Waveguide Design at Infrared Wavelength with Asymmetric Dielectric Surface Gratings

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***Abstract*—In this article, we propose waveguide design at infrared wavelength with asymmetric dielectric surface gratings. Surface gratings are able to serve as an outlet for a surface plasmon polariton to radiate light and the property is the key concept behind generating collimated beams from sub-wavelength slits or holes surrounded by corrugated surfaces. Design of gratings is conducted by topology optimization based on the density method. The design objective is set to maximize the Poyting vector in the measuring area. The simulation and the optimization processes are performed by using the commercial package COMSOL associated with Matlab programming.**

***Index Terms* — Electromagnetic wave, surface plasmon, waveguide design, topology optimization.**

I. INTRODUCTION

The transmission of electromagnetic (EM) waves through a single sub-wavelength aperture has been studied for many years. As defined in the standard diffraction theory by Bethe [1], EM waves that transmit through such apertures are fully diffracted in all directions and it is the main problem in controlling wave. Therefore, there have been many studies to solving this problem. Lezec *et al.* showed that it is possible to obtain directional beaming from sub-wavelength apertures using the surface plasmon effect on corrugated metallic surfaces [2]. There are many works related to the optical field beaming such as on-axis beaming light from sub-wavelength apertures [3] the phenomenon of enhanced transmission in sub-wavelength single hole [4] and beaming light with photonic crystals [5]. Recently it was found that beaming through a sub-wavelength single metal slit using dielectric surface grating is very effective [6]. However, most studies investigated on-axis beaming and researches about off-axis beaming are limited in the visible wavelength range.

In this article, we propose waveguide design at infrared wavelength with asymmetric surface gratings. The topology optimization method based on the density method is adopted with the update scheme using the reaction diffusion equation. In the proposed method, dielectric gratings are asymmetrically arranged on the metal slit surface and their optimal shapes are obtained. Previous studies on grating structures are based on the parameter study [7] or using density method based topology optimization [8]. Therefore, obtained structures are limited to having rectangular shapes or suffered from gray scale elements. This study is using the reaction-diffusion equation based on the topology optimization scheme [9] and it will be expanded to the level set method combined with the double well potential function [10].

II. REACTION-DIFFUSION METHOD

The reaction-diffusion method supports flexible changes in structural topology according to the design sensitivity. The employed design sensitivity is the derivative of the objective function with respect to the design variables and it is directly used as the reaction term in the reaction-diffusion equation [9].

$$\frac{\partial \phi(\mathbf{x},t)}{\partial t} = \alpha \nabla^2 \phi(\mathbf{x},t) - \frac{\partial}{\partial \phi}\bar{F}(\mathbf{x},\phi,\mathbf{u}(\phi)) \quad in \;\; \mathbf{x} \in \Omega, \;\; 0 < t \le T \tag{1}$$

$$\frac{\partial \phi(\mathbf{x},t)}{\partial \hat{\mathbf{n}}} = 0 \qquad on \;\; \partial\Omega \tag{2}$$

where $\Omega \subset \mathbf{R}^N$ (N=2,3) is a bounded domain with boundary $\partial\Omega$ and $\phi(\mathbf{x}, t)$ is the density field parameter which interpolates the material properties as in the ordinary density method. When the density field takes values close to 1, it becomes the solid region whereas it becomes the void in case of 0 values. $\hat{\mathbf{n}}$ is the outer unit vector normal to $\partial\Omega$. T and α represent the time required for convergence and the diffusion coefficient, respectively. The reaction term $\partial\bar{F}/\partial\phi$ is the derivative of the augmented Lagrangian $\bar{F}$ with respect to the density variable ϕ and it is a function for ϕ, the position $\mathbf{x}$ and the state variable $\mathbf{u}(\phi)$. α is the diffusion coefficient with very small constant.

III. NUMERICAL ANALYSIS

In the waveguide model for analysis and design, it is composed of 160nm deep dielectric gratings with their period of 500 nm at the left side and 300 nm at the right side on the 400 nm thick silver film combined with a 200 nm width slit. The grating structure is made of silicon (SiO_2) Figure 1 shows the schematic of the model. Incident beam has the wavelength of 1064 nm with *p*-polarization (TM polarization). At the wavelength, the refractive index value of the silver clad is 0.23424+*j*7.2143. For the non-periodic structure modeling, perfectly matched layers (PMLs) are placed at left, right and bottom sides of the computation region to avoid the effect by the wave reflection from those boundaries. The measuring domain is located at about 20 degrees from the center of slit so that the transmitted beam through the slit may be refracted to the direction. The following is the governing equation for solving two-dimensional (2D) wave problems.

$$\nabla \bullet \left(\varepsilon_r^{-1} \nabla H_z \right) - \frac{\omega^2}{c^2} H_z = 0 \tag{3}$$

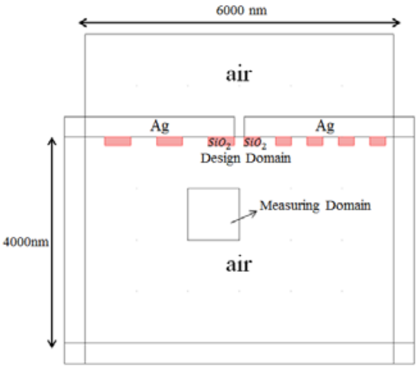

Fig. 1. Schematic model of the waveguide system.

The finite element method using the commercial package COMSOL is used for analysis. To evaluate the intensity of the light, the energy flux is calculated at the measuring area based on the Poyting vector value:

$$\begin{aligned} P(Poynting\ vector) &= \mathrm{Re}(\mathbf{E}\times\mathbf{H}^*) \\ &= \mathrm{Re}\left(-\frac{H_z^*}{j\omega\varepsilon}\left(\frac{\partial H_z}{\partial x}\hat{i}+\frac{\partial H_z}{\partial y}\hat{j}\right)\right) \end{aligned} \tag{4}$$

where **H*** means the complex conjugate of the magnetic field strength vector **H**. Since the modeling and analysis is performed for 2D cases, only the z-directional component of **H** is used as in (4). ω is a wavelength of incident light and ε represents the permittivity value of each materials.

IV. OPTIMIZATION

In optimization process, after solving for state variables, the design objective is calculated and the design variable is updated according to the sensitivity analysis value. The optimization problem is set as follows:

$$\begin{aligned} &\underset{\phi}{\text{maximize}} \quad F = P\big|_{at\ the\ measuring\ area} \\ &\text{subject to} \quad G(\phi) = \int_\Omega \phi\, dx - V_{req}\int_\Omega dx \le 0, \quad 0 \le \phi \le 1 \end{aligned} \tag{4}$$

where F is the objective function, G(ϕ) and V_{req} represent the volume constraint and the required volume fraction, respectively. During the design process, the design variable ϕ is updated and it determines the element density in the design domain. The design domain is determined as the SiO_2 grating area as designated in Fig. 1.

The optimal shapes for different volume fractions are show in Fig. 2. The Poynting vector value of the initial model which has no grating is measured as 9.7022e-38 W/m^2 and it is set to the normalizing value of 1. Table 1 shows the comparison of normalized objective values and it is confirmed that the optimized structure give dramatic improvement in the desired performance. Figure 3 displays the wave contour plot and the optimal model by topology optimization process shows clear off-axis beaming after transmission of the slit.

V. ACKNOWLEDGEMENTS

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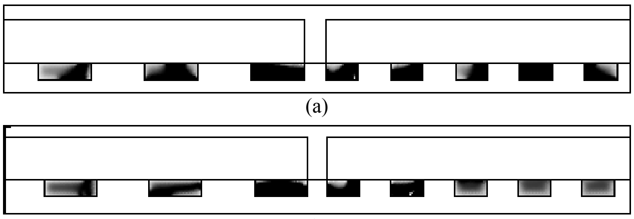
(a)

(b)

Fig. 2. Optimization results depending on the volume fraction: (a) volume fraction=0.8 and (b) volume fraction=0.7.

TABLE I
Comparison of the normalized objective values.

	Initial model	Case (a)	Case (b)
Objective value	1	3.1640	3.0815

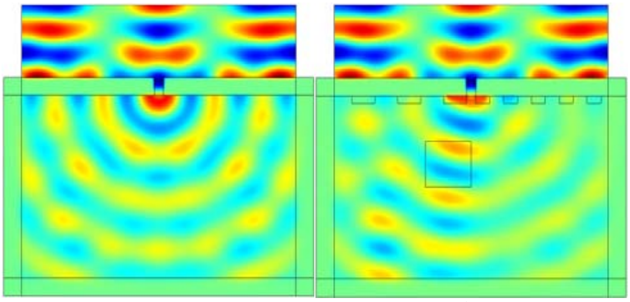
(a) (b)

Fig. 3. Wave contour plots for (a) initial model (non-grating model) and (b) the optimal model (volume fraction=0.8).

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