Spectral tuning of SPP reflection by quasi-symmetric metal nano-block arrays

Naoki Ichiji[1†], Atsushi Kubo[2*]

[1]Graduate School of Pure and Applied Science, University of Tsukuba, Ibaraki, Japan
[2]Division of Physics, Faculty of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
E-mail: †s2030036@s.tsukuba.ac.jp, *kubo.atsushi.ka@u.tsukuba.ac.jp

Abstract

We investigate the spectral tuning of the SPP wave packets by quasi-symmetric arrays composed of metal blocks with two different structural lengths. The FDTD simulations showed a resonance phenomenon in the gap between the blocks when the two blocks have different lengths in the longitudinal direction. Furthermore, the resonance of the gap resulted in a significant spectral modulation of the reflected SPP wave that depended on the structural length and positional relationship of the blocks.

1. Introduction

Metamaterials consisting of nanoscale structures have led to a significant development of optical manipulation techniques, such as polarization control and nonreciprocal transmission [1,2]. The artificial modulation of optical properties realized by metamaterials is one of the foundations for the control of light in free space and Surface Plasmon Polariton (SPP). SPP manipulation techniques, such as unidirectional excitation and wavelength selective focusing, have been demonstrated theoretically and experimentally by arranging nanorod and slit structures [3,4].

The specific optical properties of the metamaterial are determined by the design and arrangement of the individual resonator structure. In addition, when the distance between resonators is shorter than the wavelength of the incident light, mode coupling between resonators and near-field resonance can occur. Therefore, the interaction between resonators must be taken into account in metamaterials where the resonators are densely arranged.

In this work, we investigate the interaction between the SPP wave packet and a one-dimensional periodic structure of metal blocks. The periodic structure was constructed by periodically arranging Au blocks with two different structural lengths at intervals less than the wavelength of the incident SPP wave. An FDTD simulation reveals that the walls of the adjacent blocks behave as MIM resonators, with the gap between the blocks as an insulator layer only when the longitudinal length of the two blocks are different. This MIM resonator, referred to as gap MIM structure, caused spectral modulations in the transmitted and reflected wave, especially in the reflected wave. The spectral modulation observed in the reflected wave can be adjusted by arranging the two types of blocks.

2. Result

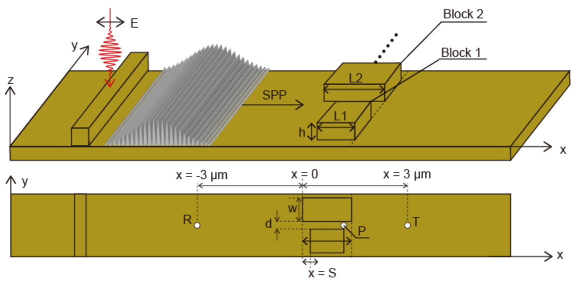

Figure 1: Schematic of periodic structure used for FDTD simulations.

Figure 1 (a) shows a schematic of the quasi-symmetric array constructed by Au blocks with two different lengths in the longitudinal direction. The height h and width w of the two blocks was fixed at 100 nm, and they were arranged periodically with a spacing d of 60 nm. In this study, we fixed the length L_1 of Block 1 at 200 nm, and the length L_2 of Block 2 was set as a variable. We defined the left edge of Block 2 as the origin of the x-axis. The left edge of Block 1 was placed at a distance S shifted from the origin. In this paper, we call the "left edge model" when the left edges of the blocks are coincident ($S = 0$ nm) and the "right edge model" when the right edges are coincident ($S = L2 - L1$ nm). The model with $L1 = L2 = 200$ nm was defined as the reference model. A Au ridge as a coupler for launching SPP WPs was placed on the same surface. The time evolution in the vertical component of the electric fields ($E_z(t)$) for reflected and transmitted waves of the array structure were recorded at points T and R, respectively. To analyze the effect of resonance between blocks, the horizontal component of the electric fields (E_z(t)) was also recorded at point P placed between blocks shown in Fig. 1.

Figs. 2 (a,b) show typical reflected and transmitted spectra calculated by the fast Fourier transform (FFT) of the $E_z(t)$ measured at points R and T. The reflected spectra obtained with the left edge model (red) and right edge model (blue) at the condition of L_2 = 290 nm show large modulation compared to the reference model (black). The modulation in the reflection spectrum occurs mainly at two wavelengths: an increase in intensity around 650 nm and an asymmetric shape around 820 nm. Compared with the reflected wave, which has a large difference in spectrum between the left- and right-edge models, there is almost no difference in the transmitted spectrum (Fig. 2 (b)).

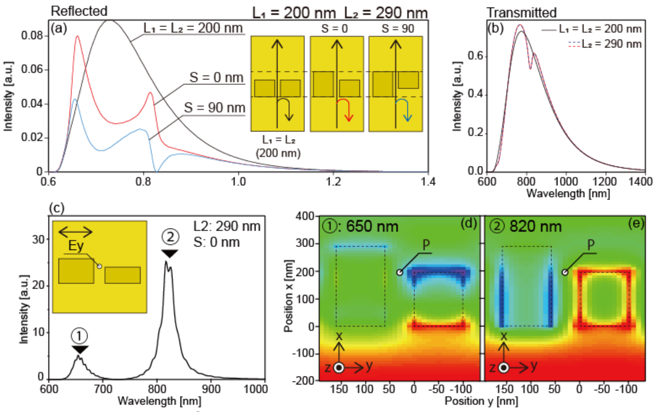

Figure 2: (a,b) Reflected and transmitted spectra obtained at point *T* and *R*. (c) Resonance spectra of the gap between blocks obtained at point *P*. (d,e) Electric field amplitudes E_z on the *xy* plane at the wavelength of 650 nm and 820 nm.

Fig. 2(c) shows the resonance spectra $F(\omega)$ calculated by the Fourier transform from the horizontal component of the electric field E_y(t) acquired at the *P*. This graph indicates clear peaks at 650 nm and 820 nm, which coincide with the characteristic spectral modulation in the reflected spectrum shown in Fig. 2 (a). These resonance peaks do not occur when the length of the two blocks is the same. Fig. 2(d,e) shows the vertical components of the electric field distributions $E_y(x, z)$ obtained at plane 8 nm above the Au surface. The blocks show two types of resonances at 650 nm and 820 nm. In this model, the two metal walls of adjacent blocks act as semi-open MIM nanocavities [5], with the gap between the blocks as an insulating layer.

3. Discussion

We attribute the spectral modulation with a characteristic asymmetric shape to the Fano resonance between the reflected wave from the block wall and the resonance in the MIM gap. Fano resonance is an asymmetric spectral modulation caused by the interference of a narrow discrete resonance with a broad spectral line or continuum [5]. The characteristic spectral shape of the Fano resonance $I(\omega)$ is described by the following equation [6].

$$I(\omega) = \left[\frac{(q+\Omega)^2}{1+\Omega^2}\eta + (1-\eta)\right]B^2, \qquad (1)$$

where q is the Fano asymmetry parameter, Ω is the dimensionless frequency, η is the interaction coefficient, and B is a constant. In this model, the reflection of the wall and resonance at the gap corresponds to the broad spectral line and narrow discrete resonance. In this model, Ω is determined by the resonance wavelength of the MIM resonance occurring in the gap (650 nm, 820 nm), and q is determined by the positions of blocks and the MIM gap. Figure 3 (a) shows the reflection spectrum obtained by varying S from 0 to 220 nm for the model with L_2 = 440 nm. A series of graphs indicate that a characteristic Fano-like spectrum modulation around 820 nm. As shown in Figs. 3 (b-d), varying S corresponds to varying the position of the MIM gap relative to Block 1. We performed a fitting based on the Fano resonance. The fitting curves were defined by multiplying the reflected wave spectrum in the reference model by Fano spectra (eq. (1)) with the center wavelength of 650 nm and 820 nm. The fitting results shown by the red lines in Fig. 3 (a) are well fitted with the simulation results.

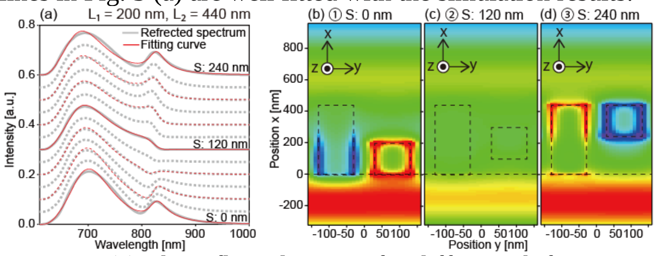

Figure 3: (a) The reflected spectra for different shift S at L_2 = 440 nm structures. (b-d) Related maps of the electric field amplitudes E_y at wavelength of 820 nm. S = 0 nm (b), S = 120 nm (c), S = 240 nm (d).

4. Conclusions

In conclusion, we numerically investigated a quasi-symmetric array structure composed of two metal blocks with different structural lengths. This structure revealed that the reflected wave has a spectral modulation highly depending on the positional relationship of blocks caused by Fano resonance. The incident direction dependence phenomenon observed in this study has potential applications to various optical devices, such as variable reflectivity structures and unidirectional excitation of SPP.

Acknowledgements

This work was supported by the JSPS KAKENHI ((JP14459290, JP16823280, JP18967972, JP20J21825), and MEXT Q-LEAP ATTO, Japan

References

[1] M. Lawrence, D. R. Barton, III, J. A. Dionne, Nonreciprocal flat optics with silicon metasurfaces, *Nano Lett*., 18, 2, 1104-1109, 2018

[2] A. Arbabi, Y. Horie, M. Bagheri, A. Faraon, Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission, Nat. Nanotech., 10, 937-943, 2015

[3] J. S. Q. Liu, R. A. Para, F. Afshinmanesh, W. Cai, M. L. Brongesma, A submicron plasmonic dichroic splitter. *Nat Commun* **2,** 525. 2011.

[4] S. Wang, C. Zhao, X. Li, Dynamical Manipulation of Surface Plasmon Polaritons. *Appl. Sci. 9*, 3297, 2019.

[5] H. T. Miyazaki, Controlled plasmon resonance in closed metal/insulator/metal nanocavities, *Appl. Phys. Lett*., 89, 211126, 2006.

[6] B. Luk'yanchuk, N. I. Zheludev, S. A. Maier, N. J. Halas, P. Nordlander, H. Giessen, C. T. Chong, Nat. Mater., 9, 707-715, 2010.

[7] M. V. Rybin, P. V. Kapitanova, D. S. Filonov, A. P. Slobozhanyuk, P. A. Belov, Y. S. Kivshar, M. F. Limonov, Fano resonances in antennas: General control radiation patterns, *Phys. Rev. B*, 88, 205106, 2013.