Tailoring the resonances of surface plasmas on fractal-featured metal film by adjusting aperture configuration

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Metal films perforated with two types of Sierpinski carpet patterns (SCP) are fabricated on silicon wafer, where one pattern possesses open square aperture as the building block and the other has square ring-shaped aperture as the building block. Enhanced transmissions are observed in both structures. However, for SCP made of square ring-shaped apertures, resonance of surface plasmon of both surface and localized modes has been identified. This feature does not exist in SCP made of open square apertures. This finding provides an effective way to control the extraordinary transmission through the metal film perforated with fractal-like structures. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2908972]

According to classical electrodynamics, transmission intensity of electromagnetic wave through a subwavelength aperture is proportional to the fourth power of the ratio of diameter and wavelength, which turns out to be extremely low.[1] However, it has been reported in 1998 that once a metal film is perforated with periodic array of subwavelength apertures, the optical transmission can be tremendously enhanced[2] than that predicted by the diffraction theory. Since then, enduring efforts have been devoted to the extraordinary transmission through the subwavelength structures on metal film.[3–21] It has been revealed that the enhanced transmission depends on aperture diameter and spatial periodicity of the array,[7–9] on the wavelength and the angle of incidence,[10] as well as on the type of materials with which the structured film is made.[14,15] It is generally accepted that on the metal surface perforated with subwavelength aperture array, surface plasmon exists in two ways. One is the surface wave known as surface plasmon polariton (SPP).[2,22] The other is a regional resonance localized around subwavelength apertures, known as localized surface plasmon (LSP).[7,16,18] The propagation of SPP is greatly influenced by the lattice symmetry of the aperture array. Recently, enhanced transmission through an array of apertures arranged in Penrose tiling has been reported.[19] Another known self-similar pattern is the Sierpinski carpet pattern (SCP),[20] which is composed of iteratively shrinking apertures arranged in a hierarchy manner, with different aperture sizes on different scales. The fractal surface can be used as a unit cell of frequency selective surface to achieve multiband structures, which can be ascribed to the resonance of SPP (Ref. 21) or LSP around each individual aperture.[23–25] We previously studied the resonance of SPP in SCP with open square apertures[21] where no contribution of LSP has been identified. However, once a piece of metal patch is placed at the center of the aperture, forming a coaxial ring pattern, LSP mode can be excited.[26] It has been pointed out that the resonance of LSP is attributed to TE_{11} mode with cutoff frequency, yet previously, this contribution was ascribed to TEM_{00}.[26–28] In this letter, we show the transmission properties of SCP perforated on metal surface with both open square apertures and square ring-shaped apertures as building blocks, respectively. We demonstrate that the resonance of SPP and LSP can be tailored on the fractal-featured surface by selecting proper building blocks.

We construct SCP with iteratively shrinking building blocks of open square aperture and square ring-shaped aperture, respectively. A thin film of gold (200 nm thick) was deposited on a double-polished 0.5 mm thick silicon wafer. SCP is fabricated with standard projection lithography. The SCP of open square aperture is shown in Fig. 1(a), where the smaller aperture is 2.0 μm and the larger one is 6.0 μm in size. The SCP of open square ring-shaped apertures is shown in Fig. 1(b), where the smaller one is 2.0 μm square aperture centered with 1.0 μm square metal patch and the larger ones are 6.0 μm square aperture centered with a 3.0 μm square metal patch. The whole samples had a dimension of 2.0 $\times$ 2.0 cm^2 and was composed of periodically duplicated SCP units of 18×18 μm^2.

Before studying the transmission behavior of the aperture array, we first pinpoint the transmission properties of individual aperture of each type. Numerical simulation was performed with a software based on finite-difference-time-domain method (FULLWAVE 4.0). The Lorentz–Drude model proposed by Rakic *et al.* is used to describe the permittivity of gold.[29] To optimize the calculation of transmission spectrum, perfect match layer[30] (PML) condition is applied for an individual aperture, whereas both periodic boundary condition and PML condition are used for the SCP array. Silicon substrate is simplified to a nonabsorbing medium with refractive index $n=3.4$ and the thickness is taken as infinite. The calculated transmission spectrum for open square aperture is shown in Fig. 2(a), where the transmission monotonically increases as wavenumber increases. For the open ring-shaped aperture, the calculated transmission spectrum is shown in Fig. 2(b), where a resonant peak appears at 968.75 cm^{-1}, which corresponds to the resonance of LSP around each ring-shaped aperture.

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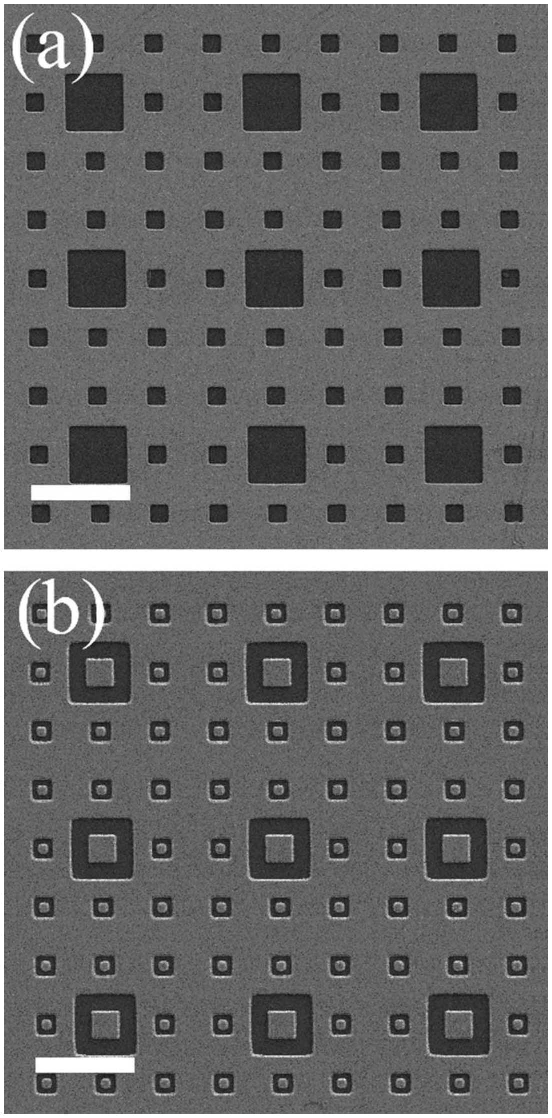

FIG. 1. Scanning electron microscopy micrographs of the gold thin film perforated with SCP. The bar in each image presents 10 μm. (a) The gold film perforated with two generations of SCP made of open square apertures, the edge of the smallest apertures is 2.0 μm. (b) The gold film perforated with two generations of SCP made of square ring-shaped apertures. The sizes of the smallest aperture and the compact square patch inside are 2.0 and 1.0 μm, respectively.

The transmission spectra of the samples were measured by using vacuum infrared Fourier transform spectrometer (Bruker IFS 66 v/s). The zero-order transmission spectra of the fractal structures were studied. In order to get the pure information of the metallic fractal structures, a bare double-polished silicon wafer is used as the reference. For metal film perforated with SCP of open square apertures [shown in Fig. 1(a)], the calculated peaks appear at 160.16, 222.66, 312.5, 347.66, 476.56, 664.06, 949.22, and 1046.88 cm^{-1}, as shown in Fig. 3(a) For metal film perforated with SCP of open square ring-shaped apertures [shown in Fig. 1(b)], the calculated peaks appear at 160.16, 222.66, 308.59, 476.56, 664.06, and 1007.81 cm^{-1} as shown in Fig. 3(b). The calculations are in excellent agreement with the experimental data.

As normal incidence electromagnetic wave interacts with the apertures in metal film, extraordinary transmission induced by SPP occurs at frequencies[2]

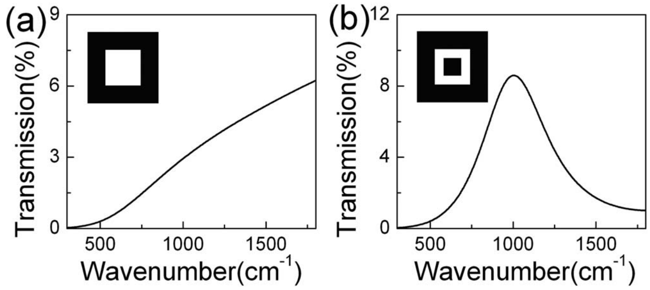

FIG. 2. The transmission spectra of individual aperture for open square aperture and square ring-shaped aperture, respectively. (a) The calculated transmission spectrum of an individual open square aperture with edge size of 2.0 μm. (b) The calculated transmission spectrum of an individual square ring-shaped aperture. The outer rim of the ring-shaped aperture is 2.0 μm in size and the central square patch inside is 1.0 μm.

$$\nu_{\mathrm{ext}} = \frac{c}{n_{\mathrm{eff}}} G_{i,j}, \qquad (1)$$

where n_{eff} is the effective refractive index of the perforated metallic surface, c is the vacuum light velocity (for convenience, c is taken as unity), $G_{i,j}=\sqrt{i^2+j^2}/P$ is the reciprocal vector of subwavelength aperture array, P is the spatial peri-

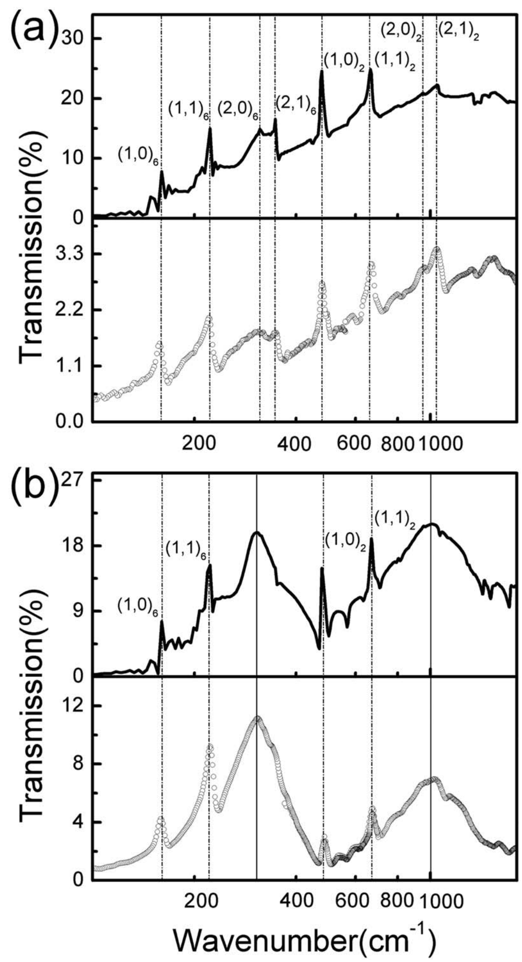

FIG. 3. The transmission spectra of metal film perforated with SCP of (a) open square apertures and (b) square ring-shaped apertures, respectively. The solid lines are the calculated spectra and the circled lines are the measured spectra. The peaks of SPP resonances are indexed and marked with dashed lines and the peaks of LSP resonances are marked by solid lines. The footnotes in the index represent the size of the open square aperture or that of the square ring-shaped aperture.

odicity of the array, and i and j are integers. All the peaks in the transmission spectrum can be indexed with (i,j). Each mode of SPP resonance is decided by a specific reciprocal lattice vector. For metal film perforated with SCP of open square apertures, the enhanced transmission at 160.16, 222.66, 312.5, 347.66, 476.56, 664.06, 949.22, and 1046.88 cm^{-1} can be set into two groups. In the first group, the first four peaks at 160.16, 222.66, 312.5, and 347.66 cm^{-1} correspond to the SPP resonance modes (1, 0), (1, 1), (2, 0), and (2, 1) of 6 μm open square apertures in SCP. The second group consists of the rest four peaks at 476.56, 664.06, 949.22, and 1046.88 cm^{-1}. These peaks come from the SPP resonance modes (1, 0), (1, 1), (2, 0), and (2, 1) of 2 μm apertures in SCP. The frequencies corresponding to the peaks in each group can be scaled by a factor 3. For example, the (1, 0) mode in the first group occurs at 160.16 cm^{-1}, and the (1, 0) mode of the second group occurs at 476.56 cm^{-1}, which is about three times of the former one. This property originates from the geometric feature of SCP. For metal film perforated with SCP of open square ring-shaped apertures, the peaks at 160.16, 222.66, 308.59, 476.56, 664.06, and 1007.81 cm^{-1} can also be set into two groups. In the first group, the first three peaks at 160.16, 222.66, 308.59 cm^{-1} correspond to the surface plasma resonances of 6 μm square ring-shaped apertures centered with 3 μm square metal patches. The first two peaks at 160.16, and 222.66 cm^{-1}, respectively, correspond to SPP resonance modes (1, 0) and (1, 1), whereas the third peak at 308.59 cm^{-1} corresponds to LSP resonance mode. In the second group, the last three peaks 476.56, 664.06, and 1007.81 cm^{-1} correspond to the surface plasma resonances of 2 μm square ring-shaped apertures centered with 1 μm square metal patch. The first two peaks, 476.56, and 664.06 cm^{-1}, correspond to the SPP resonance mode (1, 0) and (1, 1), whereas the last peak 1007.81 cm^{-1} corresponds to LSP resonance mode. Both SPP and LSP resonances are excited in the SCP of open square ring-shaped apertures. The corresponding peaks induced by SPP resonances in each group can be scaled by a factor 3, whereas the peaks corresponding to LSP resonance are scaled by a factor 3.27, deviating from the geometric parameter 3. This discrepancy may associate with the resonant feature of LSP. It is known that the resonant frequency of LSP is determined by the geometric shape of aperture, and is also related the depth of the aperture, i.e., the thickness of metal film.[9] In our experiment, the metal film thickness is a constant. When the aperture is laterally scaled by a factor of 3, the ratio of thickness versus lateral size decreases. Consequently, the resonance frequency of LSP redshifts.

The fractal pattern contains hierarchy arrangement of certain geometrical unit on different scales. These units are squeezed to a very limited geometrical space. In the experiment, enhanced transmission at different wavelengths are simultaneously obtained from the microstructured sample. By adjusting the geometrical shape of the aperture, SPP and LSP can be simultaneously excited in the transmission of metal film perforated with SCP. This provides an additional way to modify the extraordinary enhanced transmission of metal film perforated with fractal featured pattern. The properties demonstrated here imply potential applications of this fractal structure in the miniaturization and integration of optical devices based on SPP, and in designing light-emitting devices, spectroscopic devices, and sensors for chemical and biological applications as well.

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