Optical Interconnects: A Viable Solution for Interconnection Beyond 10 Gbit/sec

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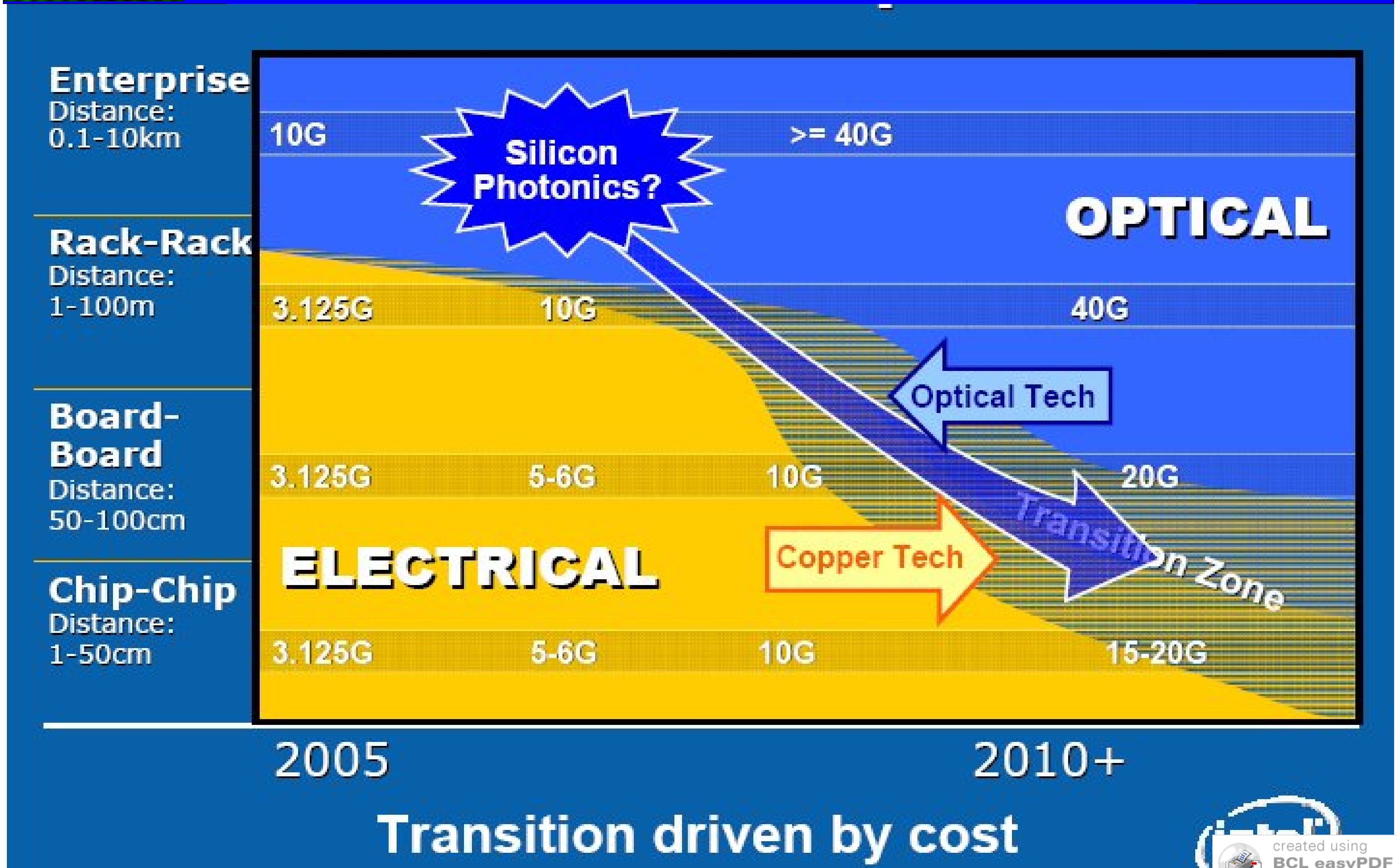
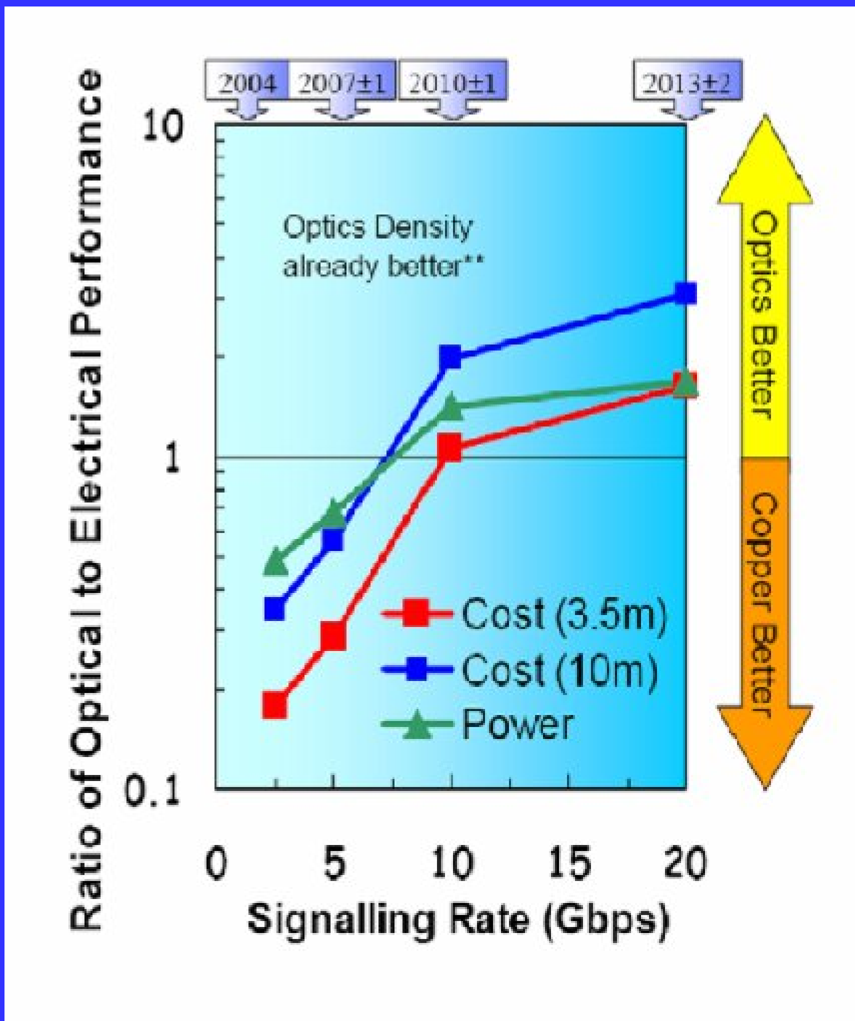
3-20-2007

Introduction: Projection of Bandwidth



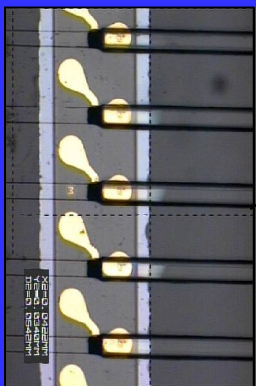
Potential Markets for UT's IP Portfolio



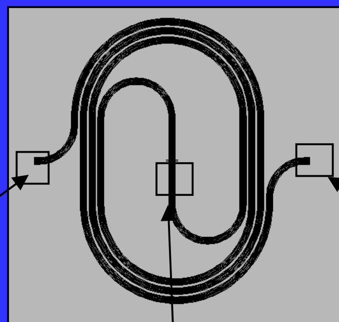
- Optical backplane
- Optical PC Board
- Passive Waveguide Components
- Active Optical Components
- Optical Biosensor

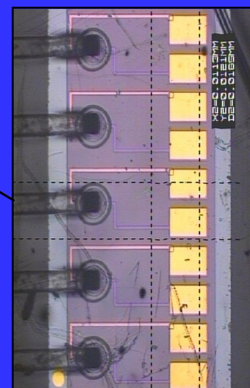
Fully Embedded Board Level Optical Interconnection

- *Unique Architecture for Optical PWB (Printed Writing Board)*
  ; All the optical components are interposed inside the PCB
  Solve the package problem / Reduce Cost Effects

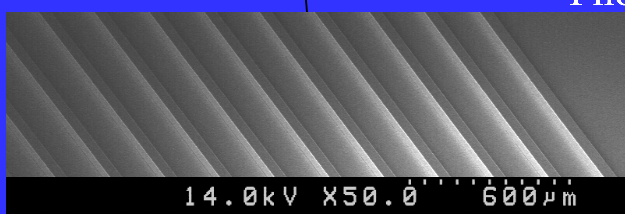


1x12 VCSEL

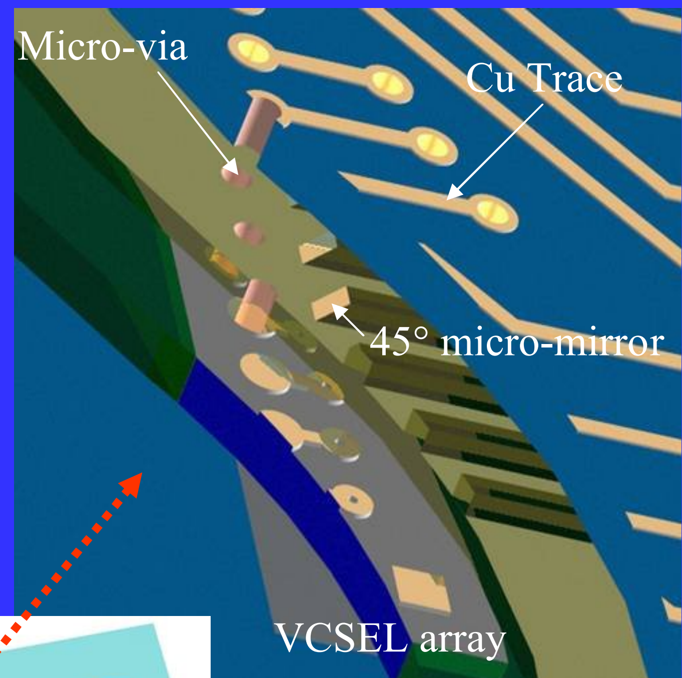


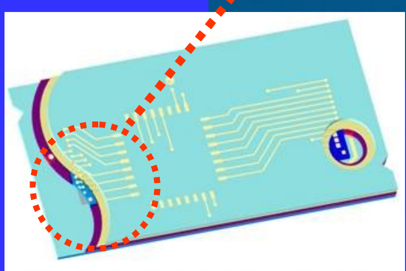


1x12 PIN Photodiode



12-channel Polymer Waveguide [109 cm]

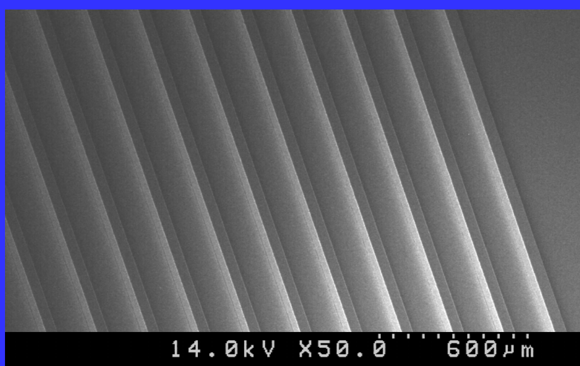


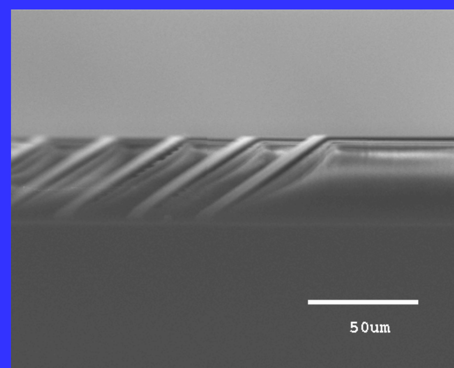


Optical PCB

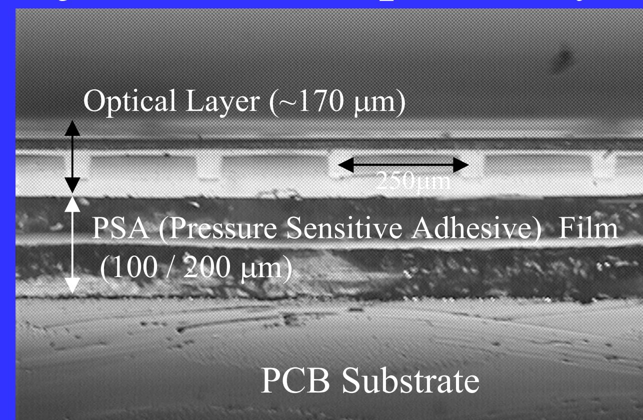
Lamination of Optical Waveguide Film & Integration of Thin Film VCSEL

- *12-Channel Polymer Waveguide & 45º Micro-Mirror*

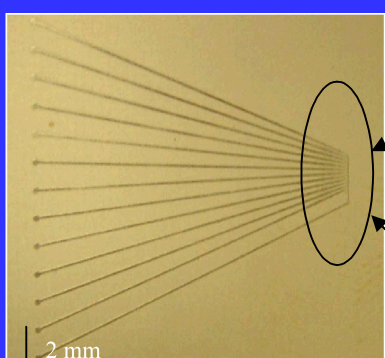


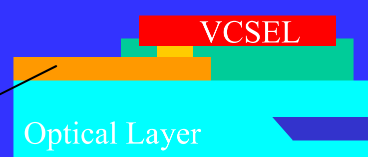


- *Cross Section View of Laminated Optical Layer*

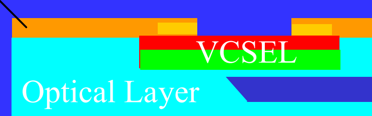


- *Cu Transmission Lines for VCSEL (or PD) Integration*

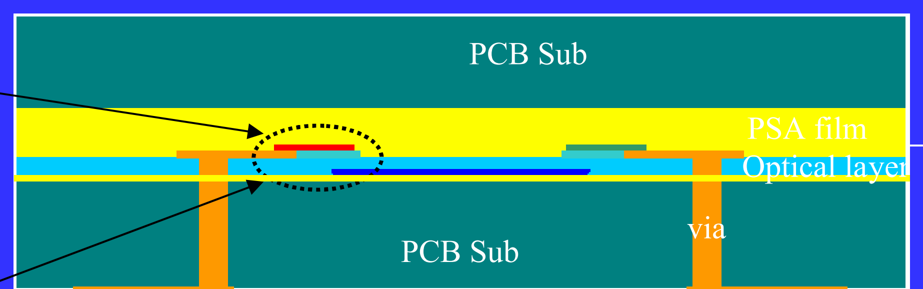




Top Emitting VCSEL

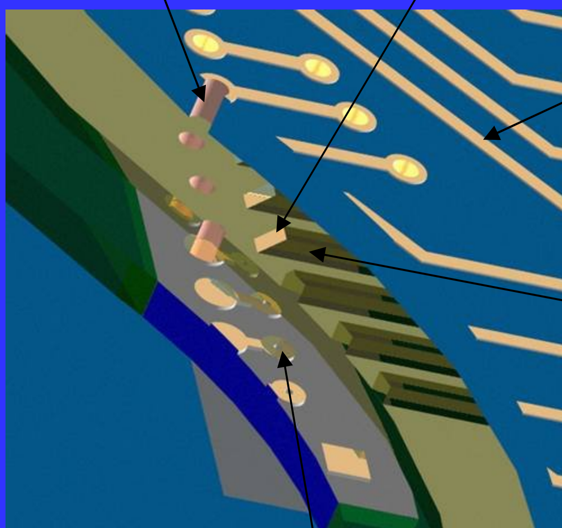


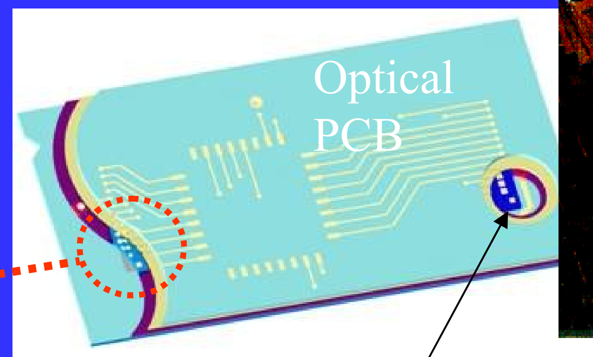
Bottom Emitting VCSEL

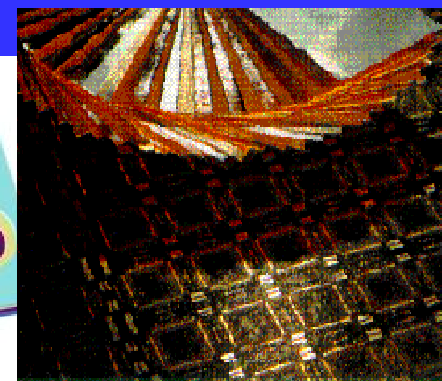


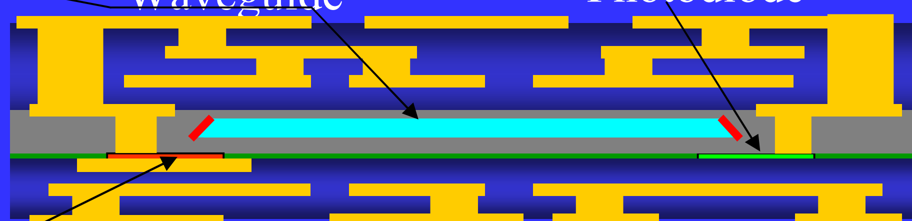
- PSA (Pressure Sensitive Adhesive) Film : 100 / 200 µm
- Optical Waveguide Film Layer = ~ 170 µm

Fully Embedded Board Level Optical Interconnection







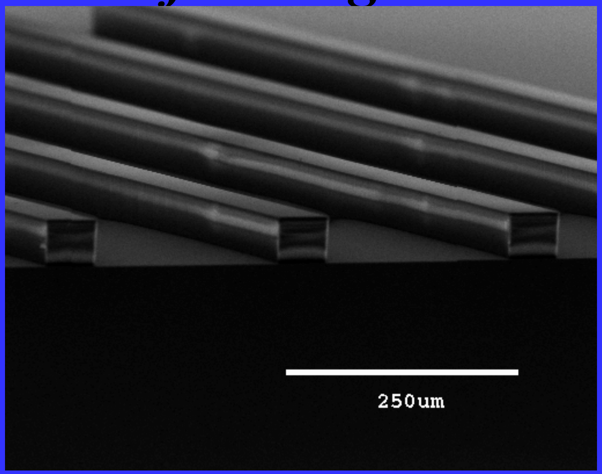


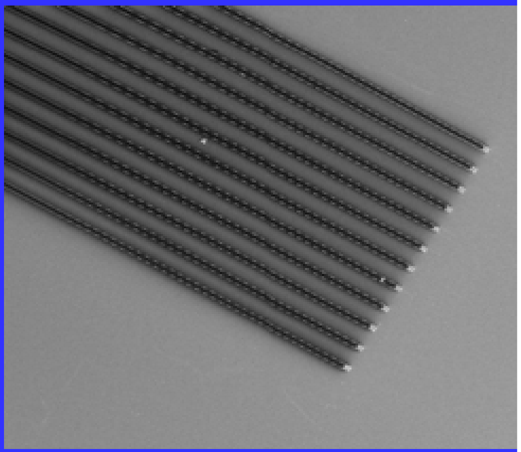
Cross section view of optical PCB

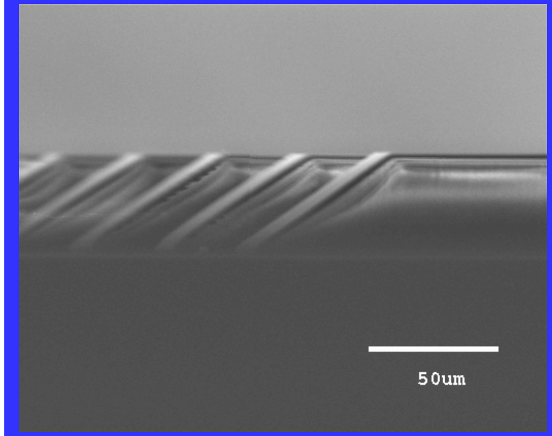
R. T. Chen, et al, Proc. IEEE, **88**, 780-793 (2000).

Fabrication of Flexible Optical Waveguide Film(1)

➢ *Physical Dimensions of Waveguide Structures*



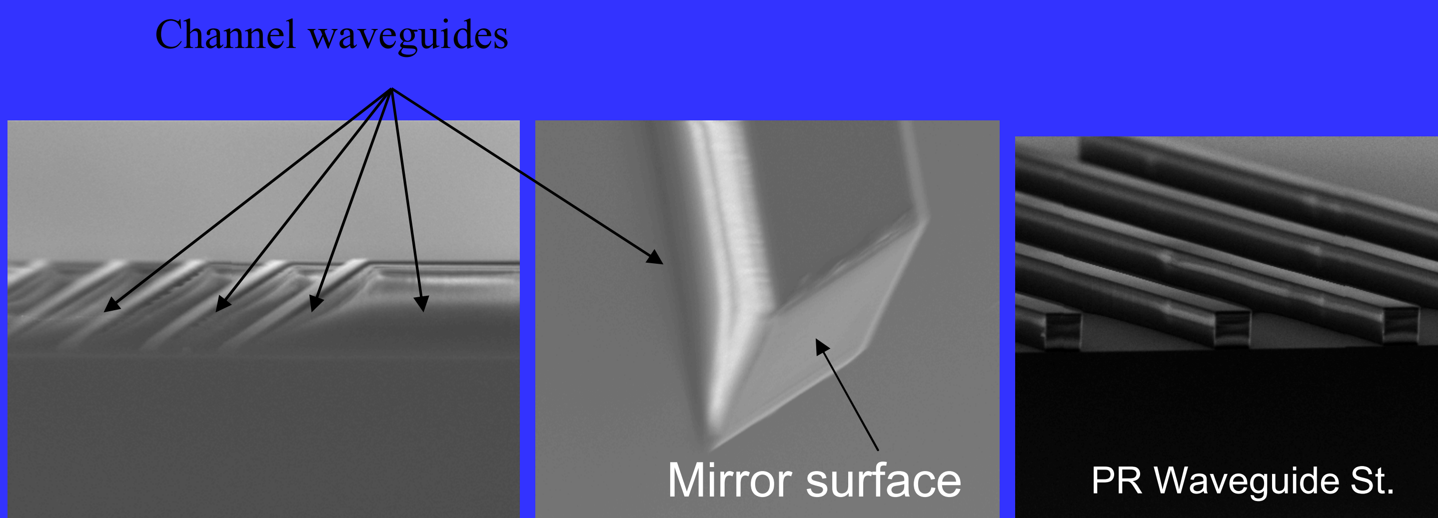


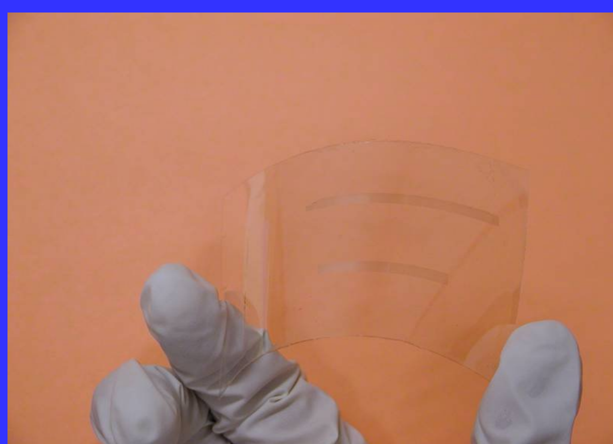


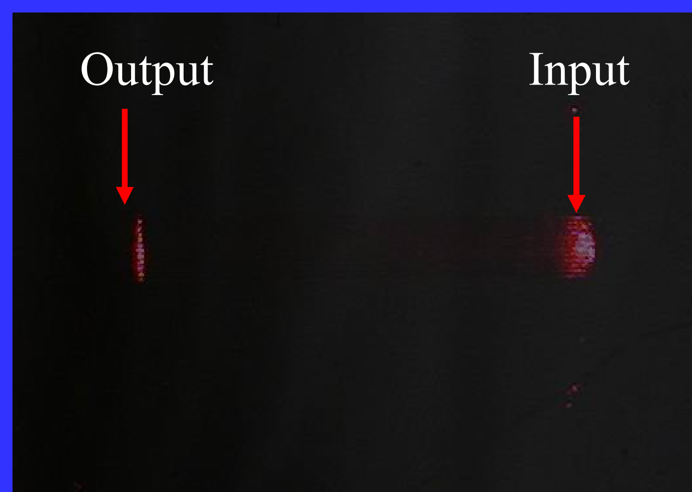
No. of channels : 12
Cross-Section : 50 X 50 μm^2
Channel to channel separation : 250 μm
Total Length : ~ 109 cm
Curvatures : 3.68 cm / 1.72 cm

SEM image of
45^o Micro-mirror

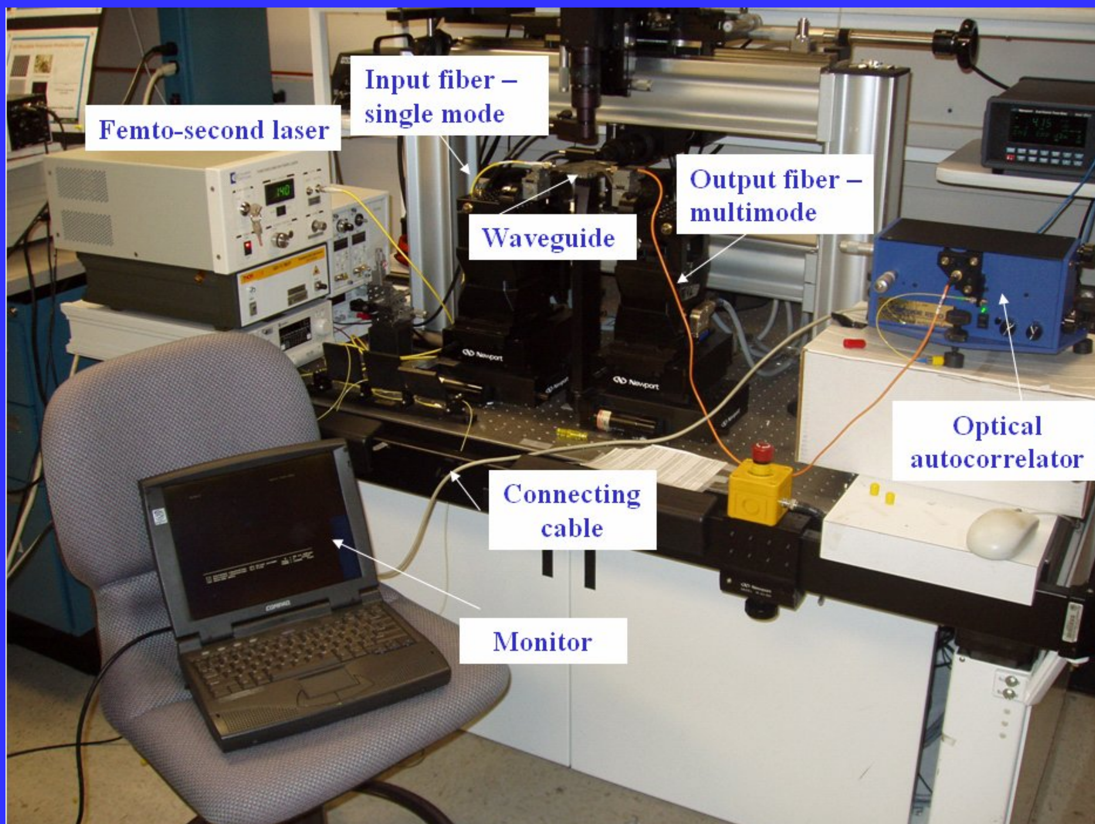
Master Waveguide Structures for Mold

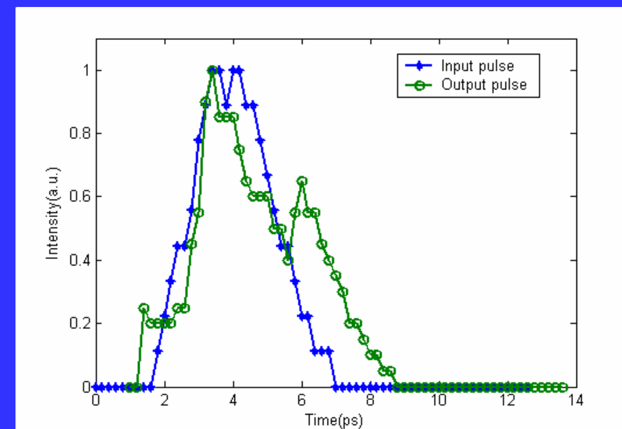


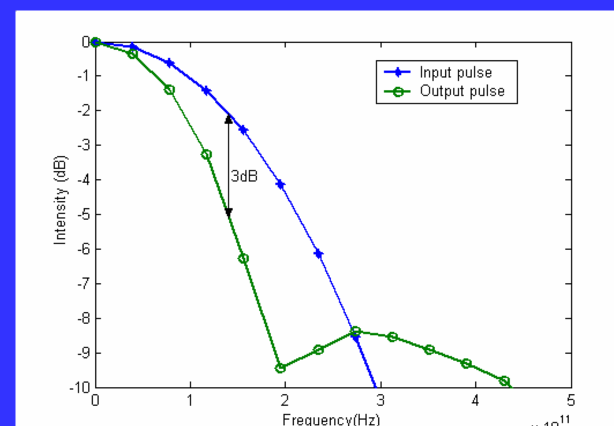




Optical Bandwidth Measurement of the 51 cm Long Waveguide

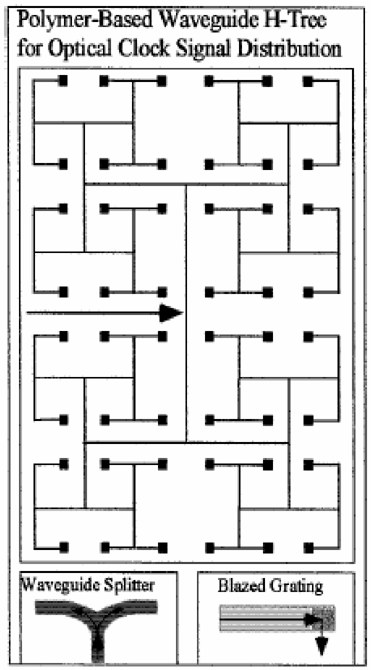




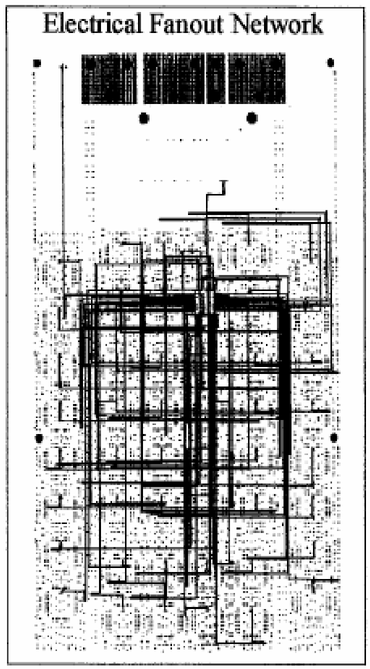


The 3-dB optical bandwidth is determined to be **150GHz** for the 51cm long waveguide

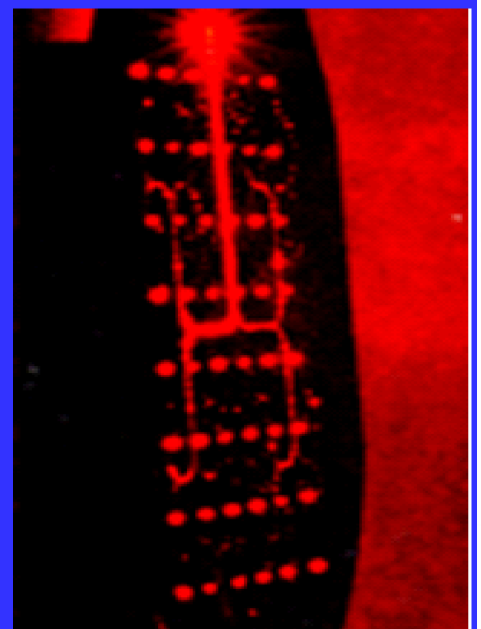
Polyimide Based 1-to-48 Fanout H-tree Optical Waveguide on Si-Substrate



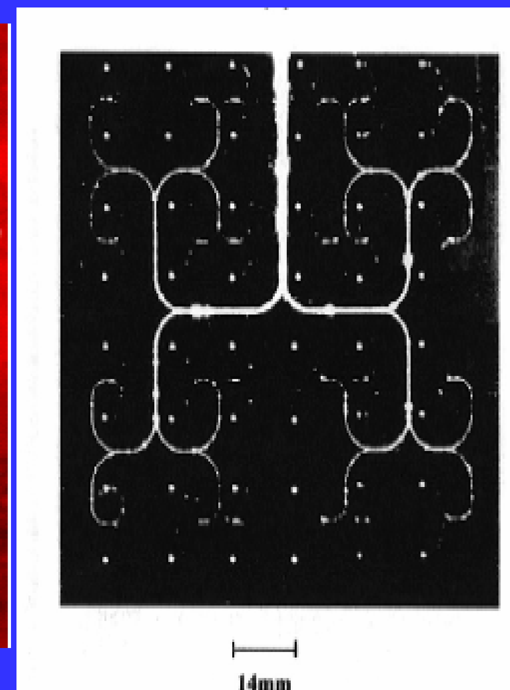
(a)



(b)

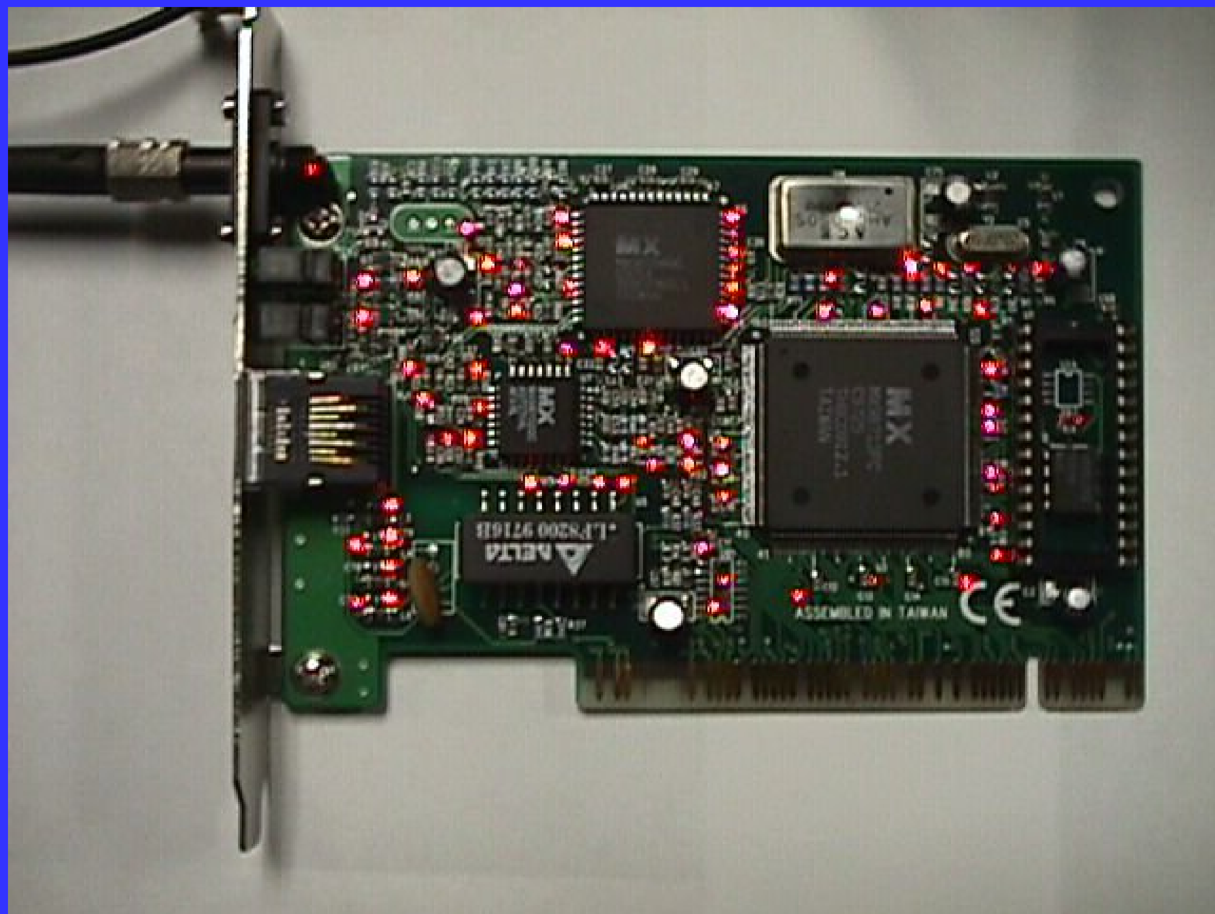


(c)



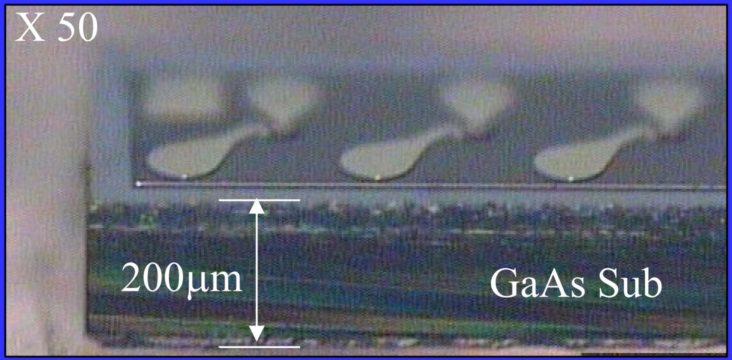
(d)

Optical Signal Distribution in a Network Card

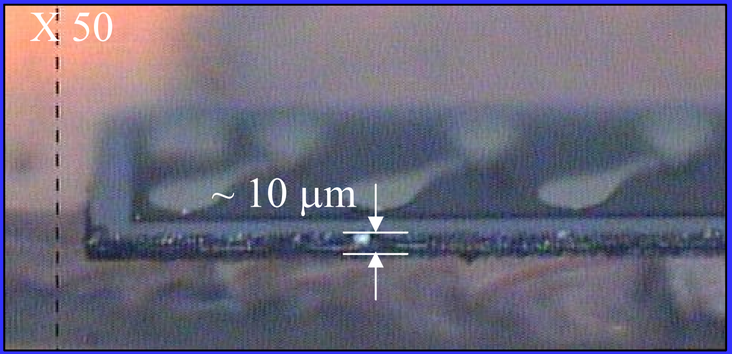


Substrate Removed 1 X 12 GaAs VCSEL Array

- *Flatten Optical Layer to Facilitate Embedded Structure*
- *~ 10 µm Thickness VCSEL Formation*
  - *- Mechanical Lapping : ~ 50 µm*
  - *- Chemical Wet-etching (Citric Acid : H_2O_2) : ~ 10 µm*



Original VCSEL on GaAs Substrate

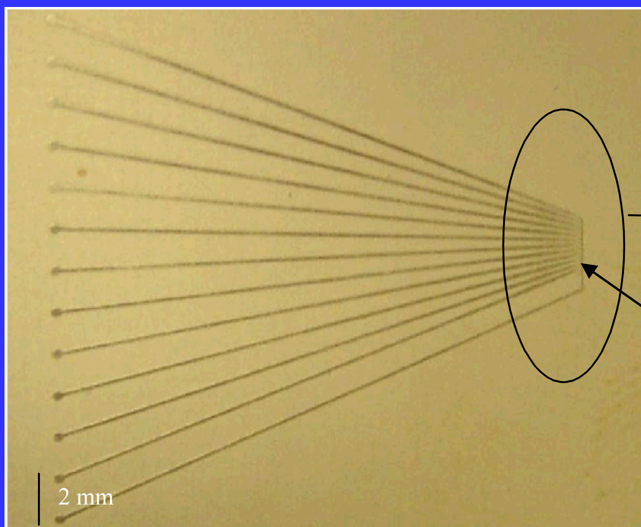


Substrate Removed VCSEL (~ 10 µm)

Fabrication of Cu Transmission Lines & Gold Stud Bump for Flip Chip Integration

- *Design of Cu Transmission Lines for Flip Chip Integration*

Separated 12 N-contact Transmission Lines

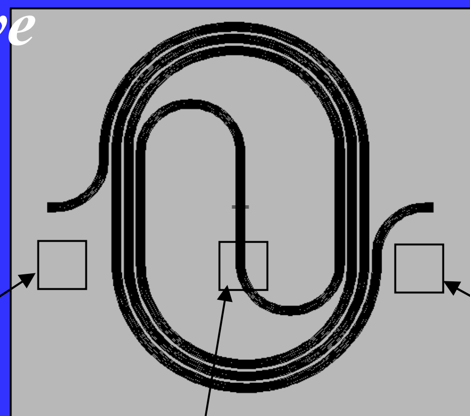


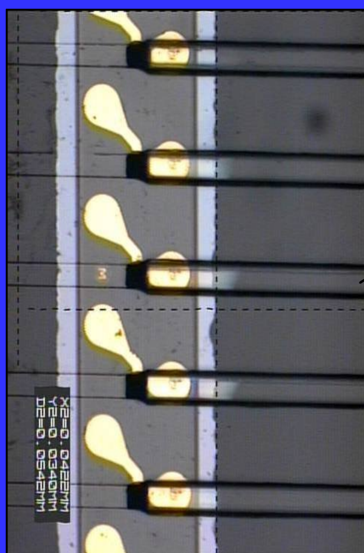
Cu Plated Transmission Lines

Common P-contact Transmission Lines

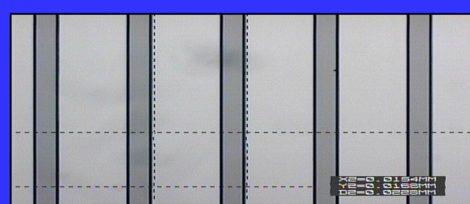
Integration of VCSEL and PIN Photodiode with Optical Waveguide Film

- ***Photolithography UV-Aligner***
- ***UV-Curable Adhesive***

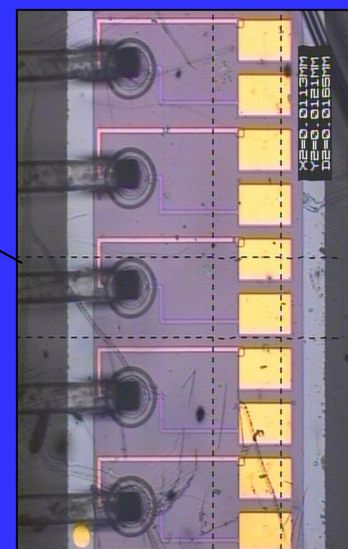




1x12 VCSEL



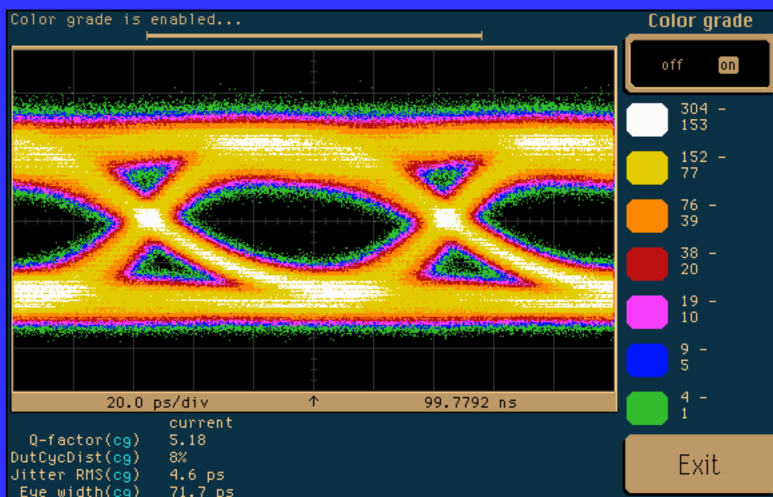
12-channel Polymer Waveguide [109 cm]



1 x 12 PIN Photodiode

Speed Measurement of Substrate Removed 850 nm Wavelength VCSEL

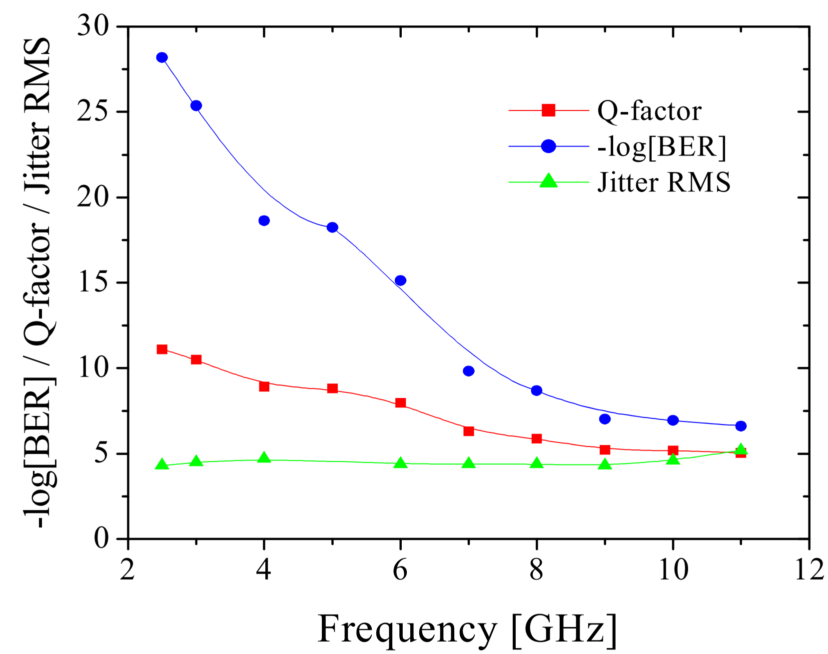
➢ Eye-diagram



V_{bias} = 2.0 V	NRZ mode
I_{bias} = 5.0 mA	PRBS = 2^{31}-1
Ampl = 0.5 V	Jitter RMS = 4.6 ps
Offs = 0 V	Q-factor = 5.18
Freq.= 10 Gb	Eye width = 71.7 ps

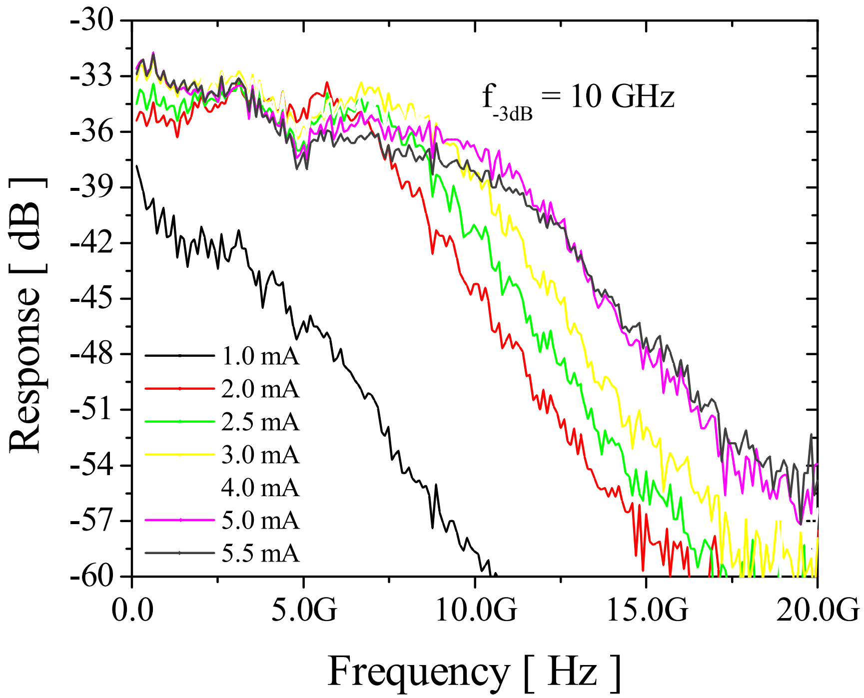
➢ BER/Q-factor/Jitter RMS

[V_{bias} = 2.0 V / I_{bias} = 5.0 mA]

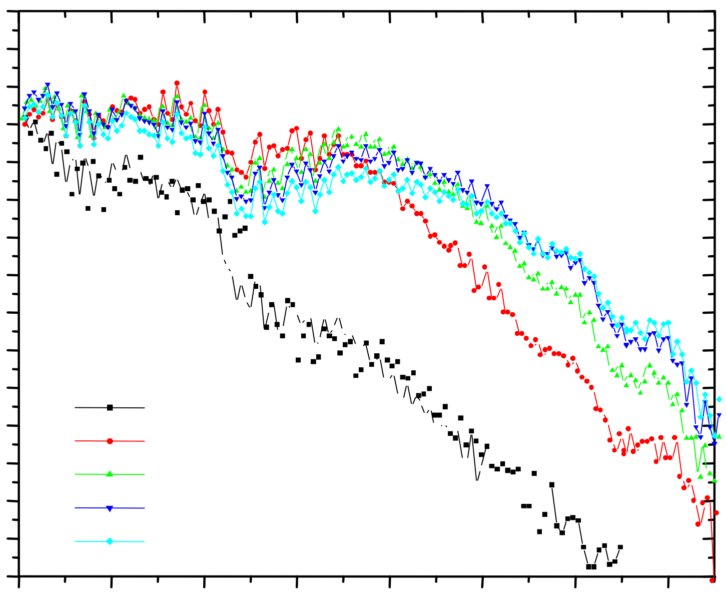


Speed Measurement of Substrate Removed VCSEL and PIN Photodiode

➢ *Frequency Response of 850 nm VCSEL*

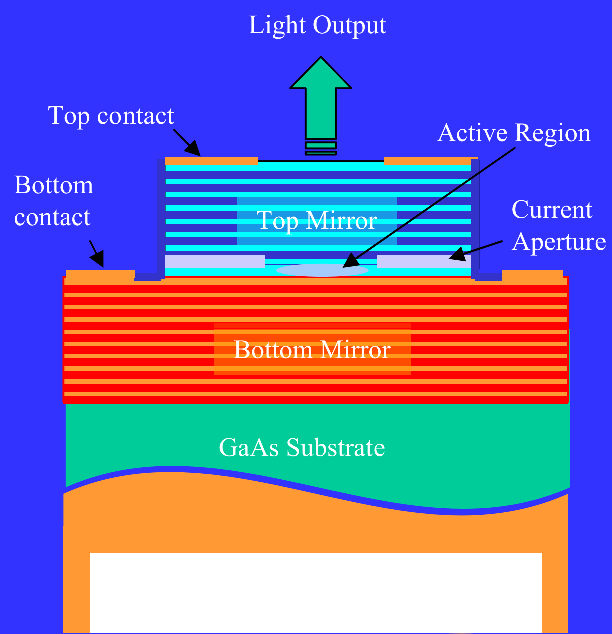


➢ *Frequency Response of 850 nm PIN Photodiode*



Coupled Field Thermal-Electric Analysis for Heat Generation of Thin Film VCSEL

➢ *2-D Modeling of VCSEL for Coupled Field Analysis*



- Electrical Potential : $$\sigma_z\left(\frac{\partial^2 V}{\partial z^2}\right)+\sigma_r\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right)=0$$

- Joule Heating In DBR : $$q=\sigma_z\left(\frac{\partial V}{\partial z}\right)^2+\sigma_r\left(\frac{\partial V}{\partial r}\right)^2$$

➢ *Material Properties (thermal/electrical) & Physical Dimensions*

	Electrical Resistivity [ohm-um]	Thermal Conductivity [W/um-K]	Thickness [um]
P-DBR	$\sigma_r = 496$	k_r = 1.2 x 10^{-5}	3.30
	$\sigma_z = 6{,}6667$	k_z = 1.0 x 10^{-5}	
N-DBR	$\sigma_r = 24.8$	k_r = 1.2 x 10^{-5}	3.497
	$\sigma_z = 3500$	k_z = 1.0 x 10^{-5}	
GaAs sub.	$\sigma_r = \sigma_z = 30$	$k_r = k_z$ = 4.5 x 10^{-5}	10 ~ 200
Au	$\sigma_r = \sigma_z = 2.2 \times 10^{-2}$	$k_r = k_z$ = 3.15 x 10^{-4}	0.2
Copper	$\sigma_r = \sigma_z = 1.7 \times 10^{-2}$	$k_r = k_z$ = 3.98 x 10^{-4}	0 ~ 200
Polymer	$\sigma_r = \sigma_z = 10^{18}$	$k_r = k_z$ = 2.0 x 10^{-7}	30 ~ 100

➢ *Coupled Field Analysis*

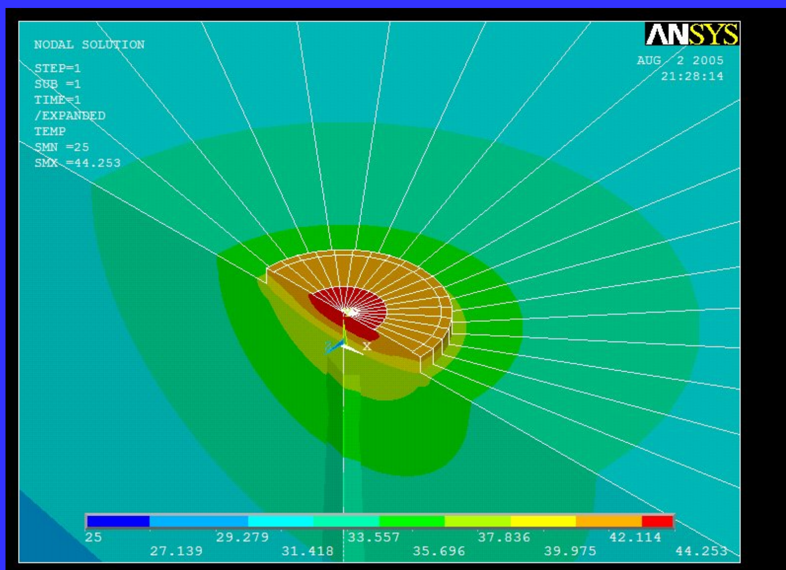
Electric Field Analysis
- Electrical Potential
- Current Density

→

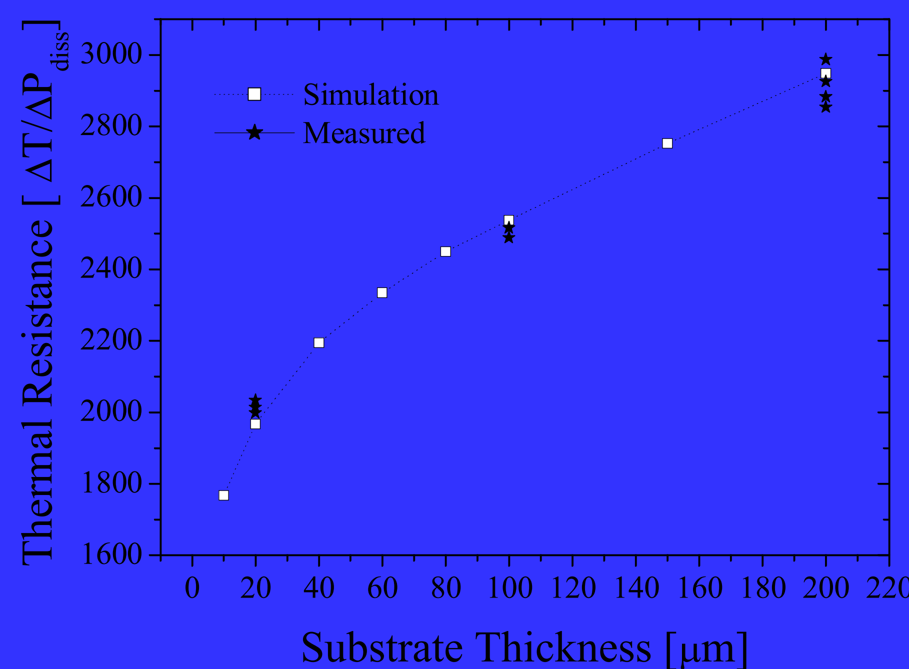
Thermal Analysis
- Joule Heating in DBR
- Heat Generation in Active Region

Experimental & Simulation Results
Thermal Resistances(R_{th}) of Thin Film VCSEL

➢ ***Temperature Distribution inside Thin Film VCSEL***



➢ ***Thermal Resistances of Thin Film VCSEL as a Function of Substrate Thickness***



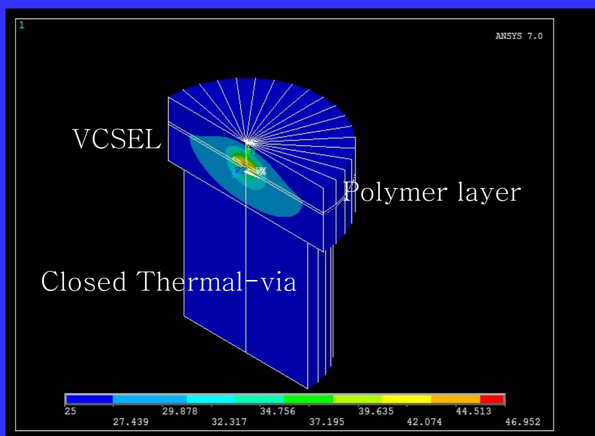
Simulation & Experimental Parameters
- Bias Conditions : 5 mA / 2 V
- Thickness of VCSEL = 10 μm ~ 200 μm
- Substrate Cooling Condition by TEC (25 ^{o}C)

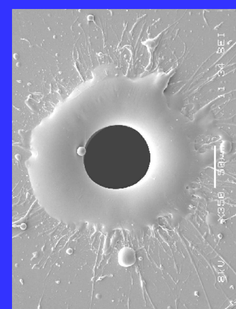
Substrate Thinning (200 μm ⟶ 10 μm)

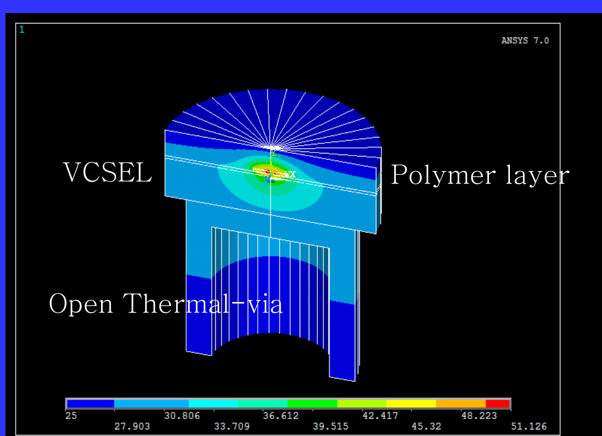
⟶ 40 % Thermal Resistance Reduction

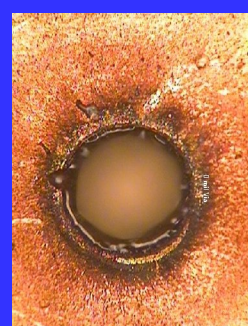
Effects of Thermal-Via Structures for the Fully Embedded Thin Film VCSEL

➢ ***Temperature Distribution of Thin Film VCSEL with Thermal Via***





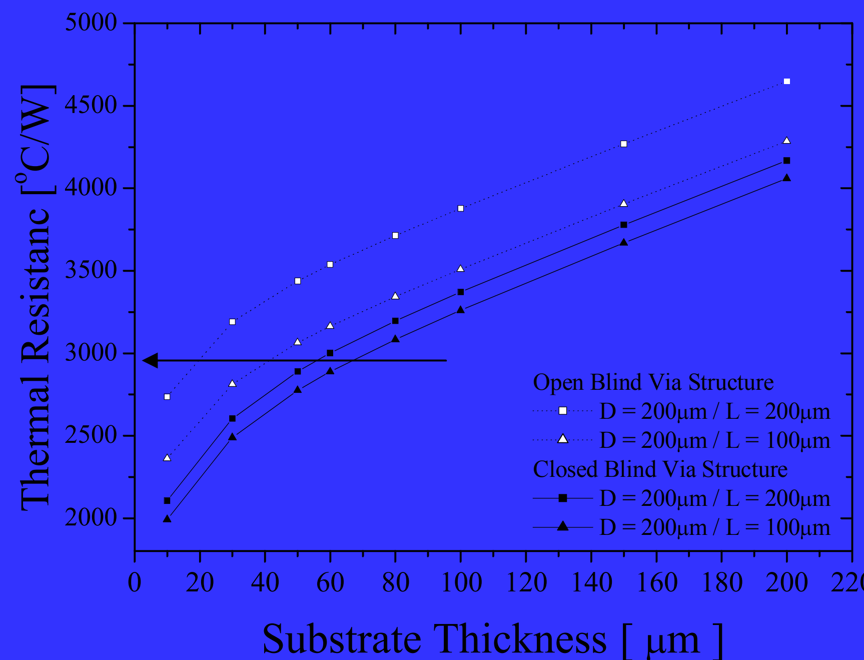




Fabricated via-hole on the optical film layer

(D = 200 mm, Aspect ratio = 0.5)

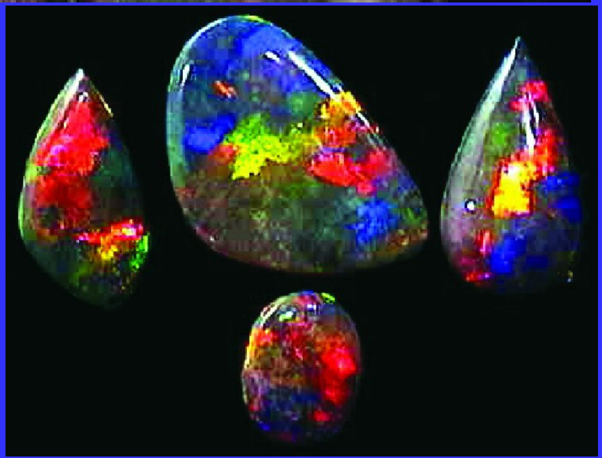
➢ ***Thermal Resistances of Thin Film VCSEL as a Function of Substrate Thickness***



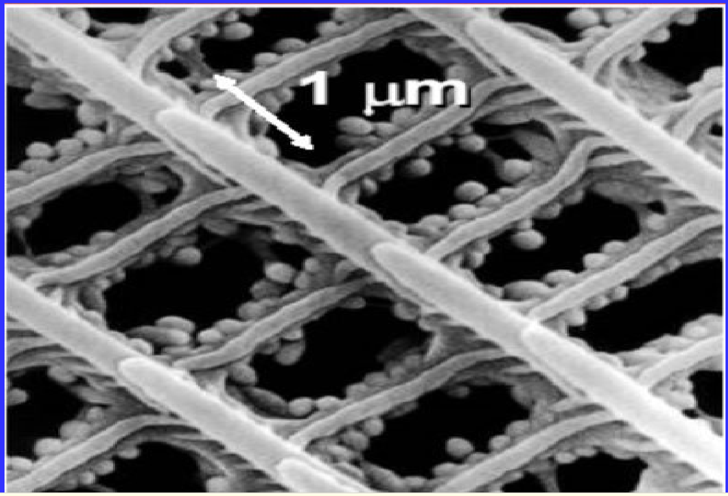
Optimized VCSEL Thickness = 44 µm ~ 72 µm

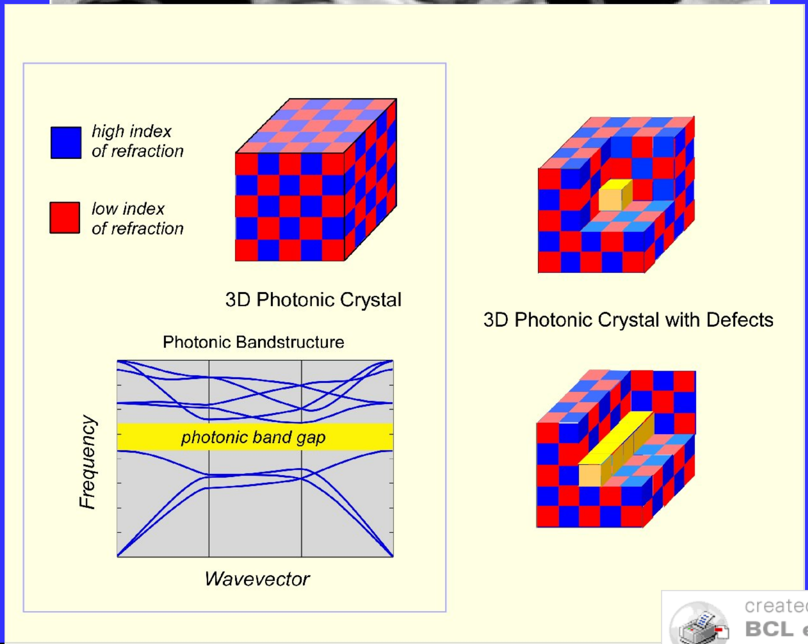
Silicon Thin Film Photonic Crystal Waveguide Modulator

Photonic crystal structure in nature

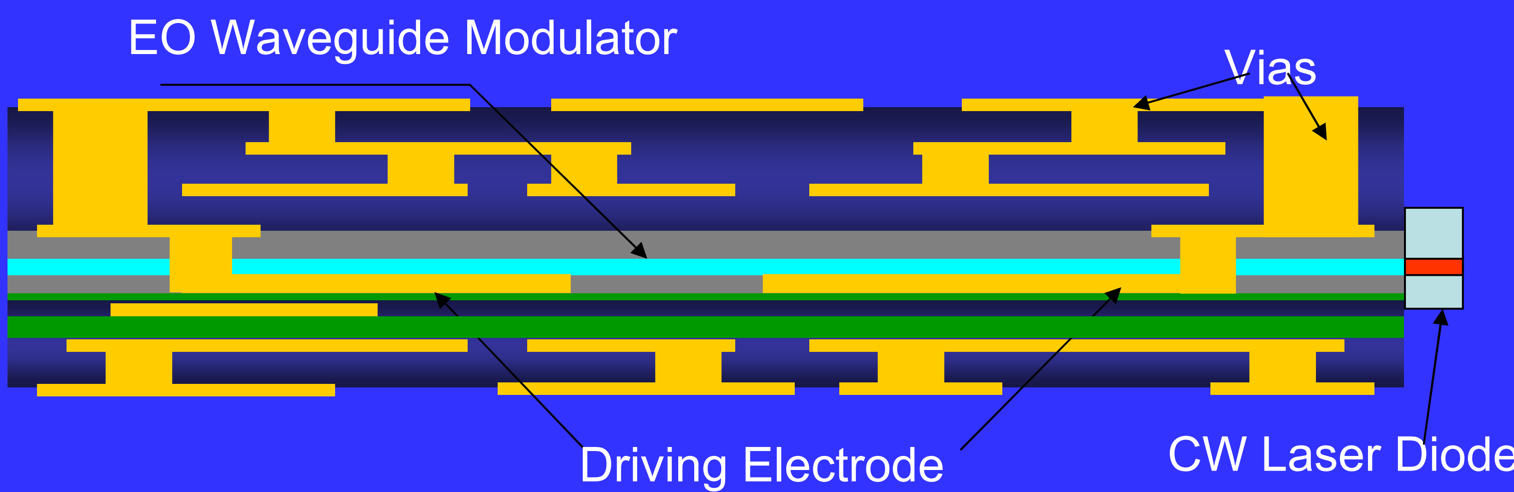


Opal, the best known periodical structure in nature.



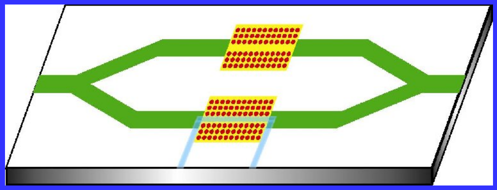


Schematic of Fully Embedded External Modulator for Analog Signal Transmission

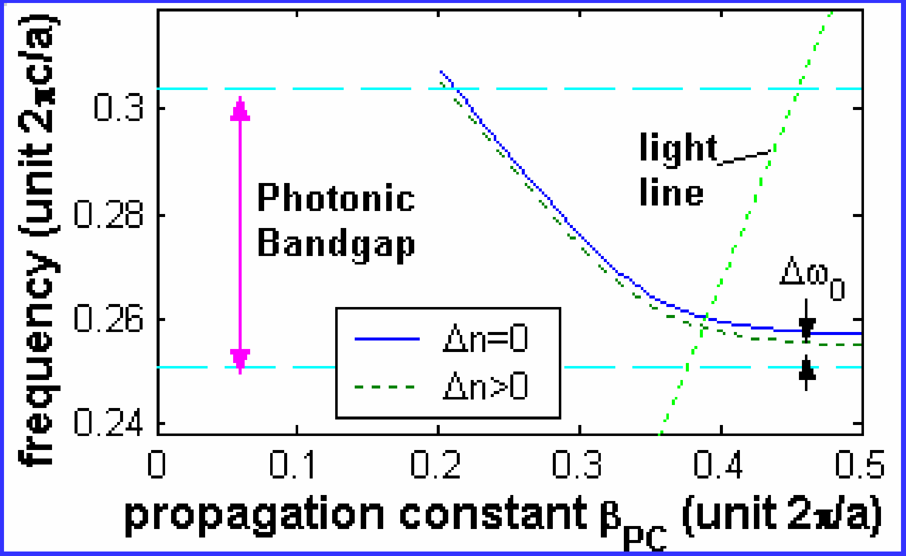


Fully-Embedded Silicon Thin Film Nano-Photonic Crystal Waveguide Modulator

- **In-plane structure: Photonic crystal waveguide**



- **High dispersion enhances modulation efficiency, up to 100 times**

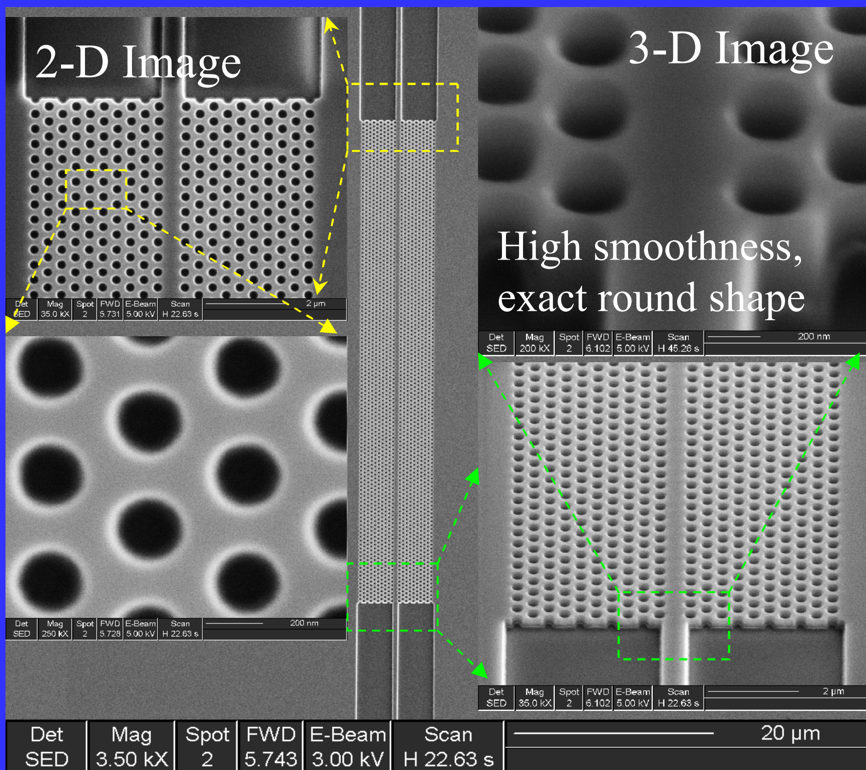


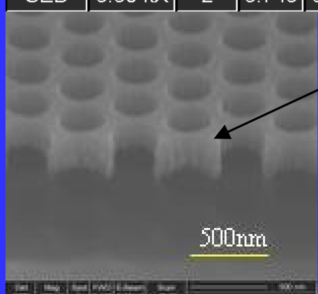
Key Performance Improvement

	Conventional Mach-Zehnder Modulator	*Proposed Si PCW Modulator*	*Improvement Factor*
Size	~ 4mm	~ 40 um	100 X reduction
Power consumption	~ 0.3 W	~ 0.01 W	10X to100X reduction
Integration	No integration potential	Potential for high density integration	N/A

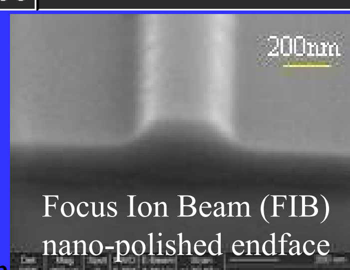
* Conventional Mach-Zehnder modulator performance represents typical specifications.

SEM Micrographs & Key Facilities





Rough sidewall without post-etching oxidation

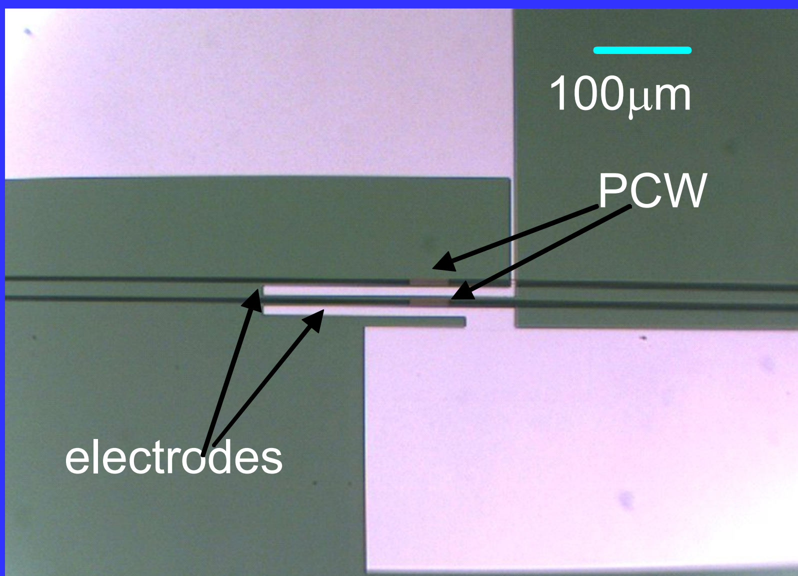


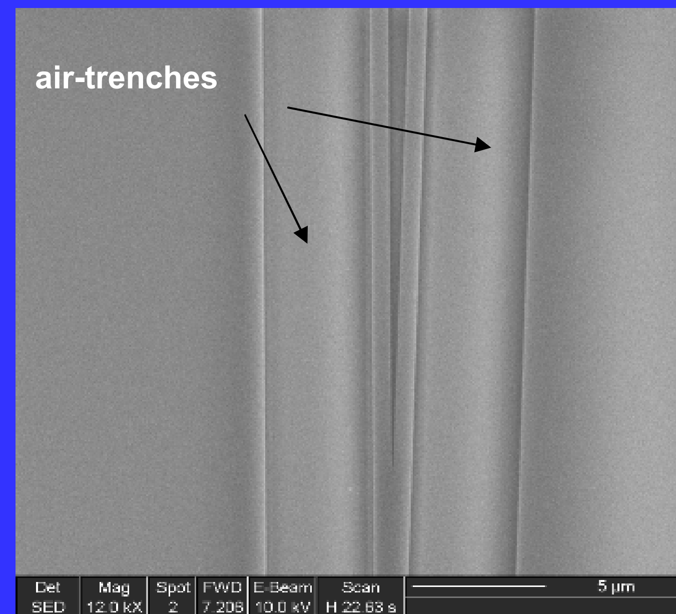
JEOL JBX-6000FS/E E-Beam Nano-Lithography

FEI Strata DB235
Dual Beam SEM/FIB
Nano-characterization System

Plama-Therm 790 Si and SiO_2 Reactive Ion Etching (RIE)

Photonic Crystal MZI Modulator

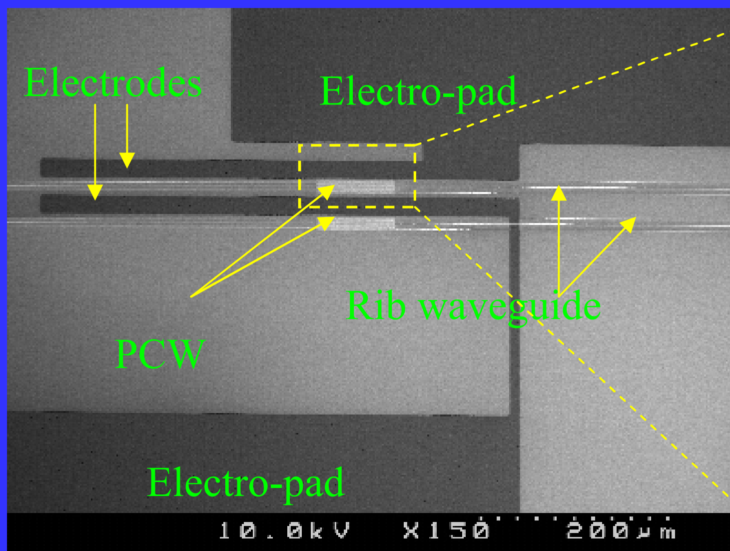


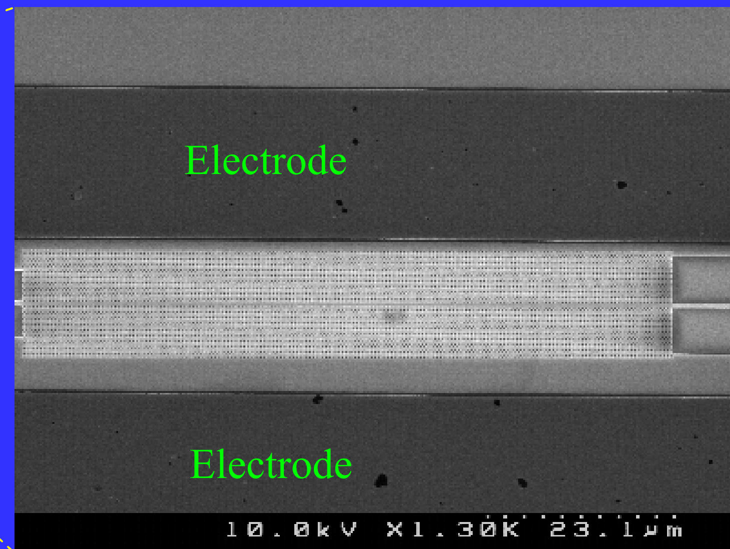


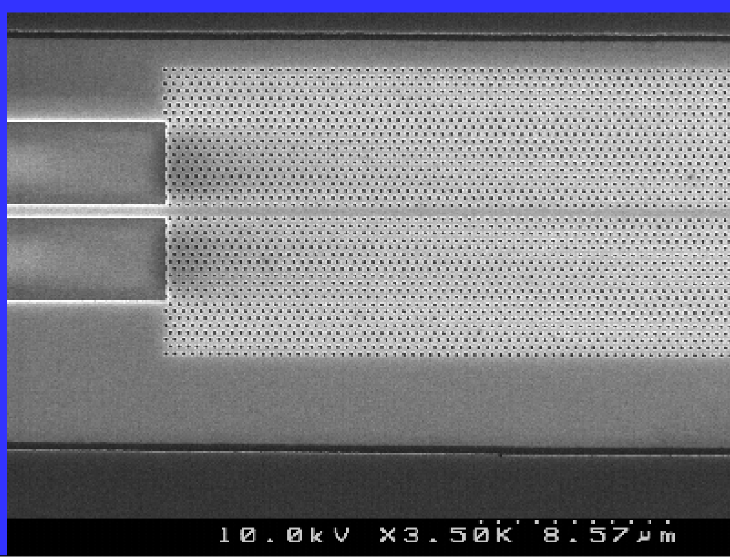
Micrographs of Mach-Zehnder(MZ) modulator: electrodes, pads, and photonic crystal waveguides (in lighter color)

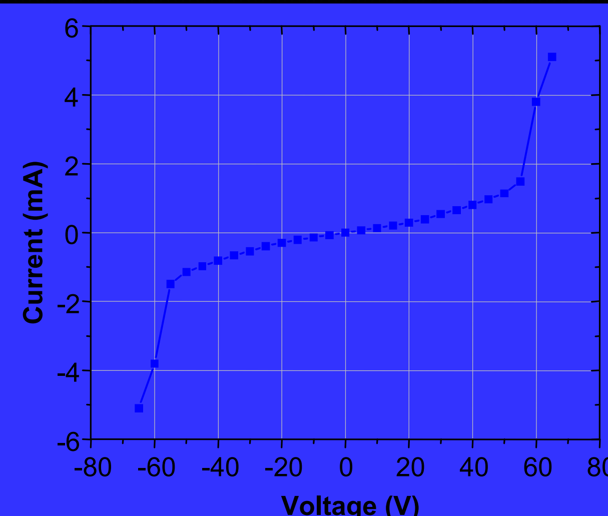
Y-junction of the MZ modulator, the rib waveguide splits as it extends up. Two 4μm wide air-trenches (etched through the entire upper silicon layer) separate the rib waveguides from the surrounding silicon.

Photonic Crystal MZI Modulator - more SEM micrographs

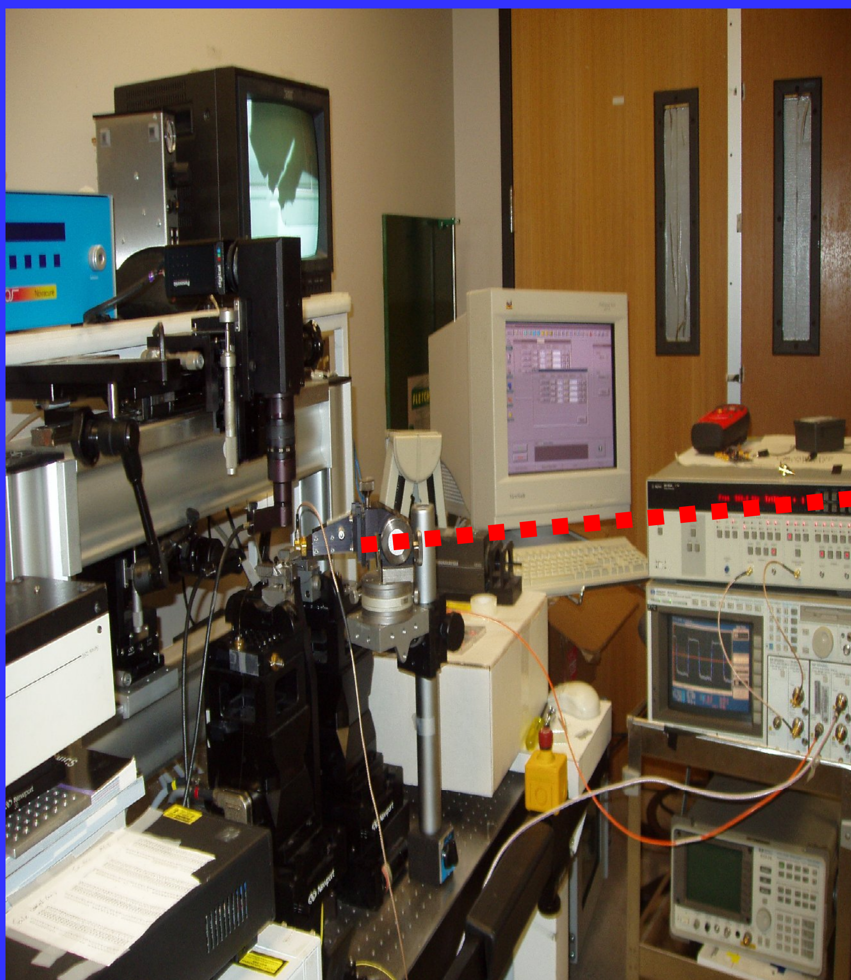








High-speed measurement set-up



Switching characteristics : Modulation traces

λ = 1541 nm and I_π = 7.1 mA

Modulation depth = 92 %

Operating wavelength: λ =1541 nm
Applied voltage: V_{on} = 2 V, V_{off} = -1 V

1 Gbit/sec