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# *Plasmonic Filters*

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**Abstract**

Metal films perforated with subwavelength hole arrays have been show to demonstrate an effect known as Extraordinary Transmission (EOT). In EOT devices, optical transmission passbands arise [1] that can have up to 90% transmission and a bandwidth that is only a few percent of the designed center wavelength. By placing a tunable dielectric in proximity to the EOT mesh, one can tune the center frequency of the passband. We have demonstrated over 1 micron of passive tuning in structures designed for an 11 micron center wavelength. If a suitable midwave (3-5 micron) tunable dielectric (perhaps $BaTiO_3$) were integrated with an EOT mesh designed for midwave operation, it is possible that a fast, voltage tunable, low temperature filter solution could be demonstrated with a several hundred nanometer passband. Such an element could, for example, replace certain components in a filter wheel solution.

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# NOMENCLATURE

| | |
|---|---|
| Near-IR | Near infrared, 1 micron to 3 microns wavelength |
| Mid-IR | Mid-infrared, 3 microns to 5 microns wavelength |
| Far-IR | Far-infrared, 8 microns to 12 microns wavelength |
| FTIR | Fourier Transform Infrared Spectrometer |

# 1. BACKGROUND

## 1.1. Motivation

Perforated metal films exhibiting plasmonic resonances have been a topic of intense study over the past decade [1]. While most related research deals with visible to near-infrared structures that require sub-micron processing, the mid-infrared (mid-IR) and far-infrared (far-IR) regimes can be easily accessed using standard lithography. In this longer wavelength regime, there also exist additional dielectric tuning mechanisms, such as free-carriers in a semiconductor, that are not available at shorter wavelengths. Despite the numerous publications on plasmonic mesh structures, largely due, we believe, to the fabrication complexity of near-IR and visible devices, we have not seen evidence of any research groups performing imaging experiments through these plasmonic filters. Since, in the mid-IR, we can use conventional lithography to produce relatively large area structures, we desired to perform basic imaging experiments through mid-IR and far-IR plasmonic filters in order to understand their potential as basic infrared components. Combined with the ability to tune the bandpass of these filter elements through application of a voltage bias, this could lead to a hybrid filter design that could replace multiple standard filters in an imaging system.

# 2. ACCOMPLISHMENTS

## 2.1: Plasmonic Filters

Perforated metal hole arrays exhibit bandpass characteristics that are described to first order by surface plasmon excitation on the metal film [1]. For smooth metal films, the dispersion relation for surface plasmons is given by

$$k_{spp} = \frac{\omega}{c}\left[\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right]^{\frac{1}{2}} \quad \text{Eq. 1}$$

where $k_{spp}$ is the surface plasmon wavevector, $\omega$ is frequency, and $\varepsilon_m$ and $\varepsilon_d$ are the dielectric function of the metal and surrounding dielectric respectively. It turns out that free-space radiation can not couple to surface plasmons directly, but it can with the help of a grating to provide the additional momentum. In this case, the condition for surface plasmon excitation becomes

$$k_{spp} = k_{photon} \sin\theta \pm \frac{2\pi}{a_o} \text{m} \quad \text{Eq. 2}$$

where $\theta$ is the angle of incidence and $a_o$ is the grating period. In the case of a metal hole array, schematically shown in Fig. 1(a), surface plasmon excitations permit resonant transmission at particular wavelengths governed by Eq. 1,2. Figure 1(b) shows transmission measurements performed on metal hole arrays, having a periodicity of 3 microns, that are fabricated on InSb of various doping levels [2]. As doping density is increased, changing the dielectric constant of the substrate, a shift is observed in the transmission passband.

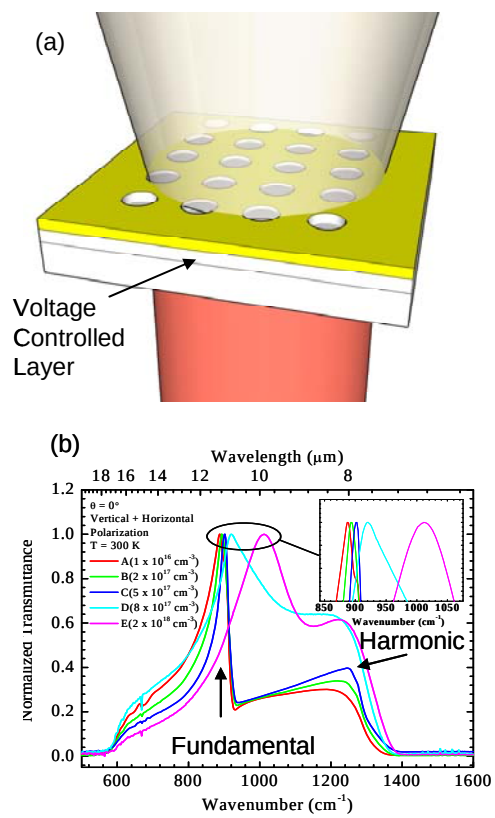


Fig. 1: Perforated metal hole arrays. In part (a) a voltage tunable plasmonic filter is shown. Here, the dielectric constant at the metal/substrate interface would be tuned through application of a voltage bias. Part (b) shows experimental results for shifting the transmission passband of a hole array by using InSb of various doping levels.

## 2.2: Plasmonic structures

For imaging experiments, we fabricated hole arrays with periodicity of 3 microns, and 10 microns on GaAs. The 3 micron structure was designed to have a 10 micron resonance for surface plasmons at the metal/GaAs interface, while the 10 micron devices were designed to have an air/metal resonance at 10 micron wavelength.

The transmission spectra, referenced to air, of these structures were measured using a Fourier transform infrared spectrometer (FTIR) and are displayed in Fig. 2. All of our previous experience had been in manipulating the bandpass

resonance at the metal/dielectric interface as opposed to the air/metal mode. We were somewhat surprised to observe an extremely broad air/metal structure at 10 microns wavelength (1000 $cm^{-1}$) in the 10 micron period device as shown in the black trace of Fig. 2 when compared to the dielectric/metal mode that appears sharp in the green trace for the 3 micron period device. The explanation for this effect is likely related to diffraction which occurs when light transmits from the air side to the dielectric side of the filter element. Due to the higher index material, in the 10 micron period devices, diffraction is possible up to 30 microns wavelength. This could lead to enhanced radiative damping that would broaden the resonance. While attempts were made to remove the substrate through etching in order to remove these effects, those samples were unfortunately destroyed during the process. We believe it is feasible to make such a structure, but we were not able to achieve that goal during this late-start effort. Regardless of those problems, the primary goal of this work was to demonstrate imaging through these filter elements in order to understand their potential as basic filter replacements.

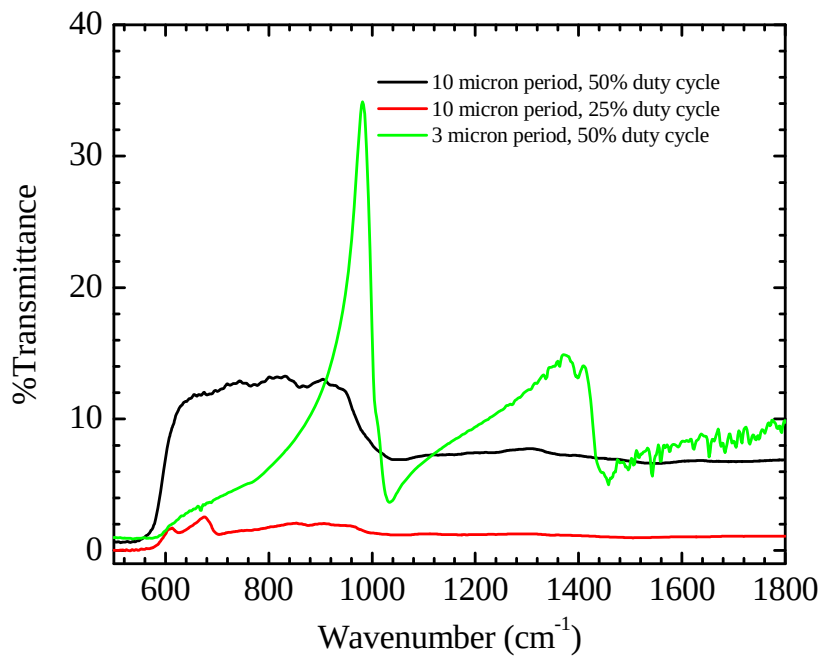


Fig. 2: Transmission spectra of several plasmonic filters. The air/metal structure designed for 10 micron wavelength was extremely broad compared to the metal/dielectric 10 micron mode in the 3 micron period devices.

## 2.3: Imaging experiments

Two sets of imaging experiments were performed using a 3-12 micron bolometric camera, as shown in Fig. 3 (real camera not shown). In configuration (a), the filter is held directly in front of a hot object (400 degree F soldering iron), and in (b), a more realistic scenario, the filter was placed directly in front of the imaging optics.

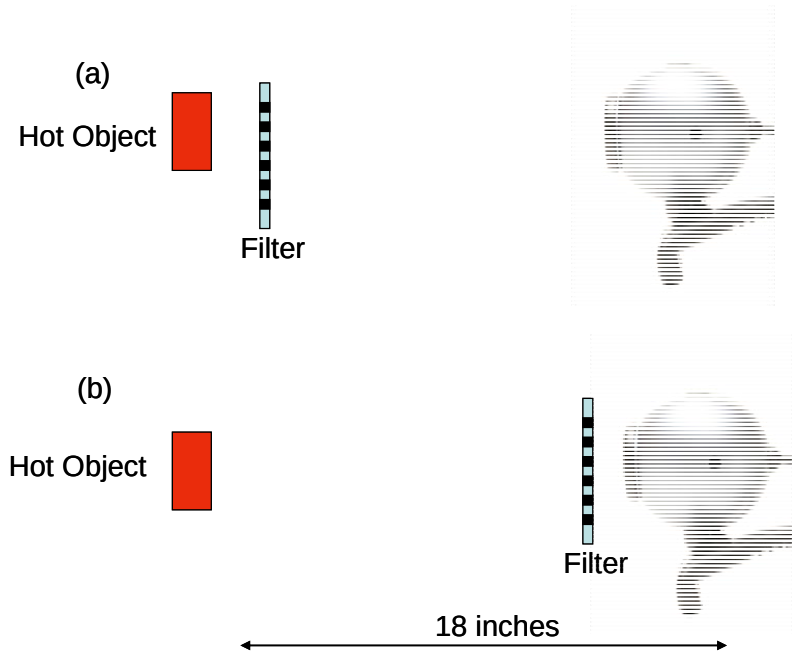


Fig. 3: Experimental arrangements for filter imaging. The 'hot object' used as a source was a soldering iron at 400 degrees F.

Figure 4 shows a representative image of the object passing through two filter elements (10 micron period, 50% on the right and 25% duty cycle on the left) simultaneously. As the FTIR data in of Fig. 2 would suggest, transmission is higher in the 50% duty cycle element.

In the more practical arrangement for image filtering, shown in Fig. 3 (b), the filter was placed directly in front of the imaging optics. In this case, the filter sample was placed on a 5 mm aperture in order to block extraneous rays from being collected by the 1.5 inch collection optics. This situation significantly cuts down the amount of collected light, however, as shown in Fig. 5, the object was still imaged successfully.

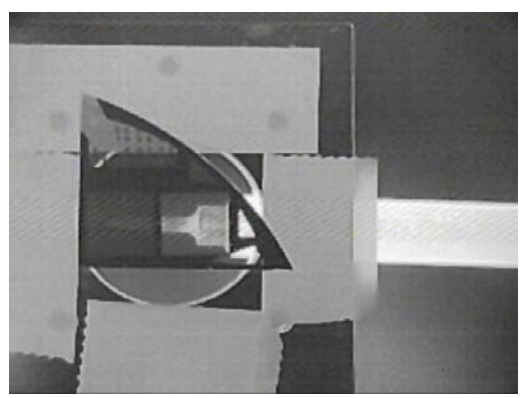

Fig. 4: Imaging with filter directly in front of object.

In Fig. 5(a), an image of the object was acquired with no aperture or filter in place. Then, in Fig. 5(b), the 5mm aperture was placed in front of the optics for a reference image (this aperture cuts a large amount of the signal by itself). In Fig. 5(c,d) the 3 micron period and 10 micron period device respectively were used to filter the image.

Overall, it is difficult to discern absolute intensities seen by the imager as it has built in auto-gain correction that we are not yet able to circumvent, however, we can still illustrate some basic points. Most notably, images are passing through the filter elements without noticeable distortion. The overall reduced intensity of the filtered images when

compared to the apertured image of Fig. 5(b) is easily explained by the FTIR transmission data of Fig. 2 that show the general bandpass behavior of the filters (rejecting much of the blackbody emission from the hot source). The fact that the 3 micron and 10 micron period devices show relatively the same brightness of the image can be explained by the fact that while the peak transmission of the 10 micron period device was much lower than that of the 3 micron period device, the overall transmission amplitudes are similar.

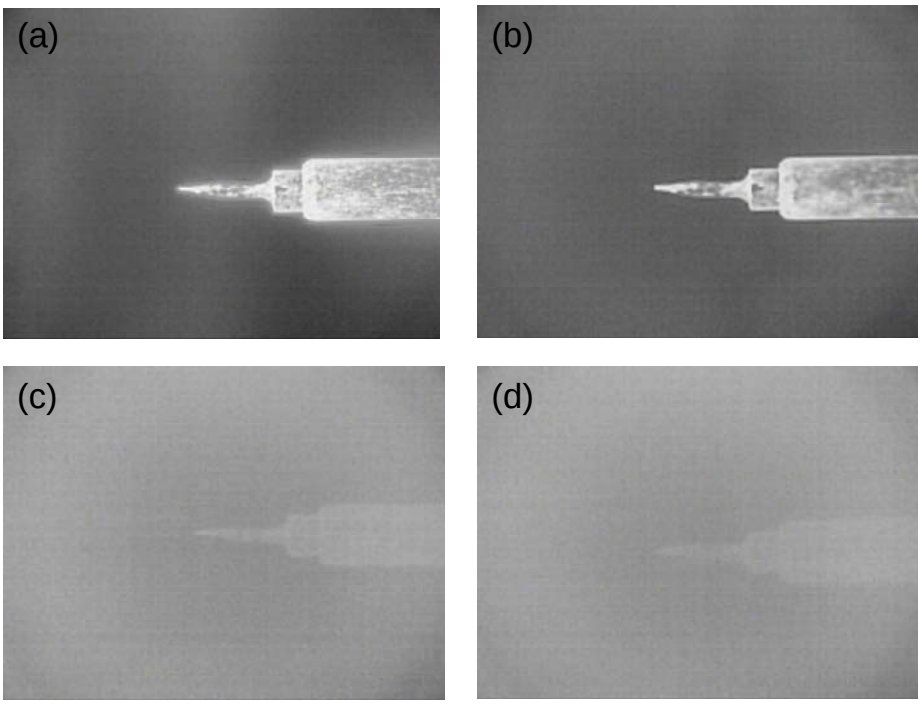


Fig. 6: Imaging through a filter with the element placed in front of imaging optics. Part (a) shows a raw image of the object taken with the camera having no aperture in place. In (b), the 5mm aperture was placed in front of the camera for a reference image. In parts (c) and (d) images were taken using the 3 micron and 10 micron period hole arrays respectively.

## 3. CONCLUSIONS

While a great deal of work is still necessary in order to realize voltage controlled imaging filters, the primary result of this effort which demonstrates the basic image transmission through a plasmonic filter element is promising. Moving forward, efforts must be undertaken in order to control higher order transmission modes of the filter elements to produce a cleaner bandpass characteristic. By moving to more symmetric devices (rather than discontinuous air/substrate designs), we believe that the transmission through these device can be substantially increased. Most importantly, in order to provide an advantage over standard interference filter elements, dynamic tuning of the filter elements of at least 100 nm must be demonstrated.

# 4. REFERENCES


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