Infrared Polarization-Sensitive Imaging with Meta-Technology

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ABSTRACT

A Johns Hopkins Applied Physics Laboratory (APL) team developed infrared (IR) metasurface imaging lenses designed to selectively focus specific states of polarized light (linear and circular) to different locations on a detector array. The lenses' operational characteristics make them well suited to miniaturize future optical sensor systems planned for deployment on small platforms or personnel that cannot support the volume or mass of large optical sensor systems.

Applications associated with infrared (IR) light continue to increase within the civilian and military sectors due, in part, to the need for accurate detection of biological[1] and chemical species[2] as well as the monitoring and control of thermal signatures.[3] In the latter domain, for example, thermal signatures are key indicators of objects and are routinely used for targeting applications.[4] As a result of this interest, technical advances associated with IR sources,[5] detectors,[6–7] and system hardware have continued to emerge over the past decade.

Regarding hardware, a new class of materials based on metasurface technology is currently under intense development to address the miniaturization of operational systems and introduce multifunctional behavior that is not typically available with conventional bulk components.[8–10] Investigators at APL are actively involved in this technical discipline, and through APL independent research and development funding have developed IR metasurface imaging lenses designed to selectively focus specific states of polarized light (linear and circular) to different locations on a detector array. This article reviews results from a recently developed mid-IR polarization-sensitive reflective lens designed to focus two different states of linear polarized light, transverse magnetic (TM) and transverse electric (TE), to separate locations on a common focal plane. This flat, submicron-thick lens exhibits exceptional discrimination between the two polarization states with near diffraction limited focusing from ~4.2 to 4.7 μm. This component's diffraction limit, a parameter defined as the minimum-sized feature that can be resolved with the lens, is ~ 60 μm.

The details associated with the design, electromagnetic modeling, and nano-fabrication of the mid-IR lens can be found in a previous publication on this topic.[11] An optical image of a portion of the 1 cm^2 metalens is shown in Figure 1, where the inset shows a scanning electron micrograph (SEM) image from a small region within the lens surface area. Each of the geometric shapes in the SEM image, referred to as "unit cells," imparts a carefully engineered "optical phase" to the light that is scattered from this element. For this particular metasurface, the unit cells have been designed and spatially distributed to enable focusing of mid-IR radiation a distance of 12 cm from the lens. Additionally, the array has the ability to deflect TE and TM polarized light to opposite sides of

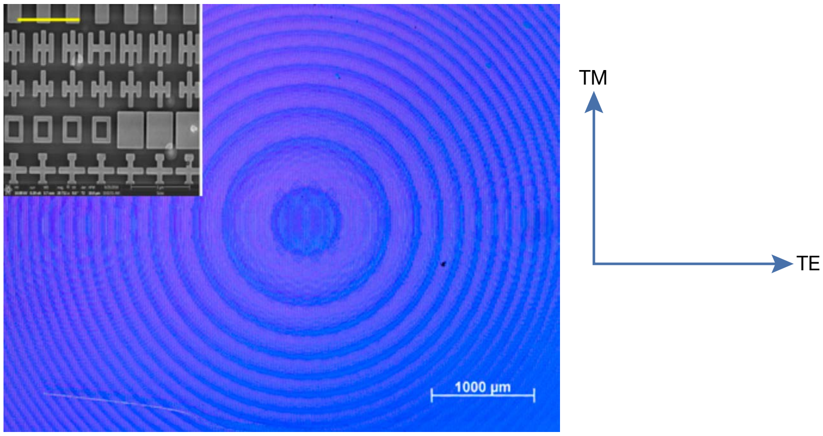

Figure 1. Optical micrograph and SEM images from the 1-cm-diameter metalens. The yellow scale bar in the SEM image is 3 µm in length. The TM and TE polarization designations are shown on the right.

the surface normal (±15°) when the lens is illuminated at normal incidence. This latter feature is the basis for polarization selective imaging.

A graphical illustration of the metalens's operational performance under mid-IR illumination is shown in Figure 2. As noted above, normally incident TE and TM beams will deflect by ~15° to their respective focal planes on either side of the surface normal. APL developed a simple procedure for characterizing the polarization selectivity of the metalens within two narrow spectral regions of the mid-IR (4.26 and 4.67 µm), which enabled the use of a single mid-IR detector to collect images associated with the four combinations of input polarization/sample orientation arrangements. First, with a linear polarizer in the incident beam and the sample orientated as shown in Figure 2, the metalens was illuminated with a sequence of TE and TM inputs. TM light was deflected to the detector while the TE response was directed away from the TM focal plane. After collecting these two images, the sample was rotated 180° about the source normal, which produced a corresponding rotation of the TE and TM focal planes. The sample was then illuminated by the TE and TM sequences of polarized mid-IR light to generate the final two images at the detector plane.

Figure 3 shows the four images captured using this measurement procedure and the two narrowband filters. The metalens exhibited high selectivity with regard to the input state of the polarization source. The dynamic range for discriminating between co- and cross-polarized signals (i.e., beam deflection) was determined to be ~400, which was derived by determining the ratio of the maximum signal count under co-polarized detection and the minimum detectable count. These results highlight the high discrimination capability of the metalens over a relatively wide band of wavelengths, where imaging quality is primarily limited by the intrinsic spectral dispersion of the diffractive nature of the lens design.

The operational characteristics associated with this type of IR lens—high numerical aperture, polarization selectivity, and low weight and volume—are attributes well suited for the miniaturization of future optical sensor systems. Such systems are critical for deployment on small platforms (e.g., unmanned aerial vehicles) or personnel that cannot support the volume or mass of large optical sensor systems. In addition to developing this polarization-sensitive metalens, the APL team is developing meta-based components that will enable miniaturized imaging systems for operation on unmanned aerial vehicle platforms, as well as spectrally selective gratings for sensor protection against high-power lasers.

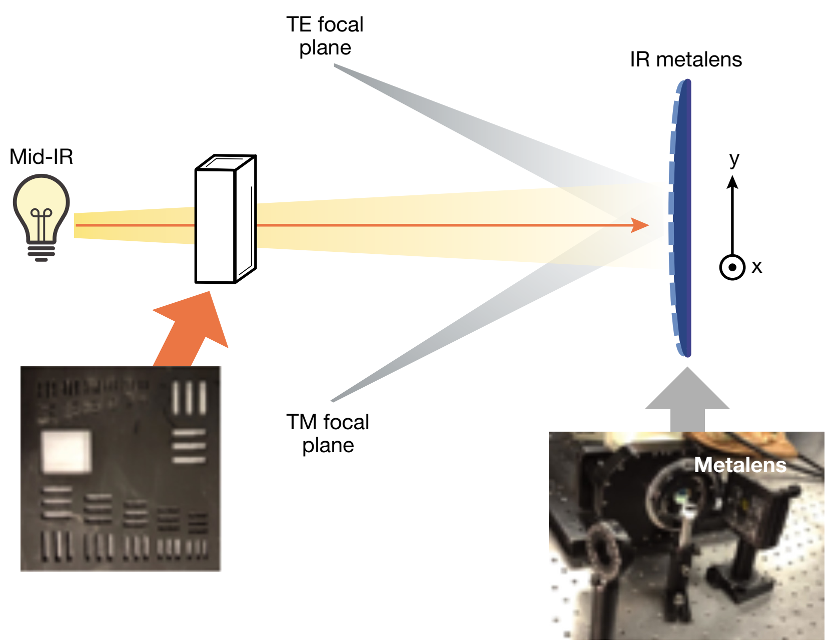

Figure 2. Illustration of the mid-IR metalens's performance when illuminated by an unpolarized source. Under this sample orientation, the two different states of linear polarization are deflected and imaged to the TE and TM focal planes. The actual metalens is shown on the right side.

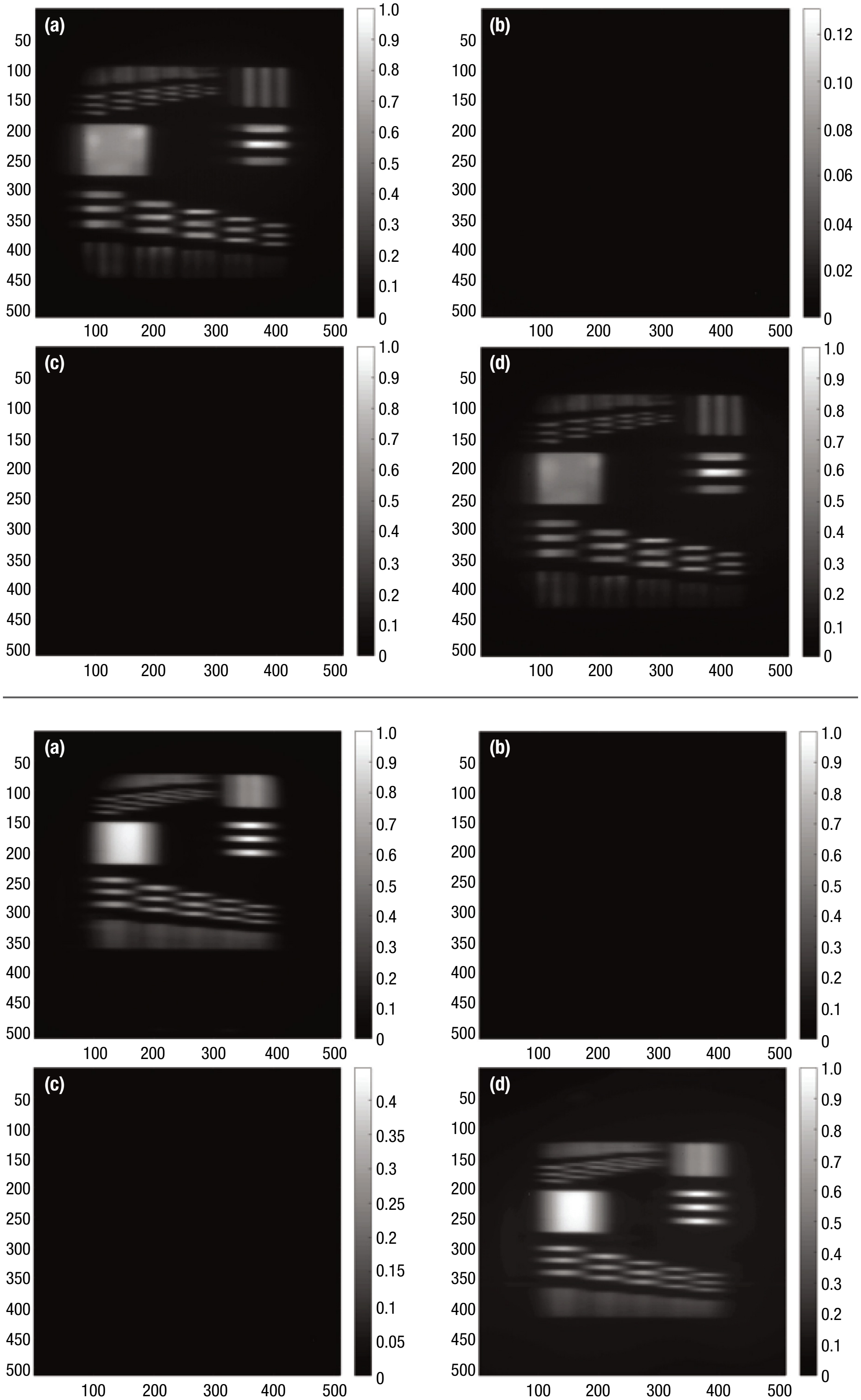

Figure 3. The images captured. Images of the 4.26-µm (top four panels) and 4.67-µm (bottom four panels) reflected from the metalens associated with the following polarization sequences: (a) TE input, TE detect; (b) TE input, TM detect; (c) TM input, TM detect; and (d) TM input, TE detect.

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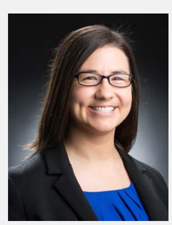

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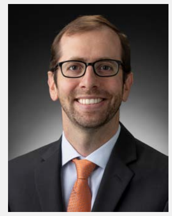

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