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# Transmission enhancement of metal-patterned resonant filters on silicon substrates in terahertz frequencies

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## 1. Introduction

Optical passive components in terahertz (THz) frequencies become increasingly important with the development of THz physics and technologies. Optical components with high performance, such as lenses[1], polarizers[2], compensators[3], and filters[4], therefore receive great attention in recent years. Metal mesh resonant filters have been investigated widely since the pioneering works done by Ulrich.[5] The resonant filters are formed by perforating a metallic film with holes periodically in an array configuration. The period of the holes determines the center frequency of the band-pass filters. The filters can be fabricated with or without (i.e. free standing) supporting substrates. Free standing mesh filters can have a higher peak transmittance and a quality factor than substrate-supported ones. However, the fabrication processes for the free standing filters are quite complex and the filters are not mechanically robust. Fabricating filters on a substrate solves the mentioned difficulties. The substrate-supported filters usually have a peak transmittance of about 80-85 % (normalized to the substrate transmittance). The performance of the filters, including the peak transmittance and the quality factor, in fact, can be further improved by changing the shape of the holes.

In the paper, we demonstrate a substrate-supported metal-patterned filter with a peak transmittance limited predominantly by the transmittance of the substrate in THz frequencies. The filter was composed of an undoped silicon substrate and a perforated metallic film with snowflake-like holes arranged in a hexagonal array. Compared with the conventional filters with cross-shaped holes arranged in a square array, our filter showed more than 10 % increase in the peak transmittance with a comparable quality factor. The enhancement in the peak transmittance allows cascading several filters to attenuate the stop-band transmittance while keeping the high peak transmittance. The peak transmittance can further be improved by replacing the silicon substrate with a low loss or low reflectivity polymer film.

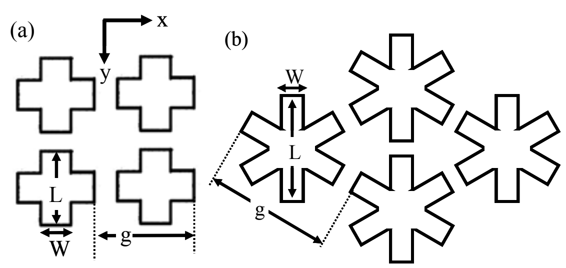


Fig. 1 Holes in (a) cross shape in a square array, (b) snowflake-like shape in a hexagonal array. L, W, and g represent arm length, arm width and period, respectively

## 2. Experiments

We fabricated two sets of filters. One had cross-shaped holes arranged in a square array [Fig. 1(a)] while the other had snowflake-like holes arranged in a hexagonal array [Fig. 1(b)]. Parameters of the arrays of holes include the arm length (L), the arm width (W), and the period (g). The period g was 24 μm for both sets of the filters. For the set of filters with cross-shaped holes, we prepared five samples with different width W= 2, 6, 10, 14, 18 μm but with the same length L=18 μm. For the set of filters with snowflake-like holes, we had two samples (A and B) with (L, W) = (19 μm, 5 μm) and (18 μm, 6 μm), respectively. The filters were fabricated as follows. An aluminum film of 2000 Å was deposited by thermal evaporation on an undoped silicon substrate which had prior been cleaned by RCA process. A positive photo-resist was then coated on the metal. The hole array was made by first patterning the photo-resist with standard lithographic processes then etching the aluminum with an acid solution. The photo-resist was then removed. All the samples were cut to

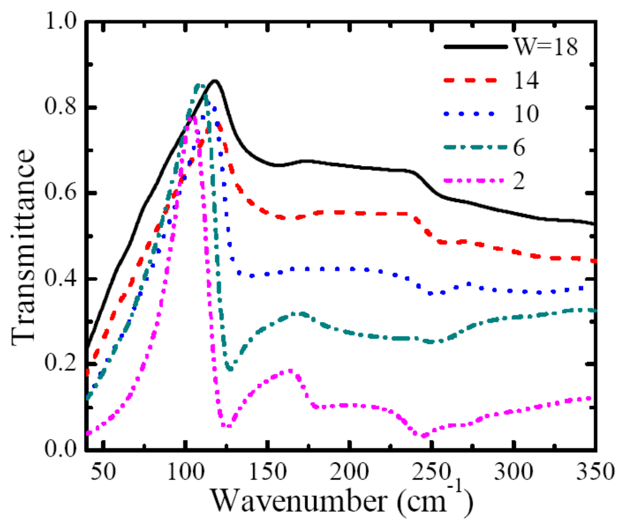


Fig. 2 Transmittance spectra of filters with cross-shape holes. The arm width of the cross changes from 2-18 μm.

an area of 1x1 cm$^2$. A Fourier transform infrared (FTIR) spectrometer, IFS 66V/s, was employed to measure transmission spectra of the filters. The measurable spectral range extended from 50 cm$^{-1}$ to 700 cm$^{-1}$ and the resolution was set at 4 cm$^{-1}$. We used a mercury lamp as a light source. To visualize the enhancement in the peak transmittance more clearly, we present relative transmittance spectra which are obtained by taking the ratio of the transmission spectrum of a substrate with a metal mesh to that of a bare substrate.

## 3. Results and discussion

Figure 2 shows measured transmission spectra of filters perforated with cross-shaped holes arranged in a square lattice. The arm width, W, of the cross varies from 0-18 μm. For W = 18 μm, the transmission peak is at k = 118 cm$^{-1}$ or λ = 84.7 μm, corresponding to the wavelength at which the Wood anomaly occurs. We can therefore infer the refractive index (n) of the undoped silicon substrate as 3.53 from the following relation:

$$k_{Wood} \approx \frac{10000}{g(\mu m)\times n}(cm^{-1}),$$

where g is the period of the holes in μm. As W decreases, the transmission peak shows a red shift in energy. Furthermore, an obvious improvement in the quality factor and in the stop-band attenuation can also be observed. However, the peak transmittance remains around 0.85 without obvious enhancement. The appearance of the peak is attributed to resonant transmission as a result of interactions between the incident EM waves and the electromagnetic mode of the periodic structures.[6] The cross-hole filters have resonant interactions along x- and y-directions, as shown in Fig. 1(a). To enhance the resonant interactions between the surface EM waves and the incident EM waves, we change the configuration of the filters to snowflake-like holes in a hexagonal array, as shown in Fig. 1(b). Figure 3 shows the transmittance spectra of sample A

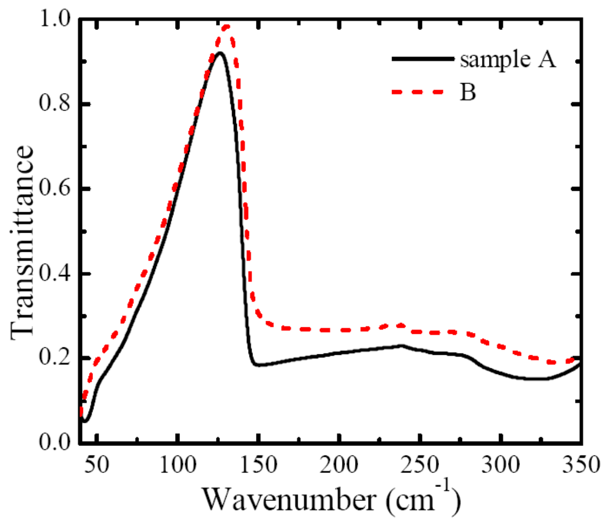


Fig. 3 Transmittance spectra of two filters with snowflake-like holes. Sample B (g=24 μm, L=18 μm, W=6 μm) has higher peak transmittance (approaching unity) than sample A (g=24 μm, L=19 μm, W=5 μm).

(g = 24 μm, L = 19 μm, W = 5 μm) and sample B (g = 24 μm, L = 18 μm, W = 6 μm). Sample A has a transmission peak at k = 126.5 cm$^{-1}$ with Q = 2.51 and sample B has a peak at k = 130.5 cm$^{-1}$ with Q = 2.39. It is clearly seen that the peak transmittance of both samples increases beyond 0.9. Furthermore, sample B has even higher peak transmittance approaching unity (0.98) than sample A. With such high peak transmittance, we can attenuate the stop-band transmittance by cascading the filters while maintaining the high peak transmittance. The transmission loss is now limited mainly by absorption and reflection of the silicon substrate. The loss can further be reduced by replacing the substrate with a thin polymer film, such as a high-density polyethylene film.

## 4. Conclusions

We demonstrated a limiting peak transmittance, which is limited by the loss of the substrate, by a metal-patterned resonant filter. The filter had center frequency at 3.91 THz. The peak transmittance was about 0.98 and the quality factor was 2.39. Our filter showed more than 10 % increase in the peak transmittance with a comparable quality factor when compared with the conventional filters having cross-shaped holes. The enhancement in the peak transmittance allows us to cascade several filters in series to attenuate stop-band transmittance. The performance of the filter can be improved even more by using low loss polymer films as supporting substrates.


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