Nanoscale metamaterials enable development of novel nano-optical lenses.

Developments in higher-resolution optics have often led to rapid scientific and technological progress in the life sciences and engineering. In 1873, Ernst Abbe showed\(^1\) that the spatial resolution of optical-imaging instruments is limited by diffraction because of the finite wavelength of light. Abbe’s diffraction-limit theory implies that the resolving power of optical components cannot be smaller than half the wavelength of the incident light.

Nanoscale optical elements that can mold the flow of light offer the potential of entirely new modalities of superresolution imaging. With a vision to build superlenses capable of resolving subwavelength details, in the last decade the photonics community has focused on fabricating tiny metallic inclusions (or, closely related, plasmonic architectures) characterized by a negative index of refraction.\(^2\) Unfortunately, such metamaterials suffer from material losses enhanced by resonances, leading to a degradation of functionality. Instead, our group has demonstrated successful performance of highly functional nanostructured metamaterials in ‘low-loss’ dielectric platforms such as metal-dielectric composites and III-V semiconductors (composed of indium phosphide/indium gallium arsenide phosphide: InP/InGaAsP).

We recently reported the experimental realization of superresolution imaging with a low-loss 3D nanolens,\(^3\) comprised of gold nanowires embedded in nanoporous alumina: see Figure 1 (right). This 3D nanolens, manufactured using a combination of bottom-up self-assembly and electrochemical process, transmits subwavelength details down to \(\lambda/4\) (\(\lambda\): Wavelength) and over a significant distance of more than \(6\lambda\). We show an example of the superresolution imaging achieved in Figure 1 (left). The nanolens guided modes do not penetrate the nanowires, so that most of the energy propagates between them. Consequently, image reconstruction can be done with low loss and over a broad spectral range. The nanolens possesses a figure of merit (a metric for functionality) that is four times higher than the best fabricated metallic-based metamaterial\(^4\) at telecommunications wavelengths. Manufacturable on large scales, the nanolens has immediate applications in contact-lithography techniques or optical projection printing.

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\(^1\) Abbe, E. (1873).<br>
\(^3\) Casse, B. D. F., Sridhar, S., & Thomas, J. (2010).<br>
We have also developed nano-optical lenses using III-V semiconductors capable of superlensing and superfocusing at \( \lambda = 1550\text{nm} \) using negative refraction. We designed flat and planoconcave lenses using dispersion-engineering principles. We subsequently fabricated them nanolithographically in InP/InGaAsP semiconductor heterostructure platforms. We achieved flat-lens imaging of a point source with a photonic-crystal superlens consisting of air holes in a dielectric medium of 290nm diameter and with a lattice spacing of 470nm: see Figure 2 (left). By designing an appropriate lens-surface termination, we achieved an image spot size of 0.12\( \lambda \)—see Figure 2 (right)—demonstrating superlens imaging with a resolution well below Abbe’s diffraction limit of 0.5\( \lambda \).

We also realized a nano-optical microlens with an effective negative index of refraction (\( -0.7 \)), shown in Figure 3 (left), and with a world-record ultrashort focal length (\( \sim 8\lambda \)). This unique lens also possesses superior properties compared to positive-index planoconvex lenses, including a compact footprint, near-diffraction-limited spot size (\( \sim 0.68\lambda \)), larger numerical aperture (close to unity), and reduced aberrations. We also demonstrated successful performance of a planoconcave binary-staircase lens in the InP/InGaAsP platform—see Figure 3 (right)—that achieves superfocusing by surface engineering of a bulk medium. By exploiting the periodicity of the surface corrugation, the optical element can exhibit an effective negative index of refraction and focus plane waves. Potential applications are in high-density pixel digital imaging including integrated optics for focal-plane arrays, night-vision goggles, and laser-beam shaping.

In summary, we have designed, fabricated and characterized nanoscale negative-index metamaterials-based optical components that offer the prospect of revolutionary developments in imaging and optoelectronics. Low-loss platforms include III-V optoelectronics semiconductors and metal-dielectric nanowire composites. The ability of these nanoscale metamaterials to beat the diffraction limit offers tremendous opportunities in biomedical imaging, nanolithography, high-capacity storage systems, transformation optics, and IR imaging applications. Our future efforts will focus on imaging biomolecules in vitro and optimizing the 3D nanolens for other spectral ranges. Other ongoing work is focusing on metamaterials-based lithography at UV frequencies.

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