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Tuning plasmon resonance in depth-variant plasmonic nanostructures

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ABSTRACT

We demonstrate coaxial-aperture-based plasmonic nanostructures for tunable plasmon resonances in optically thick metal films. Accurate control of etching depth is achieved via cross-section investigation under a scanning electron microscope. Colorful surfaces are observed with varying geometries. The approach developed in this work is potentially useful for optical devices design and development in nanophotonics and integrated optics, especially for imaging and display applications.

Plasmonic color filters have drawn considerable attention and wide interest most recently. Various structures including nanoholes [1], nanorings [2], nanorods [3], nanoslits [4], metal-insulator-metal strips [5], and nanogratings [6], have been experimentally used for color generation thus far. Moreover, actively tunable color filters [7, 8] have also been realized by employing liquid crystals. Plasmonic color filters have irreplaceable advantages over conventional ones based on colorant pigmentation since they are ultra-compact, antifading, and integratable. Therefore, they are of particular importance for the development of display and imaging applications in the visible range [9–18].

Coaxial apertures are a unique structure for single layer metamaterials in the visible range in combination with electro-optical materials [19, 20]. Coaxial apertures are highly symmetrical in the 2D plane and therefore they could be polarization insensitive. This independency is extremely desirable for designing elegant plasmonic color filters with both high efficiency and simple architectures. Compared with conventional geometries (cylindrical nanoholes, for instance), nanorings can support propagating plasmon modes and they can transmit energy up to 90% at certain wavelengths [21] by properly designing the structural parameters. More importantly, such apertures are also potentially useful for plasmon assisted sensing [22–24], waveguiding [25, 26], and Raman spectroscopy [27]. Furthermore, such coaxial apertures can be used to enhance the second harmonic generation when combined with nonlinear materials [28]. Here, we report on coaxial-aperture-based plasmonic nanostructures in optically thick metal films. By precisely controlling the etching depth of the coaxial apertures, we are able to achieve accurate control of plasmon resonances in the visible regime.

Metal films (both Ag and Au) with various thicknesses and an adhesion (5 nm Ti) layer were deposited on quartz substrates using electron beam evaporation (Edwards Auto 306 E-Beam Evaporator) at 4×10^{-7} mbar with a deposition rate of 0.07 nm/s. Afterwards, direct focused ion beam (FIB) milling was carried out to define different patterns with varying etching depths. A single-beam (only the ion source) setup (FIB 200, FEI Corporation) was used and the milling current was set to be 70 pA. More details regarding the FIB milling process can be found elsewhere [29, 30]. Note that several important parameters may affect the final etching results and fine adjustment is thus necessary during the milling process. Transmission measurement was carried out using CRAIC QDI 2010™ with a 75 W broadband light source (xenon lamp). The probe light beam was focused to have a detecting area of 7.1×7.1 μm [2] using a 36× objective lens combined with a variable aperture. The measured transmission was normalized with the light through a bare quartz substrate. Both optical spectra and the corresponding optical images were collected using the attached spectrometer and CCD camera, respectively.

Fig. 1a is the sketch showing the coaxial structure proposed in this study. Coaxial nanocavities are supported by a quartz substrate (the adhesion is not shown). Fig. 1b demonstrates three most important parameters of coaxial apertures: the etching depth (d), the inner radius (r_i) and the outer radius (r_o). Typical top- and side-view SEM images are shown in Fig. 1c and d, respectively. A clear coaxial aperture can be observed from the top-view. In addition, the border region of the apertures shows slightly brighter colors compared with other regions due to material redeposition and long-time milling. From the cross-sectional image, one can clearly see that the gap width of the cavity is nonuniform

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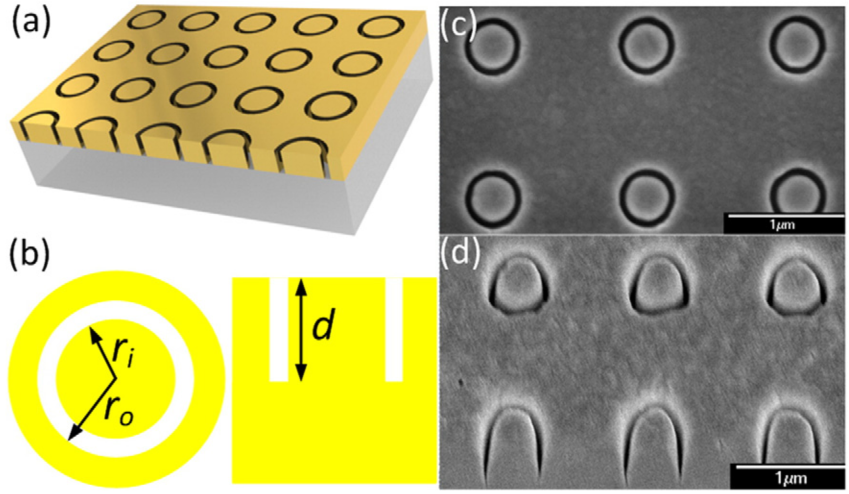

Fig. 1. (a) Schematic of gold coaxial apertures supported by a quartz substrate. (b) Top- and side-view sketches showing critical parameters for a coaxial aperture. (c) Top- and (d) side-view SEM images of coaxial apertures fabricated via FIB milling.

from top to bottom. In general, it decreases with increasing etching depth, giving rise to a tapered profile of the ring cavity.

It has been shown that coaxial apertures with varying gap widths are capable of filtering out individual colors from a broadband light source [2, 7]. Selective transmission can be obtained through the TE_{11} modes by engineering coaxial apertures with various geometrical designs [31, 32]. With the fixed thickness of a metal film, different combinations of diameters and gaps from the designed coaxial apertures can be used to generate various phase retardations in both transmission and reflection, hence affecting the propagation mode inside the cavities and leading to selected transmission/reflection of certain modes. In previous reports [33, 34], it was shown that two main types of surface plasmons in a coaxial aperture array can affect the transmission/reflection properties greatly: cylindrical surface plasmons (CSPs) and planar surface plasmons (PSPs). CSPs are highly dependent on the structural parameters. On the other hand, PSPs are mainly affected by the periodicity of the array. Finite difference time domain (FDTD) calculations were carried out (Lumerical, https://www.lumerical.com/). The dispersion model of metals is based on Johnson and Christy [35]. Fig. 2a shows the calculated transmission for coaxial aperture arrays with a fixed period of 1200 nm and different gap widths (r_o–r_i) from 40 nm to 120 nm in the step size of 40 nm. As can be seen, two apparent transmission peaks for each array are clearly observed. One peak strongly depends on the variation of the gap width, which is mainly attributed to the CSPs. The CSP peak red-shifts with reducing gap widths. In contrast, the other one remains almost unaltered since the periodicity of the array is fixed to a constant (1200 nm in this case), which therefore results from PSPs. Using such a color-filtering working principle, different colors can be filtered out with various ring arrays, as shown in Fig. 2b. It is worth mentioning that the coaxial aperture arrays discussed here are milled through the metal film. The plasmon resonance effect can be well controlled by changing the gap width of the coaxial apertures and hence selective transmission can be obtained through the whole visible range using such aperture arrays with different gap widths.

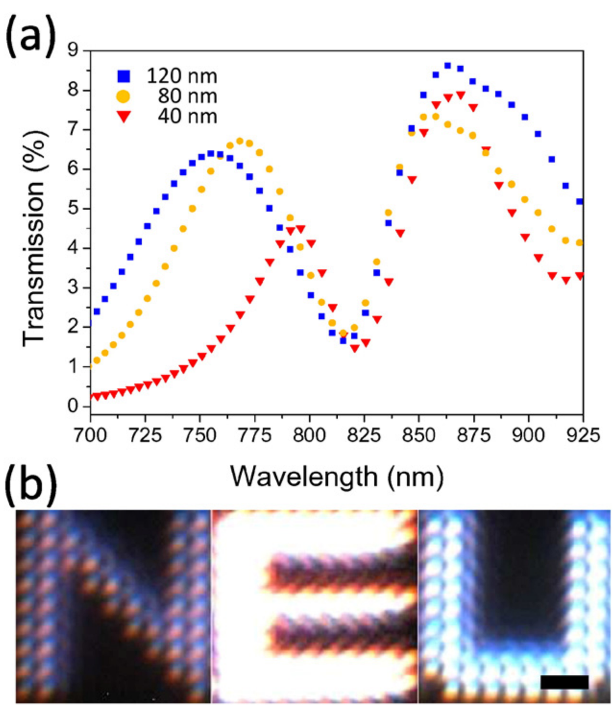

Fig. 2. (a) Calculated transmission for coaxial apertures with fixed period at 1200 nm and different gap widths (r_o–r_i) from 40 nm to 120 nm in increments of 40 nm with r_i fixed at 200 nm. (b) Optical image showing letters 'NEU' fabricated in a 140 nm gold film with 40 nm, 80 nm and 120 nm gap width for 'N', 'E' and 'U', respectively. The scale bar represents 2 μm.

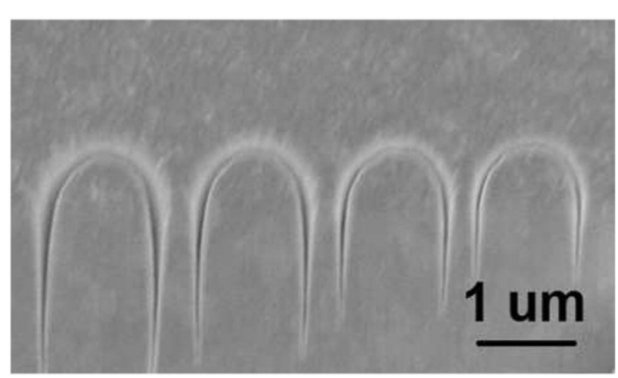

Fig. 3. SEM image showing fine adjustment on etching depth using FIB milling. Decreasing depth is shown from left (1600 nm) to right (700 nm) in the SEM image with the gap width of all four coaxial apertures set to 20 nm (r_o = 470 nm and r_i = 450 nm).