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Short communication

Fabrication and optical measurement of double-overlapped annular apertures

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ABSTRACT

We demonstrate double-overlapped annular aperture (DOAA) arrays fabricated in a gold film via focused ion beam milling. The high order resonance modes of DOAA are investigated both theoretically and experimentally. Polarization dependency is observed for DOAA arrays and lower order resonance modes in the mid-infrared range exhibit extraordinary optical transmission and dependency on geometric parameters.

Localized surface plasmon resonances (LSPRs) and surface plasmon polaritons (SPPs) in metallic nanostructures have attracted intensive interest [1–4], because the resonant frequency depends on the geometrical shapes and local dielectric environment [5]. The extraordinary optical transmission (EOT) phenomenon proposed by Ebbesen and coworkers [6] has found many potential applications [2,7–12]. Many configurations have been theoretically proposed and experimentally built to investigate the underlying physics [13–18]. Annular aperture arrays (AAAs) [19–23] have been widely studied because of their unique optical properties. Recently, double-overlapped annular aperture (DOAA) arrays have been proposed for the sharp apexes formed in the structures [24,25], which can act as optical antennas and significantly enhance the electromagnetic field. However, experimental investigations have not been performed, and the physical mechanism of high order resonance modes has not been discussed or well-studied yet. In this work, we investigate both the high order resonance modes and low order modes of DOAAs. Sensitivity of optical properties of structural parameters on lower resonance modes is observed.

Fig. 1(a) schematically shows the structure of symmetrical DOAA arrays. Electron-beam evaporation was used to deposit a 3 nm-thick titanium film and subsequently a 50 nm-thick gold film onto a pre-cleaned quartz substrate. Then we used focused ion beam (FIB) milling to directly fabricate the DOAAs, whose geometry is characterized as follow: the inner radius $R_i = 360$ nm, outer radius $R_o = 410$ nm, the period in x direction $P_x = 3.48$ μm and in y direction $P_y = 1.32$ μm, and the center distance D between the left annular aperture and the right annular aperture. Fig. 1(b) is the scanning electron microscope (SEM) image of DOAAs with D = 400 nm. A microspectrophotometer (CRAIC QDI 2010) was used to obtain the transmission spectrum with an unpolarized broadband light source (xenon lamp).

To further investigate the working mechanism of DOAAs, finite difference time domain (Lumerical FDTD Solutions) calculations were performed to examine the electric field distribution and obtain the transmission spectrum. The dispersion model of gold was based on the Johnson and Christy [26] model in the material library of the software. Perfectly matched layers (PML) were applied as absorbing boundary conditions for the z direction, and symmetric or anti-symmetric boundary conditions were applied for the x and y directions. A plane wave was illuminated on the top plane of the metallic film.

As shown in Fig. 2(a), there is a strong resonance peak locating at 520 nm for both x- and y-polarized incidence, because the

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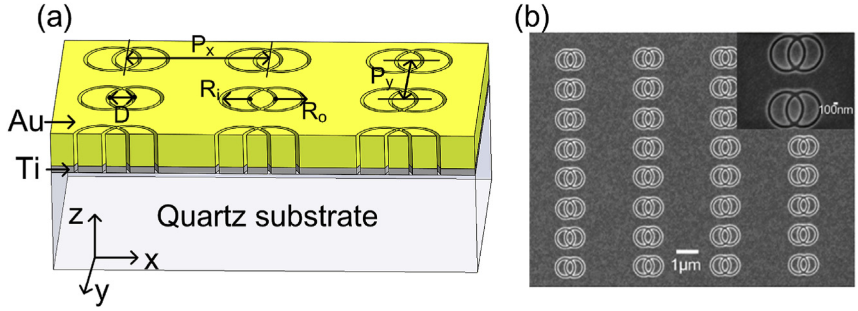

Fig. 1. (a) Schematic illustration of the DOAA structures proposed in this work. (b) SEM image of the fabricated 4 × 8 DOAA array with the center distance D = 400 nm. Inset, magnified view showing two DOAA units with more topography details.

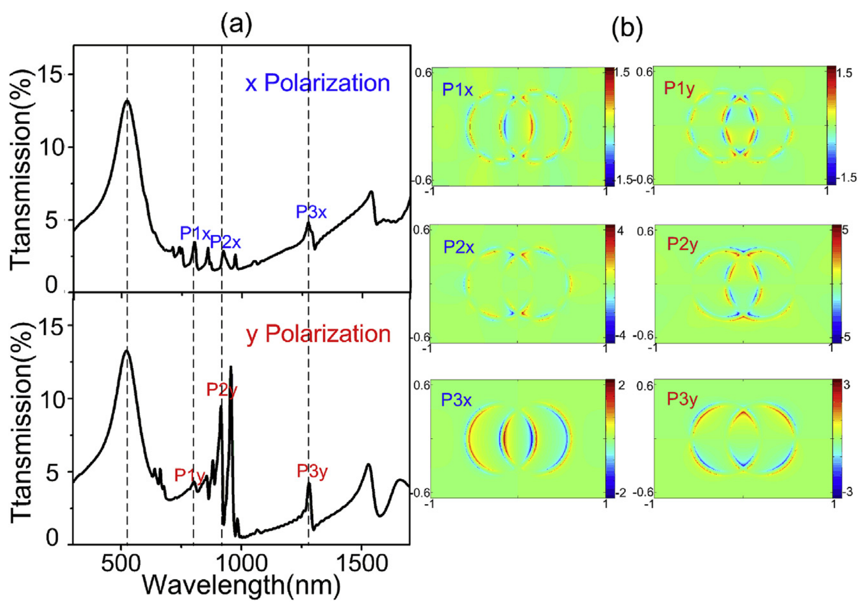

Fig. 2. (a) Calculated transmission spectra of DOAAs with D = 400 nm. Top: x polarization incidence and bottom: y polarization incidence. Black dotted lines show the same location of the transmission peaks under both polarizations, indicated as P1x, P1y, P2x, P2y, P3x, and P3y. (b) Electric field distribution in z direction of the peaks as marked in Fig. 2(a).

interband transition onset of bulk gold locates at 520 nm. At this wavelength, inflection point is present in the real part of refractive index [27,28]. There are more transmission peaks with narrower bandwidth in high frequency band than in the low frequency range. Taking resonance peaks at 801 nm, 916 nm and 1282 nm as examples, which are labeled as P1x/y, P2x/y and P3x/y correspondingly, we investigate the electric field distribution in z direction (Ez) of these peaks. Ez of shorter wavelengths proves a higher order resonance mode, which is mainly concentrated in the nanocavity and sharp apexes of DOAA (P2x and P2y). That means the LSPRs of cavity and SPPs of apexes play an important role in the transmission process. The plasmon resonance of two dimensional structures can be estimated as [21].

$$\lambda = \frac{P_x P_y}{\sqrt{i^2 P_x^2 + j^2 P_y^2}} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \tag{1}$$

where i and j are integers which define the resonance order of x- and y-direction. In this case, ε_m represents the permittivity of gold and ε_d represents the permittivity of quartz. The period in x direction is $P_x = 3.48$ μm, period in y direction $P_y = 1.32$ μm. Therefore, higher order SPPs densely occur in the shorter wavelength range, and the same i, j lead to approaching SPP wavelength under two different polarizations. For the ultraviolet range, the incident light is absorbed because of interband transition of bulk gold. Compared with x polarization, transmission peaks under y polarization show higher amplitude in some resonance modes, and the maximum transmission efficiency (the peak locating at 948 nm) is over twice than the fraction of area occupied by annular apertures. We attribute the EOT under y polarization to the apexes introduced by DOAA structures. There are more apexes pairs in y direction, as shown in Fig. 2(b), which form more complicated electric field distribution. In general, these apexes pairs in the DOAA structures working as nanoantennas can couple with nanocavities and form steep resonance modes with dramatically enhanced electromagnetic field, leading to higher quality factors and refractive index sensitivity than other structures such as nanodisks, nanorings and normal AAAs.

Fig. 3 shows a comparison of the measured transmission spectra on all samples and the simulated spectra with varied center distance D. The results shown in Fig 3(c) are the average of the transmission in x polarization plus that in y polarization. The spectra in measurement and calculation reveal similar line shapes. However, the intensive sharp peaks in Fig 3(c) disappear in experiments, and only several broad peaks reveal at the same positions. On the other hand, the transmission of measurement is lower