Simulation of Ring Resonator Optical Switches

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1. Introduction

Optical interconnection is an attractive candidate to solve signal delay of metal interconnection. Optical interconnection consists of light-emitting devices, waveguides, photodetectors, and optical modulators. It is not easy to integrate many light-emitting devices made of compound semiconductors on silicon chips. More promising method is to integrate optical switches monolithically. Tunable microring resonator [1] is useful for optical switch because of its compactness. It has been shown that microring resonator is attractive candidate of small size optical filter [2].

The waveguide whose refractive index is changed by electric field is needed for high speed switching. There are two solutions to realize such waveguide: Electro-optic (EO) material core waveguide and silicon core waveguide [3]. We focus on EO material because faster operation is expected.

2. Optical simulation of the ring resonator

Ring resonator switch consists of ring and signal buses as shown in Fig. 1. The light with resonance wavelength goes to output 2. Optical properties were simulated to estimate the operation voltage and speed of this switch. In these simulations, ring radius and waveguide width were 12 μm and 2 μm, respectively.

Figure 2 shows the cross section of the ring. The cladding SiO_2 layer must be thin for applying electric field to EO materials effectively, so was fixed at 0.1 μm. The core EO material layer must be thick enough to reduce propagation loss by aluminum absorption. Figure 3 shows simulated propagation loss of this waveguide. We chose the thickness of the core 3 μm to reduce the propagation loss to less than 1 dB/cm. Then resonance properties of the ring resonator are simulated as shown in Fig. 4. Refractive index change of 5×10^{-4} is needed for switching operation.

3. Estimation of operation voltage and speed

From these simulation results, we can estimate the operation voltage and speed. Operation voltage depends on the EO coefficient and dielectric constant of the core materials of the ring waveguide. We calculated for $LiNbO_3$ (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 silicon process yet. BST has been already introduced in silicon process as ferroelectric material [4]. KTN has very large EO coefficient and recently developed by NTT [5]. The results are summarized in Table 1. The dielectric constant of KTN has not been known yet, so is assumed between the value of LN and BST. From these results, KTN is promising if a thin film will be available in Si process. LN is fairly useful by device parameter optimization. BST has high operation voltage, so new ideas are required to use BST. One solution is to use other materials with larger dielectric constant than SiO_2 as cladding layer.

Next operation speed was estimated. Operation speed depends on RC delay, polarization of EO materials for refractive index change, and resonation time which is defined as light propagation distance divided by light speed in the matter. We assumed the light propagation distance is 15-100 rounds in the ring. The operation speed is limited by resonation time as shown in Fig. 5. To confirm our estimation, resonance characteristics were calculated using simple model in which coupling constant *Kc* between bus and ring, and effective index and bending loss of the ring waveguide are given. We calculated resonance characteristics in the case of weak coupling and strong coupling as shown in Fig. 6. After 100 rounds, behaviors are sufficiently saturate in both cases.

We also estimated the speed of tunable ring resonator with Si core instead of EO material core. Refractive index change is obtained by free carrier accumulation in Si. The typical time of accumulation is 10^{-9} s, therefore switching speed is limited by not resonation time but accumulation. Finally we stress that because refractive index change is small for both EO material and Si core, high-Q ring resonator is indispensable to obtain a high switching gain.

4. Conclusion

We have proposed the ring resonator switches using EO materials. The characteristics of the ring resonator switches using EO materials were estimated with simulation. We compared it with ring resonator switches with Si core. The ring resonator switches with EO materials are promising devices for their compactness and high operation speed.

References

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[2] B.E. Little, S. T. Chu, H. A. Haus, J. Foresi, and J.-P. Laine, J. Lightwave Technol. **15**, 998 (1997).
[3] A. Liu *et al.*, Nature **427,** 615 (2004).
[4] M. Yamato, H. Yamada and T. Kikkawa, Jpn. J. Appl. Phys. **43**, 5221 (2004).
[5] S. Toyoda *et al.*, Electro. Lett. **40**, 830 (2004).

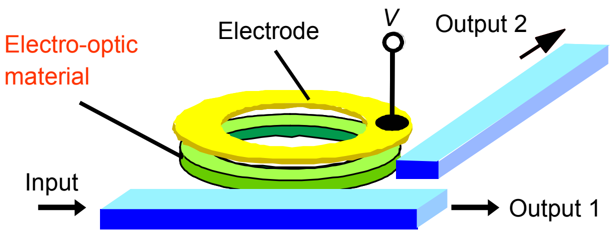

Fig. 1 Ring resonator optical switches using electro-optic materials.

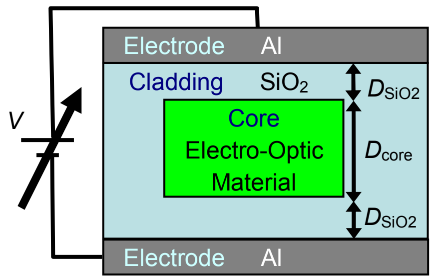

Fig. 2 Cross section of the ring waveguide.

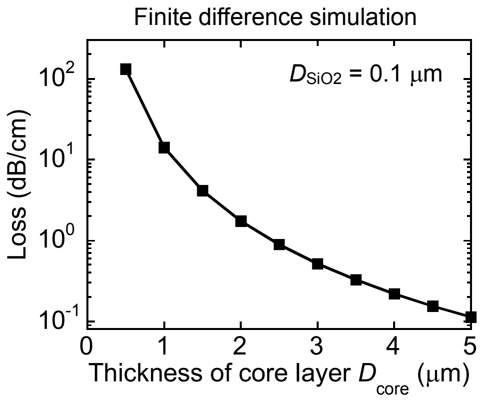

Fig. 3 Simulated propagation loss. The core thickness should be larger than 0.25 μm to reduce propagation loss less than 1 dB/cm.

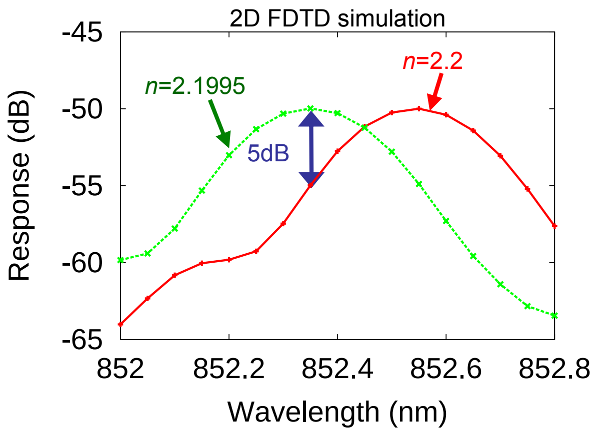

Fig. 4 Simulated resonance properties for different refractive index of core. 5 dB change of output response is obtained for refractive index change 5×10^{-4}.

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

	LN	BST	KTN
Electro-optic coefficient (pm/V)	30.8	23	600
Dielectric constant	28	300	28-300 (assumed)
Operation voltage (V)	13.5	91.9	0.57-2.36

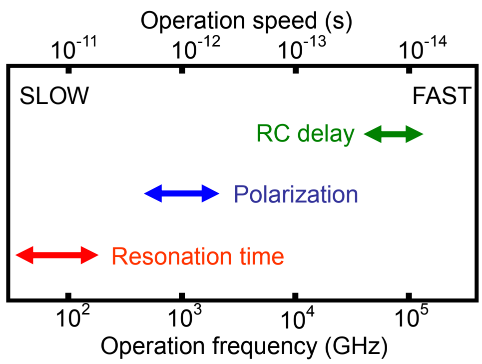

Fig. 5 Operation speed and frequency of ring resonator switches.

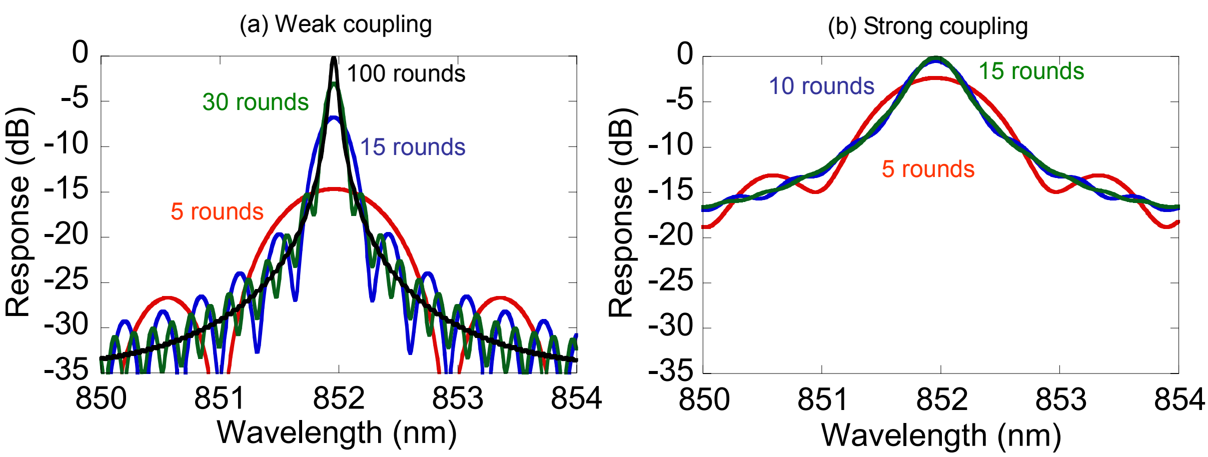

Fig. 6 Resonance characteristics after light propagates *m* rounds in the ring for (a) weak coupling (Kc=0.2) and (b) strong coupling (Kc=0.5). The waveguides have effective index of 2.0 and no bending loss. The ring resonator with weak coupling has higher-Q resonance characteristics and longer resonation time.

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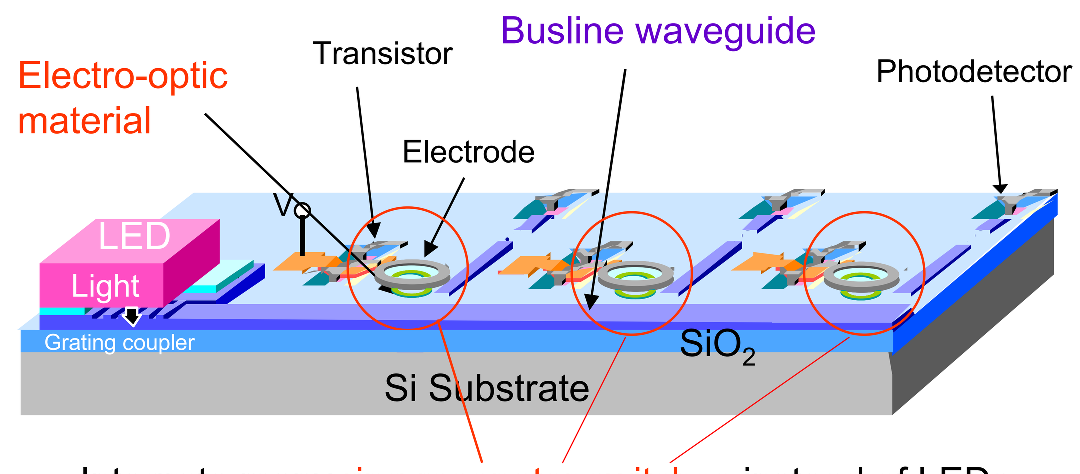
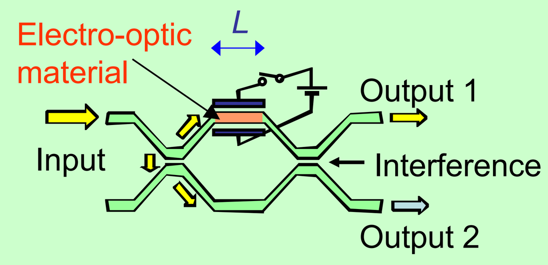
Introduction



Integrate many ring resonator switches instead of LEDs

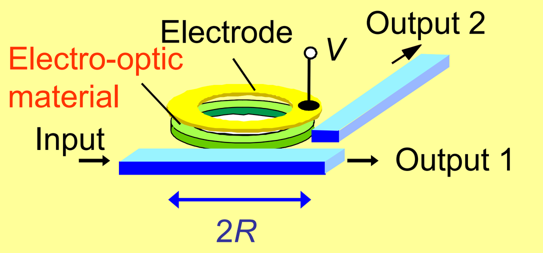
All devices except for LEDs can be monolithically integrated

Mach-Zehnder interferometer type



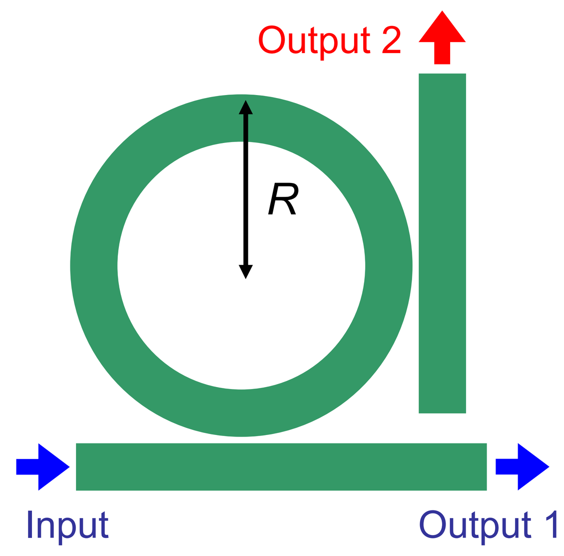
Waveguide length for switching
Assuming Δn=5x10^{-4},
$L=\lambda/(2\Delta n)$=850 μm (λ=0.85 μm)

Ring resonator type



Ring diameter
$2R$=10-50 μm

Suitable for integration due to its compactness



Resonance wavelength λ_{res}

$$\lambda_{res} = n_{eff}\frac{2\pi R}{m}$$

n_{eff}: effective refractive index
m : integer

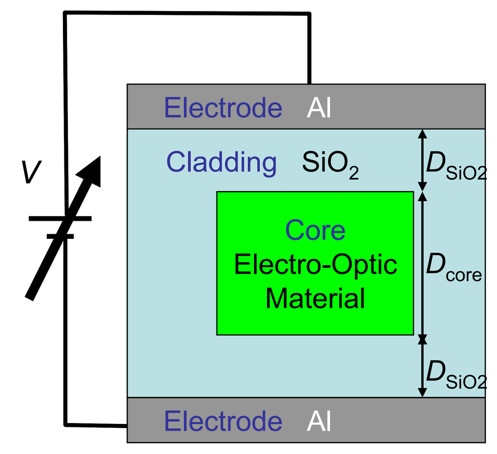
Pick up only light with resonance wavelength to Output 2

Ring resonator switches

λ_{res} depends on n_{eff}

λ_{res} can be controlled by electric field if the core of the ring is made of electro-optic (EO) materials

Optical Simulation



Bias V for applying electric field E

$$V = D_{core}E + 2D_{SiO_2}\frac{\varepsilon_{core}}{\varepsilon_{SiO_2}}E$$

ε: dielectric constant

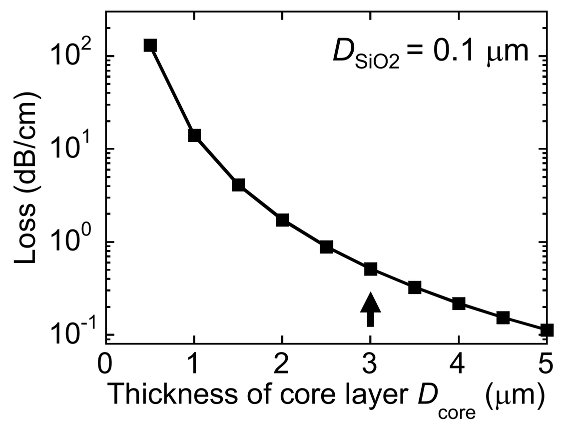
Most of applied bias is applied to SiO_2 because $\varepsilon_{core} > \varepsilon_{SiO2}$

ε_{SiO2}	3.9
ε_{LN}	28
ε_{BST}	300

Candidates of EO materials

- LN $LiNbO_3$ Widely used
- BST $(Ba,Sr)TiO_3$ Introduced in silicon process already

Finite difference method

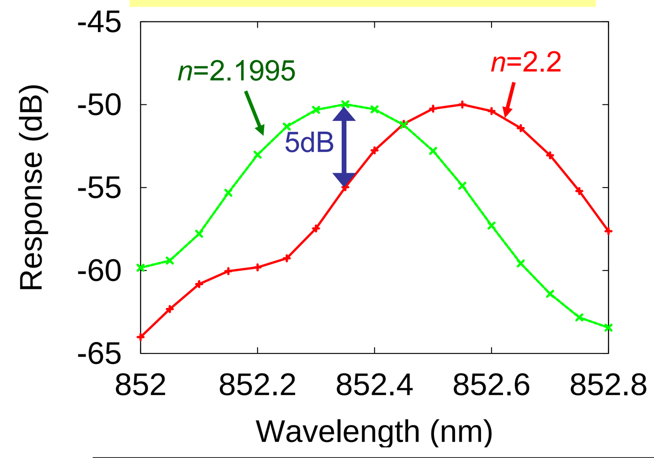


Thickness of cladding layer is fixed as D_{SiO2} = 0.1 μm to reduce the operation voltage

D_{core} > 3 μm for Loss < 1 dB/cm

We use D_{core}= 3 μm and D_{SiO2}= 0.1μm for estimation

2D finite difference time domain



Waveguide width	2 μm
Ring radius	12 μm
Gap	0.1 μm

5 dB gain for Δn=5x10^{-4}

Change in refractive index of EO material

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

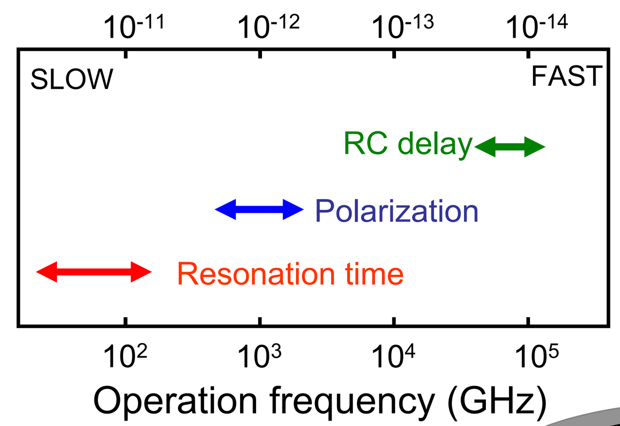
r : electro-optic coefficient

Operation Voltage and Speed

LN	$LiNbO_3$	Widely used as EO materials
BST	$(Ba,Sr)TiO_3$	Sputtering film available on Si process
KTN	$K(Ta,Nb)O_3$	Very large electro-optic coefficient

	LN	BST	KTN
Electro-optic coefficient (pm/V)	30.8	23	600
Dielectric constant	28	300	28-300 (assumed)
Operation voltage (V)	13.5	91.9	0.57-2.36

- LN is fairly useful by device parameter optimization
- BST has relatively high operation voltage
- KTN is promising if a thin film is available in Si process



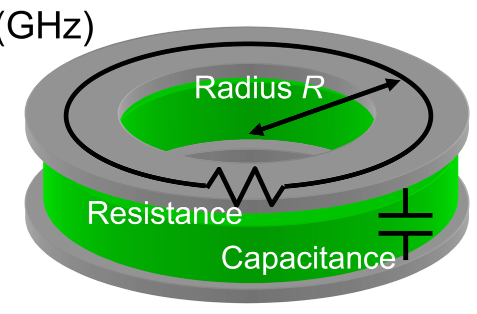
Operation speed is limited by resonation time

Operation frequency ~ 100 GHz

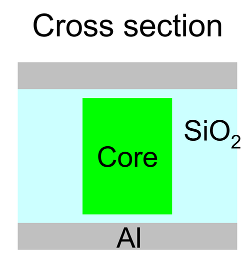
Resonation time is defined as

$$t = \frac{m \times 2\pi R}{c/n}$$

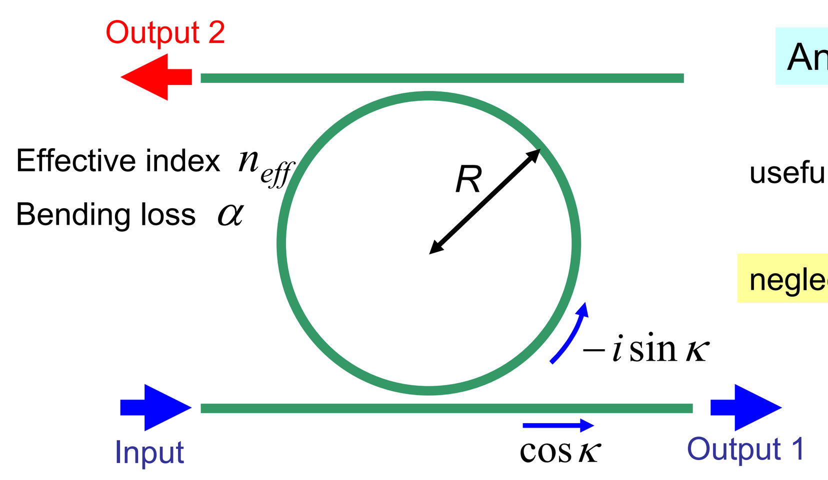
m	15-100
R	12 μm
n	2.0



Cross section



Resonance Characteristics by Simple Model



Analytic solution

useful for understanding

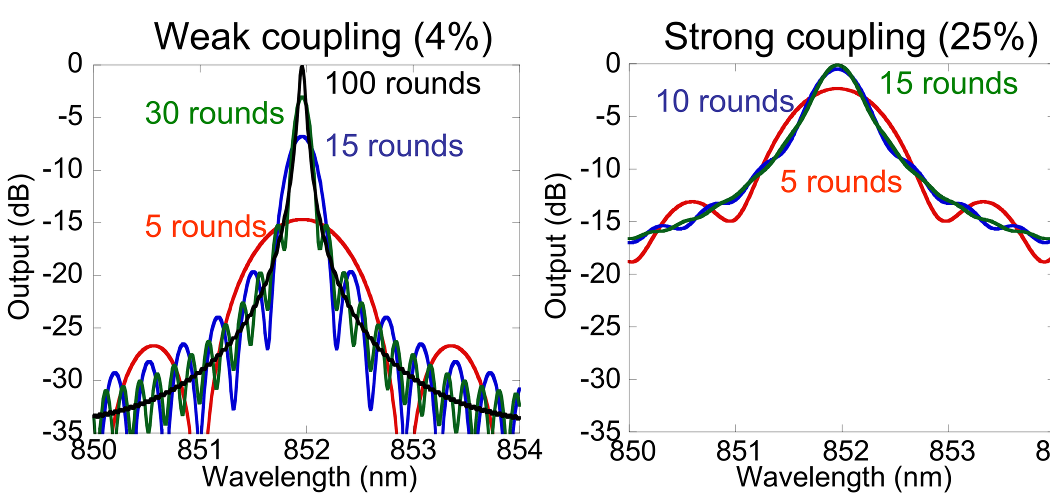
neglect waveguide width

Parameter
Effective index n_{eff}
Bending loss α
Coupling κ

Determined from device parameter
Index of core and cladding
Thickness of core and cladding
Waveguide width
Gap
Ring radius

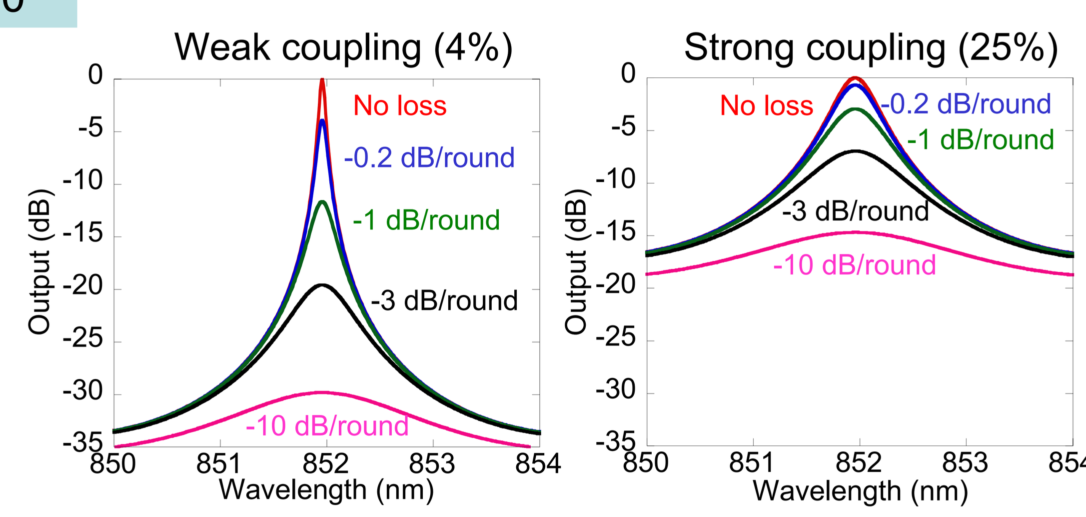
m rounds

R = 12 μm
n_{eff} = 2.0



Number of rounds	5	10	15	30	100
Response time (ps)	2.5	5.0	7.5	15.1	50.3
Response frequency (GHz)	398	199	133	66.3	19.9

Bending Loss Dependence



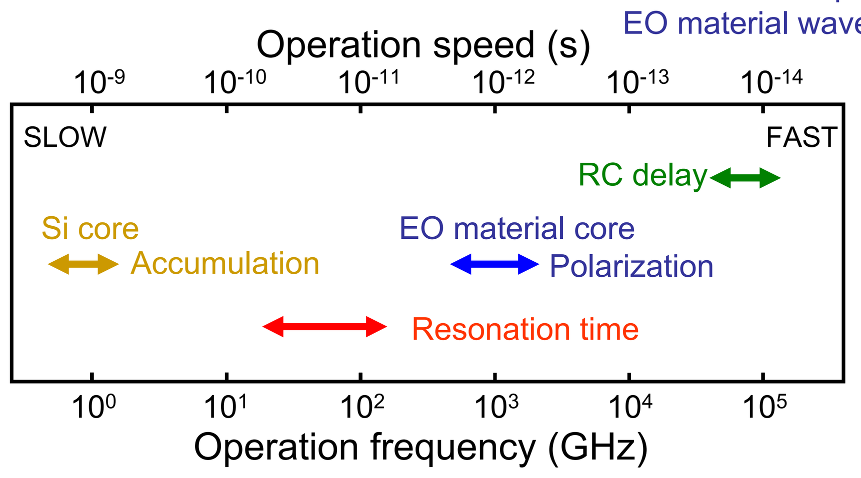
Large effect by loss for weak coupling

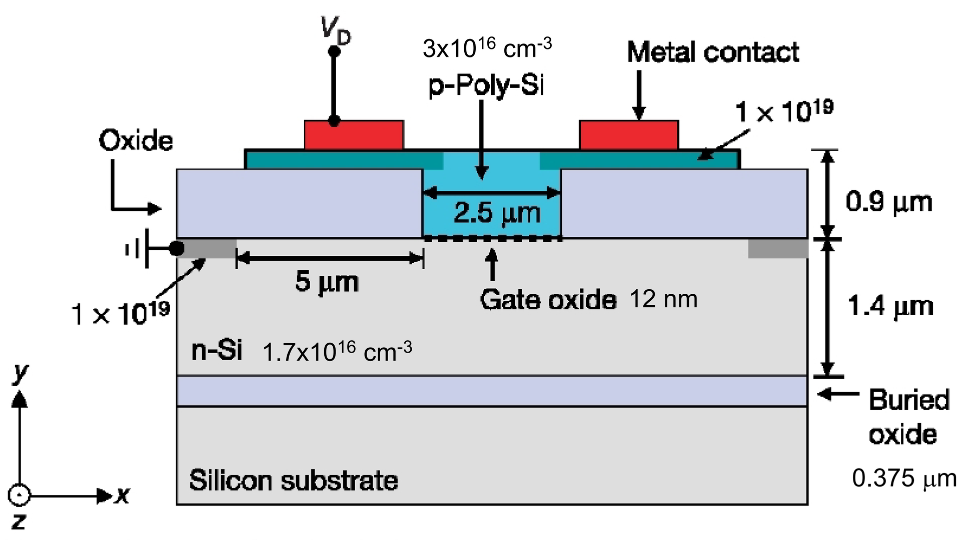
-0.2 dB	-1 dB	-3 dB	-10 dB
0.955	0.794	0.501	0.1

Comparison with Si Core

Si core
Wavelength 1.3 μm -
Operation frequency 1 GHz
Not many problems

EO Material core
Wavelength 0.4 μm -
Operation frequency 100 GHz
Many problems
Select EO materials
Introduce to Si process
EO material waveguide





How to chance refractive index
1. Accumulate free carriers by electric field ⇦ Bottleneck for switching speed
2. Change refractive index
3. Change effective refractive index of waveguide

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

Summary

- We have proposed the ring resonator switches using electro-optic materials.
- The ring resonator switches are promising devices for their compactness and around 100 GHz operation frequency in our estimation.

Future work

- Electro-optic (EO) materials for Si process available
- Waveguide with EO material core
- Ring resonator switches using EO materials