Development of Metamaterial Elements with Polarization Sensitivity

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Program: Spontaneous

Project Objective:

Full control of light has never been possible by using conventional optical components. Frequency-selective transmission (filtering) is common, but is generally not optimized because individual control of optical parameters is not possible. Refractive focusing optics have bulk and are generally limited to simple profiles. Diffractive optics overcomes many of these limitations, but multiple orders must be dealt with. In this case also, full control of optical parameters is not available.

Metamaterials (and their 2D analogue Metasurfaces) are artificial electromagnetic media nanostructured on a scale much shorter than their operating wavelength, having effective optical properties not found in nature. Metamaterials take advantage of the resonant behavior of small structures of particular materials as they interact with light. Their effective permittivity and permeability can be separately controlled, and can be negative. Metamaterials can be designed to tailor the reflectance or transmittance via not only phase and amplitude control but also by proper surface impedance engineering.

The objective of this task is to demonstrate proof-of-concept metamaterials optical components. This includes the design, fabrication, and characterization of frequency-selective metamaterial structures. The effort focused on 2D arrays of features to provide wavelength and *polarization* selectivity of optical transmission in the ultraviolet.

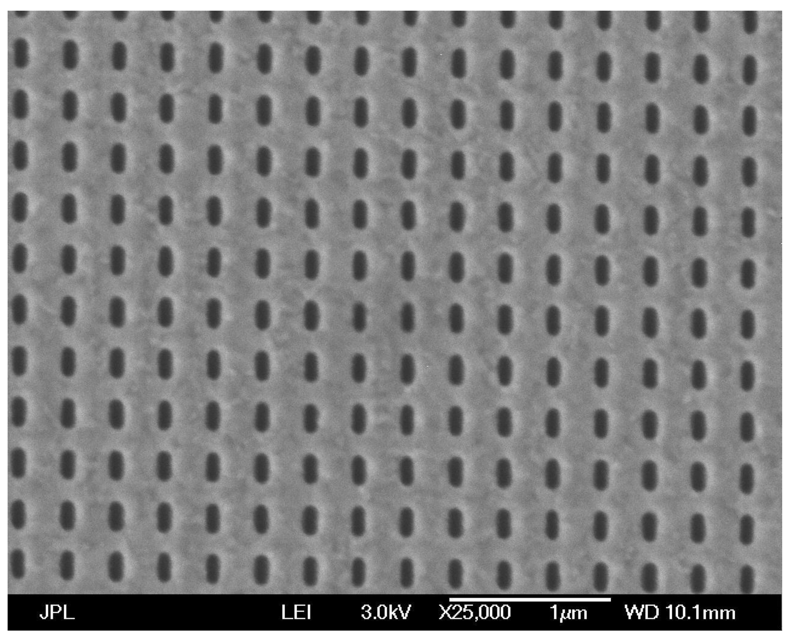
Summary

We have shown a proof-of-concept demonstration of metamaterials elements and arrays for UV operation. We (1) Designed structures for the specific response, (2) Fabricated nanometer-scale patterned surfaces using electron-beam lithography methods, and (3) Characterized the optical properties of the structures. We verified the behavior of the surfaces as frequency- and polarization-selective elements. Rectangular apertures have shown the predicted polarization-dependent transmission. The next goals are to optimize throughput at target wavelengths, and reduce out-of-band transmission.

FY18/19 Results:

Metasurfaces for polarization sensitivity

We are focused on selective transmission in the UV range. We have modeled simple hole arrays in Al designed to transmit at UV wavelengths and reject longer wavelengths. Fabrication of these structures has been done using JPL's e-beam lithography expertise. The surface structures consist of arrays of holes in a thin metal (aluminum) layer. Our goal was to demonstrate polarization-dependent operation at UV wavelengths. Although the fabrication is challenging in UV, the payoff is substantial because of the lack of efficient materials at these shorter wavelengths.

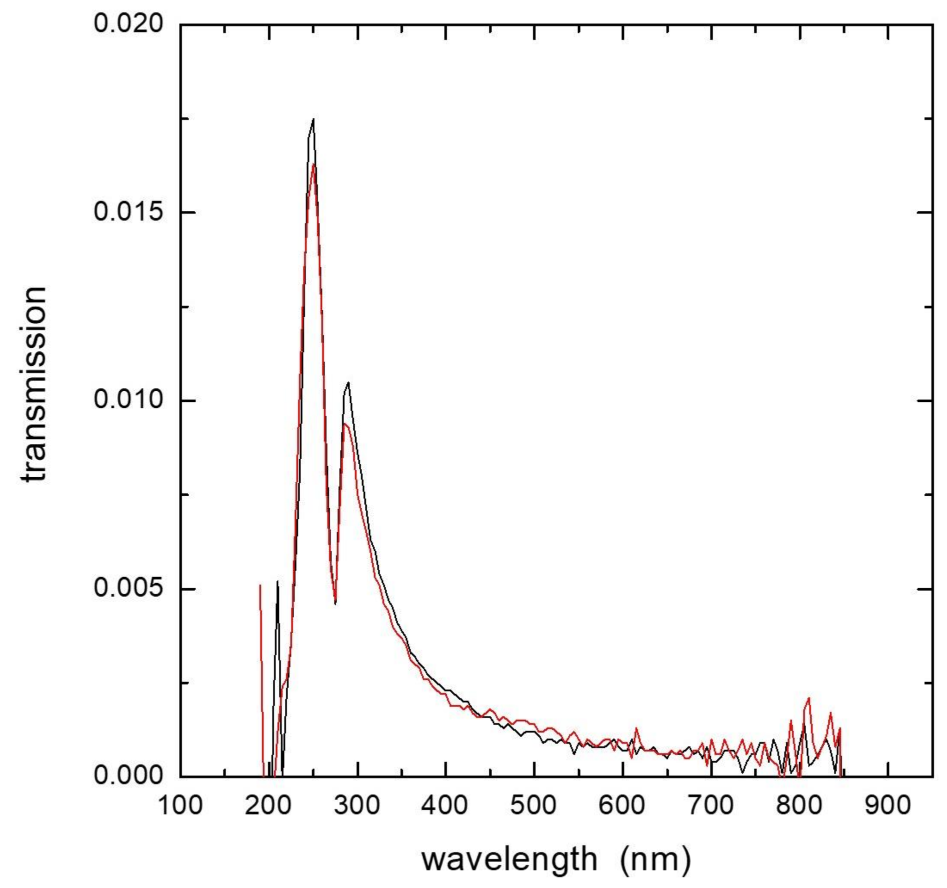


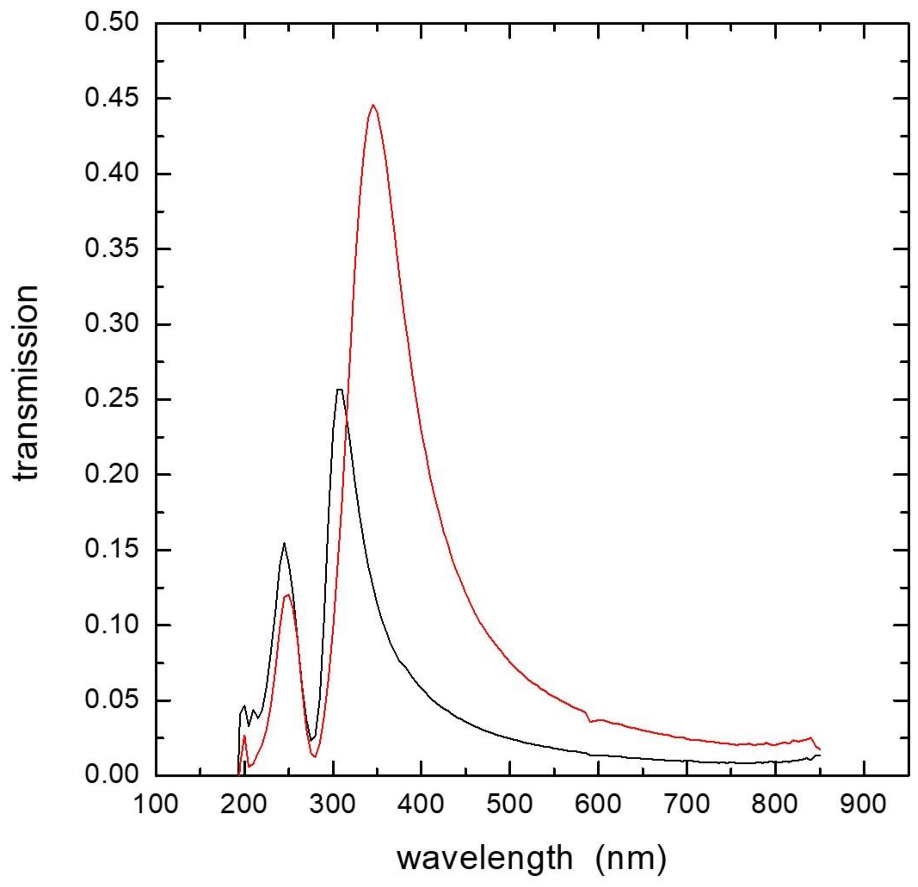
Scanning electron microscopy (SEM) SEM image of a rectangular hole array in Al. The holes are 50 x 150 nm, with a periodicity of 300 nm in both directions. Rounding of the hole corners occurs due to finite size of the electron beam used to write the pattern. The Al film (50 nm thickness) is deposited on quartz.

Horizontally and vertically polarized transmission (black, red) for an array of 40 nm x 40 nm square apertures. Periodicity of the apertures is 160 nm in both directions. The two curves are essentially the same, as expected because the apertures have the same dimension in both directions.

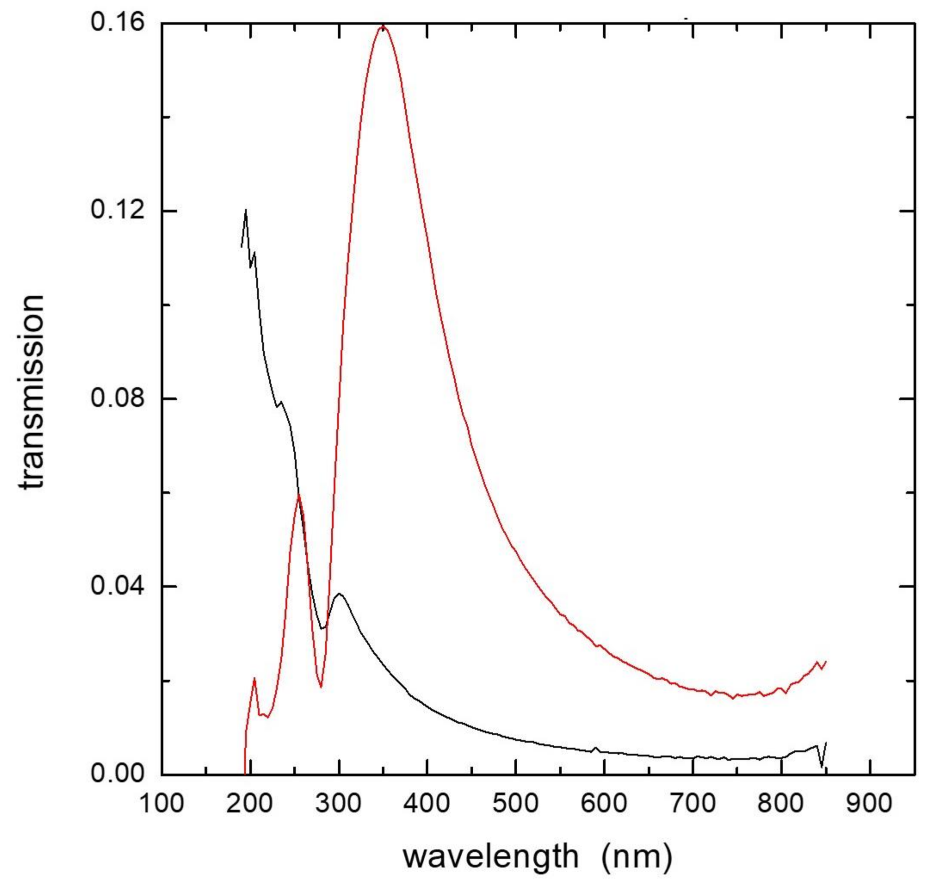
The response can be roughly interpreted as a combination of two effects: the resonance properties of each aperture individually, and the effects of the regular periodicity of the apertures.

The periodicity of the "lattice" of rectangles is responsible, for instance, for the minimum in transmission at 275 nm, which is superimposed on the resonant transmission peak from the individual apertures.





Even smaller (30 nm) apertures produced shorter wavelength response (~200 nm) but displayed very low transmission. This was likely due to incomplete etching of the aperture openings.



Horizontally and vertically polarized transmission (black, red) for an array of 40 nm x 80 nm rectangular apertures. Periodicity of the apertures is 160 nm in both directions. A relative shift in the maxima can now be observed, due to the different aperture size in the two directions.

The transmission peak is much stronger than in the previous example. In fact, the transmission maximum for the two polarizations is 45% and 25%, even though the fractional open area represented by the aperture array is only 12.5%. This illustrates the fact that transmission via resonances in the pattern cannot be thought of in terms of a "fill-factor" for the array.

Horizontally and vertically polarized transmission (black, red) for an array of 40 nm x 120 nm rectangular apertures. Periodicity of the apertures is 160 nm in both directions.

The large aspect ratio of the rectangles produces a large splitting in the transmission peak of the two polarizations, and the overlap between the two transmission peaks is now small. The goal of discrimination between polarizations has been achieved in this case

Benefits to NASA and JPL:

The UV spectrum is rich with information but is underutilized, in part because of a lack of suitable optical materials and devices. Current materials provide low system throughput and low (or no) out-of-band rejection. This work focuses on these limitations, with the goal of applying the new field of optical metamaterials to provide new solutions to the problem of UV optical components. Development of revolutionary new components and instruments using metamaterials would provide JPL a critical advantage in optics systems with lower mass, lower complexity, and higher throughput. Artificial optical materials can provide separate control over normally fixed parameters such as permittivity and permeability; impedance matching can be controlled separately; and these resonant structures also have intrinsic polarization sensitivity. Mission concepts such as HabEx and LUVOIR require optical solutions across a wide wavelength range, with high efficiency and high selectivity.

We expect that metamaterials will provide new solutions for high-efficiency optical elements. These applications span visible wavelengths, for which compact wavefront-shaping optics would reduce mass and complexity, and UV wavelengths, for which higher-efficiency optics are necessary.

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