Numerical Investigation of a Three-Dimensional Stub-Type Plasmonic Filter

Jun Shibayama, Hiroki Kawai†, Junji Yamauchi, and Hisamatsu Nakano
Faculty of Science and Engineering
Hosei University, Tokyo 184-8584, Japan
†Email: hiroki.kawai.2m@stu.hosei.ac.jp

***Abstract*—A three-dimensional (3D) stub-type plasmonic filter is analyzed using the FDTD method based on the trapezoidal recursive convolution technique. The peak transmissivity of the 3D filter is calculated to be $\simeq$50%, while the two-dimensional filter yields more than 90% transmissivity. To improve the transmissivity of the 3D filter, we insert a dielectric material into the stub section. It is found that the transmissivity is increased to more than 80% with the stub section being filled with SiC.**

I. Introduction

Surface plasmon polaritons propagate along a metal-insulator interface at optical frequencies. In particular, a metal-insulator-metal (MIM) structure has received attention, since the light can be confined and guided in a subwavelength region. Using the MIM structures, several plasmonic filters have been investigated, e.g., the characteristics of stub-type filters have been studied theoretically [1], [2]. Note, however, that most of these investigations have been performed using two-dimensional (2D) structures, and not so much attention has been paid to practical three-dimensional (3D) structures, except for our recent work regarding grating- and slit-type filters [3].

The purpose of this article is to investigate the transmission characteristics of a 3D stub-type plasmonic filter, in comparison with a 2D filter. To analyze these filters, we use the frequency-dependent FDTD method based on the trapezoidal recursive convolution (TRC) technique [3], [4]. It is shown that the 2D filter yields a peak transmissivity of more than 90%. In contrast, the transmissivity of the 3D filter is reduced to about 50%. This reduced transmissivity is mainly due to the fact that appreciable radiation occurs at the structural discontinuities in the stub section. To improve the transmissivity of the 3D filter, we introduce dielectric materials such as SiC and SiO_2 into the stub section. It is found that the transmissivity is increased to more than 80% with the stub section being filled with SiC.

II. Discussion

The stub-type filter to be analyzed is shown in Fig. 1. The metal gap width w of the input/output sections is fixed to be 0.05 μm. The metal thickness is chosen to be h=∞ for the 2D filter, and h=0.05 μm for the 3D filter (the latter is a typical thickness of the 3D plasmonic gap waveguide [5]). The stub length and width are set to be L_{S}= 0.59 μm and W_{S}=0.1 μm, respectively. The refractive index in the stub section is denoted by n_{S}. The metal is chosen to be Ag, the dispersion of which is expressed by Drude model [6]. The Drude model is incorporated into the FDTD method using the TRC technique [3], [4]. The spatial sampling widths are Δx=Δy=Δz=0.005 μm. The wavelength response at the output port is calculated using Fourier transform together with the pulse excitation technique.

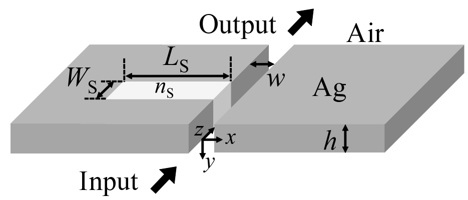


Fig. 1. Stub-type filter.

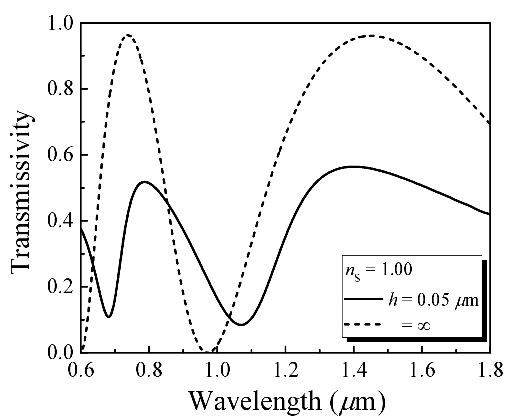


Fig. 2. Transmission spectra.

Fig. 2 shows the transmission spectra for n_{S}=1.00, in which the 3D result is compared with the 2D one. It is seen that a high transmissivity of 96% is obtained for the 2D filter at λ=0.74 μm. Note that the field in the 2D filter is completely confined to the waveguide and stub, leading to the high transmissivity. In contrast, the transmissivity of the 3D filter deteriorates to 51% at λ=0.78 μm. This low transmissivity is mainly due to the fact that appreciable radiation occurs at the large structural discontinuities in the stub section. Although not illustrated, the metal thickness should be more than h=2 μm to achieve the comparable transmissivity of the 2D filter.

978-1-4673-8603-6/16/$31.00 ©2016 IEEE

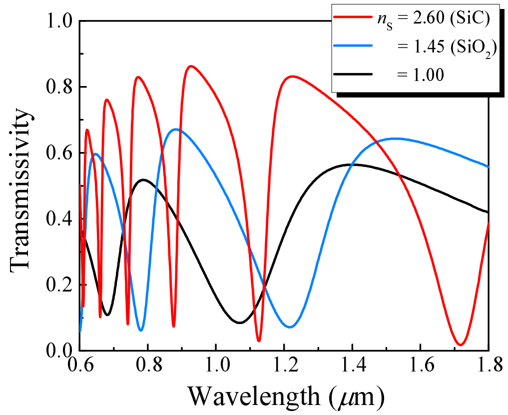


Fig. 3. Transmission spectra (h=0.05 μm).

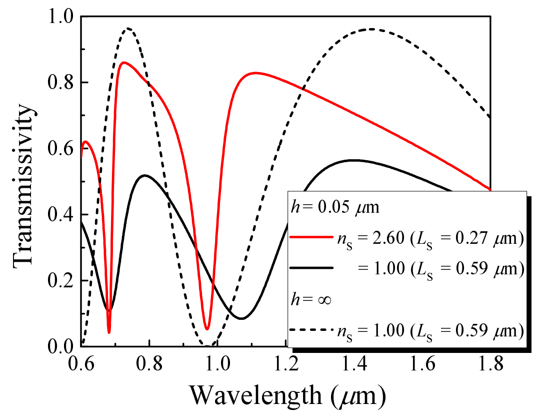
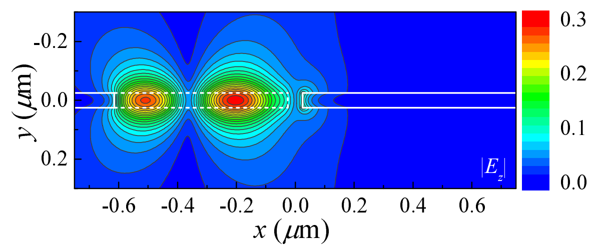


Fig. 4. Transmission spectra. The stub length for n_S=2.60 is adjusted.

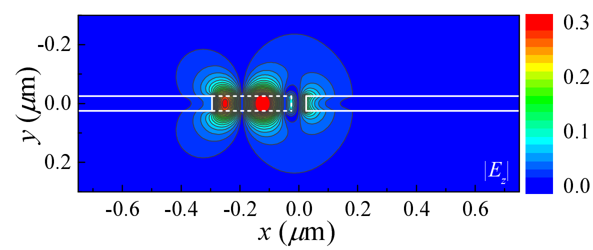
To suppress the radiation at the discontinuities for the 3D filter, we insert dielectric materials such as SiC and SiO_2 into the stub section. The refractive indices of SiC and SiO_2 are n_S=2.60 and 1.45, respectively. Fig. 3 depicts the transmission spectra for several n_S values. It is found that the peak transmissivity increases, as n_S is increased. For n_S=2.60, a high transmissivity of 83% is achieved at λ=1.23 μm, which results from the increased confinement of the field into the stub section. In other words, the Q value of a cavity is increased with the dielectric material.

Note that the transmission peak shifts towards the longer wavelength for a large n_S. This comes from the fact that the effective length of the stub becomes longer with an increase of n_S. Fig. 4 shows the transmission spectra, in which the stub length is adjusted in such a way that the peak frequency for n_S=2.60 becomes close to that for n_S=1. When L_S is reduced from 0.59 to 0.27 μm, the peak frequency shifts to 0.73 μm with a transmissivity of 85%. Even for the 3D stub-type filter with a thin metal layer, a high transmissivity comparable to the 2D counterpart is obtainable with a stub filled with a dielectric material.

Finally, we explain the reason for achieving the high transmissivity by illustrating the propagating field in the stub section of the 3D filter. Fig. 5 shows the E_z field distributions in the x-y plane observed in the stub section at the peak frequency, in which (a) is for n_S=1.00 (L_S=0.59 μm) and (b) is for n_S=2.60 (L_S=0.27 μm). In Fig. 5(a), appreciable radiation is seen in the $\pm y$ directions, yielding a radiation power of 19%. On the other hand, in Fig. 5(b) the field is effectively confined into the stub section, leading to a reduced radiation power of 2.6%.



(a) n_S=1.00 and L_S=0.59 μm.



(b) n_S=2.60 and L_S=0.27 μm.

Fig. 5. E_z field distributions in the x-y plane observed in the stub section.

III. Conclusion

We have improved the transmission characteristics of a 3D stub-type filter, in which a dielectric material is inserted into the stub section. The transmissivity is increased from 51% to 85% with the stub being filled with SiC.

References

[1] Y. Matsuzaki, T. Okamoto, M. Haraguchi, M. Fukui, and M. Nakagaki, "Characteristics of gap plasmon waveguide with stub structures," *Opt. Exp.*, vol. 16, no. 21, pp. 16314-16325, 2008.

[2] S. R. Mirnaziry, A. Setayesh, and M. S. Abrishamian, "Design and analysis of plasmonic filters based on stubs," *J. Opt. Soc. Am. B*, vol. 28, no. 5 pp. 1300-1307, 2011.

[3] J. Shibayama, Y. Wada, J. Yamauchi, and H. Nakano, "Analysis of two- and three-dimensional plasmonic waveguide band-pass filters using the TRC-FDTD method," *IEICE Trans. Electron.*, vol. E99-C, no. 7, 2016 (in press).

[4] J. Shibayama, R. Ando, A. Nomura, J. Yamauchi, and H. Nakano, "Simple trapezoidal recursive convolution technique for the frequency-dependent FDTD analysis of a Drude-Lorentz model," *IEEE Photon. Technol. Lett.*, vol. 21, no. 2, pp. 100-102, 2009.

[5] G. Veronis and S. Fan, "Modes of subwavelength plasmonic slot waveguides," *J. Lightw. Technol.*, vol. 25, no. 9, pp. 2511-2521, 2007.

[6] Z. Han, E. Forsberg, and S. He, "Surface plasmon Bragg gratings formed in metal-insulator-metal waveguides," *IEEE Photon. Technol. Lett.*, vol. 19, no. 2, pp. 91-93, 2007.