

# Transmission Characteristics of a Thin Metal Film Sandwiched Between Dielectric Gratings

Yuu Wakabayashi, # Takato Fukui, Junji Yamauchi, and Hisamatsu Nakano  
 Faculty of Science and Engineering, Hosei University  
 3-7-2 Kajino-cho, Koganei, Tokyo 184-8584 Japan, e-mail: takato.fukui.7e@stu.hosei.ac.jp

## 1. Introduction

There are a great number of optical devices based on the surface plasmon resonance (SPR) [1]- [3]. One of the important applications of these devices is to construct a polarizer, which is used as a sensing device [1], [3] and a polarization splitter [2]. Recently, the high transmission of the transverse magnetic (TM) wave is realized using a thin metal film sandwiched between dielectric gratings [1], [4]- [6]. We have revealed that the high transmission properties of this structure are based not only on the SPR but also on the Fabry-Pérot resonance (FPR) [7]. On the other hand, the high transmissivity for the transverse electric (TE) wave was discussed in terms of the guided-mode resonance (GMR) through the analysis of subwavelength slit gratings and hole arrays [8].

In this paper, we discuss the relation between the high transmissivities and these resonances in more detail. It is revealed that the high transmissivity based on the FPR is determined by the grating thickness, while the GMR and SPR by the periodicity. On the basis of these results, we design the polarizer which operates at a required wavelength by changing the periodicity. A high transmissivity of more than 85% is observed at each of the resonances.

## 2. Configuration and Numerical Method

Fig. 1 illustrates the periodic structure of the polarizer, in which a two-dimensional model is treated. The configuration is similar to that treated in Ref. [1]. The refractive indices of the dielectric materials are taken to be  $n_H = 3.715$  and  $n_L = 2.049$ . The periodicity and the widths of the high- and low-index dielectric regions are, respectively, designated as  $\Lambda$ ,  $w_H$ , and  $w_L$ . The fill factor is defined as  $f_H = w_H/\Lambda$ . The thicknesses of the dielectric grating and the metal film are set to be  $t_d = 0.22 \mu\text{m}$  and  $t_m = 0.03 \mu\text{m}$ . We express the dispersion of the metal (Ag) film as the following Drude-Lorentz model [9], [10]:

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\omega_D^2}{j\omega(\nu_D + j\omega)} + \frac{\Delta\varepsilon\omega_L^2}{j\omega\nu_L + \omega_L^2 - \omega^2}, \quad (1)$$

where  $\omega$  is the angular frequency. The dielectric constant of the material at an infinite frequency is  $\varepsilon_\infty = 3.91$ , the electron plasma frequencies  $\omega_D = 13420 \text{ THz}$ ,  $\omega_L = 6870 \text{ THz}$ , the effective electron collision frequencies  $\nu_D = 84 \text{ THz}$ ,  $\nu_L = 12340 \text{ THz}$ , and the weighting coefficient  $\Delta\varepsilon = 0.76$ .

We illuminate a uniform plane wave of either the TE or TM wave from the input side and intend to extract either the TE or TM wave, or both as a transmission field at the output side. To analyze the present polarizer, we adopt the FDTD method with the periodic boundary condition [11]. The piecewise linear recursive convolution technique [12] is employed to treat the dispersive medium.

## 3. Discussion

Fig. 2 shows the transmissivity as a joint function of wavelength  $\lambda$  and  $f_H$ . It is seen that, for the region 1, both of the TE and TM waves can be transmitted at  $\lambda = 1.19 \mu\text{m}$ . This transmission is related to the FPR. In contrast, the region 2 for the TE wave and the region 3 for the TM wave are related to the GMR and the SPR, respectively. Each of these behaviors is discussed in more detail in the following.

We first consider the FPR. For simplicity,  $f_H$  is taken to be unity; the dielectric gratings become homogeneous layers. Fig. 3 shows the transmissivity as a function of wavelength. Since the results of the TE and TM waves are the same, we only show the TE wave results. For reference, we also plot the data for the case without the metal film, i.e., a homogeneous high-index dielectric layer with the thickness of  $T_d = 2t_d + t_m$ . The structure without the metal film achieves a maximum transmissivity of 100% at  $\lambda = 0.87 \mu\text{m}$ ,  $1.16 \mu\text{m}$ , and  $1.75 \mu\text{m}$ . This is due to the FPR, which provides the following relationship:

$$T_d = \frac{m\lambda}{2n_H} \quad (m = 1, 2, 3, \dots). \quad (2)$$

On the other hand, for the structure with the metal film, a transmissivity of more than 83% is obtained at  $\lambda = 1.19 \mu\text{m}$ . In this case, the considerable incident wave is reflected from the metal film with a phase shift of approximately  $\pi$  rad. As a result, the phase matching condition in the dielectric layer for the input side is governed by

$$t_d = \frac{(2m' - 1)\lambda}{4n_H} \quad (m' = 1, 2, 3, \dots). \quad (3)$$

It should be noted that the remaining power penetrates through the thin metal film because the thickness is comparable to the skin depth, and then the transmitted wave satisfies the same condition for the output side. This leads to the resonance in the dielectric regions with a subsequent high transmissivity.

Here, we assume that the phase shift within the thin metal film is significantly small, so that the thickness of the metal film can be neglected, i.e.,  $T_d = 2t_d$ . Combining Eqs. (2) and (3) under the condition of  $T_d = 2t_d$  results in  $2m' - 1 = m$ . This means that Eq. (3) corresponds to Eq. (2) with the odd number of  $m$ . Therefore, the high transmissivities observed at  $\lambda = 0.87 \mu\text{m}$  and  $\lambda = 1.75 \mu\text{m}$  disappear for the case with the metal film.

We next consider the GMR and the SPR. At normal incidence, the propagation constant of the diffracted wave parallel to the grating surface is defined by

$$k_d = \pm i \frac{2\pi}{\Lambda}, \quad (4)$$

where  $i$  is the diffraction order. Each of the GMR and SPR is excited, when  $k_d$  agrees with the propagation constants of the modes which propagate in the grating regions. Then, we obtain the high transmissivity at these resonances.

For the SPR, there are two high transmission regions (3a and 3b) in Fig. 2(b). These regions stem from the existence of the two surface plasmon modes which exhibit the asymmetric and symmetric distribution with respect to the middle plane of the metal film. When  $f_H$  approaches zero, the wavelengths corresponding to the region 3a and 3b move toward  $\lambda \cong 1.2 \mu\text{m}$  and  $1.1 \mu\text{m}$ , although the transmissivity is reduced because of the weak SPR resonance. Therefore, it is expected that the propagation constants at these wavelengths agree with  $k_d$ . Fig. 4 shows the propagation constant  $\beta$  against wavelength, where  $\beta$  is evaluated by the eigenmode analysis for  $f_H = 0$ . As expected, the propagation constants for the asymmetric and symmetric modes cross  $k_d$  at  $\lambda = 1.22 \mu\text{m}$  and  $1.08 \mu\text{m}$ , respectively. Although not illustrated, a similar tendency is also observed for the GMR.

The discussions so far encourage us to design the polarizer which operates at a required wavelength, since the FPR is determined by the grating thickness, while the GMR and SPR by the periodicity. Figs. 5 and 6, respectively, show the transmissivities for the TE and TM waves as a function of wavelength, in which the periodicity is taken to be  $\Lambda = 0.58 \mu\text{m}$ ,  $0.68 \mu\text{m}$ ,  $0.78 \mu\text{m}$  with  $f_H \cong 0.7$ . It is revealed that the wavelengths corresponding to the GMR and SPR shift toward longer wavelengths as the periodicity is increased. On the other hand, the high transmissivity based on the FPR is maintained at  $\lambda = 1.15 \mu\text{m}$ . As a result, we obtain a high transmissivity of more than 85% at each of the resonances.

## 4. Conclusions

We have analyzed the polarizer consisting of the thin metal film sandwiched between the dielectric gratings using the FDTD method. It is revealed that the surface plasmon resonance (SPR) and the guided-mode resonance (GMR) depend on the periodicity, whereas the Fabry-Pérot resonance (FPR) depends on the thickness of the gratings. Therefore, the wavelengths corresponding to the GMR and SPR shift toward longer wavelengths as the periodicity is increased, while the high transmissivity based on the FPR is maintained at  $\lambda = 1.15 \mu\text{m}$ . This fact enables us to design the polarizer which operates at a required wavelength.

## Acknowledgments

This work was supported in part by MEXT, Grant-in-Aid for Scientific Research (c) (22560350).

## References

- [1] V. M. Fitio and Y. V. Bobitski, "High transmission of system 'dielectric grating-thin metal film-dielectric grating'," *Laser and Fiber-Optical Networks Modeling*, pp. 163-166, 2005.
- [2] M. Kuwata-Gonokami, N. Saito, Y. Ino, M. Kauranen, K. Jefimovs, T. Vallius, J. Turunen, and Y. Svirko, "Giant optical activity in quasi-two-dimensional planar nanostructures," *Phys. Rev. Lett.*, vol. 95, 227401, 2005.
- [3] J. Shibayama, "Three-dimensional numerical investigation of an improved surface plasmon resonance waveguide sensor," *IEEE Photon. Technol. Lett.*, vol. 22, no. 9, pp. 643-645, 2010.
- [4] J. Yamauchi, K. Sumida, and H. Nakano, "A TM-pass/TE-stop polarizer consisting of a metal film sandwiched with dielectric gratings," *Contemporary Photonics Technol.*, Tokyo, Japan, G-15, pp. 93-94, 2007.
- [5] J. Yamauchi, T. Yamazaki, K. Sumida, and H. Nakano, "TE/TM wave splitters using surface plasmon polaritons," *Integrated Photonics and Nanophotonics Research and Applications*, Salt Lake City, Utah, USA, ItuB7, 2007.
- [6] Y. Wakabayashi, J. Yamauchi, and H. Nakano, "A TM-pass/TE-stop polarizer based on a surface plasmon resonance," *Advances in OptoElectronics*, vol. 2011, Article ID 867271, 2011.
- [7] Y. Wakabayashi, T. Fukui, J. Yamauchi, and H. Nakano, "Wavelength characteristics of a thin metal film sandwiched between dielectric gratings," *IEICE Tech. Rep.*, vol. 111, no. 266, OPE2011-100, pp. 43-48, 2011.
- [8] E. Popov, S. Enoch, G. Tayeb, M. Nevière, B. Gralak, and N. Bonod, "Enhanced transmission due to nonplasmon resonances in one- and two-dimensional gratings," *Applied Optics*, vol. 43, no. 5, pp. 999-1008, 2004.
- [9] T. Laroche and C. Giard, "Near-field optical properties of single plasmonic nanowires," *Appl. Phys. Lett.*, vol. 89, pp. 233119(1)-233119(3), 2006.
- [10] J. Shibayama, A. Nomura, R. Ando, J. Yamauchi, and H. Nakano, "A frequency-dependent LOD-FDTD method and its application to the analyses of plasmonic waveguide devices," *IEEE J. Quantum Electron.*, vol. 46, no. 1, pp. 40-49, 2010.
- [11] A. Taflov and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, Norwood, MA: Artech House, 2000.
- [12] D. F. Kelley and R. J. Luebbers, "Piecewise linear recursive convolution for dispersive media using FDTD," *IEEE Trans. Antennas Propagat.*, vol. 44, no. 6, pp. 792-797, 1996.

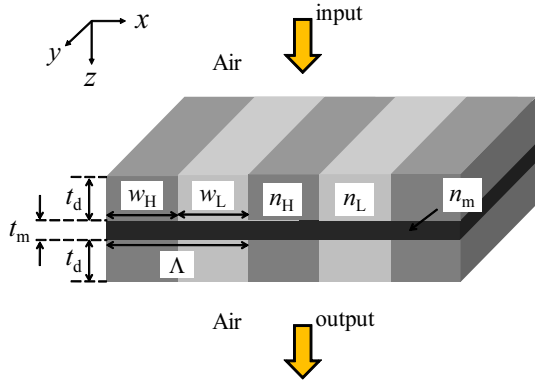


Figure 1: Configuration.

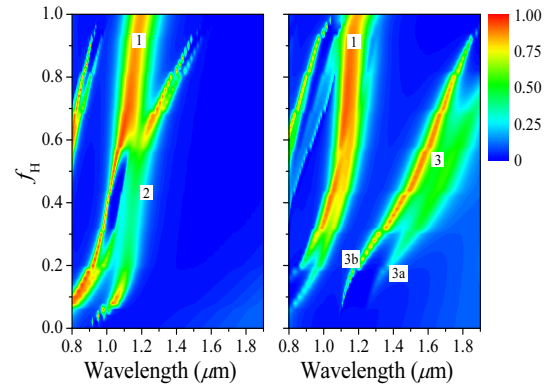


Figure 2: Transmissivity as a joint function of wavelength and  $f_H$  for  $\Lambda = 0.58 \mu\text{m}$ .

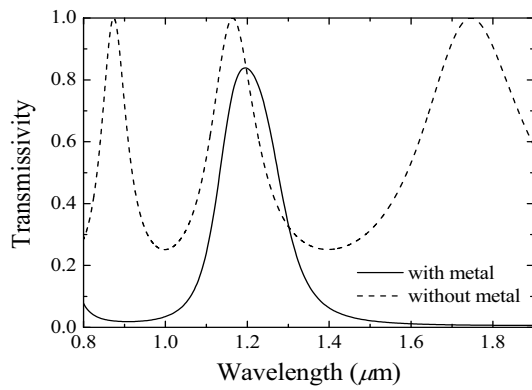


Figure 3: Transmissivity as a function of wavelength for  $f_H = 1.0$ .

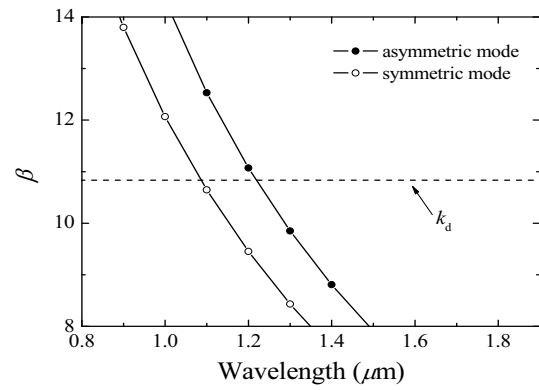


Figure 4: Propagation constant against wavelength.

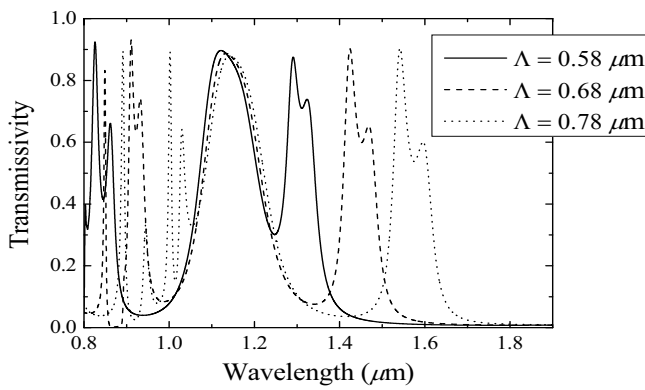


Figure 5: Transmissivity as a function of wavelength for TE wave ( $f_H \approx 0.7$ )

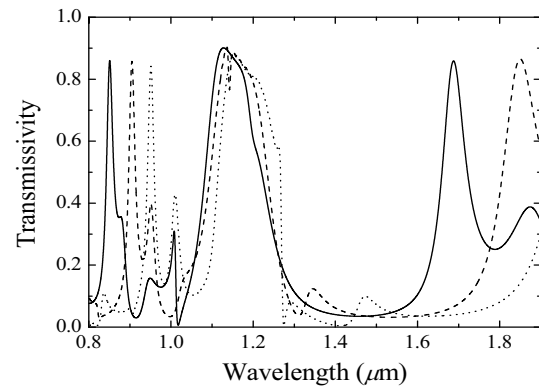


Figure 6: Transmissivity as a function of wavelength for TM wave ( $f_H \approx 0.7$ )