

Shape resonance omni-directional terahertz filters with near-unity transmittance

J. W. Lee, M. A. Seo, D. J. Park and D. S. Kim

School of Physics, Seoul National University, Seoul 151-747, Korea
denny@snu.ac.kr

S. C. Jeoung

Optical Nano Metrology Group, Korea Research Institute of Standard and Science, Daejeon 305-304, Korea

Ch. Lienau

Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie, D-12489 Berlin, Germany

Q-Han Park

School of Physics, Korea University, Anam-Dong, Sungbuk-Gu, Seoul 136-701, Korea

P. C. M. Planken

Delft University of Technology, Faculty of Applied Sciences, Department of Applied Physics, Lorentzweg 12628 CJ Delft, Netherlands

Abstract: Terahertz transmission filters have been manufactured by perforating metal films with various geometric shapes using femtosecond laser machining. Two dimensional arrays of square, circular, rectangular, c-shaped, and epsilon-shaped holes all support over 99% transmission at specific frequencies determined by geometric shape, symmetry, polarization, and lattice constant. Our results show that plasmonic structures with different geometric shaped holes are extremely versatile, dependable, easy to control and easy to make terahertz filters.

©2006 Optical Society of America

OCIS codes: (240.6690) Surface waves; (050.1220) Apertures; (300.6270) Far infrared spectroscopy

References and links

1. T. W. Ebbesen, H. L. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, "Extraordinary optical transmission through sub-wavelength hole arrays," *Nature (London)* **391**, 667 (1998).
2. L. Salomon, F. Grillot, A. V. Zayats, and F. Fronel, "Near-field distribution of optical transmission of periodic subwavelength holes in a metal film," *Phys. Rev. Lett.* **86**, 1110 (2001).
3. S. A. Maier, G. K. Pieter, A. A. Harry, M. Sheffer, H. Elad, E. K. Bruce, and A. G. R. Ari, "Local detection of electromagnetic energy transport below the diffraction limit in metal nanoparticle plasmon waveguides," *Nature Materials* **2**, 229 (2003).
4. D. S. Citrin, "Coherent excitation transport in metal-nanoparticle chains," *Nano Letters* **4**, 1561 (2004).
5. T. Zentgraf, A. Christ, J. Kuhl, and H. Giessen, "Tailoring the ultrafast dephasing of quasiparticles in metallic photonic crystals," *Phys. Rev. Lett.* **93**, 243901 (2004).
6. J. B. Pendry, "Negative refraction makes a perfect lens," *Phys. Rev. Lett.* **85**, 3966 (2000).
7. J. T. Shen, R. B. Catrysse, and S. Fan, "Mechanism for designing metallic metamaterials with a high index of refraction," *Phys. Rev. Lett.* **94**, 197401 (2005).
8. M. J. Lockyear, A. P. Hibbins, J. R. Sambles, and C. R. Lawrence, "Microwave transmission through a single subwavelength annular aperture in a metal plate," *Phys. Rev. Lett.* **94**, 193902 (2005).
9. J. B. Pendry, L. Martin-Moreno, and F. J. Garcia-Vidal, "Mimicking surface plasmons with structured surfaces," *Science* **305**, 847 (2004).

10. F. J. Garcia-Vidal, E. Moreno, J. A. Porto, and L. Martin-Moreno, "Transmission of light through a single rectangular hole," *Phys. Rev. Lett.* **95**, 103901 (2005).
11. A. Nahata, and H. Cao, "Influence of aperture shape on the transmission properties of a periodic array of subwavelength apertures," *Opt. Express* **12**, 3664 (2004), <http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-16-3664>
12. Y. Takakura, "Optical resonance in a narrow slit in a thick metallic screen," *Phys. Rev. Lett.* **86**, 5601 (2001).
13. F. Yang, and J. R. Sambles, "Resonant transmission of microwaves through a narrow metallic slit," *Phys. Rev. Lett.* **89**, 063901 (2002).
14. D. Qu, D. Grischkowsky, and W. Zhang, "Terahertz transmission properties of thin, subwavelength metallic hole arrays," *Opt. Lett.* **29**, 896 (2004).
15. M. Tanaka, F. Miyamaru, M. Hangyo, T. Tanaka, M. Akazawa, and E. Sano, "Effect of a thin dielectric layer on terahertz transmission characteristics for metal hole arrays," *Opt. Lett.* **30**, 1210 (2005).
16. J. A. Porto, F. J. Garcia-Vidal, and J. B. Pendry, "Transmission resonances on metallic gratings with very narrow slits," *Phys. Rev. Lett.* **83**, 2845 (1999).
17. S. Astilean, R. Lalanne, and M. Palamaru, "Light transmission through metallic channels much smaller than the wavelength," *Opt. Commun.* **175**, 265 (2000).
18. M. M. J. Treacy, "Dynamical diffraction explanation of the anomalous transmission of light through metallic gratings," *Phys. Rev. B* **66**, 195105 (2002).
19. F. J. Garcia-Vidal, and L. Martin-Moreno, "Transmission and focusing of light in one-dimensional periodically nanostructured metals," *Phys. Rev. B* **66**, 155412 (2002).
20. F. J. Garcia de Abajo, G. Gomez-Santos, L. A. Blanco, A. G. Borisov, and S. V. Shabanov, "Tunneling mechanism of light transmission through metallic films," *Phys. Rev. Lett.* **95**, 067403 (2005).
21. L. M. Moreno and F. J. Garcia-Vidal, "Optical transmission through circular hole arrays in optically thick metal films," *Opt. Express* **12**, 3619-3628 (2004), <http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-16-3619>
22. F. J. Garcia de Abajo, R. Gomez-Medina, and J. J. Saenz, "Full transmission through perfect conductor subwavelength hole arrays," *Phys. Rev. E* **72**, 016608 (2005).
23. L. Martin-Moreno, F. J. Garcia-Vidal, H. J. Lezec, K. M. Pellerin, T. Thio, J. B. Pendry, and T. W. Ebbesen, "Theory of extraordinary optical transmission through subwavelength hole arrays," *Phys. Rev. Lett.* **86**, 1114 (2001).
24. A. Degiron, and T. W. Ebbesen, "The role of localized surface plasmon modes in the enhanced transmission of periodic subwavelength apertures," *J. Opt. A: Pure Appl. Opt.* **7**, S90 (2005).
25. K. J. K. Koerkamp, S. Enoch, F. B. Segerink, N. F. van Hulst, and L. Kuipers, "Strong influence of hole shape on extraordinary transmission through periodic arrays of subwavelength holes," *Phys. Rev. Lett.* **92**, 183901 (2004).
26. R. Gordon, and A. G. Brolo, "Increased cut-off wavelength for a subwavelength hole in a real metal," *Opt. Express* **13**, 1933-1938 (2005), <http://www.opticsinfobase.org/abstract.cfm?URI=oe-13-6-1933>
27. H. Shin, P. B. Catrysse, and S. Fan, "Effect of the plasmonic dispersion relation on the transmission properties of subwavelength cylindrical holes," *Phys. Rev. B* **72**, 085436 (2005).
28. W. Wen, L. Zhou, B. Hou, C. T. Chan, and P. Sheng, "Resonant transmission of microwaves through subwavelength fractal slits in a metallic plate," *Phys. Rev. B* **72**, 153406 (2005).
29. J. Dintinger, S. Klein, F. Bustos, W. L. Barnes, and T. W. Ebbesen, "Strong coupling between surface plasmon-polaritons and organic molecules in subwavelength hole arrays," *Phys. Rev. B* **71**, 035424 (2005).
30. R. Gordon, A. G. Brolo, A. McKinnon, A. Rajora, B. Leathem, and K. L. Kavanagh, "Strong polarization in the optical transmission through elliptical nanohole arrays," *Phys. Rev. Lett.* **92**, 037401 (2004).
31. H. Lochbihler, and R. Depine, "Highly conducting wire gratings in the resonance region," *Appl. Opt.* **32**, 3459 (1993).

1. Introduction

Surface plasmon exists in the metal-dielectric interface. Perforating metal films with arrays of holes or slits, or periodically arranging metal nano-particles [1-5] result in the surface plasmonic crystals or plasmonic waveguides, potential applications of which are expected in such diverse areas as subwavelength light localization, negative index materials and perfect lensing, bio-sensing, surface energy transfer and waveguiding [3-8]. Recently the concept of surface plasmons have been extended to include perfect metals [9-13], thereby encompassing any phenomena involving strong surface electric field in microwave and terahertz frequency range [14, 15]. Strong surface field and its scattering into the far field can result in strong transmission, as has been predicted by many theoretical groups [16-23]. In this paper, we

demonstrate shape resonance terahertz filters with near-unity transmission through various plasmonic structures with diverse hole shapes where we can easily control the transparent frequencies through hole shapes [24-28], incident angle [29], and polarization direction [30].

2. Experiments and theory

The terahertz transmission filters have been manufactured by perforating metal films, commercial aluminum foil with a $17\mu\text{m}$ thickness, with various geometric shapes using femtosecond laser machining. The period is set at $400\mu\text{m}$ and the sample size is 2 cm by 2 cm. Figure 1(a) shows images of the plasmonic structures perforated with various shapes: square, circular, rectangular, c-shaped, and epsilon-shaped holes. Terahertz time domain spectroscopy [Fig. 1(b)] is performed to obtain transmittance in the frequency range of 50 GHz to 2 THz, from comparing time traces of pulses before and after passing through the sample.

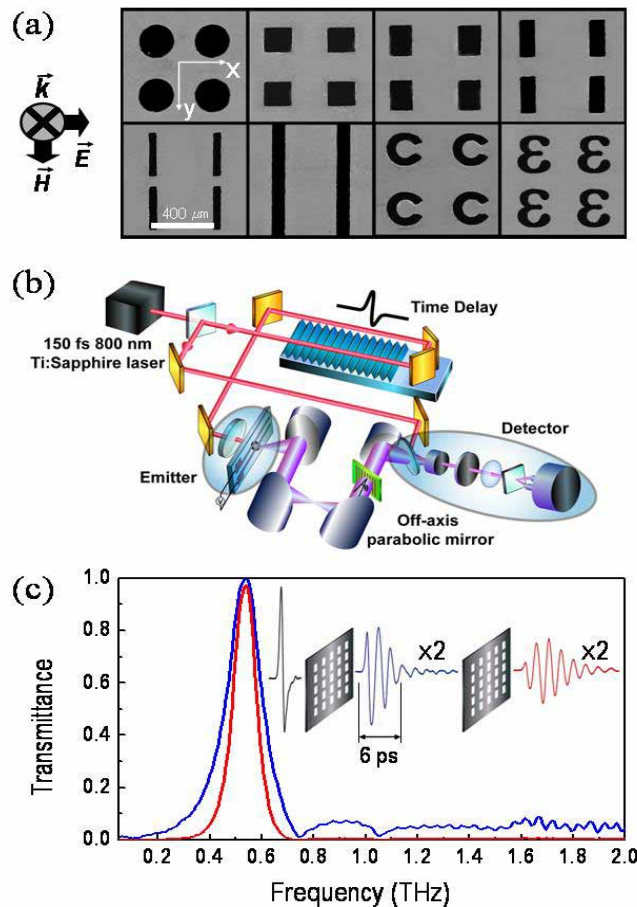


Fig. 1. (a) SEM images of the plasmonic structures perforated with various shapes. (b) The experimental setup. (c) Transmission spectra measured after passing through a circular hole sample (blue) and after another nearly identical one (red). The insets show time traces for the two cases.

In the inset, Fig. 1(c), time traces for the incident beam, the transmitted beam after a circular hole sample, and the beam after another nearly identical sample is shown. From the single cycle incident pulse, quasi-monochromatic waves are generated after passing through

the sample, and become even more monochromatic after passing through the second sample. Transmittance is plotted in Fig. 1(c), where the peak transmittance is near unity for both cases although the line width is narrower after passing through two samples. The peak position of 0.54 THz is determined by combined effects of both the periodicity and the circle diameter, which makes precise prediction of the transmission frequency, which has important technological implications, rather difficult. In the following, we show cases where one can easily predict perfect transmission position.

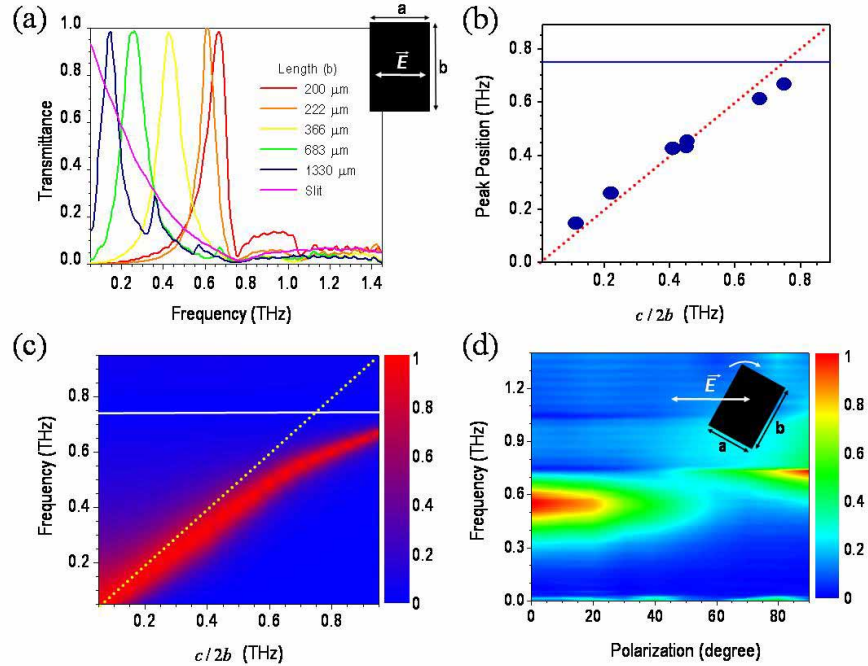


Fig. 2. (a) Transmission spectra for samples with rectangular arrays of holes with varying length b . (b) Spectral peak positions (circles) plotted versus the half wavelength cutoff frequency. The blue line represents the first Rayleigh minimum. (c) Theoretical calculations by using the perfect conductor model. (d) Polarization dependence for the rectangle hole sample with the width to length ratio of 2 to 3. Two resonance frequencies of 0.560 and 0.734 THz appear at the perpendicular polarization angles of 0 and 90° respectively.

Samples with rectangular arrays of holes with varying length b are investigated, with polarization of the incident light along the width a [Fig. 2(a)]. We first note that in all spectra, a transmission minimum exists near the frequency $f_R = \frac{c}{d} = 0.75$ THz, which corresponds to the first Rayleigh minimum for normal incidence: in transmission grating at an incidence angle θ , first order diffracted waves graze at the sample surface at frequencies $f_R(\theta) = \frac{c}{d(1 \pm \sin \theta)}$, taking away energies from the 0th order transmitted wave.

With increasing b , the peak position shifts toward smaller frequency while maintaining transmittance of near unity. Interesting case is seen at the slit sample ($b = \text{infinity}$), where the transmittance keeps increasing with decreasing frequency, until at the low frequency limit of our detection method (50 GHz), over 90% transmittance is seen. Our results suggest that the first *shape resonance* (the half wavelength mode along the length) is where the transmittance

of unity occurs. Plotting spectral peaks versus the half wavelength mode cut-off frequency $c/2b$ shows that it is indeed close to a straight line of slope one [Fig. 2(b), dotted line], although it bows toward lower frequency as the peak position approaches f_R much like an anti-crossing. This is expected, because at frequency f_R or higher, first diffraction inevitably takes energy away from the 0th order transmitted beam.

We analytically calculate transmittance through periodic arrays of rectangle holes with width a along the x-direction and length b along the y-direction, with periods d_x and d_y respectively. With the assumption that the metal is a perfect conductor, an excellent approximation in the terahertz range, we obtain an exact solution. Boundary matching between cavity mode expansion inside the holes and Rayleigh expansion outside the holes [31] result in the following zeroth order transmittance for the x-polarization:

$$T_0 = \frac{ab}{d_x d_y \pi} \left[\frac{2 \frac{i\mu}{k\pi}}{\sin(\mu h) \left(W^2 - \left(\frac{i\mu}{k\pi} \right)^2 \right) + 2 \frac{i\mu}{k\pi} W \cos(\mu h)} \right] \quad (1)$$

where k is the wave vector of the incident light and μ is the waveguide vector, $\mu^2 = k^2 - (\pi/b)^2$. W is a self-illumination term [10] describing coupling of the hole-eigenmodes with the incident wave:

$$W = \sum_{mn=-\infty}^{+\infty} (\chi_{mn}^2 + \alpha_m^2) K_{mn} J_{mn} / \chi_{mn} k \quad (2)$$

where $\alpha_m = 2\pi m/d_x$, $\beta_n = 2\pi n/d_y$, $\phi_{mn} = \alpha_m (x-a/2) + \beta_n (y-b/2)$, $\chi_{mn}^2 = k^2 - \alpha_m^2 - \beta_n^2$, $K_{mn} = (d_x d_y)^{-1} \int_0^b \int_0^a \sin(\pi y/b) e^{-i\phi_{mn}} dx dy$ and $J_{mn} = (2ab)^{-1} \int_0^b \int_0^a e^{i\phi_{mn}} dx dy$.

The theoretical figure shown in Fig. 2(c), contour-plotting transmission spectra versus b is in excellent agreement with experimental results, including the bowing behavior near f_R . In addition, electric field profile inside the rectangular hole indeed is close to that of the half wavelength mode (not shown). Since the lowest shape resonance frequency is determined by the rectangular dimension in the direction perpendicular to the polarization, we expect that when we rotate the sample by 90 degrees, the shape resonance frequency switches from $c/2b$ to $c/2a$. Figure 2(d) displays contour plot of rotational angle dependent transmission for a sample with $a = 203 \mu\text{m}$ and $b = 301 \mu\text{m}$, and indeed, the transmission frequency switches as we rotate the sample.

Transmission spectra shown in Figs. 1 and 2 have been taken at normal incidence. In many applications, an incident-angle independent filter would be much desired. Our shape resonance filter with rectangular hole shape has exactly this property. Shown in Fig. 3(a) is a contour plot of angle dependent transmission spectra, for an array of strongly rectangular shaped holes with width to length ratio of 1 to 8. The transmission peak is completely independent of incident angle and lies very close in frequency to the half wavelength mode. This angle independence is essentially because the half wavelength mode cut-off $c/2b = 0.24$ THz and the first Rayleigh minima are far from each other in the range of angles investigated, so that only the length b , not the period d is important in determining the transmission maximum. As the length becomes shorter all the way to square shape holes, shape resonance and Rayleigh minima interact with each other to generate surface plasmon-like, angle-dependent transmission peaks, which lies below the Rayleigh minima line much like in the

visible range [Fig. 3(b)]. We now show that a dual or multiple frequency filter can be made simply by choosing an asymmetric hole shape.

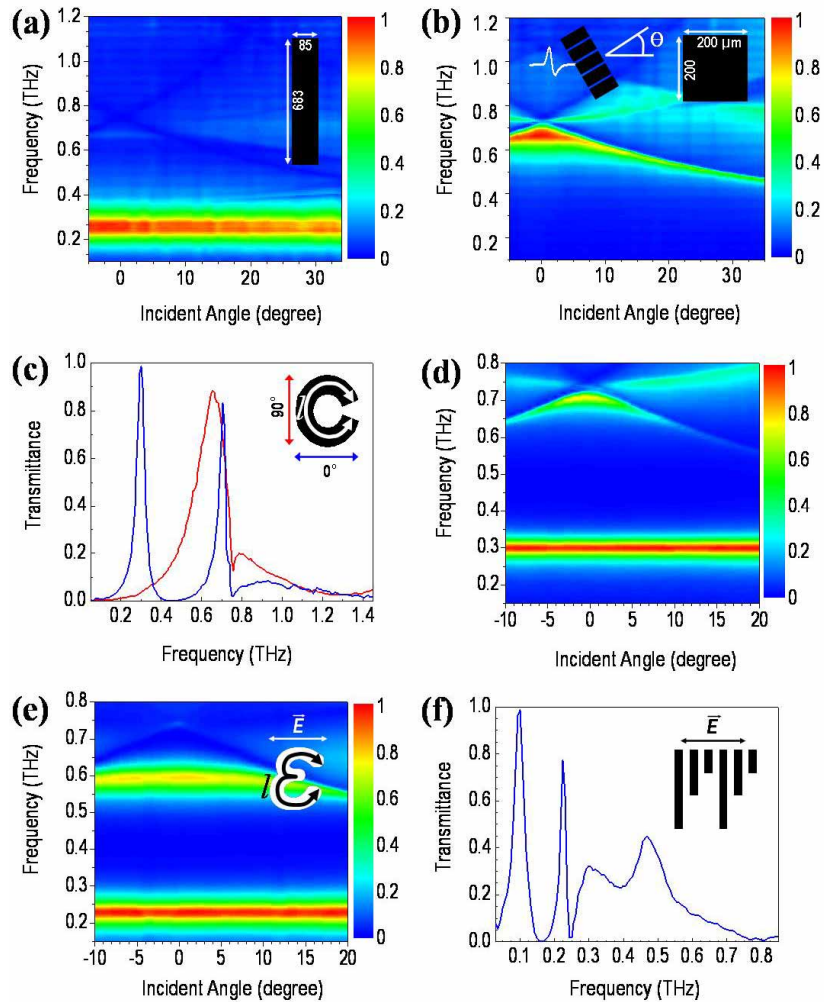


Fig. 3. (a) A contour plot of the incident angle (θ) dependent transmission for the rectangle hole sample with width to length ratio of 1 to 8. (b) Angle dependent transmission for the square hole sample. (c) Normal incidence transmission spectra at the horizontal (blue line) and vertical (red line) polarizations for the c-shaped sample. (d), (e) Angle dependent transmissions for the c- and epsilon-shaped samples. (f) Transmission spectrum for the sample consisted of rectangular holes with three different lengths, 390, 650 and 1500 μm , at normal incidence.

Readily available multiple frequency filters may find applications in selecting signature frequencies, while rejecting the background. In symmetrical shapes such as circles, rectangles, and squares, it seems clear that the fundamental, lowest frequency resonance determines the dominant transparency frequency, together with a smaller effect of the period d . For more complex c- and epsilon-shaped structures, more than one frequencies support strong transmission. Figure 3(c) shows dual resonance, one near unity at 0.28 THz and the other over 80% at 0.70 THz at horizontal polarization (Blue line), in contrast for vertical polarization (Red line), which shows a predominant peak at 0.62 THz. The near-unity transmission at 0.28 THz for horizontal polarization can be thought of as corresponding to the ‘half-wavelength’

mode of the entire length l along the c-shape, and is consistent with the result on a rectangle sample with the same length, $l=590\ \mu\text{m}$. The second peak at 0.70 THz, slightly below f_R , is due to the combined effects of another, higher frequency shape resonance and the periodicity, as is clear from the angle dependence shown in Fig. 3(d): while the lower frequency transmission peak position is completely angle-independent, the higher transmission peak sees the period. It is clear that l along the shape is an important parameter in determining the shape resonance positions and therefore the peak positions. We now investigate an epsilon shaped hole sample, which has a longer $l=703\ \mu\text{m}$ and therefore smaller shape resonance frequencies.

The transmission Fig. 3(e) shows that even the higher frequency peak is essentially angle-independent, making this an angle independent dual frequency filter. This is because the longer l makes both transmission peaks at 0.58 THz and 0.26 THz to be sufficiently removed from f_R . Transmission properties of such asymmetric shapes offer us the possibility of multi-resonances which can be designed by proper combination of shape resonances and the crossings of Rayleigh lines. Asymmetric structure consisted of rectangular holes with three different lengths shows four dominant resonances [Fig. 3(f)]. The crossings of Rayleigh lines appear as transmission minima at 0.78 and 0.25 THz, where the former is caused by the period of 390 and the latter the super-period, 1170. These two minima, particularly the first Rayleigh minimum interfere with three fundamental shape resonances for each rectangle, apparently resulting in four transmission peaks. This interference of Rayleigh minima with shape resonances gives yet another means of tailoring transmission spectra for the desired multiple frequency peaks.

3. Conclusion

We have demonstrated that near-unity transmittance is obtained at desired terahertz frequencies in plasmonic metamaterials through the shape resonance. Strong transmission peaks, single, dual, and multiple, result by designing various shape holes, combined with the Rayleigh minima. Our results also show that plasmonic metamaterials with different geometric shaped holes are extremely versatile, dependable, easy to control and easy to make terahertz filters. In particular, angle dependent transmission spectra for square, rectangle, c- and epsilon-shaped holes show an omni-directional property when the fundamental shape resonance is far away from the Rayleigh minima. We believe that our work could be particularly useful as multiple-color filters to select incommensurate signature frequencies in terahertz and infrared regime where coating is impractical and, in contrast to Fabry-Perot filters where integer-multiple frequencies always transmit even when undesired.

Acknowledgments

This research was supported by MOST, MOCIE and KOSEF.