Mid-infrared Metalens Engineering based on the High Refractive Index PbSe Material

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Abstract:
We present the design and demonstration of polarization insensitive all-dielectric metalenses operating in the mid-wave infrared (MWIR) region at around 4.6 μm based on the high refractive index PbSe thin film on the BaF2 substrate.

1. Introduction

Mid-wave IR (MWIR) thermal imaging is widely employed in applications such as surveillance, navigation, medical diagnostics, building inspections, and hazardous gas leak detection [3, 4]. However, its widespread adoption is limited by challenges in conventional mid-IR lenses, which are essential for imaging systems. High imaging quality often necessitates multiple cascading lenses, resulting in bulky setups and complex alignment. Diffractive lenses, which manipulate light through the spatial arrangement of microstructures via constructive interference [5], offer a planar alternative. However, these are often constrained by low efficiency, high dispersion, shadowing effects, and integration challenges [2]. Recent advancements in metasurface-based flat lenses, or metalenses, address many of these limitations. Metasurfaces, composed of two-dimensional arrays of subwavelength artificial structures, provide a versatile platform for comprehensive light manipulation, enabling compact, high-performance optical systems [7]. Metalenses focus light by imparting abrupt phase changes locally through subwavelength structures known as meta-atoms. Most mid-IR metalens designs are based on silicon and germanium materials. However, silicon's absorption losses, particularly in the LWIR range, and germanium's high temperature coefficient of refractive index present certain limitations [6]. In this study, we investigate the potential of using PbSe material to design all-dielectric metalenses for MWIR imaging, specifically engineered to focus light 4.6 μm. The metasurface leverages the optical properties of PbSe, particularly its high refractive index, combined with a BaF_2 substrate with a relatively low refractive index, resulting in a thinner overall structure. PbSe meta-atoms with a height of 1.8 μm and varying diameters are utilized for efficient wavefront control. The metalenses achieve nearly diffraction-limited focusing and are capable of resolving features at the wavelength scale, with a numerical aperture (NA) of 0.447.

2. Method and Summary

We outline the design methodology for a MWIR metalens utilizing high-refractive-index PbSe meta-atoms. The metalens is constructed from PbSe nanopillars arranged on a BaF_2 substrate. Its primary function is to focus collimated incident light into a spot in transmission mode. Each nanopillar at a given position (x,y) imparts a phase defined by the equation:

$$\phi(x,y) = -2\pi/\lambda \left(\sqrt{x^2+y^2+f^2} - f\right). \quad (1)$$

where f is the focal length. To enhance efficiency, we optimized the nanopillar height (H) and the unit cell period (P) for the design wavelength of 4.6 μm. In this design, the phase accumulation mechanism relies on the propagation phase, requiring the nanopillars to have sufficient height to achieve full 2π phase coverage across a range of diameters [7]. Thanks to the high refractive index of PbSe, the proposed metasurface can achieve full 2π phase coverage with a nanopillar height of 1.8 μm. Figure 1(b,c) illustrates the transmittance and phase delay as functions of the height and diameter of the nanopillars for light incident from the substrate side. The results in Figure 1(d) demonstrate substantial phase variation with the diameter, while the transmission remains above 90% across all radii at the optimized height of 1.8 μm . Our objective is to design a metalens with a 500 μm aperture diameter and a 500 μm focal length, corresponding to a numerical aperture (NA) of 0.447. The unit cell period

(P) is kept below $\lambda/(2\text{NA})$, to satisfy the Nyquist sampling criterion [1].
The wavefront manipulation achieved by the designed metasurface is confirmed through a beam steering simulation. The unit cell comprises eight structures arranged linearly along the x-axis (Figure 1e), with each structure imparting a phase delay incrementally increasing from 0 to $7\pi/4$ in steps of $\pi/4$. The simulation demonstrates that light incident normally from the substrate onto the structures is deflected by 22° from the normal after passing through the meta-atoms. This result confirms the metasurface's capability for independent phase control. Figure 1(f) shows the phase profile of the metalens. Full-wave simulations were performed using the finite-difference time-domain (FDTD) method to evaluate the focusing performance of the metalens. Figure 1(g) illustrates the normalized electric field distribution in the x-y plane at the focal plane, where the full-width at half-maximum (FWHM) of the focal spot is 5.5 μm, close to the diffraction limit. Figure 1(h) shows the propagating electric field in the x-z plane at y = 0 μm . The incident light is sharply focused around z = 500 μm (focal point), verifying the effectiveness of the design methodology.

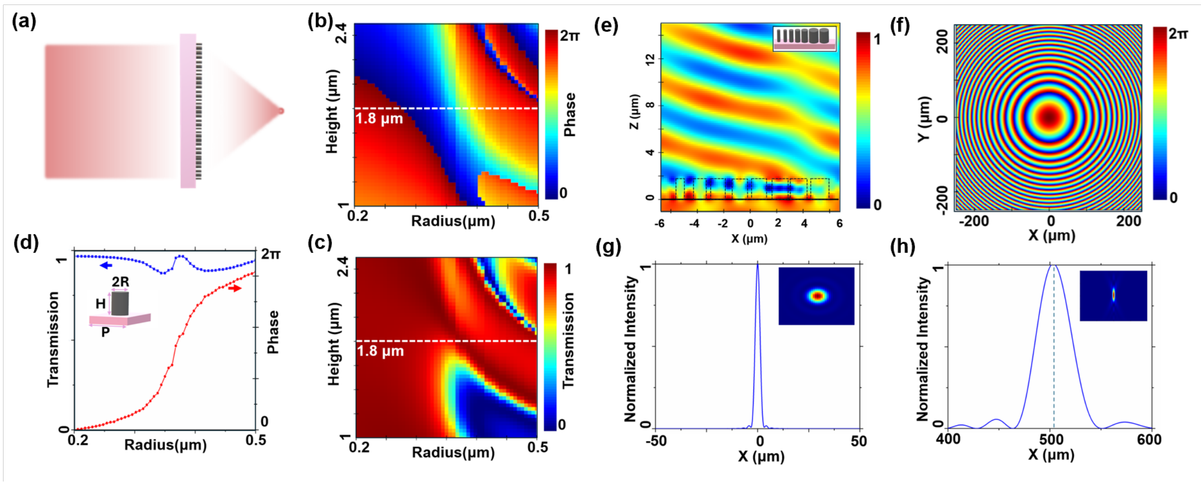

Fig. 1. (a) Schematic of the MWIR PbSe metalens. (b,d) Transmission and phase diagram as functions of the meta-atom radius (R) and height (H), for a wavelength of 4.6 μm and a lattice constant (P) of 1.5 μm. (c) Transmission and phase of meta-atom with different radius for the optimized P = 1.5 μm and H = 1.8 μm. (e) Transmitted field profile of a beam deflector with a deflection angle of 22°. (f) Phase profile of the PbSe metalens with a diameter of 500 μm. (g) The normalized field intensity on x-y plane at the focal plane. (h) Normalized field intensity on x-z plane at Y = 0, showing the focal point at around 500 μm

Lastly, besides the design work as mentioned, we will also share our experimental efforts to fabricate the PbSe metalens, including the deposition, patterning and etching process, and the characterization results at the conference.

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