UCSB

High speed modulation of hybrid silicon evanescent lasers

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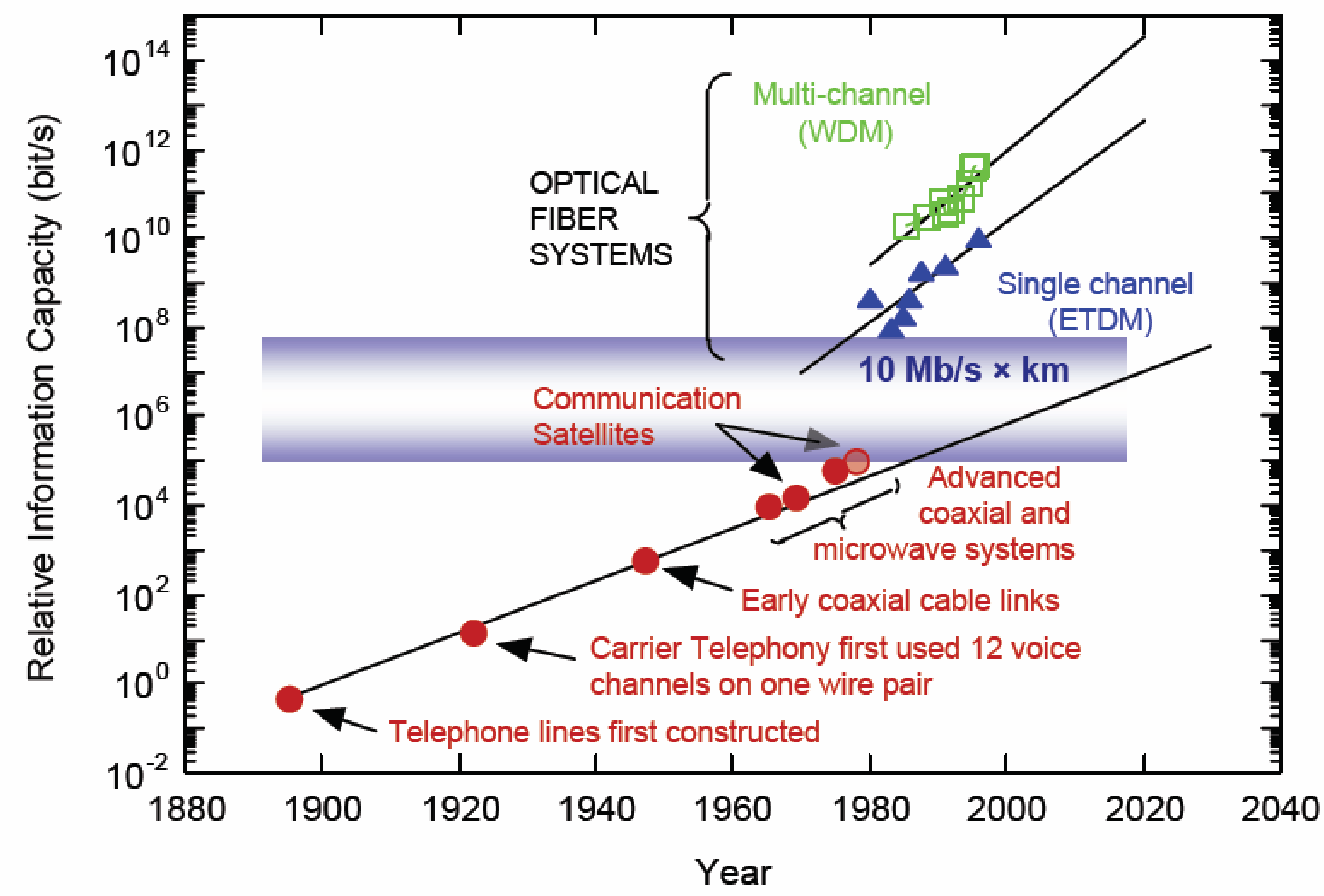
Outline

- Background & motivation
- Silicon light emission
- Silicon modulators
- τ_p modulation
- Two structures for τ_p modulation
  - Loss modulation
  - Mach-Zehnder coupled ring cavity
- Summary & conclusion.

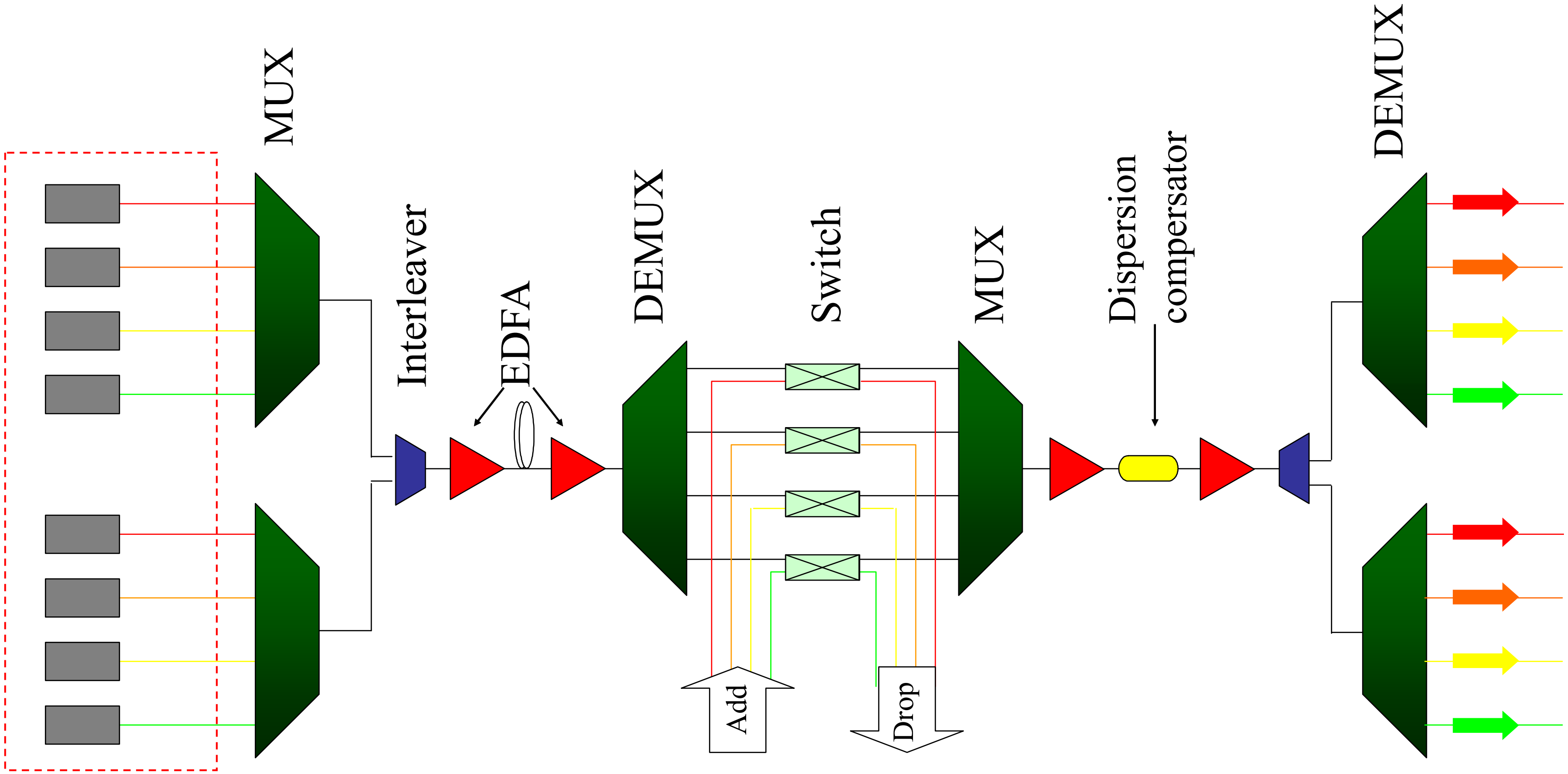
Background & motivation

Higher Capacity Required



http://www.signallake.com/innovation/MicrophotonicsCommRoadmap2005.pdf

Long-distance DWDM system



High Speed Optical Transmitter

Optical communications

Long-haul

Last mile

Short-distance
Fiber to the home

Optical interconnect

Ultra-short distance

overcoming communications bottlenecks.

Optical interconnect

Silicon photonics has many advantages for chip-to-chip and intra-chip communication

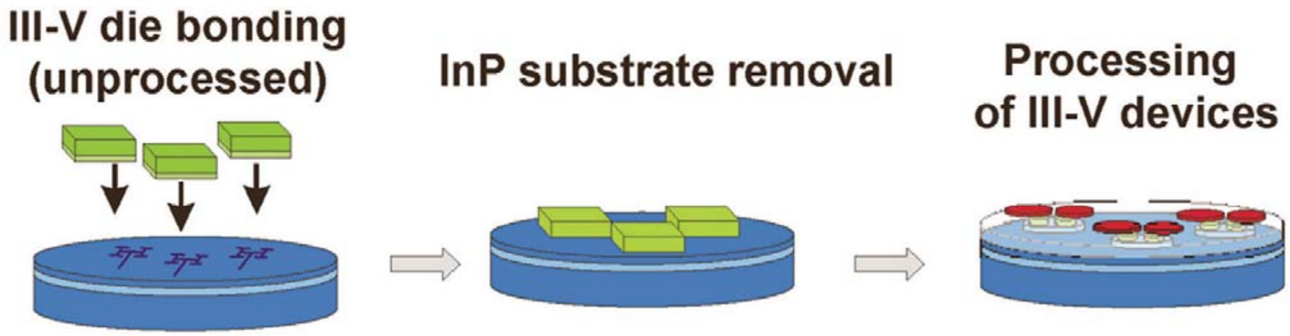
The advantages:

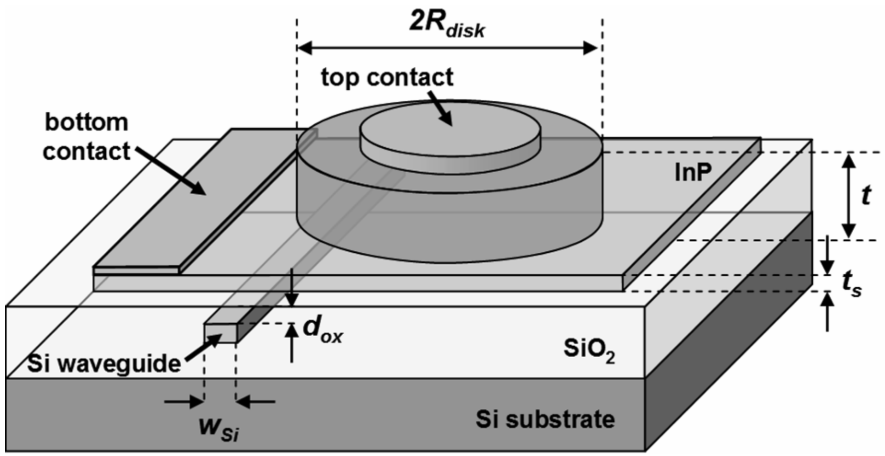
- Large transparent window (1.1~4μm)
- Low loss (~0.1dB/cm)
- Process compatibility with CMOS
- Integrate photonics and electronics on the same chip
- Minimized footprint due to the ultrahigh index contrast of SOI nanowires (R~2μm): very attractive for ultrasmall passive components, (AWG, microring …)

How to make a laser on silicon?

- Nanocrystals (Pavesi L, *Nature.* 408, 440, 2000)
- Si/SiO_2 superlattices (Lockwood D, *PRL.* 76, 539, 1996)
- Erbium-doped silicon-rich oxides (Kik PG, *APL.* 76, 2325, 2000)
- Si/SiGe quantum cascade structures (Dehlinger G, *Science.* 290, 2277, 2000)
- Optically pumped Raman lasers (Rong HS, *Nature* 433 292, 2005)
- Hybrid III-V silicon laser
  - UCSB (H. Park, et al. Opt. Expr. 13, 9460, 2005)
  - Intel (M. N. Sysak, et al. Opt. Expr. 16: 12478, 2008)
  - Ghent Univ (G. Roelkens, et al. Opt. Expr. 14: 8154-8159, 2006)
  - Tokyo Univ (Hiroshi Wada, et al. IEEE JSTQE. 3: 937, 1997).

Hybrid III-V silicon laser

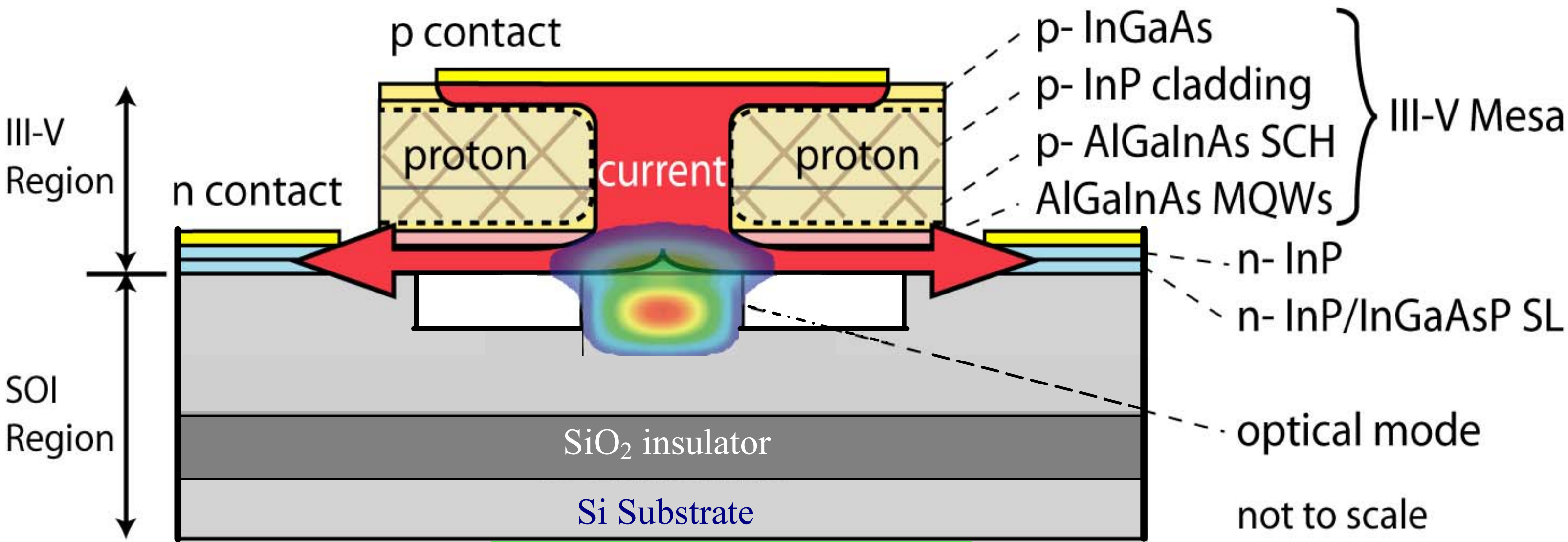


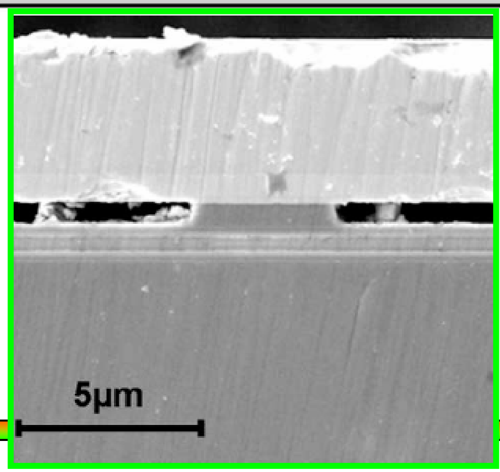


III-V/Si photonics by die-to-wafer bonding (Roel Baets, Ghent Univ)

Hybrid III-V silicon laser structure

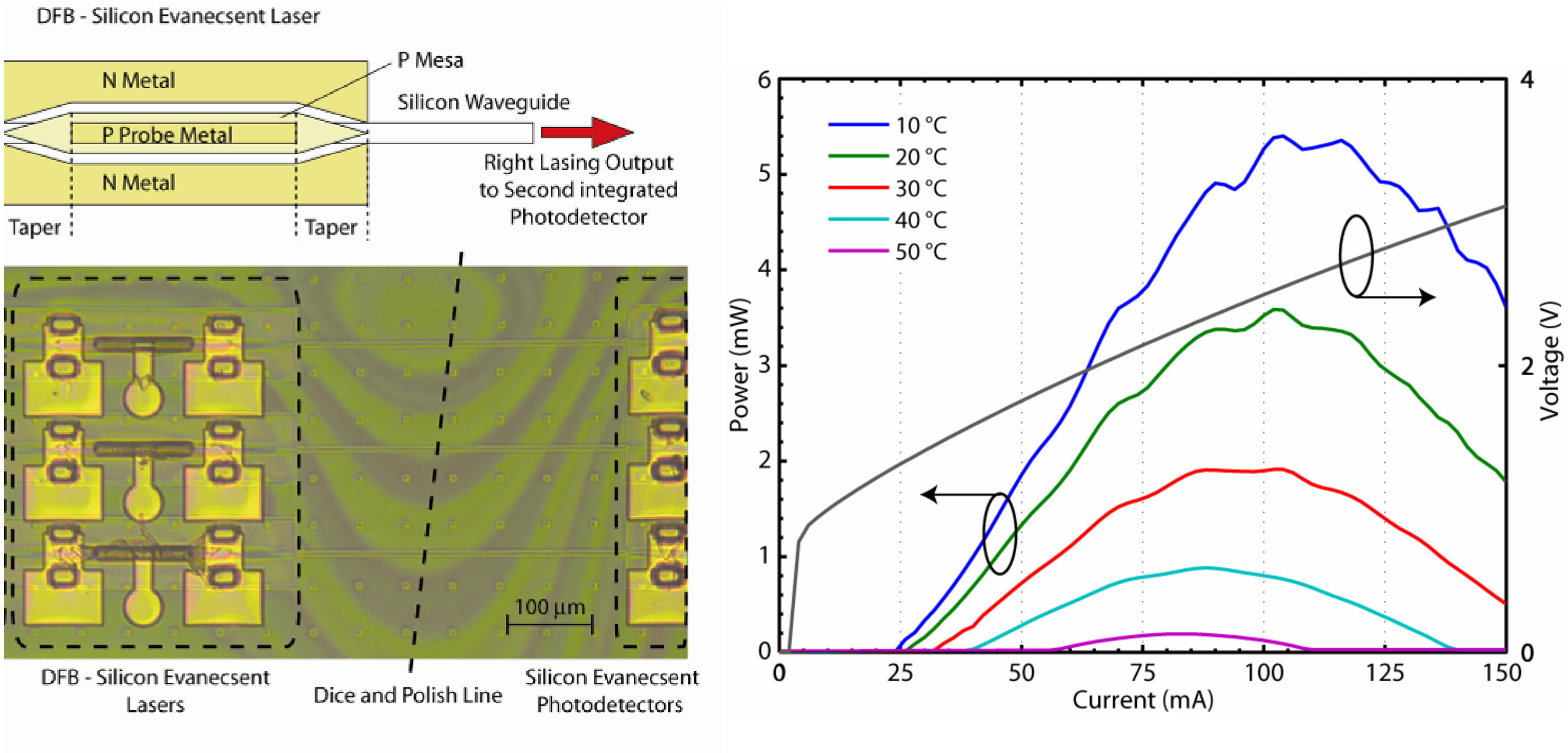
UCSB and Intel



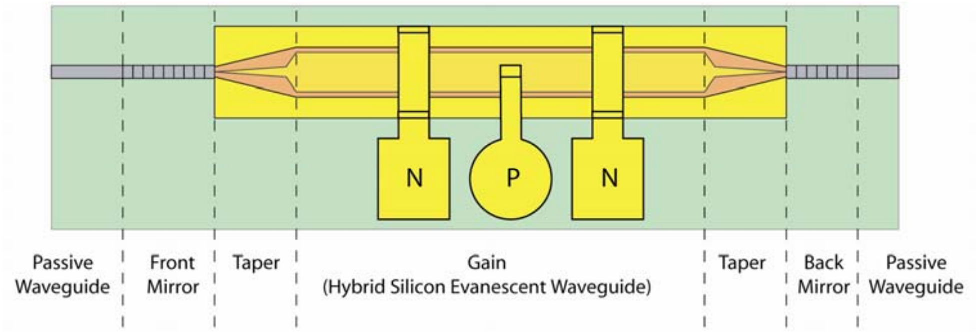


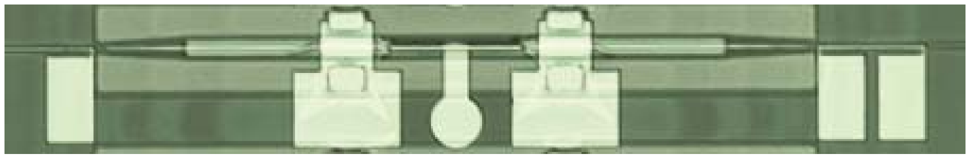
- Self-alignment.

The L-I-V characteristics of DFB-SEL

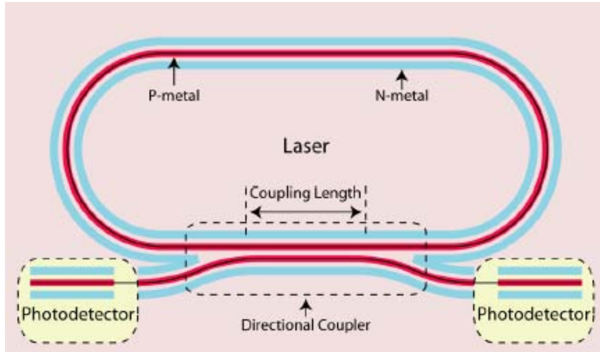


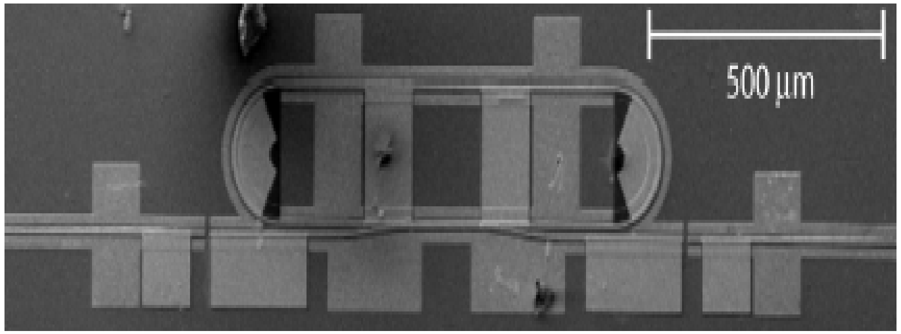
Hybrid III-V silicon laser structure





DBR laser.
AW Fang, et al. JSTQE, 15(3): 535, 2009.





Ring laser.
AW Fang, et al. Opt. Expr. 15(5): 2315, 2007.

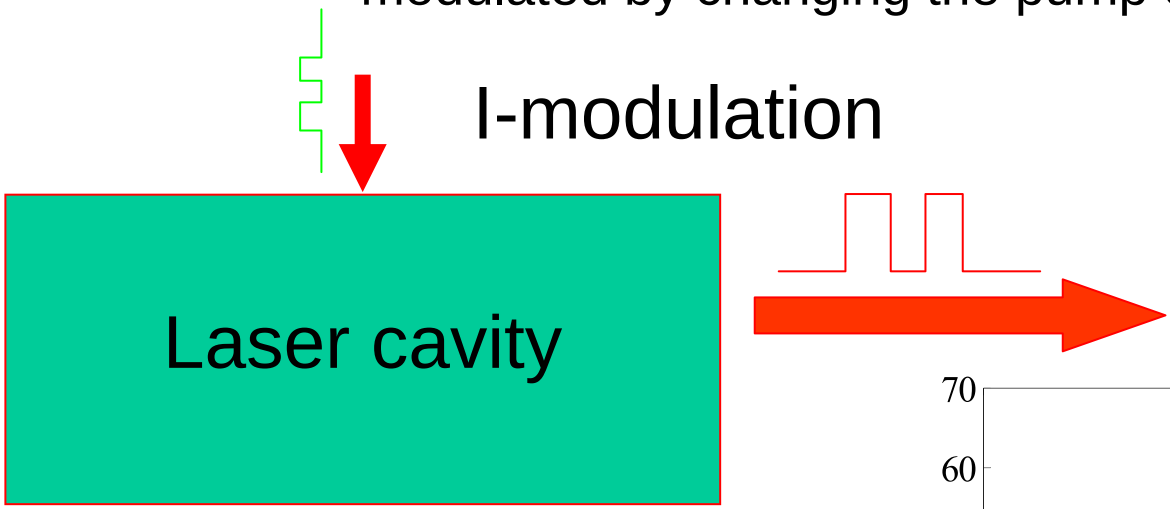
Modulation in optical transmitters

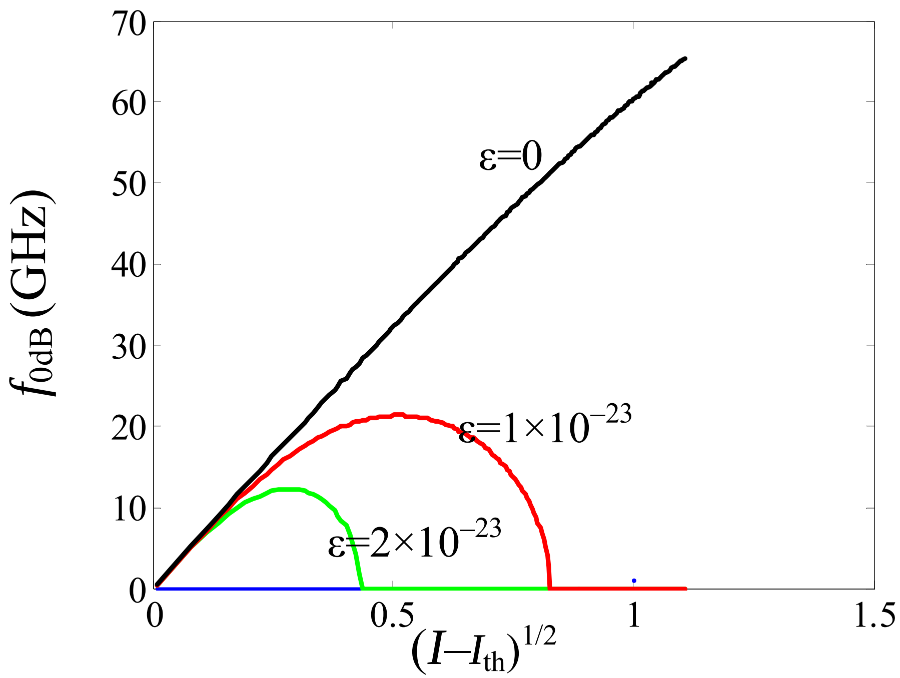
Two ways:

- – Direct-Modulation
- – External-Modulation

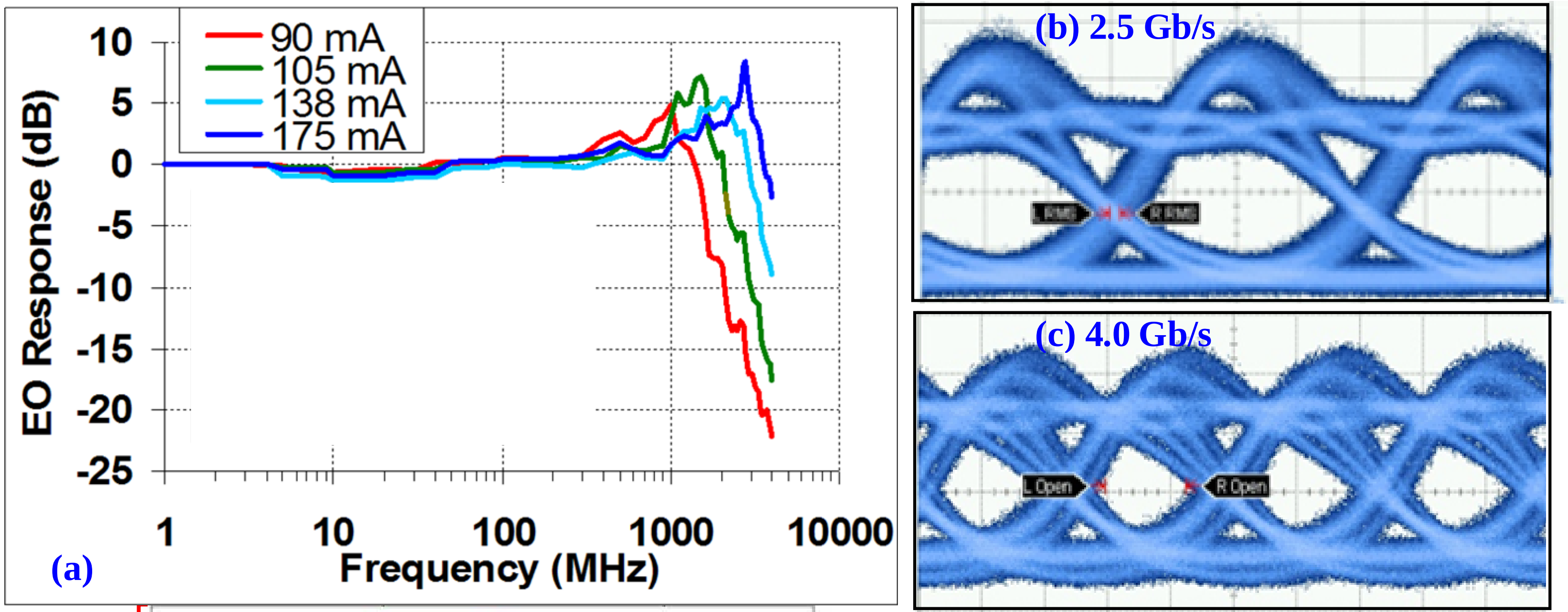
Direct-Modulation

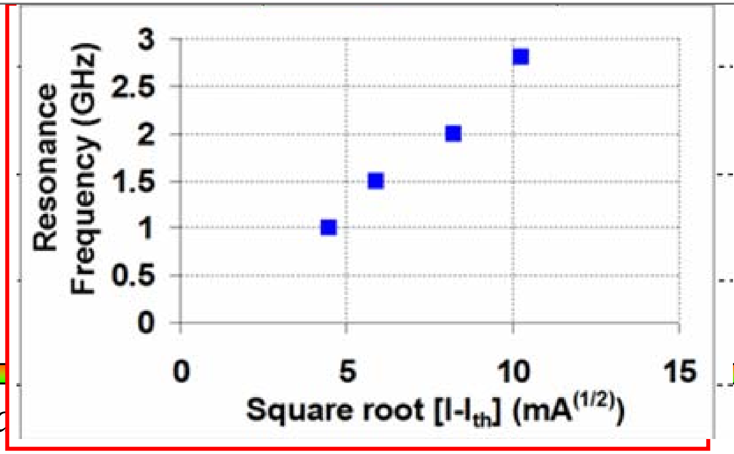
modulated by changing the pump current directly





Direct-modulation of the DFB-hybrid silicon laser

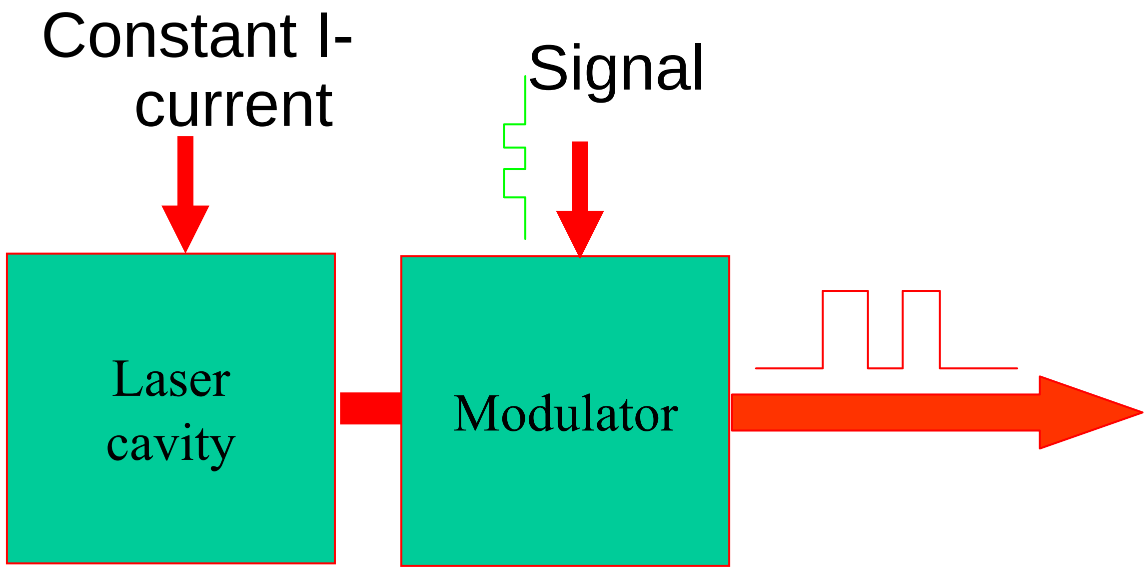




AW Fang, et al. JSTQE, 15(3): 535, 2009.

External-Modulation

modulated by an external modulator



e.g., using directional Couplers, MZI, EAM, etc…

Low chirp, high speed.

Silicon optical modulators

(1) MZ silicon modulator

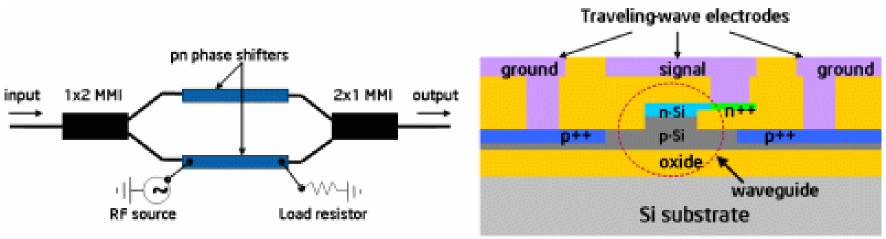
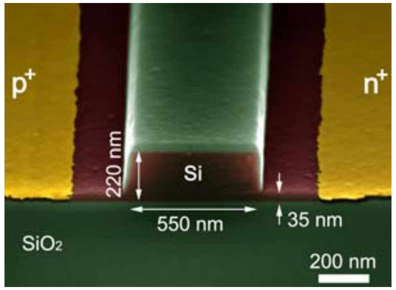


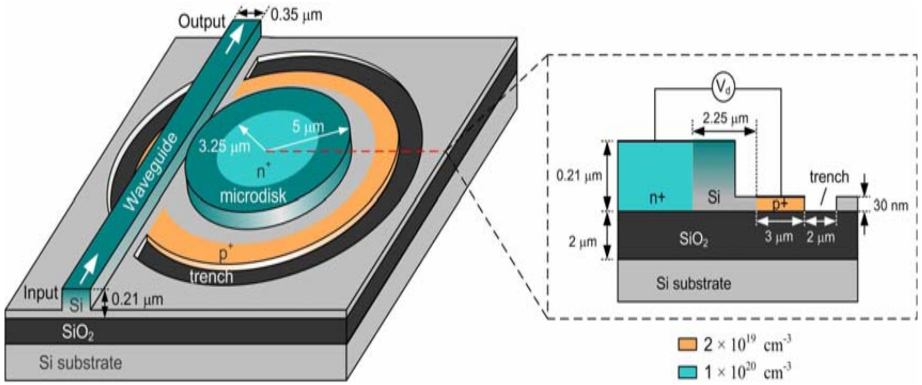
Figure 1a Figure 1b

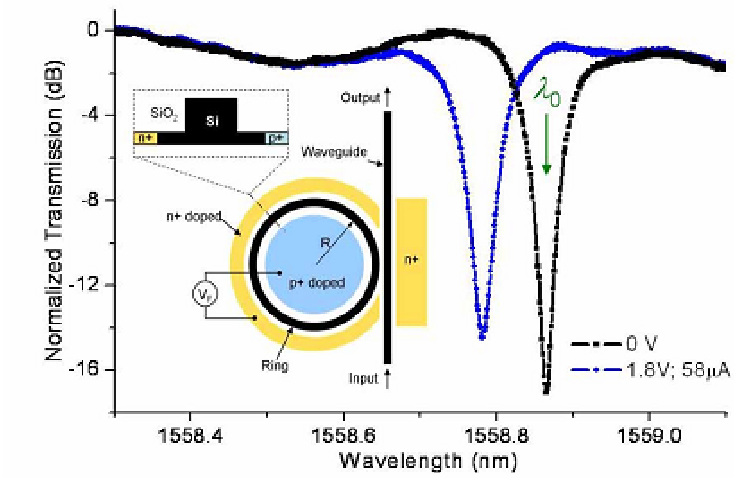


Intel. A. Liu. 40Gbps (L>1mm)

IBM. W. Green. 10Gbps (L>100um)

(2) Microring/disk modulator

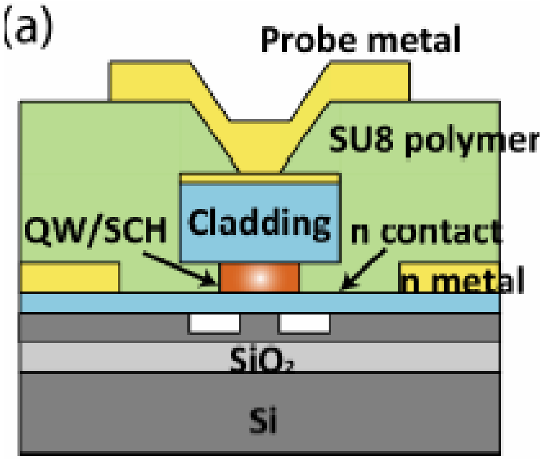




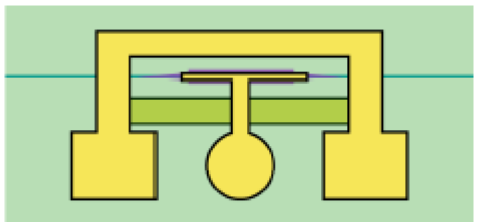
HKUST. A. Poon. 0.5 Gb/s

Cornel Univ. M. Lipson. 12.5Gpbs

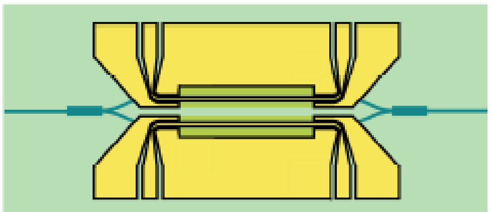
External modulator



Cross section

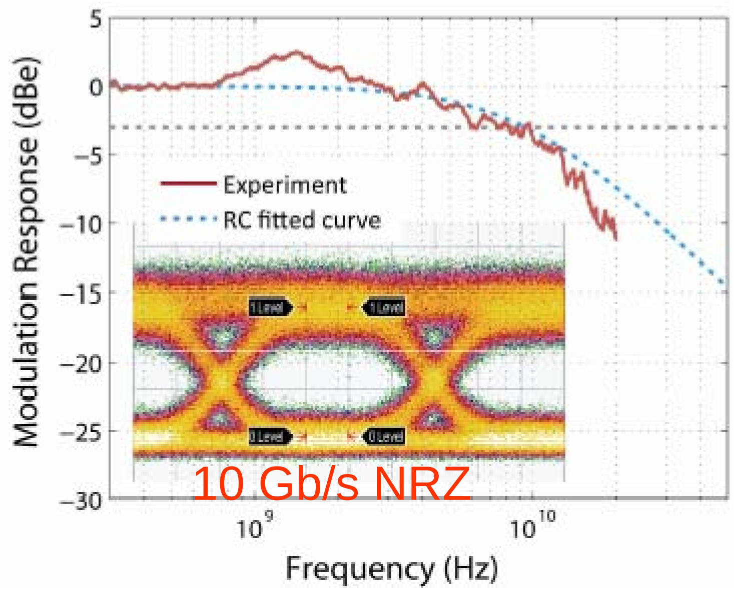


←EAM



←MZM

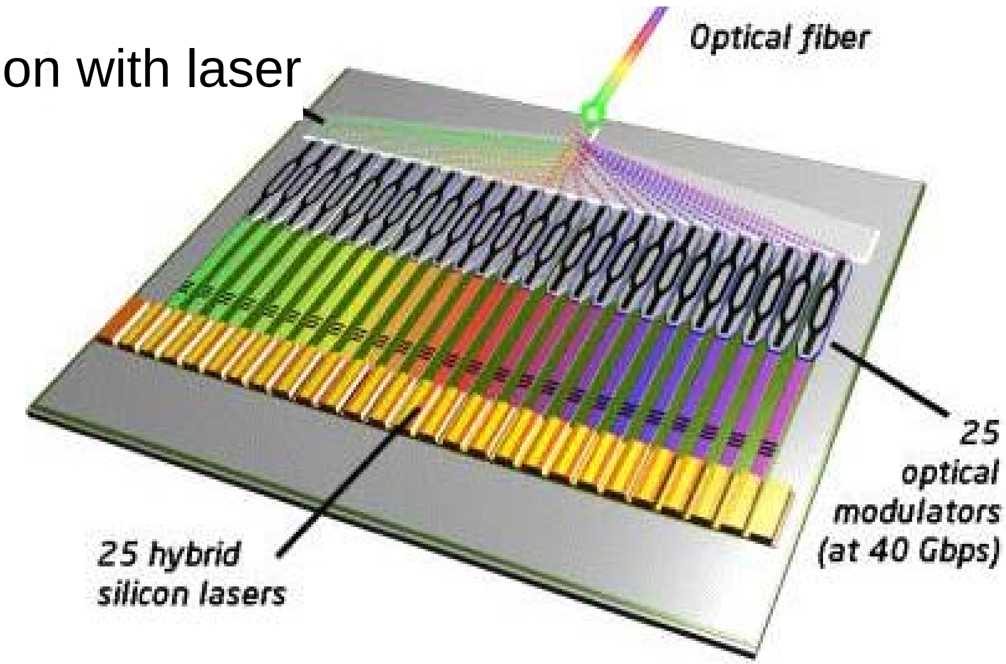
MZM: utilizes carrier depletion within AlGaInAs quantum wells



H. Chen, Y. Kuo, J. E. Bowers.
Opt. Expr. 16: 20571, 2008.
PTL. 20: 1920, 2008.

- Drawbacks of Direct modulation:
  - Large frequency chirp
  - Small modulation bandwidth

- Drawbacks of external modulation:
  - Large size
  - Difficult integration with laser



Increasing the modulation speed of hybrid silicon lasers

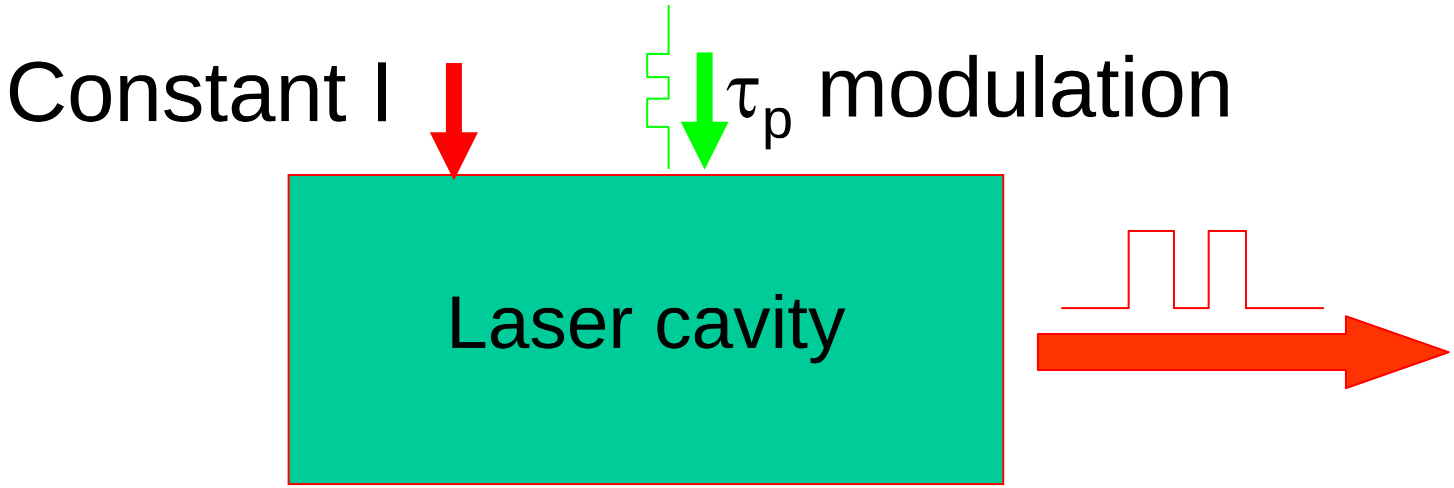
"τ_p-modulated laser"

$$\begin{cases} \dfrac{dN}{dt} = -\dfrac{g_0(N-N_t)S}{1+\varepsilon S} + \dfrac{I}{qV} - \dfrac{N}{\tau_n}, \\ \dfrac{dS}{dt} = \dfrac{\Gamma g_0(N-N_t)S}{1+\varepsilon S} - \dfrac{S}{\boxed{\tau_p}} + \dfrac{\beta\Gamma N}{\tau_n} \end{cases}$$

Distribution loss

$$\boxed{\frac{1}{\tau_p} = v_g(\bar{\alpha} + \frac{1}{l}\ln\frac{1}{R})}$$

reflectivity



Small-signal modeling

$$\frac{1}{\tau_p} = \frac{1}{\tau_{p_0}} + \frac{1}{\tilde{\tau}_p} e^{j\omega t}$$

$$N = N_0 + n e^{j\omega t},$$

$$S = S_0 + s e^{j\omega t}$$

$$\frac{1}{\tilde{\tau}_p} << \frac{1}{\tau_{p_0}}$$

$$n << N_0,$$

$$s << S_0,$$

$$s = \frac{S_0 (j\omega + B) \frac{1}{\tilde{\tau}_p}}{-\omega^2 + j\omega(A+B) + AB + CD}$$

$$n = -g_0 \frac{N_0 - N_t}{(1+\varepsilon S_0)^2} \frac{1}{j\omega + g_0 \frac{S_0}{1+\varepsilon S_0} + \frac{1}{\tau_n}} s$$

$$A = \left(\frac{1}{\tau_p} - \Gamma g_0 \frac{N_0 - N_t}{(1+\varepsilon S_0)^2}\right), \qquad B = \left(g_0 \frac{S_0}{1+\varepsilon S_0} + \frac{1}{\tau_n}\right)$$

$$C = g_0 \frac{N_0 - N_t}{(1+\varepsilon S_0)^2}, \qquad D = \left(\Gamma g_0 \frac{S_0}{1+\varepsilon S_0} + \frac{\beta\Gamma}{\tau_n}\right)$$

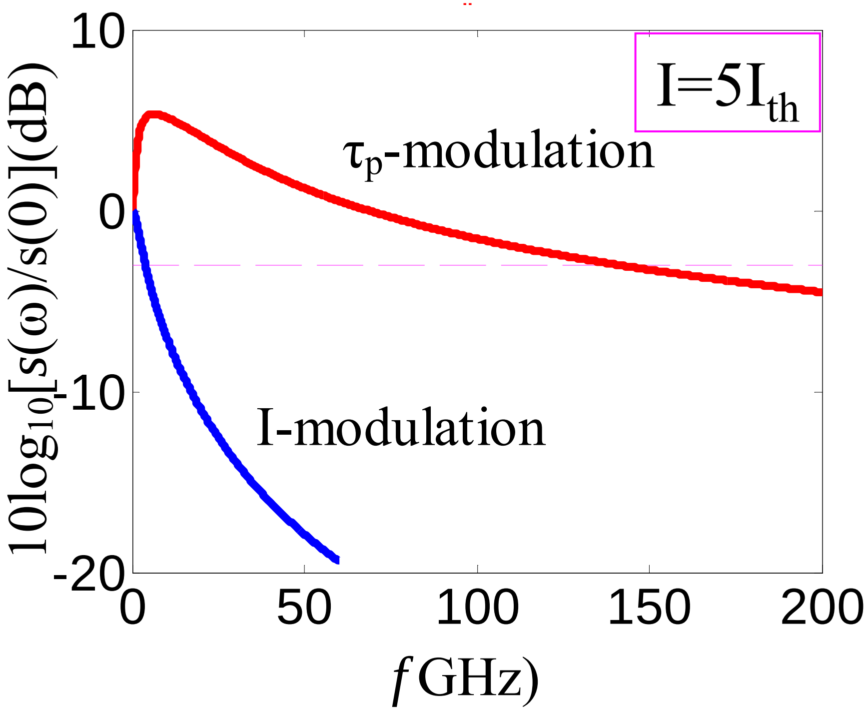
Comparison

I-modulation

$$s = \frac{\frac{i}{qV} D}{-\omega^2 + j\omega(A+B) + AB + CD}$$

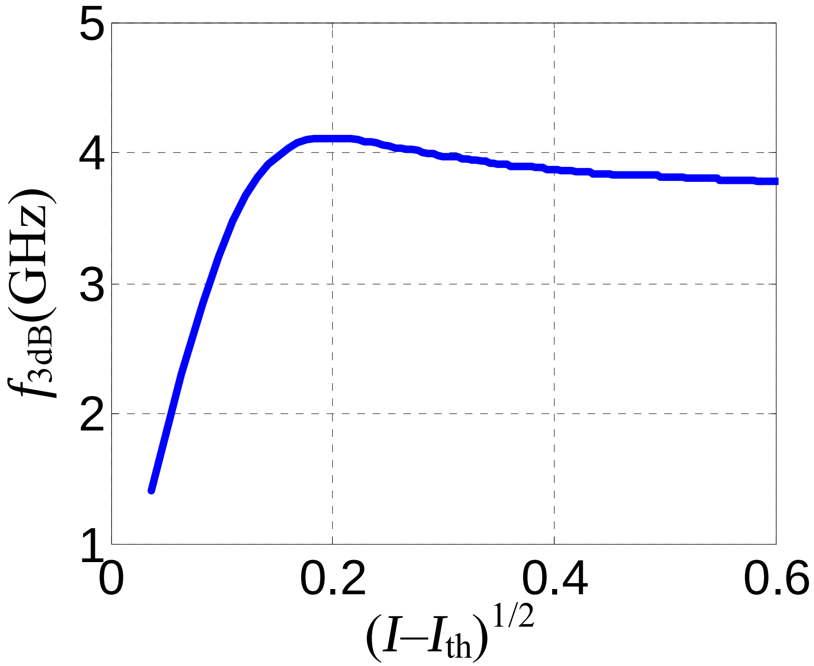
τ_p-modulation

$$s = \frac{S_0 (j\omega + B) \frac{1}{\tilde{\tau}_p}}{-\omega^2 + j\omega(A+B) + AB + CD}$$

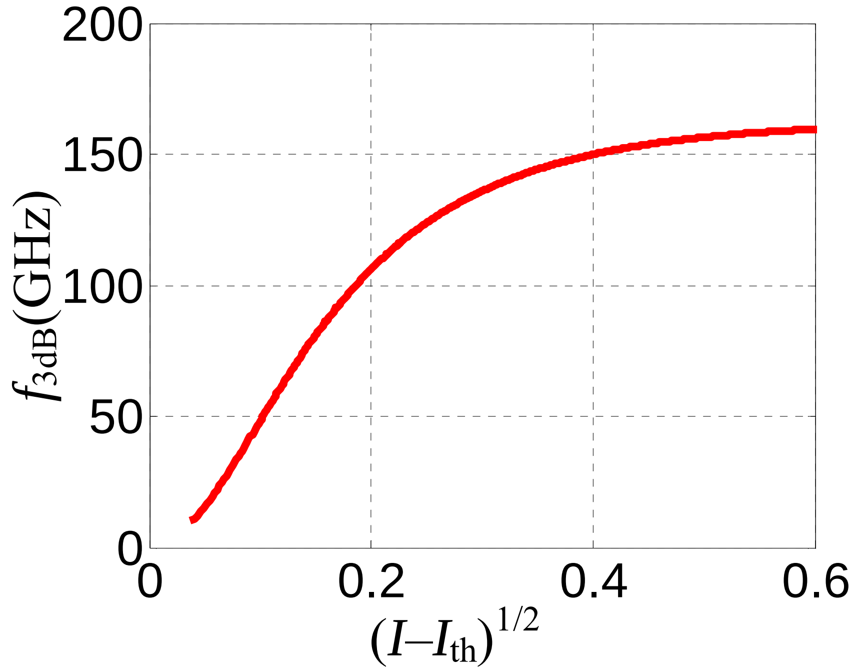


3dB bandwidth

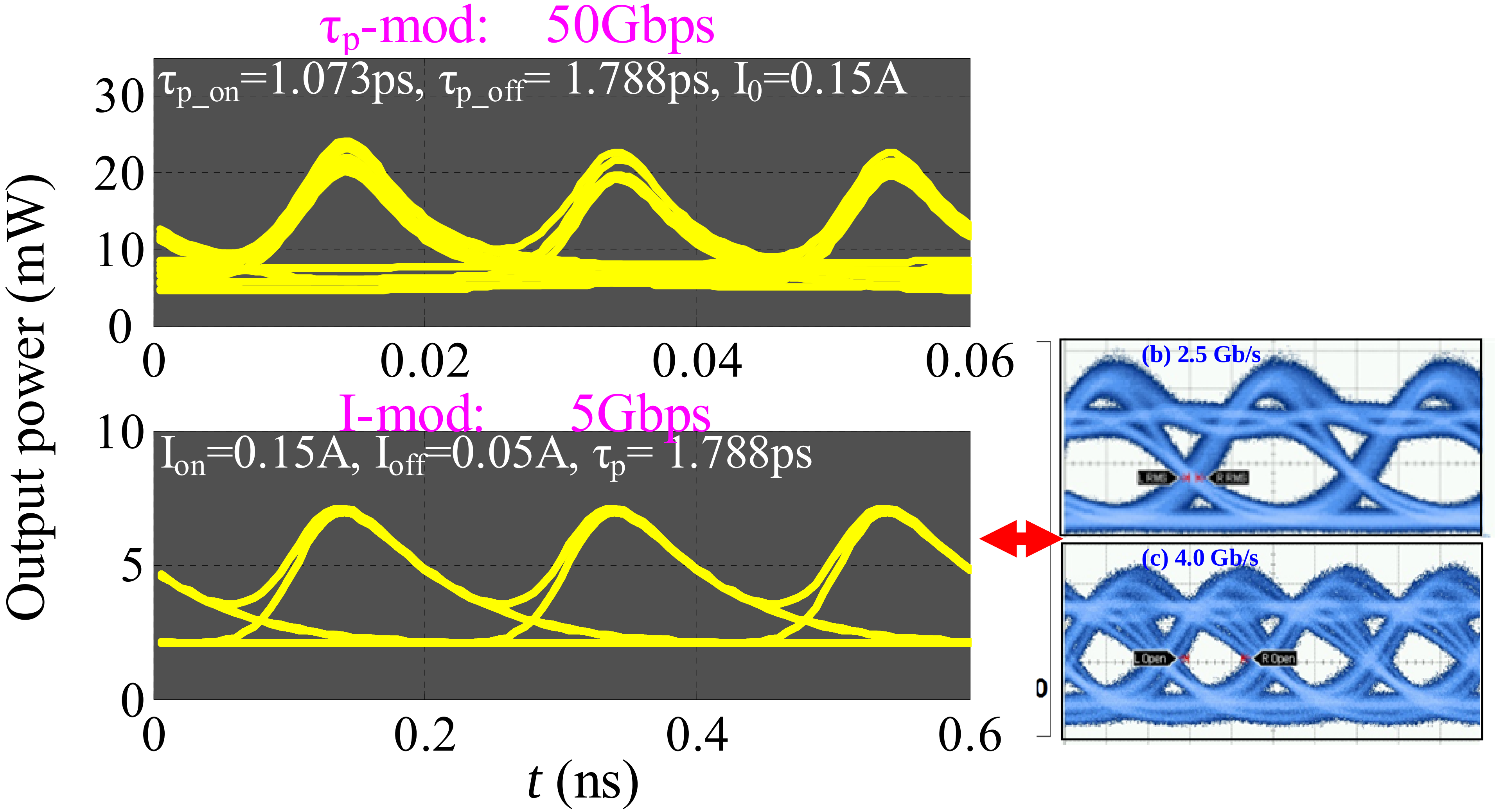
I-modulation



τ_p-modulation



Time-domain response



How to realize τ_p-modulation?

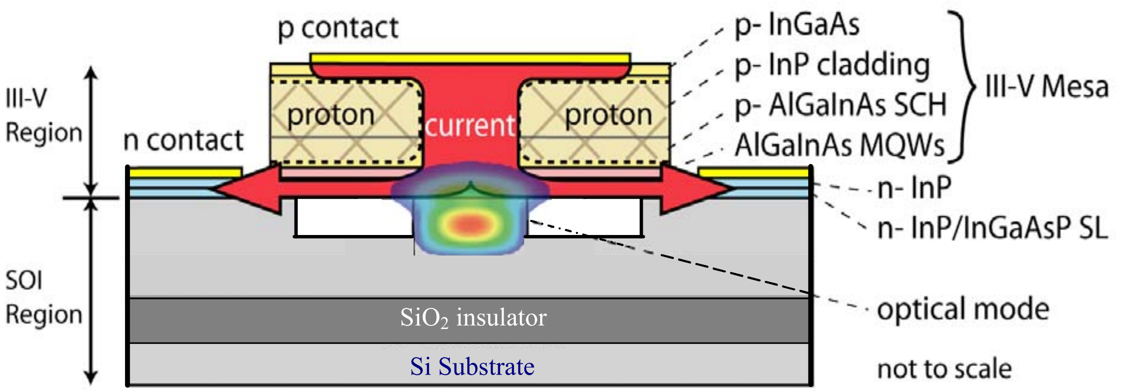
Two ways for τ_p-modulated laser

$$\frac{1}{\tau_p} = v_g(\overline{\alpha} + \frac{1}{l}\ln\frac{1}{R})$$

Two ways of modulating the photon lifetime τ_p:

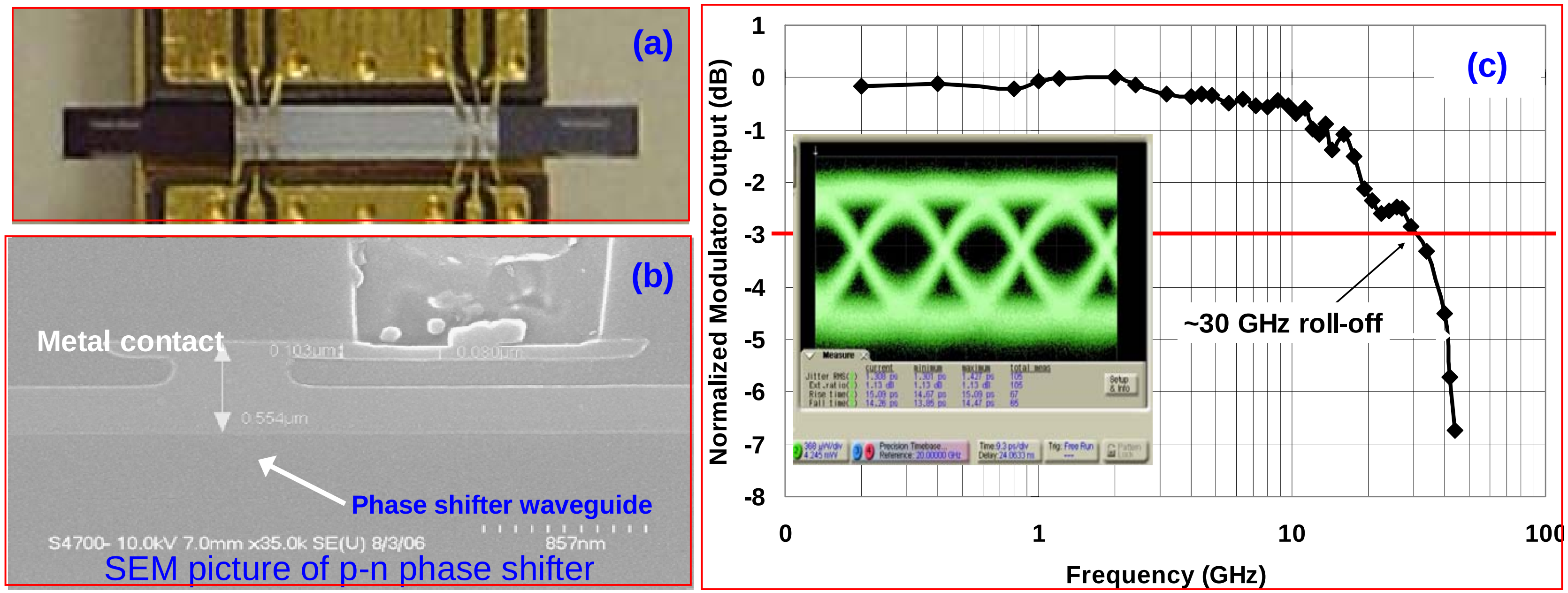
(1) change the distribution loss α;

(2) change the feedback coefficient R.



Free carrier dispersion plasma effect in Si

$$\Delta n = \Delta n_e + \Delta n_h$$
$$= -\left[8.8\times10^{-22}\cdot\Delta N + 8.5\times10^{-18}\cdot(\Delta P)^{0.8}\right]$$
$$\Delta\alpha = \Delta\alpha_e + \Delta\alpha_h$$
$$= 8.5\times10^{-18}\cdot\Delta N + 6.0\times10^{-18}\Delta P$$

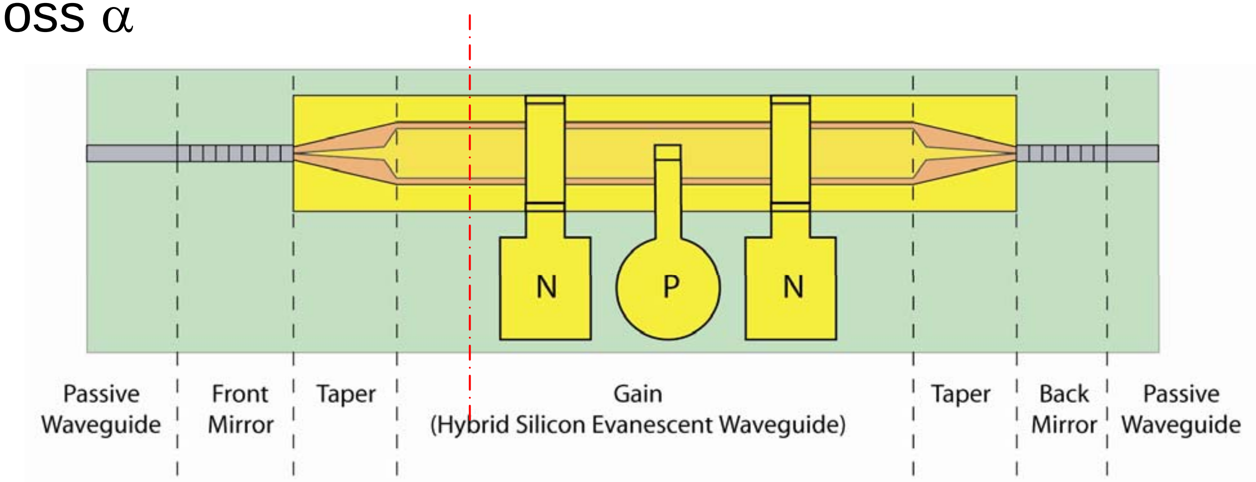


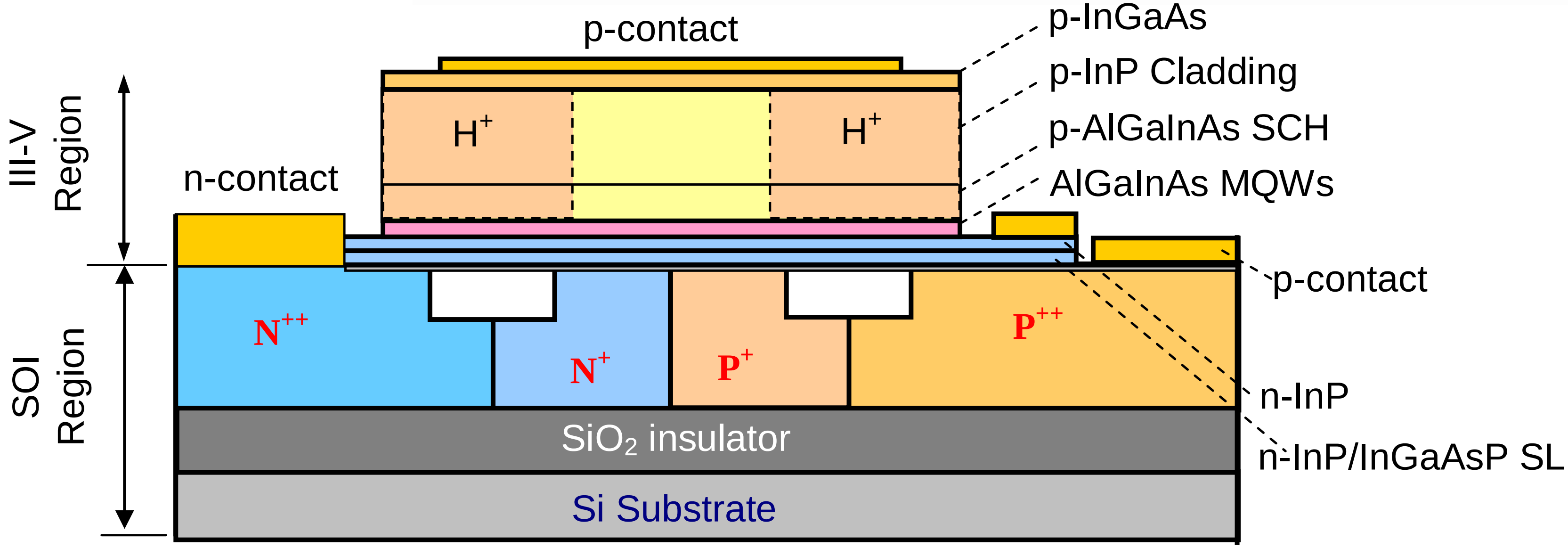
Intel A. Liu. High speed modulation in Silicon by depleting the carriers.

(1) F-P cavity laser

change the distribution loss α

$$\frac{1}{\tau_p} = v_g\left(\overline{\alpha} + \frac{1}{l}\ln\frac{1}{R}\right)$$





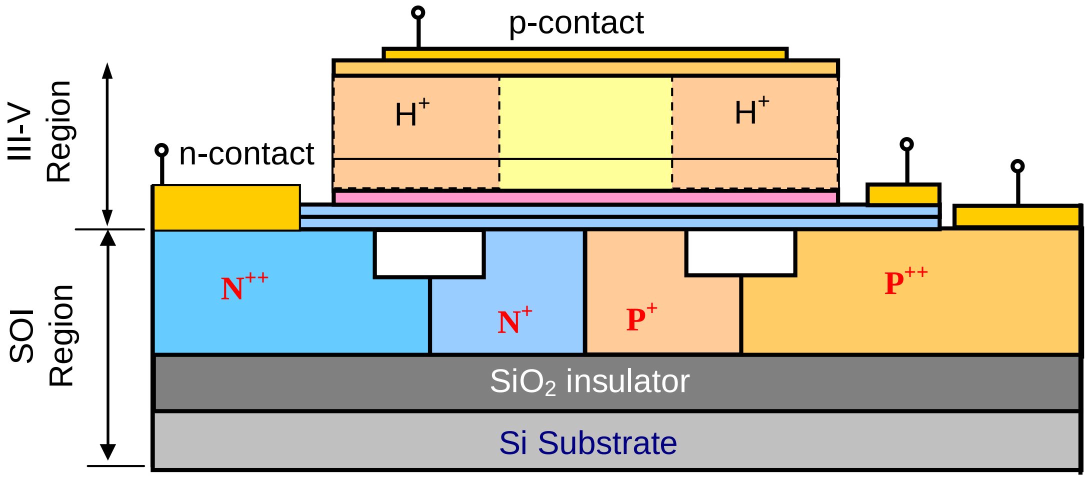
Chirp due to the modulation section

$$\Delta n = -8.8\times 10^{-22}\Delta N_e - 8.5\times 10^{-18}(\Delta N_h)^{0.8} \quad \Rightarrow \quad \Delta\lambda = \frac{\Delta n \Gamma_{\mathrm{Si}}}{n}\frac{l_{\mathrm{mod}}}{L_{\mathrm{cav}}}\lambda$$

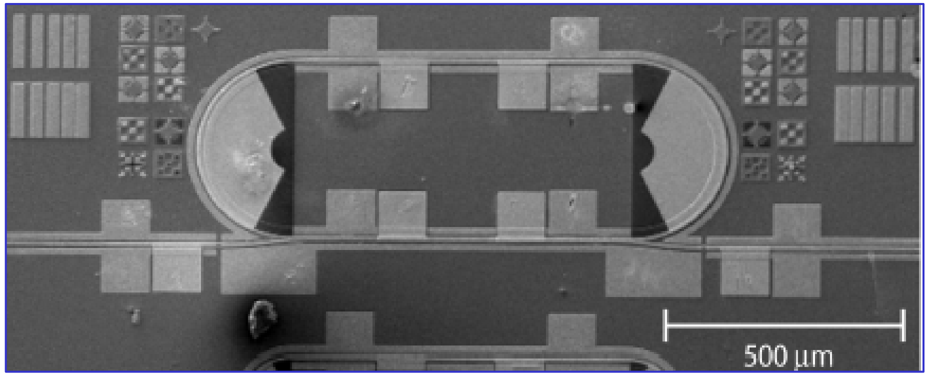
$$\Delta\alpha = 8.5\times 10^{-18}\Delta N_e + 6.0\times 10^{-18}\Delta N_h$$

A solution to minimize the chirp:

Modulate the carrier concentrations in the III-V region and the Si region simultaneously. When depleting the carriers from the Si waveguide, increase the inject current to the III-V gain section in the same time.

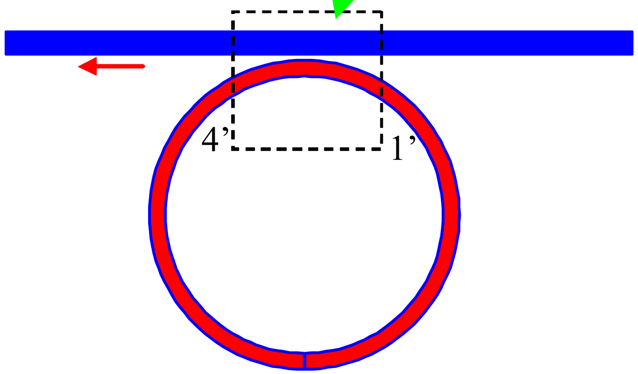


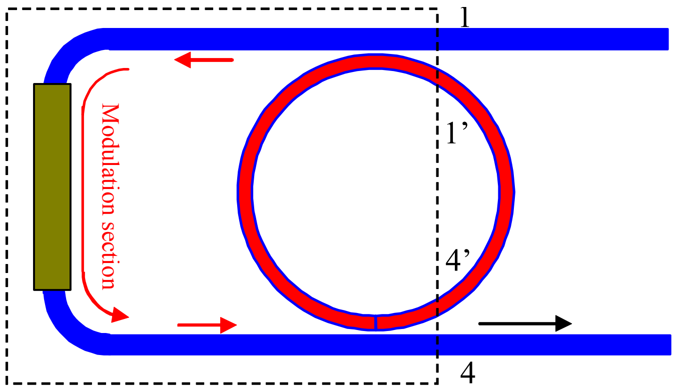
(2) Mach Zehnder coupled Ring laser



$$\frac{1}{\tau_p} = v_g\left(\overline{\alpha} + \frac{1}{l}\ln\frac{1}{R}\right)$$

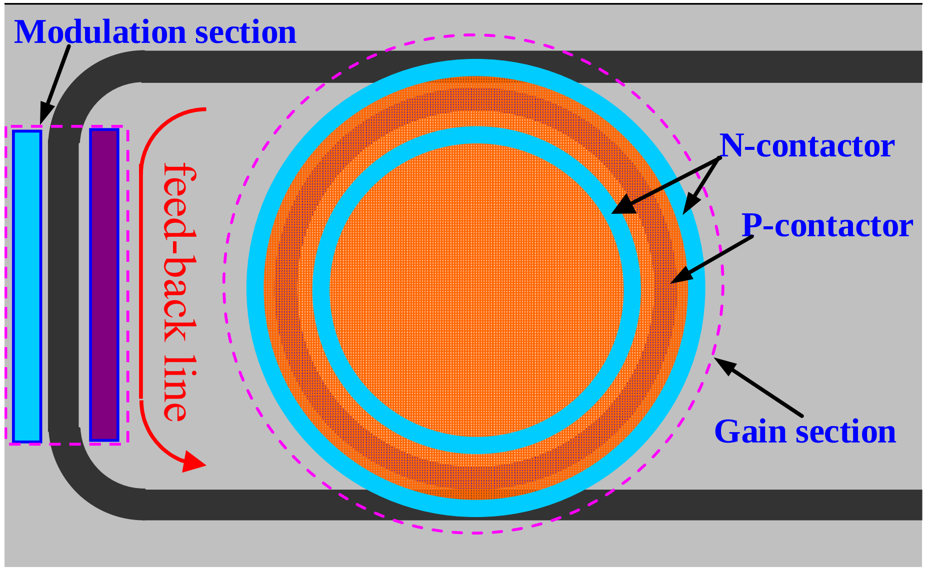
The coupling coefficient $k_{1'4'}$

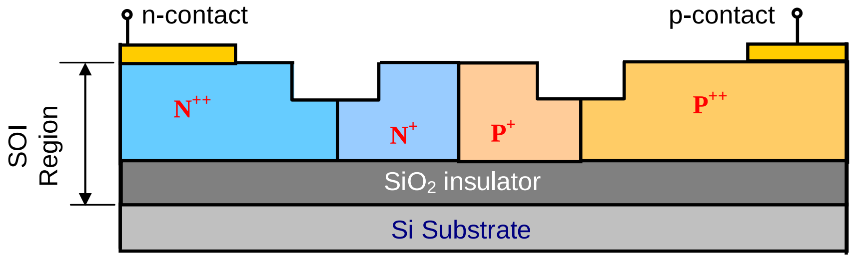


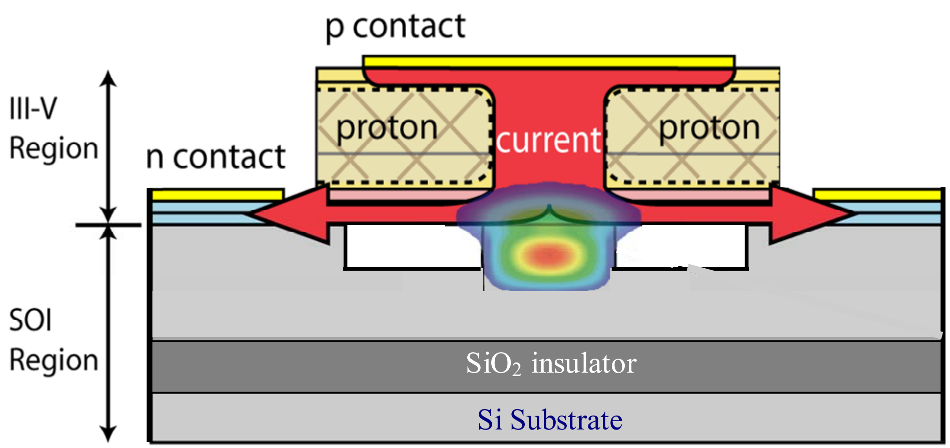


The configuration:
MZI-coupled MRR laser

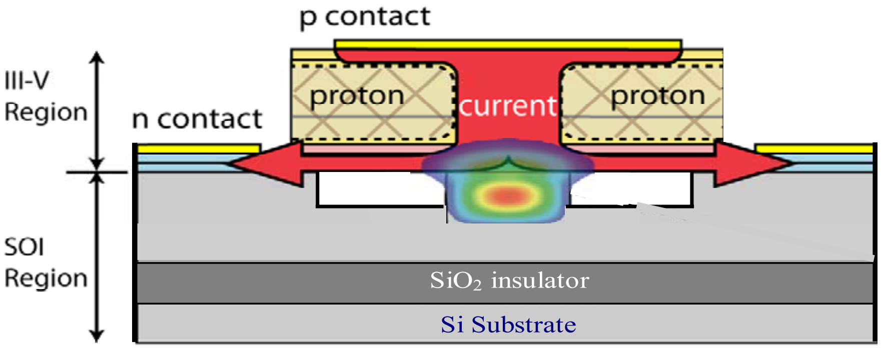
The ring laser modulator

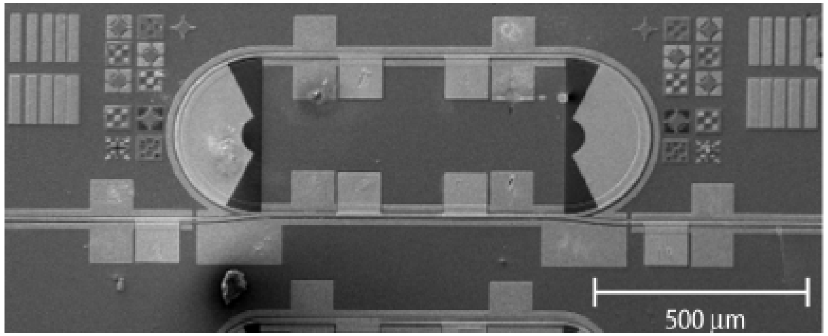




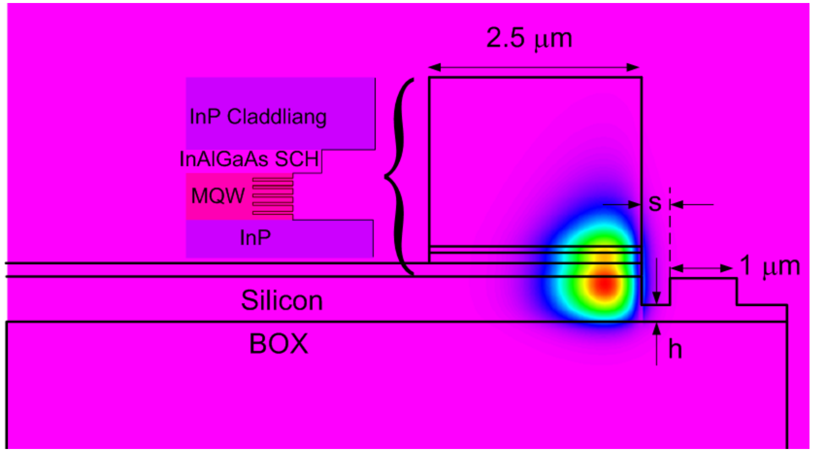


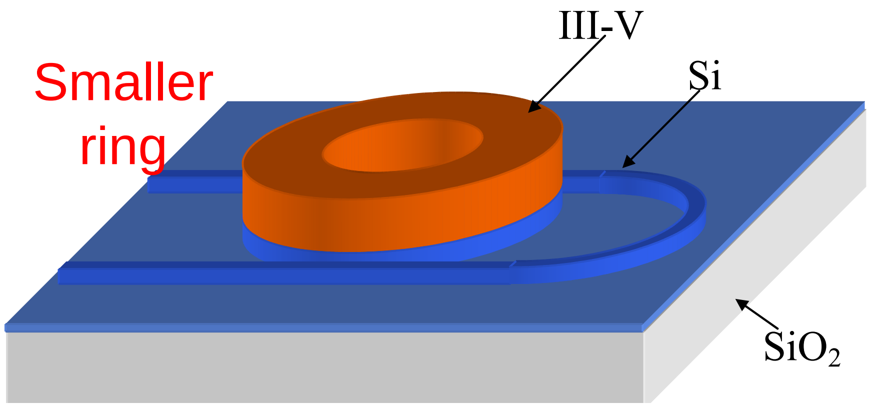
Ring structures





AW Fang, et al. Opt. Expr. 15: 2315, 2007.





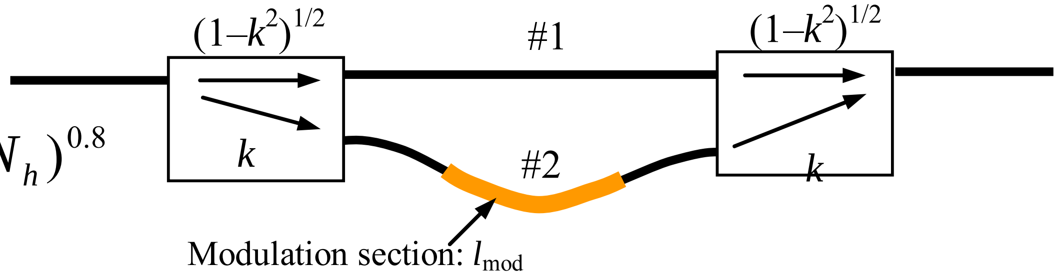
Smaller ring

Di Liang, et al. GFP conference, 2009.

Chirp due to the modulation section

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

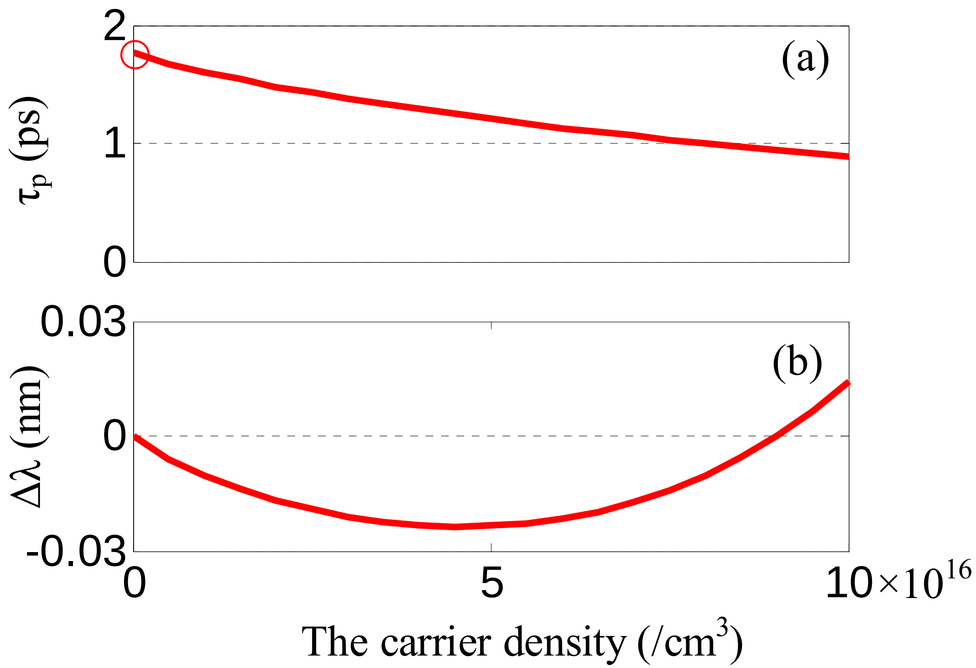
$$\Delta \alpha = 8.5\times10^{-18}\Delta N_e + 6.0\times10^{-18}\Delta N_h$$



$$\boxed{\Delta\phi_{21}} = \Delta\phi_{21(0)} + \Delta n_{\text{eff}} l_{\text{mod}} \frac{2\pi}{\lambda}$$

$$\delta\phi_{\text{MZI}} = \tan^{-1}\left[\frac{-\kappa^2\gamma\sin(\Delta\phi_{21})}{(1-\kappa^2)-\kappa^2\gamma\cos(\Delta\phi_{21})}\right]$$

$$\delta\phi_{\text{MZI}(\lambda_m)} + n_{\text{eff}}\frac{2\pi}{\lambda_m}L_{\text{cav}} = m2\pi$$

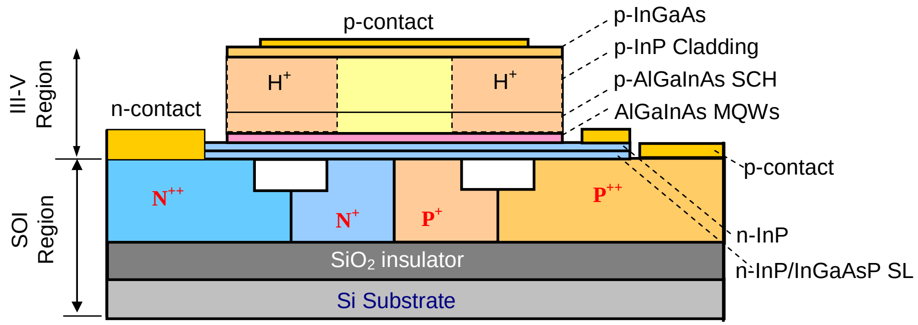


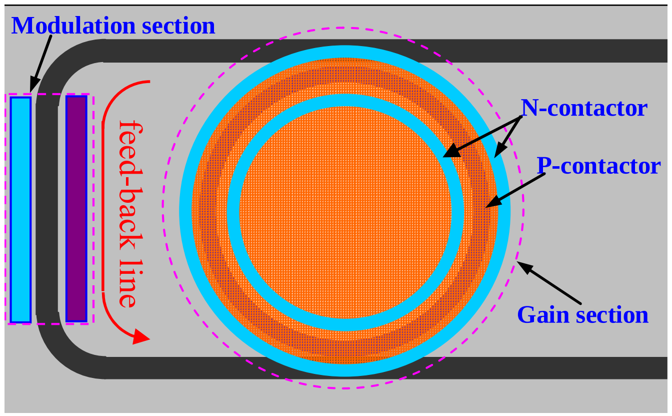
L_{mod}=400 μm

Daoxin Dai, dxdai@ece.ucsb.edu.

Summary & Conclusion

- Many recent advances in hybrid laser and modulator technology
- High speed direct modulation possible using τ_p modulation
- τ_p modulation possible with loss modulation or Mach Zehnder couple rings
- Zero chirp possible with dual drive





Thanks.