Systematic Design of Grating Structure to Induce Surface Plasmon Resonance at the Prescribed Wavelength

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In this paper, we propose a design approach for plasmonic gratings resonating at the prescribed target wavelength. In the specific condition of circumstance, surface gratings are able to induce the surface plasmon propagation using the diffraction effect. The grating shape is essential to define the resonance wavelength of the surface plasmon propagation. The grating configuration was designed by topology optimization using the phase field design method. The design objective is set to minimize the gap between the present resonance wavelength and the preset target wavelength. Simulation and optimization process was performed using the commercial package COMSOL combined with MATLAB programming.

***Index Terms*—Grating structure design, resonance wavelength, surface plasmon resonance, topology optimization**

I. Introduction

SURFACE GRATINGS on metal film induce the surface plasmon polariton between a dielectric and a metal surface. When incident wave meets surface plasmon resonance condition by grating diffractions, intensive coupling phenomenon between light and electromagnetic energy occurs. Many works were studied on grating couplers such as focused ion beam, biosensor, and beam splitter [1]. However, majority of such works are based on intuitive ideas supported by physics theories and experimental approaches with various parametric studies. On the other hand, this study proposes a topology optimization scheme to design the configuration of a grating coupler.

The topology optimization method is a structural design scheme which changes the structural configuration by creating and merging holes. It was adopted by many studies including stiff structure design [2] and structure design in magnetic [3] and electromagnetic fields [4, 5]. Previous topology optimization studies of the surface plasmon grating couplers are focused on maximizing intensity at the prescribed target wavelength [5]. However it may cause the undesirable result that the resonance wavelength is deviated from the target wavelength. Because the resonance wavelength needs to be matched with the target wavelength, our study focuses on it matching and compares the results with those by the previous intensity maximizing approach.

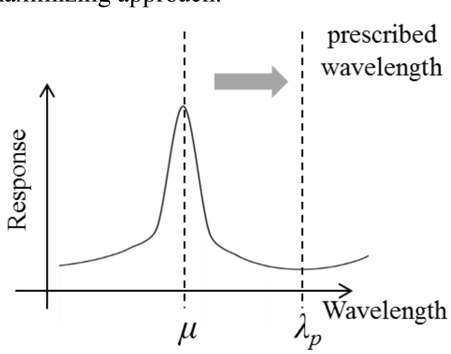

Fig. 1. Concept of the design process.

To shift a present resonance wavelength toward a target wavelength, the design objective is defined as minimizing the gap between the present resonance wavelength μ and the target wavelength λ_p. As displayed in Fig. 1, the peak wavelength would move toward the target resonance wavelength by satisfying the design objective. This study employs the phased field design method as the topology optimization scheme [6].

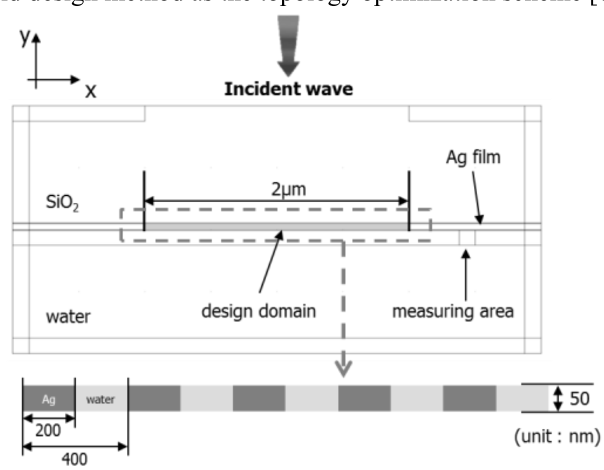

Fig. 2. Schematic diagram of the grating coupler for the design process. Initial design is displayed at bottom part.

II. Problem Formulation

The schematic of numerical problem is displayed in Fig. 2. When polychromatic transverse magnetic (TM) wave meets the silver (Ag) film after passing through the dielectric layer, the surface plasmon resonance phenomenon occurs and it propagates to the measuring area. The target wavelength for the grating coupler is set as 625 nm. The polychromatic TM wave has 380~720 nm wavelength and it is considered with 20 nm interval. The initial structures of the Ag gratings are located between silicon dioxide (SiO_2) and water with 200 nm width and 400 nm period as shown in Fig. 2. The film thickness is 50 nm. A resonance wavelength for the initial grating shape is located around 560 nm. To define the formulation of the resonance wavelength, the wavelength response of the grating is mapped onto the probability distribution function [7] where the mean (or expectation) value of probability distribution represents a resonance wavelength. The probability for each wavelength and the expectation value is formulated as

$$P(\phi,\lambda_k) = f(\phi,\lambda_k) / \sum_{i=0}^{n} f(\phi,\lambda_i), \quad \text{where } \lambda_i = \{\lambda_0, \lambda_1, \cdots, \lambda_n\} \tag{1}$$

$$\mu = \sum_{k=0}^{n} \lambda_k P(\phi,\lambda_k) \tag{2}$$

where ϕ is the design variable which infers existence of material. ϕ=0 means water while ϕ=1 means the portion composed of Ag. The interpolation function for phi is defined as $n(\phi,\lambda_k)=n_{water}+\{n_{Ag}(\lambda_k)-n_{water}\}\phi+jn'_{Ag}(\lambda_k)\phi$. $f(\phi,\lambda_k)$ is the integrated Poyinting vector in the measuring area at k_{th} wavelength. μ is the mean value derived by multiplying probability and wavelength in the desired wavelength range of $\lambda_0 \sim \lambda_n$ where λ_0 means the wavelength of 380 nm and λ_n means that of 720 nm. The formulation of optimization problem is expressed as follows:

$$\begin{aligned} &\underset{\phi}{\text{minimize}} \quad F(\phi) = s_1\sqrt{(\mu-\lambda_p)^2} - s_2\eta P(\phi,\mu) \\ &\text{where} \quad 0 \le \phi \le 1 \\ &\eta = \sqrt{\left(\partial\left(\sqrt{(\mu-\lambda_p)^2}\right)\Big/\partial\phi\right)^2} \Bigg/ \sqrt{\left(\partial P(\phi,\mu)/\partial\phi\right)^2} \end{aligned} \tag{3}$$

where μ is the resonance wavelength defined by (2), and λ_{p} is the target wavelength, 625 nm. The later term of $F(\phi)$ means intensity level at the resonance wavelength μ and it is set to maintain intensity at the resonance wavelength. Sign of the later term is negative because the overall optimization problem is defined as minimization. s_1 and s_2 are weighting factors for two design objectives [7] and η is the sensitivity normalizing term for balancing the functions.

III. Numerical Result

Fig. 3 shows the result configurations of the previous maximizing intensity method and our minimizing wavelength gap method. Black part represents Ag area while the white one represents water portion.

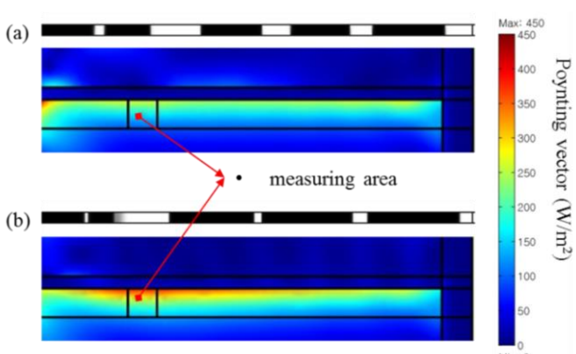

Fig. 3. Optimized configurations and their contour plots of the Poynting vector in 625nm wave at the measuring area for (a) maximizing the intensity and (b) minimizing the wavelength gap.

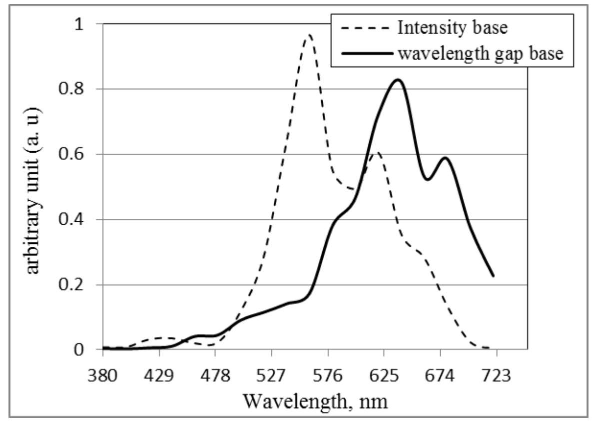

Fig. 4. Comparison of the wavelength response results for maximizing the intensity with minimizing the wavelength gap.

Fig. 4 compares the wavelength response results for a previous method for maximizing intensity and the proposed method for minimizing the wavelength gap. Each of both results has a second resonance peak because grating configuration shows irregular periodic shape. In case of design for maximizing intensity, location of the resonance wavelength is still similar to that of the initial shape, far from the target wavelength 625nm. On the other hand, the result from the proposed approach shows that the resonance wavelength is located at the target of 625 nm.

IV. Conclusion

This study intends to minimize the wavelength gap between the resonance one and the target. Compared with the previous approach that just focuses on the intensity at the prescribed target wavelength, the proposed design approach shows an effective shift of the resonance wavelength.

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