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

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Primary CNF Tools Used: ASML DUV stepper, Oxford 81 etcher, Logitech CMP, Zeiss Supra SEM

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, 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].

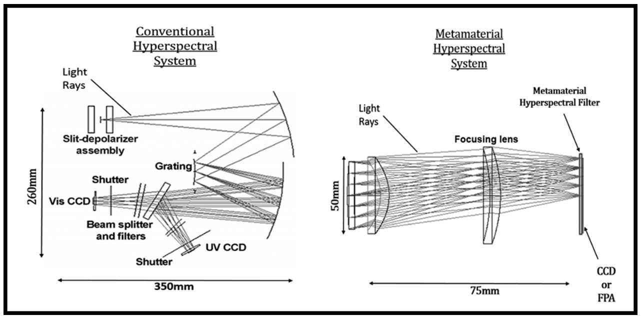

Figure 1: Phoebus's Metamaterial Spectrometer (MS) technology (right) eliminates much of the size and weight of conventional hyperspectral spectrometer technologies (left). Note the significant difference in scale of the two images.

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 integration of our high-performance sensor onto weight-sensitive platforms (i.e., 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) region (defined as 3-5 µm wavelength), while reducing adjacent channel latency to less than 10 ms.

Using the ASML DUV stepper, an entire wafer can rapidly be lithographically patterned with 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. As we can see in the optical microscope image in Figure 3, the ASML can easily produce highly uniform, large-area arrays of test features of an appropriate size. Equally critical for photonics applications, relatively narrow spaces between these features can be etched with moderately high aspect ratios, to form structures with nearly vertical sidewalls, as shown in Figure 4. These vertical structures both minimize optical losses, and ensure that the real fabricated devices will perform as closely as possible to the optimal designs predicted by simulations.

Conclusions and Future Steps:

Our overall metasurface technology can be easily adapted to other spectral ranges, from the visible to the microwave, by substituting appropriate materials, and scaling feature sizes in proportion to the desired wavelength of imaging. In addition to fabricating the MWIR device, we have completed the design of a visible-wavelength counterpart of the current technology, and are about to begin fabrication using all of same tools as the MWIR project, plus the Oxford PECVD and AJA sputter tool to deposit the thin films. Thus, 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., and Keshavareddy, P. “Polarization independent enhanced optical transmission in one-dimensional gratings and device applications.” Optics Express 15.4 (2007): 1415-1427.

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

[5] Jung, Y.U; Bendoym, I.; Golovin, A.B.; and Crouse, D.T. “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., and Keshavareddy, P. “A method for designing electromagnetic resonance enhanced silicon-on-insulator metal-semiconductor-metal photodetectors.” J. of Optics A: Pure and Applied Optics 8.2 (2006): 175.

[7] Mandel, I.; Gollub, J.; Bendoym, I; Crouse, D. 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.

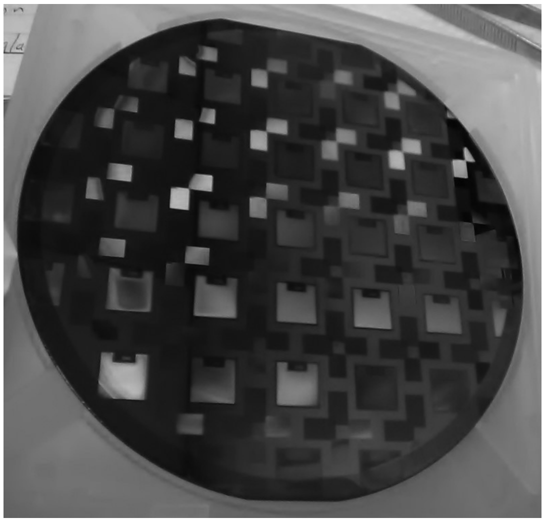

Figure 2: Wafer lithographically patterned with optical metastructures, using the ASML DUV stepper. (See pages vi-vii for full color version.)

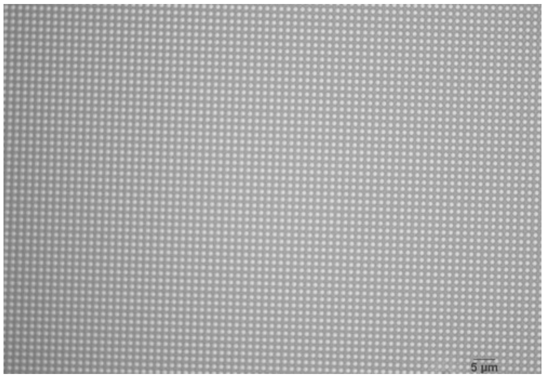

Figure 3: Optical microscope image of test pattern of array of ~ 1 µm pillars, lithographically patterned on the ASML DUV stepper.

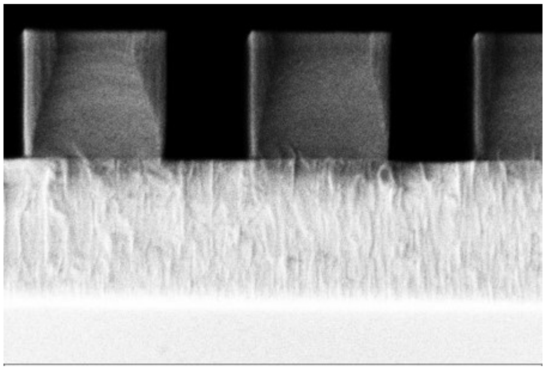

Figure 4: SEM image (cross section) of etched pillars with near-vertical sidewalls. Imaged at ~ 90 kX in the Zeiss Supra SEM, the grain structure of the etch stop layer is clearly visible.