Optical Modulators for Transparent Analog Fiber Link

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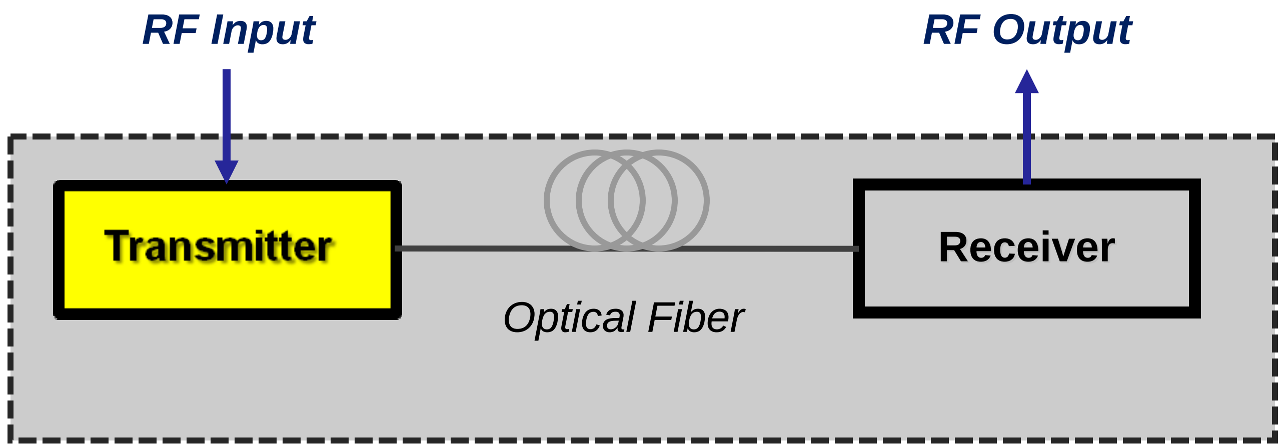
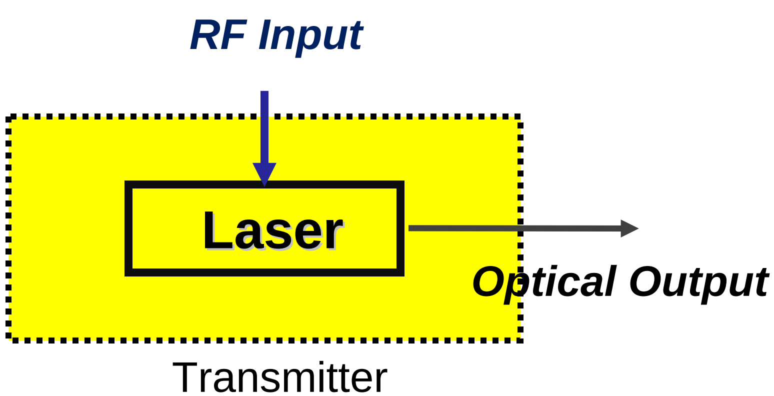
Outline of Presentation

- Introduction: Analog fiber link
- Electroabsorption Modulator
- Multiple Quantum Wells and Gain Saturation
- Large SFDR modulation
- E-O effect in InP nanowires
- Conclusion

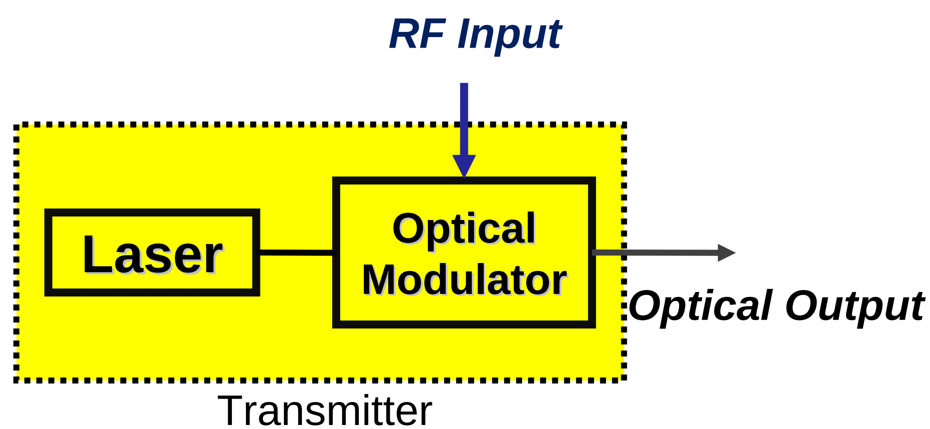
Analog Fiber-Optic Link



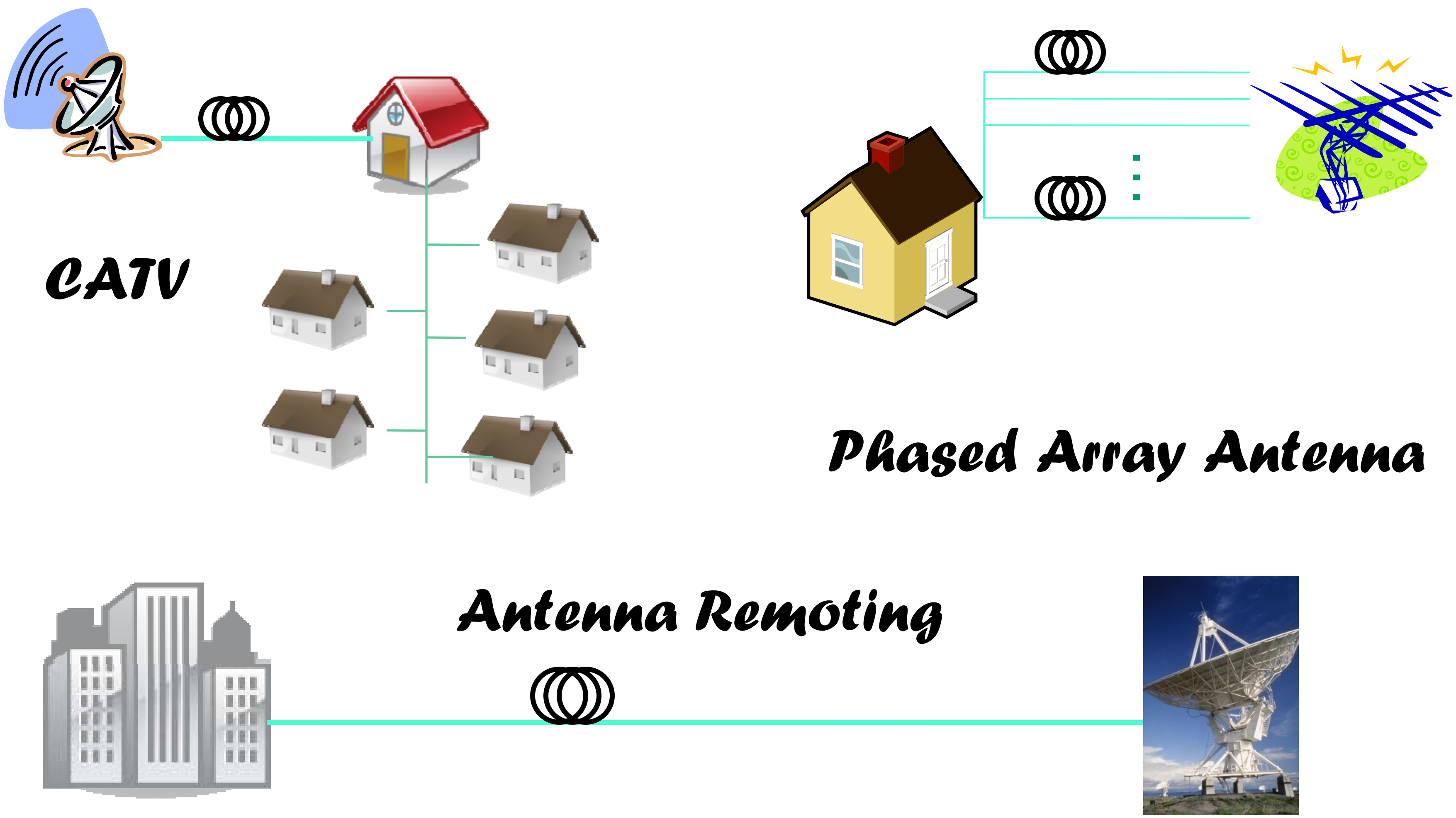
Direct Modulation



External Modulation



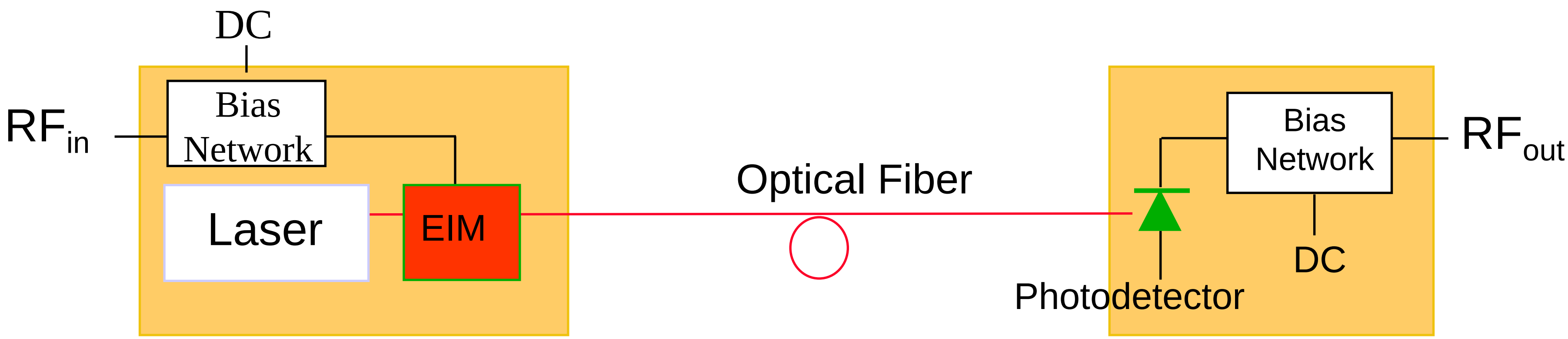
Analog Fiber-Optic Link Applications



Externally Modulated Analog Fiber Optics Link

UCSD

Externally Modulated Link



EIM= External Intensity Modulator

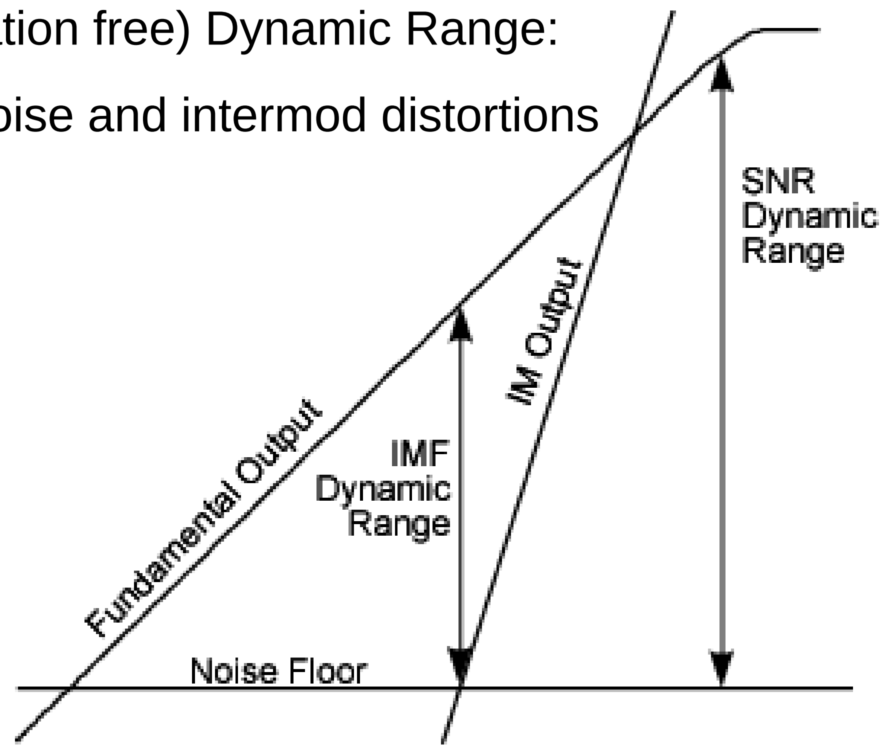
- Avoids the relaxation oscillation and reduces the chirp of the direct modulated laser diode; good for wide bandwidth modulation.

- Link RF gain, $G \sim (P_{opt})^2$

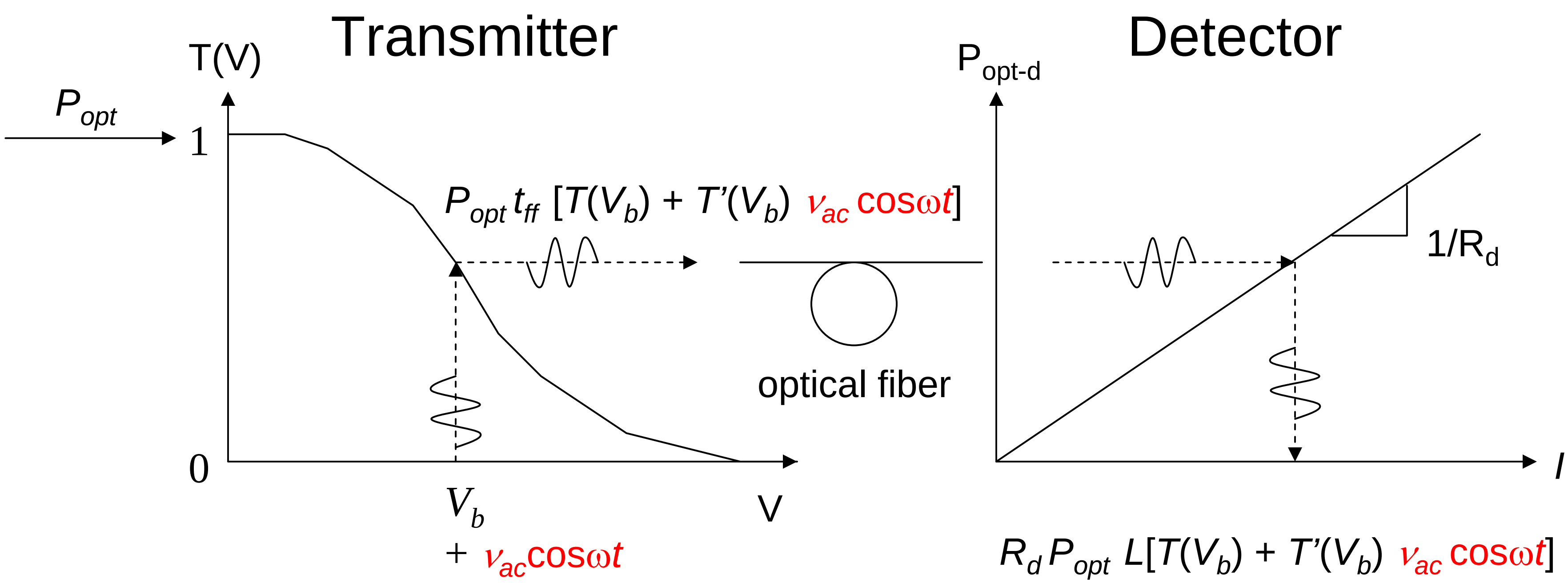
Important Analog Link Parameters

1. RF Gain: Output RF power/Input RF power
2. Bandwidth: 3 dB RF gain cut-off frequency bandwidth
3. Noise Figure: Input SNR/Output SNR
4. Spurious Free (or Intermodulation free) Dynamic Range:

   RF power range above noise and intermod distortions



RF Gain of the External Intensity Modulated link



$$G = \frac{P_{RF-out}}{P_{RF-in}} \propto P_{opt}^{\ 2}\left[T'(V_b)^2\right]\cdot\left[L_f\right]\cdot\left[R_d^2\right]$$

Modulator Detector

$$G = P_{opt}^{\ 2}\left[\frac{\pi^2 t_{ff}^2 R_{in}}{V_\pi^2}\right]\cdot L_f^{\ 2}\cdot\left[R_d^2 R_{out}\right]$$

where equivalent V_π

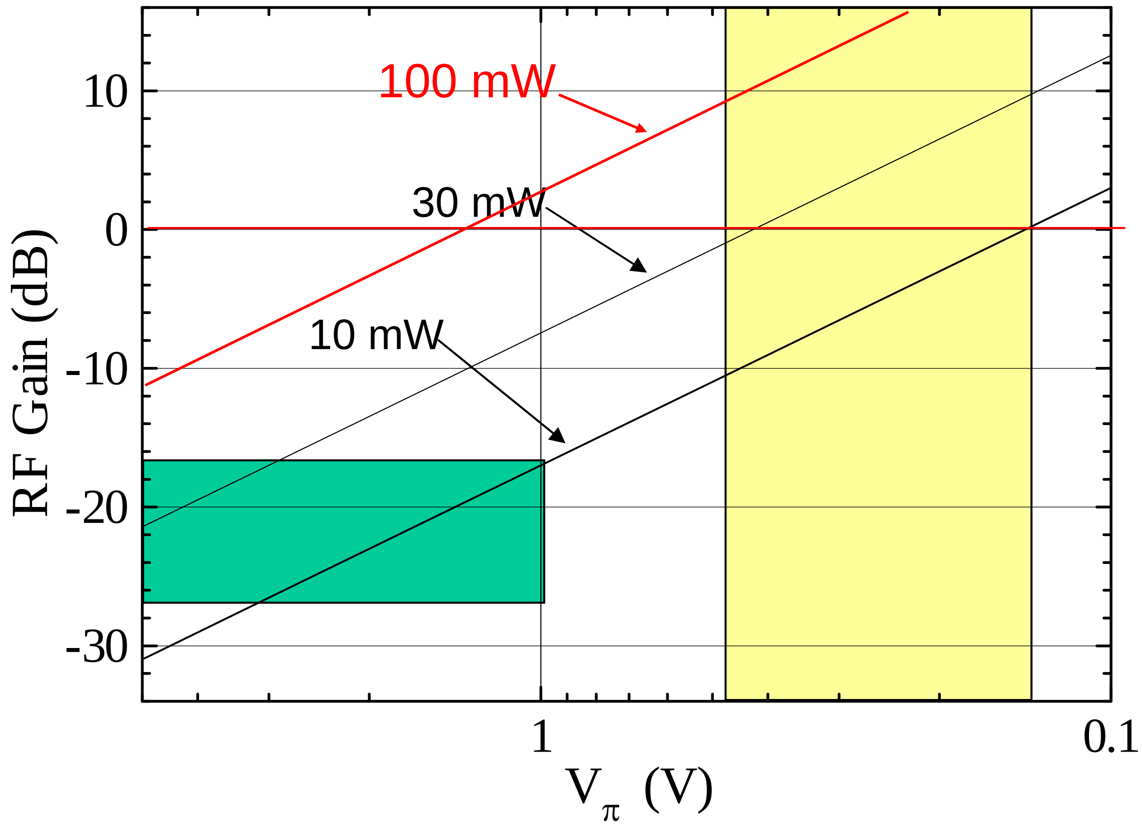
$V_\pi = \pi/(2\ dT/dV)$,

RF Gain as a function of V_π at different optical powers

η_{ins} = 0.1;

η_d = 1 A/W

L_f = 1

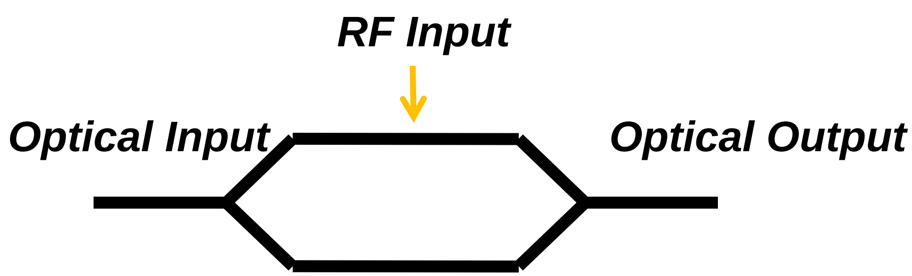


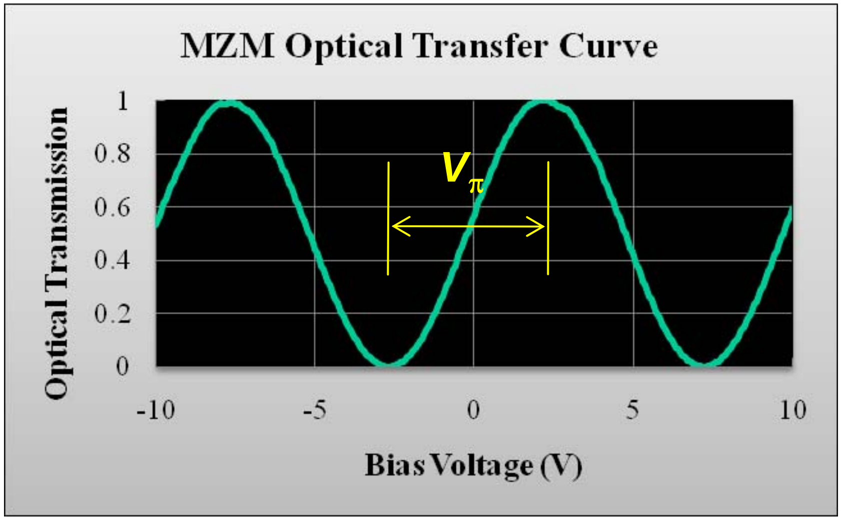
External Modulator Candidates

Electro-optic Modulator:
(a) Lithium Niobate
(b) Semiconductor
(c) Polymer (large r's)

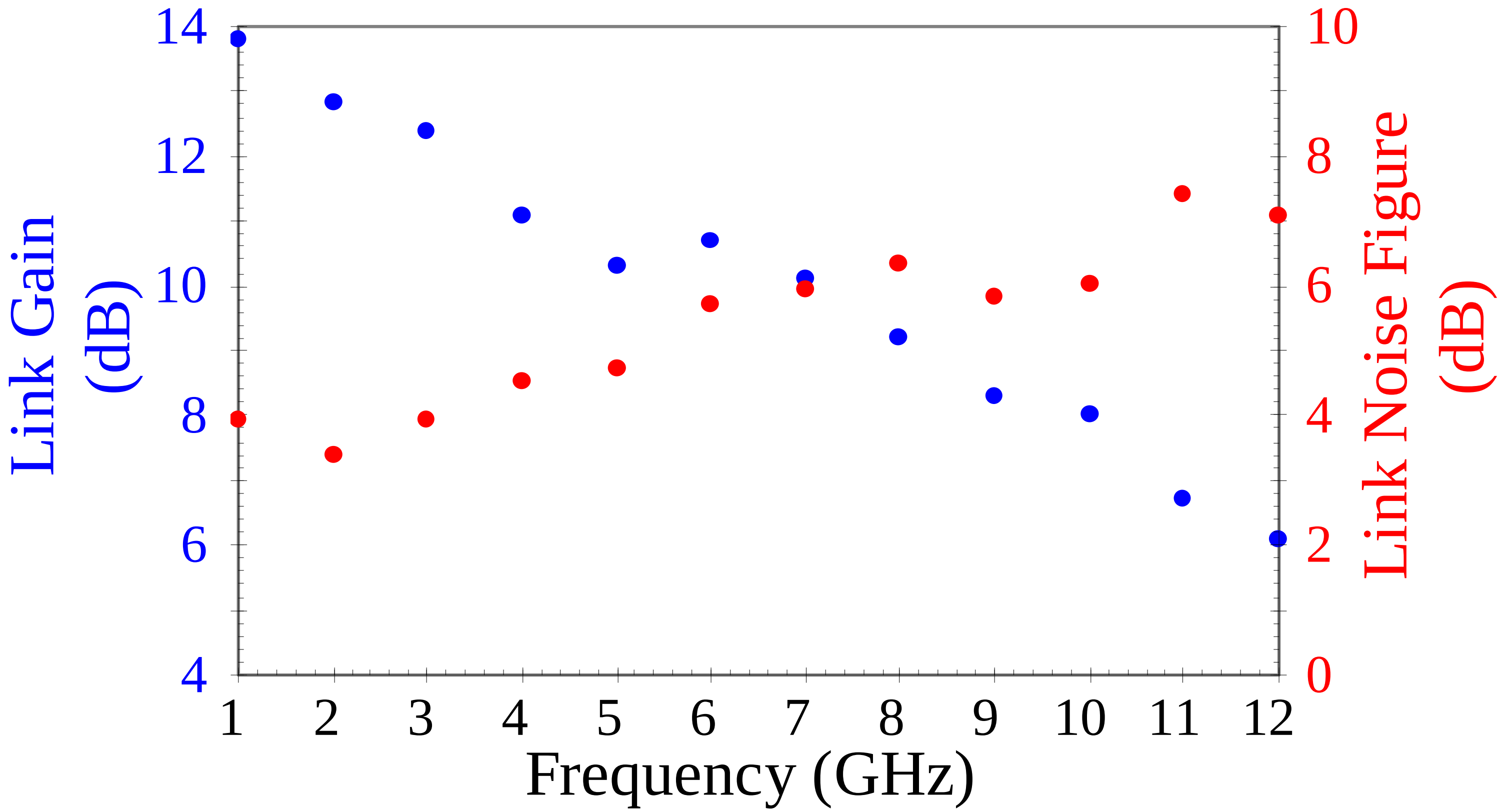
Semiconductors typically have smaller EO coefficients; one can also exploit the effects near a bandgap. We will describe those in nanowires

Electrooptic Modulator





State-of-the-Art $LiNbO_3$ Externally Modulated Link



*** Courtesy of Ed Ackerrman, PSI**

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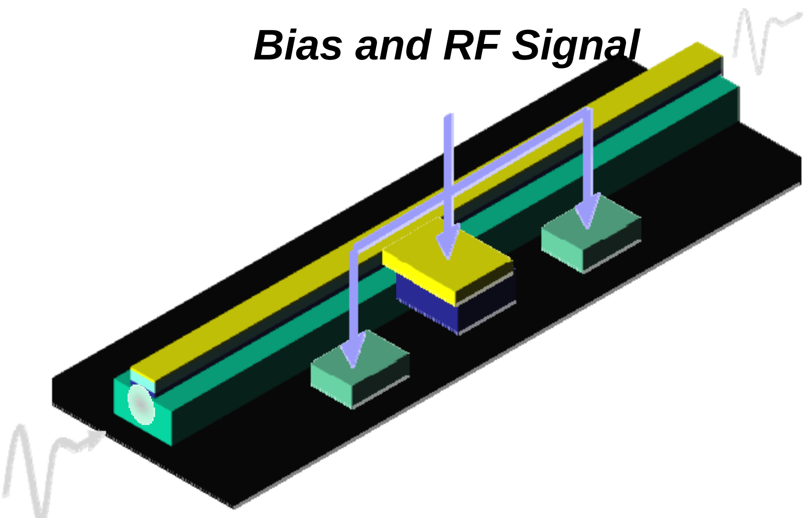
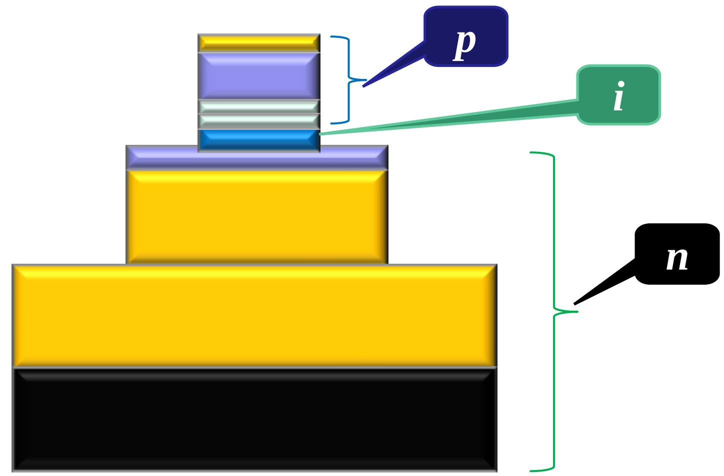
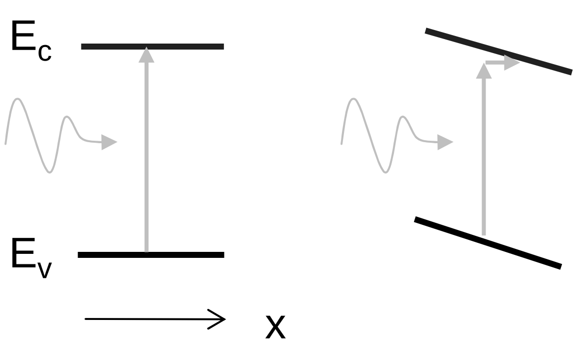
Electroabsorption Modulator

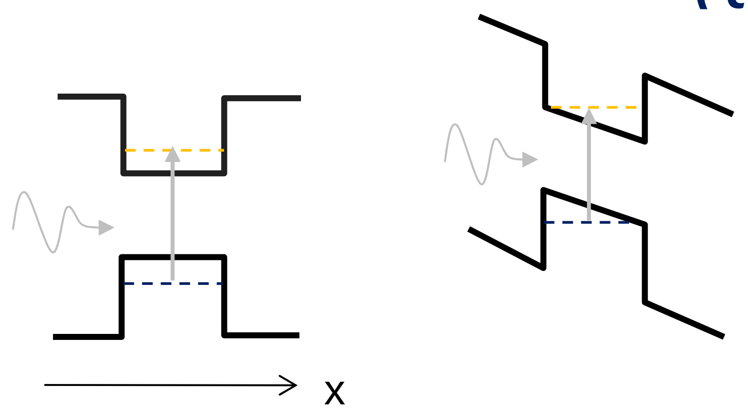




Franz-Keldysh Effect (FKE)



Quantum Confined Stark Effect (QCSE)



Semiconductor Electroabsorption Waveguide Modulators

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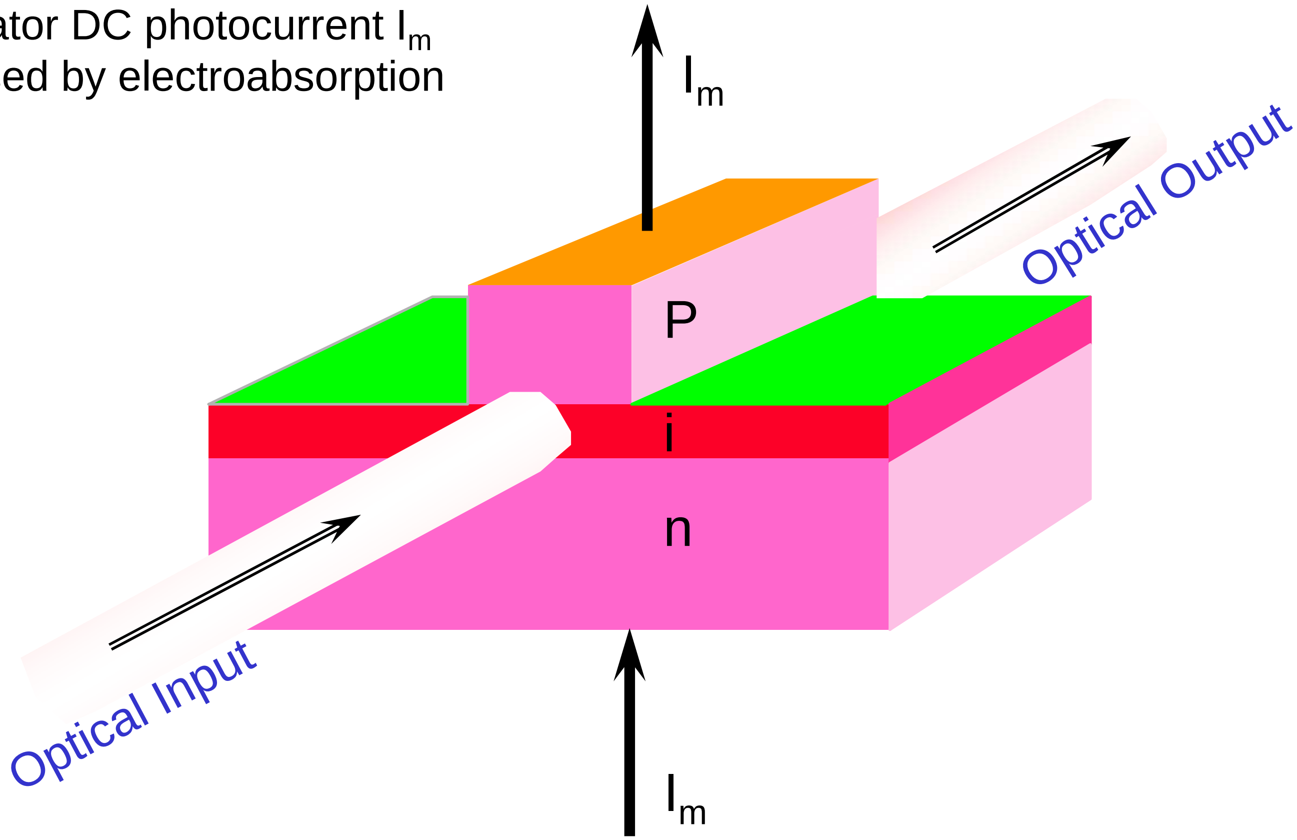
Modulator DC photocurrent I_m
is caused by electroabsorption



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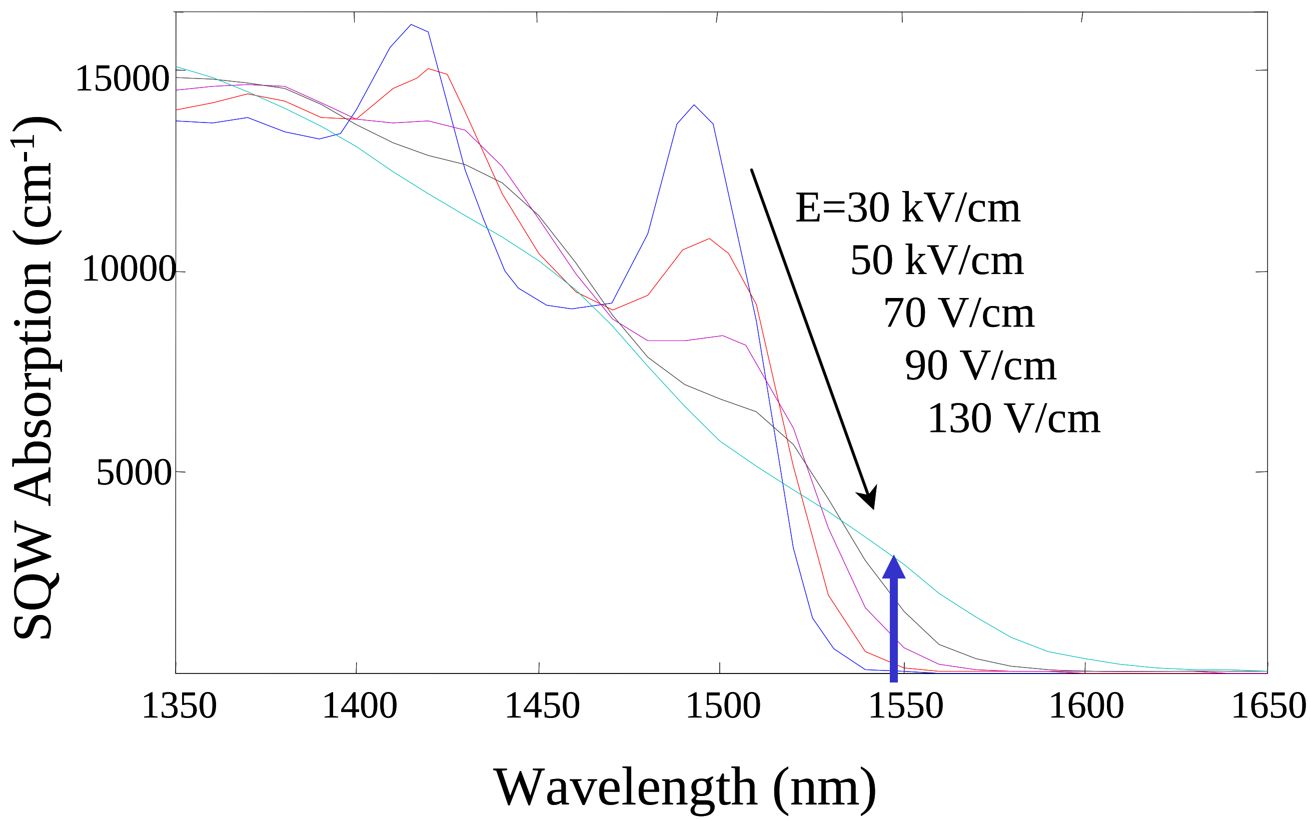
Broadened optical absorption spectra of a quantum well



Design Strategy for achieving High Link Gain

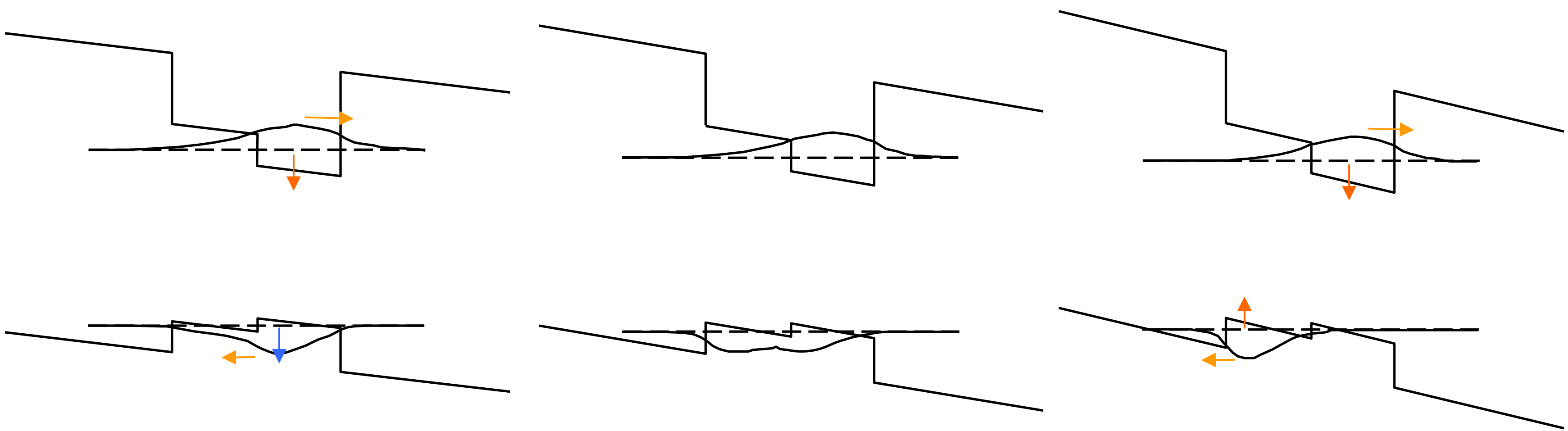
UCSD

$$G = P_{opt}{}^{2}\left[\frac{\pi^{2} t_{ff}^{2} R_{in}}{V_{\pi}^{2}}\right]\cdot L_{f}{}^{2}\cdot\left[\mathrm{R}_{d}^{2} R_{out}\right]$$

- To overcome the RC bandwidth limit with minimum reduction of the modulation efficiency.
- To achieve high RF link gain, high power operation with good coupling to fiber is needed.
- Low optical residual propagation loss to ensure small insertion loss.
- Large optical/microwave field interaction volume to ensure low V_{π}, hence high RF link gain.

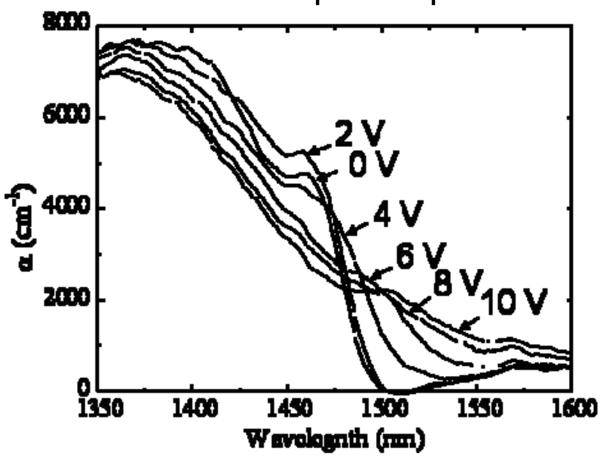
Intra Step Quantum Well (IQW)

← Electric field

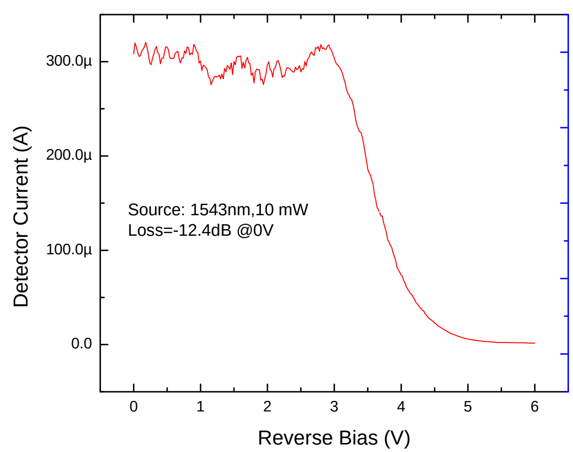


F = 100 kV/cm | F = 140 kV/cm | F = 200 kV/cm

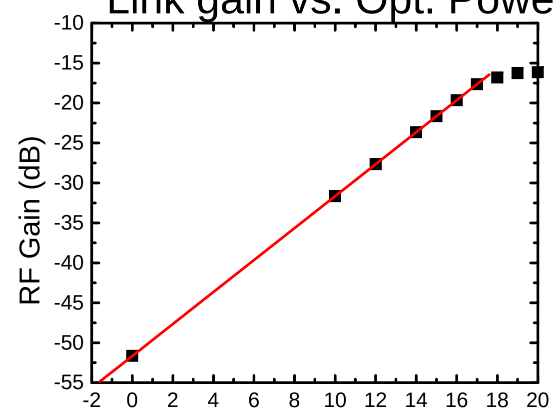
Electroabsorption Spectrum



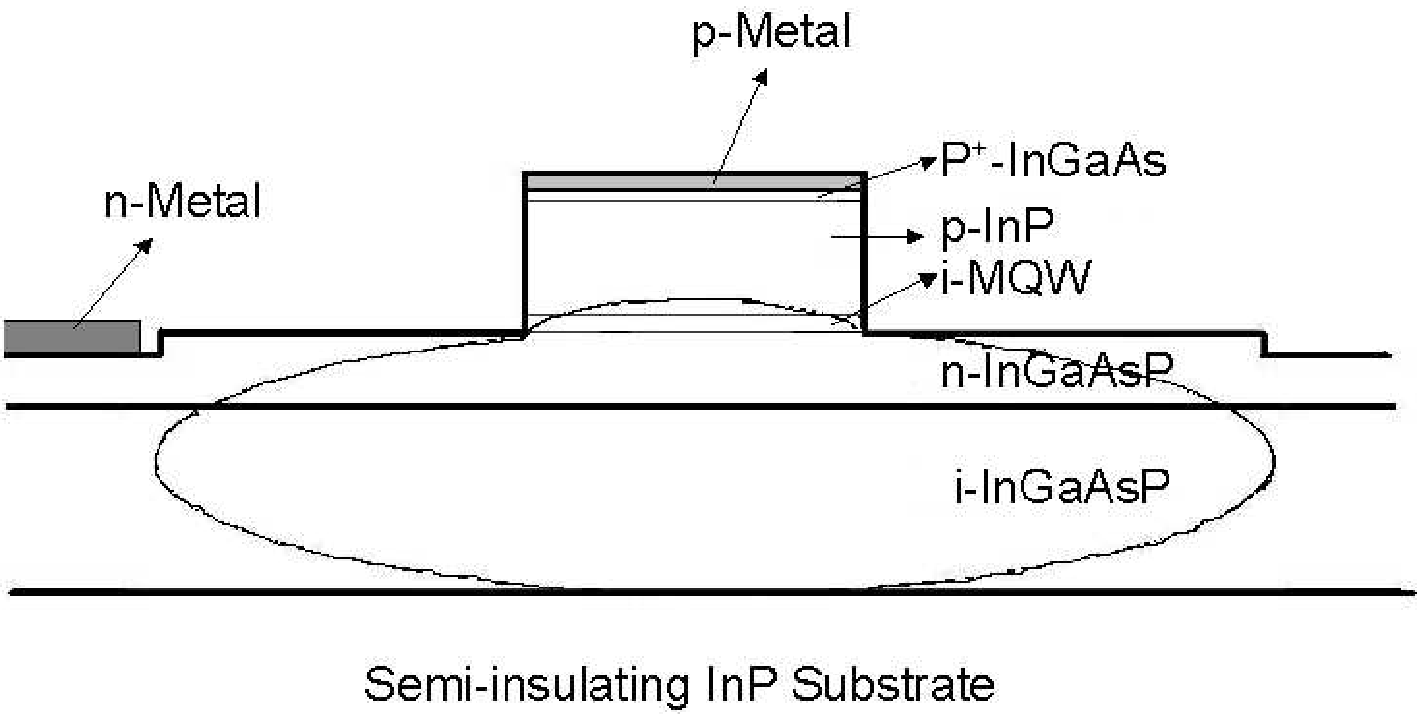
Transfer curve



Link gain vs. Opt. Power



Peripheral Coupled Waveguide Electro-absorption Modulator

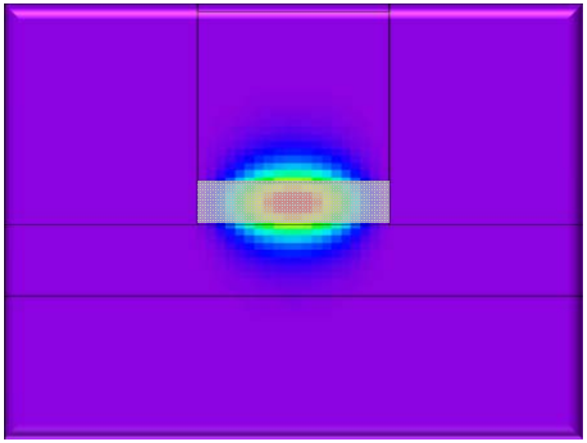


- Small confinement factor !!

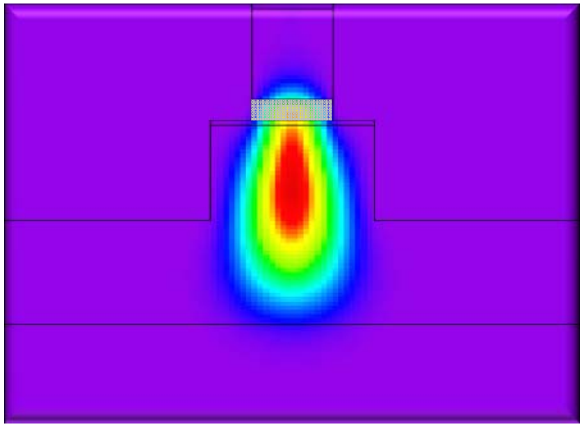
By placing the active absorption layer in the evanescent portion of the optical mode, we can decouple the optical waveguide design & electroabsorption material design.

Optical Mode and Confinement Factor in EAM

Typical EAM



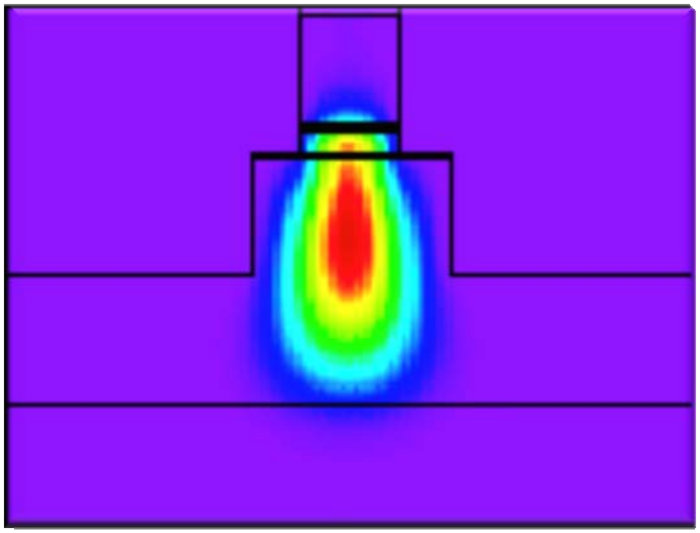
PCW EAM



Confinement factor Γ: the ratio of optical power within the active absorption layer.

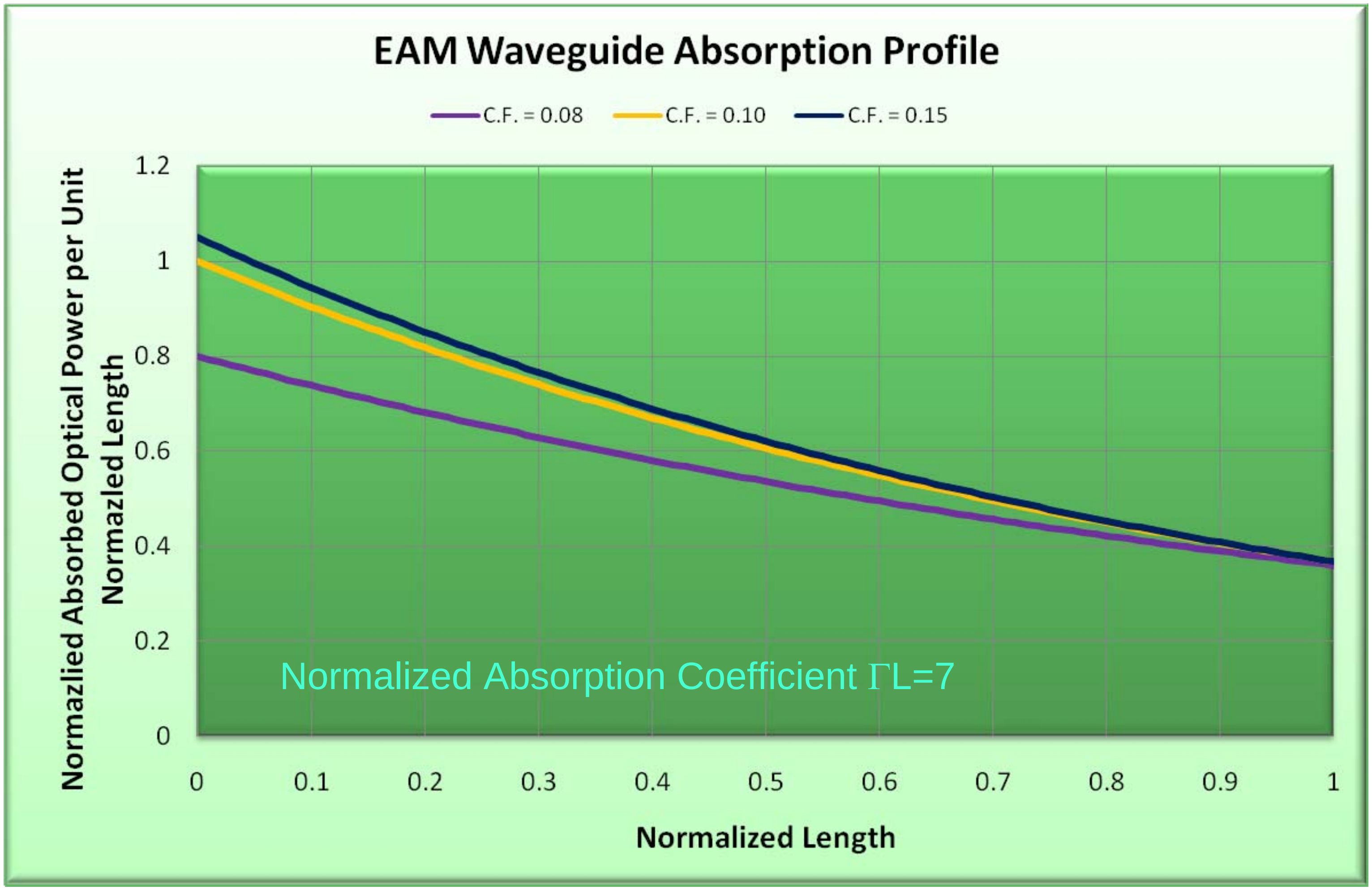
- Smaller confinement factor
- Larger optical mode
- Smaller scattering loss
- Decoupling between optical and microwave waveguide

Reducing Insertion Loss

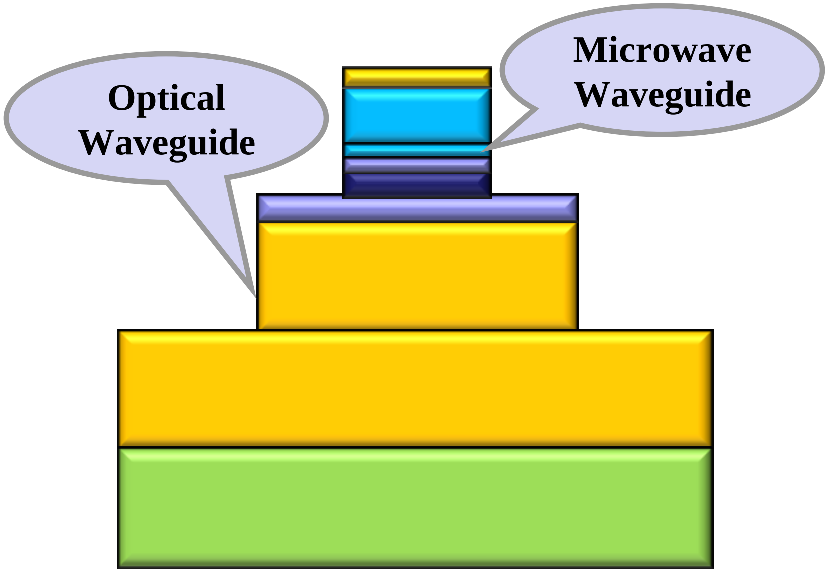


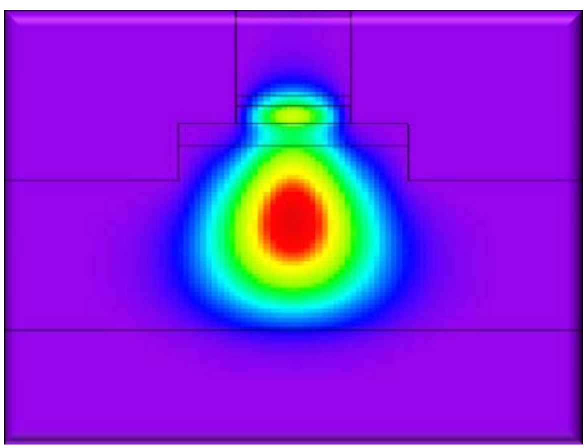
- Large optical mode improves fiber to EAM coupling to be around 2 dB per facet;
- Submerged mode reduces scattering loss;
- Small confinement factor reduces propagation loss with best result of 0.8 dB/mm;
- Best fiber-to-fiber loss was measured to be 4 dB.

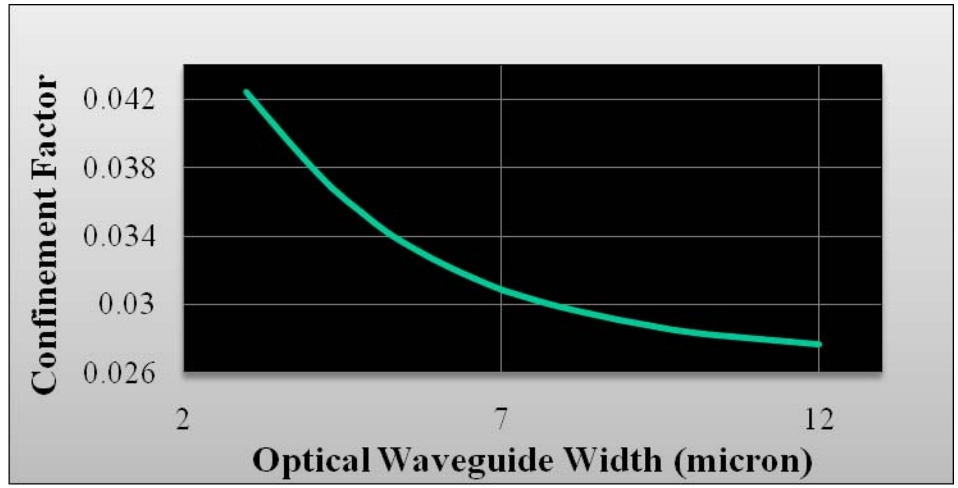
Absorption along EAM Waveguide

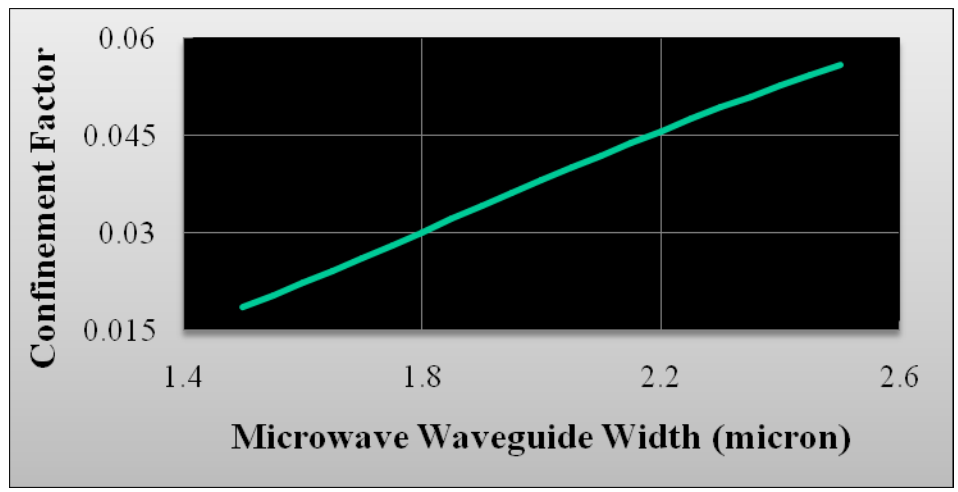


PCW EAM Waveguide Design



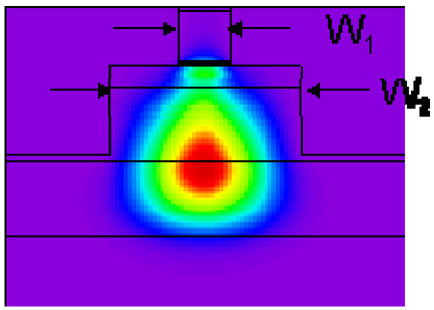


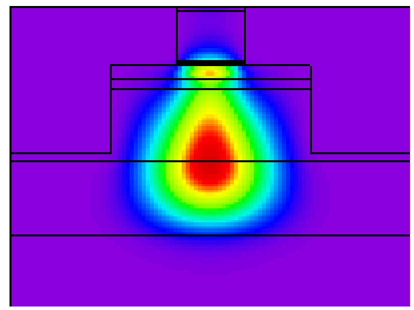


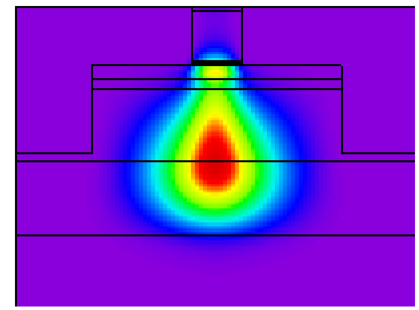


Peripheral Coupled Waveguide EA modulator

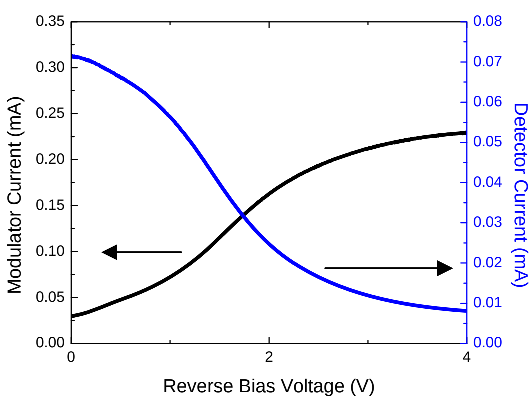
W_1=1.5μm, W_2=W_1+4μm	W_1=2μm, W_2=W_1+4μm	W_1=2μm, W_2=W_1+8μm

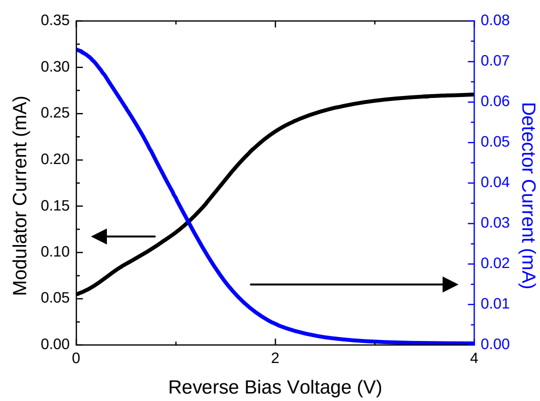


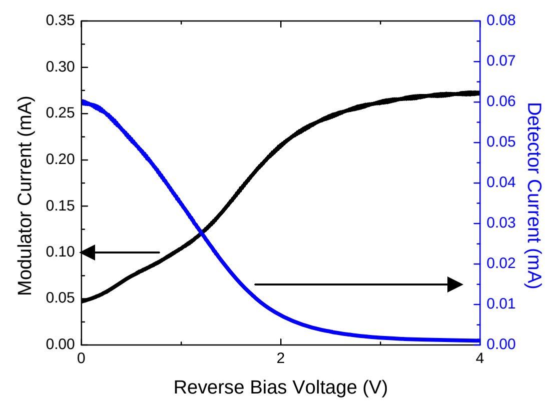




Confinement factor. = 2.64% | 4.26% | 3.44%



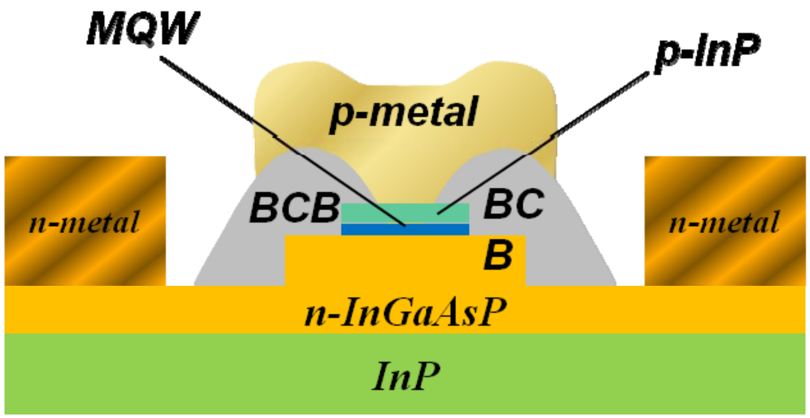


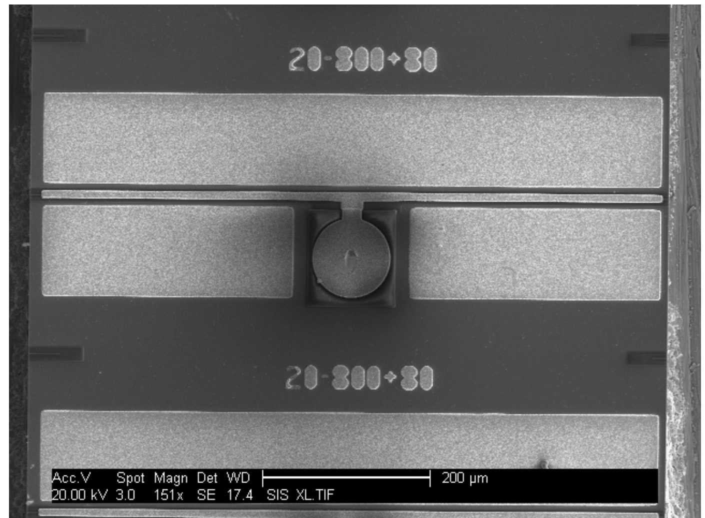


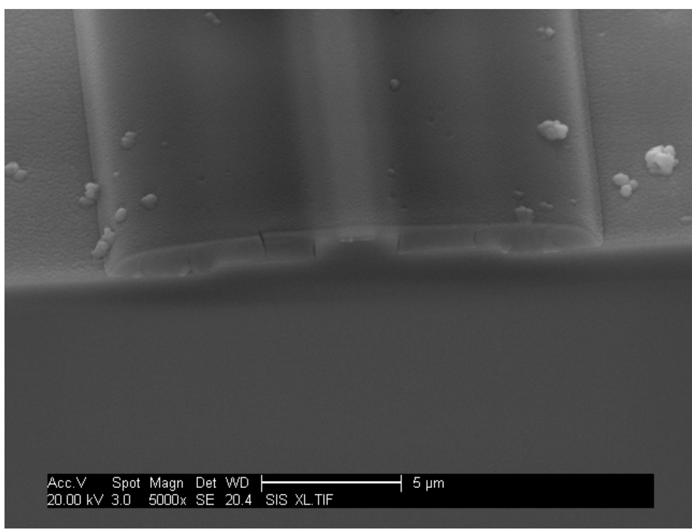
Propagation loss =0.97dB | 2.09dB | 1.43dB

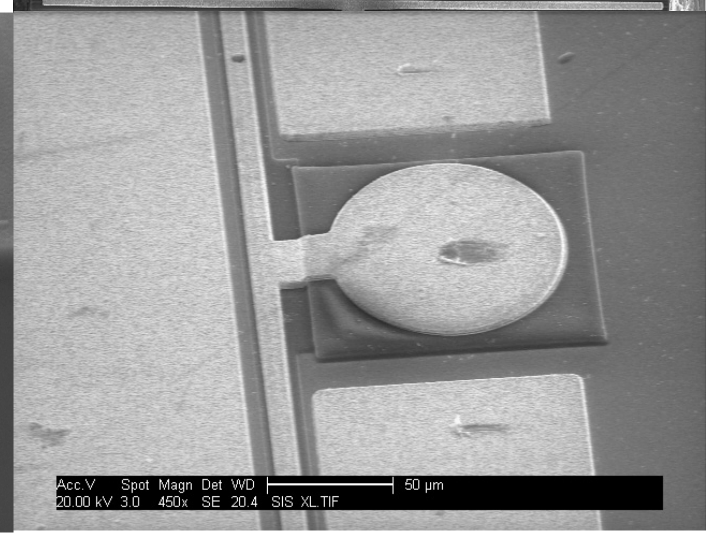
(length = 1.2 mm)

Fabricated PCW EAM



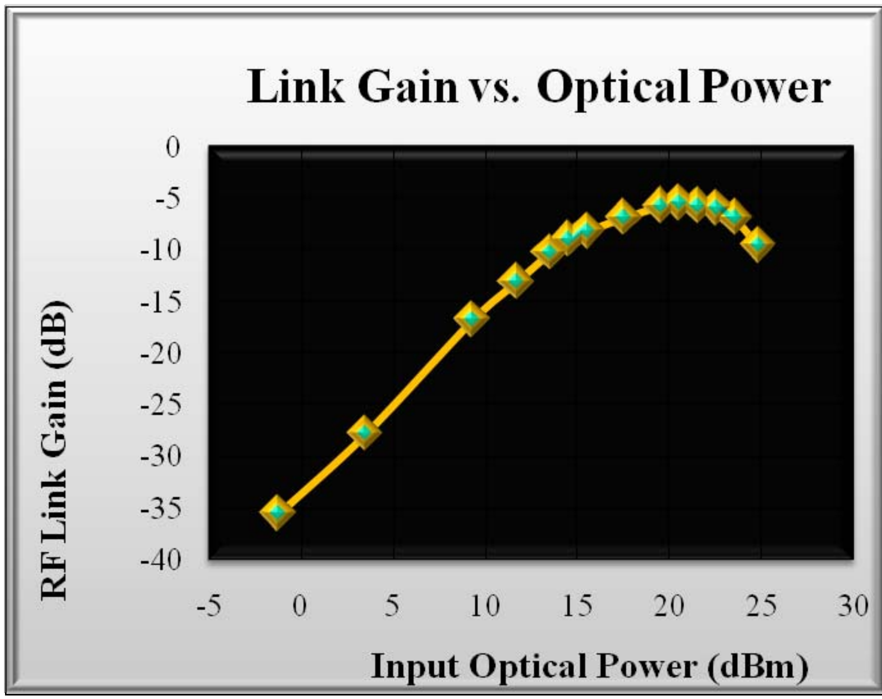


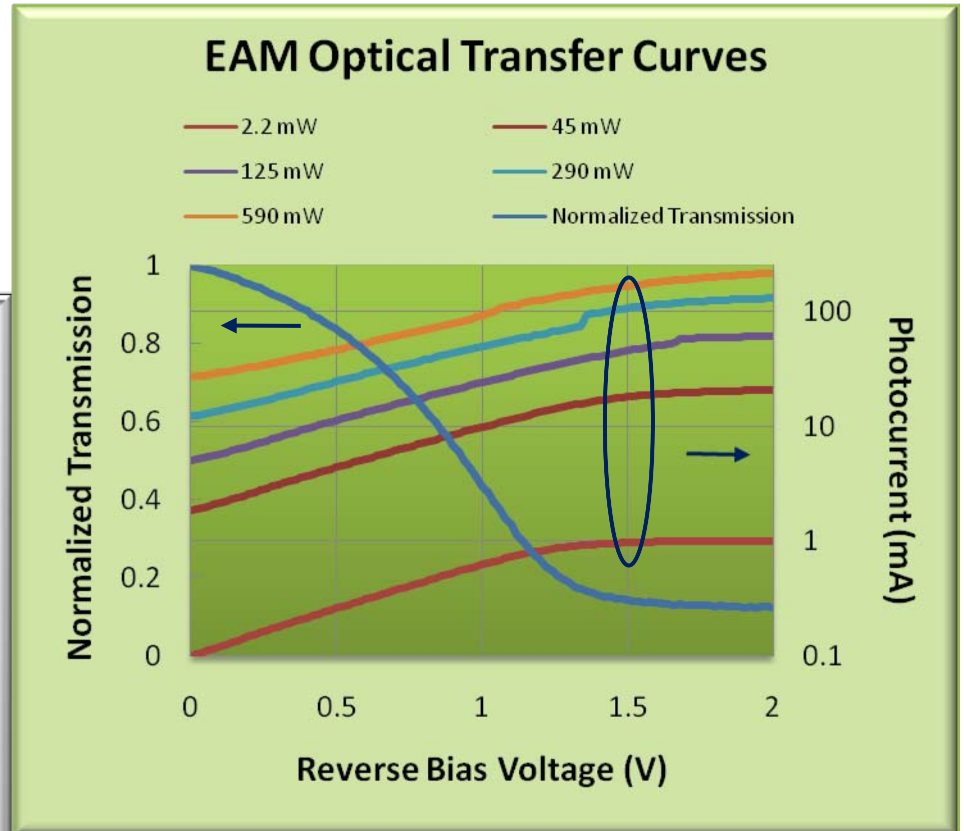




High Power EAM

Link gain higher close to transparency

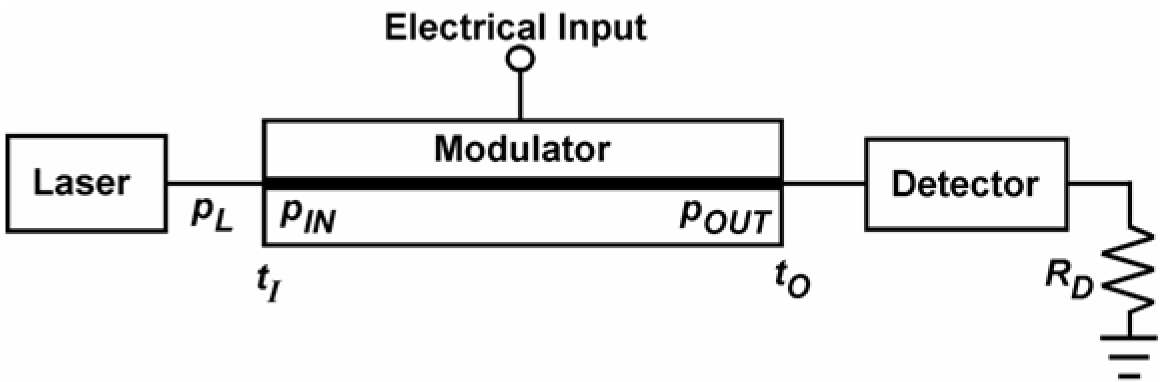




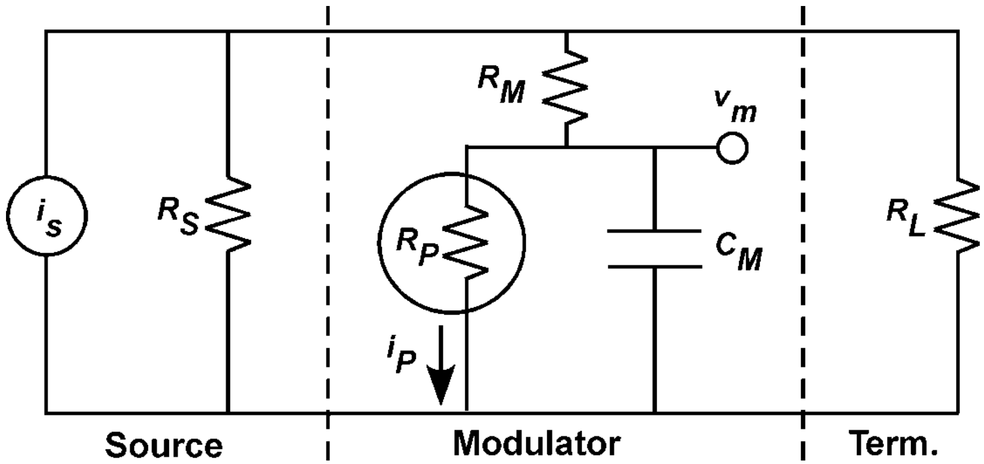
590 mW input optical power
222 mA photocurrent

Gain Limitation of EM modulator

Analog fiber link



Small-signal Equivalent circuit of EA Modulator: Effect of Modulator Photocurrent



Analysis of photocurrent feedback effect on Gain

For simplicity, consider low frequency modulation, the effect of C_p, C_M L's can be neglected, defining η_m as the modulator photocurrent efficiency:

The modulator photocurrent at the biasing point is given by:

$$i_P = p_{IN}\eta_M(1 - t_B) + \underline{p_{IN}\eta_M \frac{\pi}{2V_{\pi e}} v_m}$$

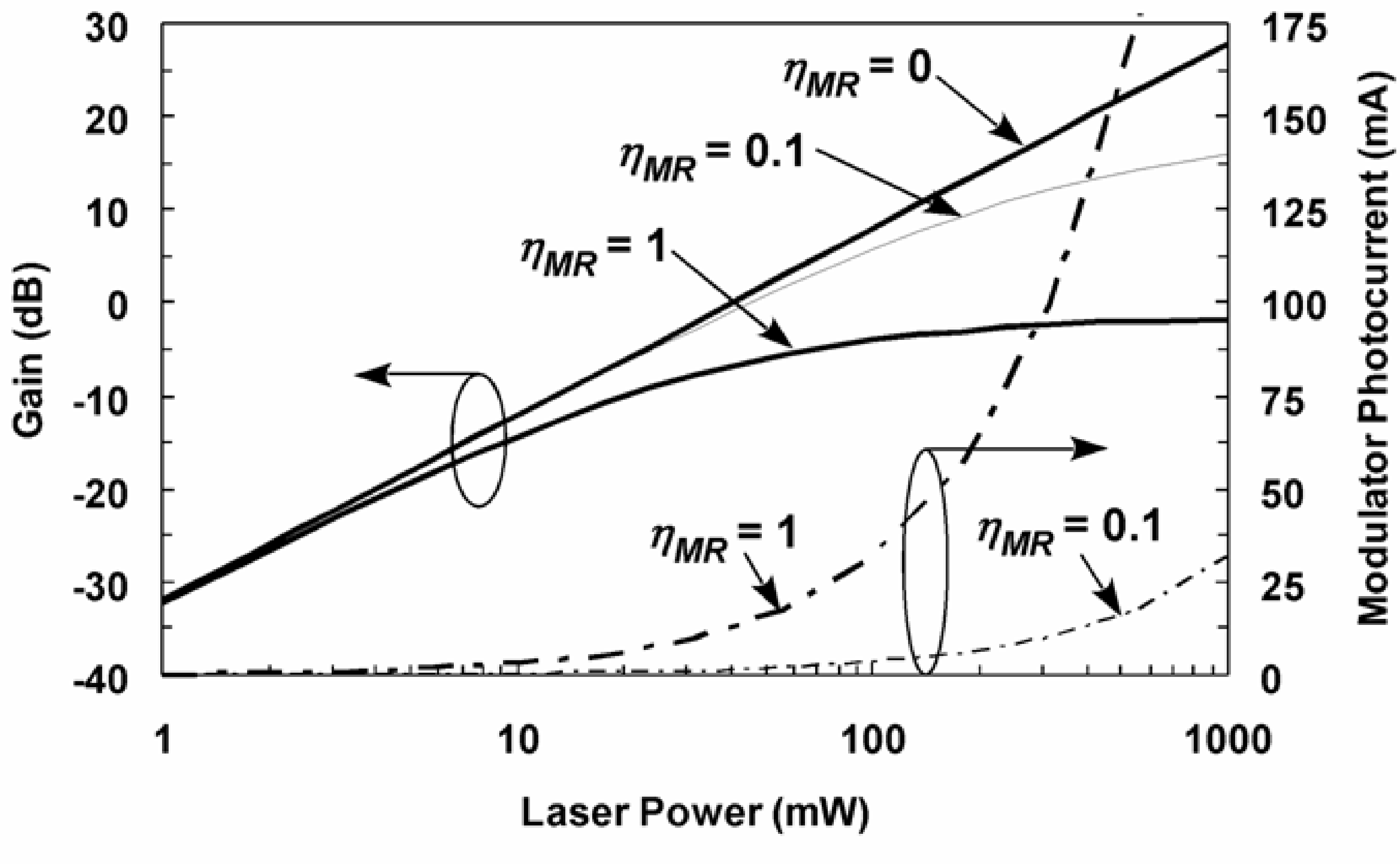
We can define an effective small-signal ac photocurrent resistance R_P:

$$R_P = \frac{2V_{\pi e}}{p_L t_I \eta_M \pi}$$

It is seen that as power go up, R_P decrease in value, therefore the link gain saturates under high power, reaching a limit independent of power or $V_{\pi e}$:

$$G \propto \left[\left(\frac{p_L}{V_{\pi e}}\right)^2\right]\left[\frac{1}{1 + \frac{1}{R_P}\left(R_M + \frac{R_L R_S}{R_L + R_S}\right)}\right]^2 \longrightarrow G_{Limit} = \left(\frac{t_O \eta_D}{\eta_M}\right)^2 \frac{4\frac{R_D}{R_S}}{\left(1 + \frac{R_M}{R_S} + \frac{R_M}{R_L}\right)^2}$$

Gain Saturation



G. E. Betts et al., PTL, 2006

Modulator Input Impedance

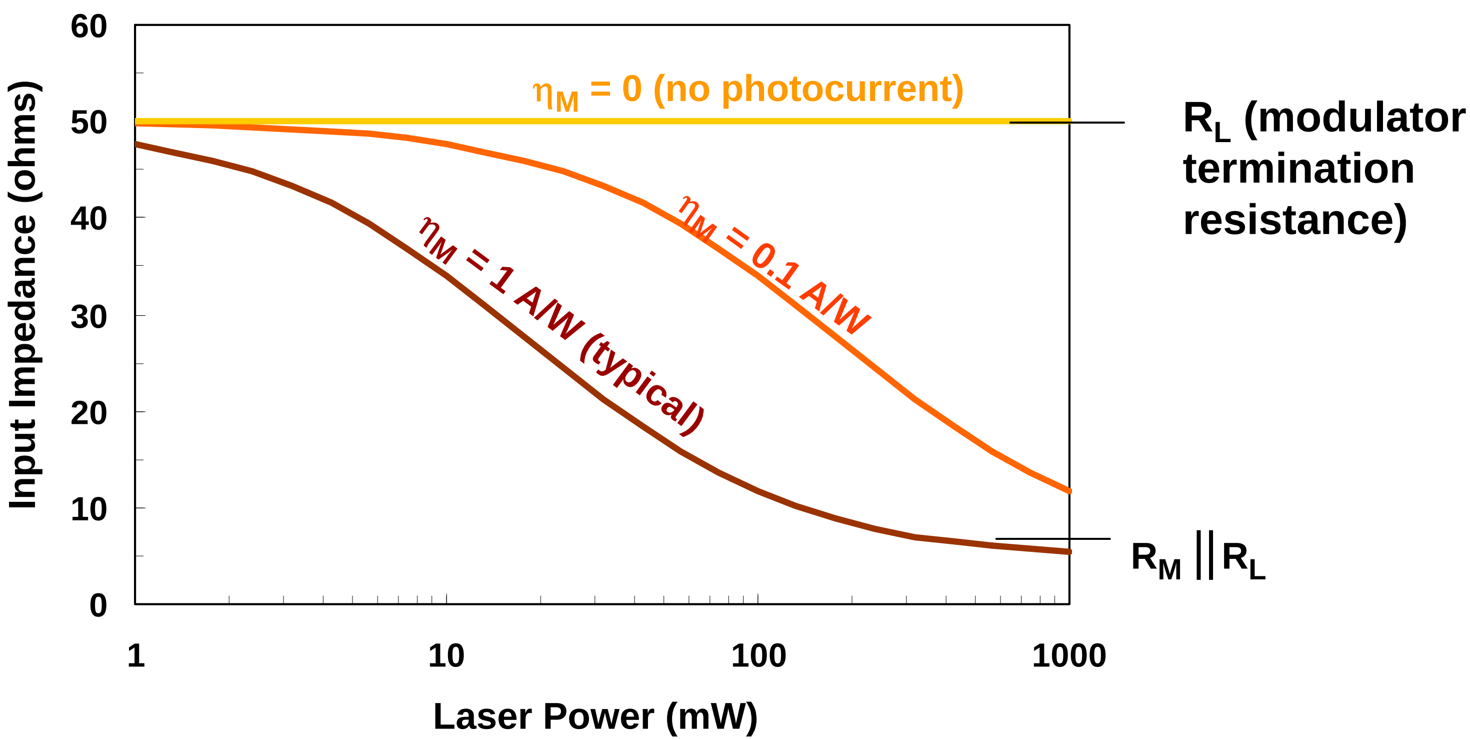
η_D = 0.8 A/W

$t_I = t_O$ = -2 dB

η_M = 1 A/W

R_L = 50 Ω

R_M = 5 Ω



As photocurrent becomes large, input impedance approaches modulator series resistance R_M

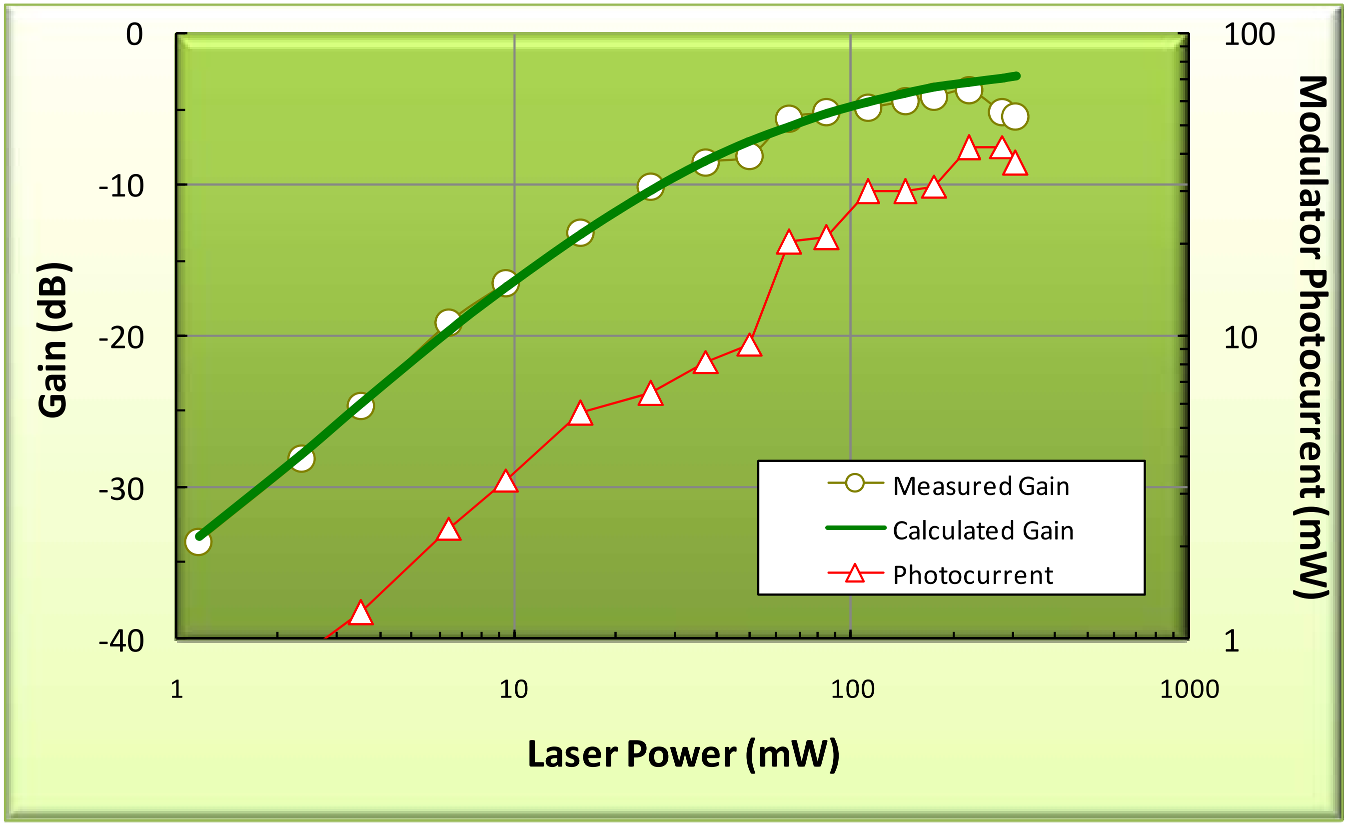
Experimental Verification of Photocurrent Effect

η_M = 0.8 A/W

η_D = 0.8 A/W

$t_I = t_O$ = -3 dB

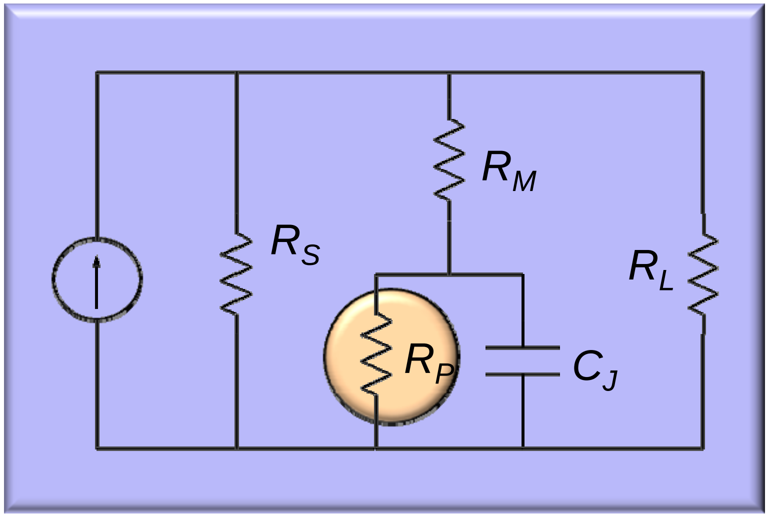
V_π = 0.85 V



Measured gain closely matches gain from model.

Possible solutions:

1. Blue shift Quantum Confined Stark Effect:



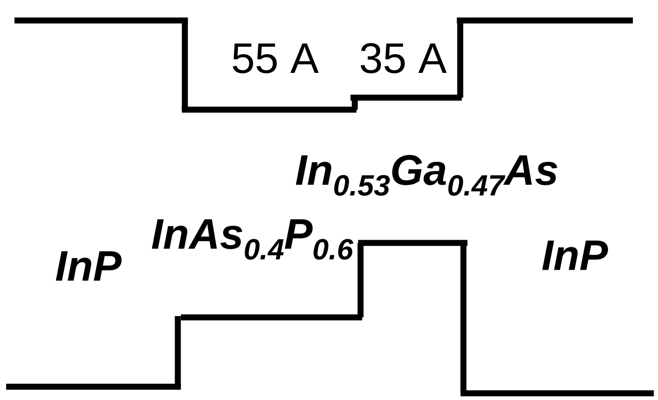
Red-shift (regular) QCSE EAM: positive equivalent resistance

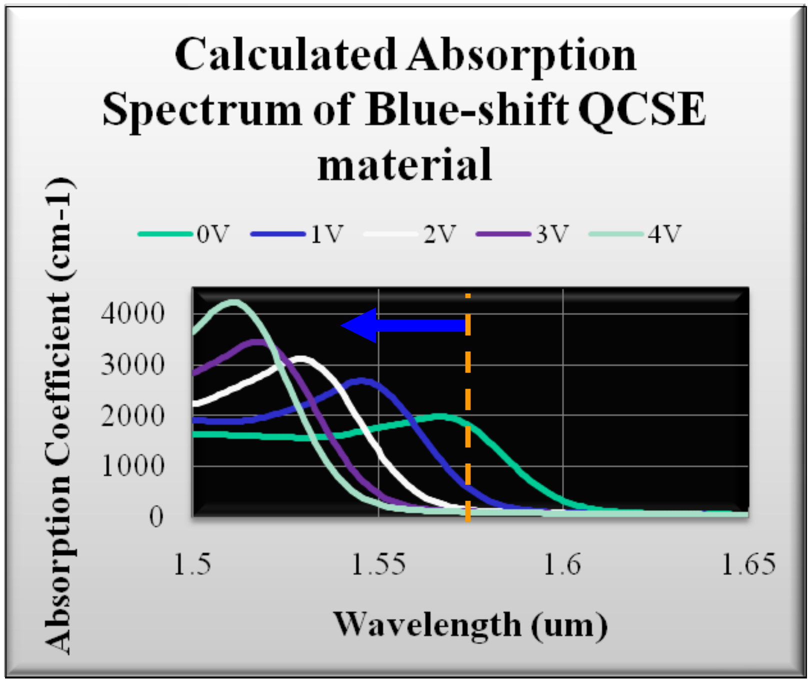
Blue-shift QCSE EAM: negative equivalent resistance

$$g = \left[\left(\frac{p_L t_I t_O \eta_D \pi}{2V_{\pi e}}\right)^2 R_D R_L\right]\left[\frac{4R_L R_S}{(R_L + R_S)^2}\right]\left[\frac{1}{1 - \frac{p_L t_I \eta_M \pi}{2V_{\pi e}}\left(R_M + \frac{R_L R_S}{R_L + R_S}\right)}\right]^2$$

Material Structures

Pre-biased quantum well structure for blue-shift QCSE





S.K. Haywood, *et al*., "Demonstration of a blueshift in type II asymmetric InP/InAsP/InGaAs multiple quantum wells," *Journal of Applied Physics*, Vol. 94, No. 5, pp. 3222-3228, September, 2003.

Possible Solutions (Cont'd)

2. By reducing the photocurrent generates inside the QWs.

This can be done via "defects", or by enhancing the probability that electrons and holes can combine through localization.

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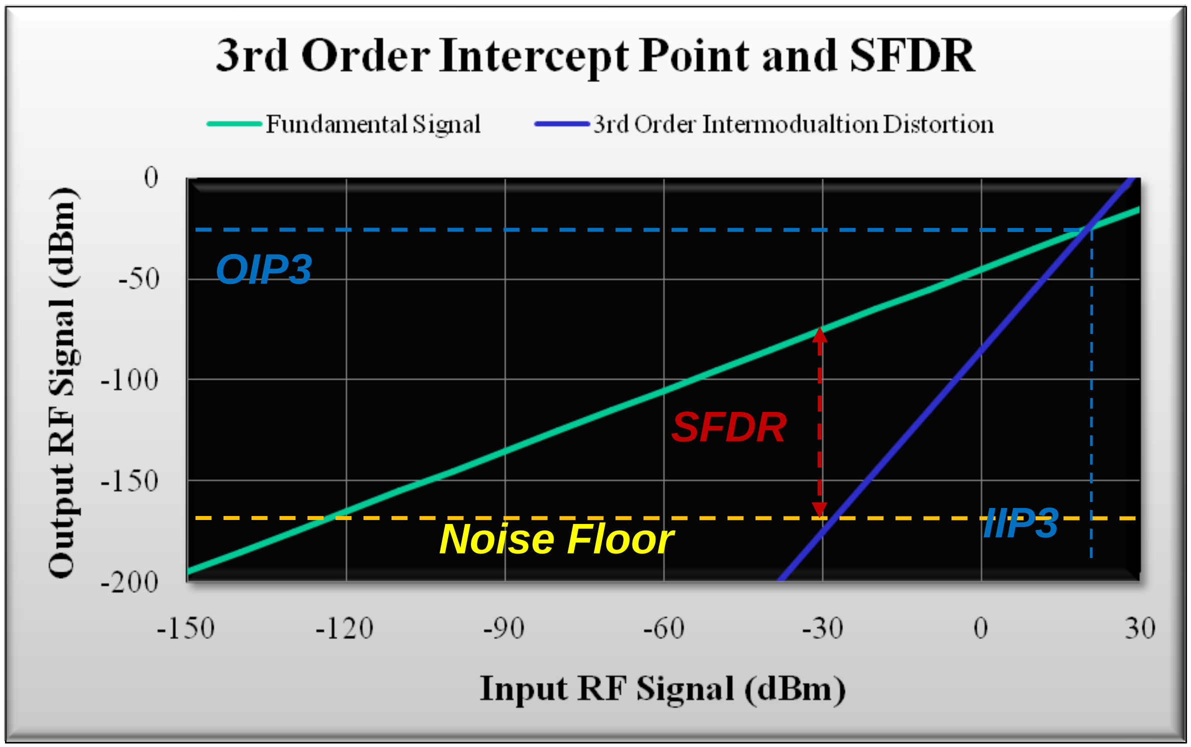
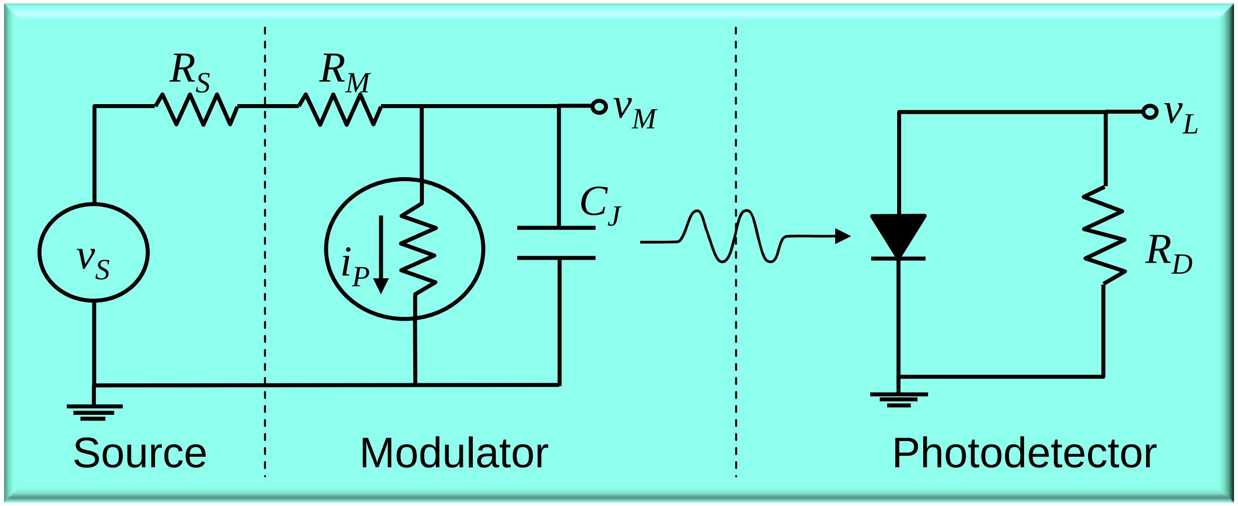
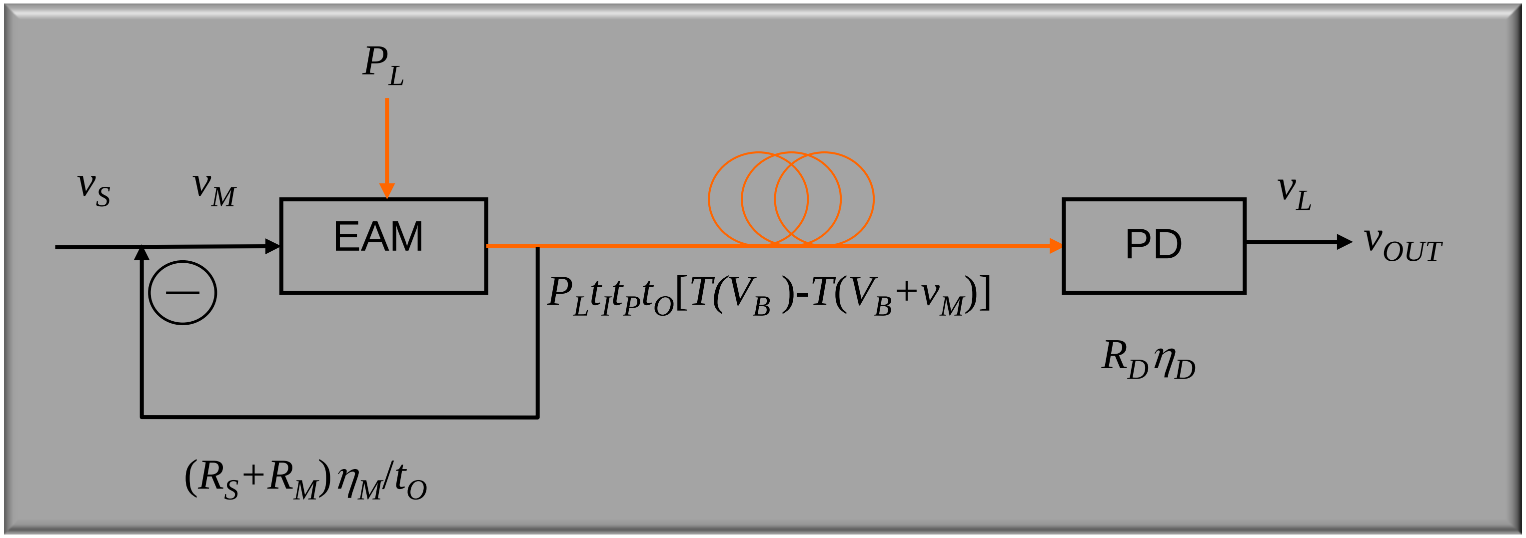
Linearity of Analog Fiber-Optic Link: Two-tone SFDR



EAM as a Negative Feedback System at High Power

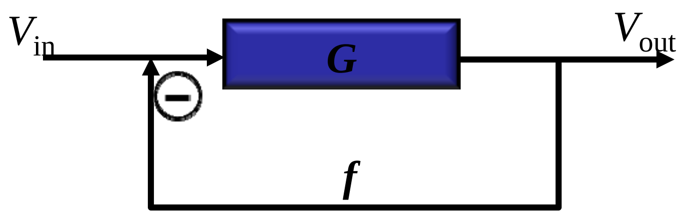




Negative Feedback System for Improving Linearity

UCSD

Electronic Negative Feedback System



$$\frac{V_{out}}{V_{in}} = \frac{G}{1+fG}$$

$$fG >> 1 \Rightarrow \frac{V_{out}}{V_{in}} \approx \frac{1}{f}$$

EAM Link with Photocurrent Feedback

$$G = \frac{P_L t_I t_O \eta_D \pi}{V_{\pi e}} \frac{R_L}{R_L + R_S} \sqrt{R_D R_S}$$

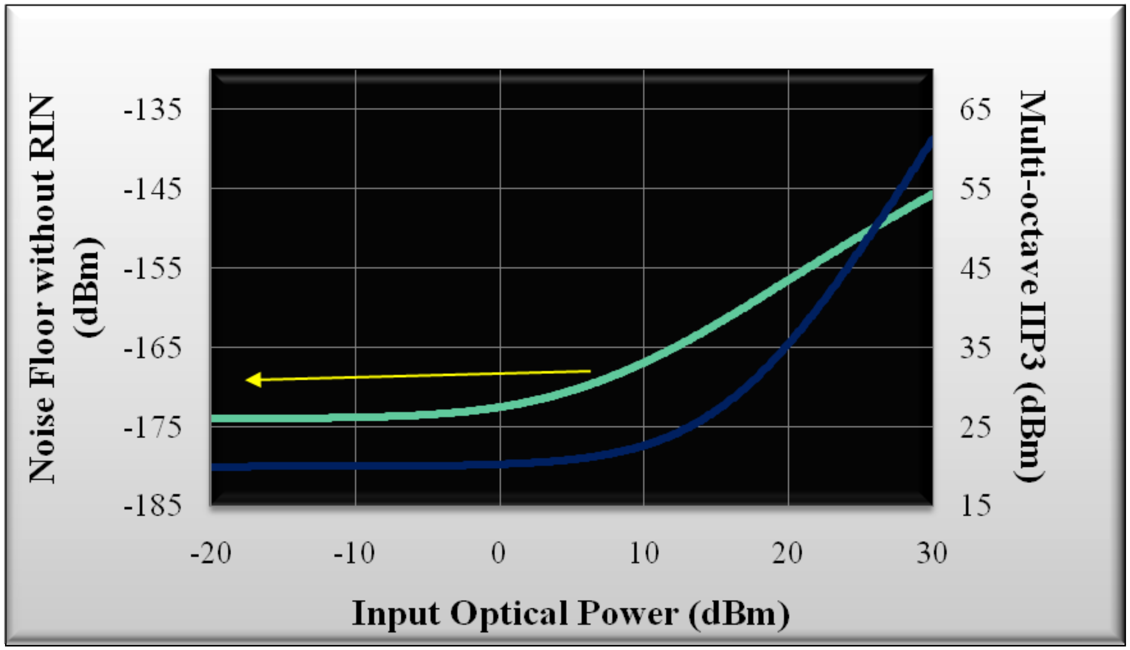
$$f = \frac{(R_S + R_M)\eta_M}{2\eta_D R_D t_O}$$

SFDR improves even as the modulator saturates

$$\mathrm{IIP2} \propto \left(\frac{dT}{dV} \Big/ \frac{d^2T}{dV^2} \right)^2 \propto k^4$$

$$\mathrm{IIP3} \propto \frac{dT}{dV} \Big/ \frac{d^3T}{dV^3} \propto k^3$$

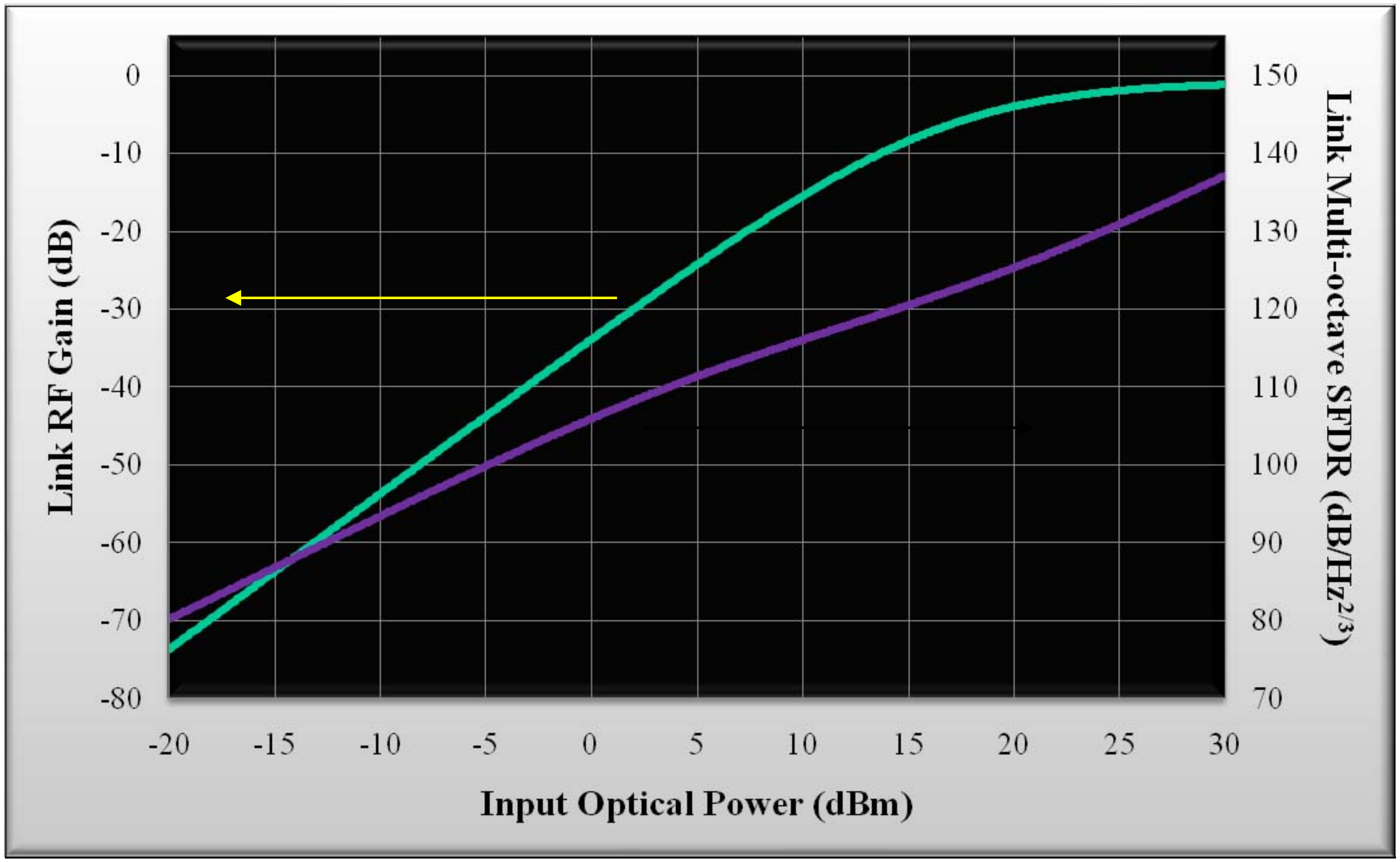
$$\mathrm{SFDR} \propto k^{4/3}$$



where

$$k = 1 - P_L t_I t_P \eta_M (R_S + R_M) \frac{dT}{dV_M} = 1 + \frac{P_L t_I t_P \eta_M (R_S + R_M)\pi}{2V_\pi} = 1 + \frac{R_s + R_m}{R_P}$$

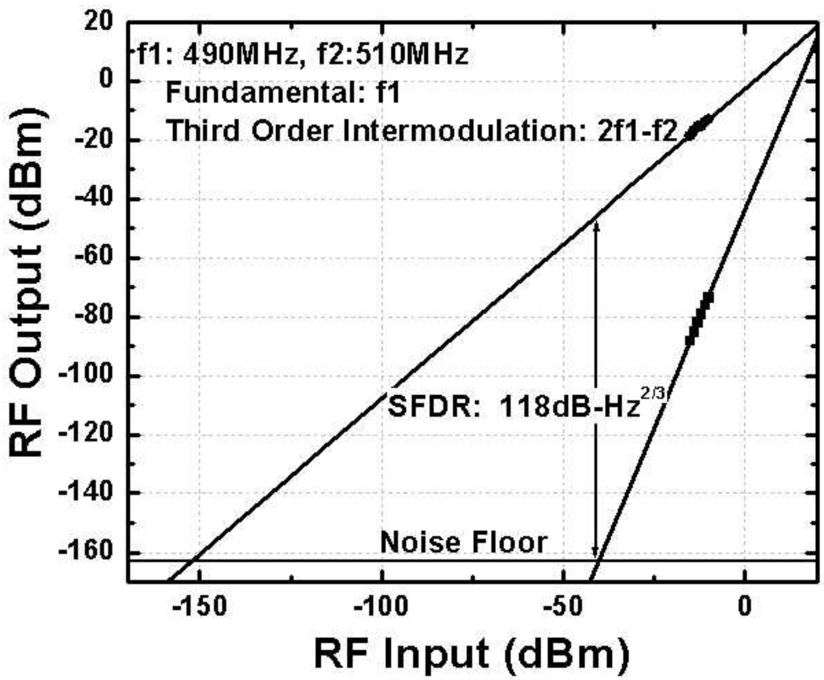
High Power EAM Linearity Analysis (cont'd)



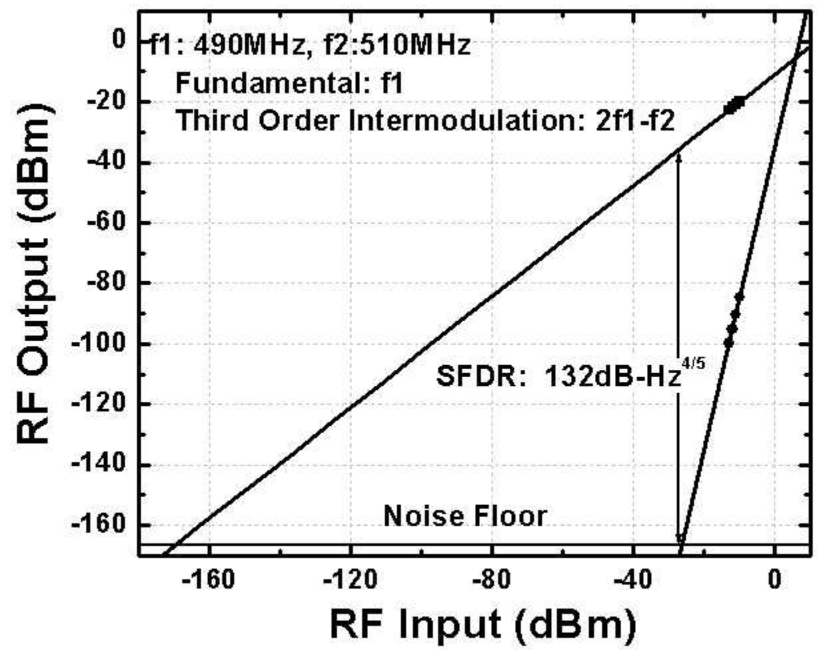
SFDR of 135 $dB/Hz^{2/3}$ at 700 mW

PCW EAM SFDRs

Multi-octave SFDR



Sub-octave SFDR



At 80 mW optical input power,

- Multi-octave SFDR of 118 dB-$Hz^{2/3}$, sub-octave SFDR of 132 dB-$Hz^{4/5}$.

Outline of Presentation

- Introduction: Analog fiber link
- Electroabsorption Modulator
- Multiple Quantum Wells and Gain Saturation
- Large SFDR modulation
- E-O effect in InP nanowires
- Conclusion

Electrooptic Coefficient

- Electrooptic effect:

$$\Delta\left(1/n^2\right)_{ij} = r_{ijk}E_k + s_{ijkl}E_kE_l$$

- Linear electrooptic coefficient, *r*, of quantum dots:
  - [1]CdSe (dispersed in polymer) → 5-60 pm/V
  - [2]InAs (grown on GaAs substrate)→ 243 pm/V
  - [2]$In_{0.4}Ga_{0.6}As$ (grown on GaAs substrate)→25.8 pm/V

- QD systems exhibit 1-2 orders of magnitude enhancement over bulk electrooptic coefficient, due to quantum confinement effects and surface effects

- In the same token, it would be of much interest to examine the electrooptic coefficient of nanowires

[1]F. Zhang, L. Zhang, Y. X. Wang, and R. Claus, Appl. Opt. **44**, 3969 (2005).
[2]S. Ghosh, A. S. Lenihan, M. V. G. Dutt, O. Qasaimeh, D. G. Steel, and P. Bhattacharya, J. Vac. Sci. Technol. B **19**, 1455 (2001).

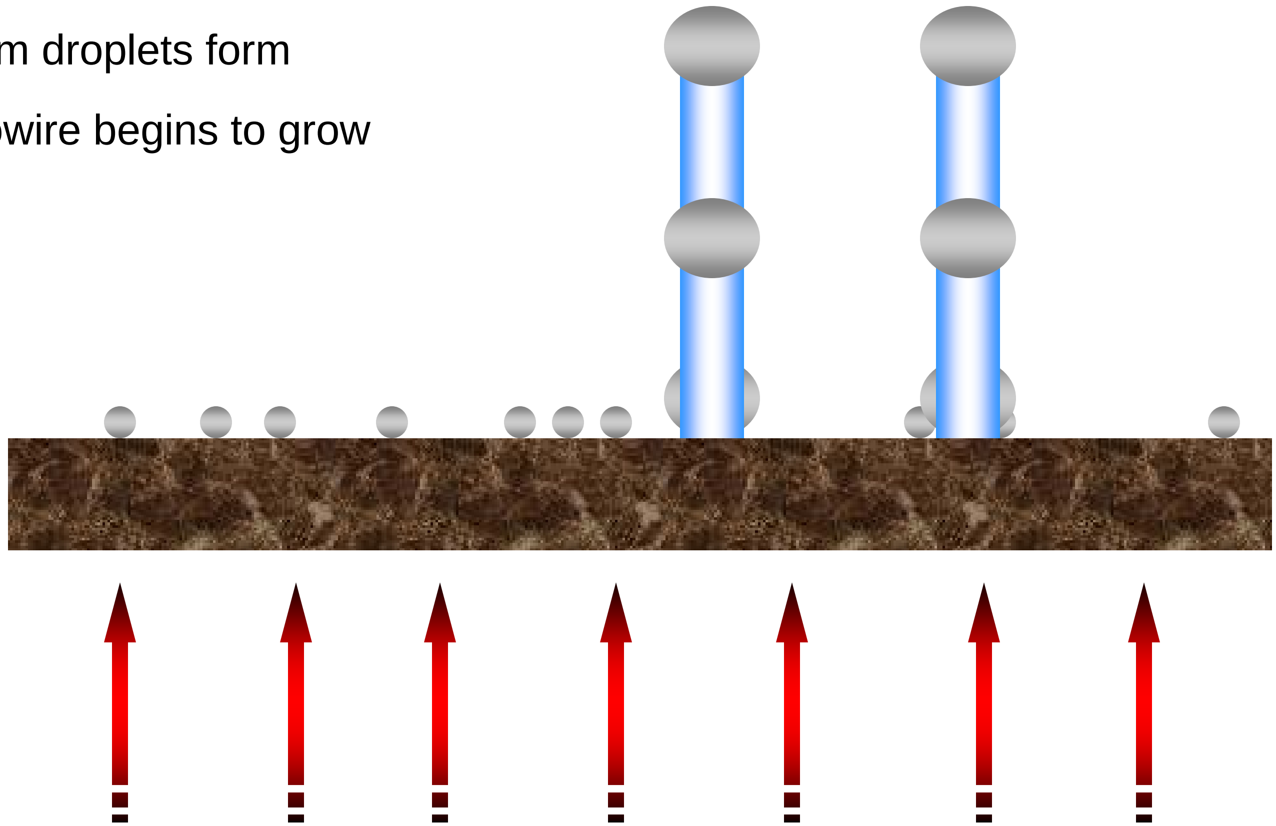
InP Nanowire Growth

1) Heat Sample in MOCVD reactor under PH_3 flow

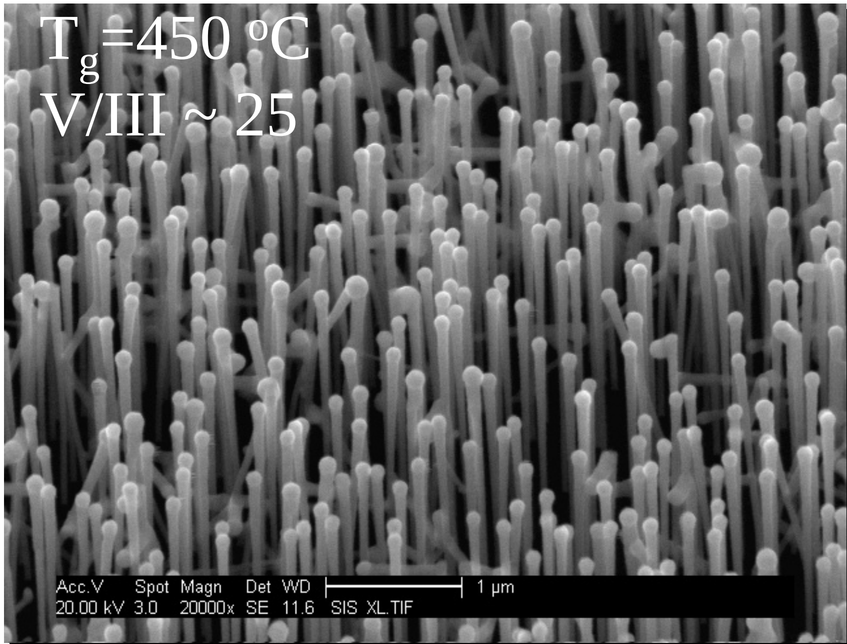
2) Start TMIn flow

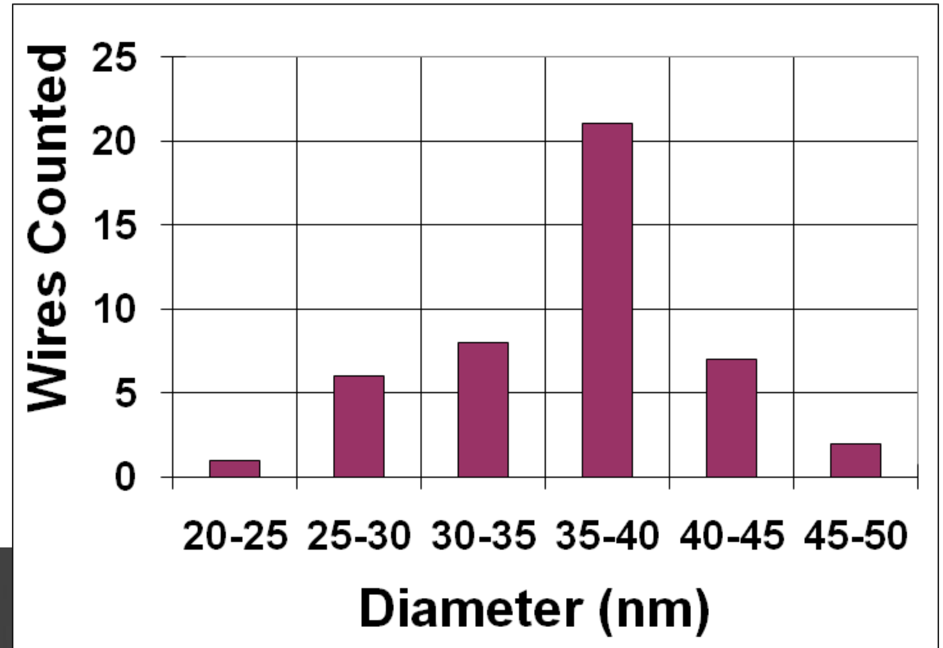
3) Indium droplets form

4) Nanowire begins to grow



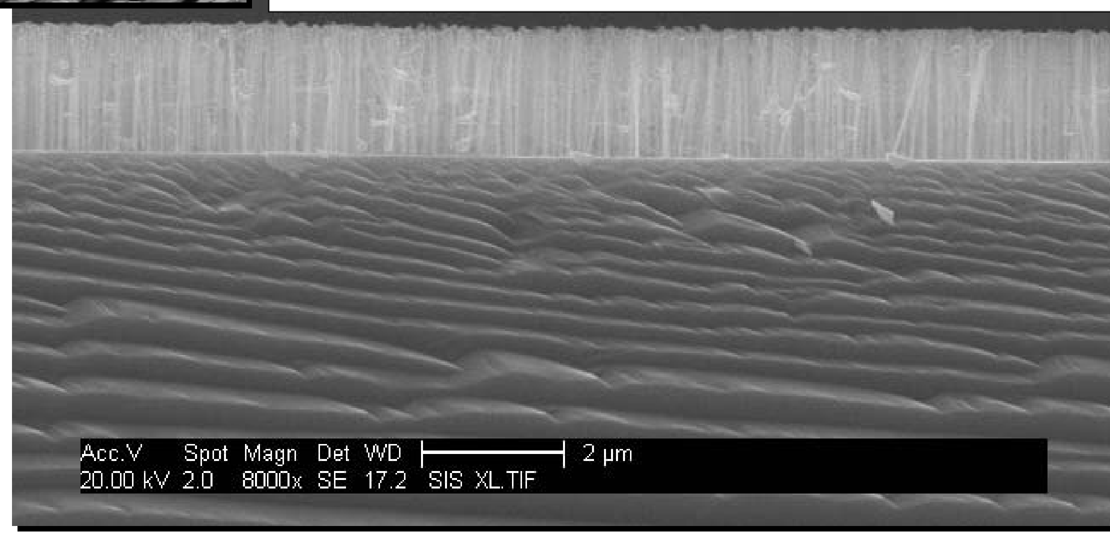
Optimized Growth



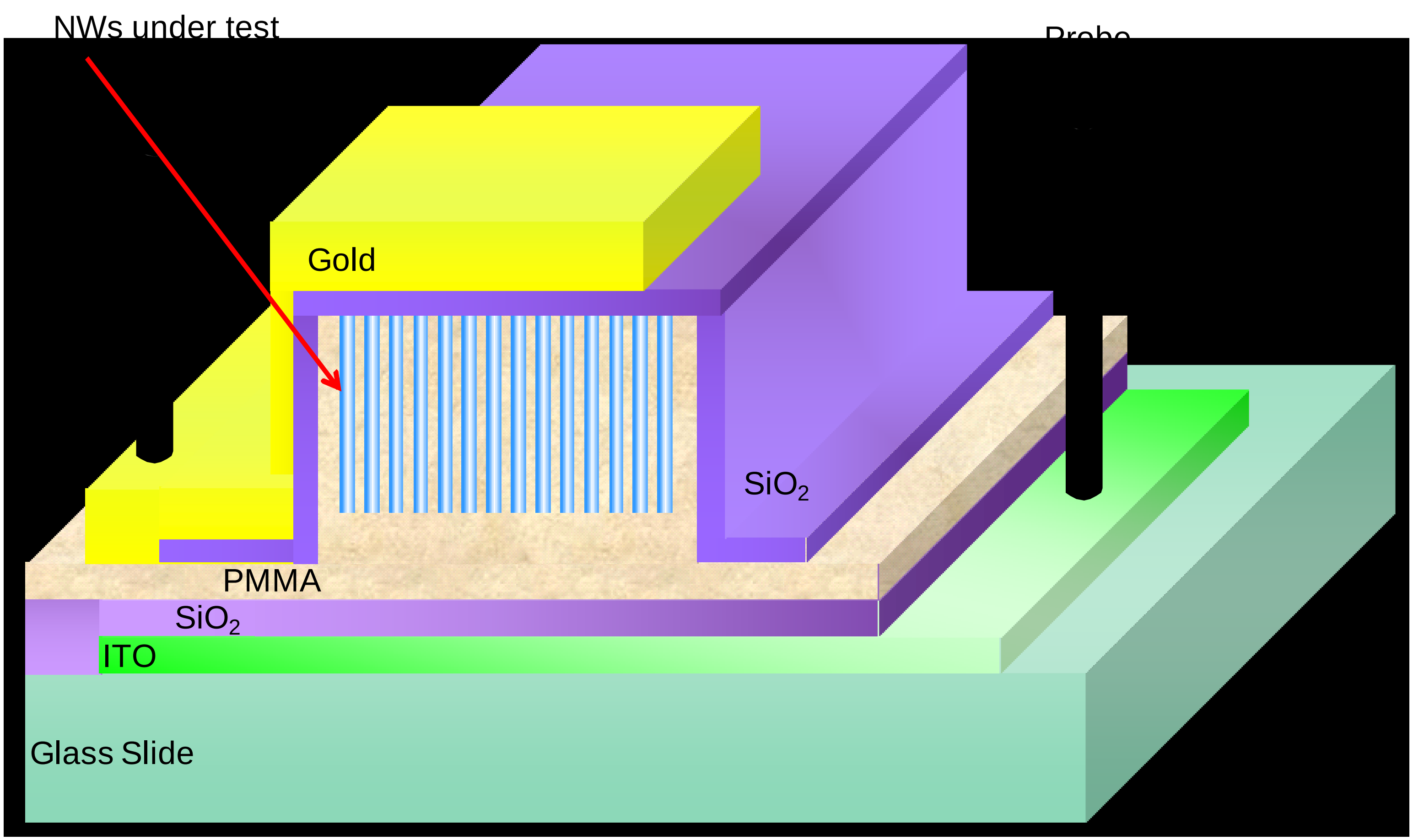


Very uniform diameter, length

High density (~10^9NWs/cm^2)



Test Structure



Measurement Results

UCSD

	Diameter (nm)	Fill Factor	r (pm/V)	n^3r (pm/V)
InP NW	24 – 50	0.83 – 4.50 %	31 – 147	1010 – 4817
Bulk InP	N/A	N/A	1.53	50
Bulk $LiNbO_3$	N/A	N/A	r_{33} = 34.1 n_e = 2.14 r_{13} = 10.3 n_o = 2.22	$n_e^3r_{33} - n_o^3r_{13}$ = 222

- NW electrooptic coefficient exhibits an enhancement of 1-2 orders of magnitude over bulk InP

- Largest figure of merit is 20 times larger than $LiNbO_3$

- This fabrication technique provides a method to transfer a layer of aligned NWs to a host substrate.
- A waveguide with embedded NWs could provide adequate phase modulation.

Conclusion

- Major advances in link gain has been made in links using lithium niobate MZM modulator
- The electroabsorption modulator (EAM) can be designed to have low optical loss and high power properties
- The RF link gain using EAM saturates due to the photocurrent feedback effect which may be alleviated using blue shifted QCSE; or by reducing the photocurrent generated.
- Nonetheless, electroaborption modulators can achieve high SFDR due to the same feedback effect.
- InP nanowires have great potential for effective electro-optic modulation.

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