Substrate effects on resonance behaviors of rectangular holes with nano-sized widths

H. R. Park[a], S. M. Koo[b], O. K. Suwal[c], Y. M. Bahk[a], J. S. Kyoung[a], M. A. Seo[a], S. S. Choi[c], N. K. Park[b], D. S. Kim[a], and K. J. Ahn[a*]
[a]*Center for Subwavelength Optics and Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea*
[b]*Photonic Systems Laboratory, School of EECS, Seoul National University, Seoul 151-744, Korea*
[c]*Department of Physics and Advanced Materials Science, Sun Moon University, Asan 336-708, Korea*
**E-mail: kwangjun@phya.snu.ac.kr*

Optical properties of metallic sub-wavelength apertures have strongly been focused in near infrared and visible frequency regimes after the report by Ebbesen and his coworkers [1] on extraordinary transmission of light via surface plasmon polariton. Even in lower frequencies where most metals are considered as perfect electric conductor (PEC), it has theoretically [2] and experimentally [3] been studied that the transmitted electric fields through half-wavelength slot antennas are substantially enhanced when the thickness and the width of slot antennas are both in extreme sub-wavelength region. In the cases of thin metallic structures or other metallic compositions with a thickness below 10 μm [4-7], they cannot be free-standing samples. Such thin samples must inevitably be sustained by rigid and transparent materials, namely, dielectric substrates. It should be noted that optical properties of the substrate can influence on resonant features of sub-wavelengh metallic structures [8].

In our work, we show that resonance behaviors of a single rectangular hole perforated in a thin metallic film on a finite dielectric substrate depend on the substrate thickness as well. As the substrate thickness is reduced to several microns, the resonance frequency is clearly blue-shifted for the increasing rectangular hole width. We also demonstrate these resonance shifts can be seen not only in real metal but in perfect electric conductor (PEC) cases. All in all, the substrate thickness and the hole width in the extreme sub-wavelength limit are additional crucial factors determining the resonance frequency of rectangular holes on a finite substrate.

We perform three-dimensional finite difference time-domain (FDTD) simulations and obtain transmitted electric fields through two different widths of rectangular holes (w = 5 μm and 150 nm) on various thicknesses of SiN substrate (t = 0, 2 μm, 10 μm, 60 μm, and infinity), with a fixed length l of 150 μm and metal thickness h of 60 nm (Fig. 1(a)). In Fig. 1(b), we compare their resonance behaviors, depending on the substrate thickness. Two interesting features in this result are that *i*) the resonance frequency is blue-shifted for the increasing hole width and *ii*) the effective refractive indices of finite substrates for the rectangular hole resonance is determined not only by the substrate thickness but by the hole width as well.

We experimentally study resonance behaviors of rectangular holes in two limiting cases. Rectangular holes with a fixed length but different widths are fabricated in a 60 nm-thick gold film deposited on a combined 2 μm-thick SiN and SiO_2 substrate and on a Si substrate with a 500 μm thickness, respectively. In Fig. 1(c) and (d), we show commonly blue-shifted peaks on two substrates for the increasing hole width, as a real metallic feature of the thin gold film in terahertz (THz) frequencies. Especially, the resonance frequency difference between the smallest and the widest width holes on the 2 μm-thick substrate is larger than that on the 500 μm-thick Si substrate, being in good agreement with simulation results.

In conclusion, we present the resonance behaviors of a single rectangular hole perforated in a gold film on finite substrates. We find that the slot width and the substrate thickness are other crucial parameters for determining resonance behaviors of rectangular holes on finite substrates, while the slot width has almost no influence on the resonance of freestanding metallic apertures. Moreover, when the substrate thickness decreases below 2 μm, the blue shift of resonance peak can be found in both real metal and PEC film. We can apply our results to research area where accurate resonance control is requested, such as THz filters, active THz devices, and nanoparticle detection.

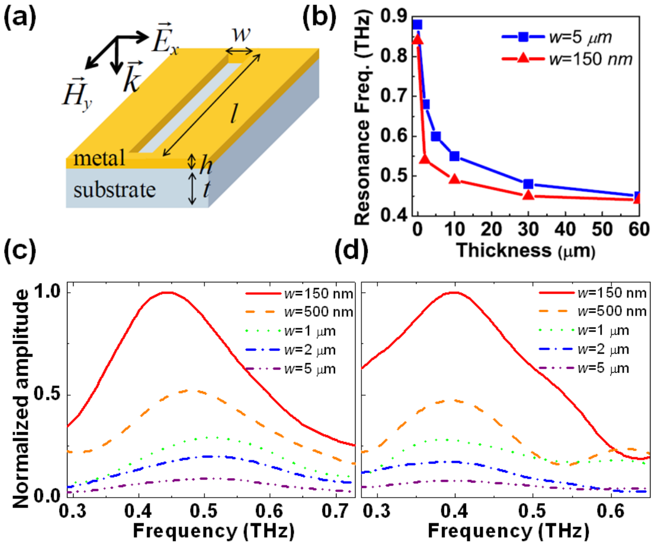

Figure 1 (a) Spatial dimensions of a rectangular hole on a finite substrate. (b) Resonance frequency shifts of rectangular holes with a 5 μm and a 150 nm width as a function of SiN substrate thickness. (c) Normalized transmitted amplitude spectra measured through rectangular holes with a fixed length of 150 μm and different widths (*w*=150 nm, 500 nm, 1 μm, 2 μm, and 5 μm) on the 2 μm-thick SiN substrate. (d) The same as (c) except the 500 μm-thick Si substrate.

Acknowledgement

This work was supported by the Korea Science and Engineering Foundation (KOSEF) (No:2010-0029648) (SRC, No:R11-2008-095-01000-0), the Korea Research Foundation (KRF, No:2009-0071309), KICOS (GRL, K20815000003) and Hi Seoul Science / Humanities Fellowship from Seoul Scholarship Foundation.

References

1. T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature **391**, 667 (1998).
2. F. J. García-Vidal, Esteban Moreno, J. A. Porto, and L. Martín-Moreno, Phys. Rev. Lett. **95**, 103901 (2005).
3. M. A. Seo, A. J. L. Adam, J. H. Kang, J. W. Lee, K. J. Ahn, Q. H. Park, P. C. M. Planken, and D. S. Kim, Opt. Express **16**, 20484 (2008).
4. L. Ren, C. L. Pint, L. G. Booshehri, W. D. Rice, X. Wang, D. J. Hilton, K. Takeya, I. Kawayama, M. Tonouchi, R. H. Hauge, and J. Kono, Nano Lett. **9**, 2610 (2009).
5. S. M. Koo, M. Sathish Kumar, J. H. Shin, D. S. Kim, and N. K. Park, Phys. Rev. Lett. **103**, 263901 (2009).
6. K. Lindfors, T. Kalkbrenner, P. Stoller, and V. Sandoghdar, Phys. Rev. Lett. **93**, 037401 (2004).
7. T. J. Yen, W. J. Padilla, N. Fang, D. C. Vier, D. R. Smith, J. B. Pendry, D. N. Basov, and X. Zhang, Science **303**, 1494 (2004).
8. J. H. Kang, J.-H. Choe, D. S. Kim, and Q.-H. Park, Opt. Express **17**, 15652 (2009).