Metamaterial Spectrometer: A Low SWaP, Robust, High Performance Hyperspectral Sensor for Land and Atmospheric Remote Sensing

CNF Project Number: 3003-22
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Primary Source(s) of Research Funding: National Aeronautics and Space Administration (NASA)

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Primary CNF Tools Used: ASML DUV Stepper, Oxford ALD, Oxford PECVD, Ultra and Supra SEM, CHA Evaporator, Oxford 81 Etcher, Logitech CMP

Abstract:

Since 2003, Phoebus Optoelectronics has enabled custom R&D solutions in the fields of Plasmonics, Metamaterials, Antennas, and Sensors. We work closely with our customers throughout device development, from simulation and design, to prototype realization, testing, and small volume manufacturing. Our R&D portfolio spans the spectral ranges of visible light, infrared, terahertz (THz), and microwave radiation, for applications in high resolution imaging systems, wavelength and polarization filtering, tunable optical components, beam forming and steering, solar cells, renewable energy devices, and chemical and biological toxin sensors. We routinely partner with large, industry-leading businesses to develop products in all of these areas, jointly performing advanced testing and working together to scale up to medium- and large-volume manufacturing. Our agile team makes extensive use of the resources at the CNF for our nano/micro fabrication and testing, to provide cost efficiency and rapid turnaround.

In the present report, we discuss the ongoing development of a metamaterial-based hyperspectral imaging filter.

Summary of Research:

Phoebus uses the resources of the CNF to fabricate plasmonic chips patterned with a metamaterial surface to enable Extraordinary Optical Transmission (EOT), a phenomenon unique to metastructures in which light is transmitted through apertures much smaller than the incident wavelength, at anomalously large intensities relative to the predictions of conventional aperture theory. EOT was first observed by T.W. Ebbesen in 1998 [1]. Since its founding in 2003, Phoebus has successfully harnessed EOT by incorporating metasurfaces into devices used to perform light filtering [2-3], photon sorting [4-5], polarimetric detection [6], high speed optical detection [7], and SPR plasmonic sensor chips [8].

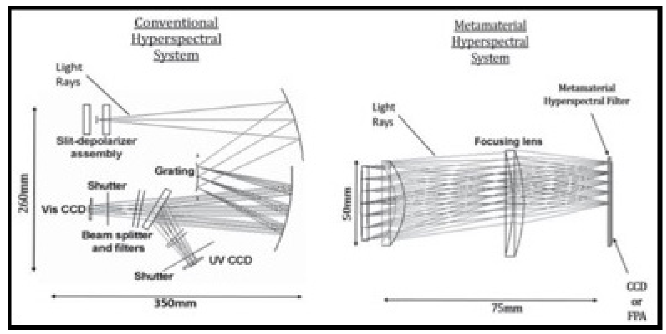
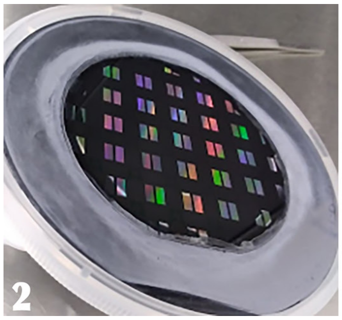
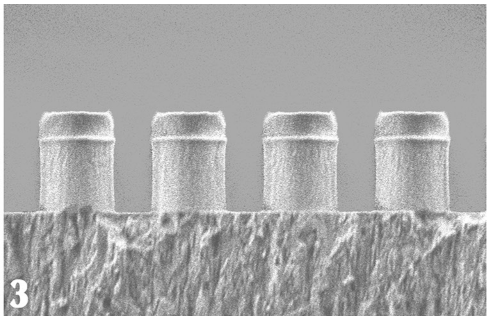


Figure 1: Phoebus's Metamaterial Spectrometer (MS) technology (right) eliminates much of the size and weight of conventional hyperspectral spectrometer technologies (left). Note the significant difference in scale of the two images.

In our current project, we are developing a hyperspectral imaging system, shown schematically in Figure 1. Our technology (Figure 1b) uses a metasurface to precisely target very narrow spectral bands of interest, enabling a significant reduction in the size and number of optical components relative to current state-of-the-art imaging systems (Figure 1a), which in turn will enable the integration of our high-performance sensor onto weight-sensitive platforms (ie. satellites) far more readily than existing systems. Our initial goal is to detect and image trace gases in the Earth's atmosphere in the midwave infrared (MWIR), defined as 3-5 μm wavelength, while minimizing dependence on the Angle of Incidence (AoI) of light upon the sensor, up to an angle of 12° off-normal.





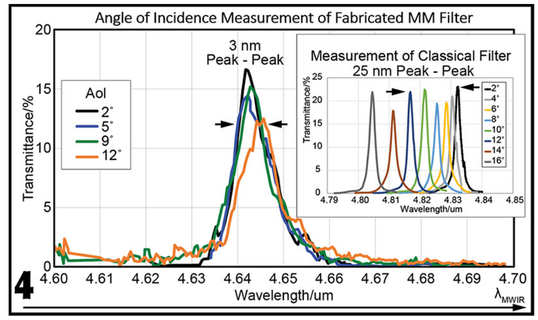


Figure 2: Wafer lithographically patterned with optical metastructures, using the ASML DUV stepper

Figure 3: SEM image (cross section) of etched pillars with near-vertical sidewalls.
Imaged at ~ 15kX in the Ultra SEM, the grain structure of the etch stop layer is clearly visible.

Figure 4: Measured optical performance of fabricated metamaterial filter showing the angle of incidence independence up to a cone of 12° (f/2.4). (Inset) Same measurement performed on a classical Fabry-Pérot filter. Reproduced from reference 9.

Using the ASML DUV stepper, entire wafers can rapidly be lithographically patterned with highly uniform, large-area arrays of metastructures, as shown in Figure 2. In general, the optimal feature size and period of these metastructures depends primarily upon the desired wavelength of operation and the refractive indices of the constituent materials. In the MWIR, typical feature sizes are on the order of ~ 1 μm. Equally critical for minimizing optical losses in photonics applications, the relatively narrow spaces between features can be etched to form high-aspect-ratio structures with nearly vertical sidewalls, as shown in Figure 3.

Conclusions and Future Steps:

With strong, ongoing support from the National Aeronautics and Space Administration (NASA), we have successfully completed three generations of MWIR devices. As shown in Figure 4, they demonstrated the desired AoI insensitivity up to 12°. As we finish optimizing a few key process improvements in our fourth generation devices, we are beginning to integrate pixelated versions of our MWIR devices with commercially available ROIC's, for incorporation into a full camera system.

In addition, we are adapting our metasurface technology to other spectral ranges, from the visible to the microwave, by substituting appropriate materials, and scaling feature sizes as appropriate to the imaging wavelength. The extensive resources of the CNF are enabling us to rapidly develop our Metamaterial Spectrometer technology for a broad range of imaging and sensing applications.

References:

[1] Ebbesen, T.W., et al. "Extraordinary optical transmission through sub-wavelength hole arrays." Nature, (1998). 391(6668): p. 667-669.

[2] Crouse, D. "Numerical modeling and electromagnetic resonant modes in complex grating structures and optoelectronic device applications." Electron Devices, IEEE Transactions on 52.11 (2005): 2365-2373.

[3] Crouse, D., et al. "Polarization independent enhanced optical transmission in one-dimensional gratings and device applications." Optics Express 15.4 (2007): 1415-1427.

[4] Lansey, E., et al. "Light localization, photon sorting, and enhanced absorption in subwavelength cavity arrays." Optics Express 20.22 (2012): 24226-24236.

[5] Jung, Y.U., et al. "Dual-band photon sorting plasmonic MIM metamaterial sensor." Proc. SPIE 9070, Infrared Technology and Applications XL, 90702X (June 24, 2014); doi:10.1117/12.2050620.

[6] Crouse, D., et al. "A method for designing electromagnetic resonance enhanced silicon-on-insulator metal–semiconductor–metal photodetectors." Journal of Optics A: Pure and Applied Optics 8.2 (2006): 175.

[7] Mandel, I., et al. Theory and Design of A Novel Integrated Polarimetric Sensor Utilizing a Light Sorting Metamaterial Grating. Sensors Journal, IEEE, (2012): Vol. PP, 99

[8] Lepak, L., et al. "Handheld chem/biosensor using extreme conformational changes in designed binding proteins to enhance surface plasmon resonance (SPR)" Proc. SPIE 9862, Advanced Environmental, Chemical, and Biological Sensing Technologies XIII, 9862-7 (April 17, 2016); doi:10.1117/12.2222305.

[9] Bendoym, I., et al. "Low SWaP-C hyperspectral metamaterial spectrometer (MMS) for narrow-band, wide angle-of-incidence MWIR atmospheric sensing," Proc. SPIE 12091, Image Sensing Technologies: Materials, Devices, Systems, and Applications IX, 120910J (30 May 2022); https://doi.org/10.1117/12.2632794.