of the speckle is limited by the numerical aperture (NA) of the detection system. However, when an NSOM is used to observe the same speckle pattern, the average speckle size can be seen to be at subwavelength

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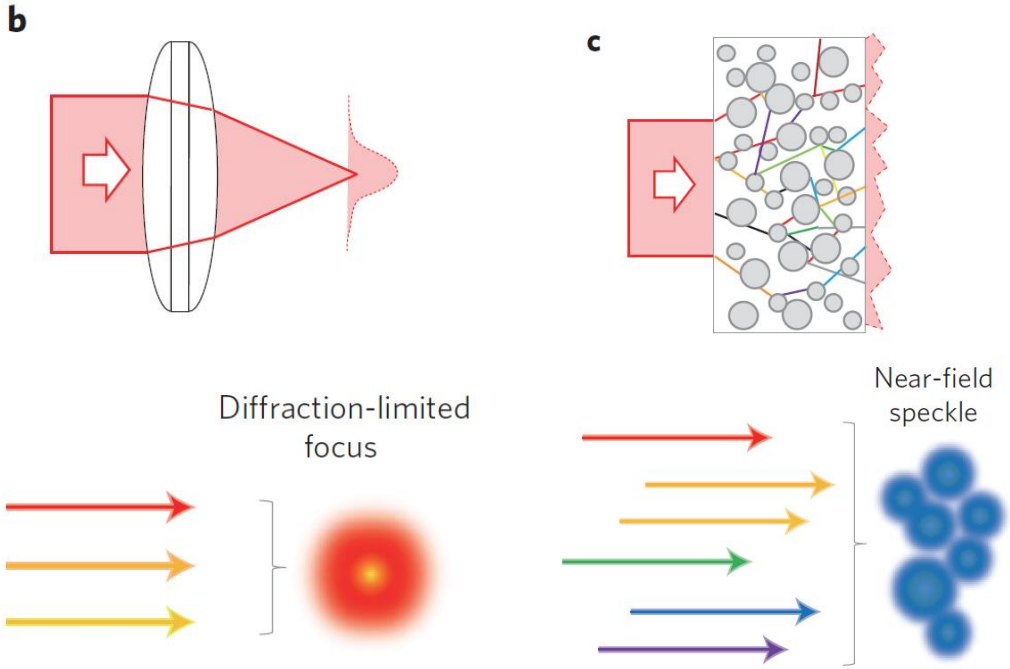
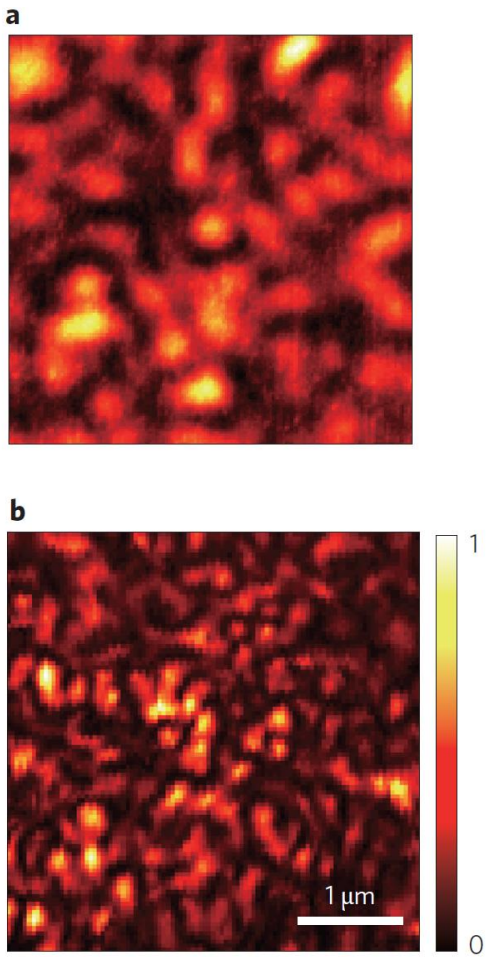
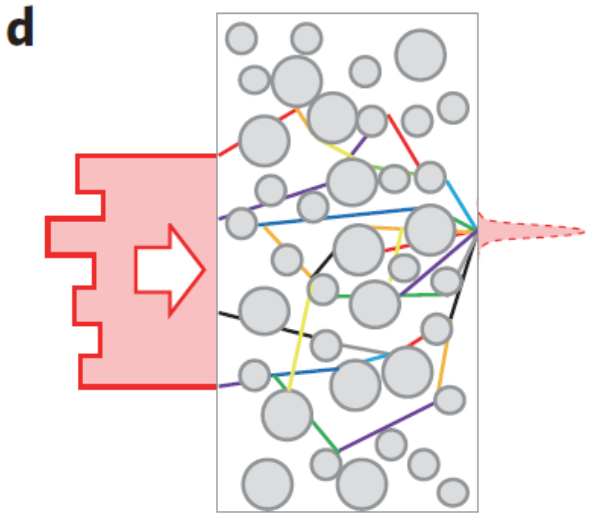
# Scattering control



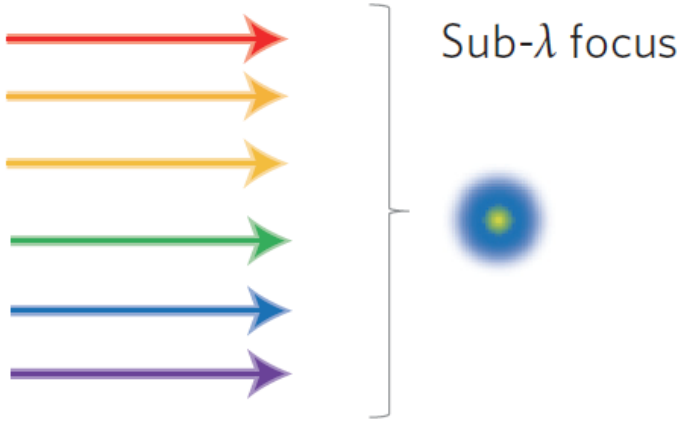

Far- and near-field components of the speckle field generated from multiple scattering in random nanoparticles.

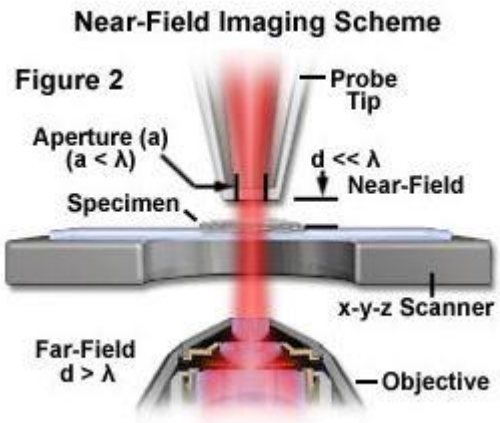
# Phase matching




When the impinging wavefront is controlled at a target position

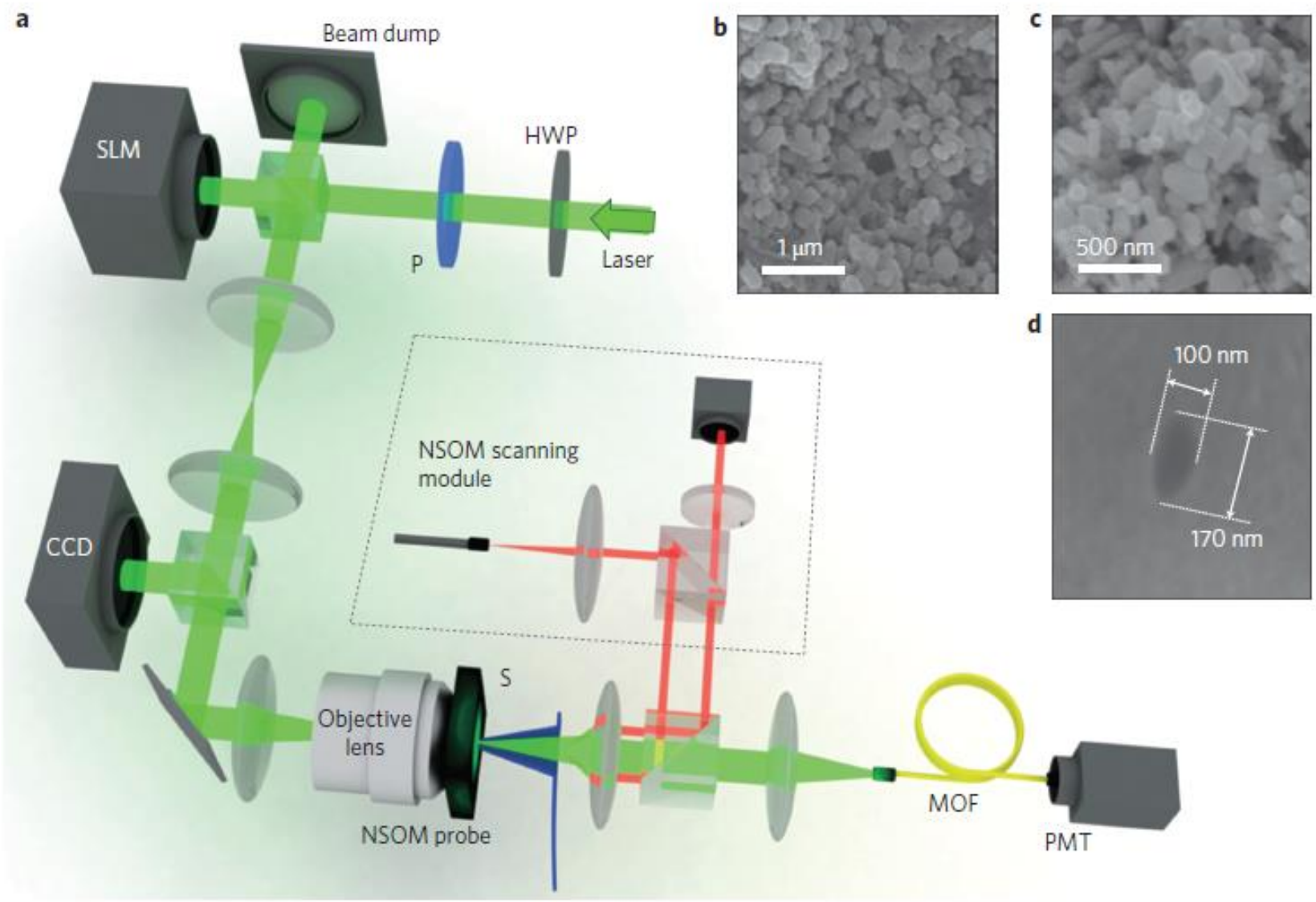
the resulting wave vectors can be phase-matched to construct a subwavelength focus
at a target position.



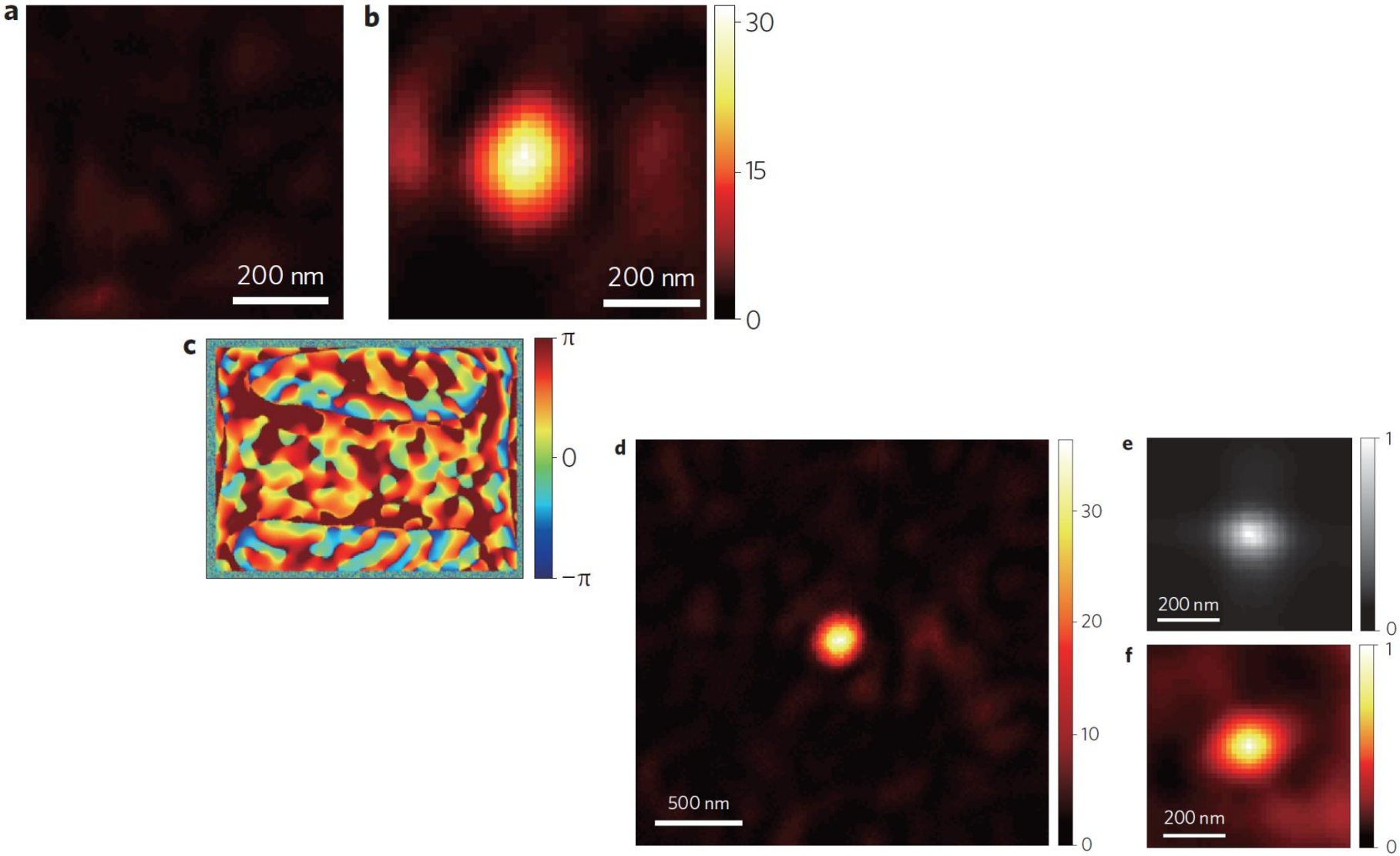

http://www.olympusmicro.com/primer/techniques/nearfield/nearfieldintro.html

# Experimental Setup



# Result

## Construction of subwavelength focus



# Result

## Wavelength- and position-independent subwavelength focusing