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Dual resonance mechanisms facilitating enhanced optical transmission in coaxial waveguide arrays

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Here we experimentally and computationally demonstrate high transmission through arrays of coaxial apertures with different geometries and arrangements in silver films. By studying both periodic and random arrangements of apertures, we are able to isolate transmission enhancement phenomena due to surface plasmon effects from those due to the excitation of cylindrical surface plasmons within the apertures themselves.
Ebbesen et al.’s [1] report of Enhanced Optical Transmission (EOT) through periodic arrays of sub-wavelength holes in thin metallic films has sparked considerable interest in understanding the mechanisms producing high transmission through apertures in metallic films. In the experiment of Reference 1, enhanced transmission arose as a consequence of Planar Surface Plasmons (PSPs) coupling to the fields in the apertures and the nature of the resonance depends critically on the periodic arrangement of apertures [2-6]. An alternative enhancement mechanism arises from localized resonances of the apertures themselves. In general it is difficult to isolate the roles played by the different enhancement mechanisms. In the case of arrays of coaxial (or annular) apertures, [7-11] however, the aperture resonances can be tailored to occur at wavelengths well-separated from any PSP resonances.

Transmission enhancement facilitated by Cylindrical Surface Plasmons (CSPs) in coaxial waveguides has been shown to be a waveguide resonance effect, [7-11] where a field incident on a coaxial waveguide couples to the TE\textsubscript{11} mode at the waveguide opening. The TE\textsubscript{11} mode then propagates along the waveguide with CSPs on the inner and outer metallic surfaces [10,11]. The resonant wavelength for this phenomenon is given by the cutoff wavelength for the TE\textsubscript{11} CSP mode. An important feature of this waveguide resonance is that the resonant wavelength depends solely on the attributes of the individual waveguide and does not rely on the presence of a periodic arrangement of waveguides. This is in contrast to transmission enhancement facilitated by PSPs with resonances that depend on the periodicity of the array and the dielectric constants of the metal and dielectric at the interface. In this letter, we report on experimental and computational investigations into the far-field transmission characteristics of sub-wavelength coaxial waveguides in the presence and absence of planar surface plasmons (PSPs).
Coaxial waveguide structures were fabricated in a 140nm thick silver film on a glass substrate using a FEI Nova NanoLab FESEM-FIB focused ion beam system. Periodic (31 × 31 arrays) and random arrangements of structures were produced. The silver films were thermally evaporated onto a glass substrate with a refractive index of 1.52. Table 1 shows the parameters describing the structures investigated in this study. Note that sample 2 consists of a random arrangement of coaxial waveguides, rather than a periodic array, although a minimum separation of 800 nm was maintained between the apertures to prevent touching or overlap.

Normal incidence transmission spectra were obtained by illuminating the samples from the substrate side using a supercontinuum white light source, with the transmitted fields being collected by a SMF-28 optical fibre and analyzed with an ANDO AQ6317B optical spectrum analyzer. The supercontinuum source was created by passing 1.5kW, 10ps pulses from a mode-locked Nd:YVO4 laser (λ=1064nm) through a 20m long section of silica photonic crystal fiber with zero dispersion at 1040nm. The transmitted light was collected with an optical fiber single-moded at 1550 nm. All experimental spectra were smoothed using a Fourier band-stop filter to remove Fabry-Perot fringes due to interference within the glass substrate and normalized to the power collected in the absence of the device. Incident light was polarized along the long period axis of the arrays (y-direction).

Periodic structures illuminated with a normally incident plane wave were modeled using the Finite-Difference Time-Domain (FDTD) method (NRL High Accuracy Scattering and Propagation (HASP) code)) [10,11]. It was anticipated that the transmission characteristics of single apertures would be similar to a random arrangement of apertures where the minimum separation is such that coupling between the apertures is extremely weak. Since the implementation of the FDTD method used assumed periodic boundary conditions, Finite Element Method (FEM) simulations of the transmission of a 1.0μm field radius Gaussian beam
through single apertures were undertaken using the COMSOL Multiphysics software package. For all simulations, the optical properties of the silver film were taken from the data of Johnson and Christy [12] and the transmitted power normalized to the power incident on the structure.

Experimental transmission spectra for three different samples are shown in figure 1, along with simulated spectra calculated using the FDTD and FEM techniques as appropriate. The corresponding CSP peak positions were calculated using the method derived by Haftel et al. [10,11], whilst the PSP positions for samples 1 and 3 were determined using the well-known expression for the wavelength of the (0,±1) silver-silica PSP [2]. Note that sample 2 possesses a lower density of waveguides per unit area than sample 3. For this reason, the experimental spectrum for sample 2 shown in figure 1(b) has been normalized to sample 3 with respect to its hole-area fraction.

Reasonable agreement is found between the experimental data and FDTD simulation for sample 1 shown in figure 1(a). Both spectra exhibit a transmission peak with position (1418nm for the experiment and 1330nm for FDTD) that closely matches the predicted CSP resonant wavelength of 1302nm. Both spectra also display a low intensity peak with a position that can be attributed to the predicted PSP resonant wavelength. Note that for this particular geometry, the CSP peak is considerably higher than the maximum associated with excitation of the PSP. The relatively low intensity of the PSP peak determined experimentally compared to that computed is partly a consequence of the fact that the model assumes plane wave illumination rather than a finite focused spot of diameter ~ 100 μm.

The experimental transmission spectrum through sample 2 (figure 1(b)) displays a very low intensity peak centered on a wavelength of 1040nm, only slightly red-shifted from the predicted CSP resonant wavelength of 993nm. Since sample 2 consists of a random arrangement of waveguides no PSP resonances were anticipated and none observed. FEM simulations for a
single, isolated waveguide were performed, with the results predicting a transmission efficiency peak position of 1050nm, which is also in close agreement with the predicted CSP resonant wavelength. Note that the differences between the experimental set-up and the simulation, which assumes only a single aperture, mean that it is not possible to draw quantitative conclusions about the magnitude of the transmission maximum. We thus conclude that the enhancement in transmission in sample 2 is facilitated only by CSP resonant phenomena.

To further investigate the excitation of PSP resonances in coaxial waveguide arrays, a periodic array of coaxial waveguides with aperture geometries identical to that of sample 2 was fabricated, with the resulting transmission spectrum shown in figure 1(c). The spectra clearly show two different high transmission efficiency peaks, a broad peak positioned at 1063nm and a much narrower peak with higher intensity positioned at 1319nm. This first peak has approximately the same location as the predicted CSP resonant wavelength of 993nm, but has a different shape and peak height than the CSP peak shown for sample 2. The position of the second peak is in good agreement with the predicted PSP resonant wavelength of 1264nm.

It is clear that despite the fact that samples 2 and 3 possess waveguides with identical geometries, the two samples reveal very different transmission spectra. The PSP peak in sample 3 provides experimental evidence for PSP facilitated EOT in an array of coaxial waveguides in thin silver films, and is well-explained by the work of many authors [1-6]. The peak in the transmission spectrum of sample 2 is well-characterized by Haftel et al.’s [10,11] CSP prediction and is fundamentally due to waveguide resonance effect for the TE$_{11}$ coaxial waveguide mode. The low intensity of this peak compared with the corresponding feature in sample 3 is partly attributed to relatively poor coupling of the light transmitted through the random array into the collection fiber. Furthermore, wavelength-dependent coupling between the apertures may also lead to changes in the shape and magnitude of the measured peak from that calculated. This issue
is the subject of on-going investigation. The broad peak present in sample 3 has a position which also closely matches the CSP model prediction of 993nm although the shape of this peak is quite different to that of sample 2. The broad peak observed in sample 3 is, therefore, the CSP facilitated peak, superimposed on the diffraction effects outlined in references 5 and 6. Rockstuhl et al. [13] have also recently reported investigations of transmission through random and periodic arrangements of coaxial apertures. Their research was primarily aimed at the study of the CSP resonances, whereas we here extend this research to devices where clear PSP and CSP resonances can be identified.

In summary, we have demonstrated enhanced transmission through coaxial waveguides in thin silver films clearly identifiable as being mediated by alternative surface plasmon resonance phenomena. Furthermore, we have shown strong experimental and theoretical evidence that CSP resonance effects are also capable of facilitating high transmission through such systems both separately to and simultaneously with PSP phenomena. CSPs can also enhance PSP peaks by raising the cutoff wavelengths of the apertures compared to what one would expect from apertures with perfectly conducting walls, and this effect can be increased by using coaxial apertures. We also re-iterate that coaxial waveguide arrays provide an ideal platform for investigating the difference between PSP and CSP facilitated EOT, due to the ability to fabricate coaxial waveguides with PSP and CSP resonant wavelengths that are well separated from each other.

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**Figure captions**

Figure 1. Experimentally measured and calculated transmission spectra for samples 1 (a), 2 (b) and 3 (c) displaying enhanced facilitated by CSP and/or PSP resonant phenomena. Scanning electron microscope images of sections of each sample are shown as insets.

**Table captions**

Table 1. Geometric properties describing the three structures studied. Where relevant, $d_1$ and $d_2$ are the periodicities of the array in the $x$- and $y$-directions respectively, $a$ is the outer radius of the apertures and $b$ is the inner radius [7,10,11].
References


Figures

**Figure 1(a)**

**Figure 1(b)**
Figure 1(c)
Table

Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>a</th>
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