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90% Extraordinary optical transmission in the visible range through annular aperture metallic arrays

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We demonstrate what we believe to be the first experimental extraordinary optical transmission (EOT) of up to 90%, thanks to a well-identified guided mode that propagates through annular apertures engraved into an optically thick silver layer. In spite of the metal losses, high transmission can be obtained by adjusting the geometrical parameters of the fabricated structure, as was already theoretically demonstrated. To our knowledge, this is the first study showing such a large transmission in the visible range.

Enhanced light transmission through nanostructured metallic films involves many research teams over the world. Many configurations have been theoretically proposed and experimentally built to demonstrate this phenomenon, which is of great interest for many applications as varied as nano-optics [1,2], nanophotolithography [3,4], fluorescence [5,6], and chemical sensors [7]. In our view, annular aperture arrays (AAAs) [8] are the most interesting structures because they can dramatically increase the light transmission compared with cylindrical or rectangular apertures [9]. A first study has already been performed and was presented in [10] that demonstrates 17% experimental transmission in the visible range with an AAA engraved in gold layers. Extraordinary transmission was demonstrated in the infrared [11,12] and in the ultraviolet [13] domains. Recently, Rybczynski *et al.* demonstrated light transmission in the visible range through very long (some micrometers) coaxial waveguides based on carbon nanotubes [14,15]. The TEM guided mode of the coaxial aperture is often cited by the authors of [14,15]; we have noted that this mode cannot be excited under normal incidence with a linearly polarized plane wave because of symmetry considerations [16]. Nevertheless, the transmission obtained in [14] is less than 30% because of the large length of the coaxial channels. In this Letter, we propose an experimental demonstration of an enhanced transmission reaching 90% in the visible range.

The design of the fabricated structure (thickness, diameters, and metal nature) is determined by theoretical calculations to achieve large transmission in the visible range [8]. Focused ion beam (FIB) milling combined with a very accurate metal deposition process allows us to build AAAs with very small radii. The FIB milling is an adequate method for rapid fabrication compared with electron-beam lithography. A thin chromium layer (5 nm) is deposited as an adhesion layer on a glass substrate. Next, a silver film (thickness $h=100$ nm) is deposited by evaporation. Last, the AAA grating is obtained by FIB milling of

the metallic layer. The FIB operates at 30 keV, and the intensity of the beam is 12 pA. These parameters lead to an ionic beam diameter around 30–40 nm. The geometrical parameters of the AAA deduced from theoretical calculations are inner diameter $d_i=100$ nm, outer diameter $d_o=200$ nm, and period $p=350$ nm. Scanning electron microscope (SEM) images, shown in Fig. 1, allow us to check the quality and the geometrical parameters of the samples.

Numerically, the studied structure consists in an infinite biperiodic array (in x and y directions) of annular apertures in a metallic film lying upon a glass substrate. To fit the experimental conditions as much as possible, we built the theoretical object from the SEM image of Fig. 1. We chose by chance one coaxial cavity that has been introduced into the calculation code as the periodic pattern. Figure 2 shows a 2×2 periodic structure based on the digitized object: the randomly chosen aperture is slightly out of shape (as any aperture can be) as a result of the fabrication process. In this way, we take into account the geometry and especially the lack of symmetry of the real object.

The calculations have been computed with a 3D homemade code based on the finite-difference time domain (FDTD) algorithm. This method consists of the direct resolution of Maxwell's equations by discretizing both space and time [9,17,18]. To have an appropriate description of the AAA, the metallic layer

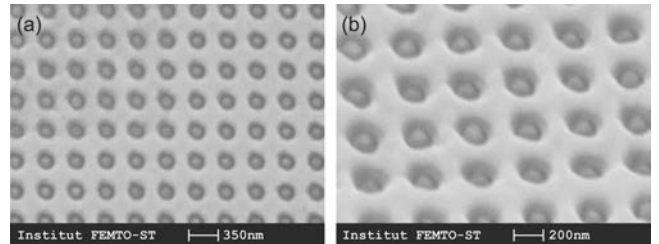


Fig. 1. SEM images of the studied AAA (inner diameter $d_i=100$ nm, outer diameter $d_o=200$ nm, and period $p=350$ nm) fabricated in a $h=100$ nm thick silver layer: (a) top view; (b) 40° tilted view.

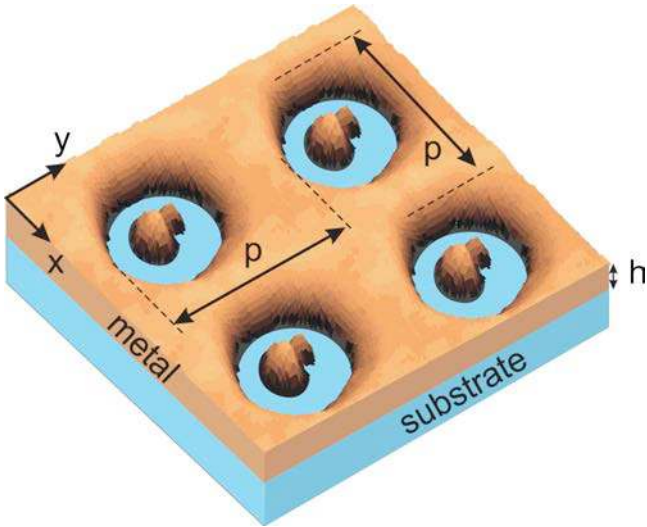


Fig. 2. (Color online) 2×2 periods of the infinite theoretical periodic structure used for the calculations and deduced from the SEM image of Fig. 1.

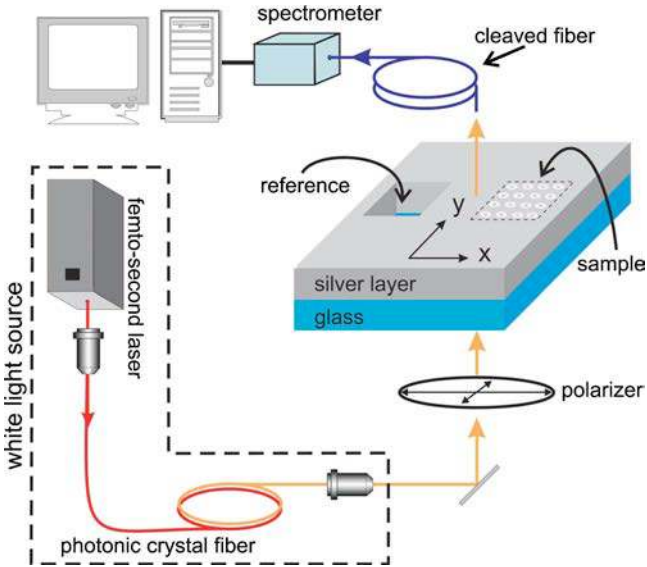


Fig. 3. (Color online) Experimental setup used for the transmission measurements.

is meshed with a spatial step of $\delta=5$ nm. For the rest of the calculation window, the spatial step increases gradually to $\Delta=25$ nm. This nonuniform meshing greatly reduces the time and memory consumption for the calculations by decreasing the total number of spatial nodes for the whole computational window. To avoid parasitical reflections from the window edges, the perfectly matched layers technique of Bérenger [19] has been incorporated. Moreover, an appropriate Drude's model is used to describe the permittivity of the silver layer [16]. The calculated theoretical transmission is then defined as the energy associated with the diffracted zero order transmitted through the infinite AAA structure divided by the same quantity calculated through the substrate without the metal layer.

The experimental transmission spectra are recorded through the setup depicted in Fig. 3. A powerful white-light source is generated thanks to a femto-

second laser (MaiTai from Spectra Physics) at $\lambda=800$ nm and is pulsed at 80 MHz. Its output is injected into a photonic crystal fiber that allows the generation of the white light via nonlinear phenomena [20]. The emitted light is then collimated, linearly polarized, and sent toward the sample under normal incidence. The light transmitted through the AAA structure is detected by a cleaved-end multimode fiber (core diameter $62.5 \mu\text{m}$). One fiber end is positioned in front of the sample by means of microposition stages, while the other is connected to the optical spectrometer (USB2000 by Ocean Optics). As mentioned above for the theoretical simulations, the experimental transmission spectrum is defined as the ratio between the intensity transmitted through the AAA divided by the same quantity measured through the reference. This last consists of a square hole made in the same silver film and with the same area as the whole AAA structure under study.

Figure 4 shows the theoretical extraordinary optical transmission (EOT) spectrum (solid curve) and the experimental ones recorded for two different matrices (same period and diameters but different areas). We emphasize here the good reproducibility of the experimental spectral responses in spite of the fact that the two matrices do not have the same area. Theoretical and experimental curves show quite good agreement even if the theoretical spectrum is obtained for an infinite periodic structure. The wide peak occurring around $\lambda \approx 675$ nm for the experimental curves and at $\lambda=690$ nm for the theoretical one corresponds to the TE_{11} -like mode of the infinite-length coaxial waveguide [16]. This mode can be easily excited by an incident linear polarization, unlike the TEM mode, which is prohibited under normal incidence. The small discrepancy between the experimental and the theoretical curves can be related to various reasons. First, as already shown elsewhere [21], the position of the EOT peak strongly depends on the diameter values. In fact, the FIB used to mill the structure has a beam diameter around 40 nm, which implies a lack of accuracy of about 20 nm in

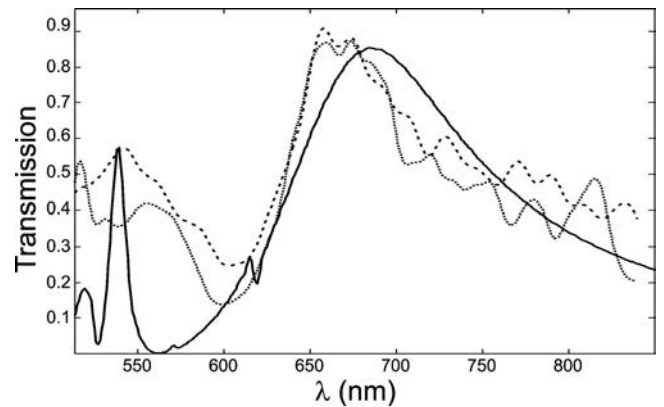


Fig. 4. Theoretical and experimental transmission spectra through two AAAs having the same period and inner and outer diameters but different areas. Dotted curve, matrix with 30×30 periods ($\approx 100 \mu\text{m}^2$); dashed curve, matrix with 40×40 periods ($\approx 190 \mu\text{m}^2$); solid curve, theoretical transmission spectrum obtained with the infinite object deduced from the SEM image (Fig. 2).

the geometrical parameters. Moreover, the theoretical model used implies a rigorously biperiodic object, while each annular aperture of the real sample is slightly different from the others. Second, because of the metal deposition method, the real dispersion characteristics of silver may be different from both the tabulated ones [22,23] and the Drude model used. Work is in progress to accurately determine the influence of the deposition method on the metal properties. Finally, the finite spatial extension of our structures may induce a blueshift together with a widening of the transmission peak, as was demonstrated in [24] (see Fig. 3 of [24]). This is clearly shown in Fig. 4 by comparing the EOT peak position of the experimental spectra and the theoretical spectrum obtained with an infinite object.

Other experiments have been performed to study the influence of the incident polarization (see Fig. 5). Due to the noncylindrical symmetry of the real apertures, these transmission spectra show a substantial modification versus the polarization direction. The theoretical results presented in Fig. 5(a) are in good agreement with the experimental ones [Fig. 5(b)]. Note that the position of the transmission maxima seems to be directly connected to the inner and the outer radii measured along the direction of the incident electric field.

To conclude, we have shown what we believe to be the first experimental EOT of visible light up to 90% through an opaque nanostructured silver layer. FIB milling allowed us to overcome the technological limitation encountered during the fabrication of nanom-

eter annular apertures. By using silver instead of gold [10], the metallic losses are reduced and the EOT peak is blueshifted to the visible range. The experimental data are in good agreement with the theoretical results that were used to design the fabricated sample. Many applications can be found for this structure, including spectral filters, flat displays, and modulators. It is indeed possible to imagine a device based on an electro-optical material (such as lithium niobate) that could allow one to tune the transmission peak.

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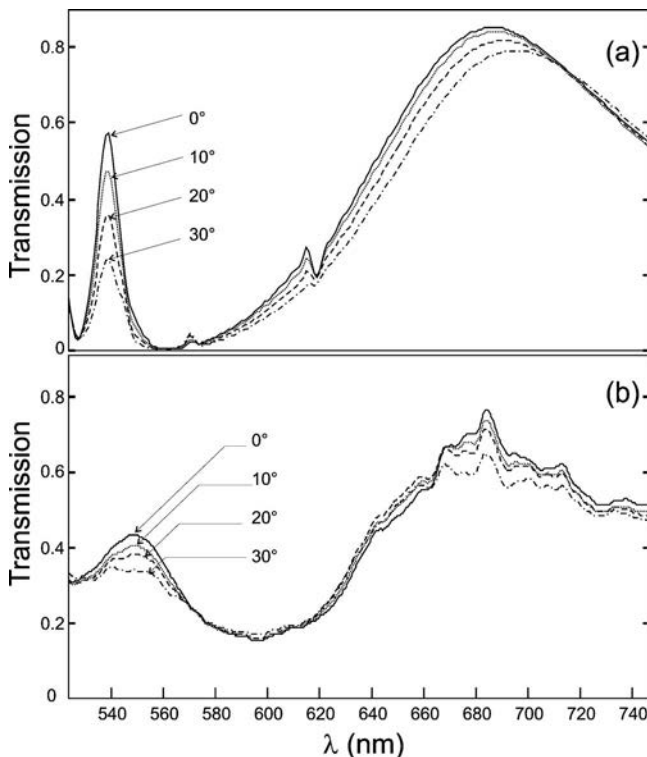


Fig. 5. Transmission spectra for different directions of polarization of the incident field: 0° (solid curve), 10° (dotted), 20° (dashed), and 30° (dashed-dotted) with respect to the y axis of Fig. 2: (a) theoretical curves; (b) experimental results.