Infrared frequency selective surfaces: design, fabrication and measurement

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ABSTRACT

A frequency selective surface (FSS) is designed and fabricated to resonate in the infrared. This IR FSS is designed using Periodic Method of Moments (PMM) software and is based on circuit-analog resonance of square loop conducting elements. The FSS is fabricated via electron beam lithography. The spectral characteristics of this surface are studied in the mid-infrared employing a spectral radiometer. The IR FSS may operate as an emissive narrowband source or reflective bandpass filter centered at a wavelength of 6.5μm, sharply cutting off short wavelength radiation and gradually filtering longer wavelengths. The addition of a superstrate layer, intended to further shape the FSS spectral signature, is also studied and the results discussed.

Keywords: Frequency selective surfaces, Infrared filters, Infrared sources, Infrared radiometry.

1. INTRODUCTION

Patterning a surface with conducting elements or with apertures in a conducting sheet can modify a surface's spectral radiation signature. Such a device is called a frequency selective surface (FSS) and has been used to modify radio frequency and millimeter wave radiation [1-4]. Recent success has been reported to scale FSS to resonate in the infrared [4-8]. The design, fabrication and characterization of an infrared frequency selective surface are covered in this paper. This IR FSS demonstrates infrared spectral characteristics of a reflecting bandpass filter. Whereas previous IR FSS designs [6-7] showed less than 20% modulation of its emission spectrum, this IR FSS demonstrates over 90% modulation of its emission spectrum.

This paper details each step of the square loop FSS composition: design, fabrication, and measurement. The design is performed using Periodic Method of Moments (PMM) code, software that has been used in the millimeter spectral regions for FSS modeling. For infrared operation, the FSS needed to be fabricated by means of electron beam lithography (EBL) because standard etching techniques offer too low resolution. FSS nanofabrication by EBL has been demonstrated [5-7] and many improvements to these designs are explored. Measurement of the IR FSS is accomplished by comparing the surface to a blackbody radiator at an elevated temperature. The emission of both sources is studied with an infrared spectral radiometer.

2. DESIGN

Periodic Method of Moments (PMM) code is well-known for design of millimeter wave FSS and is capable of scaling FSS to infrared frequencies. The details of this code are discussed in Ref. 1 and Ref. 9. It is chosen for IR FSS modeling because of its robustness over a wide frequency range and its relatively rapid speed of calculation.

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Fig. 1 shows a schematic of the designed square loop FSS. An analog circuit for this FSS can be illustrated, similar to a RLC circuit network. Current is excited in the metal loops of the FSS as it is elevated in temperature, causing the surface to radiate. Lossy metal loops on a substrate are resistors to this current. The thin metal structures also act as inductors when the FSS elements radiate. Gaps between the metal loops compose capacitors separated by an air gap. Thus, a resonant RLC circuit is formed over the entire surface.

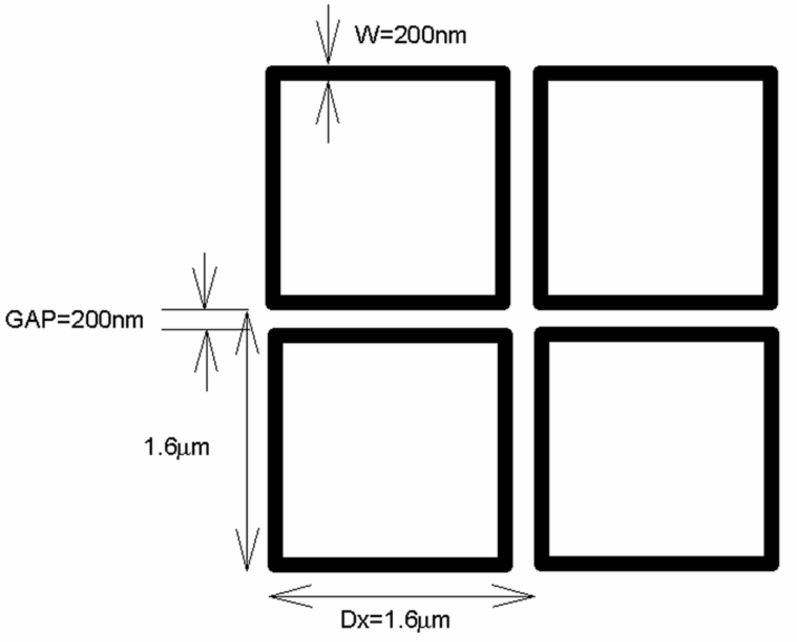

Fig. 1. A schematic of a portion of the repeated FSS.

The IR FSS consists of a metal ground plane and an amorphous silicon standoff layer. The patterned FSS layer is written atop this standoff. PMM code models FSS performance including the effects of the ground plane layer and standoff layer. A resonant cavity is formed if the thickness of the standoff layer is appropriate. Therefore, this amorphous silicon standoff layer is tuned such that its thickness is approximately one-quarter wavelength at the resonant wavelength. The IR FSS emission spectrum is enhanced by this tuned stratified structure. Therefore, FSS is the top layer of the composite device, as initially tested in this paper.

3. FABRICATION

The base of the stratified substrate is a silicon wafer for structural stability during fabrication and testing. A metal ground plane is deposited via thermal evaporation and the amorphous silicon standoff layer is rf diode sputtered. This special substrate is thoroughly cleaned and prepared for EBL by spin-coating a bilayer of electron-sensitive resist. The EBL system is a JEOL 5900 scanning electron microscope (SEM) converted for EBL. It writes the fine FSS pattern using Raith ELPHY Quantum pattern generation and overlay software. Minimum IR FSS feature size is 200nm (as shown in Fig. 1), well within the sub-100nm resolution of the EBL system. The FSS metal is also deposited via thermal evaporation; features are lifted off in a methylene chloride bath to reveal the square loop structure. Fig. 2 shows an SEM micrograph of a portion the completed IR FSS. The largest fabricated FSS covers 40mm^2 and has a total of $9.76 \cdot 10^8$ individual square loop elements!

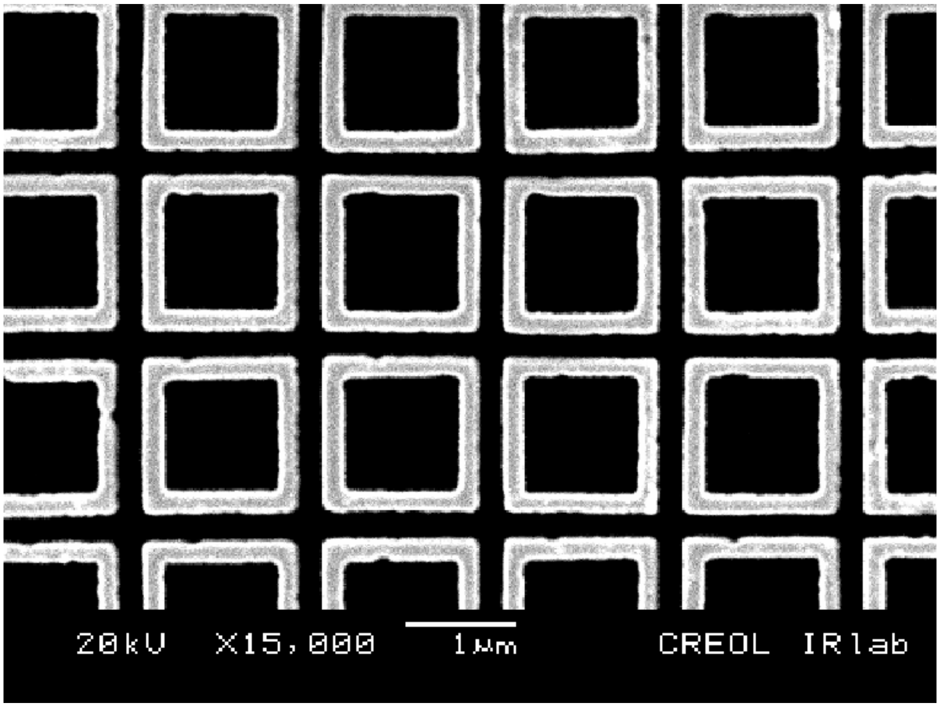

Fig. 2. SEM micrograph of a small portion of the completed IR FSS.
The entire IR FSS covers 40 square millimeters and is composed of $9.76 \cdot 10^8$ elements.

4. CHARACTERIZATION AND RESULTS

An infrared spectral radiometer, manufactured by Infrared Systems Development Corporation of Orlando, Florida, is used to characterize the IR FSS from 3 to 15µm. An image of this system and its functional accessories are shown in Fig. 3. It is used in an imaging configuration in which a 1mm^2 image field is filled by the sample under test. The radiometer collects emitted energy and measures the spectral signal at using a continuous variable filter. For this IR FSS study, the system is calibrated with a blackbody source at 200ºC.

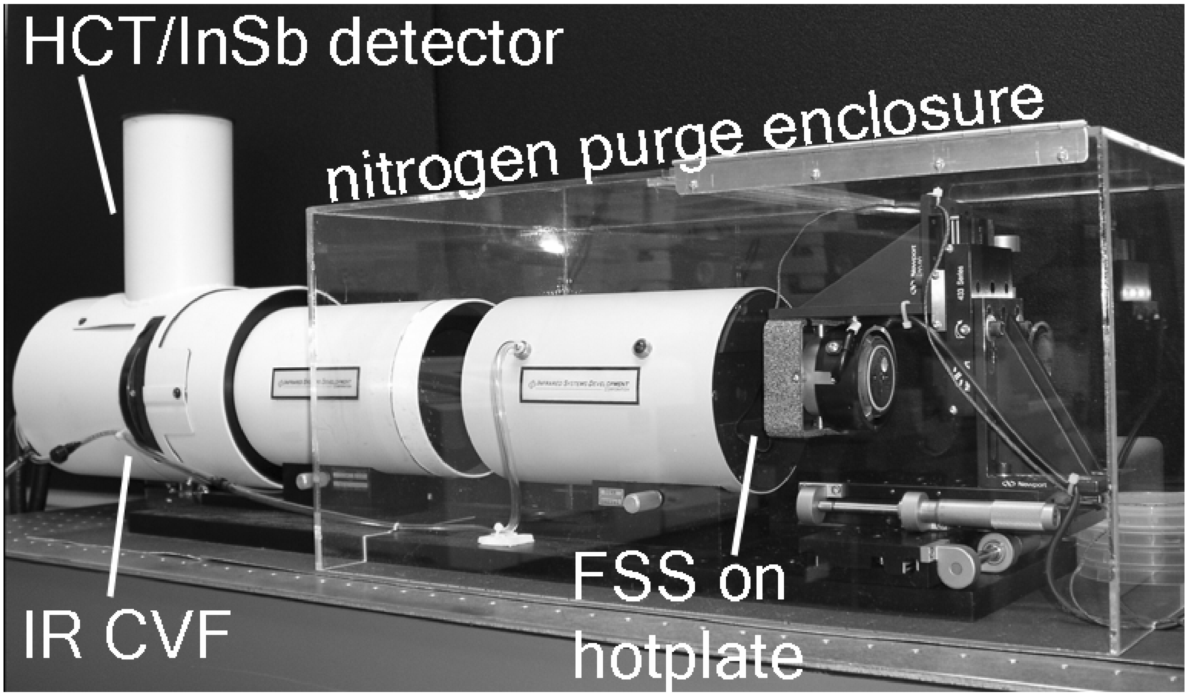

Fig. 3. A schematic of the spectral radiometer, including the nitrogen purge enclosure, hotplate and alignment stage used for FSS characterization.

4.1 IR FSS radiance and emissivity characterization

The IR FSS is elevated to a temperature of 200ºC and its spectral radiance spectrum is compared to blackbody emission at 200ºC in Fig. 4. The IR FSS uniquely functions because of its precisely chosen standoff layer thickness and square metallic loop elements, distributed in a square grid – these features yield a resonance in emission at 6.5µm. Maximum contrast is over 90% between emission near 4µm and emission at resonance.

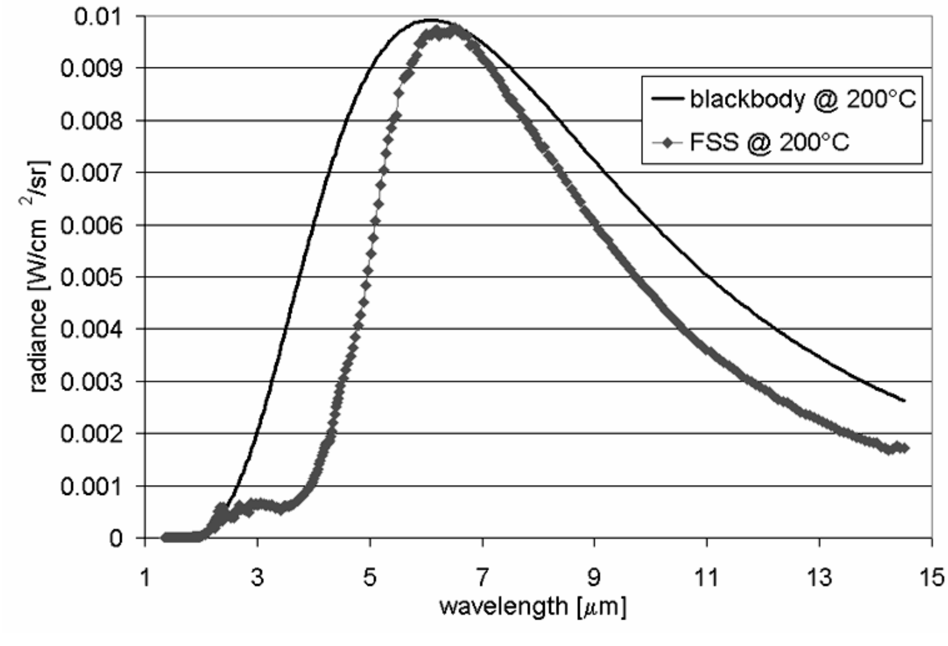

Fig. 4. Radiance of a blackbody and the IR FSS at 200°C

A further metric of IR FSS performance is its spectral emissivity. This ratio of IR FSS radiance to blackbody radiance is shown in Fig. 5. The emissivity approaches unity at resonance, indicating that the IR FSS radiates like a blackbody at a specific wavelength, with a steep drop off to shorter wavelengths and a more gradual drop off in emission to longer wavelengths.

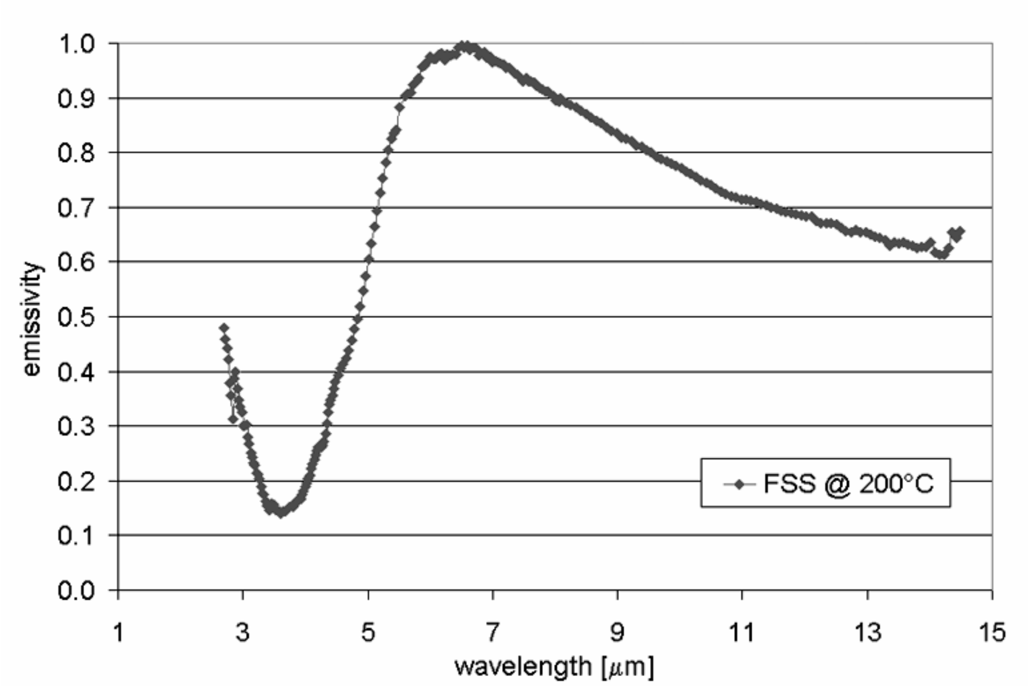

Fig. 5. A plot of IR FSS emissivity at 200°C shows a steep increase in emission to resonance at 6.5μm and a gradual decrease to longer wavelengths, composing a narrowband, emissive bandpass filter.

4.2 Influence of superstrate on IR FSS performance

It is desired to shape the resonate behavior of this infrared signature to more abruptly cut off the emissivity at longer wavelengths. An attempt was made to alter this signature by means of a transparent superstrate. In millimeter applications of FSS, it has been shown [1, 3] that the addition of a superstrate layer narrows the FSS spectral response and decreases sensitivity of the spectral response to operational angle. Furthermore, successful application of a superstrate layer can allow for the addition of cascaded FSS layers, which also have the effect of contouring the spectral signature.

This study involved the deposition of a silicon dioxide layer atop the fabricated FSS. (This study was performed after the above measurements were recorded.) The thickness of this layer is one-quarter wave at resonance; the circuit-analog to this layer is to more closely impedance match the complete FSS impedance to that of free space. Measurements of the FSS with the SiO_2 overcoat are shown in Fig. 6. It remains apparent that the FSS has a resonance near 6.5μm. However, other interesting, albeit undesirable, features appear. The primary resonance is greatly reduced and shifted to a slightly longer wavelength. A second resonance is evident at 9.9μm; this resonance corresponds to material absorption of silicon dioxide [10]. A narrower spectral signature is not evident, but these findings support the potential to use a superstrate to cascade FSS, if a suitable material can be found with a flat absorption spectrum over this wavelength range.

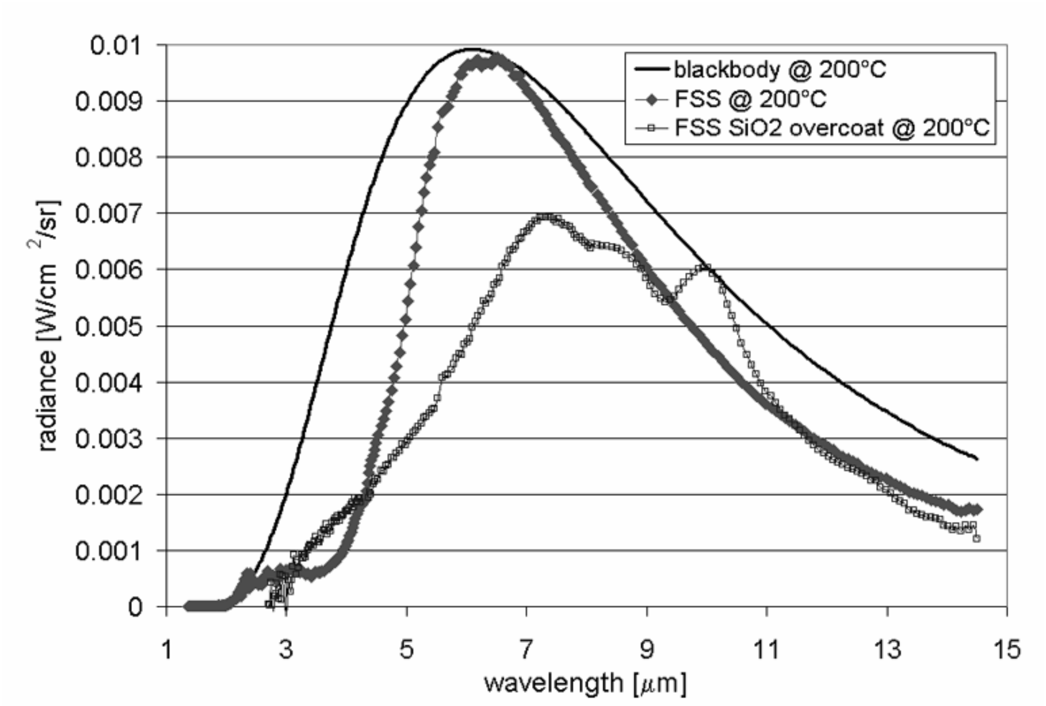

Fig. 6. Comparison of blackbody radiance to FSS radiance with and without SiO_2 superstrate. The addition of a second resonance due to SiO_2 material absorption is detrimental to desired FSS behavior.

4.3 Comparison of the PMM model to experimental data

To illustrate the validity of PMM in the infrared spectral region, Fig. 7 compares the results of the PMM model to the experimental data for the IR FSS. Typical PMM output plots the modeled FSS reflection or transmission spectrum for discrete wavelengths within the spectral region of study. Illustrated in Fig. 7 is the experimental spectral emissivity; because the IR FSS is designed for zero transmission (no radiation will pass the metal ground plane), FSS emissivity equals one minus FSS reflection by Kirchhoff's Law. Therefore, a valid comparison between the modeled output and measured data can be made.

Deviations of the experimental data from the model could stem from modeling shortcomings or fabrication imperfections. For instance, PMM is unable to model spectral permittivity of the FSS materials; a constant permittivity must be assumed across the spectrum for each material. Experimentally, stitching errors between lithographic write fields and intermittent broken metallic loops also cause discrepancies. Overall, the comparison is favorable and the modeling is taken to be valid. In particular, the resonant behavior is predicted well, and transitions across the spectrum are closely matched.

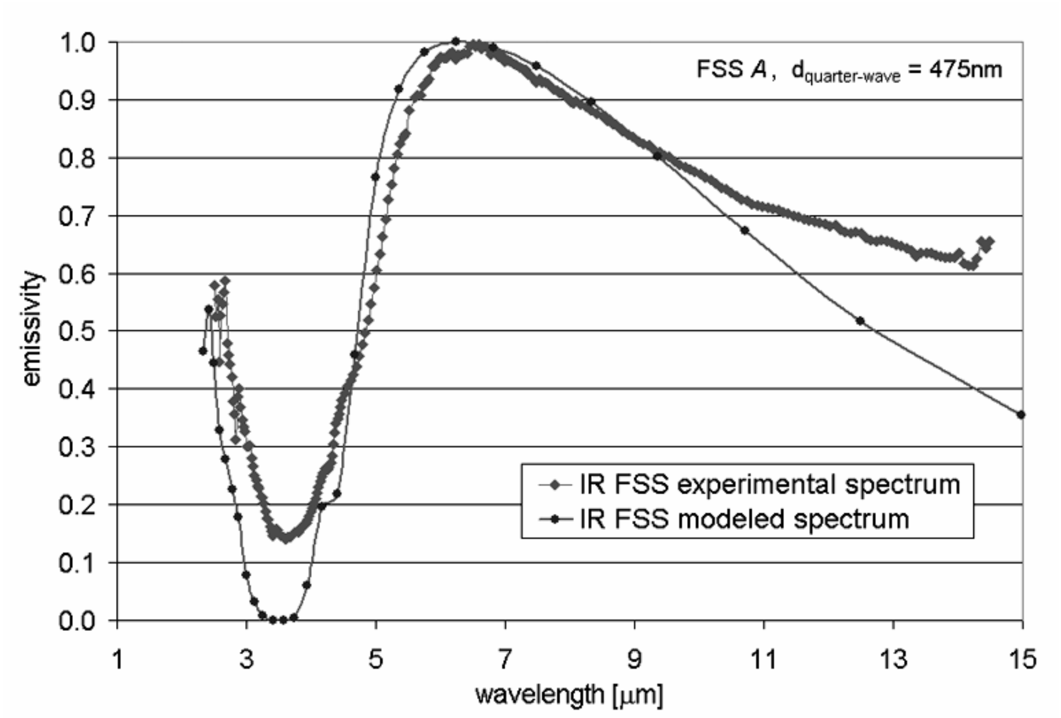

Fig. 7. Periodic method of moments-modeled FSS performance is compared to experimental data, as measured via spectral radiometry.

5. CONCLUSION AND FUTURE WORK

Packing conducting square loops in a dense square grid array shapes the emission spectrum of the resulting frequency selective surface. Each step of the modeling, composition and evaluation of this IR FSS is detailed in this study. PMM modeling is shown to be viable in the infrared. Nanolithography used to scale the FSS to dimensions necessary for infrared operation has proved successful. Results show infrared resonant FSS behavior, with an emission maximum at a wavelength of 6.5μm. In fact, other resonant wavelengths are attainable by varying FSS parameters such as the standoff layer thickness and FSS element size and distribution. Furthermore, out of band emission is 90% less than emission at resonance, making this IR FSS an excellent narrowband emissive source or reflective filter.

Research is presently being conducted to realize a FSS capable of resonant tuning, i.e., a structure with variable properties such that the wavelength of resonance can be *actively* changed. The feasibility of such a device can be demonstrated by physically altering the FSS to ground plane standoff distance and thus shifting the resonant wavelength. Alternative element structures and element distributions are being considered. Success in composing resonant FSS devices has been shown with closely packed honeycomb structure elements [1] and dipole elements can produce polarization-selective FSS operation [3,6].

Alternative substrate or superstrate media are being examined in ongoing work. If a superstrate material with infrared transparency can be employed, the FSS spectral signature can be contoured, producing an even more selective bandpass signature. For instance, FSS resonance can be shaped by incorporating a second, cascaded FSS layer [1], specifically designed to filter longer wavelengths.

Yet another desirable FSS configuration under continuing study is fabrication on a flexible substrate. This can allow the FSS to be contoured to any surface. This application can make a large-scale IR FSS a useful surface treatment for spectral signature modification.

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