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Excitation mechanism of surface plasmon polaritons in a double-layer wire grid structure

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Abstract We characterize the optical properties of a double-layer wire grid structure and investigate in detail the excitation mechanism of surface plasmon polaritons (SPPs). Angular spectra for the transmittance of the transverse magnetic polarized light that are obtained through the experiment reveal two peaks. In addition, simulated mapping of the transmittance and the magnetic field distribution indicate that SPPs are excited in two areas of the wire grid structures: at the interface between the Au layer and the resist layer or the glass substrate and at the interface between the Au layer and air. The experimental data are consistent with the transmittance mapping result and the distribution of the magnetic field. Accordingly, we constructed a model of SPPs propagation. We consider that SPPs excited at the interface between the Au layer and the resist layer or the glass substrate strongly contribute to the extraordinary transmission observed in the wire grid structures.

1 Introduction

Wire grid polarizers (WGPs) are filter-type polarizers comprising many fine metallic wires arranged in parallel over a plane that create a grating structure. Free electrons can move easily along this plane but are unable to move in the direction perpendicular to the plane. Thus, transverse magnetic (TM) and transverse electric light can easily be separated by optical anisotropy. In the 1960s, WGPs operating in the infrared region were first fabricated [1–3]. Since the 1990s, WGPs for the visible region have been fabricated with nanostructures using electron beam lithography (EBL) [4–9]. Wang et al. fabricated WGPs using narrow strips of less than 100 nm that could be used over a large range of wavelengths, such as deep-UV to near-infrared light [9]. The advantages of WGPs compared with the prism-type polarizers are that they have thin and flat structures and can cover a wider range of incident angles. However, their polarization parameters, such as the extinction ratio, are inferior to those of prism-type polarizers. Moreover, wave plates, such as azimuthal or radial polarization converters, were developed using these WGP structures [10–12]. Recently, sub-wavelength structures or surface plasmon polaritons (SPPs) have been used to improve these polarization properties [13, 14].

Given these advantages, in this study, we use a double-layer WGP that uses two layers of metal wires to realize a high optical extinction ratio when compared to a conventional WGP. Furthermore, the fabrication of the double-layer WGP is simpler because it does not require removing the EB resist. Yu et al. fabricated a double-layer WGP and obtained a higher extinction ratio compared with the conventional single-layer WGP [15]. There are two reasons for the high extinction ratio exhibited by the double-layer WGP—the Fabry–Perot interference and the surface plasmon resonance. Ekinci et al. [16] explained the Fabry–Perot interference and near-field coupling in double-layer WGPs through simulation and experiment. Ye et al. [17] simulated surface plasmon resonance in double-layer WGPs and fabricated a color filter using bilayer metallic nanowire grating

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or nanowire arrays [18, 19]. Despite the theoretical speculation concerning double-layer WGPs in these studies, surface plasmon resonance has not been confirmed in double-layer WGPs experimentally. Furthermore, Ebbesen et al. [20] showed extraordinary optical transmission using periodic Ag sub-wavelength hole arrays. This phenomenon can be explained by surface plasmon resonance combined with transmitted light. Related studies on the extraordinary optical transmission using SPPs have already been performed [21, 22]. Koerkamp et al. [21] fabricated periodic arrays of sub-wavelength holes, and Schouten et al. [22] fabricated a double slit structure. The results of the transmission using sub-wavelength hole arrays indicated that the excited SPPs cause extraordinary optical transmission with normal light incidence. Conversely, we confirmed extraordinary transmission using a metal grating structure such as a double-layer WGP [23], a surface plasmon sensor with a single-layer wire grid structure [24], and a wavelength filter with a 2D metal grating structure [25]. In particular, we fabricated a double-layer WGP and attributed the peak shift of the incident angle of TM polarized light to extraordinary transmission due to SPP excitation [23]. In the present study, we clarify the relationship between the structural and polarization properties of a double-layer WGP. Our results indicate that the peak incidence angle for TM transmittance varies with the grating period owing to the extraordinary optical transmission provided by SPPs. Furthermore, we found two kinds of peaks in the transmittance spectra of our previous study [23]. Therefore, we clarify the excitation mechanism for SPPs and the origin of these peaks through an experiment, transmittance mapping, and the distribution of the magnetic field calculated by rigorous-coupling wave of analysis (RCWA) simulation.

2 Experiment and simulation

The double-layer WGP was fabricated on a glass substrate using EBL and DC magnetron sputtering. Moreover, the transmittance of p-polarized light depends on the incidence angle. The methods of the fabrication and the optical characterization were the same as those used by us in our previous study [23]. In this study, the sample is fabricated by the same method used by us in our previous study [23]. The double-layer wire grid structures are fabricated on a glass substrate. The thicknesses of the Au layer and the EB resist are 40 and 100 nm, respectively. The duty ratio is 0.5. The light is come from air side of metal grating, and the wavelength of light is 635 nm.

The transmittance mapping was performed by the RCWA method using MATLAB-based commercial software [rcda-1d (SourceForage, http://rcwa-1d.sourceforge.net/)] by arranging the calculation results of the transmittance with respect to the incident angle obtained for each period. The simulation model and the method of simulation are same as those used in our previous study [23].

3 Results and discussion

Figure 1 shows the experimental results that indicate that the TM polarized light transmittance depends on the incident angle when the period of the double-layer WGP (p) is between 500 and 800 nm; the data of 600 and 800 nm are referred from our previous paper [23]. In the case of $p = 600$, 700, and 800 nm, there are two kinds of peaks, which are called peak A and peak B. However, in the case of $p = 500$ nm, there is only one peak. The fitting curves of these data represent the curves prepared by the spline extrapolation to clear these peaks. Moreover, we identified these peaks in the experimental results obtained in our previous study [23]. We found that there are two peaks between 300 and 1000 nm, except in case of $p = 500$ nm.

Furthermore, transmittance mapping through RCWA simulation allows obtaining a relationship between the transmittance and the incident angle for different periodic structures of the WGP (Fig. 2). In this mapping, the horizontal axis represents the period, the vertical axis represents the incident angle, and the transmittance is represented by colored bars in the right side of the graph. We observe two transmittance loci that may be related to peaks A and B. At $p = 500$ nm, these loci have an intersection. It is speculated that this peak overlaps with peaks A and B. The difference of the value of the transmittance seems to denote that the actual shape is not perfectly same as the simulation model. For example, it is speculated that the resist layer is trapezoidal

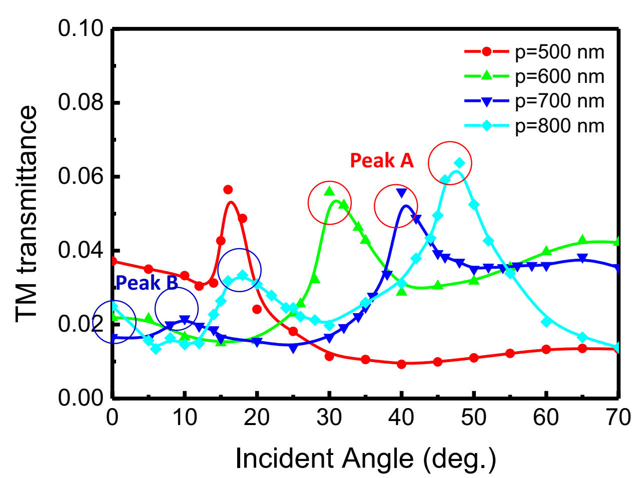

Fig. 1 Experimental results of the dependence of the TM polarized light transmittance on the incident angle when the period of the double-layer WGP is between 500 and 800 nm

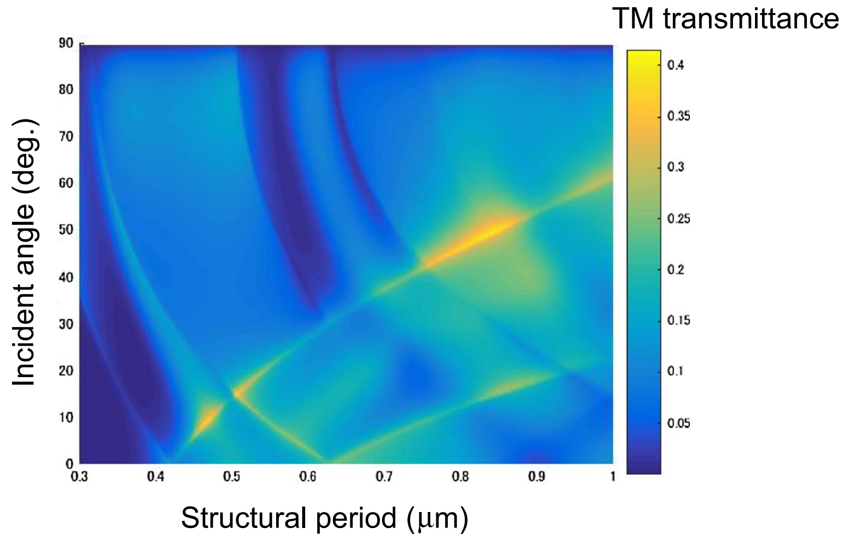

Fig. 2 Obtained transmittance mapping for the wire grid structure calculated by the RCWA method

in shape and that the side of the resist layer is a sputtered, thin Au layer.

In our previous study [23], we considered that the transmission of the TM polarized light is due to the extraordinary phenomenon caused by the propagating surface plasmon polariton at the interface between Au and the EB resist layer or the glass substrate. This consideration was based on the observed relationship between the transmittance and the incident angle calculated by SPP dispersion curve and the distribution of the magnetic field. In the present study, the origins of peaks A and B are considered in the same way. First, the relationship between the transmittance and the incident angle is calculated from the SPP dispersion curve using a model in which the periodical gold layer is surrounded by the effective medium, as shown in Fig. 3a. The reason for using this model is that in our previous study [23], we succeeded in explaining the transmission mechanism of the TM polarized light using the model of single-layer periodic structure surrounded by an effective medium and by adjusting its refractive index; in this study, using SPP dispersion curve, we would like to confirm the validity of transmittance mapping calculated by RCWA method. By changing the refractive index of the effective medium, the relationship between the transmittance and the incident angle is obtained from the dispersion curve, as shown in Fig. 3b. From these results, the curves expressing the relationship between the transmittance and the incident angle vary by changing the refractive index of the effective medium. In this study, these curves are known as the SPP excitation curves.

Then, using the SPP excitation curve in Fig. 3b, we fit the loci in Fig. 2. Figure 4 shows the fitting results of the loci in the transmittance mapping. One locus is fitted when the refractive index of the effective medium is 1.39, and the other is fitted when the index is 0.97. By comparing the fitted curve with the experimental results in Fig. 2, we hypothesize that the former locus corresponds to peak A and the latter corresponds to peak B.

Then, to confirm the speculation and the model of the SPP propagation mechanism in the double-layer wire grid structure, the distribution of the magnetic field is calculated

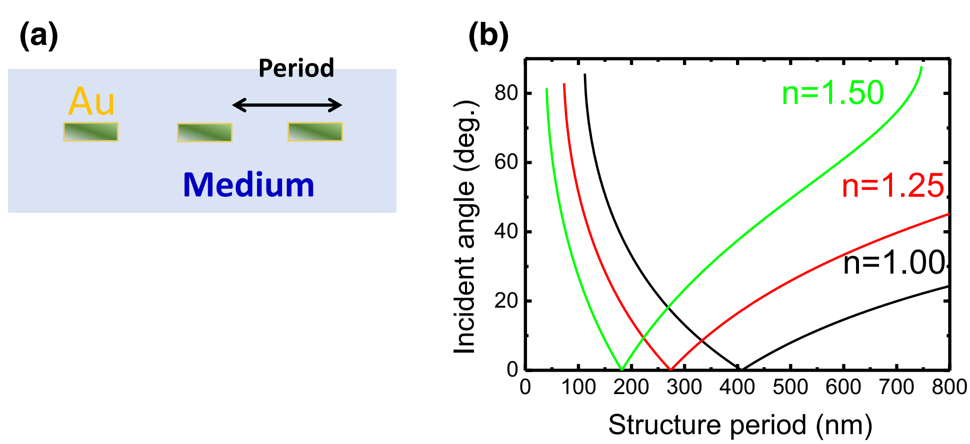

Fig. 3 **a** Model for calculating the SPP exciting curve, and **b** obtained SPP exciting curve

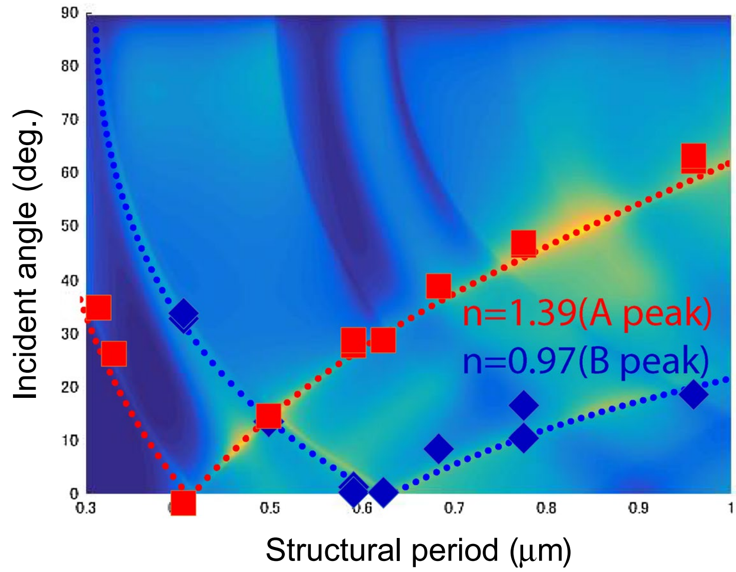

Fig. 4 Fitting results of the loci in the transmittance mapping. The dots are experimental data from Fig. 2 and Ref. [23]

by the RCWA method for a period of 600 nm. From Figs. 2 and 4, the incident angle of peak A is 27° and that of peak B is 3°. Figure 5 shows the distribution of the magnetic field when the incident angle is 27° (Fig. 5a) and 3° (Fig. 5b). For an incident angle of 27° (Fig. 5a), the magnetic field is concentrated at the interface between the Au and the resist layer or the glass substrate. The refractive index of the resist layer is 1.55 and that of the glass is 1.45. These values are close to 1.39 in Fig. 4. Thus, peak A originates from the SPP excitation at the interface between the Au layer and the resist layer or the glass substrate. Conversely, for an incident angle of 3° (Fig. 5b), the magnetic field is concentrated at the interface between the Au layer and the air. The refractive index of the air is close to 0.97 in Fig. 4. Thus, peak B originates from the SPP excitation at the interface between the Au layer and the air. Consequently, SPP excitation takes place at two planes in the double-layer WGP.

Finally, we consider the model of the SPP excitation. Figure 6 shows the model of the SPP in the double wire grid structure for a period of 600 nm. From the above results, the SPP corresponding to peak A is propagating at the interface between the Au layer and the resist layer or the glass substrate. Conversely, the SPP corresponding to peak B is propagating at the interface between the Au layer and air. The arrow of the direction of the SPP propagation is opposite direction each other based on the calculation results of the SPP dispersion curve. However, from Figs. 2, 3, the transmittance of peak A is larger than that of peak B. It is

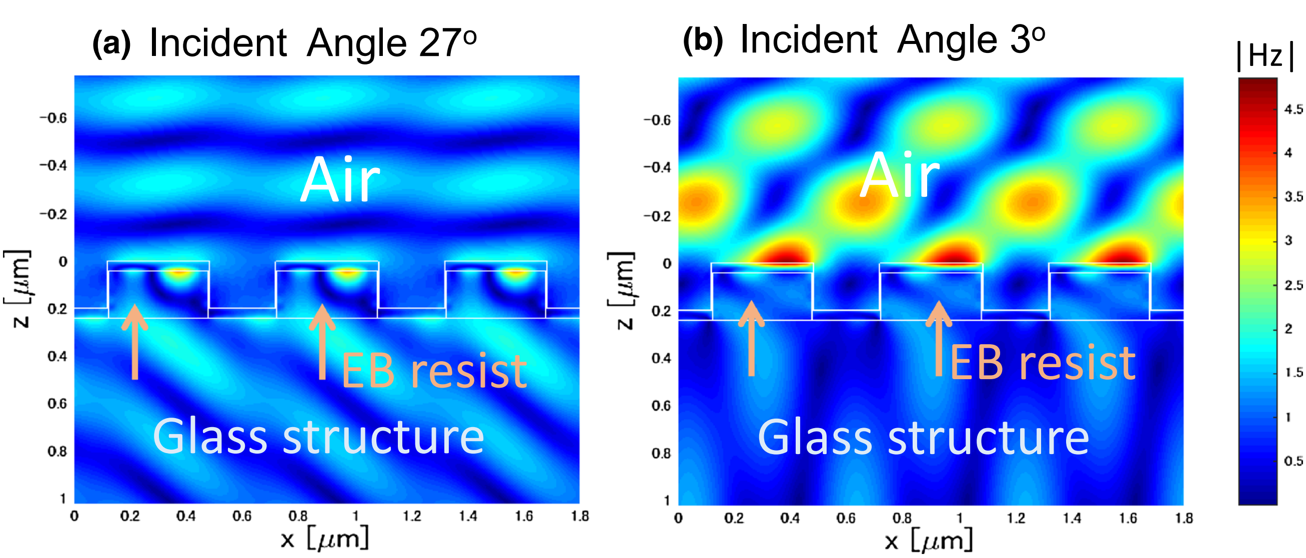

Fig. 5 Distribution of the magnetic field when the incident angle is 27° (**a**) and 3° (**b**)

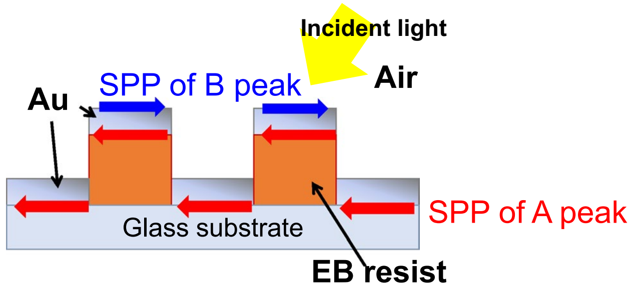

Fig. 6 Model of the SPP in the double-layer wire grid structure when the period is 600 nm

considered that the SPP corresponding to peak A can be coupled with the transmitted light in the glass substrate. Therefore, strong extraordinary transmission occurs. In contrast, the SPP corresponding to peak B cannot be easily coupled with the transmitted light in the glass substrate. Therefore, the contribution to the extraordinary transmission from the air to the glass is stronger for peak A. From these results, the excitation efficiency for the SPP waves is not clear from these data. We would like to study the relationship between the transmittance and the efficiency to excite the SPP in the future.

4 Conclusion

We clarified the excitation mechanism for SPPs by experiment and simulation. The experiment, transmittance mapping, and the distribution of the magnetic field calculated by RCWA simulation demonstrate that SPPs are excited at two interfaces in a double-layer structure. One is the interface between the Au layer and the resist layer or the glass substrate, and the other is the interface between the Au layer and the air. However, the contribution to the extraordinary transmission from the air to the glass is stronger for peak A.

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