Nanoscale Optical Elements Using Negative Index Metamaterials

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Nanoscale optical elements offer the potential of entirely new modalities of imaging with sub-wavelength resolution utilizing the phenomenon of negative refraction. We have developed new types of superlenses and ultra-short focal microlenses using nanolithographic techniques in InP/InGaAsP and SoI semiconductor heterostructures at near infrared frequencies.

An image spot size of $0.12\lambda^2$ was achieved at 1.5 μm wavelength in a generalized photonic crystal superlens nanofabricated in InGaAsP/InP heterostructure, demonstrating superlens imaging with sub-wavelength resolution below the diffraction limit of $0.5\lambda^2$. A generalized superlens theory gives excellent explanation of wave refraction and image formation.

An ultra-short focal length plano concave microlens in an InP/InGaAsP semiconductor 2D photonic crystal with negative index of refraction (–0.7) was also realized experimentally. At λ=1.5μm, the lens exhibits ultra-short focal length of 12 μm (~8λ) and numerical aperture close to unity. The focused beam has a spot size of 1.05 μm (~ 0.68λ) at full-width half-maximum.

We show that a binary-staircase optical element can be engineered to exhibit an effective negative index of refraction, thereby expanding the range of optical properties theoretically available for future optoelectronic devices. The mechanism for achieving a negative-index lens is based on exploiting the periodicity of the surface corrugation. By designing and nanofabricating a planoconcave binary-staircase lens in the InP/InGaAsP platform, we have experimentally demonstrated at 1.55 μm that such negative-index concave lenses can focus plane waves. The beam propagation in the lens was studied experimentally and was in excellent agreement with the three-dimensional finite-difference time-domain numerical simulations

A new class of negative index metamaterials was demonstrated based on metal-dielectric nanocomposites prepared using a versatile bottom-up nanofabrication approach of vertically aligned metal nanowires such as Au and Ag inside dielectric aluminum oxide nanotemplates. Optical absorbance measurements show resonance peaks corresponding to the transverse and longitudinal surface plasmon modes. A quantitative model based on effective medium theory is in excellent agreement with experimental data, and points to specific composite configurations and wavelength regimes where such structures can have applications as negative refraction media for imaging.

These negative index metamaterials and devices offer the prospect of revolutionary developments in imaging and optoelectronics.

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