SC-1-4 体積積分方程式による表面プラズモン空隙導波路を使った光ナノ回路三次元シミュレーション

田中嘉津夫　田中雅宏
Kazuo Tanaka　Masahiro Tanaka

岐阜大学工学部
Department of Computer Engineering, Gifu University

1. Introduction

The size and density of optical devices employing conventional optical waveguide and photonic crystals is limited by the diffraction limit of light.[1] However, the size of optical waveguide using surface plasmon polaritons (SPPs) can be significantly decreased as compared to the conventional diffraction-limited optical waveguide.[2-4] The SPPs are waves that result from an intimate interaction between electromagnetic waves and metallic surface electrons. The optical circuit using SPPs is one of the promising candidates for nanoscale optical circuits. Many interesting experimental or theoretical works that treat practical and concrete nanometric optical circuits using SPPs have been reported so far.[2-10] In this paper, we propose a nanoscale optical waveguide and show that this waveguide can be employed in the nanometric optical circuits by three-dimensional numerical simulations.

2. Simulation

Through this paper, we assume that the light wavelength is given by λ =532 nm and material that support SPPs is a silver whose relative permittivity is given by $\varepsilon_1 = -12.6\text{-j}0.91$ under the assumption of time dependence $exp(\mathrm{j}\,\omega t)$. Considering the behavior of SPP, we can have an idea of a waveguide made of silver whose cross section is shown in Fig. 1. A narrow gap region exists in the wide gap region between two metallic plates. Since the phase-velocity of SPP in the narrow gap region is smaller than that in the wide gap region, from the analogy of optical fiber, it is possible to expect that field is confined near the narrow gap region and is guided along the narrow gap region in Fig. 1. We call this guiding structure SPP gap-waveguide (SPGW). Using the idea of SPGW, we can construct nanoscale simple optical circuits shown in Fig. 1. We consider a H-plane optical circuit that consists of straight and branched bend SPGWs as shown in Fig. 1. The rectangular parallelepiped of free space whose size is given by $C_x \times C_y \times C_z$ is completely covered by the six silver plates with thickness d. The straight and branched bend SPWGs are made by constructing rib-structures of silver on the floor and ceiling inside the rectangular parallelepiped as shown in Fig.3. An small aperture with cross section $b \times C_z$ is made on one side of the rectangular parallelepiped as an entrance of the incident wave shown by broken lines in Fig. 1. A plane wave $\boldsymbol{E}^{\mathrm{i}}$ is incident normally to the entrance-aperture on the side surface from negative y-direction as shown in Fig. 1. To excite SPP of the SPGWs inside the circuit, the incident electric field must be z-direction. We solved the scattering problem of a plane wave by the structure in Fig. 3 by the volume integral equation[11-14].

$$\mathbf{E}(\mathbf{x}) = k_0^2 \iiint_V [\varepsilon_r(\mathbf{x}') - 1]\underline{G_e}(\mathbf{x} \mid \mathbf{x}') \cdot E(\mathbf{x}')\,dv' + \mathbf{E}^{\mathrm{i}}(\mathbf{x}), \tag{1}$$

We discritized the integral equation (1) by the pulse function and point matching (collocation) method and solved the resultant large system of linear equations by the iteration method called Generalized Conjugate Residual (GCR) combined with FFT [14-16]. We have confirmed that the scattered field obtained satisfies of

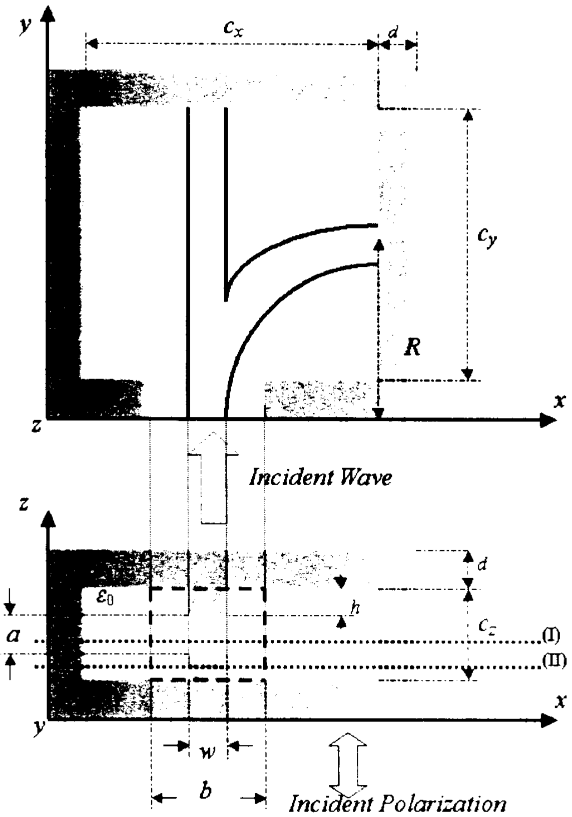
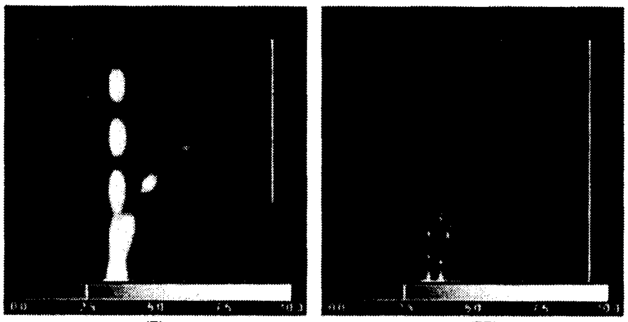


Fig.1. H-plane SPGW circuit. Circuit consists of straight and branched bend SPWGs. Polarization of the incident wave is the z-direction.

the reciprocity relation within a reasonable accuracy. Parameters of the H-plane circuits used in the simulation in Fig. 3 are given as follows: k_0C_x=k_0C_y=8.0 (677 nm), k_0C_z=1.0 (85 nm), k_0d=1.0 (85 nm), k_0a=k_0w=0.4 (34 nm), k_0h=0.4 (34 nm), k_0R=6.8 (576 nm), and k_0b=2.8 (237 nm). The size of the H-plane circuits shown in Fig. 3 is about 1.6 λ ×1.6 λ ×0.38 λ including cover plates.

Distributions of calculated total field intensities $|\boldsymbol{E}|^2$ of the H-plane circuit are shown in Fig. 2(I) and 2(II) for the case where the intensity of incident wave is given by unity, i.e., $|\boldsymbol{E}^i|^2$=1. The field distribution Fig. 2(I) is that on the center plane (I) that passes the midpoint of the gaps of SPGWs and parallel to the x-y plane shown by the dotted line in Fig. 1. The field distribution Fig. 2(II) is that on the plane (II) parallel to the x-y plane away from the center plane as shown in Fig. 1. We can clearly observe standing waves in the straight and branched bend SPGWs in Fig. 2(I). We can see three spots of standing waves maximum (SWM) from exit to junction along straight SPGW in Fig. 4(I). We can calculate Re(k_z/k_0) of the straight SPGW by using distances between these SWMs and calculated value was 1.50, which falls between Re(k_z/k_0)=1.61 for k_0a = 0.4 and Re(k_z/k_0)=1.28 for k_0a=1.0 by 2D calculation. Since the distance between boundaries parallel to the main electric fields is rather large i.e., k_0C_x=8.0, shown in Fig. 3, this value of Re(k_z/k_0) is physically reasonable.



(I) (II)

Fig. 2 Distributions of field intensity $|\boldsymbol{E}|^2$ on the planes indicated in Fig. 3 for H-plane circuit. Distributions (I) and (II) are those on the planes parallel to x-y plane indicated in Fig.3 by dotted line (I) and (II), respectively.

It is possible to make rough evaluation of losses in the circuit by the results in Fig. 2(I). The maximum intensity near the entrance was given by $|\boldsymbol{E}|^2$=58.6. The intensities of SWMs of above three spots normalized by $|\boldsymbol{E}|^2$=58.6 were 0.40, 0.41 and 0.37 from junction to exit, respectively. We can also see three spots of SWMs from exit to junction along the branched bend SPGW in Fig. 4(I). The normalized intensities of these SWMs were 0.17, 0.11 and 0.07 from junction to exit, respectively. It is found that the optical field is confined near the narrow gap region and is guided along the straight, branched bend SPWGs with acceptable losses. Notice that the intensities in the SPGWs are enhanced by SPPs .

3. Conclution

In conclusion, the H-plane nanometric optical circuits using SPGWs simulated in this paper can fulfill the basic function designed. It is possible to control the phase velocities of SPPs by the gap-width in nanoscale SPGWs. This technique may be widely applied to nanometric optical devices. It would be of great interest to know how to improve all the circuit characteristics by changing geometrical parameters, material constants and wavelength.

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