Strong Polarization in the Optical Transmission through Elliptical Nanohole Arrays

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Strong polarization dependence is observed in the optical transmission through nanohole arrays in metals. It is shown that the degree of polarization is determined by the ellipticity and orientation of the holes; the polarization axis lies perpendicular to the broad edge of the ellipse. Furthermore, the depolarization ratio shows a squared dependence on the aspect ratio of the holes, which is discussed in terms of coupling into and out of the surface plasmon modes. The observed results will be useful for tailoring the polarization behavior of metallic nanophotonic elements in many applications, including surface plasmon enhanced optical sensing and ultrafast optical switching.

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Recent works have demonstrated a 10^4 increase in the second harmonic generation from a metal [1], a 40 times increase in the fluorescence of molecules on a metallic surface [2], entanglement preservation through macroscopic plasmon propagation [3], and femtosecond modifications in the transmission through metallic holes [4]. These results are exciting to applications in several fields, including nanophotonic biosensing [5], quantum information processing, and ultrafast optical switching. The common feature in these phenomena is that they are all enhanced by the surface plasmon (SP) mediated enhancement of optical transmission through subwavelength holes in metals.

The established theory for the transmission of light through subwavelength apertures predicts that the transmitted intensity decreases with the hole diameter as $(d/\lambda)^4$, where d is the hole diameter and λ is the optical wavelength [6]. Extraordinary enhancements, over 3 orders of magnitude greater than that prediction, have been observed when subwavelength holes are patterned as a periodic array in a metal film [7]. The transmission efficiency, normalized to the hole area, has been shown to exceed unity, so the light is effectively focused through the holes. The enhanced transmission occurs at particular wavelengths that satisfy the Bragg condition, given by the periodicity of the array, using the propagation properties of SP modes [7]. Hole arrays in nonmetallic substrates do not show similar enhancements, confirming the role of the SP modes. In addition, the polarization dependent coupling of SP modes to nanoholes in a metallic film has been imaged directly using scanning near-field optical microscopy (SNOM) [8].

The enhanced transmission in arrays has been studied by varying the metal film, the lattice geometry, the hole spacing, the hole diameter, and the film thickness [7,9,10]. The effect of the shape and orientation of the holes, however, has not been considered previously. Experiments so far have suggested that in "the long-wavelength limit... the transmission coefficient depends on hole area, but does not appreciably depend on hole-shape" [11]. This is not the case when considering the polarization dependence of transmission through elliptical holes, as will be demonstrated here.

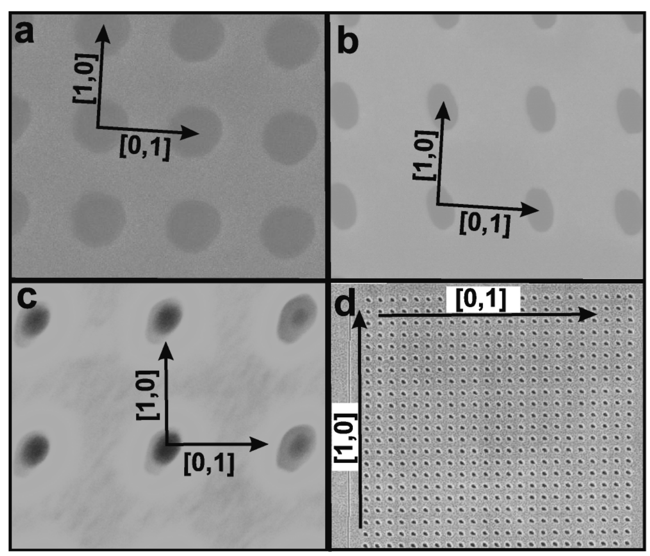

FIG. 1. Scanning electron micrographs of square nanohole arrays in gold. (a) Nearly circular holes. (b) Elliptical holes, 0.6 aspect ratio and major axis at $-12°$ to the $[1, 0]$. (c) Elliptical holes, 0.6 aspect ratio and major axis at 33° to the $[1, 0]$ axis. (d) An expanded view of (c) showing the full 16.1 μm wide array of 529 holes (holes spaced by 704 nm).

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In this Letter, the light transmission through arrays of subwavelength elliptical holes in a gold film is studied by varying the orientation and aspect ratio of the holes. The polarization of the transmitted light is found to be strongly dependent on the orientation and geometry of the holes, and the influence of the aspect ratio on the polarization is explained in terms of coupling to the SP modes.

The nanoholes were created using focused Ga-ion beam milling (30 keV) of a 100-nm thick gold film on a glass substrate. Several square arrays of 23×23 holes with different periodicities were fabricated. The ellipticity of the holes was controlled by using an astigmatic ion beam. The orientation of the major axis of the ellipse was also varied. Figure 1 shows scanning electron micrographs of three samples, demonstrating the ability to create circular and elliptical holes, as well as the ability to control the orientation of the ellipse's major axis relative to the array lattice. The optical transmission spectra of normally incident unpolarized light through all the arrays utilized in this work showed the previously reported enhanced resonances, agreeing with the Bragg condition for the SP modes [7].

Figure 2 shows the transmission spectrum for two orthogonal linear polarizations of the incident white light. The major axis of the elliptical holes was parallel to the [1, 0] axis of the lattice, the aspect ratio of the ellipse was 0.3, and the spacing between the holes was 500 nm. The peak at 655 nm agreed well with the SP resonance for the gold-glass interface. There was a dramatic reduction in this peak as the polarization was rotated from the *p* polarization to the *s* polarization (with the *p* polarization defined along the [0, 1] direction as shown in Fig. 1). Note that the [0, 1] direction was selected to be most perpendicular to the major axis of the ellipse. The resonant transmission was enhanced when the electric field polarization was perpendicular to the major axis of the elliptical hole.

Figure 3 shows the polarization dependence of the transmitted intensity at the resonant wavelength, which follows a cosine function, with the maximum for *p* polarized light (along the [0, 1] lattice direction).

The same cosine dependence on the polarization was observed for ellipses oriented parallel and tilted 33° to the [1, 0] axis. When the ellipse was tilted, the orientation of the electric field polarization corresponding to the maximum transmission followed the orientation of the ellipse. This result has been verified on five different ellipse orientations. The maximum transmission was for the *p* polarization, along the direction that was perpendicular to the major axis of the ellipse.

Ellipses with different aspect ratios were tested, each aligned with the major axis along the [1, 0] direction of the lattice, to within 20°. Figure 4 shows the depolarization ratio between the minimum and maximum transmission intensities (i.e., for the two orthogonal polarizations) as a function of the aspect ratio of the holes. The transmission ratio had a squared dependence on the aspect ratio—a log-log fit produced a slope of 2.07. The squared plot is shown with a solid line.

The strong polarization dependence of the transmission as a function of the ellipse orientation resembles previous observations of transmission through a subwavelength slit surrounded by surface corrugations [12] and also the transmission through metallic nanowire gratings [13]. In those experiments, it was shown that

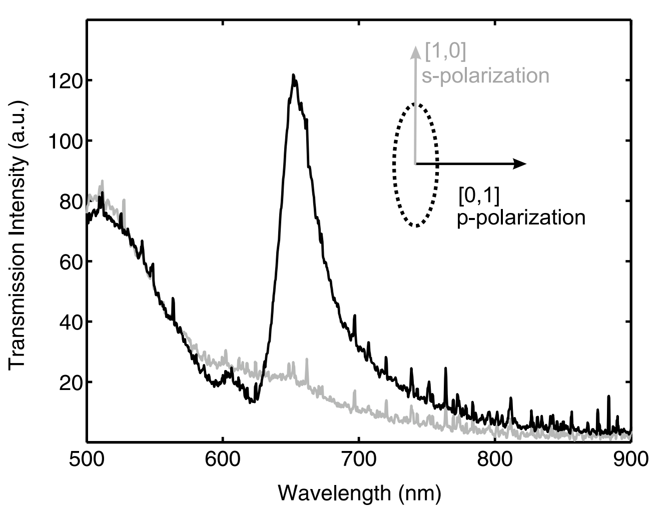

FIG. 2. Transmission spectrum through elliptical nanohole array for two orthogonal linear polarizations, with a 0.3 aspect ratio between the minor and major axes of the ellipse. The *p* polarization is parallel to the [0, 1] direction.

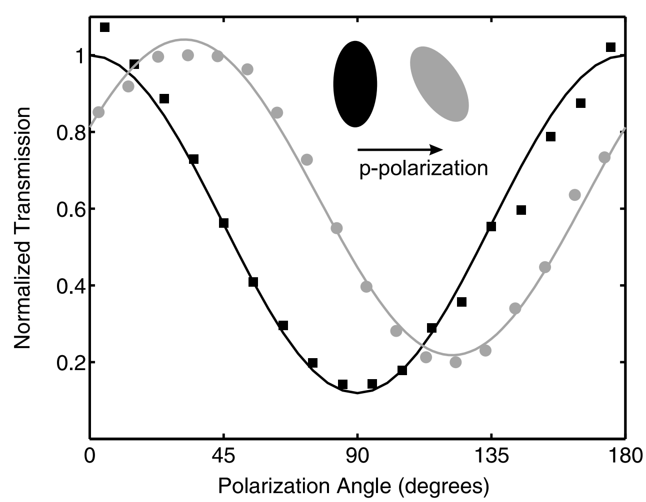

FIG. 3. Polarization dependence of transmission at the (0, 1) resonance peak, normalized to the maximum. Transmission shows cosine dependence when the major axis of the ellipse is oriented both at 0° and 33° to the [1, 0] axis of the array. The *p* polarization, along the [0, 1] direction of the lattice, corresponds to a polarization angle of zero degrees. The maximum transmission occurs for polarization perpendicular to the broad side of the ellipse.

the enhanced transmission occurred only for the p polarization, where the electric field is perpendicular to the long axis of the slits. The enhanced transmission for p polarization was also found in simulations for a 1D array of grooves in a metal [14]. If we consider an array of elliptical holes with their major axis length equal to the lattice spacing itself, and aligned along the $[1, 0]$ direction, then the holes become a series of parallel grooves, as shown in Fig. 5(a). Therefore, in the limiting case we recover a geometry that resembles the 1D case, and the enhanced polarization is expected to be perpendicular to the major axis of the ellipse, as was observed in Fig. 2.

Both the influence of the orientation and the aspect ratio dependence can be understood by noting that the direction of the SP mode propagation is parallel to the electric field [15], and by considering that the coupling into and out of the SP modes occurs at the edges of the holes. Since the SP modes propagate parallel to the electric field polarization, the Bragg resonance from the periodic array is aligned with the optical polarization. For example, the $(0, 1)$ Bragg resonance will be excited by a polarization along the $[0, 1]$ direction. Therefore, if the ellipse, by virtue of its orientation, enhances the coupling to the grating parallel to the $[0, 1]$ direction, as shown in Fig. 5(b), then the transmission will be enhanced for the polarization along the $[0, 1]$ direction as well, as was observed in Fig. 3.

Finally, we consider the squared dependence of the depolarization ratio on the aspect ratio of the holes (see Fig. 4). The SP-enhanced transmission is a resonance phenomenon whereby the SP mode interacts with a periodic lattice grating. Figure 5(c) shows that the light must couple through the edge of the hole twice to interact with the grating: (i) from free space into the SP mode, depicted by κ_1, and (ii) back out of the SP mode, depicted by κ_2. Since there are two coupling events, the efficiency of the resonance scales as $\kappa_1 \times \kappa_2$, or κ^2 when $\kappa_1 = \kappa_2 \equiv \kappa$.

This explains the observed squared dependence, provided that $\kappa \propto l$, where l is the width of the hole as seen by the incident SP plane wave. Such a dependence in the coupling arises from the perturbation the hole introduces to the SP plane wave. In particular, the p polarized SP plane wave, propagating perpendicular to the major axis of the hole, will see the hole as a wider obstacle than an s-polarized plane wave that is incident upon the minor axis.

So far, we have not considered the Wood's anomaly in our discussion, although it is expected to influence the exact transmission spectra. The Wood's anomaly occurs when light diffracts off the lattice grating parallel to the surface. This effect resonantly scatters incident light with wavelength (in the dielectric) equal to the hole spacing, thereby decreasing the enhanced transmission [16]. Fortunately, the SP propagation constant is larger than the propagation constant in the dielectric, so that the enhanced transmission occurs at longer wavelengths. As the size of the holes is increased and the length of propagation within the SP mode is decreased, the enhanced transmission peak will be blue-shifted towards the Wood's anomaly, and thereby reduce the amount of light that is transmitted. By providing the first polarization and shape dependent measurements on the SP-enhanced transmission phenomenon, the experiments presented here will assist in the ongoing development of numerical models (e.g., [11,17,18]), that incorporate both the effects of the SP resonance and the Wood's anomaly.

The phenomenon of SP-enhanced transmission through an array of holes in a metal is both physically

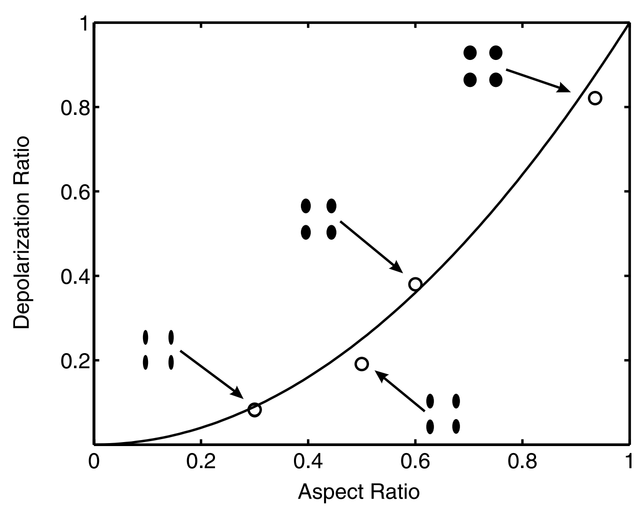

FIG. 4. The depolarization ratio of the transmitted light as a function of the aspect ratio of the holes. Solid line shows the $y = x^2$ curve.

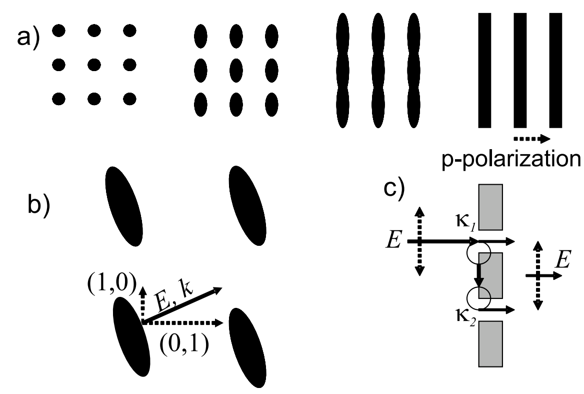

FIG. 5. (a) Elliptical holes approaching limiting case of slits, which only show enhanced transmission for p polarized light. (b) Enhanced SP excitation perpendicular to major axis of ellipse leads to preferential excitation of the $(0, 1)$ resonance with respect to the $(1, 0)$ resonance. (c) Coupling both into and out of the SP mode is required to obtain enhanced transmission from periodic array of holes, which results in a squared dependence of the enhanced transmission on the coupling strength.

interesting and relevant for a number of device applications. We have studied experimentally the transmission properties of elliptical nanohole arrays and shown that they provide a mechanism for strong polarization selectivity. These findings are important for three reasons. First, they provide a means of tailoring the polarization selectivity in nanophotonic devices utilizing the SP mechanism. Second, they quantify the sensitivity of the polarization to the shape of the holes, and thereby define fabrication tolerances for nanophotonic devices where polarization selectivity may not be desirable (e.g., those used in optical networks). Third, these are the first experimental results to explore the polarization dependence and the hole-shape dependence of the SP-enhanced transmission, and therefore they will lead to a better understanding of the physics of the SP mediated transmission.

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