# Coupled Resonator Mediated Transmission of Light through Sub-wavelength Holes for Multispectral Imaging Applications

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**Abstract**— Using finite difference time domain techniques, the transmission of light through 6 μm period arrays of sub-wavelength holes in optically thick metallic films is investigated. Over the wavelength range 2 μm to 16 μm, it is observed that by centering an additional metallic element within the sub-wavelength hole, well defined resonance peaks are produced which are strongly dependent on resonator and hole dimensions but only weakly dependent on metal film thickness. Resonant line-width however, is found to be strongly dependent on metal film thickness. Thicker films produced the narrowest full-width half-max values, which were less than 1.0 μm. Such control of resonant wavelength and line-width, along with the size of the elements investigated and the 6 μm array period used, suggests the fabrication of an optical filter with transmission properties that vary across the face of a focal plane array for use in multispectral imaging applications.

## 1. INTRODUCTION

The interaction of freely propagating electromagnetic waves with patterned metallic structures dates back to the invention of the optical diffraction grating. Investigations of those gratings led to the observation of Woods [1] anomalies and their explanation by Raether [2] as being caused by the excitation of surface plasmon oscillations. At longer wavelengths, the field of frequency selective surfaces as discussed by Munk [3] and finally the more recent extraordinary optical transmission (EOT) of light through sub-wavelength holes as observed by Ebbson [4], all rely on the excitation of some type of surface mode which has an in-plane or a near in-plane wave vector. In addition to the optical excitation of freely propagating modes with grazing angle wave vectors caused by grating or grating-like topologies, there are also the generation of surface plasmon polaritons with in-plane propagation vectors, which are governed by a dispersion relation of the form

$$k = \sqrt{\frac{\epsilon_d \epsilon(\omega)}{\epsilon_d + \epsilon(\omega)}} \tag{1}$$

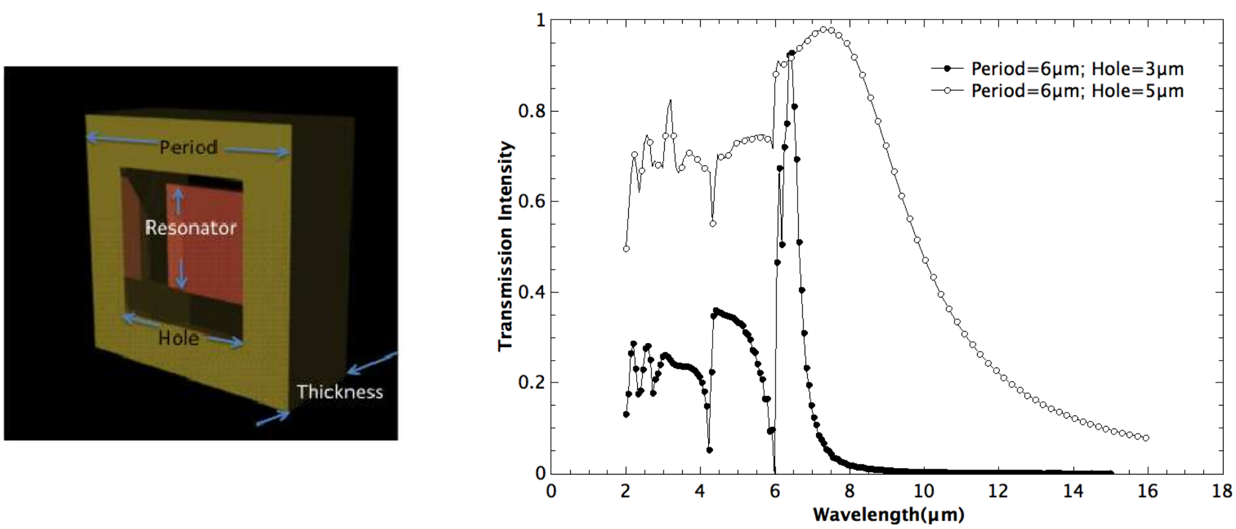
where $\epsilon_d$ is the relative permittivity of the dielectric adjacent to the metallic element surface, $\epsilon(\omega)$ is the frequency dependent permittivity of the metal, $k$ is the surface wave propagation vector, $\omega$ is the frequency of oscillation and $c$ is the speed of light in vacuum [5]. Space prohibits a detailed discussion of this dispersion relation other than to address the salient characteristics pertinent to this work. In particular, $\epsilon(\omega)$ is in general complex and two branches of solutions will result, one of which always falls below the light line for the material. This surface plasmon polaritons branch deviates little from the light line at the longer wavelengths investigated for this work. Significantly, because the branch does fall below the light line, in general there is never enough incident energy available to directly excite a surface plasmon mode from a freely propagating field. Because of this, some means, such as a grating or a scattering event, is required to impart the transverse momentum required to excite the surface plasmon mode. Evanescent excitation of plasmon modes is also possible but not pertinent to this work [6].

This work utilizes finite difference time domain numeric methods to investigate the coupled resonator characteristics of arrays of holes in thick metal films. The particular topology investigated here places an additional metallic resonator within the hole. It is observed that the addition of the central resonator produces longer wavelength resonances controlled by the lateral dimensions of the hole and resonator. It is further observed that narrower resonant line widths result when the films are of a thickness comparable to the array period.

Although no closed form analytic predictive equations are presented, the ability to vary a relatively narrow band transmission by controlling lateral dimensions, suggests such a topology's use as a filter placed directly in front of a focal plane array. An array of similar sized elements would allow distinct narrow-band spectral lines to be allocated on a pixel by pixel basis while others pixels could be allocated for broadband image formation. Such a filter, operating in the long wave 7 μm to 13 μm range, is suggested for use in multispectral imaging systems to allow for the determination of scene spectral content and in turn identification of pathogens or adverse chemical compounds in real time at video frame rates. Such a multispectral imaging system would impact cancer diagnosis and treatment as well as providing front line defense capability for homeland security applications.

## 2. FDTD SIMULATIONS

The basic metallic topology used for this work is shown in the Fig. 2(a). Fig. 1(b) shows the simulated, finite difference time domain (FDTD) transmission intensity through arrays of 3 μm and 4 μm holes, in a 2 μm thick Au plate, simulated over the 2 μm to 16 μm range without the addition of the central resonator. For all simulations, Drude theory was used to determine the frequency dependent permittivity using plasma and relaxation frequencies of $1.36 \times 10^{16}$ (rad/s) and $4.05 \times 10^{13}$ (rad/s) respectively. Periodic boundary conditions were used in the plane of the film and perfectly matched layers in the direction of incident plane wave propagation. This result of a strong transmission peak near the wavelength equal to the array period, (the arrow in the figure), is consistent with both experimental and simulated data obtained by other authors [7].




(a) (b)

Figure 1: (a) Topology and nomenclature used in this work. (b) Simulated transmission through both a 3 μm and 4 μm hole in the 2 μm thick film. For this simulation no resonator was present. The arrow marks the wavelength equal to the array period and serves as the demarcation between guided and freely propagating fields interfering to the left at shorter wavelengths and plasmon related resonances to the right at longer wavelengths as described in the later sections of this work.

Figure 2 shows the transmission intensity when a 3.5 μm wide central resonator element is centered in the 4.0 μm hole and illustrates the effect of thickness on system response. When both central resonator and Au plate are thin (i.e., 0.1 μm), a very broad peak is seen at a wavelength of roughly 14 μm and the resonance at the array period wavelength is dramatically suppressed. When the plate thickness is increased to 2 μm while keeping the resonator thin and centered between the front and back plate surfaces, the resonant frequency shifts to a lower wavelength. More significantly, a dramatic reduction is observed in the resonance line width from 7 μm FWHM to less than 1 μm FWHM. When both the resonator and plate thicknesses are increased to 2 μm, the 14 μm resonance shifts to a slightly longer wavelength and additional narrow resonance peaks are seen at roughly 7 μm and below while still maintaining a relatively narrow line width. It is this narrowing of the resonant response which makes this topology suitable as a filter element. Interestingly, it was found that the when the thin central resonator was aligned with either the front or back surface of the plate as opposed to being centered between the two surfaces, no reduction in line width was observed. This suggests that the spreading of the electric field over a larger area reduces loss, improving the resonator quality factor.

Figure 3 shows transmission intensity as a function of both 4 μm and 3 μm holes with 3.5 μm and 2.5 μm resonators respectively at array periods of both 6 μm and 7 μm. The arrows in the

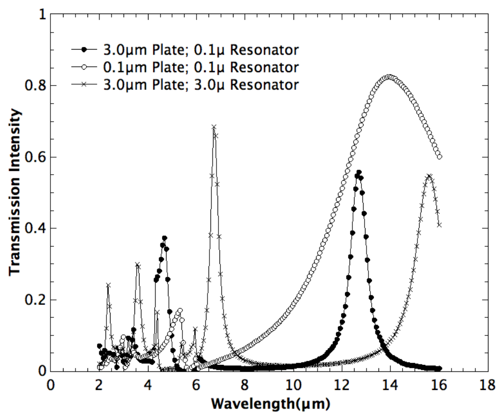



Figure 2: Array response as a function of plate and resonator thickness for a 4 μm wide hole and a 3.5 μm wide resonator.

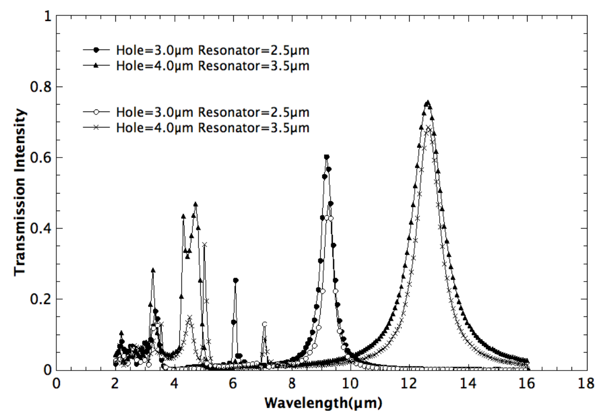



Figure 3: Transmission resonance of two different hole/resonator combinations as a function of array period. The arrows show the fundamental array period resonance for each period. No effect on resonance wavelength is observed to be a function of the array period for this system.

figure point to the resonance that correspond to each array period; no significant shift in resonance due to this change in period is observed. Figure 4 shows the effects of resonance wavelength for a fixed hole width of 3 μm as a function of both resonator width and resonator thickness. This figure illustrates the typical tuning range that could be expected for this type of metallic filter element.

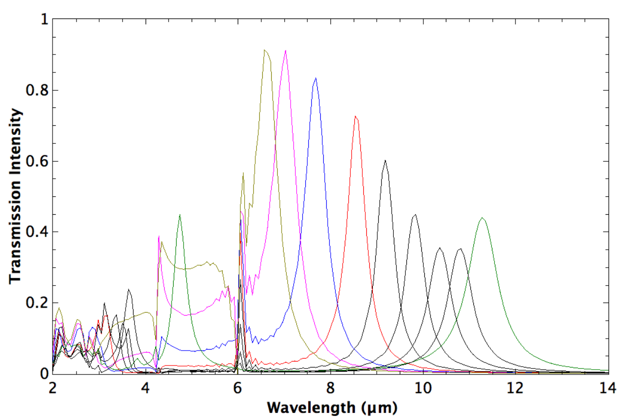



Figure 4: Resonance wavelengths for a 3 μm wide hole in a 2 μm thick Au film as the thickness and width of the initially 0.1 μm thick, 2.5 μm wide resonator is varied.

## 3. DISCUSSION

Although the predictive behavior of the loaded hole topology investigated here, in terms of any combination of hole width, array period, resonator dimension and film thickness is not immediately at hand, a few general observations are made regarding transmission through an array of holes without resonator loading.

It is generally assumed that the optical transmission of light through sub-wavelength holes is a plasmon-mediated process. Because plasmon modes require the addition of transverse momentum in order to be excited, either a scattering event, or a grating based topology is required. In this case, both the edges of the hole as well as the hole periodicity, effectively producing a grating topology, are available to provide the needed transverse momentum for plasmon mode generation. Once the plasmon modes are generated, standing waves will be resonantly established across the face of the film in order to satisfy the array periodicity of the system. Thus, the most fundamental mode will have a wavelength equal to the array period times the effective index [8]. At the wavelengths investigated here, and from Equation (1), the effective index of a freely propagating plasmon mode is seen not to deviate substantially from unity. In addition, it has previously been shown that the guided plasmon mode available to this system, namely the 90° wedge mode, also has an effective index that does not substantially deviate from unity [9]. This implies that the fundamental resonant wavelength should be roughly equal to the array period, as has been observed in this work. Additional structure in the hole-only transmission case results from the holes acting as a grating and producing waves with propagation vectors at grazing angles.

Because the array period alone sets the fundamental resonant frequency it is the array periodicity that sets the minimum energy available to excite any plasmon mode.

In other words, there is enough energy available in the incident photons to excite those plasmon modes to the right of the wavelength equal to the array periodicity once the momentum matching condition is met. All those effects to the left of the fundamental array periodicity wavelength, stem from freely propagating field interactions, which have propagation vectors out of the plane of the film.

These freely propagating fields are above the cutoff frequency of the hole when acting as a waveguide, and allow free transmission of propagating fields through the hole when appropriate boundary conditions are met.

Once excited, plasmon modes carry energy from the incident side of the film to the exit side of the film and resonate with the geometric features there. These resonant interactions can be complex in nature, but once excited, produce transmission into the far field, similar to that produced by oscillating dipoles.

Qualitatively, the structure can be described as an effective impedance encountered by the plasmon mode currents. The gaps between resonator and screen present a capacitance that depends on the width of the gap, thicknesses of the screen and resonator, front-to-back position of the resonator, and the lateral dimensions of the hole and resonator. The path length around hole presents a resistance and inductance to plasmon mode current. The interaction of these two features produces a resonance at a larger wavelength than the fundamental mode of the holes-only structure. Increasing the inductance or capacitance by modifying the geometry will increase the resonant wavelength of the structure.

It is not clear at this point the best methodology to use to model the interactions of these weakly bound plasmon modes and their trajectories over the meta-surface topology, nor how to a priori predict the resonant condition. The reduction in line width due to film thickness does suggest however a lower loss and higher quality factor resonance is achieved by increasing the metal thickness of the plate and the resonator to values comparable to the array period.

## 4. CONCLUSION

A resonator-loaded hole in a metal film has been investigated using FDTD techniques. A dramatic reduction in transmission resonance line-width has been observed when the metal film thickness is increased to values on the order of the array period. This reduction in line width, along with the overall size of the arrays, suggests a potential application of such films as a narrow band filter for multispectral imaging applications, whereby each individual pixel of a focal plane array can be assigned a specific spectral line by placing a suitably designed array directly over each pixel of the focal plane imaging array.

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