Design of Optical Waveguide with a 90° Bend Structure for High Density Photonic Integrated Circuits

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***Abstract* - A hybrid optical waveguide having a 90° sharp bend structure, composed of a dielectric straight waveguide, tapered dielectric strip waveguide, and microscale metal gap waveguide, is proposed and simulated to improve the efficiency of light coupling between dielectric and plasmonic waveguides. Our simulation result is a critical step for the hybrid integration of plasmonic components with conventional dielectric components.**

I. INTRODUCTION

There has been a growing interest in research pertaining to the optical integration of high-density photonic components as future optical circuits because of the increasing demands for low-cost, highly functional optical chips. For this goal, the sharp bend structure in a dielectric waveguide with a relatively high refractive index contrast is required to improve the packaging density of the optical elements. However, with standard dielectric waveguides, transmission performance after the sharp bend suffers; to overcome this problem for high transmission, various types of 90° bend structures have been proposed, including the use of photonic crystals, corner mirrors, waveguide resonators, and bent fibers [1].

Surface plasmons (SPs) are electromagnetic waves that propagate along a metal interface. The near-field coupling and resonant excitation of surface plasmon polaritons (SPPs) in metal and metal slot waveguide structures has recently been suggested in an attempt to build highly integrated planar lightwave circuits [2]. For dense photonic integration, metal-insulator-metal (MIM) type waveguides are especially attractive because of their strong lateral mode confinement, which enables light to propagate through very sharp waveguide bends (e.g., 90° bends) in tens of nanometer-sized plasmonic waveguides [2]. However, MIM type waveguides have displayed tremendous propagation losses due to the high field distribution in the metal interface, thereby making it difficult to achieve efficient coupling with conventional microsized dielectric waveguides. Nevertheless, it has recently been shown that plasmonic waveguides can successfully couple dielectric waveguides to MIM plasmonic waveguides [3-4]. In this paper, we simulate a hybrid optical waveguide having a 90° bend structure for high optical circuits, which consists of conventional dielectric, taper, and microscale MIM plasmonic waveguides. A hybrid optical waveguide with a 90° bend will then be presented to couple a microsize silica/air-clad dielectric waveguide to a microsize silica/gold-clad MIM plasmonic waveguide.

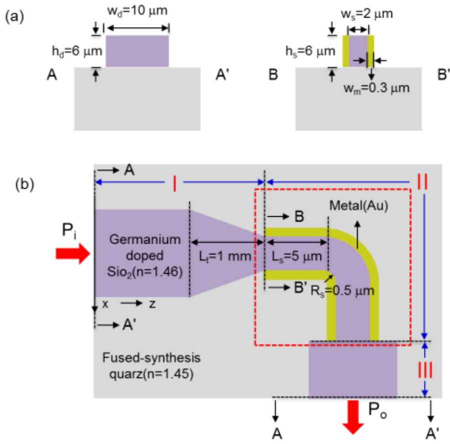

Fig. 1. Schematics of the proposed hybrid waveguide: (a) cross-sections of a structure with dimensions of w_d=10 μm, h_d=6 μm, w_s=2 μm, h_s=6 μm, w_m=0.3 μm at different locations, and (b) top view of a structure with dimensions of L_t=1 mm, L_s =5 μm, R_s=0.5 μm.

II. THE PROPOSED STRUCTURE

A schematic of the proposed hybrid optical waveguide is shown in Fig. 1(a) and 1(b). The proposed structure consists of two conventional dielectric waveguides in region I and III, and a MIM-based 90° bend structure in region II. The conventional dielectric waveguide at the input port in region I is comprised of a slab straight waveguide and a slab waveguide tapered coupler, used to connect the dielectric and plasmonic waveguides. The lossless transmission characteristic of slab waveguide tapered coupler is considered by beam propagation method with successive waveguide width change from region I to region II, employing parameter values appropriate for strong coupling and efficient conversion between dielectric waveguides and plasmonic waveguide modes. A 90° bend waveguide (gold-dielectric-gold type) as a plasmonic waveguide in region II is then designed due to extreme transmission at sharp bend structure. In region III, the width of the dielectric waveguide at the output port, which is consisted of a dielectric waveguide, is designed to be larger than that of the plasmonic waveguide due to consideration of the optical transmission efficiency from the difference of the field profile between the dielectric waveguide and SPP waveguide [4]. The employed working wavelength is set at λ = 1550 nm, which also has the advantage of lower metal losses than in the visible wavelength.

Fused-synthesis quartz (refractive index = 1.45) as the substrate, germanium-doped SiO2(refractive index = 1.46) as the core waveguide is employed. A thin film of metal (gold; permittivity value = -115.056 + 11.128j) is deposited on the surface of sidewalls of the core waveguide. The geometrical parameters of the waveguide are w_d=10 μm, h_d=6 μm, w_s=2 μm, h_s=6 μm, w_m=0.3 μm, L_t=1 mm, L_s =5 μm, and bend radius of R_s=0.5 μm. Our numerical study is based on the full-vector finite-difference time domain (FDTD) approach. In brief, a finite element method (FEM) mode solver using COMSOL Multiphysics is developed to numerically investigate the characteristics of the dielectric waveguide and MIM plasmonic waveguide modes. The entire computational domain can be seen in the red dotted area by considering the amount of numerical calculation in Fig. 1(b).

III. RESULTS AND DISCUSSIONS

Figure 2(a) shows the E_x field distribution in the horizontal plane obtained from the 3D-FDTD simulation of the hybrid optical waveguide having a 90° bend structure. The plot shows that the initial launching mode of the dielectric waveguide in Fig. 2(b) is perfectly transformed to plasmonic mode (cross-section of the field at the plasmonic waveguide in Fig. 2(b)), and propagates through the straight region of the plasmonic waveguide. Note that as this plasmonic mode travels through the 90° bend waveguide, the electromagnetic waves inside the metal interface are clipped due to the sharp radius of curvature. In addition, a few waves propagate through the total internal refection and others, which combine with outside electromagnetic waves, propagate along the metal interface. While the electromagnetic waves outside the metal interface travel along the metal interface and maintain the plasmonic mode. In order to determine the normalized power transmissivity, the extra loss can be obtained using the following expression,

$$EL = L_{c1} + L_{c2} + L_{silica} + L_{plasmonic} + L_{bend} \qquad (1)$$

where L_{c1} (from region I to region II) and L_{c2} (from region II to region III) are the coupling losses between silica dielectric waveguide and plasmonic waveguide, respectively. In addition, L_{silica} and $L_{plasmonic}$ are the propagation losses in the silica dielectric waveguide and plasmonic waveguide, respectively. Also L_{bend} is the bending loss in 90° bend region. The coupling loss L_{c1}, L_{c2} are obtained from the simulation as a coupling efficiency of 95 % and 90 %, respectively. L_{silica} is a zero loss in the simulation due to a lossless dielectric waveguide. The propagation loss of the plasmonic waveguide, $L_{plasmonic}$ is also calculated 1.2 dB. L_{bend} is obtained from the simulation as transmission efficiency of 90 %. Finally, the normalized power transmissivity through the hybrid optical waveguide having a 90° bend structure is shown in Fig. 2(c).

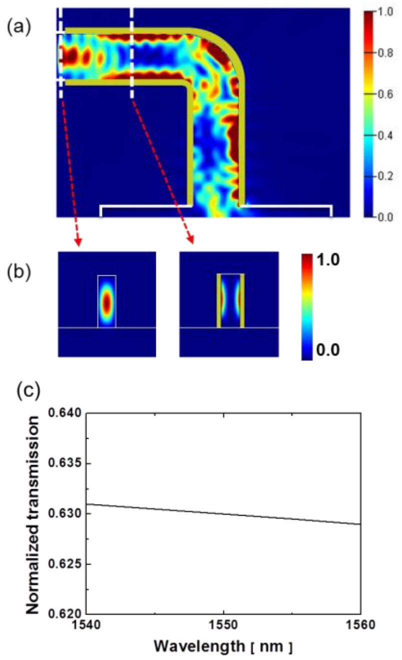

Fig. 2. (a) Top-view field distribution simulated by 3D-FDTD of the red dotted area in Fig. 1, (b) cross-sectional views of the field at the launch position and at the center of the structure, and (c) calculated optical power transmission.

The transmissivity is computed to be about 63% at λ=1550 nm; i.e., despite coupling a microsize dielectric waveguide to a microsize plasmonic waveguide and a sharp 90° bend radius, the power transmissivity is relatively high. It is expected that this transmissivity can be further improved by optimizing the coupling regions between the dielectric and plasmonic waveguides in order to achieve better mode matching

IV. CONCLUSION

In this paper, we proposed an integrated hybrid optical waveguide that combines microsize plasmonic waveguide with microsize conventional dielectric waveguide to improve the efficiency of light coupling between dielectric and plasmonic waveguides for near-IR light. We also analyzed the power transmissivity of the hybrid optical waveguide having a 90° sharp bend structure. After further optimization, it is expected that this integrated hybrid optical waveguide can be applied to the high density photonic circuits.

ACKNOWLEDGMENT

This work was supported by *the Fundamental R&D Program for Core Technology Materials, Ministry of Commerce, Industry, and Energy (MOCIE)*, Korea

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