Simulation and Fabrication of Hybrid Optical Waveguide with a Sharp Bend Structure for High Integration

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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 experimentally demonstrated in an attempt to improve the efficiency of light coupling between dielectric and plasmonic waveguides. Due to both the efficient structure of the taper and metal gap, the calculated coupling efficiency reached as high as 63% in the fiber optic communication wavelength range. A dielectric-gold plasmonic waveguide was then fabricated, demonstrating a 17-dB coupling efficiency. Our experimental demonstration is a critical step for the hybrid integration of plasmonic components with conventional dielectric components**

I. INTRODUCTION

Sharp 90° bend structures have been essential for the high density photonic integrated circuits. However, it is very difficult to implement low-loss sharp bends structure with general dielectric waveguides. To solve the this problem, several methods has been recently achieved including the use of photonic crystals, corner mirrors, waveguide resonators, and bent fibers, surface plasmons (SP) waveguides [1-3]. Among these schemes, SP waveguides can be tightly confined in a waveguide interface between a metal and dielectiric waveguide. As a result, these waveguide can provide good transmission efficiency at the sharp bend structure of optical waveguide. It is known that metal-insulator-metal (MIM) waveguides support both the subwavelength propagating mode at a wavelength range extending from dc to visible light and also high bend efficiency.

For dense photonic integration, 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 [3-4]. 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 [5], though plasmonic waveguides still suffer from coupling with a conventional dielectric waveguide due to it being a nanosized plasmonic waveguide.

In this paper, we describe a hybrid optical waveguide having a 90° bend structure for high optical circuits,

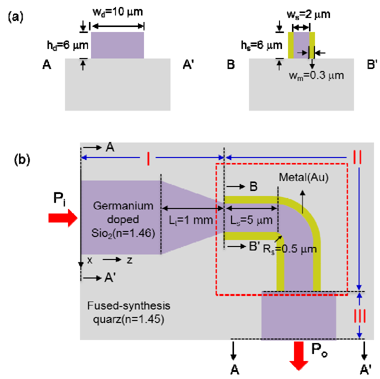

Fig. 1. Schematics of the proposed hybrid waveguide: (a) cross-sections of a structure with dimensions of w_d=10 μm, h_d=6 μm, w_s=2 μm, h_s=6 μm, w_m=0.3 μm at different locations, and (b) top view of a structure with dimensions of L_t=1 mm, L_s =5 μm, R_s=0.5 μm.

which consists of conventional dielectric, taper, and microscale MIM plasmonic waveguides. A hybrid optical waveguide with a 90° bend then is fabricated to couple a microsize silica/air-clad dielectric waveguide to a microsize silica/gold-clad MIM plasmonic waveguide.

II. THE PROPOSED STRUCTURE AND SIMULATION

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 employed working wavelength is set at λ = 1550 nm and fused-synthesis quartz (refractive index = 1.45) as the substrate, germanium-doped SiO_2(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. The transmissivity is computed to be about 63% at λ=1550 nm which was showed in detail in Ref. [3].

III. THE FABRICATION OF PROPOSED STRUCTURE

Figure 2 summarizes the stages of the fabrication process flow. A set of hybrid optical waveguide having a 90° bend structure was fabricated using a 2-step photolithography and evaporation process. Starting with a blank silica substrate, as shown in Fig. 2(a), a silica dielectric waveguide was defined through the first photolithography step by using a waveguide photomask. The pattern was then transferred to the waveguide core layer via inductively coupled plasma reactive ion etching (ICPRIE), resulting in the dielectric waveguides shown in Fig. 2(b). After forming the silica dielectric waveguide, a second photolithography step was performed on the waveguide to pattern a rectangular window, except for the top of core waveguide at the 90° bend region, in which photolithography was used to coat both sidewalls of the bend waveguide. The photoresist (AZ-2070) used in this photolithography step had a thickness of 7 m, obtained after spinning at 5,000 rpm for 30 s and then baked at 100 °C for 60 s. After using a metal mask to align and resist development, and a post-bake at 100 °C for 30 s, the pattern was transferred into the core layer and substrate. Finally, a 300 nm thick layer of gold was sputtered onto the sample using an electron beam evaporator, followed by metal lift-off in acetone to remove the gold layer, except for bend region as shown in Fig. 2(c).

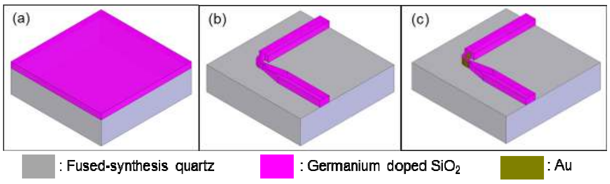

Fig. 2. Schematic of fabrication process flow: (a) blank silica substrate, (b) silica waveguide after first photolithography process and ICPRIE etching, and (c) hybrid optical waveguide after second photolithography process.

IV. Measurements and Results

For transmission characteristic measurements of the fabricated device, a straight optical waveguide as a reference sample with same propagation length but with no plasmonic waveguide was fabricated and measured. A tunable laser source around 1550 nm is employed. The source light with the polarization set to TE using a inline fiber polarizer was coupled into the input dielectric silica waveguide in region I via a single mode fiber and a multimode fiber is employed to couple into the output port in region III. The experimental setup is displayed in Fig. 3.

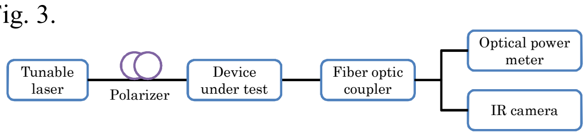

Fig. 3. Schematic diagram of the measurement setup

Figure 4 presents optical microscope images of a typical fabricated silica dielectric waveguide, a plasmonic waveguide having a 90° bend region coated by gold, and an optical output pattern at the output port. The top layer of the plasmonic waveguide is slightly coated by gold through sputtering process as shown in Fig. 4 (b), which can cause propagation loss. An infrared camera image of the output silica waveguide mode at region III after passing through a 90° bend region is shown in Fig. 4(c). The transmitted light was then measured at the output waveguide for detection by an optical power meter. From the measured transmission, the extra loss was estimated about 17 dB. This value is in stark contrast with the calculated value of 63%, which was predicted from our 3D-FDTD simulation. It is thus posited here that the discrepancy is caused by the gold pattern defects due to the limitation of resolution in the fabrication process, the higher propagation loss, the higher bending loss, misalignment, surface roughness, the imperfect polarized laser light source, and scattering losses, which is mainly due to metal loss and surface roughness. Nevertheless, a novel coupling scheme between a microsize silica/air-clad dielectric waveguide to a microsize silica/gold-clad MIM plasmonic waveguide is proposed and demonstrated.

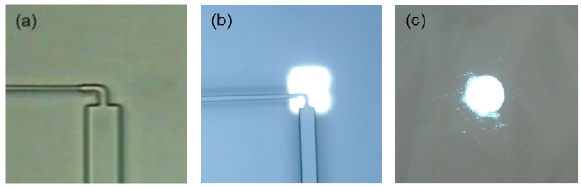

Fig. 5. Optical microscope image of (a) waveguide after first photolithography process and ICPRIE etching, (b) hybrid optical waveguide (conventional dielectric waveguide and plasmonic waveguide) after second photo- lithography process, and (c) 2-dimensional infrared camera output pattern of the mode profile of at output port of region III.

V. Conclusions

We reported on the design and demonstration of an integrated hybrid optical waveguide that combines microsize plasmonic waveguide with microsize conventional dielectric waveguide for near-IR light. Although the performance of the fabricated waveguide did not match that of the calculated waveguide, a simple coupling method between dielectric waveguide and plasmonic waveguide was shown. 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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