Design and Simulation of Ring Resonator Optical Switches using Electro- and Magneto-Optic Materials

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1. 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. We are planning to integrate many optical switches monolithically with few light-emitting devices made of semiconductors. We study microring resonator optical switches [1].

In order to realize the ring resonator switches, the waveguide whose refractive index is changed by external field is needed for high speed switching. There are two solutions for the electric field type switches: Electro-optic (EO) materials and Si [2]. We focus on EO materials because the faster operation is expected. In the case of magnetic field type, magneto-optic (MO) materials are the unique solution. In this paper ring resonator switches using EO and MO materials are designed and their operation characteristics are estimated.

2. Optical Switches using Electro-Optic Materials

Ring resonator switch consists of ring and I/O waveguides as shown in Fig. 1. Figure 2 shows the cross section of the ring waveguide. KH_2PO_4 is selected as the cladding layer because of its high dielectric constant and low refractive index.

We simulated optical properties of this switch. The core thickness should be 2.5 μm or larger if the cladding thickness is 0.1 μm. Refractive index change of $5\text{x}10^{-4}$ is needed for switching operation at λ=850 nm [1]. The operation voltage is calculated in the case of $LiNbO_3$ (LN), $(Ba,Sr)TiO_3$ (BST), and $K(Ta,Nb)O_3$ (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. KTN has very large EO coefficient [3]. 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.

The operation speed is estimated using a simple model as shown in inset of Fig. 3. We assumes equivalent index of 2.0, which is selected for LN. The other model parameters are coupling constant between ring and I/O waveguide and bending loss of the ring. Weaker coupling gives smaller peak power and higher Q-value as shown in Figs. 3 and 4. Full width at half maximum (FWHM) should be less than 0.2 nm for optical switching [1], therefore the coupling constant must be smaller than 0.3. Figure 5 shows one example of the resonance shape. Time dependence of peak power and FWHM are shown in Figs. 6 and 7, 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 also depend on RC delay (10^{-2} ps) and polarization time of the EO materials (1 ps), however both of them are faster than 15 ps. This is different from optical switches using Si [2], whose operation speed is limited by free carrier accumulation time, hundreds ps.

Next, the gap dependence of coupling constant is simulated. Device dimension and simulated results are shown in Fig. 8. Coupling constant needed for switching is obtained from 0.15-0.3 μm gap.

3. Optical Switches using Magneto-Optic Materials

MO materials are widely used to realize the optical isolators which play an important role in the optical fiber communication systems. These devices make use of the Faraday effect and are realized only one straight waveguide. However they need 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. 9. We show these switches have quite interesting feature; these can switch the light without polarizer and analyzer.

The model parameter is fixed as the values of Bismuth substituted $Y_3Fe_5O_{12}$, which has very large Faraday rotation angle −1300 deg/cm by applied small magnetic field of 3 Oe [4]. 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. The results in polarized and non polarized input light are shown in Fig. 10. In both cases, resonance peak is divided into two peaks, and the resonance characteristics are very similar. The output power at λ=1300 nm is sufficiently decreased, which indicates a good switching operation.

4. Conclusion

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, these switches do not need polarizer and suitable for LSI integration. The ring resonator switches are promising devices for their compactness and high operation speed to apply optically integrated LSI.

Acknowledgments

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References

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[2] A. Liu *et al.*, Nature **427,** 615 (2004).

[3] S. Toyoda *et al.*, Electro. Lett. **40**, 830 (2004).

[4] H. Takeuchi, Jpn. J. Appl. Phys. **14**, 1903 (1975).

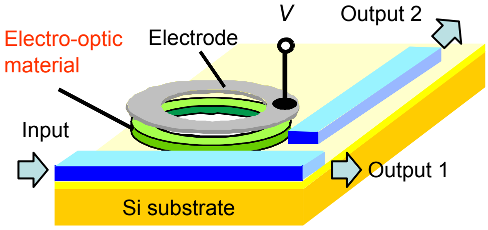

Fig. 1 Ring resonator optical switches using electro-optic materials.

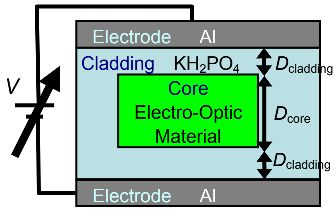

Fig. 2 Cross sectional structure of the ring waveguide.

Table I Operation voltage for ring resonator switches with various EO materials. Operation voltage is determined by EO coefficient and dielectric constant.

	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

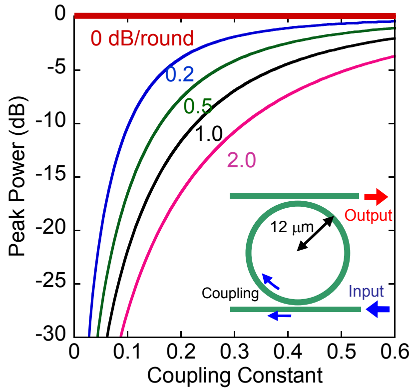

Fig 3 Coupling constant and bending loss dependence of peak power. Weaker coupling gives lower height.

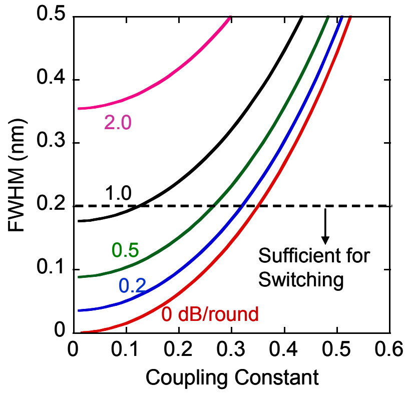

Fig. 4 Coupling constant and bending loss dependence of FWHM. Weaker coupling gives narrower width.

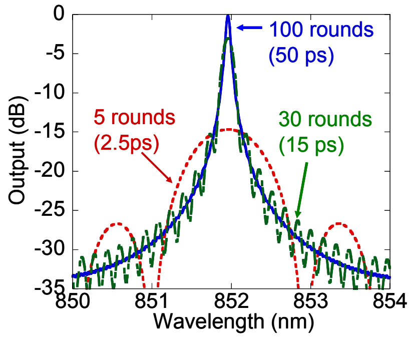

Fig. 5 Time dependence of resonance characteristics for coupling constant 0.2 and no bending loss.

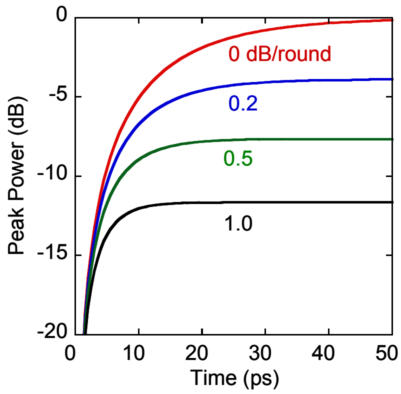

Fig. 6 Time dependence of peak power for coupling constant 0.2.

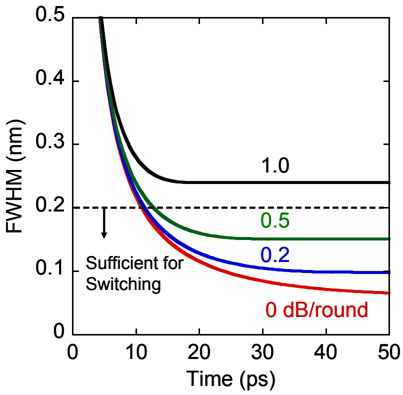

Fig. 7 Time dependence of FWHM for coupling constant 0.2. It takes less than 15 ps to reach FWHM to 0.2 nm if bending loss is sufficiently small.

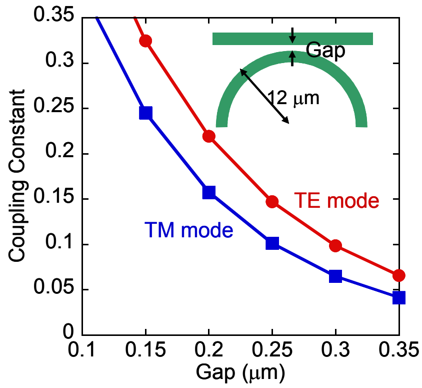

Fig. 8 2D FDTD simulation of the coupling constant. Difference in the coupling constant between TE and TM mode comes from waveguide structure.

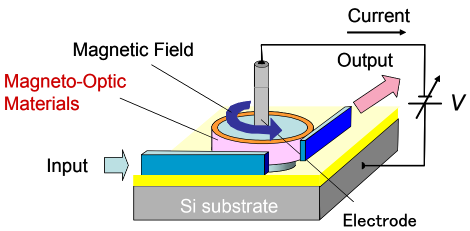

Fig. 9 Ring resonator optical switches using magneto-optic materials.

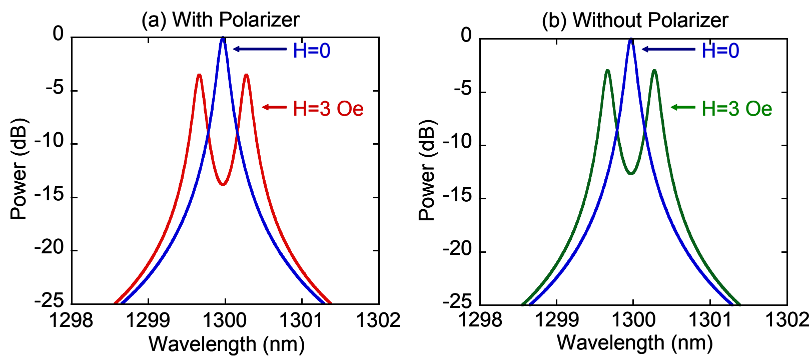

Fig. 10 Resonance characteristics of ring resonator using MO materials with and without polarizer. The resonance peak is divided to two peaks in both cases, and good switching operation is indicated.

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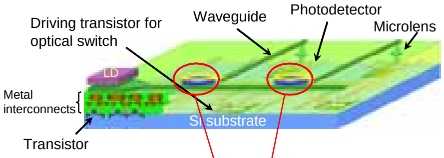
Introduction

Si LSI with Optical Interconnects

Si based light emitting devices are difficult to be realized.

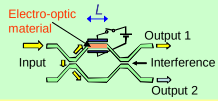


Integrate many ring resonator switches instead of LDs

Monolithic Integration except for Light Emitting Devices

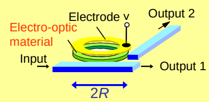
Advantage of Ring Resonator Switch

Mach-Zehnder interferometer type



Waveguide length for switching
Assuming Δn=5x10^{-4},
$L=\lambda/(2\Delta n)$=850μm (λ=0.85μm)

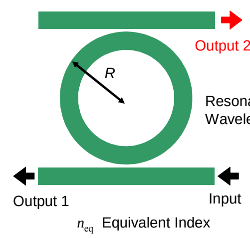
Ring resonator type

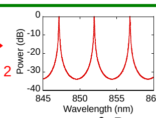


Ring diameter
$2R$=10-50μm

Suitable for integration due to its compactness

Principle and Application for Optical Switches

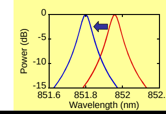




Resonance Wavelength $\lambda = n_{eq}\frac{2\pi R}{m}$ m: integer

n_{eq} Equivalent Index

Change by Bias Applied



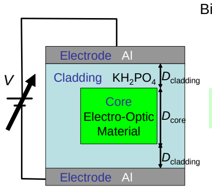
Ring Resonator Optical Switches using EO Materials

Cross Section of the Ring Resonator Switches

Bias V for applying electric field E

$$V = D_{core}E + 2D_{cladding}\frac{\varepsilon_{core}}{\varepsilon_{cladding}}E$$

ε : dielectric constant



Cladding: KH_2PO_4
Low n, High ε

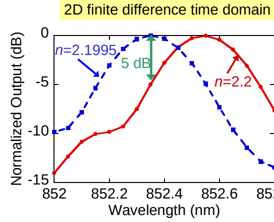
	n	ε
KH_2PO_4	1.47	42
LN	2.2	28
BST	2.1	300
KTN	2.35	666

Candidates of electro-optic materials

- LN $LiNbO_3$ — Widely used for EO materials
- BST $(Ba,Sr)TiO_3$ — Introduced in silicon process already
- KTN $K(Ta,Nb)O_3$ — Very large EO coefficient

Simulated Switching Characteristics

2D finite difference time domain



Waveguide width 2 μm
Ring radius 12 μm
Gap 0.1 μm

5 dB gain for Δn=5x10^{-4}

$$\Delta n = -\frac{1}{2}n^3 rE$$

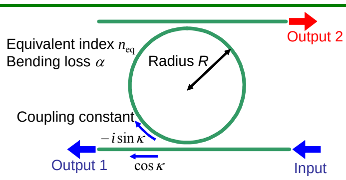
Operation Voltage

	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

- LN and BST have high operation voltage
- KTN is promising if a thin film is available in Si process

Operation voltage may be reduced by introducing other waveguide structure such as ridge type.

Model to Estimate Operation Speed



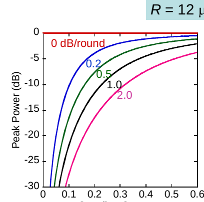
Parameters	
Ring radius	12 μm
Equivalent index	2.0
Coupling const.	sin κ
Bending loss	α

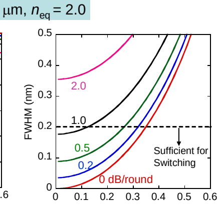
Time dependent analytic solution is obtained

Operation speed is estimated

Peak Power and FWHM

R = 12 μm, n_{eq} = 2.0

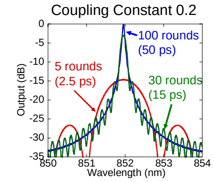


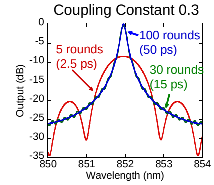


Operation speed is estimated for coupling constant 0.2

Time Dependence of Resonance Characteristics

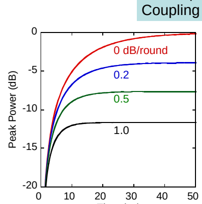
R = 12 μm, n_{eq} = 2.0
No bending loss

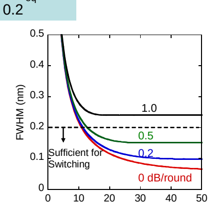




Time Dependence of Peak Power and FWHM

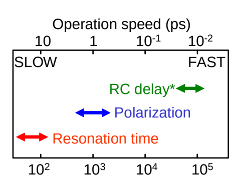
R = 12 μm, n_{eq} = 2.0
Coupling 0.2





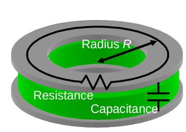
Operation Speed < 15 ps

Operation Speed



Operation speed is limited by resonation time

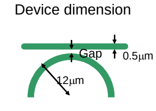
Operation frequency > 66 GHz



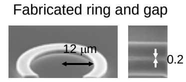
*: Core LN, Cladding KH_2PO_4

Gap dependence of Coupling Constant

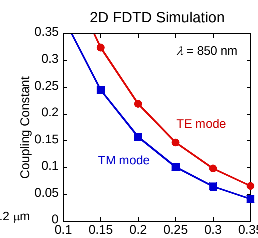
Device dimension



Fabricated ring and gap

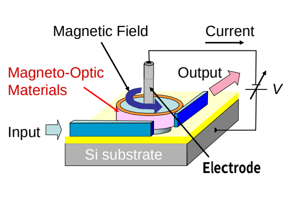


2D FDTD Simulation



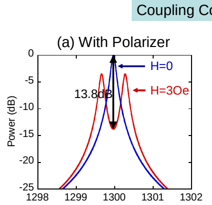
Ring Resonator Optical Switches using MO Materials

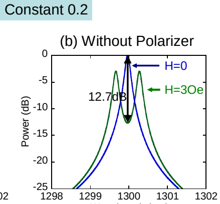
Schematics



Resonance Characteristics

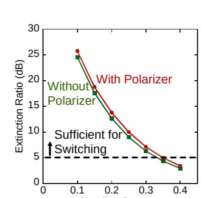
Coupling Constant 0.2





Good Switching Operation without Polarizer

Extinction Ratio



Conclusion

- We have proposed and designed the ring resonator switches using EO and MO materials.
- The operation voltage and speed are estimated by simulation and the simple model.
- Ring resonator switches using EO materials are promising devises for their compactness and high operation speed to apply optically integrated LSI.
- Ring resonator switches using MO materials is operated without polarizer, which is suitable for LSI integration.