High-Speed and Low-Voltage Ring Resonator Optical Switches Using Electro- and Magneto-Optic Materials

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Abstract—Ring resonator optical switches using electro- and magneto-optic materials are proposed and designed, and their characteristics are simulated. These switches are promising devices because of their compactness, high speed, and low voltage operation.

I. INTRODUCTION

Silicon photonics is attracting much attention toward next generation high speed computing. Our target is optical interconnection on Si chips. Most difficult problem is to realize Si-based light emitting devices. Many studies have been done to create Si compatible light emitting materials, for example Er doping [1] and β-FeSi2 [2]. We are planning to integrate many optical switches monolithically with few light-emitting devices made of compound semiconductors or using external light source. We study microring optical resonator switches.

In order to realize the ring resonator switches, the waveguide whose refractive index is changed by electric or magnetic field is needed for high speed switching. There are two solutions for the electric field type switches: electro-optic (EO) materials core waveguide and Si core waveguide [3]. We focus on EO materials because the faster operation is expected. In the case of magnetic field type, magneto-optic (MO) materials core waveguide is a unique solution. In this paper ring resonator switches using EO and MO materials are designed and their operation characteristics are estimated.

II. RING RESONATOR OPTICAL SWITCHES USING ELECTRO-OPTIC MATERIALS

A. Operation voltage

Ring resonator switch consists of ring and I/O waveguides as shown in Fig. 1(a). This device picks up the light with resonance wavelength. Fig. 1(b) shows the cross section of the ring waveguide, which consists of EO material core layer, KH2PO4 cladding layer which is selected because of its high dielectric constant and low refractive index, and aluminum electrodes.

We studied optical properties of this switch by finite difference method and finite difference time domain method simulations. The core thickness should be 2.5 µm or larger if the cladding thickness is 0.1 µm in order to apply electric field to EO materials effectively. Refractive index change of 5x10^-4 is needed for switching operation at GaAs laser diode emitting wavelength (850 nm) [4].

The operation voltage is calculated in the case of LiNbO3 (LN), (Ba,Sr)TiO3 (BST), and K(Ta,Nb)O3 (KTN). LN is widely used for EO materials, but has not been introduced in Si process yet. BST has been already introduced in Si process as the ferroelectric material. KTN has very large EO coefficient and recently developed by NTT [5]. The results are summarized in Table I. KTN is promising if a thin crystal film will be available in Si process. LN and BST have high operation voltage. These values may be reduced by introducing other structure waveguide such as rib type.

![Figure 1. (a) Ring resonator optical switches using electro-optic materials and (b) cross sectional structure of the ring waveguide.](image)

| Electro-optic material | LN  | BST | KTN |
|------------------------|-----|-----|-----|
| EO coefficient (pm/V)  | 30.8| 23  | 600 |
| Dielectric constant    | 28  | 300 | 666 |
| Operation voltage(V)   | 8.0 | 19.6| 0.73|
B. Operation speed

The operation speed is estimated using a simple model as shown in inset of Fig. 2(a). This model neglects waveguides width and assumes equivalent index of 2.0, which is selected for EO materials; LN. The other model parameters are coupling constant between ring and bus and bending loss of the ring. Weaker coupling gives smaller peak power and higher Q-value as shown in Figs. 2(a) and 2(b). Full width at half maximum (FWHM) should be less than 0.2 nm for optical switching [4], therefore the coupling constant must be smaller than 0.3. On the other hand, the coupling constant should be larger than 0.1 for practical strong output.

Fig. 3 shows one example of the resonance shape after light propagates in the ring at some rounds. Time dependence of peak power and FWHM are shown in Figs. 4(a) and 4(b), respectively. FWHM reaches 0.2 nm within 15 ps except for large bending loss. The operation speed of the ring resonator switches using EO materials depend on not only resonance time but also RC delay and polarization time of the EO materials for refractive index change. The typical time of RC delay and polarization time are 10⁻² ps and 1 ps, respectively. Therefore the operation speed is limited by the resonance time. This is different from optical switches using Si core [3], whose operation speed is limited by free carrier accumulation time, i.e. hundreds ps.

Next, the gap dependence of coupling constant between I/O waveguides and ring is simulated. Device dimension and simulated results are shown in Fig. 5. Coupling constant needed for switching is obtained from 0.15-0.3 µm gap, which can be fabricated in conventional Si process.

III. RING RESONATOR OPTICAL SWITCHES USING MAGNETO-OPTIC MATERIALS

A. Overview

Magneto-optic (MO) materials are widely used to realize the optical isolators which plays an important role in the optical fiber communication systems. The plane of linearly polarized light propagating in MO materials is rotated when magnetic field is applied in the direction of light propagation. This effect is known as Faraday effect. By using MO materials, optical switches are usually realized only one straight waveguide. However this switch needs polarizer and analyzer, which is a disadvantage for integration because it is difficult to integrate many small polarizers and analyzers.

We propose ring resonator switches using MO materials as shown in Fig. 6. These switches have quite interesting feature; these can switch the light without polarizer and analyzer. We will explain these characteristics using the simple model as follows.

The principle of Faraday effect can be understood by considering the behavior of the circularly polarized light.
In general linearly polarized light is expressed as the sum of the circularly polarized lights with different rotation direction. MO materials give opposite refractive index change for right and left circularly polarized light. As the results, the plane of linear polarization is rotated with propagation in the MO materials. The resonance wavelength of ring resonators is proportional to the refractive index, therefore the resonance wavelength in right and left circularly polarized mode are shifted to opposite direction when magnetic field is applied along the propagation direction in the ring.

B. Resonance Characteristics

We calculated resonance characteristics using revised version of the simple model as mentioned before (see inset of Fig. 2(a)). Now we assume that effective refractive index and coupling constant are the same for TE and TM modes for simplicity. This approximation is suitable for polarization independent waveguides. In this case, the characteristics of the ring resonator using MO materials can be easily calculated in circularly polarized mode. TE and TM modes are superposition of right and left handed mode,

\[ E_R = \frac{1}{\sqrt{2}}(E_{TE} - iE_{TM}), \]
\[ E_L = \frac{1}{\sqrt{2}}(E_{TE} + iE_{TM}), \]

where subscript R, L, TE, and TM denote polarization. When input light is not polarized and/or output light does not go through analyzer, output power are proportional to sum of the power of right and left handed mode,

\[ P \propto |E_R|^2 + |E_L|^2. \]

On the other hand, when both input and output light is polarized, the output power is expressed as

\[ P \propto |E_R + E_L|^2, \]

and so the interference between right and left handed modes exists in this case. We show that the interference effect does not change the characteristics substantially.

Most famous MO material is Y3Fe5O12 (YIG), which has large Faraday rotation angle and low absorption coefficient for \( \lambda > 1 \) μm. Bismuth substituted YIG (Bi:YIG) have been studied [6] because of its larger Faraday rotation angle \(-1300\) deg/cm by applied small magnetic field of 3 Oe. The model parameter is fixed as the values of Bi:YIG in this calculation. The current is 18 mA to obtain 3 Oe magnetic field for ring radius 12 μm. The power dissipation to produce this magnetic field is only 7.1 μW for Cu wire. By increasing the turn number of the coil to produce the magnetic field, the current can be deduced, e.g. to 1 mA by 18 turn coil. This value is practical, and so operation of low voltage is possible.

The results in polarized and non polarized input light are shown in Fig. 7. In both cases, resonance peak is divided into two peaks, and the resonance characteristics are very similar. The output power at original resonance wavelength is sufficiently decreased, which indicates a good switching operation.

IV. CONCLUSIONS

We have proposed and designed the ring resonator switches using EO and MO materials. In the case of EO materials, the operation voltage and speed were estimated by simulation and the simple model. In the case of MO materials, we found that the ring resonator switches operates at low voltage. These switches do not need polarizer which is different from optical switches using one straight waveguide, and suitable for LSI integration. The ring resonator switches are promising devices for their compactness and high operation speed to apply optically integrated LSI.

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