EE 232 Lightwave Devices
Lecture 23: Optical Modulators

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Physical Mechanisms for Optical Modulators

- Electro-optic modulators
  - Nonlinear crystals
  - $LiNbO_3$, GaAs, InP
- Franz-Keldysh effect
  - Sub-bandgap absorption induced by electric field
  - GaAs, InP
- Quantum confined Stark Effect (QCSE)
  - Absorption modulators in quantum wells
  - Mostly III-V, but also SiGe QWs
- Free carriers effect
  - Refractive index change due to electrons/holes
  - All semiconductors, including Si
- Thermo-optic effect
  - Refractive index change due to temperature
  - All semiconductors, including Si

Electro-Optic Effect (Pockels Effect)

$$\frac{x^2}{n_o^2}+\frac{y^2}{n_o^2}+\frac{z^2}{n_e^2}+2r_{41}F_x yz+2r_{52}F_y zx+2r_{63}F_z xy=1$$

Table 12.1 A Few Electrooptic Materials With Their Parameters [1, 4, 6, 9]

Point-Group Symmetry	Material	Refractive Index n_o	n_e	Wavelength $\lambda_0(\mu m)$	Nonzero Electrooptic Coefficients (10^{-12} m / V)
$3m$	$LiNbO_3$	2.297	2.208	0.633	$r_{13}=r_{23}=8.6$, $r_{33}=30.8$ $r_{42}=r_{51}=28$, $r_{22}=3.4$ $r_{12}=r_{61}=-r_{22}$
32	Quartz (SiO_2)	1.544	1.553	0.589	$r_{41}=-r_{52}=0.2$ $r_{62}=r_{21}=-r_{11}=0.93$
$\bar{4}2m$	KH_2PO_4 (KDP)	1.5115 1.5074	1.4698 1.4669	0.546 0.633	$r_{41}=r_{52}=8.77$, $r_{63}=10.3$ $r_{41}=r_{52}=8$, $r_{63}=11$
$\bar{4}2m$	$NH_4H_2PO_4$ (ADP)	1.5266 1.5220	1.4808 1.4773	0.546 0.633	$r_{41}=r_{52}=23.76$, $r_{63}=8.56$ $r_{41}=r_{52}=23.41$, $r_{63}=7.828$
$\bar{4}2m$	KD_2PO_4 (KD*P)	1.5079	1.4683	0.546	$r_{41}=r_{52}=8.8$, $r_{63}=26.8$
$\bar{4}3m$	GaAs	3.60 3.42 3.34	$=n_o$ $=n_o$ $=n_o$	0.9 1.0 10.6	$r_{41}=r_{52}=r_{63}=1.1$ $r_{41}=r_{52}=r_{63}=1.5$ $r_{41}=r_{52}=r_{63}=1.6$
$\bar{4}3m$	InP	3.29 3.20	$=n_o$ $=n_o$	1.06 1.35	$r_{41}=r_{52}=r_{63}=1.45$ $r_{41}=r_{52}=r_{63}=1.3$
$\bar{4}3m$	ZnSe	2.60	$=n_o$	0.633	$r_{41}=r_{52}=r_{63}=2.0$
$\bar{4}3m$	β-ZnS	2.36	$=n_o$	0.6	$r_{41}=r_{52}=r_{63}=2.1$

GaAs Electro-Optic Modulators

$$r=\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\\r_{41}&0&0\\0&r_{52}&0\\0&0&r_{63}\end{bmatrix}$$

Apply electric field in z direction:

$$\frac{x^2}{n_o^2}+\frac{y^2}{n_o^2}+\frac{z^2}{n_e^2}+2r_{63}F_z xy=1$$

$$n_{x'}=n_o+\frac{1}{2}n_o^3 r_{63}F_z$$

$$n_{y'}=n_o-\frac{1}{2}n_o^3 r_{63}F_z$$

For GaAs at 1μm wavelength

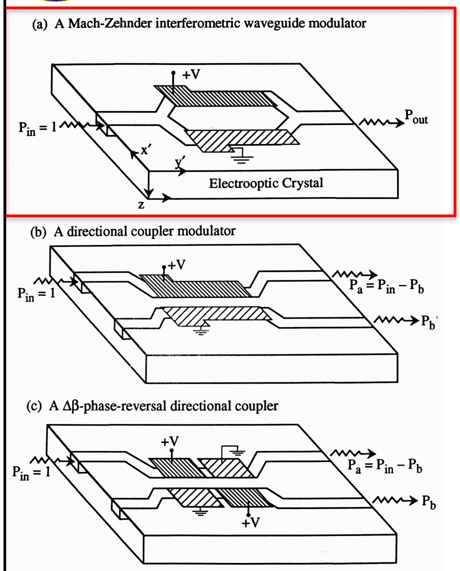
$n_o=3.42$, $r_{41}=r_{52}=r_{63}=1.5\times10^{-12}$ m/V

For applied field of 10^7 V/m

$$\Delta n=\frac{1}{2}n_o^3 r_{63}F_z\approx 3\times10^{-4}$$

Note: Si is central symmetric and has no electro-optic effect

Converting Index Change to Amplitude Change



$$I_o = |E|^2 = \left| \frac{1}{2} E \cdot e^{j\frac{2\pi}{\lambda}(n_o+\Delta n)L} + \frac{1}{2} E \cdot e^{j\frac{2\pi}{\lambda}(n_o-\Delta n)L} \right|^2$$

$$= |E|^2 \frac{1}{2}\left(1+\cos\left(\frac{4\pi\Delta n L}{\lambda}\right)\right)$$

$$= |E|^2 \frac{1}{2}\left(1+\cos\left(\frac{4\pi n_o^3 r_{63} F_z L}{\lambda}\right)\right)$$

$$F_z = \frac{V}{d}$$

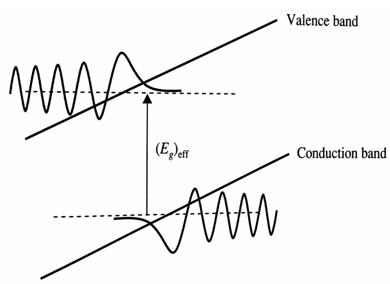
V_π : voltage at π phase shift

$$V_\pi L = \frac{d\lambda}{4 n_o^3 r_{63}}$$

GaAs at 1μm, and assume d of 1μm

$V_\pi L \approx 4$ [V·mm] $\Rightarrow$ Long devices

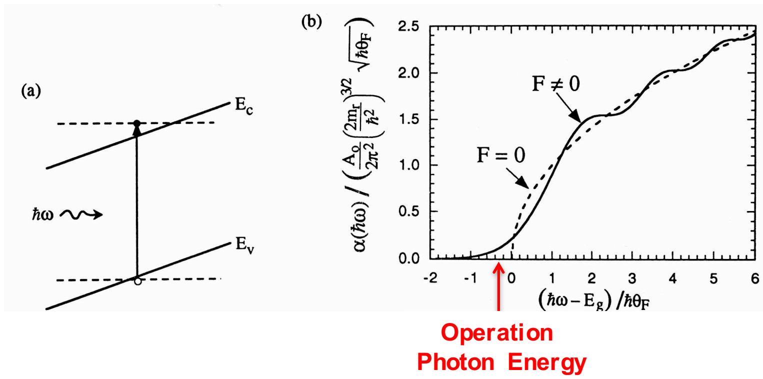
Franz-Keldysh Effect



$$\Delta E_g = \frac{3^{2/3}}{(m^*)^{1/3}} (q\hbar E)^{2/3}$$

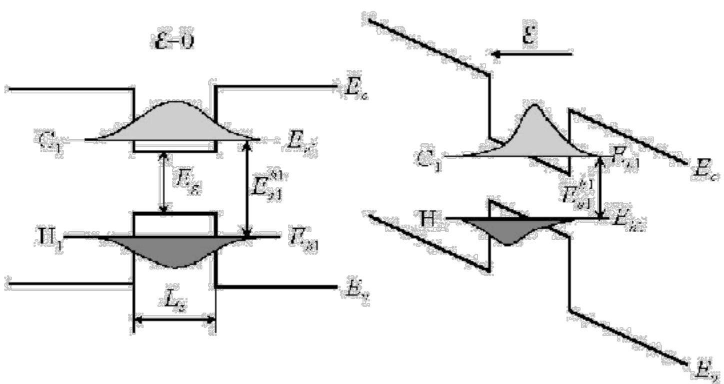
- Under electric field bias, energy bands of electrons are tilted
  - Slope = electric field
- Electron wave functions change from sinusoidal to "Airy" functions
- "Photon-assisted" tunneling
- Effective bandgap becomes smaller
  - Controllable by electric field (voltage)
- Absorption can be modulated by voltage

Absorption Modulator with Franz-Keldysh Effect



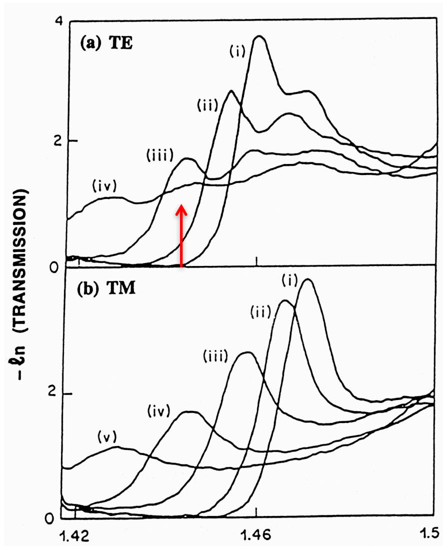
- Absorption edge shifts to lower energy with electric field in direct bandgap semiconductor (e.g., GaAs, InP)
- Absorption up to 1000 cm^{-1}
  - Short devices ~ 100μm

Quantum Confined Stark Effect (QCSE)



- Absorption edge shifts to lower energy with electric field in quantum wells
- Absorption up to 1000 cm^{-1}
  - Short devices ~ 100μm

Experimentally Measured Absorption in Quantum Wells



(i) No field
(ii) 60 kV/cm
(iii) 100 kV/cm
(iv) 150 kV/cm

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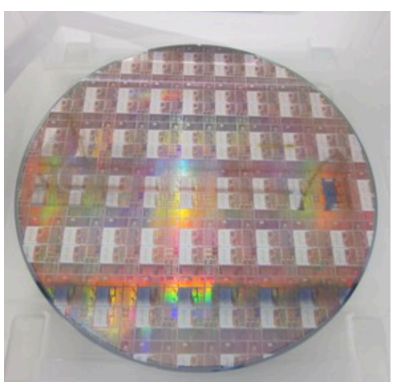
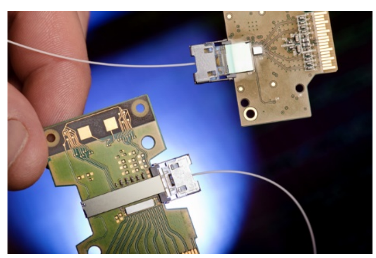
Silicon Photonics



http://www.luxtera.com



http://www.intel.com/pressroo m/

- "Photonics on a silicon chip"
- High density integration
- CMOS process
  - Improved performance
  - Better process control

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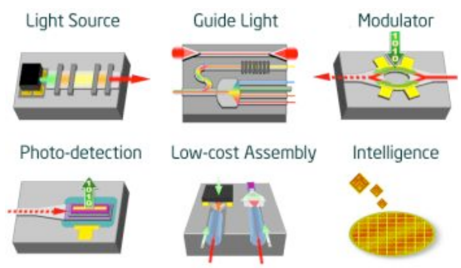
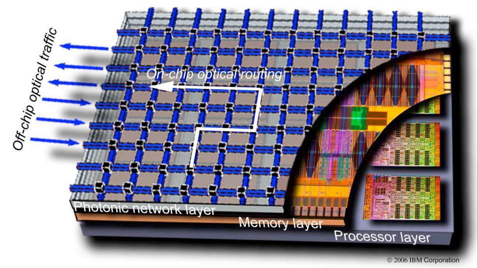
What is Silicon Photonics?

Intel

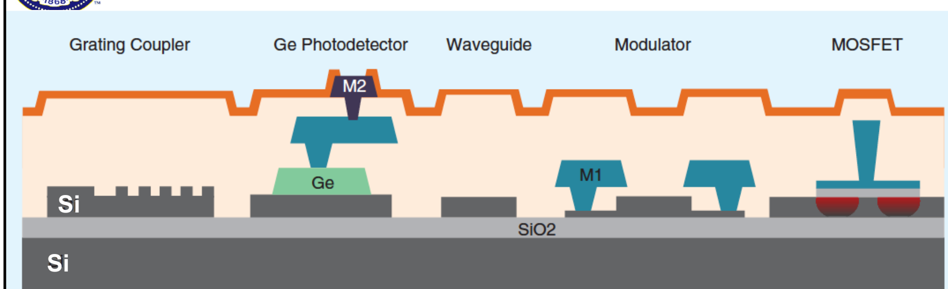


IBM



- Use Si to guide, process, and detect (Ge) light
- Leverage on CMOS fab
- Enable photonics to scale with Moore's Law
- Highly functional chip by integrating photonics with CMOS
- Enhance electronic as well as photonic performance

Most Common Platform: SOI

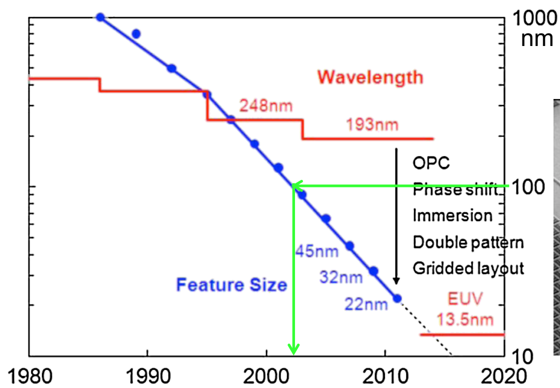


(IME's MWP Process)

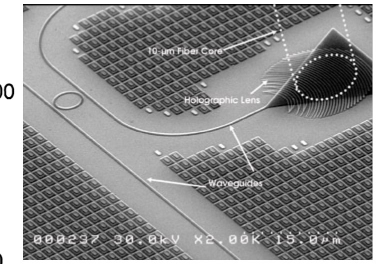
M. Hochberg , et al. *Solid-State Circuits Mag. IEEE*, 2013.

- SOI substrate
  - 220nm Si, 2um BOX
- Si waveguides
- Grating couplers
- Ge detectors
- Si modulators (usually p-i-n)
- Multiple level metals
- (Optional) CMOS

Moore's Law on Lithography



Grating coupler and microring resonator (Luxtera)



Critical feature ~ 100nm

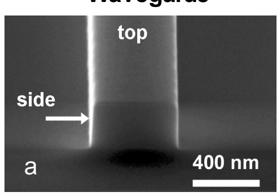
LUXTERA

Luxtera

- Founded in 2001 when lithographic feature size < ¼ wavelength (~ 100nm)
- First Si Photonics company

Properties of Si

Waveguide



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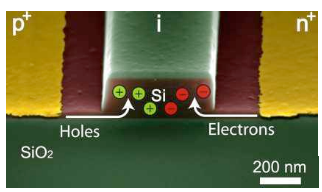
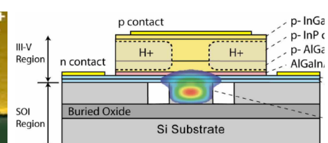
Modulator



IBM

Laser



UCSB / Intel

+ Low loss (~ 0.2 to 2 dB/cm)
+ Tight optical confinement
  - Tiny waveguides (200x500nm^2)
  - Sharp bends (radius ~ μm)

x Indirect bandgap → No Si laser

x Cubic crystal with inversion symmetry → No electro-optic effect

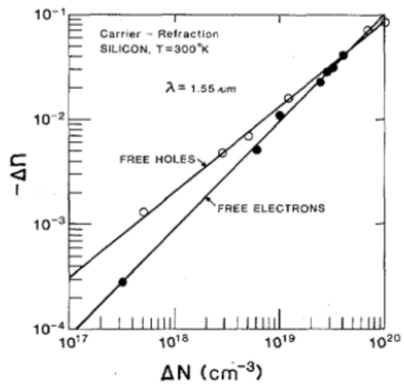
- Optical modulation:
  - Modulating carrier density

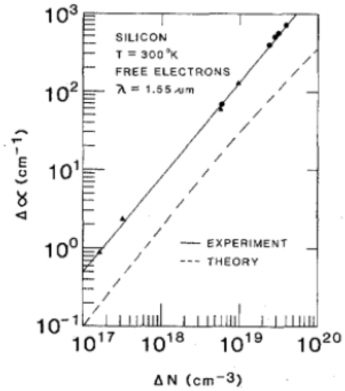
$$\Delta n = -8.8\times10^{-22}\Delta N_e - 8.5\times10^{-18}(\Delta N_h)^{0.8}$$

  - Thermo-optic effect

$$\frac{dn}{dT} = 1.86\times10^{-4}$$

Free-Carrier Effect in Si





At $1.55\mu m$,

$$\Delta n = -8.8\times10^{-22}\Delta N_e - 8.8\times10^{-18}(\Delta N_h)^{0.8}$$

$$\Delta\alpha = 8.5\times10^{-18}\Delta N_e + 6.0\times10^{-18}\Delta N_h$$

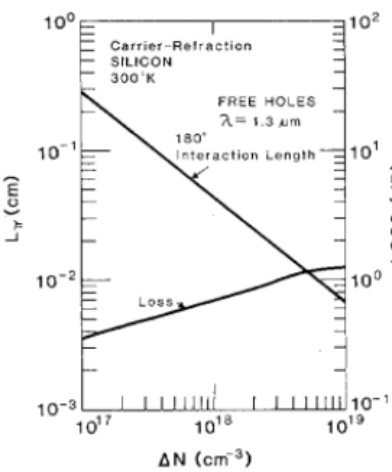
For $\Delta N_e = \Delta N_h = 10^{18}\ \text{cm}^{-3}$

$\Delta n \approx -0.003$

$\Delta\alpha \approx 14.5\ \text{cm}^{-1}$

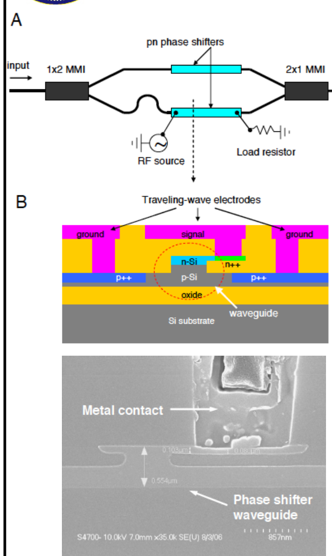
R. A. Soref and B. R. Bennett, "Electrooptical effects in silicon," IEEE Journal of Quantum Electronics, vol. 23, no. 1, pp. 123–129, Jan. 1987.

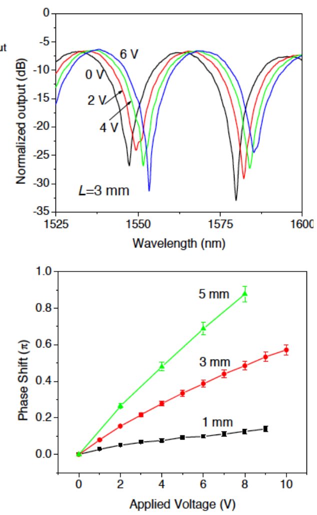
Free-Carrier Effect in Si



- **Index change due to free carrier plasma effect**
- **Index change is small ~ 10^{-3}**
- **Fundamental trade-off between index change and loss**
- **Carriers can be changed relatively fast**
- **→ Data modulators up to 50Gb/s**
- **Modulator length is relatively long**
  - **Need traveling wave electrode/amplifier**

Si Mach-Zehnder Modulator





- 3mm long
- 7dB on-chip loss
- Asymmetric MZI
  → need to match laser/modulator wavelengths
- Vpi-L = 4 V-cm
- 20 GHz bandwidth

A. Liu, L. Liao, D. Rubin, H. Nguyen, B. Ciftcioglu, Y. Chetrit, N. Izhaky, and M. Paniccia, "High-speed optical modulation based on carrier depletion in a silicon waveguide," Opt. Express, vol. 15, no. 2, pp. 660–668, Jan. 2007.

Si Mach-Zehnder Modulators

Table 1. , Performance comparison of previously reported high-speed silicon MZMs (>25 Gb/s) and devices in this work.

Reference	[17]	[15]	[25]	[27]	[24]	[26]&	L = 2 mm	L = 4 mm	L = 6 mm
Device length (mm)%	1	0.12	1.35	1	3.5	2.4	2	4	6
$V_\pi \cdot L$ (V-cm)	4	0.5	11	2.8	2.7	2.4	2.4	2.08	1.86
V_π (V) *	NA	NA	NA	NA	~8	10	12	5.2	3.1
Insertion loss (dB)#	4	2.5	15	3.7	15	4.3	4.1	6.6	9.0
Speed (Gb/s)	40	25	40	50	40	30	~50	~40	30

% Device length: the phase shifter length rather than the whole device length.

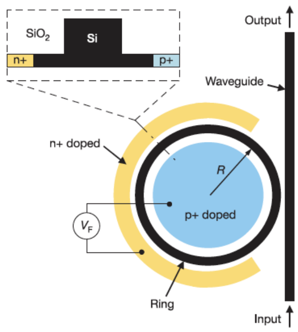
* V_π under dc. NA represents that the phase shifter is too short and a π-phase shift may not be achievable before breakdown voltage.

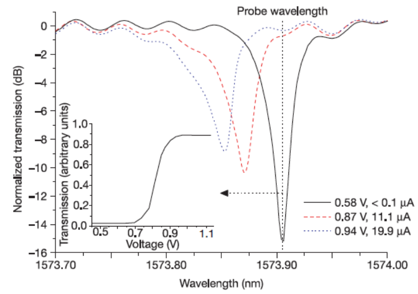
Insertion loss is defined as the on-chip loss for the wavelength at maximum transmission of the MZMs.

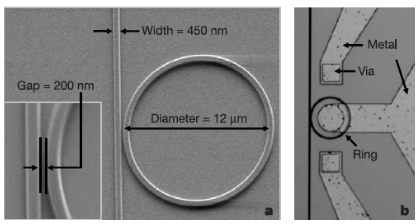
&Devices in [26] and in this work are single-drive push-pull MZMs, while the rest are not.

P. Dong, L. Chen, and Y. Chen, "High-speed low-voltage single-drive push-pull silicon Mach-Zehnder modulators," Optics Express, vol. 20, no. 6, p. 6163, Mar. 2012.

Microring Modulator



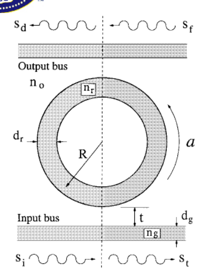


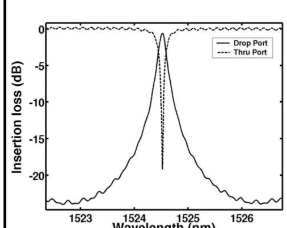


- Use resonance in microring to enhance the modulation
- Reduce modulator size from millimeters to tens of microns
- Enhanced modulation efficiency
- Reduced bandwidth
- Must match laser/resonator wavelengths

Q. Xu, B. Schmidt, S. Pradhan, and M. Lipson, "Micrometre-scale silicon electro-optic modulator," Nature, vol. 435, no. 7040, pp. 325–327, May 2005.

Basic Physics of Miroring Resonator





$$s_t = \frac{j(\omega-\omega_0)+\frac{1}{\tau}-\frac{2}{\tau_e}}{j(\omega-\omega_0)+\frac{1}{\tau}} s_i$$

$$|s_t|^2 = \frac{(\omega-\omega_0)^2+\left(\frac{1}{\tau}-\frac{2}{\tau_e}\right)^2}{(\omega-\omega_0)^2+\left(\frac{1}{\tau}\right)^2}$$

$$|s_d|^2 = |s_i|^2-|s_t|^2 = \frac{\frac{4}{\tau_e^2}}{(\omega-\omega_0)^2+\left(\frac{1}{\tau}\right)^2}$$

$$\frac{1}{\tau}=\frac{1}{\tau_l}+\frac{1}{\tau_e}+\frac{1}{\tau_d}$$

$\frac{1}{\tau_l}$: intrinsic loss

$\frac{1}{\tau_e}$: coupling to transmission

$\frac{1}{\tau_d}$: coupling to output (drop)

Critical Coupling:

$$\frac{1}{\tau_e}=\frac{1}{\tau_l}+\frac{1}{\tau_d}$$

B. E. Little, S. T. Chu, H. A. Haus, J. Foresi, and J.-P. Laine, "Microring resonator channel dropping filters," Journal of Lightwave Technology, vol. 15, no. 6, pp. 998–1005, Jun. 1997.

Thermo-Optic Effect in Si

Experimentally measured data at 1.55μm:

$$\frac{dn}{dT} = 9.48\times10^{-5} + 3.47\times10^{-7}T - 1.49\times10^{-10}T^2$$

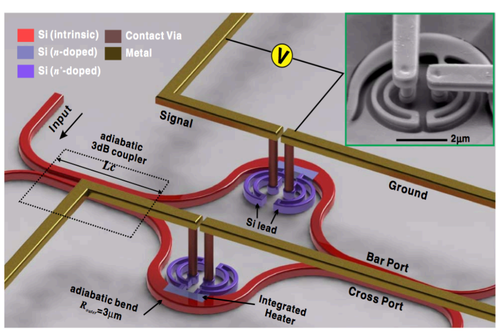
At 300K, $\frac{dn}{dT} \approx 1.86\times10^{-4}\ \mathrm{K}^{-1}$

With ΔT of 270K, $\Delta n \approx 0.05$

Corresponding length for π phase shift is 15.5μm

- **Index change due to (1) thermal expansion, (2) bandgap energy reduction with temperature**
- **Relatively strong compared with carrier effect**
- **Low optical loss introduced by heating**
- **Usually slow, limited by thermal RC time. Modulation time is on the order of milliseconds. For small structures, it could approach microsecond response time.**
- **Too slow for modulators, but often used in tunable filters, switches.**
- **High power consumption**

Thermo-Optic Effect in Silicon



M. R. Watts, et al., Optics Letters, 2013

- **Si thermo-optic coefficient**
  - **dn/dT = 1.86×10^{-4}**
- **For $\Delta T \approx 500^\circ$ C**
  - **$\Delta n \approx 3\%$, $L_\pi \approx 10$ um**
- **Steady power consumption**
  - **$P_\pi \approx 10$ mW**

Fabry-Perot Resonator

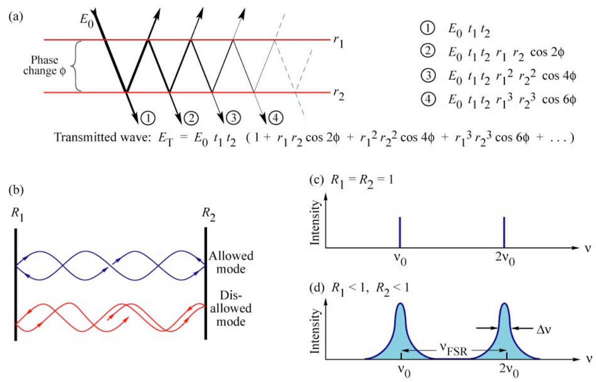


Fig. 14.1. (a) Transmission of a light wave with electric field amplitude E_0 through a Fabry–Perot resonator. (b) Schematic illustration of allowed and disallowed optical modes in a Fabry–Perot cavity consisting of two coplanar reflectors. Optical mode density for a resonator with (c) no mirror losses ($R_1 = R_2 = 100$ %) and (d) mirror losses.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

$$T = \frac{(1-R)^2}{1+R^2-2R\cos(\Delta\phi)}$$

$$\Delta\phi = 2\beta d = \frac{4\pi n_{eff} d}{\lambda}$$