Design and Fabrication of Directional Coupler Type Hollow Waveguide Optical Switch with Variable Air Core

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Abstract: We present a device design and fabrication of a novel hollow-waveguide optical switch consisting of a directional coupler with variable air cores. The numerical simulation and experimental characterization of the proposed optical switch performance is discussed. Switching operation is achieved by mode-field change and coupling beat length in the directional coupler section, as the air core thickness is adjusted mechanically. Our modeling results show a possibility of a compact optical switch with a sub-mm switch length. A proof-of-concept experimental device is fabricated with microstructured Au-mirror waveguide on GaAs substrates. We observed optical switching extinction of about 17 dB with a switching length of 0.9 mm and a small change of an air core thickness.

1. Introduction

Figure of merits for photonic switches in the state-of-the-art optical network designs include fast switching speed, low power consumption, low form factor and scalability, as a typical terabit optical switches will require hundreds of low-port-count switches. In waveguide optical switches, either an electro-optic effect or a thermo-optic effect has been used for switching operations [1-8]. However, there still remain difficulties in realizing compact and large scale optical switches since the refractive index change of these effects are not large enough for reducing the switch size.

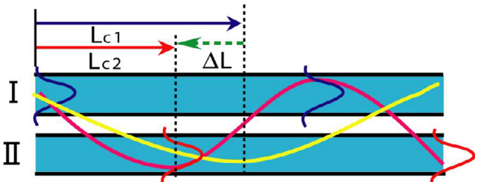
We propose and demonstrate a tunable hollow waveguide, introducing a new class of photonic integrated circuits, where a large change in the propagation constant of light can be achieved by a variable-thickness air core [9,10]. In addition, a hollow waveguide multi-mode interference (MMI) coupler is demonstrated [11,12]. We proposed a hollow waveguide optical switch composed of an MMI coupler with a variable air core [13-15]. We expect a large change in propagation constant when the air core thickness changes [9,10,15]. The relative change in propagation constant can be as large as 10 % with a small air core [16], which is very difficult to be realized in conventional dielectric waveguides. In addition, we obtain a large change of the mode-field in a three-dimensional hollow waveguide with a variable air core [15]. This large change enables us to reduce the size of a hollow waveguide optical switch.

In this paper, we present the design and fabrication of a novel hollow waveguide optical switch composed of a directional coupler with a variable air core. We present numerical calculation of the tunable propagation characteristics of a three-dimensional (3D) hollow waveguide with dielectric multilayer reflectors and an optical switch for investigating switch performances. Switching operation can be obtained by the combination of a hollow waveguide and a tunable air core. We fabricated three-dimensional hollow optical waveguides with gold (Au) film coating. The switching characteristics of the fabricated hollow-waveguide directional-coupler optical switch is presented.

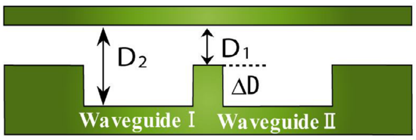
2. Modeling of directional coupler type hollow waveguide optical switch

2. 1 Operating principle of directional coupler type optical switch

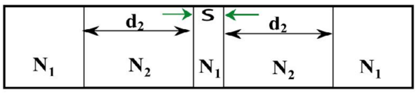
We propose an optical switch consisting of a directional coupler as shown in Figs. 1(a), (b) and (c). A directional coupler is a linear device which is used to transfer light from one waveguide to another. If two waveguides are sufficiently close so that the field overlap of the two waveguides can no longer be neglected, the optical powers carried by the two waveguides are exchanged periodically along the propagation. Figure 1(a) illustrates an example of complete power transfer. The coupling length L_C is defined as the minimum distance for a complete exchange of power between the two waveguides. An effective refractive index of 3-D hollow waveguide can be treated as an equivalent 2-D slab waveguide, and it is possible to apply to the



(a)Top view



(b) Cross-sectional view



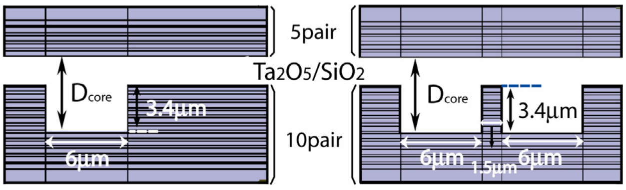
(c) Effective Index distribution

Fig. 1 Schematic of the proposed hollow waveguide optical switch composed of a directional coupler with a variable air core.

directional coupler of the slab waveguide [17,18]. The effective refractive index of the plane waveguide is shown in Fig. 1(c). If two hollow waveguides with the same core width are placed closely to each other, optical coupling between the two waveguides can be obtained as shown in the Fig. 1(a). A change in the air core thickness of this directional coupler results in the change of coupling length, which will give us switching operation. The mechanical displacement can be obtained by using electrostatic force if we manufacture the top reflector in a form of a thin membrane with metallic coating on the outer surface so that we can apply voltage to create an electric field across the air gap. The thickness of the core changes by electrostatic attraction force as the applied voltage changes.

2.2 Design and simulation result of directional coupler optical switch

Figure 2 (a) and (b) show the cross-sectional view of an input waveguide and coupling waveguide, respectively. The parameters for modeling include an air core step of 3.4 µm, a waveguide width of 6 µm, and the waveguide separation of 1.5 µm in the directional coupler region. The hollow waveguide consists of Ta_2O_5/SiO_2 multilayer mirrors. The pair numbers of the upper and bottom multilayer mirrors are 5 and 10, respectively.



(a) Input waveguide (b) Coupler waveguide

Fig. 2 Schematic cross-sectional view of the hollow waveguide type directional coupler optical switch. Input hollow waveguide, (b) Coupler hollow waveguide.

We carried out numerical simulations of the proposed hollow waveguide optical switch with a directional coupler. The calculation was carried out by using the full-vectorial simulator of FIMMWAVE/FIMMPROM (Photon Design Co.). First, a core thickness D_{core} of an input waveguide is changed so that the fundamental guided mode is confined in the air core within the range of D_{core} between 6 and 8 µms. We assumed the input light is a TE mode with an electric filed parallel to a substrate. The top and cross-sectional views of the intensity distribution in the hollow waveguide are shown in Fig. 3 (a) and (b) for different air core thicknesses of 6 µm and 8 µm, respectively. The lateral intensity peak moves from the left-hand side to the right-hand side at a distance of 600 µm as shown in Fig. 3 (a) and (b). Figures 4 (a) and (b) show the optical intensity distribution at a distance of 600 µm from the input port for the core thickness of 6 and 8 µm, respectively. The results show switching of optical power fraction of about 95 % with a switch length of 600 µm and a small displacement of air core ΔD_{core} = 2 µm, when we connect an output waveguide with the directional coupler.

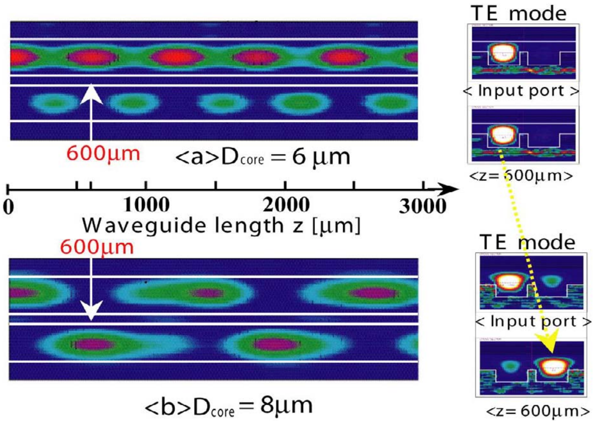
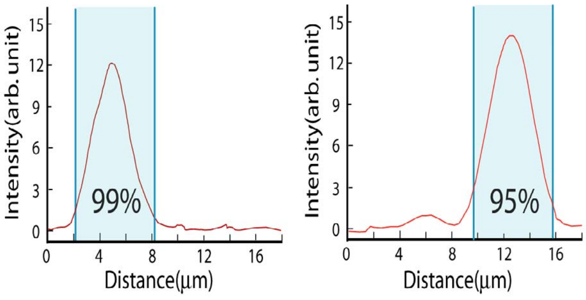


Fig. 3 Calculated field distribution of a directional coupler optical switch. Top view and cross-sectional view for (a) 6 µm and for (b) 8 µm, respectively.



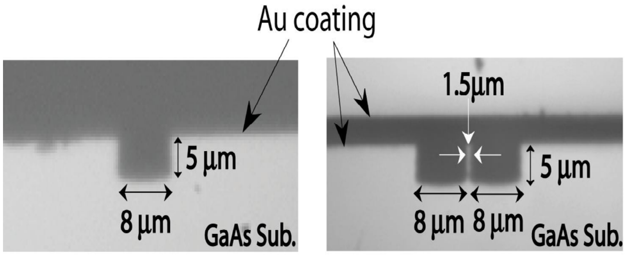
<a> D_{core}= 6 µm <b> D_{core}= 8 µm

Fig. 4 Calculated optical intensity distribution for (a) 6 µm and for (b) 8 µm, respectively at a distance of 600 µm.

The calculated insertion losses of a 600-µm-long hollow waveguide with 6- and 8-µm air-core thicknesses are 1.5 dB and 1 dB, respectively. The change in the coupling efficiency between an optical fiber (SMF) and an input waveguide is calculated to be 10 % by changing an air-core thickness (6µm ~ 8 µm). The calculated cross-talk of a 600-µm-long hollow waveguide with 6 and 8 µm air core thicknesses are -19 dB and -13 dB, respectively.

3. Fabrication and characterization of hollow-waveguide directional-coupler optical switch

Figures 5 (a) and (b) show cross-sectional views of an input waveguide and a coupler waveguide of a fabricated optical switch, respectively. In this experiment, we used a PZT actuator for the mechanical displacement, which will be replaced by a monolithic electrostatic actuator in the future. Guided modes can be confined in an Au-coated 3D hollow waveguide. First, we make a trench structure by lithography, followed by dry etching, and then we coat both the etched GaAs substrate and a planar GaAs substrate with thin Au film. The parameters of the fabricated optical switch are an air core step of 5 μm, an input waveguide width of 8 μm, and a waveguide separation of 1.5 μm for the coupling region. The air core-thickness is changed by moving the upper substrate with a PZT actuator.



<a> Input waveguide <b> Coupler waveguide

Fig. 5 Schematic cross-sectional views of the hollow-waveguide directional-coupler optical switch. (a) input hollow waveguide, (b) coupler hollow waveguide

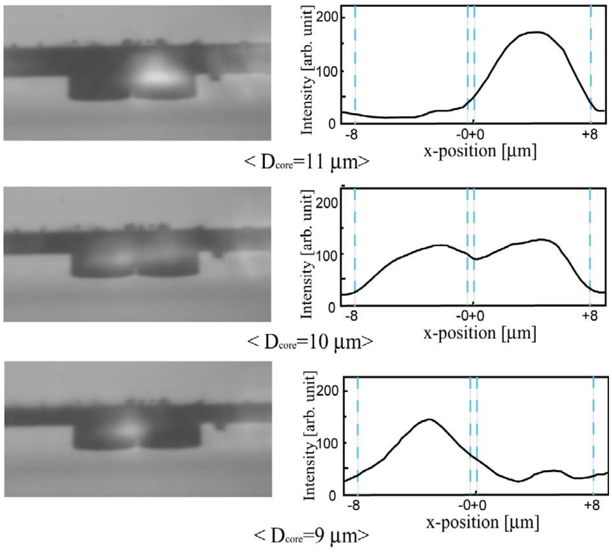


Fig. 6 Measured optical intensity distribution at a distance of 0.9 mm for (a) D_{core}= 9 μm, (b) D_{core}=10 μm and (c) D_{core}=11 μm air core thickness.

We carried out the measurement by exciting the guided mode of one input waveguide with a single-mode fiber. We precisely controlled the air core thickness by using the PZT actuator. The polarization of an input light is controlled to be TE mode by using a polarization controller. Figures 6(a), 6(b) and 6(c) show the measured lateral intensity distribution at a distance of 0.9 mm from the input port for the core thickness of 11 μm, 10 μm and 9 μm, respectively. The lateral intensity peak moves from a bar state to a cross state. The result shows the switching operation by an optical power fraction of about 80 % with a switching length of 0.9 mm and a small displacement of air core ΔD_{core}=2 μm, as we connect an output waveguide to the directional coupler region. The measured insertion losses of a 0.9-mm-long hollow waveguide with 11 and 9 μm air core thicknesses are 6 dB and 8 dB, respectively. The insertion loss includes fiber-to-chip coupling losses at both ends. The excess insertion loss mainly comes from the propagation loss of the Au-coated 3D waveguide. The loss can be reduced by avoiding the sidewall coating of the coupling region [10]. The change in the mode field distribution for switching operations is another issue for insertion losses, which can be reduced by using a tapered spot size converter [19]. The fabricated directional coupler switch is polarization dependent since metal-coated mirrors are used. The insertion loss for TM mode decreases to be 2 dB. The switching characteristics such as switching distance and on-off ratio is unchanged for a TM mode.

We expect further reduction in switching length by reducing the air core width and the air core step [15].

4. Conclusions

We propose a novel hollow waveguide optical switch composed of a directional coupler and a variable-thickness air core. We carry out the full-vectorial numerical simulation for a directional coupler hollow waveguide switch. The result shows a possibility of compact-size waveguide switches with a sub-mm switching length. We fabricate a directional coupler waveguide switch based on a tunable hollow waveguide for demonstration as a proof of concept for the proposed switch design. We present the switch performance measurement results of the fabricated sample. !!!Discuss loss, extinction ratio, crosstalk!!!! The result shows switching operation of compact-size waveguide switches with a switching length of 0.9 mm. Further reduction in the switch size can be expected with reducing the width and the core step of the directional coupler hollow waveguide.

Acknowledgments

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