The Fifth Workshop on Nanoelectronics for Tera-bit Information Processing, 21st Century COE, Hiroshima University

Optical Interconnection in Silicon LSI

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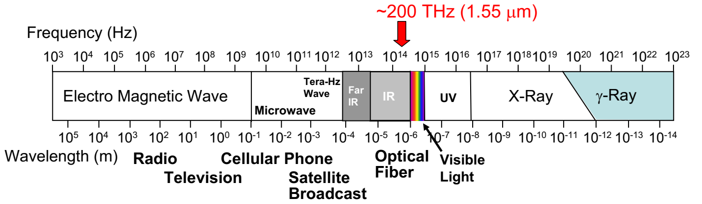
http://www.rcis.hiroshima-u.ac.jp/rcns/

Outline

Why Optical Interconnection? (①Ultra High Frequency)



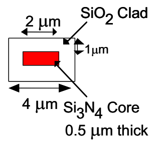
Light (1.55μm) ~100 times as High Frequency as Tera-Hz Wave

Extremely High Information Transmission Capacity>Tera bits/s

Why Optical Interconnection?

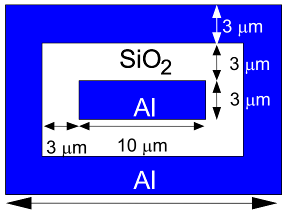
②Small Size

Optical Waveguide



0.6 dB/cm

Coaxial Transmission Line



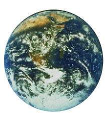
2.4 dB/cm

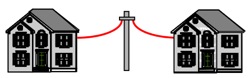
③ Low Power Dissipation

④ No Need of Impedance Matching
etc.

Present Status of Usage of Optical Communication

Submarine Optical Cable

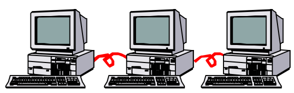




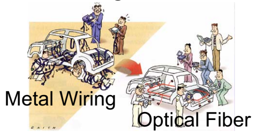
FTTH (Fiber To The Home)

Wiring in Airplane

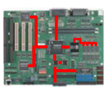
Between Computers



Wiring in Car

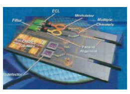


Between Computer Boards



On Board Optical Interconnection (Chip to Chip)

Near Future



On Chip Optical Interconnection

Optical Interconnection is introduced in Cellular Phone

Oct. 1, 2005 Asahi Newspaper

携帯で3D画像もOK

光配線モジュール開発

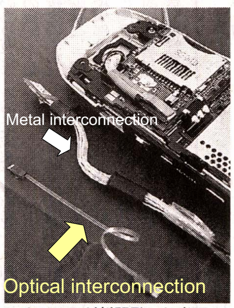
オムロン

オムロンは、携帯電話内部で光で信号をやりとりする「光配線モジュール」を新開発した。従来の電気配線に比べると通信データ量が約50倍になるため、携帯画面で立体（3D）画像を楽しめるほか、内蔵カメラで撮影する動画が格段に鮮明になるという。

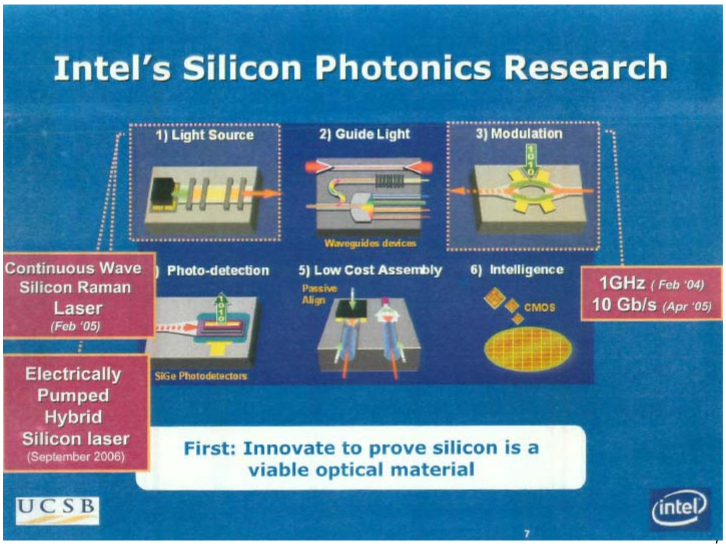
携帯電話の頭脳と言える中央演算処理装置（CPU）が出す電気信号をモジュールの送信部で光信号に変換。この光信号を光配線が液晶パネルなどに高速で伝えるため、通信データ量も大幅に増える。

光信号を通す光配線は幅1ミリで厚さ0・15ミリ。内部に厚さ0・05ミリのアクリル特殊樹脂で出来た、透明な回線を埋め込んでいる。

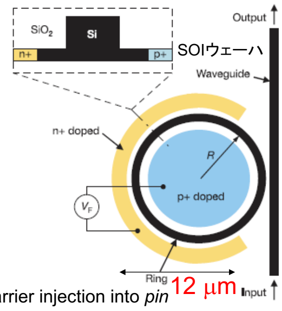
携帯電話は内部の配線が複雑になり、これ以上の機能の高度化が難しくなっていた。



オムロンが新開発した光配線モジュール（手前左）。従来の電気配線（中央）に比べ、薄くて小さい



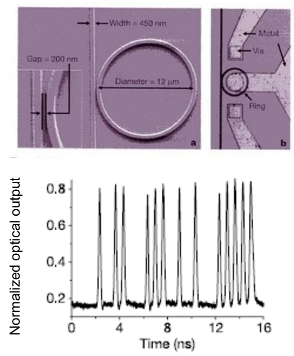
Si Ring Resonator Optical Switch



Carrier injection into *pin* junction causes modulation of refractive index.

⇩

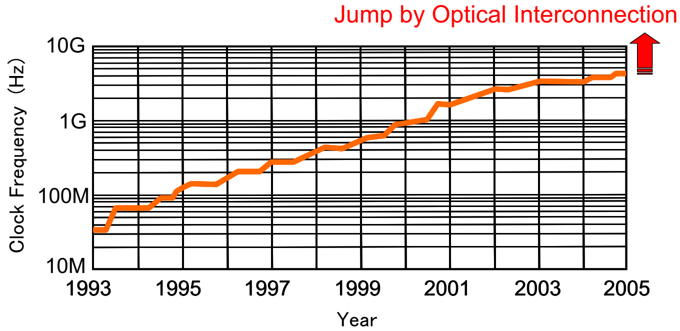
Shift of Resonance Wavelength



Operation at 1.5 Gbit/s

Qianfan Xu *et al*. Cornell Univ. Nature Vol. 435, p. 325 (2005).

Change in Clock Frequency of CPU



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II. Ring Resonator Optical Switches using Electro-Optic (EO) Material (Ba,Sr)TiO_3 (BST)

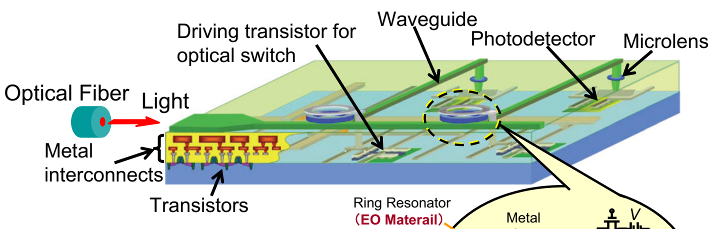
III. Mach-Zehnder Modulator using EO Material

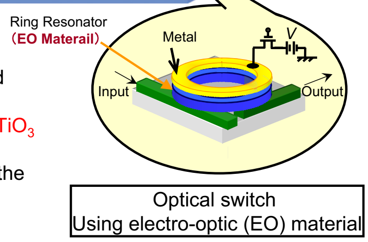
IV. Optical Switches using Magneto-Optic Material

V. Optical Switches using Si Ring Resonator

VI. Summary

Target: Optical Global Interconnection in Si LSI

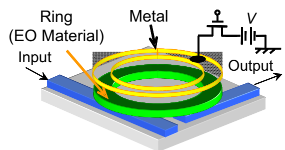




- Ring resonance type switch is used for miniaturization.
- Electro-optic (EO) material (Ba,Sr)TiO_3 (BST) is used for optical switches.
- Optical switches are integrated on the top layer (process temp.<450°C)

Optical switch
Using electro-optic (EO) material

Optical Switches using Ring Resonator



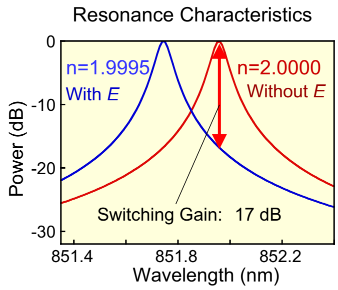
Resonance $\lambda = n_{eff} \frac{2\pi R}{m}$ (m: Integer)

EO Effect

$$\Delta\lambda = 2\pi R \cdot \Delta n_{eff}$$

$$= 2\pi R \left(-\frac{1}{2} n_{eff}^{3} r E\right)$$

(r : EO Coeff., R : Ring Radius, n_{eff} : Ref. Index, E: Electric Field)



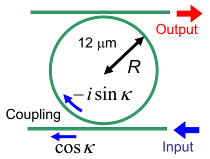
Ring Radius	12 μm
Width of Waveguide	2 μm
Gap	0.1 μm

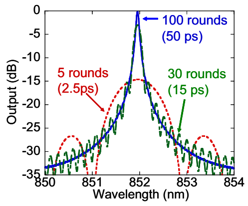
Switching Gain of 17 dB at Δn_{eff}=5x10^{-4}

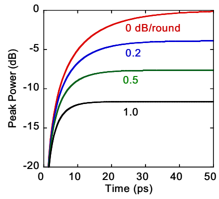
Operation Speed of Ring Resonator Switch

Factors
- Polarization Time of EO Material
- RC Time Constant of Device
- Resonance Time of Ring

- Resonance Time of Ring Model

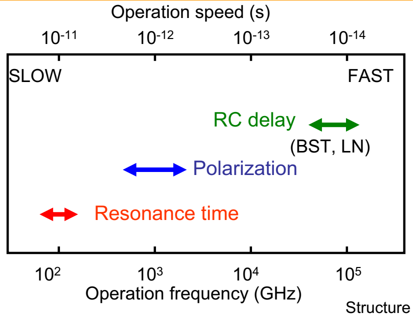






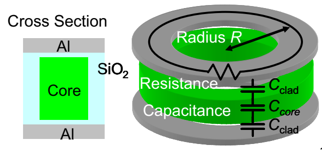
Resonance peak becomes sharp with increasing in round time of the light.

Operation Speed of Ring Switch (cont'd)



Resonance time determines the switching speed.
~ 100 GHz at R=12 μm

Structure used for Calculation



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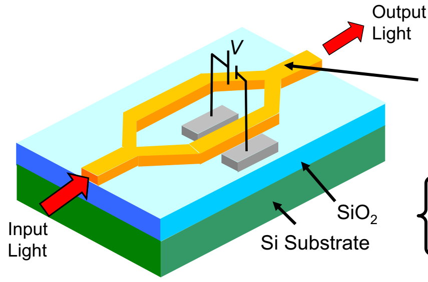
Mach-Zehnder Optical Modulator

Mach-Zehnder Interferometer (MZI)



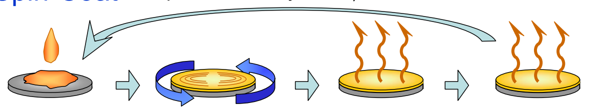
Electro-Optic Material (Ba,Sr)TiO_3 (BST)

Ever Introduced in Si Process

- Spin-Coat
  - Easy Formation
- Sputter
  - Low Temperature
  - Good Crystallinity

(Ba,Sr)TiO_3 Film Formation by Spin-Coat

Spin-Coat Repeat, 80 nm/cycle ⇨ Final Thickness 500 nm

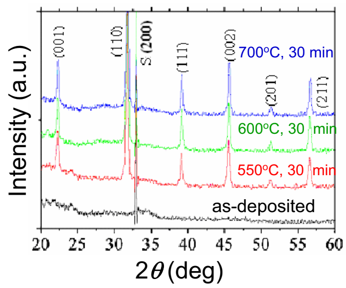


Drop Source Liquid → Rotation 600 rpm, 10 s 2000 rpm, 20 s → Low Temp. Bake 180°C, 10 min → High Temp. Bake 450°C, 30 min

Post Anneal for Crystallization 450~750°C

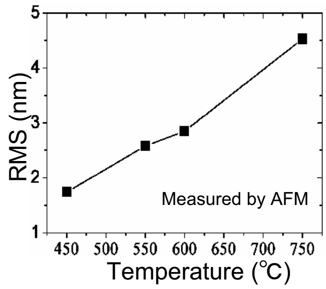
Annealing Behavior

XRD Spectra



Poly-Crystallized at >550 °C

Surface Roughness

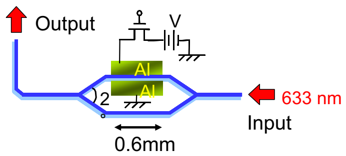


Roughness increases with Temp.

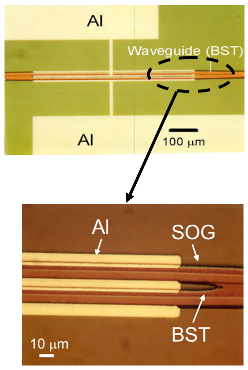
550°C Annealed Film is used.

Fabricated Mach-Zehnder Optical Modulator

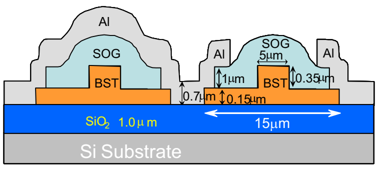
Plan View



Plan View Photograph



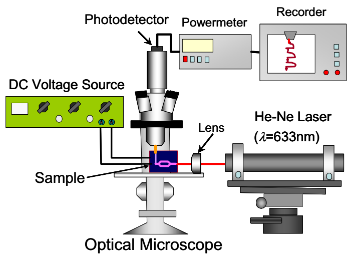
Cross Section

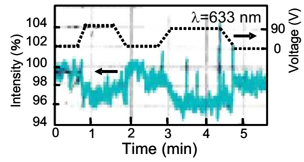


Monolithic Integration on Si Substrate

First Demonstration of Monolithic Optical Modulator using EO Mateiral

Measurement System





Optical Modulation by 2-3% at 90V (E=1.7x10^4 V/cm)

Problem:

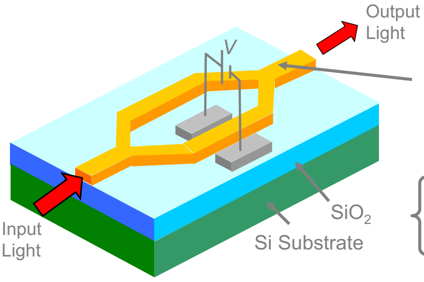
Process Temp. of 550°C ➡ ≤450°C

Too High

Our Group: Zhimou Xu *et al.* Appl. Phys. Lett. Vol. 88 No.16, 161107 (2006).

Mach-Zehnder Optical Modulator

Mach-Zehnder Interferometer (MZI)



Electro-Optic Material

(Ba,Sr)TiO$_3$ (BST)

Ever Introduced in Si Process

Spin-Coat

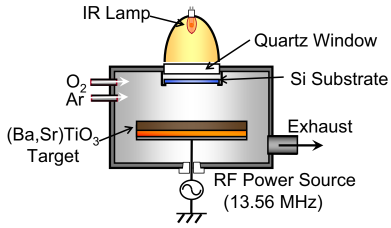
Easy Fabrication

Sputter

Low Temperature

Good Crystallinity

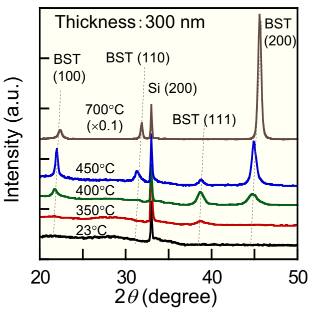
Sputter Deposition of (Ba,Sr)TiO$_3$ Film



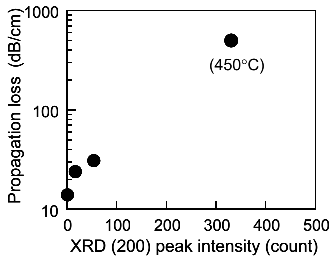
RF Power	50 W
Base Pressure	1.2 x10^{-6} Pa
Sputtering Gas	Ar : O_2= 4 : 1
Pressure	2.0 Pa
Substrate Temperature	23-700°C
Deposition Rate	1.0 nm/min

Crystallinity and Optical Property

XRD Spectra for Sputtered BST



Light Propagation Loss versus Crystallinity

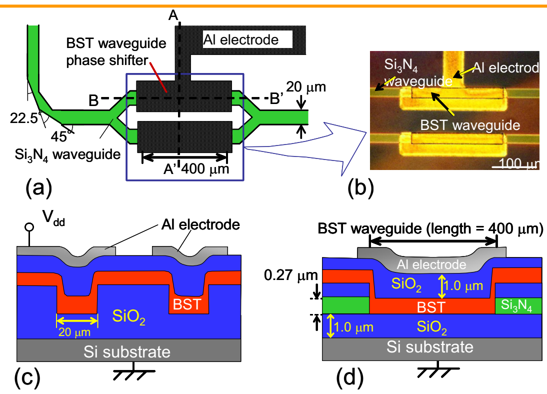


- High Crystallinity causes Loss of Light Propagation

Deposition at 450°C ➡ 470 dB/cm

Acceptable Temp. after Metallization

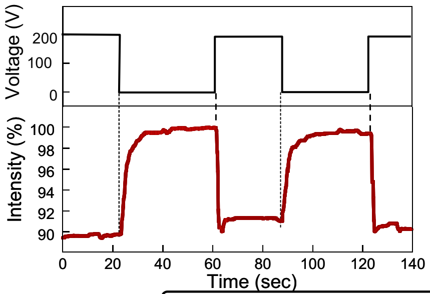
Mach-Zehnder Modulator using Sputtered BST



- Si_3N_4 and BST series connection is used because of high propagation loss of BST.
- Loss of BST phase shifter (400 μm) is ~19dB.

Optical Modulation of Mach-Zehnder Modulator using Sputtered BST

BST Sputtered at 450°C



Device

- Dep. Temp. = 450°C
- Ref. Index of BST = 2.3
- Length of BST WG = 400 μm
- Width of WG = 20 μm
- Thickness of BST= 0.27 μm

Measurement

- Input : He-Ne laser (633 nm)

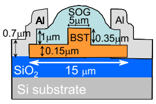
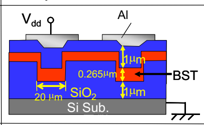
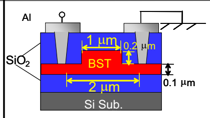
Modulation by ~10% at 200 V (E=1.2x10⁴ V/cm)

Low temperature formation of 450°C, acceptable for the process after metallization.

Various Electro-Optic Materials

Material	Phase	Substrate	EO Coeff.(pm/V)	Method
$LiNbO_3$	Bulk s-Cryst.		30.8	CZ
$KTa_{1-x}Nb_xO_3$	Bulk s-Cryst		600	CZ
$LiNbO_3$	Poly Film	Glass	1.34	RF Sputter (275°C)
$BaTiO_3$	Epi Film	MgO s-Cryst.	22	MOCVD (725°C)
$LiTaO_3$	Poly Film	Glass	0.32	RF Sputter
(Pb,La)(Zr,Ti) O_3	μc Film	ITO	102	Aerosol Dep. (300°C)
(Ba,Sr)TiO_3	Poly Film	Thermal SiO_2	25.2	RF Sputter (450°C)
This Work (Ba,Sr)TiO_3	Poly Film	Thermal SiO_2	5.2	Spin-Coat (550°C annealed)

Sub-Summary and Improvement Plan

	Spin-Coat BST	Sputtered BST	Plan (Sputtered BST)
Device Structure			
Performance Index $V_\pi L$ (V•cm)	60	36	2.7
Distance between Al Electrodes	15 μm	2.27 μm	2.0 μm
EO Coeff. (pm/V)	5.2	25.2	⇦
Dep. Temp.	550 °C	450 °C	⇦

- Al direct contact to BST
- Miniaturization

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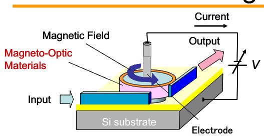
Ring Resonator Optical Switches using Magneto-Optic Material



Low Voltage Operation <0.1 V

$\lambda = n_{eff}\frac{2\pi R}{m}$, $\Delta n \propto k_m H$

- Refractive index for right handed mode: $n+\Delta n$
- Refractive index for left handed mode: $n-\Delta n$

E_R: E of positive circular-polarization wave (right handed mode)

E_L: E of negative circular-polarization wave (left handed mode)

Electric Field

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

Power

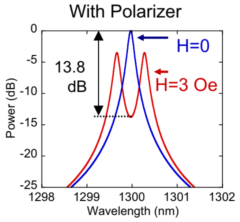
Not Polarized Light

$$P \propto |E_R|^2 + |E_L|^2.$$

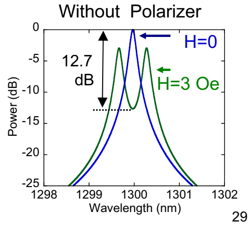
Polarized Light

$$P \propto |E_R + E_L|^2,$$

With Polarizer



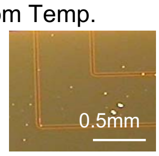
Without Polarizer

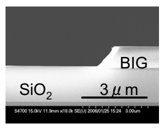


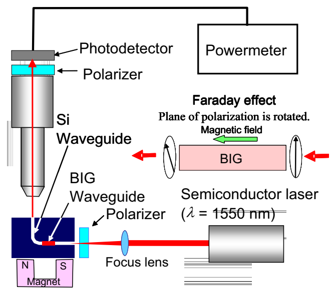
Polarizer is not necessary.

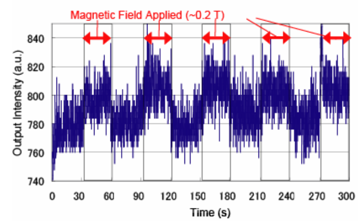
Faraday Effect of Magneto-Optic Material Sputtered $Bi_3Fe_5O_{12}$ (BIG)

Sputtered $Bi_3Fe_5O_{12}$(BIG) at Room Temp. (Amorphous)









~2% modulation is achieved at an external magnetic field of ~0.2T.

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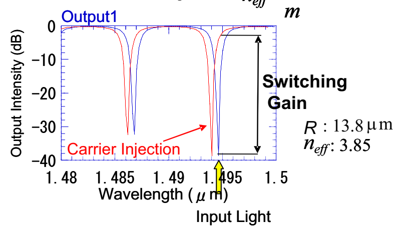
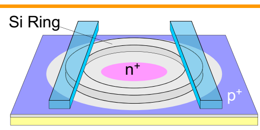
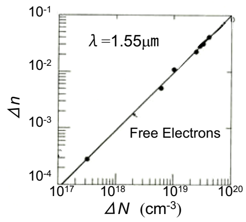
Principle of Si Ring Optical Switch

Resonance Wavelength $\lambda = n_{eff} \frac{2\pi R}{m}$





- Refractive index is changed by carrier injection.
- Stack type optical switch is proposed.



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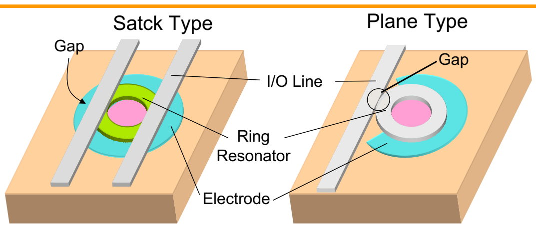
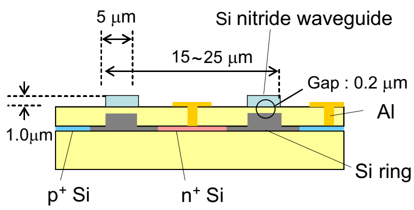
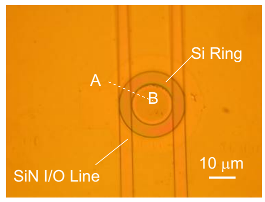
Comparison between Stack and Plane Switch

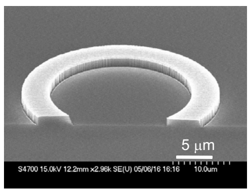


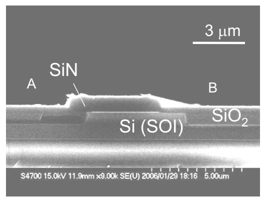
Structure	Stack	Plane
Layers of Ring and I/O	Different	Same
Key Technology	Planarization	Etching
Gap Control	Easy and Precise	Difficult
Process	Complicated	Simple
Electrode	Entire Surrounding	Partially Lack
Modulation Efficiency	Good	——

Fabricated Si Ring Resonator

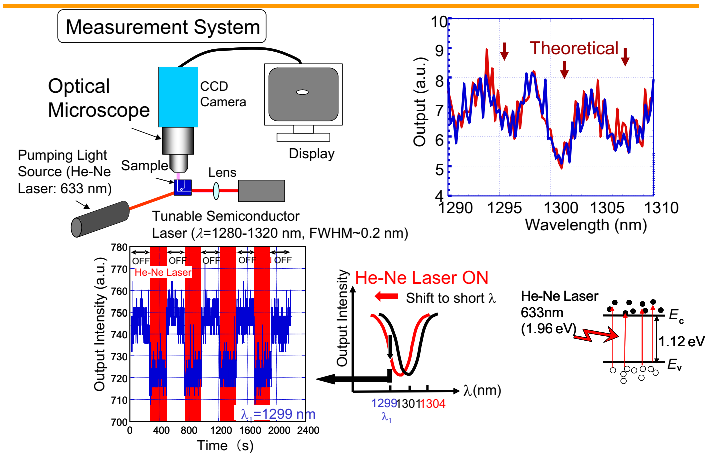








Measurement Results for Si Ring Switches



~3% of modulation is achieved by Si ring resonator optical switch.

Summary

(Ba,Sr)TiO_3 (BST) Optical Switch

- Low temperature (450°C) monolithic fabrication technology was developed.
- Optical modulation of ~10% was achieved by Mach-Zehnder modulator.

$Bi_3Fe_5O_{12}$(BIG) Optical Switch

- Ring switch without polarizer was proposed and the characteristics were simulated.
- Modulation of ~2% was achieved using amorphous BIG film.

Si Optical Switch

- Stack type ring switch was proposed and ~3% modulation was demonstrated by optical pumping.

Next Stage

- Realization of optically interconnected LSI by improving the device properties.