The effect of periodicity on the extraordinary optical transmission of annular aperture arrays

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This work systematically evaluates the effect of array periodicity on the near infrared transmission characteristics of annular aperture arrays (AAAs) in gold films. Both the experimental and theoretical transmission spectra of AAAs are shown to be sensitive to the period and the arrangement of the apertures within the array. The spectra of square arrays with periods ranging from 1400 to 600 nm show a strong correlation with surface plasmon polariton (SPP)-Bloch modes of the metal/dielectric interfaces. For rectangular AAAs the transmission spectra are significantly attenuated and reveal a polarization sensitivity that arises from the breaking of the symmetry and degeneracy of the SPP-Bloch modes. © 2009 American Institute of Physics.

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Nanoscale metal structures have generated considerable interest since Ebbesen et al.
1 demonstrated that an array of subwavelength holes transmits more light than predicted by the classical diffraction theory2 and correlated the extraordinary optical transmission (EOT) with the resonant excitation of surface plasmons3 that arise from the periodic nature of the arrays.4 On a fundamental level, this discovery has sparked interest in the basic process underlying the ability of a nanoaperture to tunnel light with high efficiency and the physics of surface plasmons. On an applied level this work has encouraged researchers to explore the potential of creating nanoscale sensors,5 communication devices,6 optical circuits,7 and other devices from such arrays.

In contrast with cylindrical hole arrays, coaxial, or annular aperture arrays (AAAs), contain a metallic island within the cylindrical nanoaperture so that a ring with a <100 nm gap is created (see Fig. 1). It was first predicted by Baida and van Labek5 that these structures would be capable of supporting coaxial TE11 waveguide modes, and it was later demonstrated that structures in a two dimensional square array exhibit excellent transmission,8–12 approaching 90% (Ref. 13) under the right geometric configuration. Orbons and Roberts14 and Haftel et al.15 proposed that the enhanced transmission arises from the excitation of cylindrical surface plasmons at the edges of the coaxial structure on both the inner and outer rings. It also was suggested that, owing to the periodic nature of the AAA, surface plasmons could be excited and thus affect the transmission.16 Most recently it was suggested that the mechanism for EOT in AAAs does not solely arise from a waveguide resonance within the individual aperture but also from array-induced surface plasmons being in resonance with the waveguide mode.17 This study extends recent work on AAAs by exploring how surface plasmon polariton (SPP)-Bloch modes are excited by a two dimensional array of annular apertures influence the EOT process. To this end, AAAs in which the array period was systematically varied were fabricated. The experimental transmission spectra are compared with the results of finite difference time domain (FDTD) calculations.

Two series of arrays (Fig. 1) were fabricated with nominally identical annular aperture geometry R1=125 nm and R2=215 nm. In the first series, the period was varied between 1400 and 600 nm while keeping the total number of apertures constant at 20×20. The second series consisted of arrays with different periodicities along the x- and y-axes of the arrays. Along one axis the period was held fixed at 1400 nm and on the other axis the period was varied from 1000 to 600 nm.18

The wavelength of SPPs excited by Bragg-type scattering over a two dimensional nanoaperture array can be approximately calculated by

\[ \lambda_{SPP}(i,j) = \frac{P}{(i^2 + j^2)^{1/2}} \left( \frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m} \right)^{1/2} , \] (1)

where P is the period of the array, i,j are integers corresponding to Bragg-type scattering modes, \( \varepsilon_d \) is the dielectric constant for the dielectric, and \( \varepsilon_m \) is the real component of the complex dielectric function of the metal. Using the above relationship it is possible to estimate \( \lambda_{SPP} \) at a given period. In Eq. (1) a Drude model was used for the dielectric

FIG. 1. (Color online) (a) Diagram of the system under study: a 150 nm gold film on quartz with annular apertures in an array. Individual annular apertures are defined by the inner radius R1 and the outer radius R2 with a fixed period that represents the spacing between each aperture. (b) SEM of FIB milled AAAs with R1=125 nm, R2=215 nm and period=800 nm. (c) SEM of AAAs with period=1400 nm on the x-axis and 800 nm on the y-axis.

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function of Au, which is fit to experimental data from 450 to 2000 nm. The dielectric constant of air was taken to be 1.0 and that of the quartz substrate was taken to be 2.10. For a more accurate comparison with the experimental data, AAA transmission simulations were done using the FDTD technique.

Figure 2 shows the experimental and FDTD simulated transmission spectra of AAAs with periods ranging from 1400 to 600 nm. Panels (a) and (b) show experimental spectra and panels (c) and (d) show simulated spectra. Systematic trends in the transmission spectra as a function of period are evident, namely, the overall transmission increases, the $\lambda_{\text{max}}$ of the dominant resonance blueshifts, and the transmission peak broadens as the period of the array is decreased. These trends correlate with SPP-Bloch modes that are excited by the AAA at the Au/quartz interface. For $R1=125$ nm and $R2=215$ nm, the cutoff wavelength of the TE$_{11}$ guided mode is 1068 nm, which is significantly to the blue of the main transmission peaks for all periods $P > 700$ nm. The simulated transmission spectra in panels (c) and (d) show strong qualitative agreement with the experimental spectra in panels (a) and (b). In particular, the modes exhibit a similar period dependence on the width of the transmission peak and the wavelength of maximum transmission.

Figure 2(a) and 2(b) show the experimental transmission spectra of AAAs as a function of period. For $P = 1400$–$1100$ nm, one primary mode is present and it correlates with the $\pm (1,1)$ Au/quartz mode, starting at $\lambda = 1575$ nm for $P = 1400$ nm. This mode blueshifts with decreasing period and the transmission reaches a maximum of roughly 12%. For $P = 1200$ and $1100$ nm, another transmission resonance appears on the red edge between 1700 and 1800 nm, and it corresponds with the $\pm (1,0)$ Au/quartz mode. Figure 2(b) shows the spectra for AAA’s with periods from 1000 nm to 600 nm. For these shorter array periods the $\pm (1,1)$ Au/quartz mode has a weak transmission and is no longer evident past a period of 800 nm. The dominant transmission band in these spectra arises from the $\pm (1,0)$ Au/quartz mode. Its transmission maximum blueshifts with decreasing period and its maximum transmission increases significantly, from 9% to 35%, between $P = 1100$ nm and $P = 900$ nm. Past the point of maximum transmission at $P = 900$ nm, the transmission maximum of the mode continues to blueshift and the full width at half maximum (FWHM) of the peak increases along with a slight decrease in overall transmission.

Figures 2(c) and 2(d) show the results of the FDTD simulations for AAAs whose geometries correspond with the experimental AAAs (c with a and d with b). All the experimentally observable resonances are reproduced well in the FDTD calculations, with a few notable exceptions. At $P = 1400$ nm [Fig. 2(c)], in addition to the $\pm (1,1)$ Au/quartz mode at 1600 nm, there is another peak at 1390 nm, which is weakly present in the experimental spectra. In the FDTD calculation, this peak blueshifts and its FWHM decreases; however, this behavior is not evident in the experimental spectra. In addition, a very weak transmission peak, also not present in the experimental spectra, appears at 1450 nm for $P = 1400$ nm and shifts to 1150 nm for $P = 1100$ nm. The calculated spectra for periods 1000–600 nm [Fig. 2(d)] show excellent agreement with the experimental spectra [Fig. 2(b)], the only noteworthy difference is the lack of decreasing transmission past $P = 900$ nm, which is not present in the calculations. In addition to these differences, the absolute transmission found in the simulation is higher than that found experimentally and the calculated resonances are always sharper than the experimental resonances. The spectral features in Fig. 2(c) at the shorter wavelength arise from a combination of the $\pm (1,1)$ Au/air SPP-Bloch mode as well as the $\pm (1,1)$ Au/air wood anomaly. These features are not seen in the experimental spectra [Fig. 2(a)] due to the low transmission of the FIB milled AAAs; however, a weakly defined $\pm (1,1)$ Au/air mode is evident. These spectral differences likely result from differences between the idealized structure of the arrays used in the simulation and the imperfect experimental structures, which may give rise to a “lossier” device that has a lower transmission and broader resonance for a given mode.

A comparison between the observed transmission peaks, FDTD simulated peaks, and the calculated $\lambda_{\text{SPP}}$ from Eq. (1) for a given period (Fig. 3) show similar trends for both the $\pm (1,1)$ and $\pm (1,0)$ Au/quartz modes. In general, the $\lambda_{\text{max}}$ of the simulated peaks are in agreement with the experimental $\lambda_{\text{max}}$ to within 50 nm and they appear to show a redshift. The $\lambda_{\text{SPP}}$ calculated from Eq. (1) shows a strong correlation but a large blueshift from the experimental $\lambda_{\text{max}}$. As the period is decreased the difference between the location of the calcu-

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**FIG. 2.** (Color online) Experimental [(a) and (b)] and simulated [(c) and (d)] transmission spectra of AAAs with periods of 1400–1100 nm and 1000–600 nm corresponding to $\pm (1,1)$ Au/quartz and $\pm (1,0)$ Au/quartz SPP-Bloch modes, respectively. For clarity, in panels (a) and (b), ★ denotes $\pm (1,1)$ Au/quartz and ▼ denotes $\pm (1,0)$ Au/quartz modes.

**FIG. 3.** (Color online) Comparison of measured $\lambda_{\text{max}}$ (squares) from transmission spectra, FDTD calculated (circles) spectra, and calculated $\lambda_{\text{SPP}}$ (triangles) for AAAs at different periods.
FIG. 4. (Color online) (a) Transmission spectra for asymmetric AAAs with the period on one axis held fixed at 1400 nm and the period along the perpendicular axis varied from 1000 to 600 nm, with the polarization of incident light along the varied axis and (b) asymmetric AAAs with the polarization along the axis with the fixed period.

The set of spectra in Fig. 4 show the dramatic effect of breaking the square symmetry of the AAAs. **Figure 4** appears to reflect a more complex collection of processes associated with the SPP-Bloch modes when the period is unique along the axis with the fixed period. As the apertures are brought closer together, however, the difference between the calculated wavelength and the measured wavelength increases substantially, approaching 400 nm for the ±(1,0) Au/quartz mode at P = 600 nm. In the regime where the apertures are spaced far enough apart so that no significant overlap of the annular aperture’s waveguide mode with the SPP-Bloch modes [λ_{max} > 1450 nm (this value obtained from an FDTD simulation for a single annular aperture)] can occur, it is possible to correlate a particular transmission peak of the AAA to a SPP-Bloch mode. As the apertures are brought closer together so that the SPP-Bloch modes and the AAA waveguide modes can interact with each other, the nanostructure’s transmission spectrum appears to reflect a more complex collection of processes occurring over the array. The FDTD simulations appear to capture these features.

The set of spectra in Fig. 4 show the dramatic effect of breaking the square symmetry of the AAAs. Figure 4(a) shows the transmission of AAAs for linearly polarized light whose field is oriented along the axis in which the period changes. As the period is decreased the transmission peak corresponding to the ±(1,1) Au/quartz mode is blueshifted and reaches a maximum transmission at 6% (half of that for the P = 1200 × 1200 nm² counterpart) and decreases to roughly 4% at P = 1400 × 800 nm². The dominant transmission peak in Fig. 4(a) is assigned to the ±(1,0) Au/quartz mode. This mode first appears near λ = 1600 nm for the 1400 × 1000 nm² array. It blueshifts and increases in transmission from 6% to 18%, for the 1400 × 800 nm² array. Changing the axis of the light polarization to be oriented along the direction of the static period gives rise to the spectra in Fig. 4(b), which are quite distinct from those in Fig. 4(a). The transmission spectra in this case do not show a strong systematic shift with the change in period. Rather, the transmission maintains the same features of the square 1400 × 1400 array, with the overall magnitude increasing as the period is decreased, along with a slight blueshift in the ±(1,1) Au/quartz mode. These data show that the SPP-Bloch modes play a significant role for the transmission of AAAs, and that the symmetry of the AAAs can be used to tailor the devices’ frequency response for particular polarizations.

These studies show that the strong transmission observed with AAAs is strongly linked to the periodicity of the annular apertures in the array and the resonant excitation of SPP-Bloch modes, especially for the metal/substrate interface. In the context of creating frequency tunable structures, it is possible to optimize the spacing between the apertures so that the width of the transmission resonance is minimized and the transmission magnitude is maximized. These findings have significant implications for the use of such structures in telecommunications and sensing applications with NIR photonic devices.

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20. It was not possible to assign the ±(1,1) Au/air SPP-Bloch modes, which for all AAA periods are ∼50 nm to the blue of the ±(1,1) Au/quartz modes. Because the FWHM for the transmission peaks is >150 nm, it may be that both modes contribute to the transmission in Fig. 2(b).
21. SPP-Aas [k_{AA}^{-1}] = P_{x}P_{y}[(P_{x}^{2}+P_{y}^{2})^{-1/2}x_{y}x_{y}]^{2} is the analogous expression for SPP-Bloch modes when the period is unique along the x- and y-axes, P_{x} and P_{y} denote the periods along the x- and y-axes.