# High-Performance Analog Optical Links


**Photonic Systems, Inc.**

**MIT**

**Sarnoff Corporation**

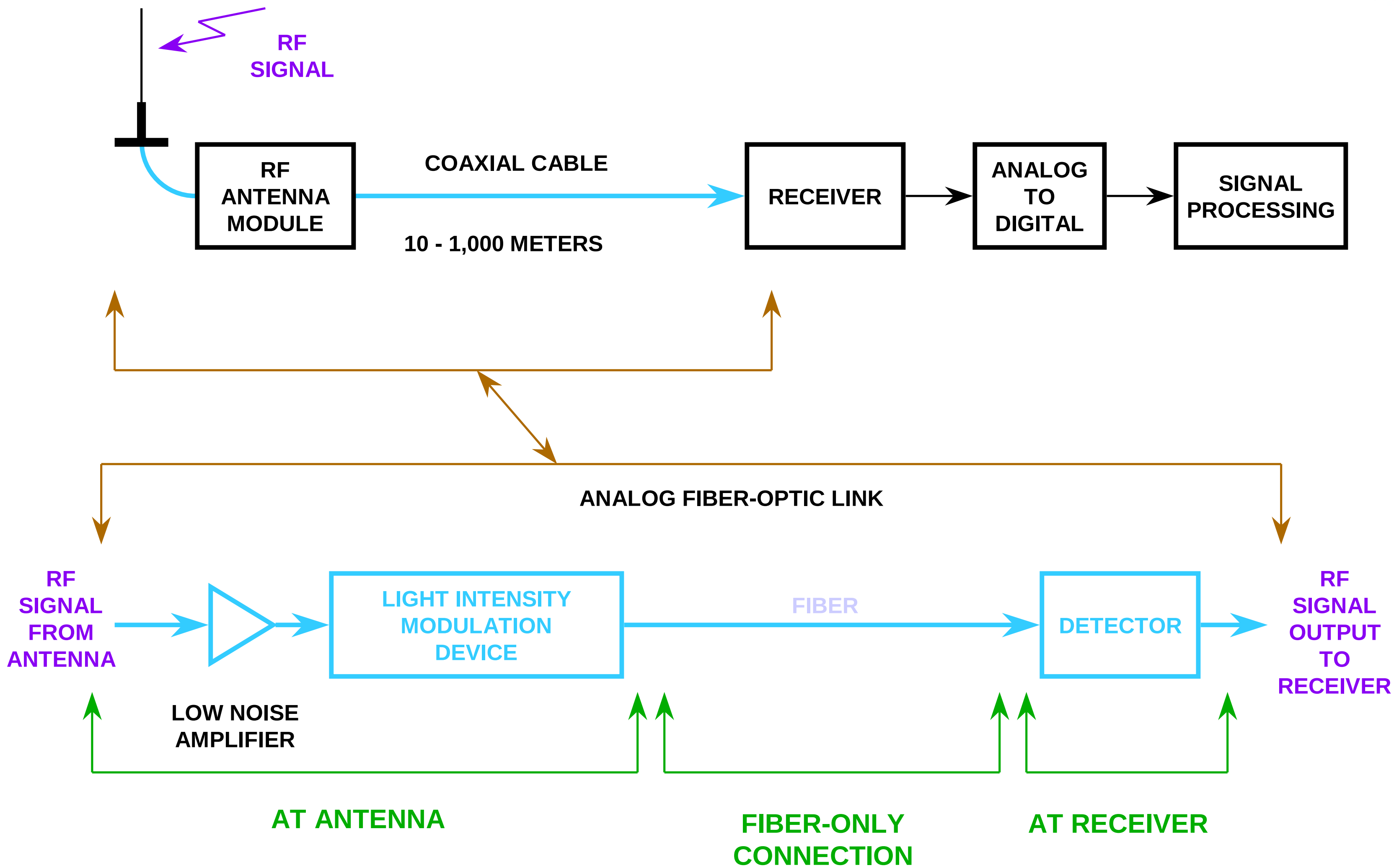
**Columbia University**


**August 1, 2001**

# Outline

- Background
- Cascade Laser Development
- Resonant Modulator Performance Tradeoffs
- Noise/Intermodulation Test Rack
- Summary

# Antenna Remoting Concept

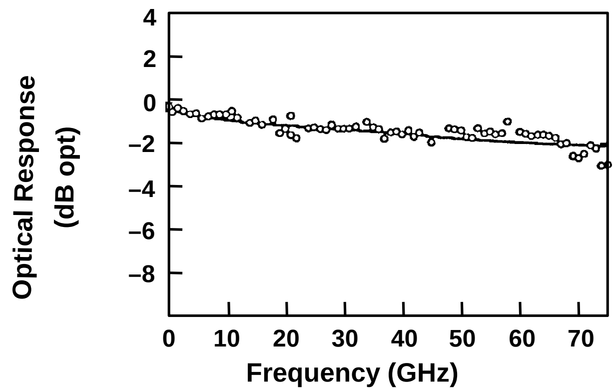


# Record Performance of Analog Links
## External Modulation

**Record Bandwidth: 75 GHz**

**Noguchi et. al, NTT Opto-Electronic Laboratories**

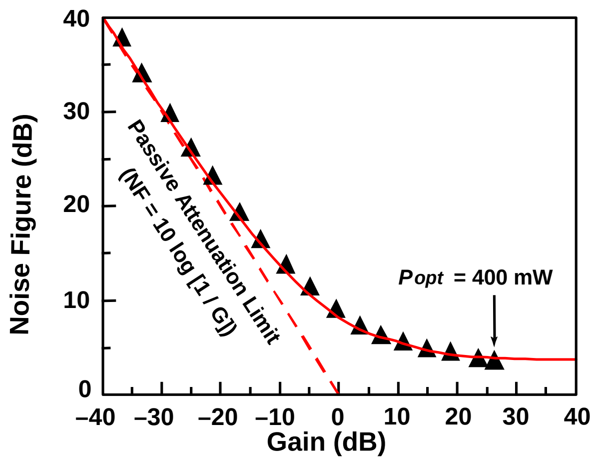
**Noise Figure: 25 dB    Dynamic Range: 110 dB Hz**




**Record Noise Figure: 2.5 dB**

**Ackerman & Cox, MIT Lincoln Laboratory**

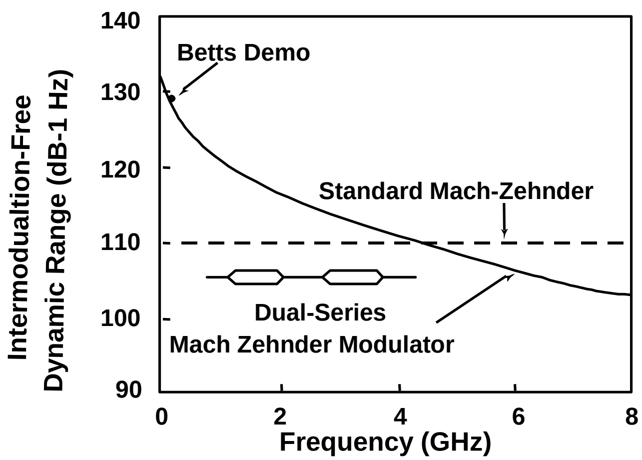
**Bandwidth: 150±10 MHz    Dynamic Range: 110 dB Hz**




**Record Dynamic Range: 130 dB**

**Betts, MIT Lincoln Laboratory**

**Bandwidth: 200 MHz    Noise Figure: 6 dB**

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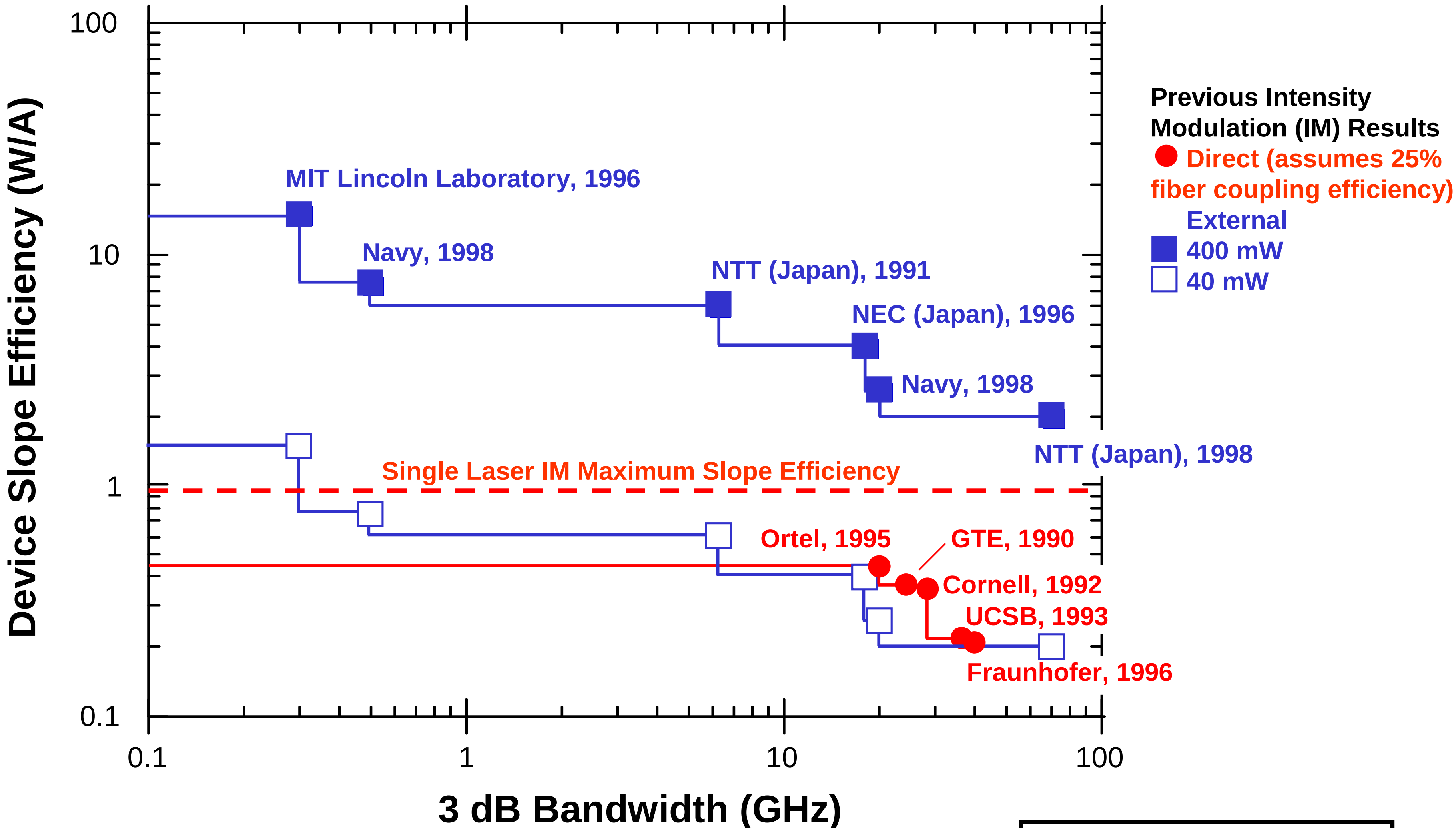
# Slope Efficiency vs Frequency

## Estimates at 1.3 µm Based on Reported Device Parameters

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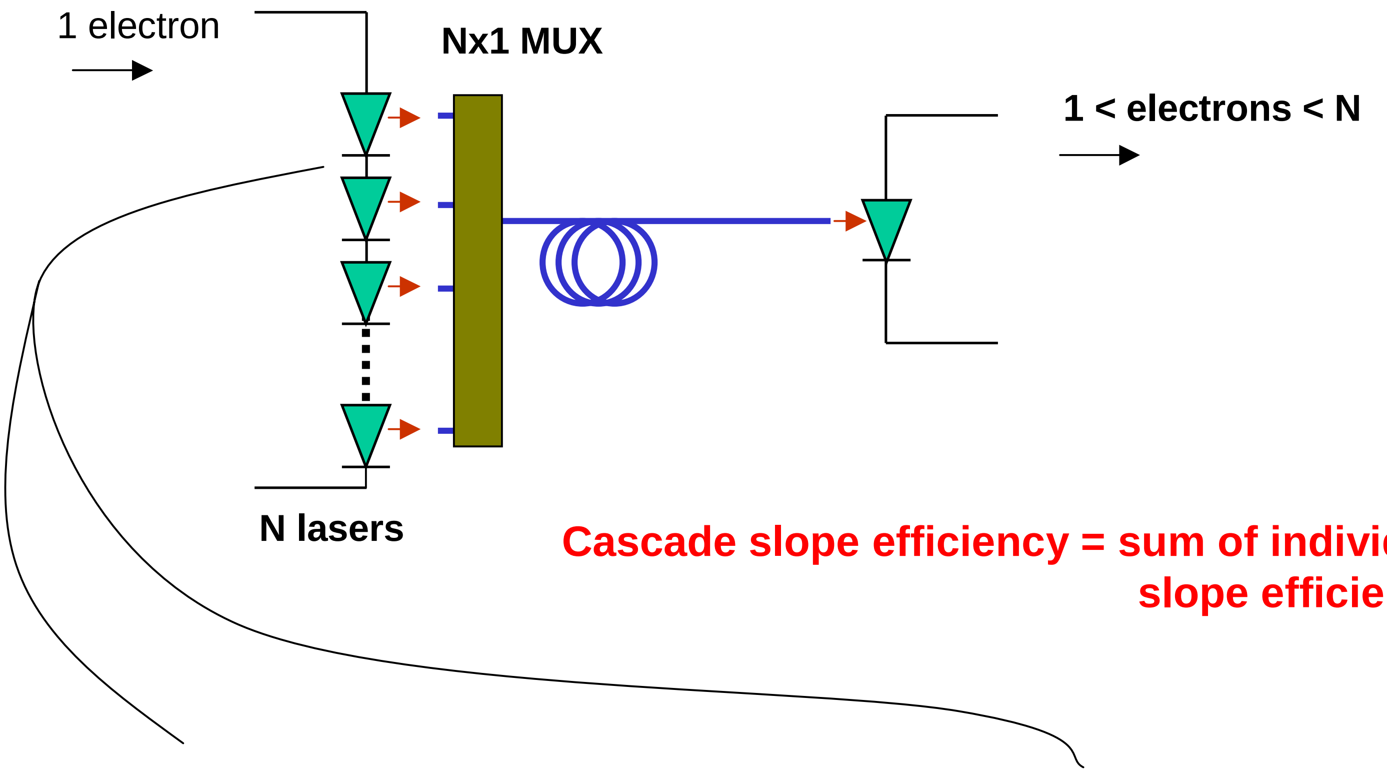
# Cascade Laser Options

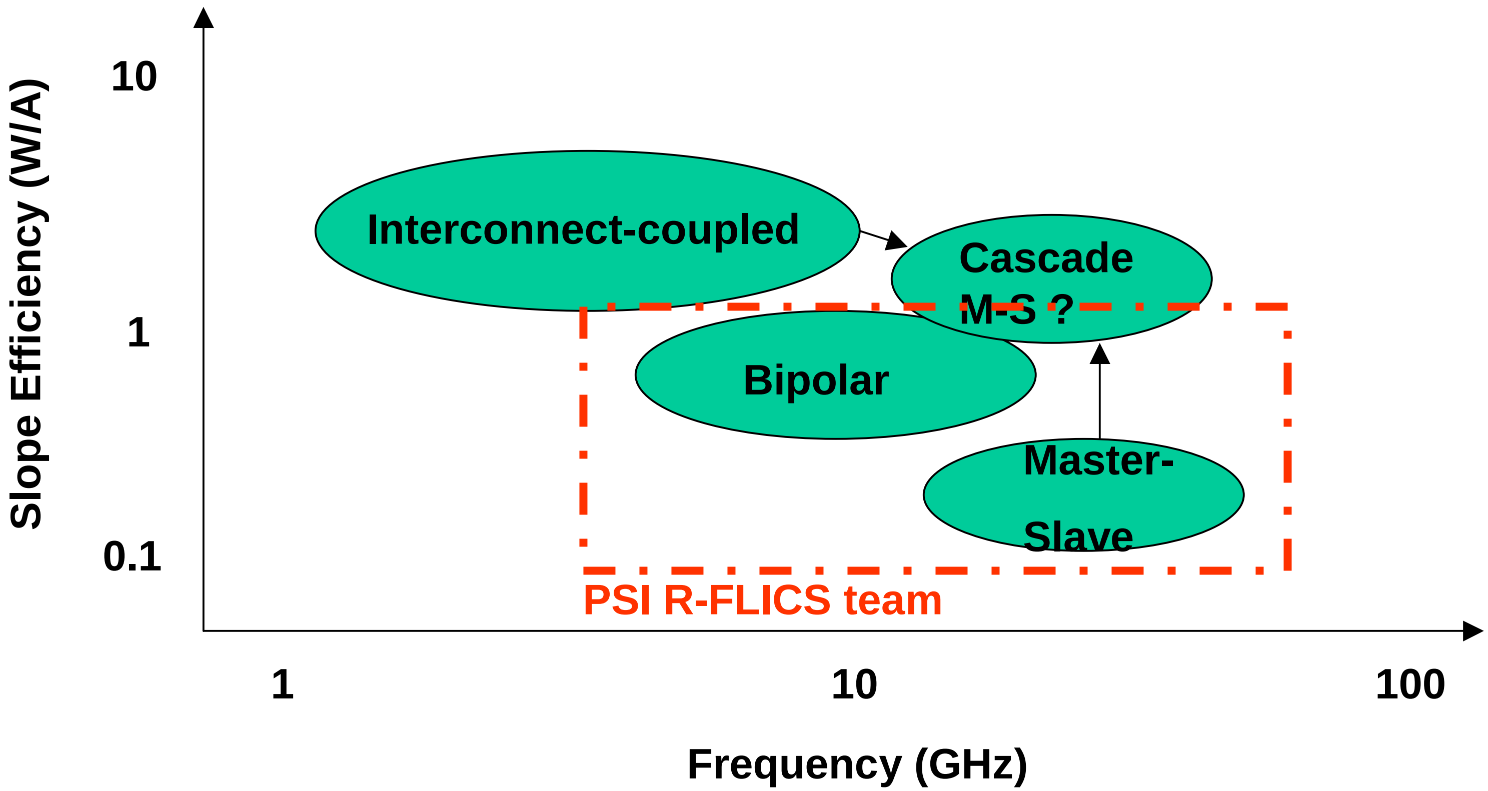



**Cascade slope efficiency = sum of individual laser slope efficiencies**

**Ohmic Connection**
- **Discrete Cascade**
  - **Cox et al. 1st demo**
- **Interconnect Coupled Cascade**
  - **PSI SBIR Phase II**

**Tunnel-junction Connection**
- **Bipolar Cascade**
  - **PSI R-FLICS team**

# Comparative Performance of Cascade Lasers



# Slope Efficiency vs Frequency

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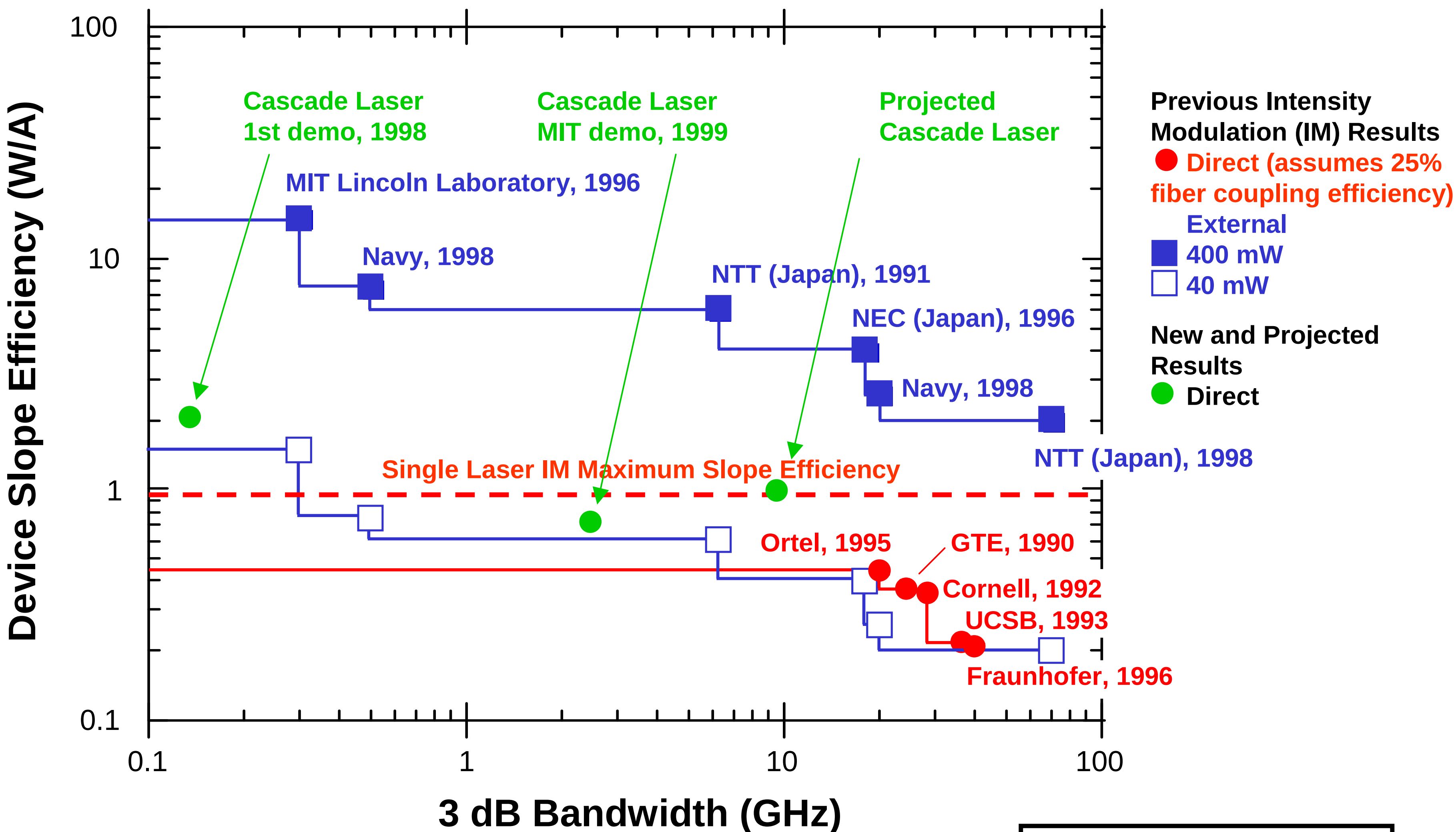


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# Outline

- Background
- Cascade Laser Development
  - Laser design
    - 1st generation
    - 2nd generation
      - Tunnel junction
      - Fiber coupling
  - Material growth and characterization
  - Resonant modulation and injection locking
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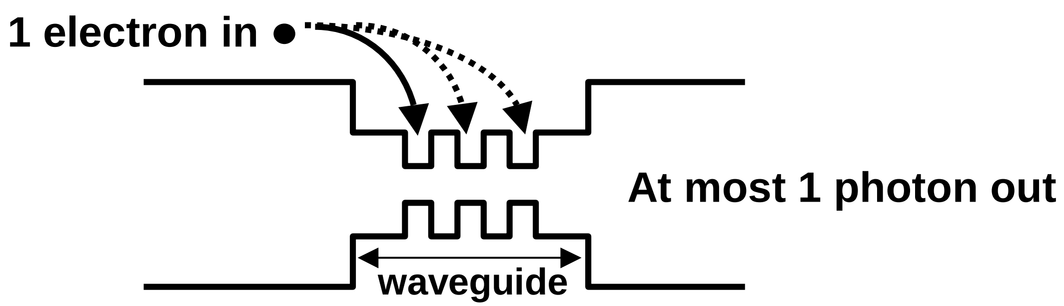
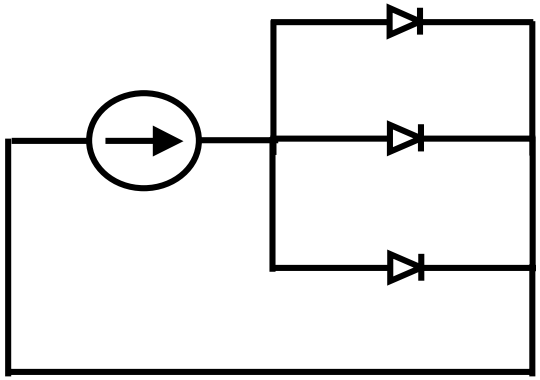
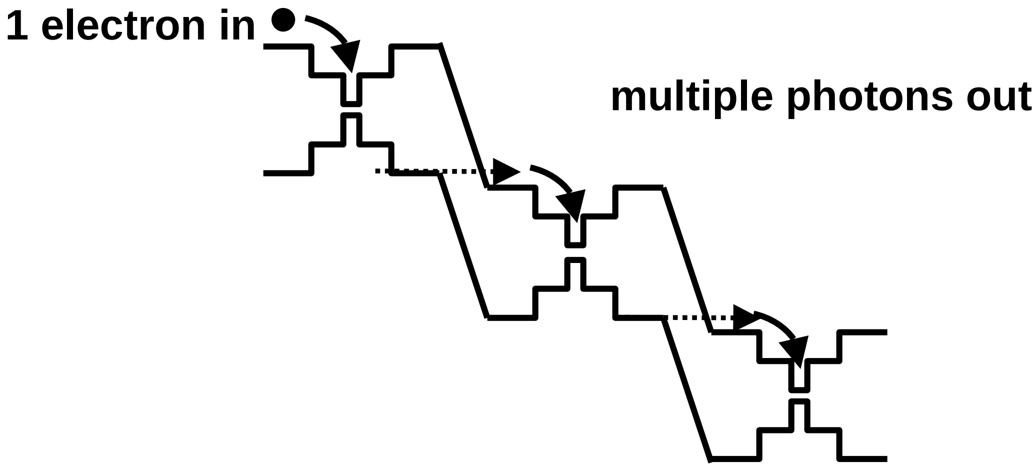
# Parallel vs. Series (Cascade) Quantum Well Coupling

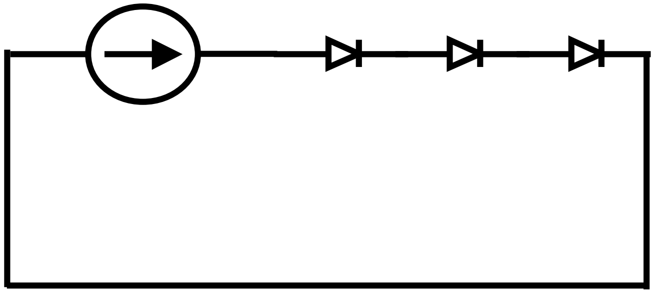
## Parallel Connection



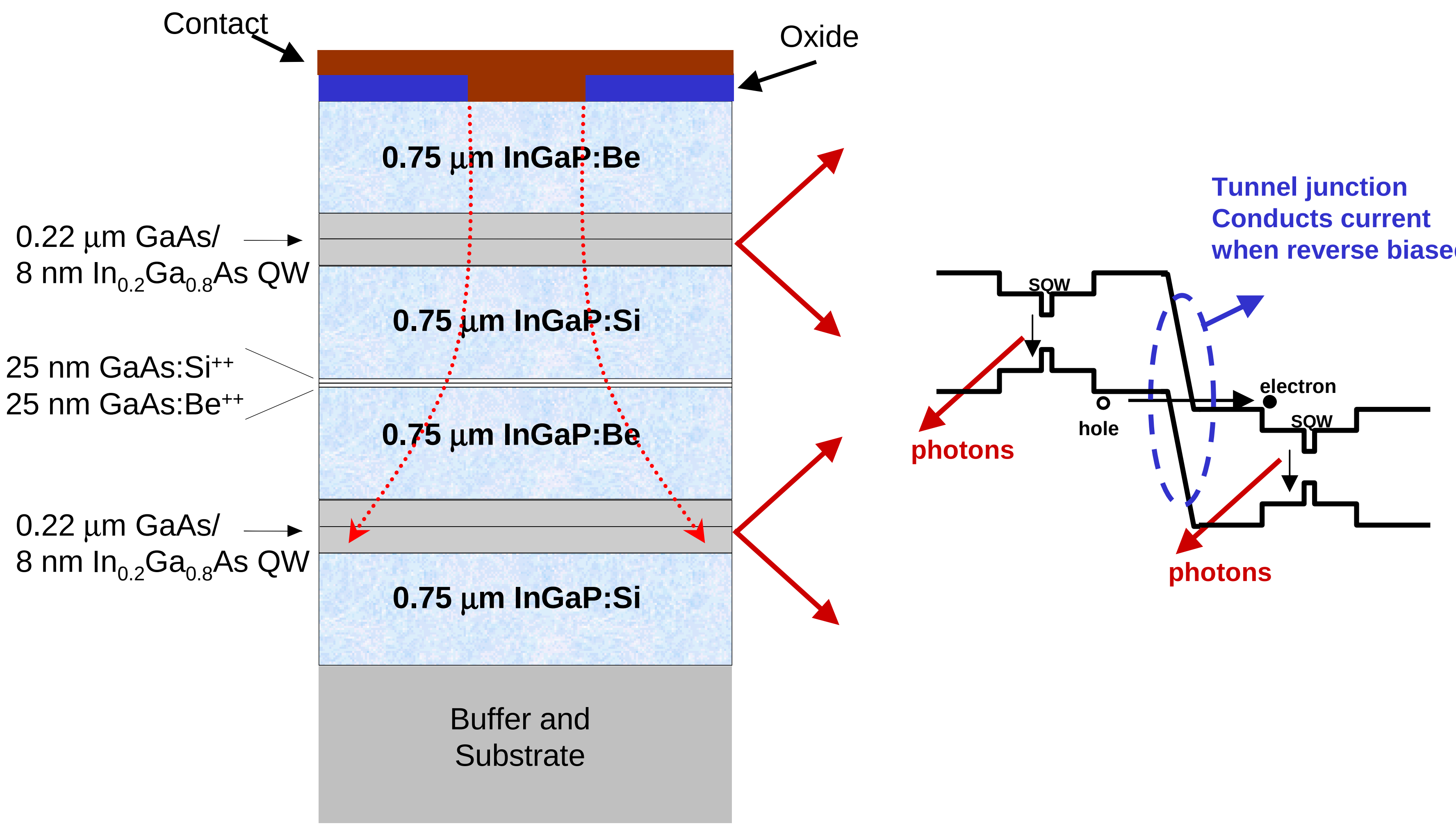



## Series (cascade) Connection



# Bipolar Cascade Laser



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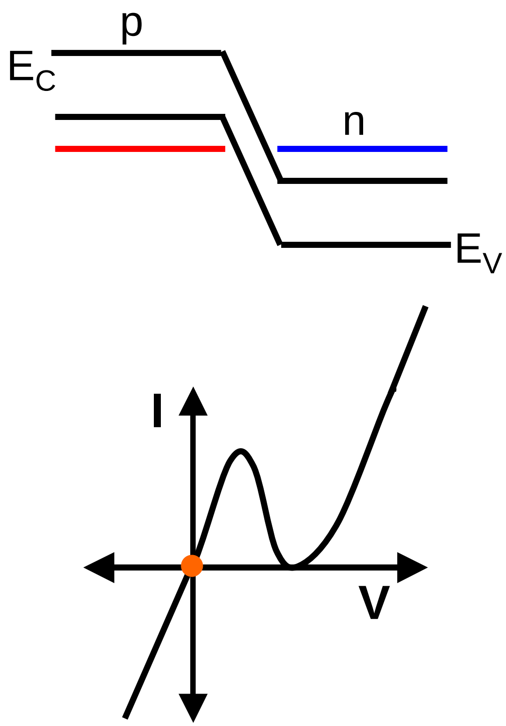
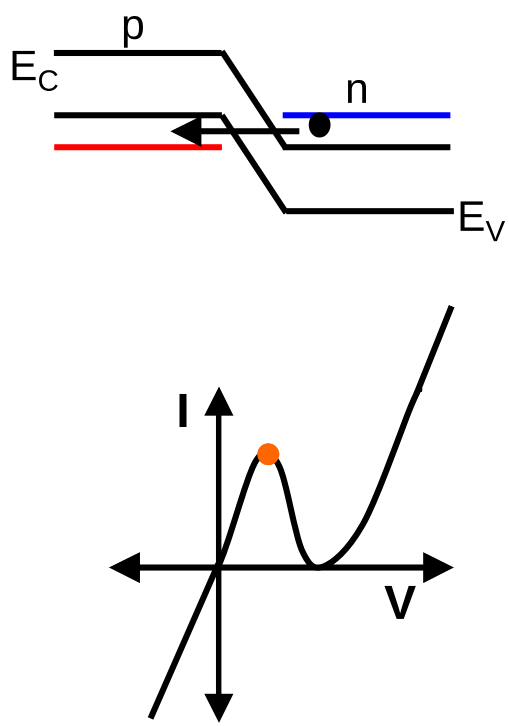
# Second Generation Bipolar Cascade

| | 1st Generation | 2nd Generation (RFLICS) |
|---|---|---|
| • Wavelength | 980 | 1550 |
| • Material System | GaAs | InP |
| • Waveguides | Uncoupled | ARROW |
| • Fiber coupling | No | Yes |
| • Number of laser junctions | 2 | 3 |

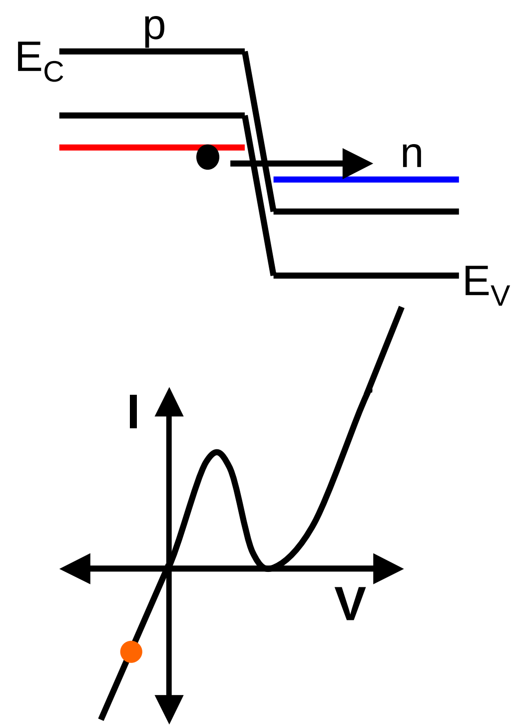
# The Tunnel Junction




*Equilibrium Junction*:
n- and p-sides degenerately doped




*Peak Forward Bias Current:*
Maximum alignment of unoccupied states on p-side with occupied states on n-side.




*Reverse Biased Junction:*
Monotonically increasing current with applied bias.

<u>Region of operation for cascade laser.</u>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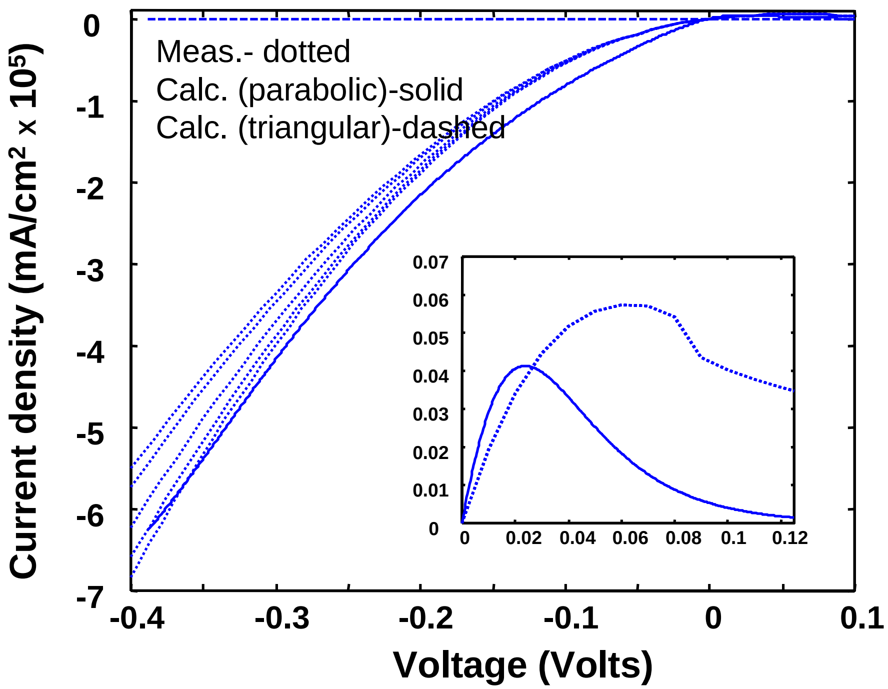
# Measurement and Calculation of Tunneling Current




**There is good agreement between the calculated and measured characteristics.**

**- Doping of test structure:**

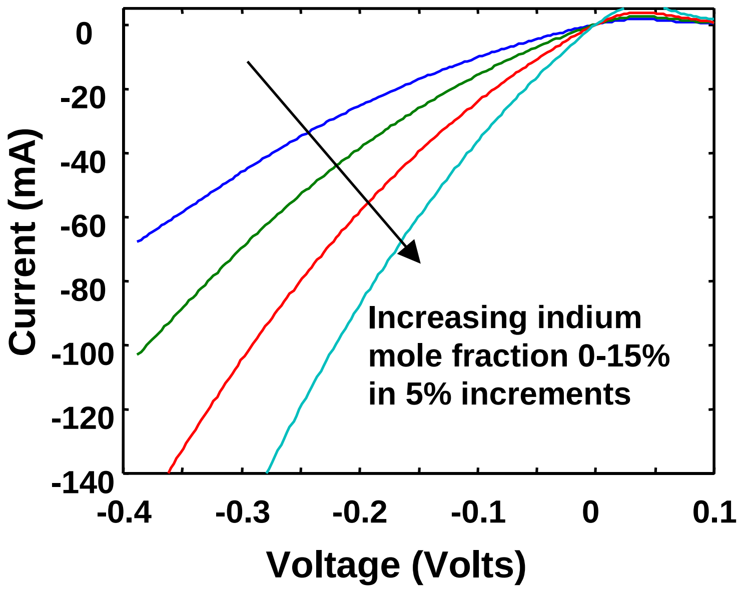
**$N_A = 8 \times 10^{18}$ cm$^{-3}$, $N_D = 1 \times 10^{19}$ cm$^{-3}$**

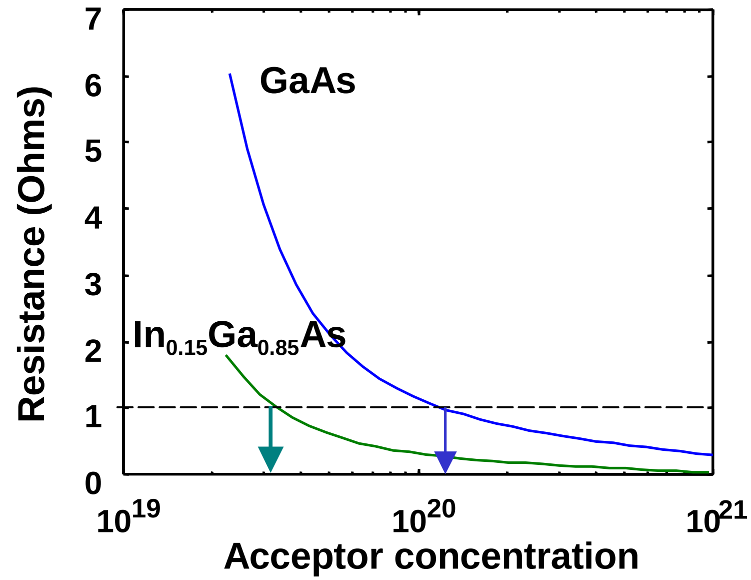
**- Test structures were 20 to 100 μm diameter posts**

**- Measurements done on an HP4145 semiconductor parameter analyzer**

**- Measured values for the contact and substrate resistance were subtracted from the measured I-V curve ($5 \cdot 10^{-4}$ Ω•cm$^2$, 4.5 Ω).**

# Effect of In Mole Fraction on Tunneling Characteristics

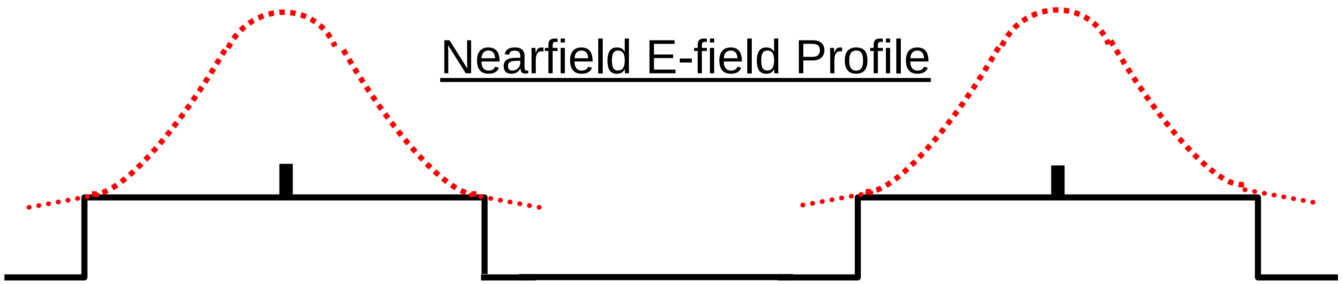



| | GaAs | $In_{0.15}Ga_{0.85}As$ |
|---|---|---|
| Bandgap | 1.42 eV | 1.28 eV |
| Effec. mass | 0.067 $m_o$ | 0.052 $m_o$ |

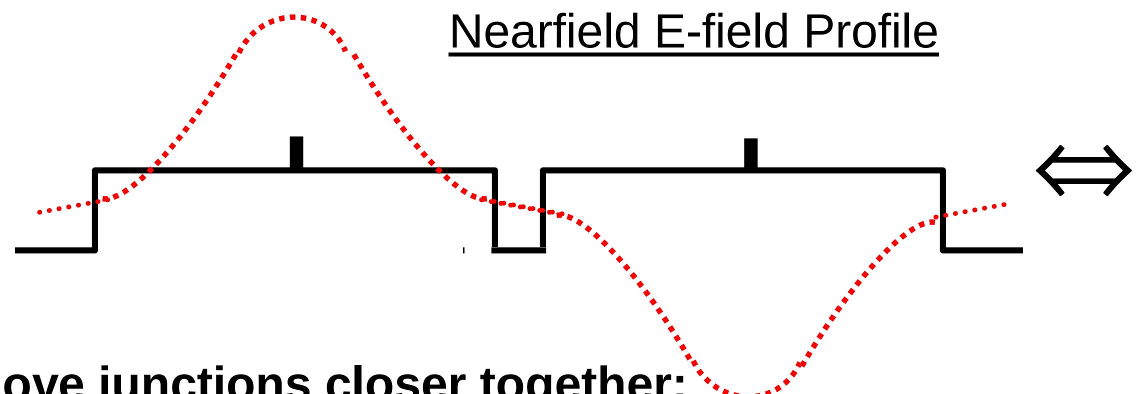
Donor and acceptor doping 2 X $10^{19}$
Device size 20 μm X 500 μm

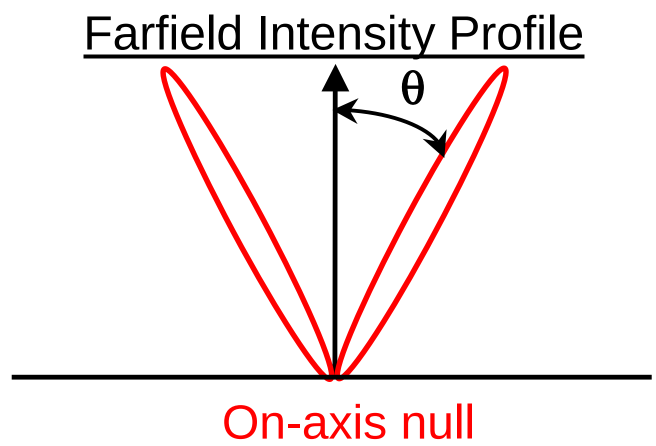
# Coupling Into Fiber




**1st Generation Bipolar cascade:**
- **Multiple waveguides are optically uncoupled**
- **Output fields of two guides are incoherent**

**IN EITHER CASE CAN'T COUPLE INTO SINGLE MODE FIBER**




**Move junctions closer together:**
- **Increases losses from tunnel junction.**
- **The fundamental lasing mode is out of phase.**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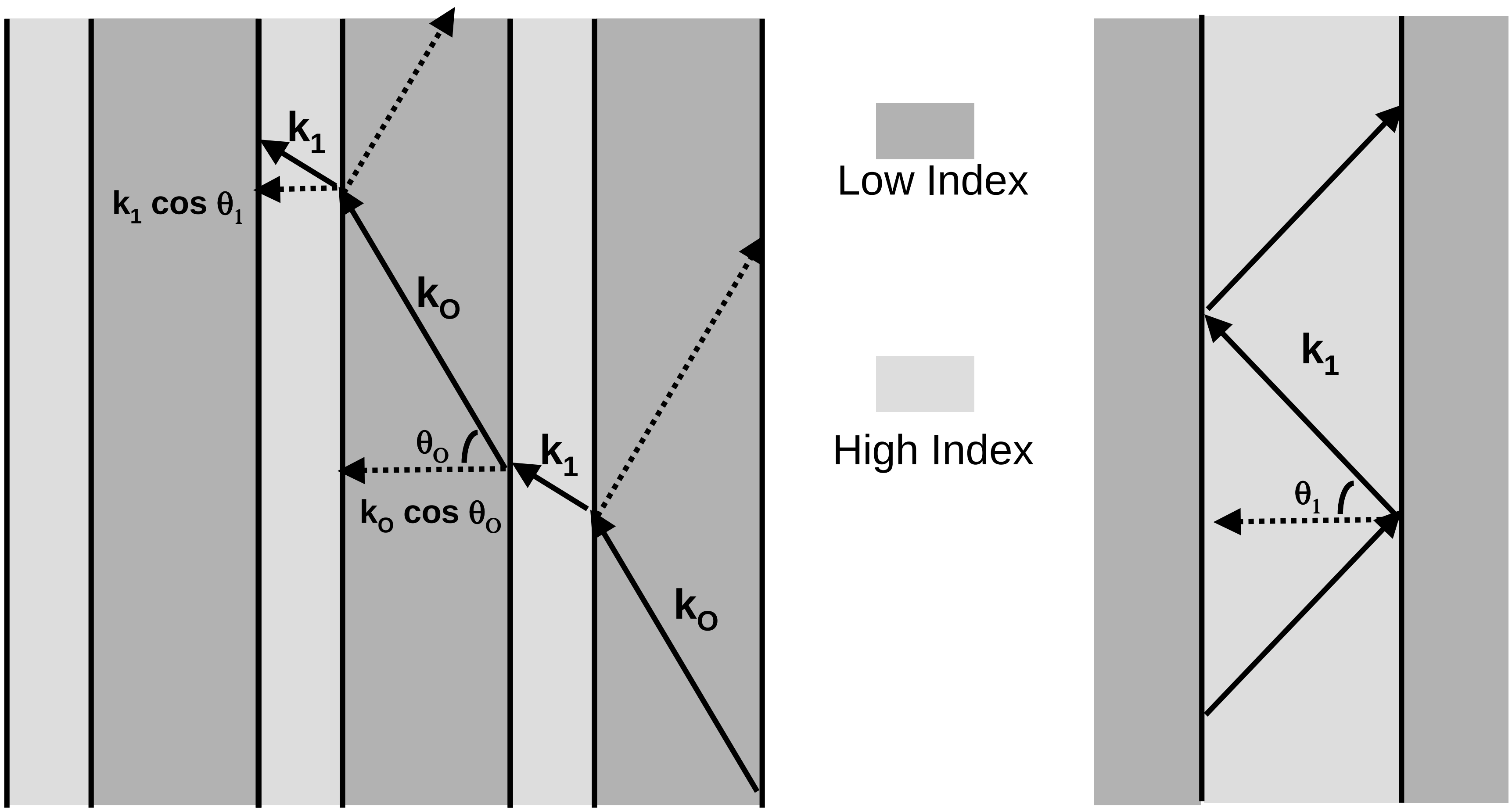
# Guiding and Anti-Guiding Waveguides

**Anti-guiding (ARROW) Waveguide** | **Guided Waveguide**




$k_O \cos \theta_O = \pi$ or equivalently $d = \lambda_0 / 2$

$k_1 \cos \theta_1 = \pi$ or equivalently $s = \lambda_1 / 2$

$\theta_1 > \theta_C$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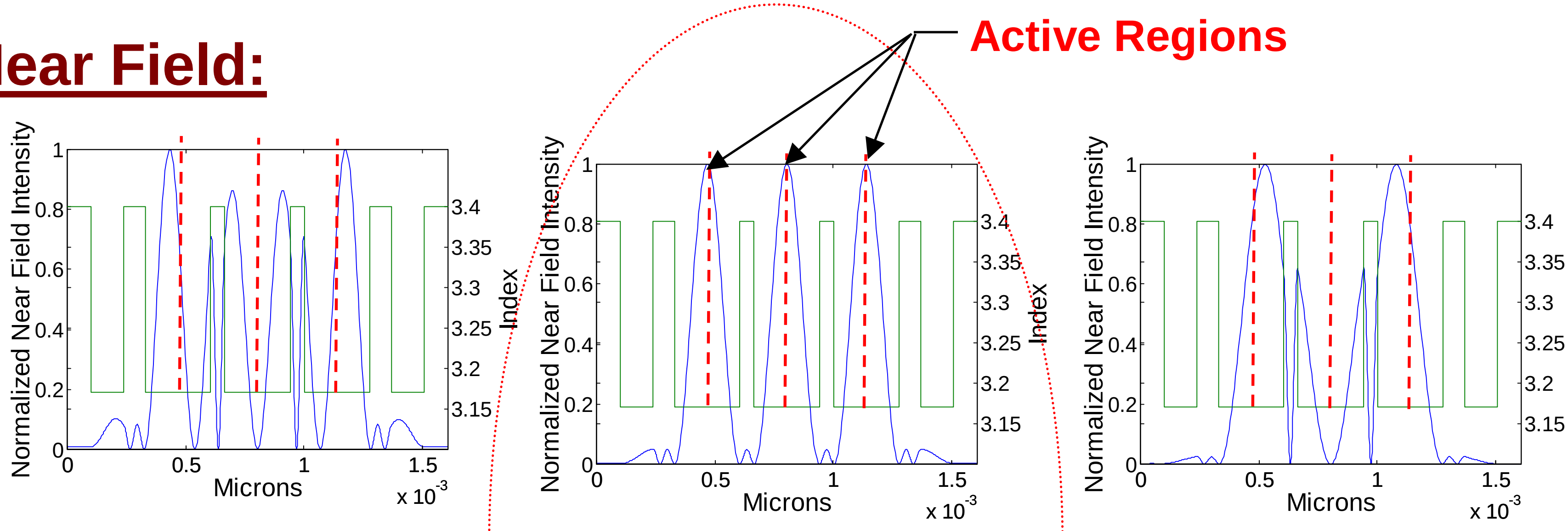
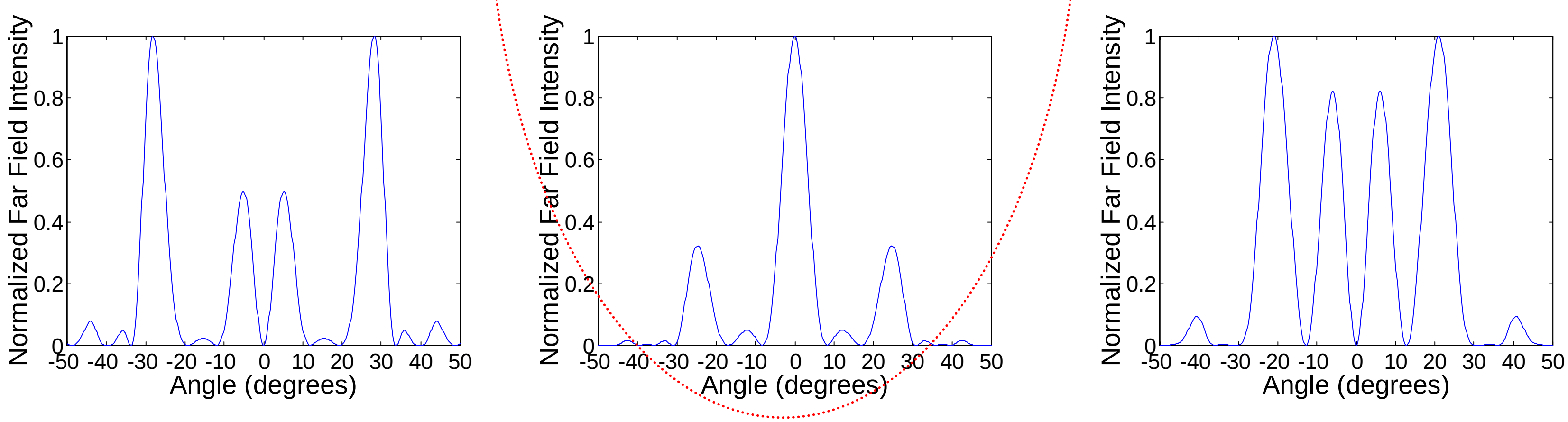
# Bipolar ARROW Cascade: Near and Far Field

## Near Field:




## Far Field:

60% power in center lobe





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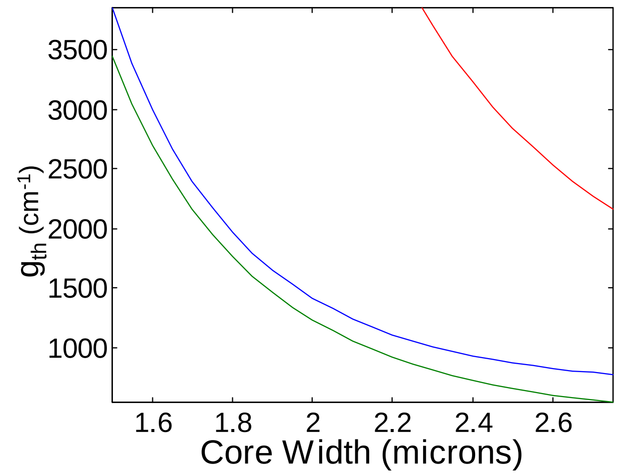
# Bipolar ARROW Cascade: Threshold Gain & Current

**Threshold gain ($g_{th}$):**

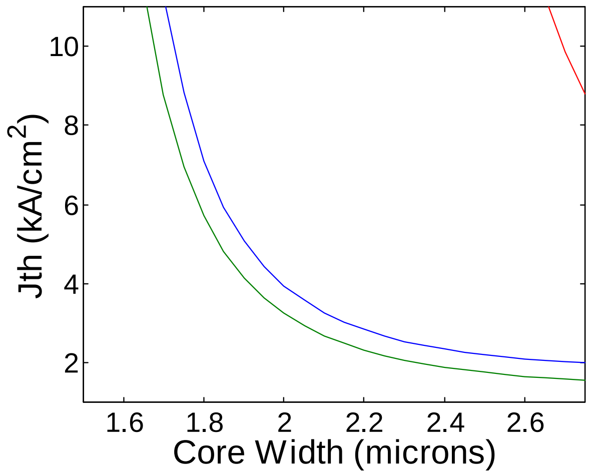
$$\Gamma g_{th} = \langle \alpha_i \rangle + \alpha_m + \alpha_r$$

- $< \alpha_i >$ = absorption loss
- $\alpha_m$ = mirror loss
- $\alpha_r$ = radiation loss
- $g_{th}$ decreases with increasing core width




**Threshold current density ($J_{th}$):**

- $J_{th}$ decreases with increasing core width
- Lowest threshold current achieved for fundamental mode



# Material Growth

- **Outside growth**
  - **Outside material facilitates technology transfer**
  - **Turn around too slow for design purposes**
    - **Submitted PO for tunnel junction material 1/00, received 8/00**
    - **Submitted PO for ARROW structure 3/00, still have not received 15 months later**
  - **Reviewing alternatives to achieve technology transfer objective**
- **MIT growth**
  - **Switched emphasis to in-house grown material for design phase**
  - **Have completed ~ 30 runs, about 2/week**
  - **Material quality and turn around time will support laser design schedule**

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# Background

## Detuned Loading (1 laser on different sides of DBR)

K. Vahala, et al., 1985 → 1.6 x bandwidth enhancment to 2.5GHz, reduced phase noise

O. Kjebon, et al., 1997 → 31GHz direct modulation bandwidth

## Injection Locking (2 FP lasers with master locking slave)

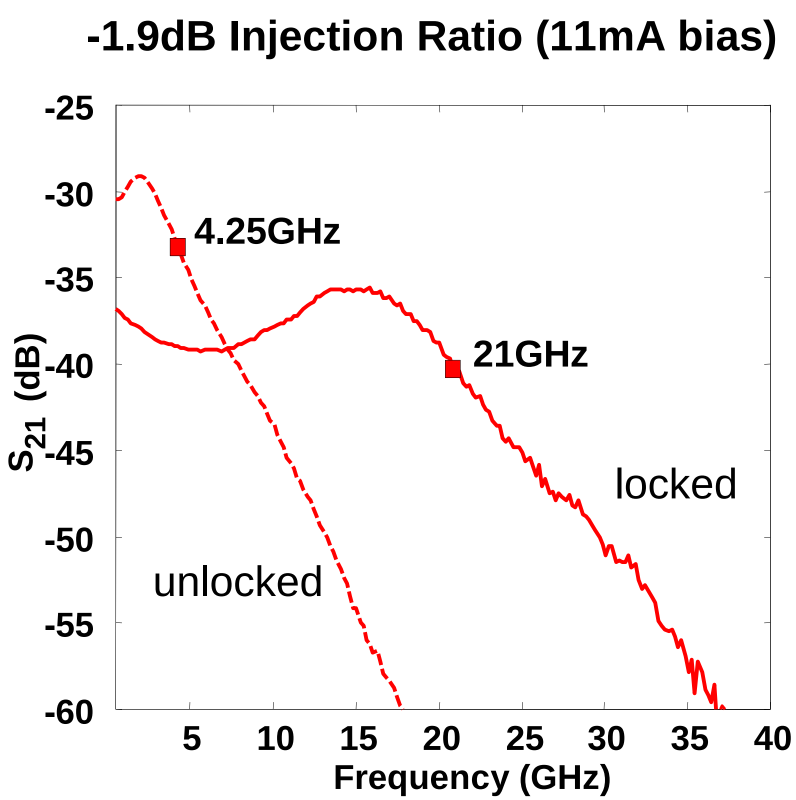
X. J. Meng, et al., 1998 → 3.7 x bandwidth enhancement to 15GHz

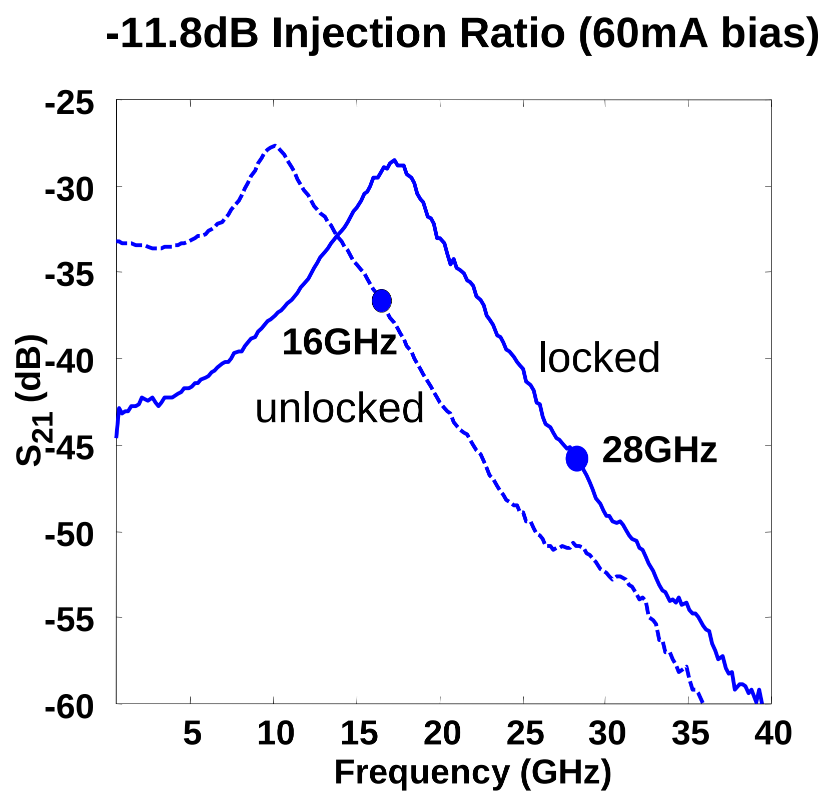
N. A. Olsson, et al., 1985 → 2Gb/s chirp free transmission over 82.5km SMF

## Resonant Modulation (2 DBR lasers)

Incorporate both effects by injection locking DBR lasers for high bandwidth and low chirp.

# Resonant Modulation Bandwidth Enhancement




**Injection Ratio:** $\frac{\textbf{Injected Master power}}{\textbf{Slave power}}$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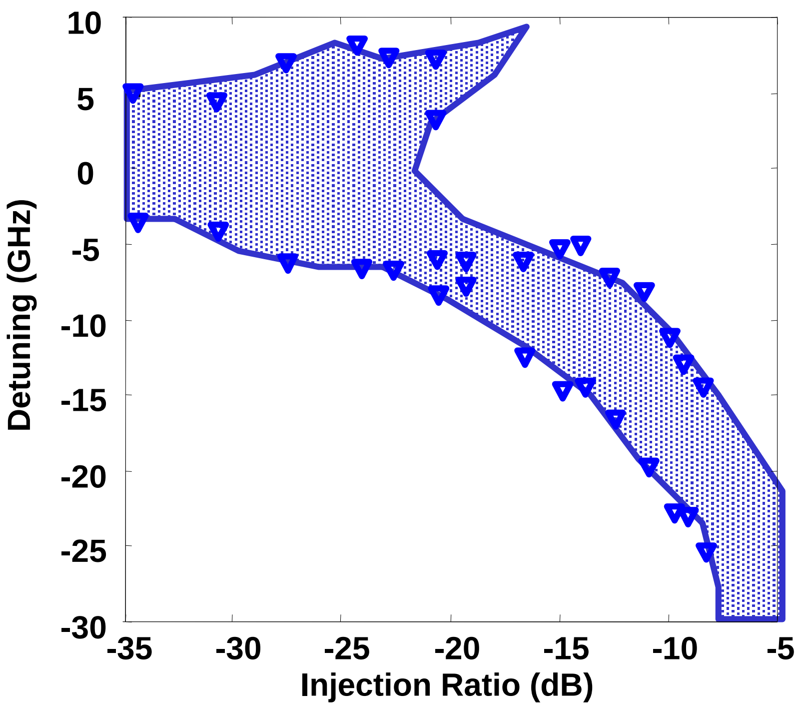
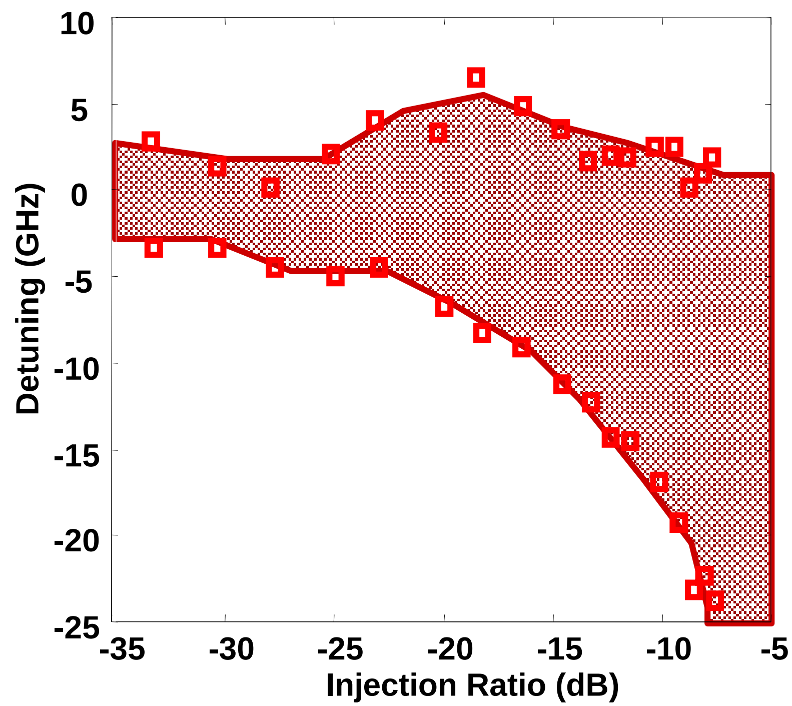
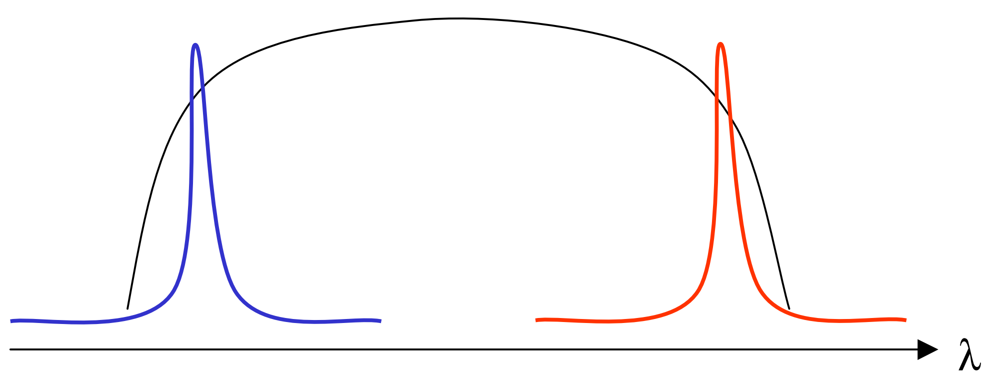
# Injection Locking Range in DBR




Short wavelength side

Long wavelength side



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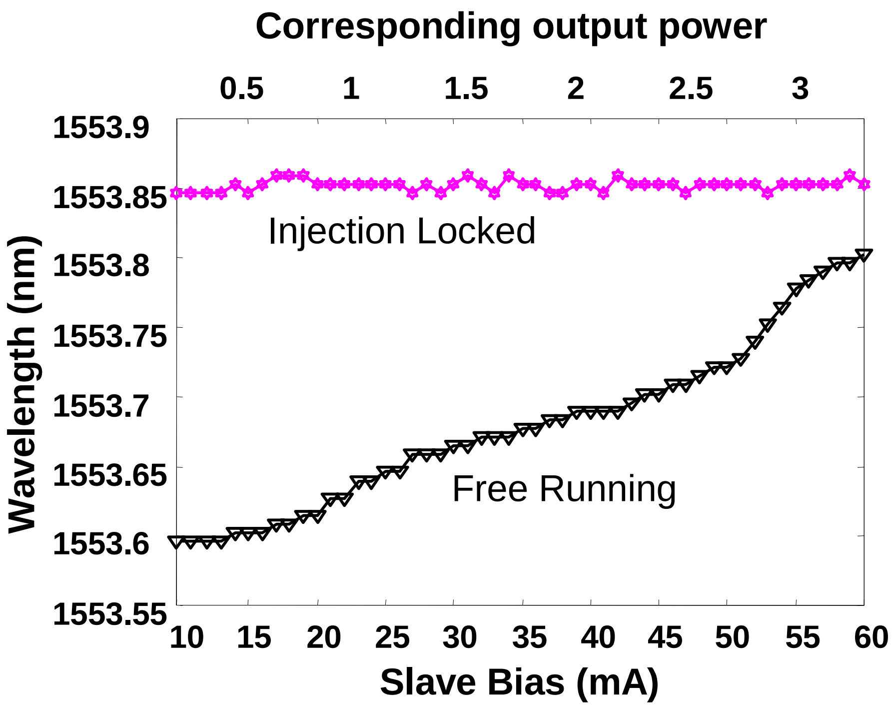
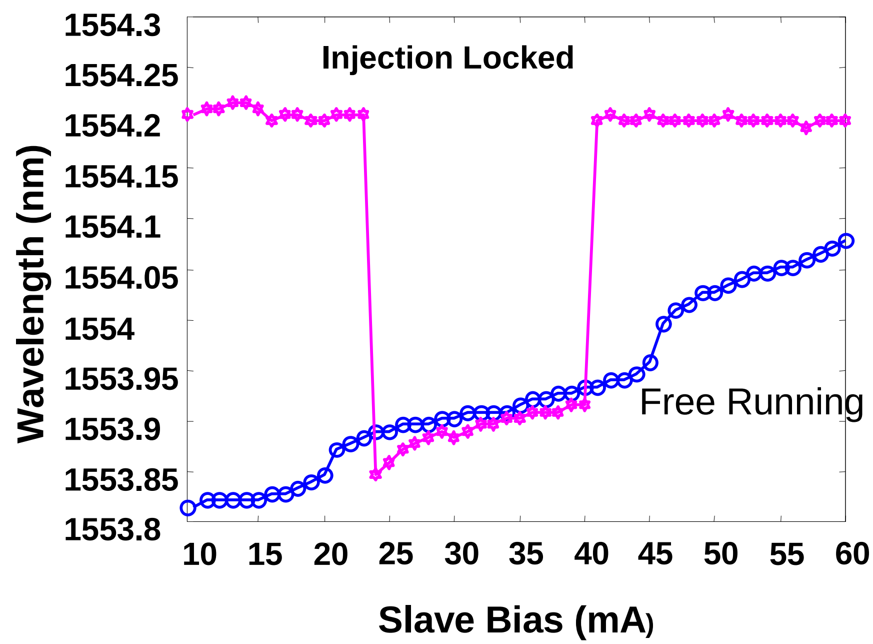
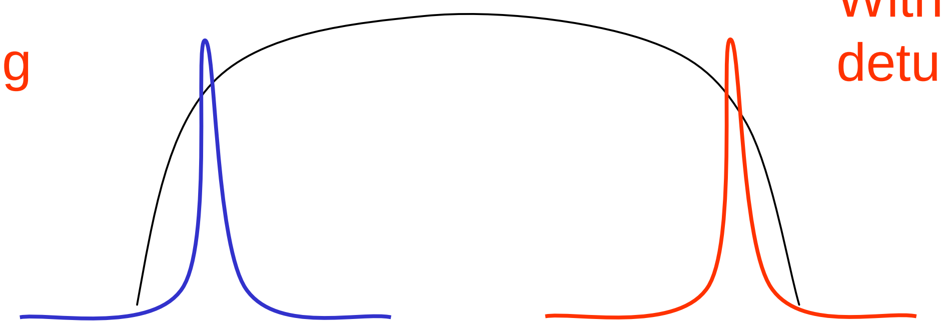
# Adiabatic Chirp Reduction




With optimal detuned loading



Without optimal detuned loading

# Summary: Bipolar Cascade

- Tunnel junction
  - Developed model of tunneling current
  - Confirmed predictions with measurements in GaAs
  - Theory transportable to InP
- Fiber coupling
  - Evaluated alternate designs
  - Selected ARROW
  - Model predicts over 60% fiber coupling from 3 junction cascade ( $\Rightarrow$ ~ 150% fiber coupled quantum efficiency)
- Material growth and characterization
  - Achieved high doping for tunnel junctions in InP/InGaAsP by low-temperature Be doping in MBE
  - Completed InP/InGaAsP process development and active region characterization

# Summary: Resonant Modulation

- **Modeling**
  - **Developed model for detuned loading and injection locking**
    - **Predicted results match well with experimental data**
  - **Model for resonant modulation still incomplete**
    - **For example model does not predict wide locking range on "right" side of DBR**
- **Experimental**
  - **Demonstrated injection locking over wide bias range (0.1 – 3 mW)**
  - **Enhanced modulation bandwidth by 75% (28 GHz) and reduced dynamic chirp**
  - **Eliminated adiabatic chirp**

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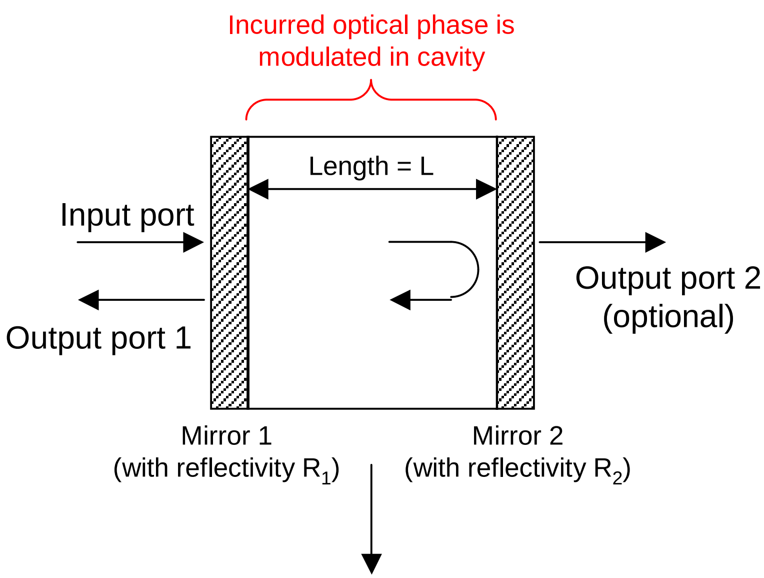
- **Cascade Laser Development**
- **Resonant Modulator Performance Tradeoffs**
  - **Modeled performance of simple resonant interferometric modulator**
  - **Cascaded resonant interferometric modulator (Sarnoff idea)**
  - **Modeled performance of modulators with combined interferometric and guide/antiguide effects**
- **Noise/Intermodulation Test Rack**
- **Summary**

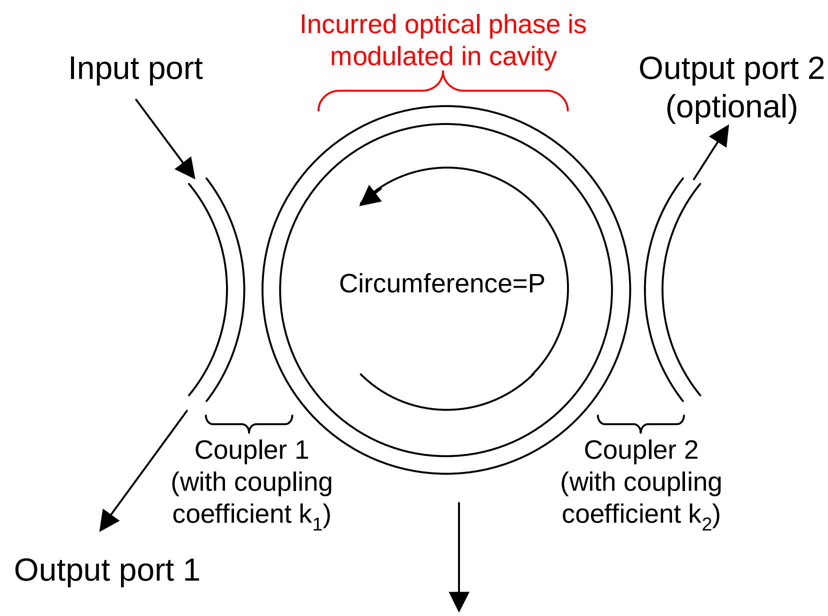
# Performance of Resonant Modulators

## Fabry-Perot




***$R_1$*, *$R_2$*, and *$L$* determine modulator performance**

## Coupled Micro-ring Resonator




***$k_1$*, *$k_2$*, and *$P$* determine modulator performance**

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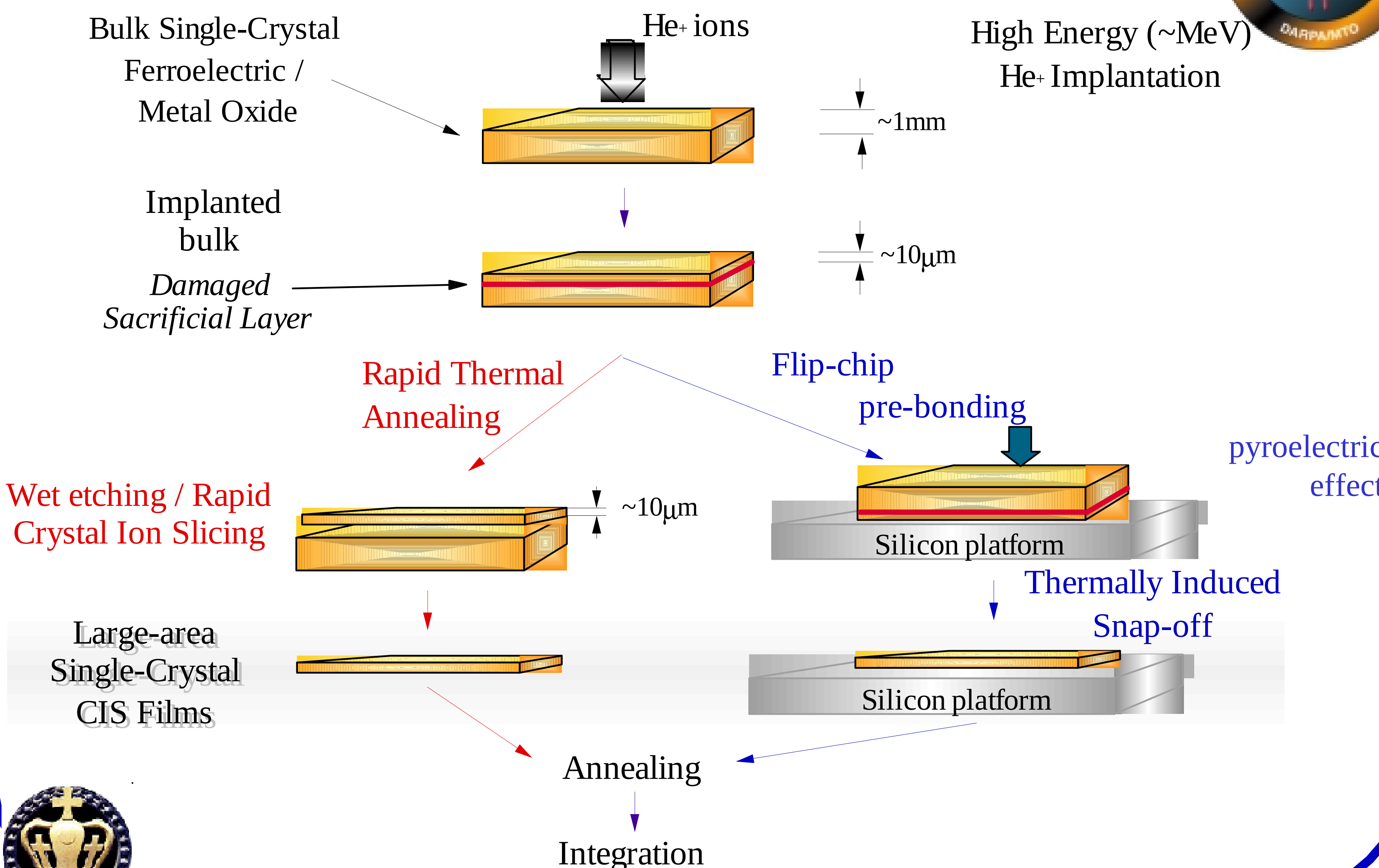
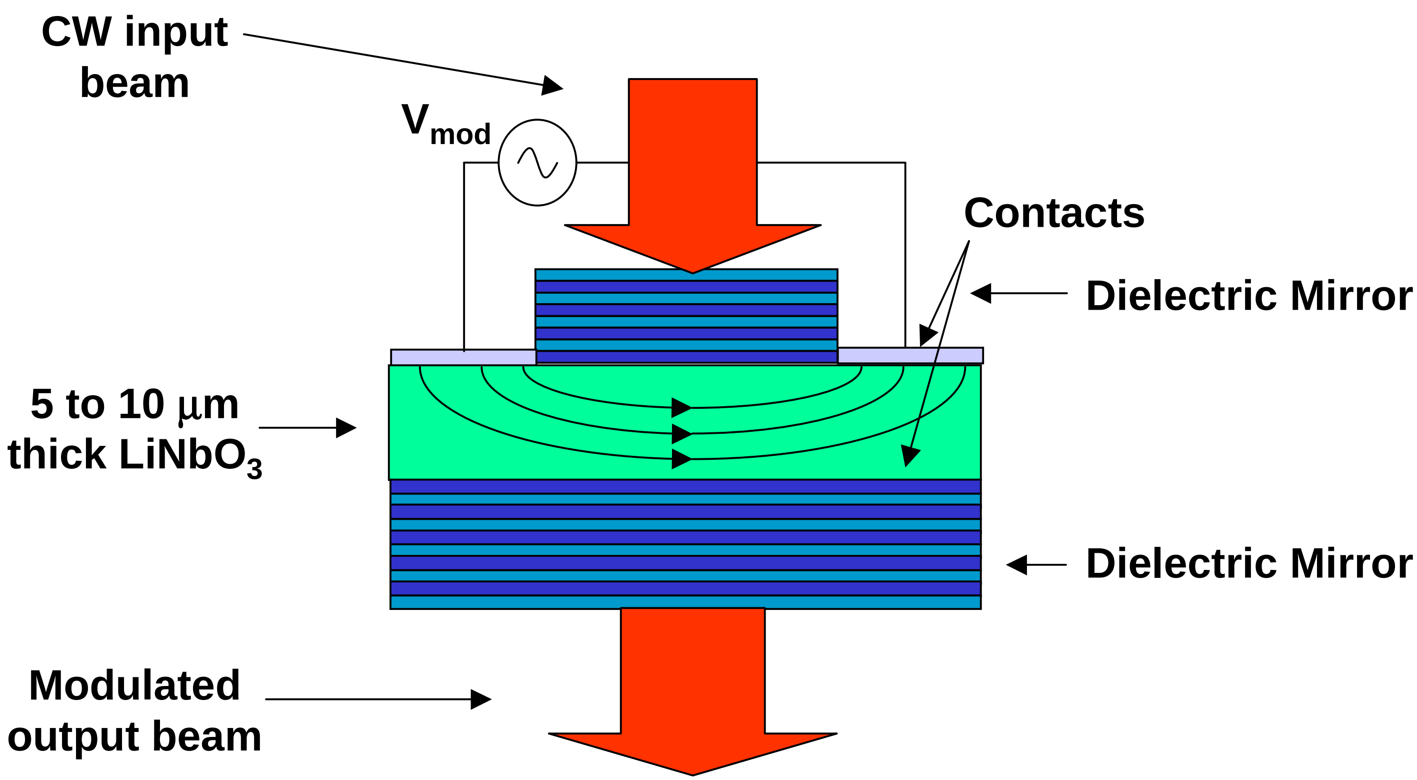
# Crystal Ion Slicing (CIS)

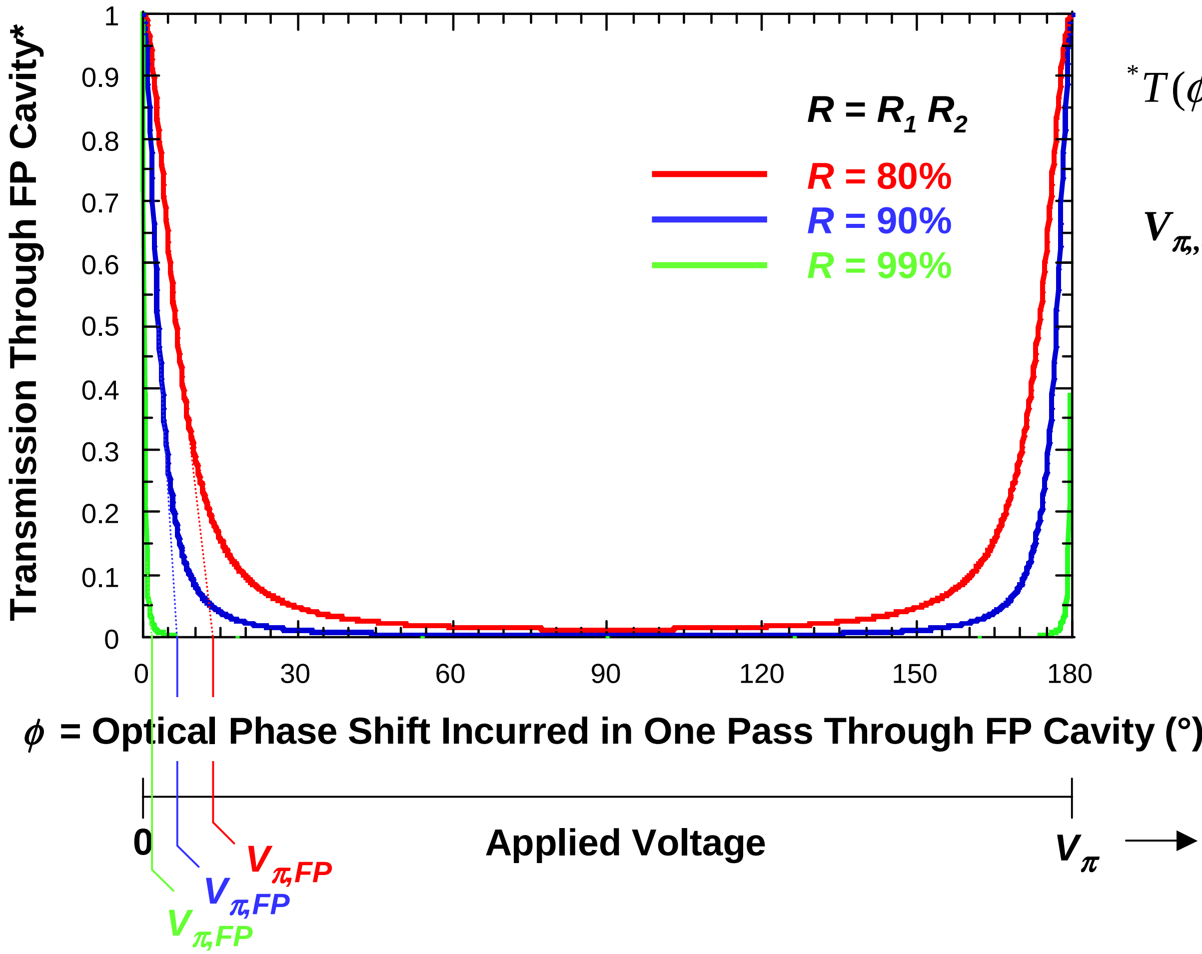


# Vertical Fabry-Perot Modulator in x-cut Crystal-Ion-Sliced Lithium Niobate



# Fabry-Perot Modulator Performance

## $V_{\pi,eq}$ Decreases with Increasing Mirror Reflectivities




$$^{*}T(\phi) \equiv \frac{P_{out}}{P_{in}} = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(\phi)}$$

$V_{\pi,eq} \equiv V_{\pi}$ *that a MZ must exhibit to have same slope efficiency*

$$= \pi \frac{P_{out}}{\left|\frac{\partial P_{out}}{\partial v_m}\right|_{P_{out}=0.5\,P_{in},\,v_m=0}} = \pi V_{\text{mod}}$$

$V_{\pi}$ → ***not dependent on R***

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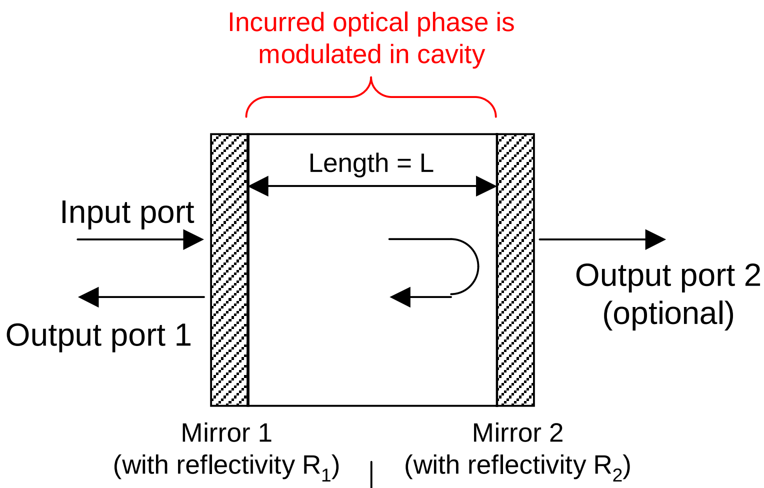
# Performance of Resonant Modulators

## Fabry-Perot

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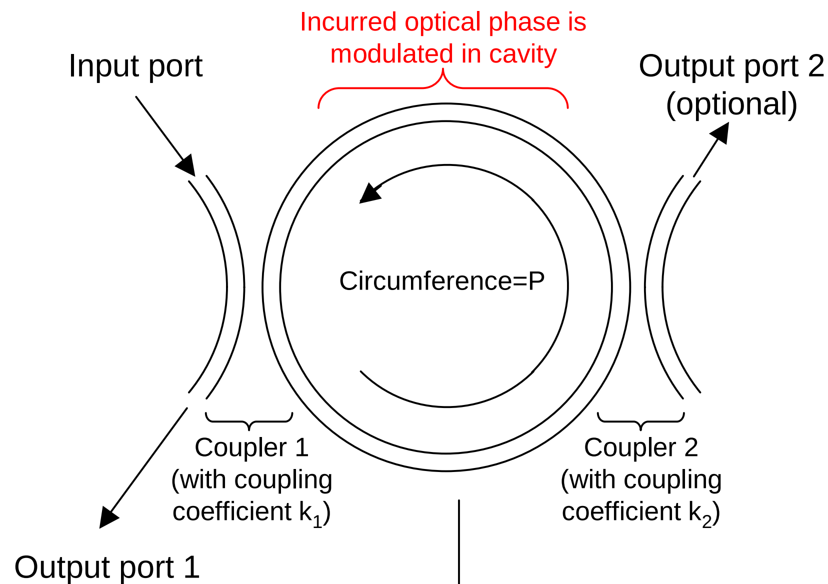


$$\tau \approx \frac{2\,n\,L}{c\left(1-\sqrt{R_1 R_2}\right)}$$

**Photon lifetime $\tau$ determines modulator performance**

$$\tau \approx \frac{n\,P}{c\,|k_1 k_2|}$$

**For either resonant interferometer,**

$$V_{\pi,eq} \propto \frac{1}{\tau} \qquad f_{3dBe} \propto \frac{1}{\tau} \qquad \frac{f_{3dBe}}{V_{\pi,eq}} \approx \frac{\sqrt{\sqrt{2}-1}}{2\pi}\,\frac{n^2 r\,\Gamma\,c}{\lambda\,g} \longrightarrow$$

Independent of $R$ and $L$, or $k$ and $P$

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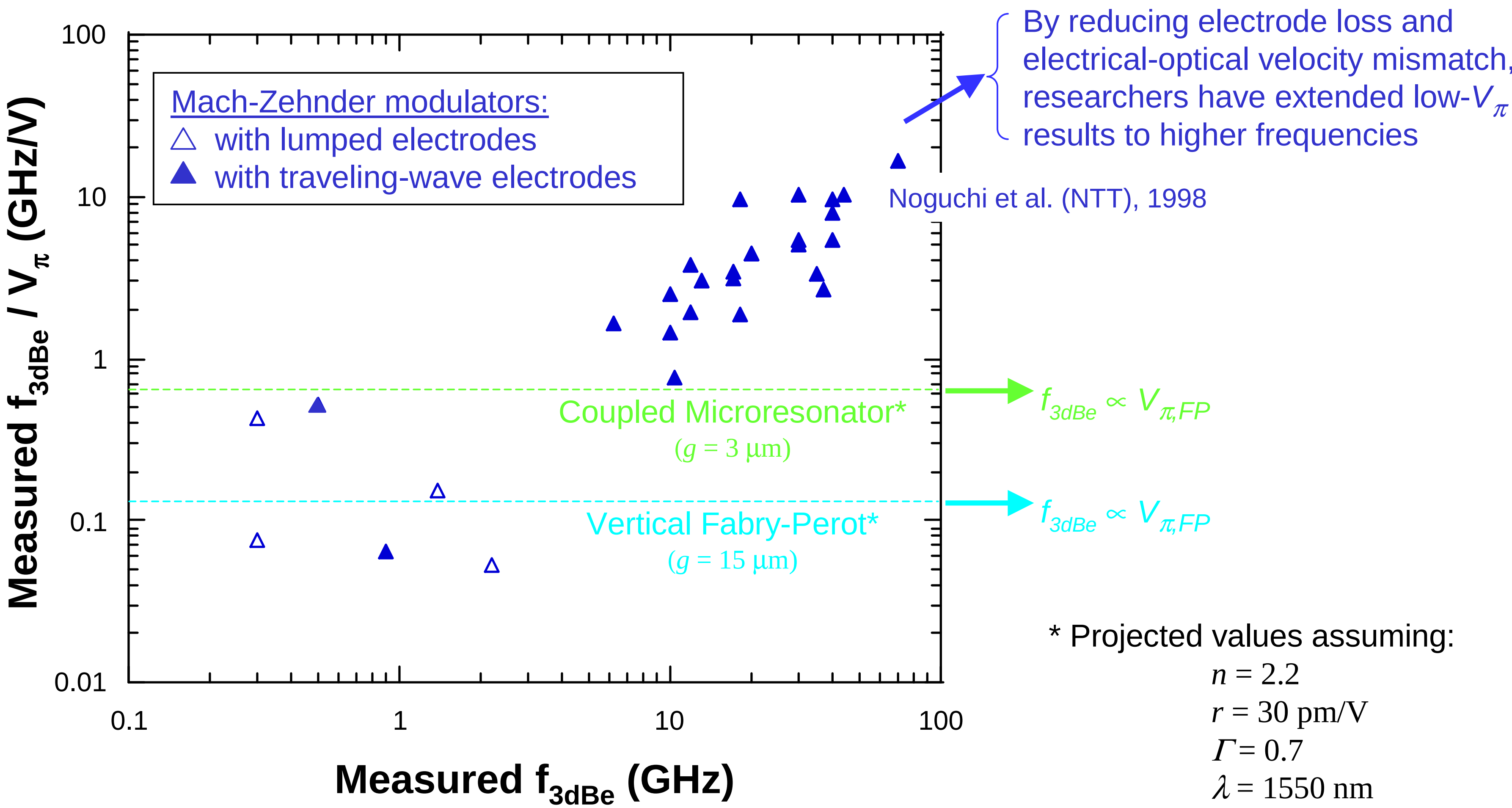
# Projected Resonant Interferometric $LiNbO_3$ Modulator Results vs. MZ




* Projected values assuming:
$n = 2.2$
$r = 30$ pm/V
$\Gamma = 0.7$
$\lambda = 1550$ nm

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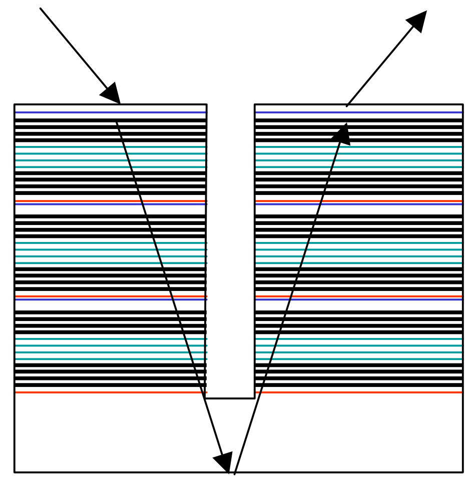
# 6x better multi-vertical Cavity Modulator

- **Each stage equivalent to a 12 μm diameter ring resonator in photon lifetime**
- **For capacitance equivalent to a 1 μm wide ring resonator, need diameter of 10 μm or less**
- **Must use electrorefractive configuration.**
- **Cannot use electroabsorption effect due to destruction of resonance**



**Photon lifetime of ~4 psec per stage***

**3 stages with double pass and individual electrical contact to each stage;**

**Must install RF delay lines between stages.**

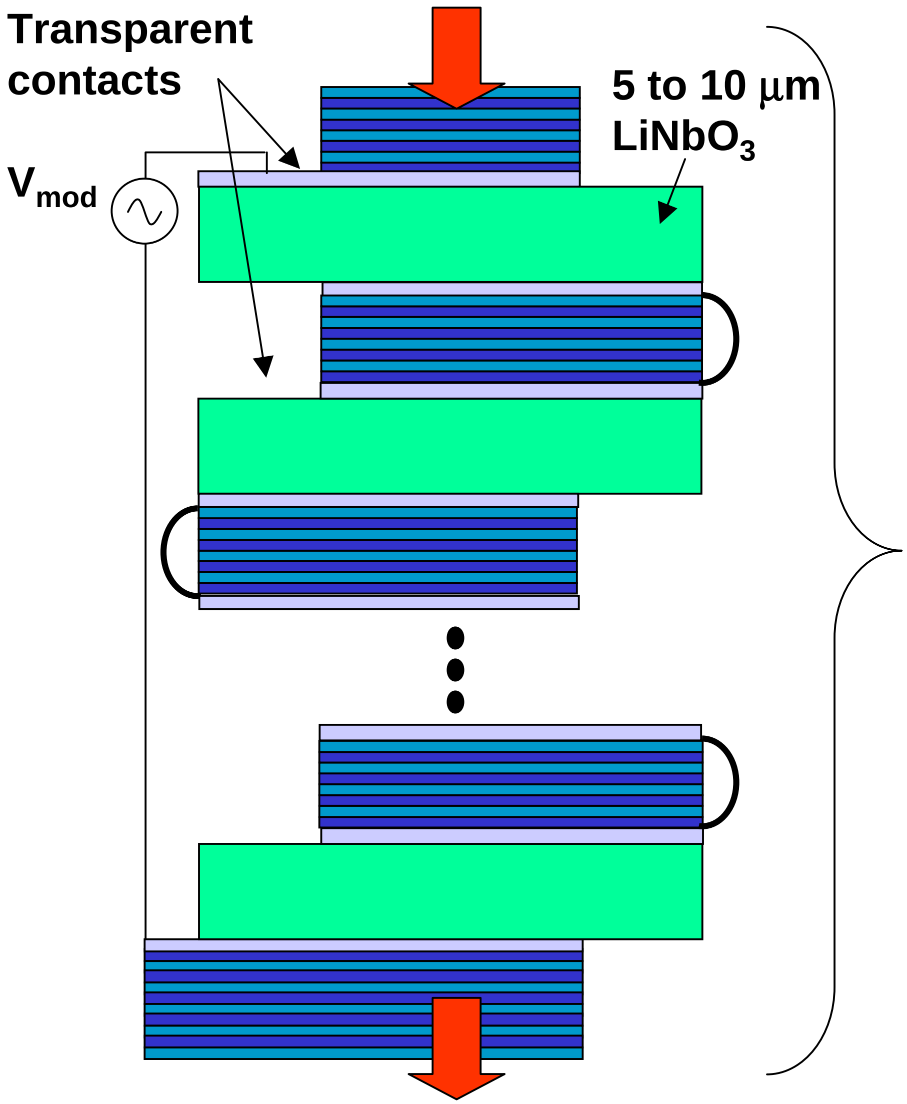
***6x lower $V_\pi$ from this arrangement***

*** 2 μm [height] × 200 [finesse] × 0.01 psec/μm;**

**N.B.: equivalent to a 400 mm straight modulator**

**$f_{3dB}$ = 1/(2π × 4 [psec]) = 40 GHz**

# Sarnoff Cascaded Fabry-Perot Modulator in z-cut CIS Lithium Niobate




**A device conceptually equivalent to this could have up to 100 cascaded FP's in 1 cm:**

$$\frac{f_{\mathrm{3dBe}}}{V_{\pi,eq}} \approx 10\ \mathrm{GHz/V}$$

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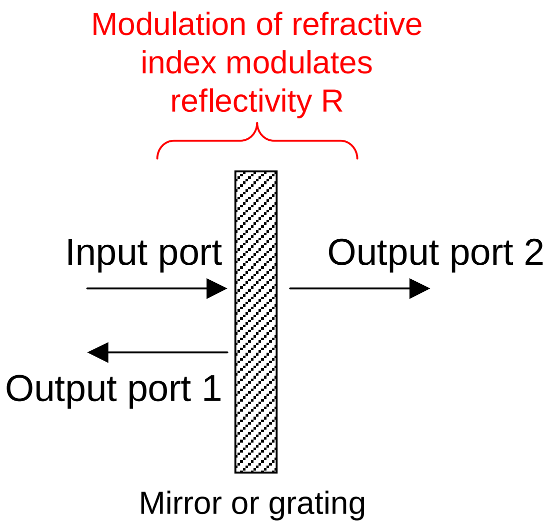
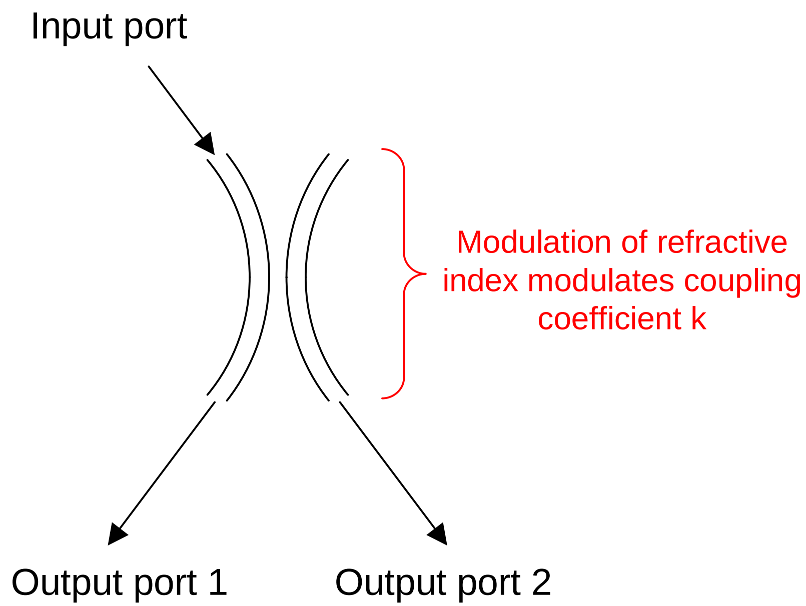
  - Cascaded resonant interferometric modulator (Sarnoff idea)
  - Modeled performance of modulators with combined interferometric and guide/antiguide effects
- Noise/Intermodulation Test Rack
- Summary

# Guide/Antiguide Modulators

## Mirror type



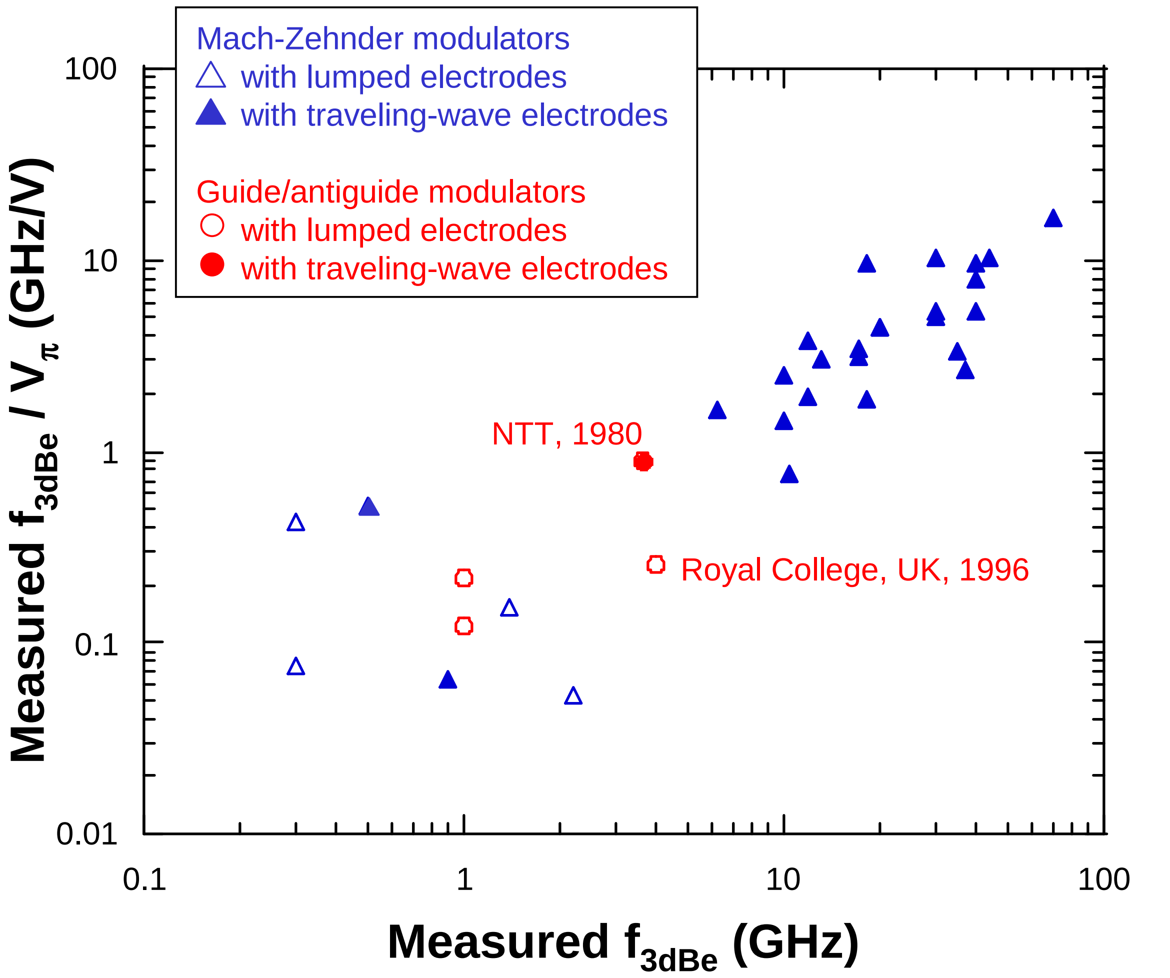

## Coupler type




$$R \Leftrightarrow 1 - |k|^2$$

# $LiNbO_3$ Guide/Antiguide Modulators

## How They Have Stacked Up Against $LiNbO_3$ MZ's

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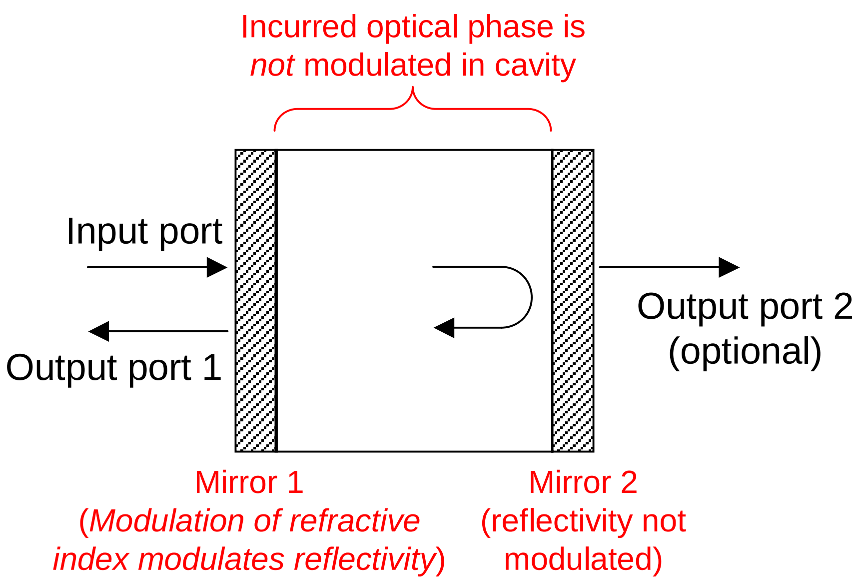
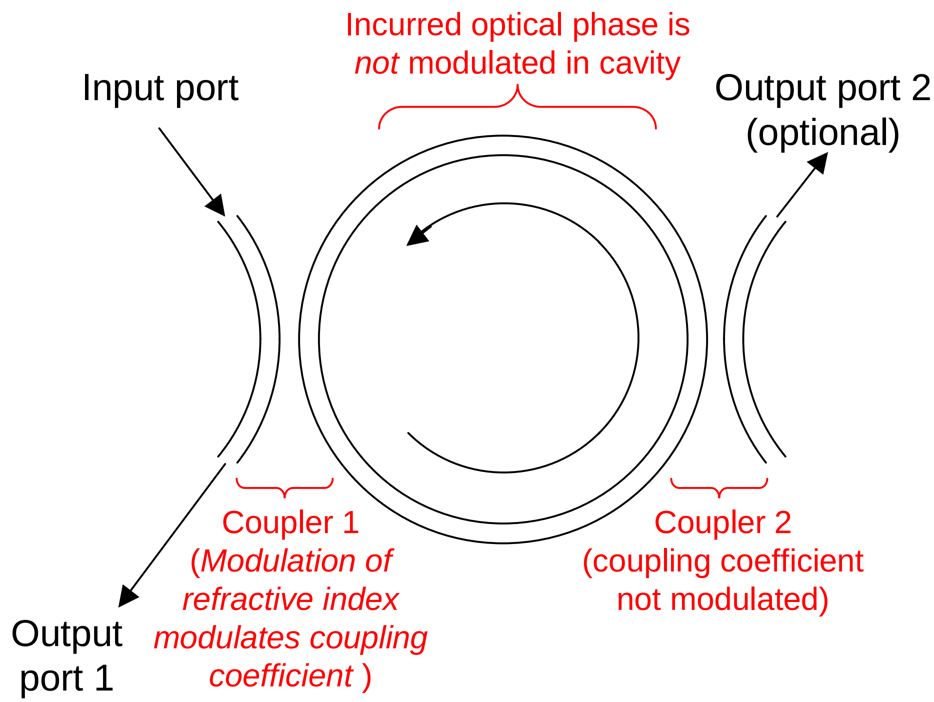
# Modulators with Combined Interferometric and Guide/Antiguide Effects




**We are investigating the efficiency-bandwidth tradeoffs of these designs.**

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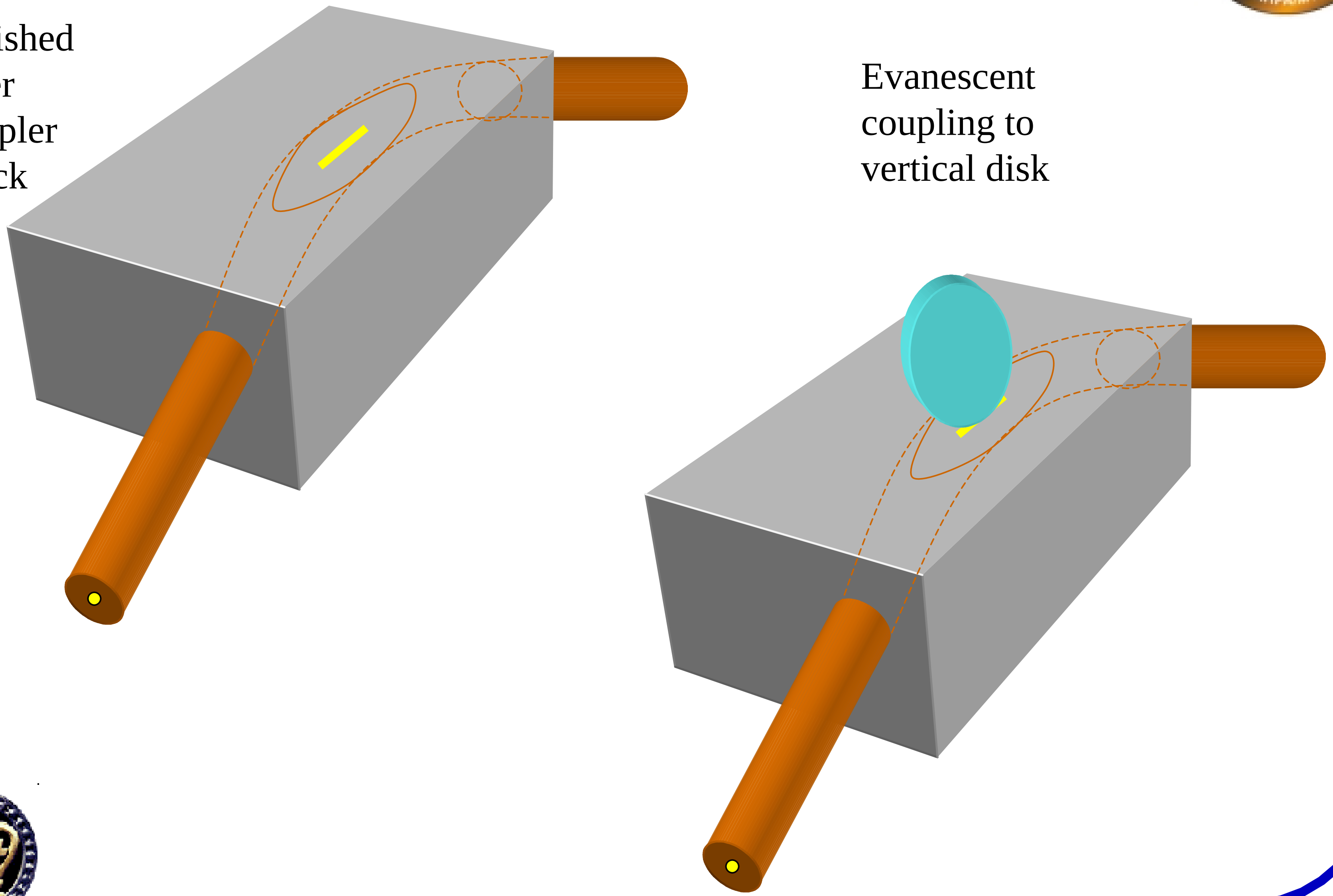
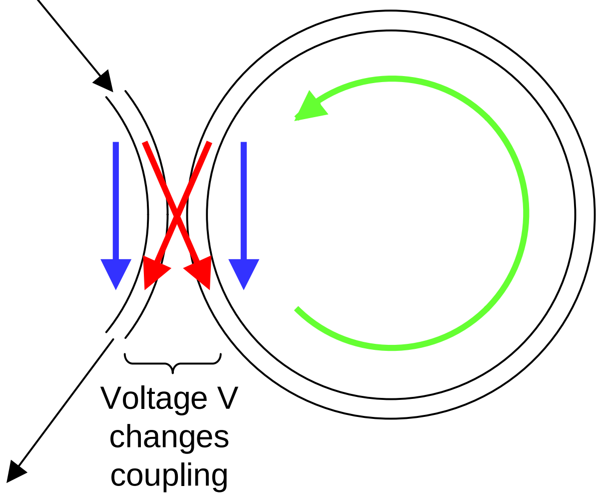
# Implementation of Disk Resonator Device

Polished fiber coupler block



Evanescent coupling to vertical disk

# Analysis of Disk Resonator Modulator




*Cross state:* $$C(V) = \frac{\sin^2\left(\frac{\pi}{2}\sqrt{1+3\left(\frac{V}{V_S}\right)^2}\right)}{1+3\left(\frac{V}{V_S}\right)^2}$$

*Bar state:* $$B(V) = 1 - C(V)$$

*Delay:* $$D = e^{j2\pi n\frac{P}{\lambda}}$$

$$V_S = \frac{2\sqrt{3}\,g\,\lambda}{n^3\,r\,L}$$

*Transmission Characteristic:* $$T(V) = [B(V)] + [C(V)\cdot D\cdot C(V)] + [C(V)\cdot D\cdot B(V)\cdot D\cdot C(V)] + [C(V)\cdot D\cdot B(V)\cdot D\cdot B(V)\cdot D\cdot C(V)] + \ldots$$

$$= B(V) + \frac{[C(V)]^2 D}{1 - B(V)\cdot D}$$

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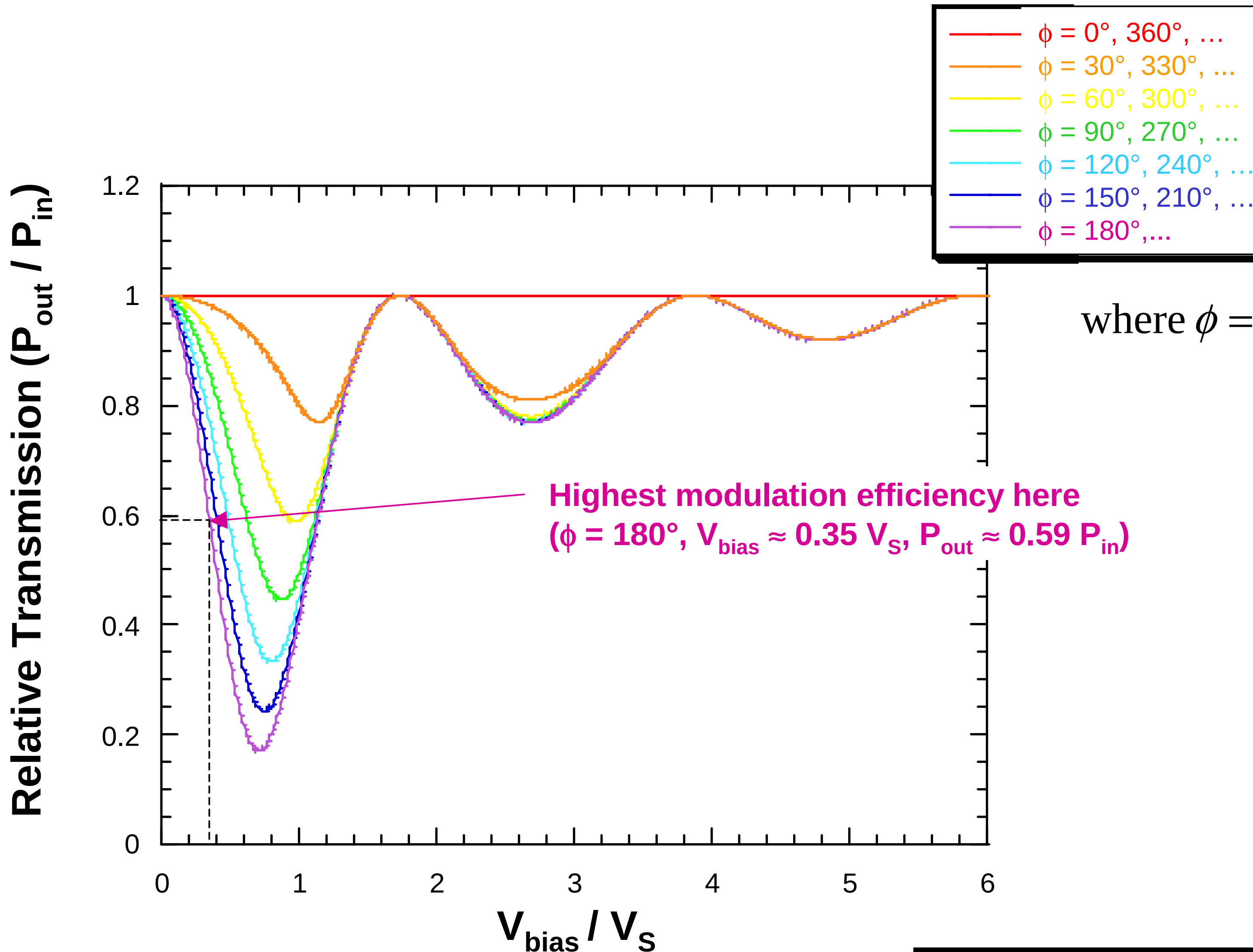
# Analysis of Disk Resonator Modulator




where $\phi = 2\pi\, n \frac{P}{\lambda}$

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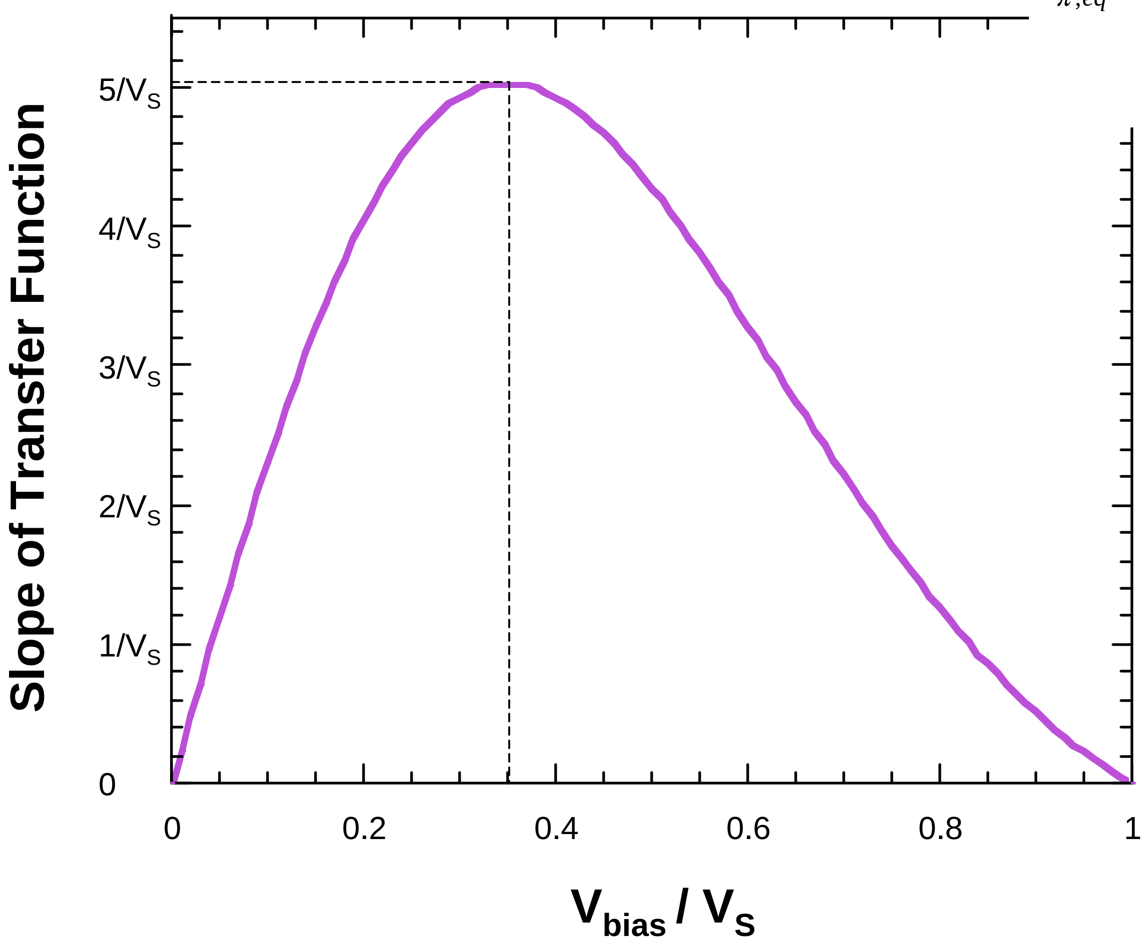
# Analysis of Disk Resonator Modulator




$$V_{\pi,eq} = \pi \frac{P_{out}}{\left|\frac{\partial P_{out}}{\partial v_m}\right|_{P_{out}\approx 0.59\,P_{in},\,v_m=0}} \approx \pi \frac{0.59}{5/V_S},$$

$$\text{where } V_S = \frac{2\sqrt{3}\,g\,\lambda}{n^3\,r\,\Gamma\,L}$$

$$\text{and } f_{3dBe} \approx \frac{\sqrt{\sqrt{2}-1}}{2\pi}\frac{c}{n\,P}B(V)$$

$$\text{so } \frac{f_{3dBe}}{V_{\pi,eq}} \approx \frac{n^2\,r\,\Gamma\,c}{4\pi\,\lambda\,g}\frac{L}{P}B(V)$$

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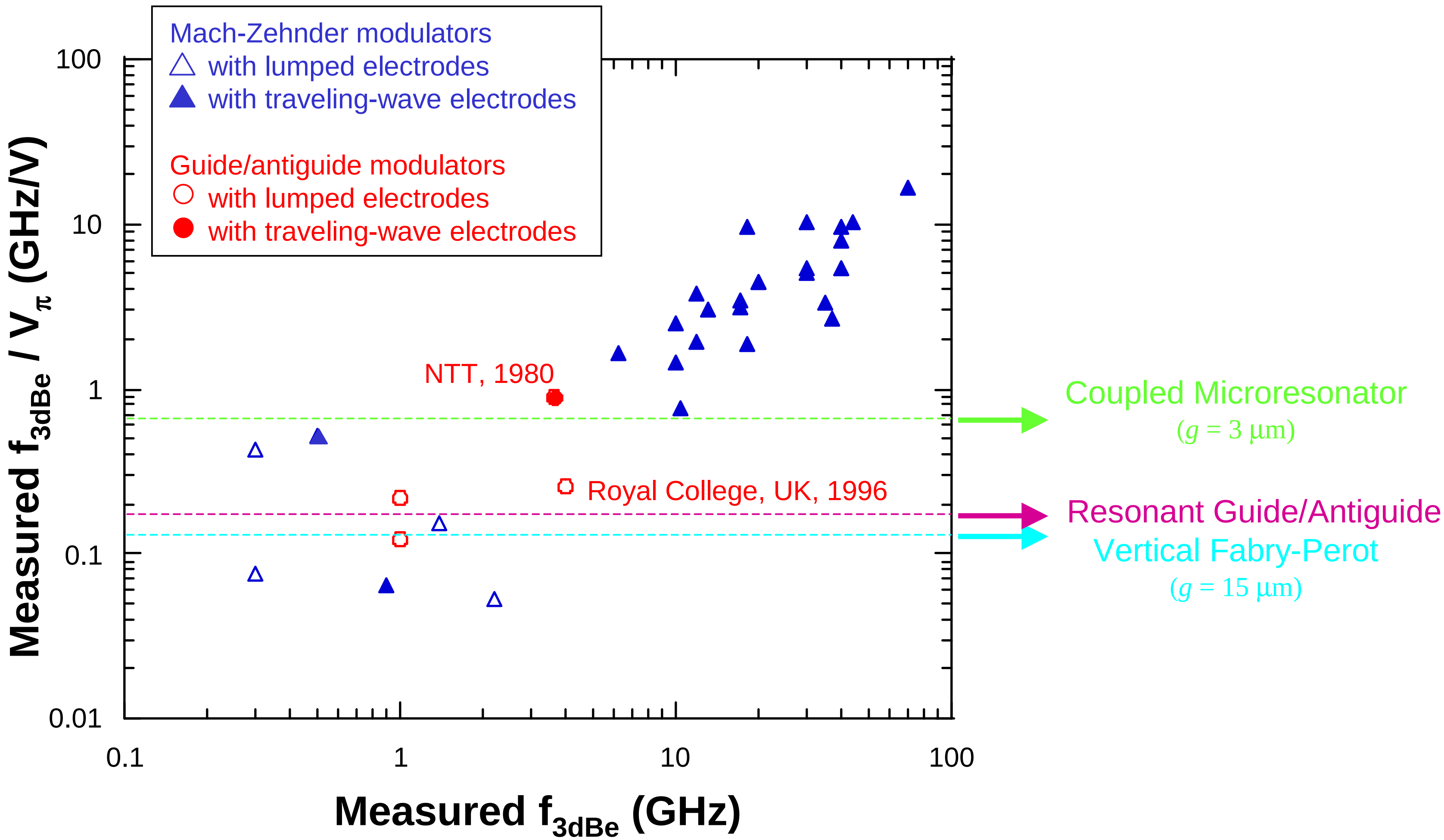
# Projected Resonant Guide/Antiguide $LiNbO_3$ Modulator Result vs. MZ

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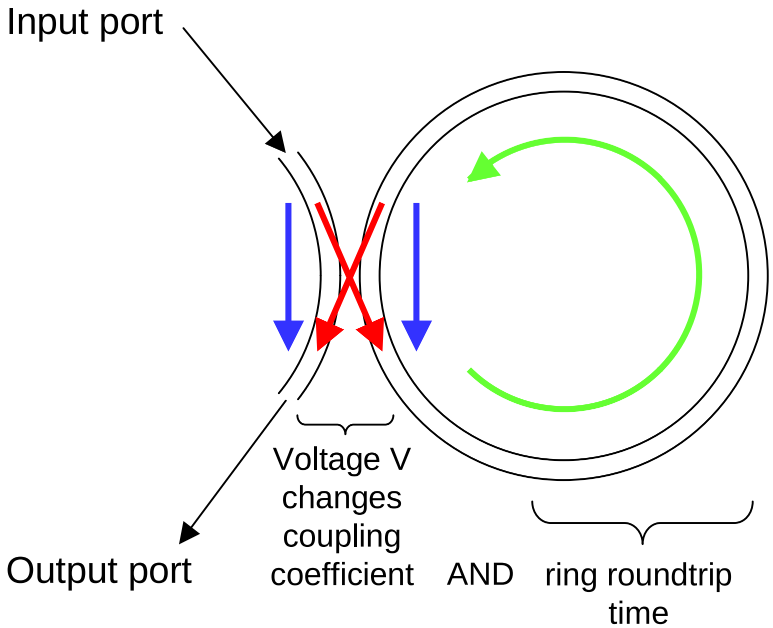
# Analysis of Disk Resonator Modulator with Cascaded Modulation Effects




*Cross state:* $$C(V)=\frac{\sin^2\left(\frac{\pi}{2}\sqrt{1+3\left(\frac{V}{V_S}\right)^2}\right)}{1+3\left(\frac{V}{V_S}\right)^2}$$

*Bar state:* $$B(V)=1-C(V)$$

*Delay:* $$D(V)=e^{j2\pi n(V)\frac{P}{\lambda}}$$

$$V_S=\frac{2\sqrt{3}\,g\,\lambda}{n^3\,r\,L}$$

*Transmission Characteristic:* $$T(V)=B(V)+\frac{[C(V)]^2 D(V)}{1-B(V)\cdot D(V)}$$

# Analysis of Disk Resonator Modulator with Cascaded Modulation Effects

$$\text{Slope of transfer function} = 2\frac{C^3(C-1)\frac{\pi}{V_\pi}\sin\phi + \left(3C^2-8C+4\right)\frac{\partial C}{\partial v}\cos\phi - \left(C^2-4C+2\right)\frac{\partial C}{\partial v} - 2(C-1)^2\frac{\partial C}{\partial v}\cos^2\phi}{\sqrt{\left[\left(C^2-2C+2\right)+2(C-1)\cos\phi\right]^3\left[\left(5C^2-6C+2\right)-\left(4C^2-6C+2\right)\cos\phi\right]}}$$

$$\text{where } \phi = 2\pi n\frac{P}{\lambda}$$

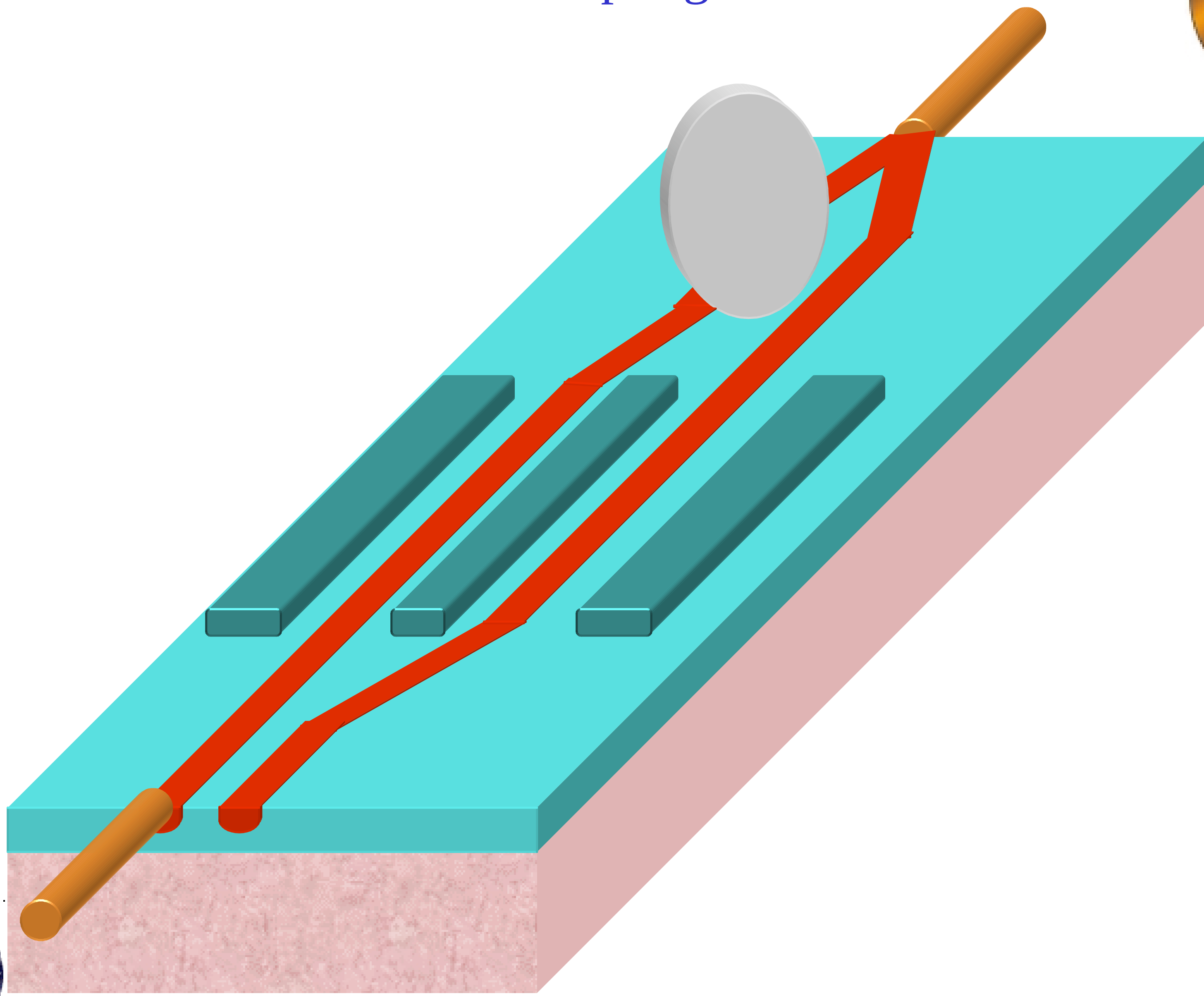
$$C = \frac{\sin^2\left(\frac{\pi}{2}\sqrt{1+3\left(\frac{V}{V_S}\right)^2}\right)}{1+3\left(\frac{V}{V_S}\right)^2}$$

Three degrees of freedom:

1. Resonator roundtrip bias $\phi$
2. Directional coupler bias $V$
3. Ratio of $V_S$ to $V_\pi$

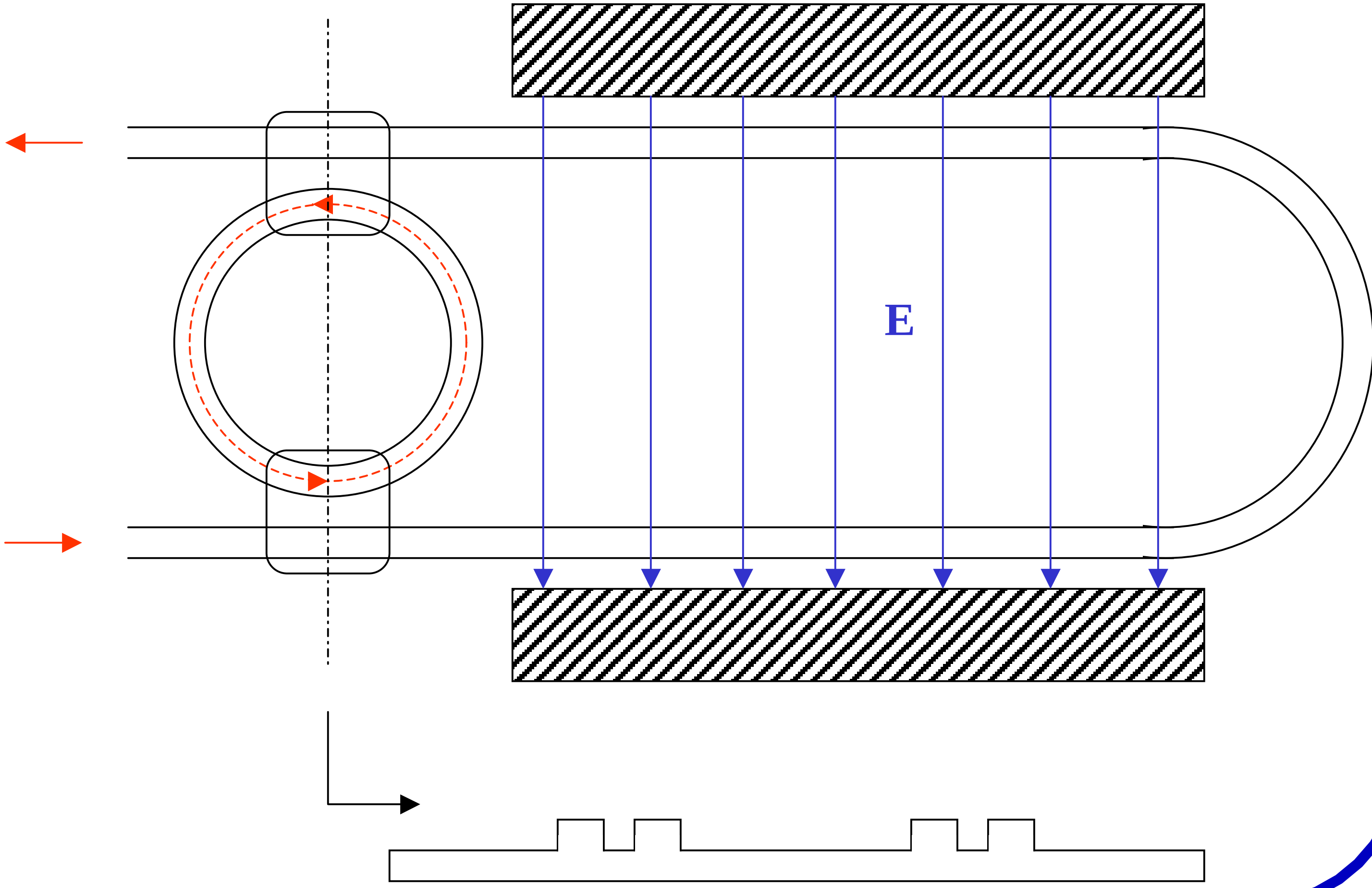
$$\text{and } \frac{\partial C}{\partial v} = \frac{3V}{V_S^2}\frac{1}{1+3\left(\frac{V}{V_S}\right)^2}\left[\frac{\pi}{2}\sqrt{1+3\left(\frac{V}{V_S}\right)^2}\sin\left(\pi\sqrt{1+3\left(\frac{V}{V_S}\right)^2}\right) - 2\sin^2\left(\frac{\pi}{2}\sqrt{1+3\left(\frac{V}{V_S}\right)^2}\right)\right]$$

# Mach-Zehnder based coupling variation



# Interferometric Coupling Modulation

Practical implementation:




~ also version with TW electrodes ~

# Outline

- Background
- Cascade Laser Development
- Resonant Modulator Performance Tradeoffs
- Noise/Intermodulation Test Rack
- Summary

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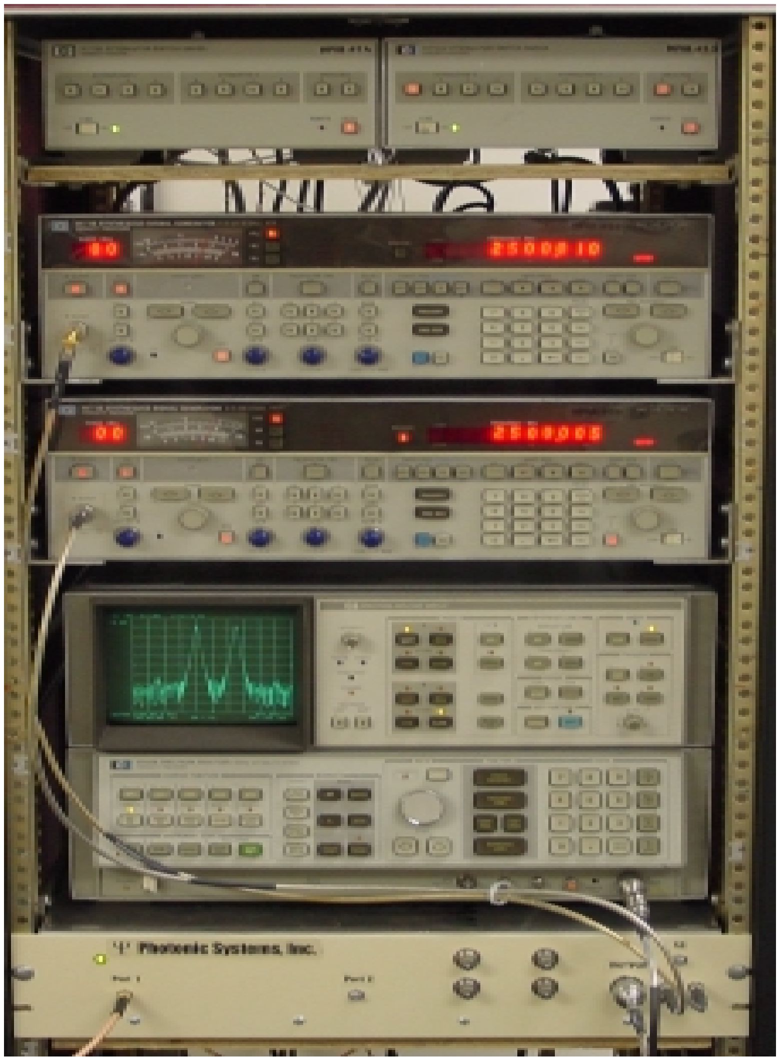
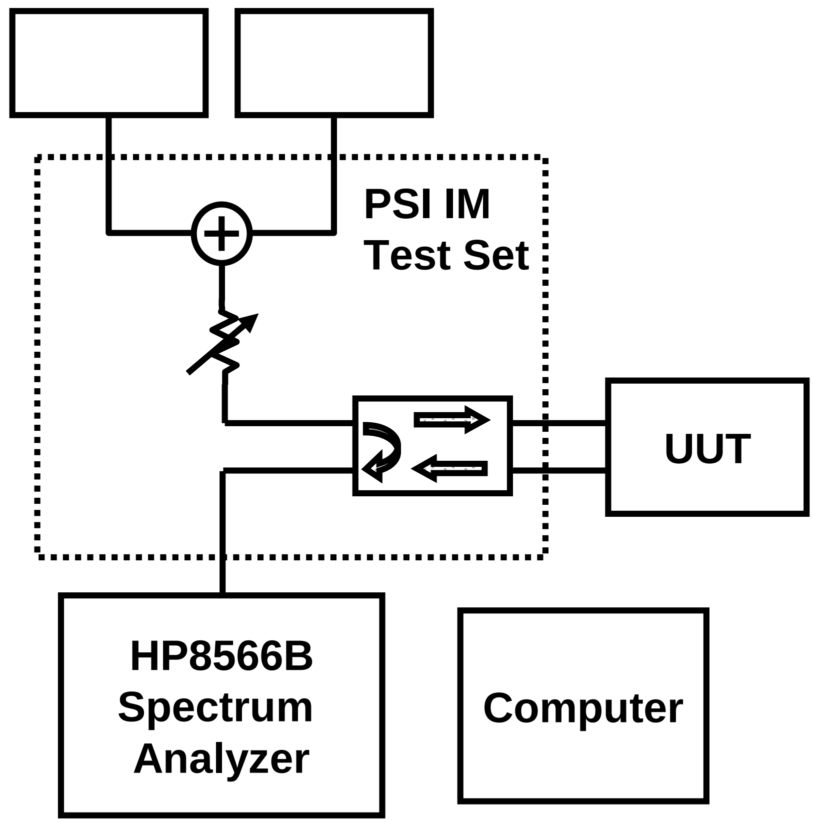
# PSI Noise and Distortion Measurement System



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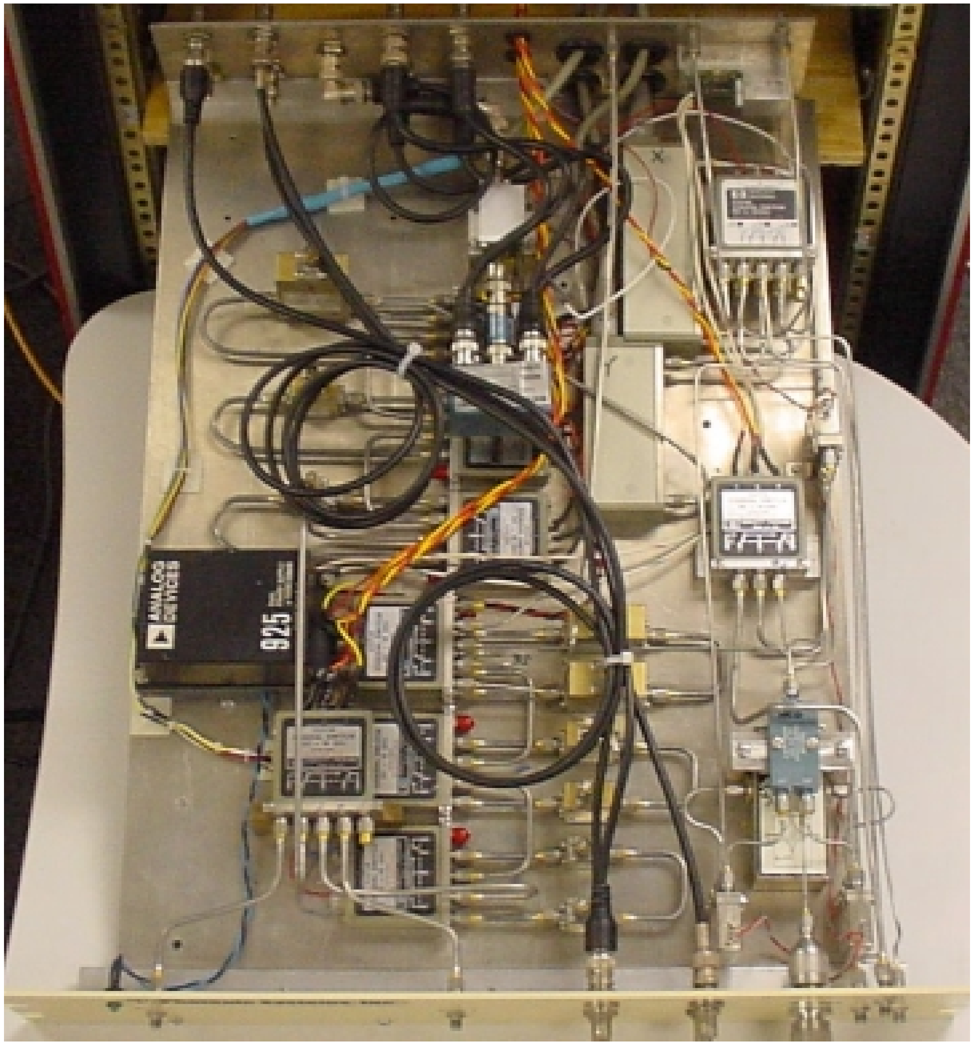
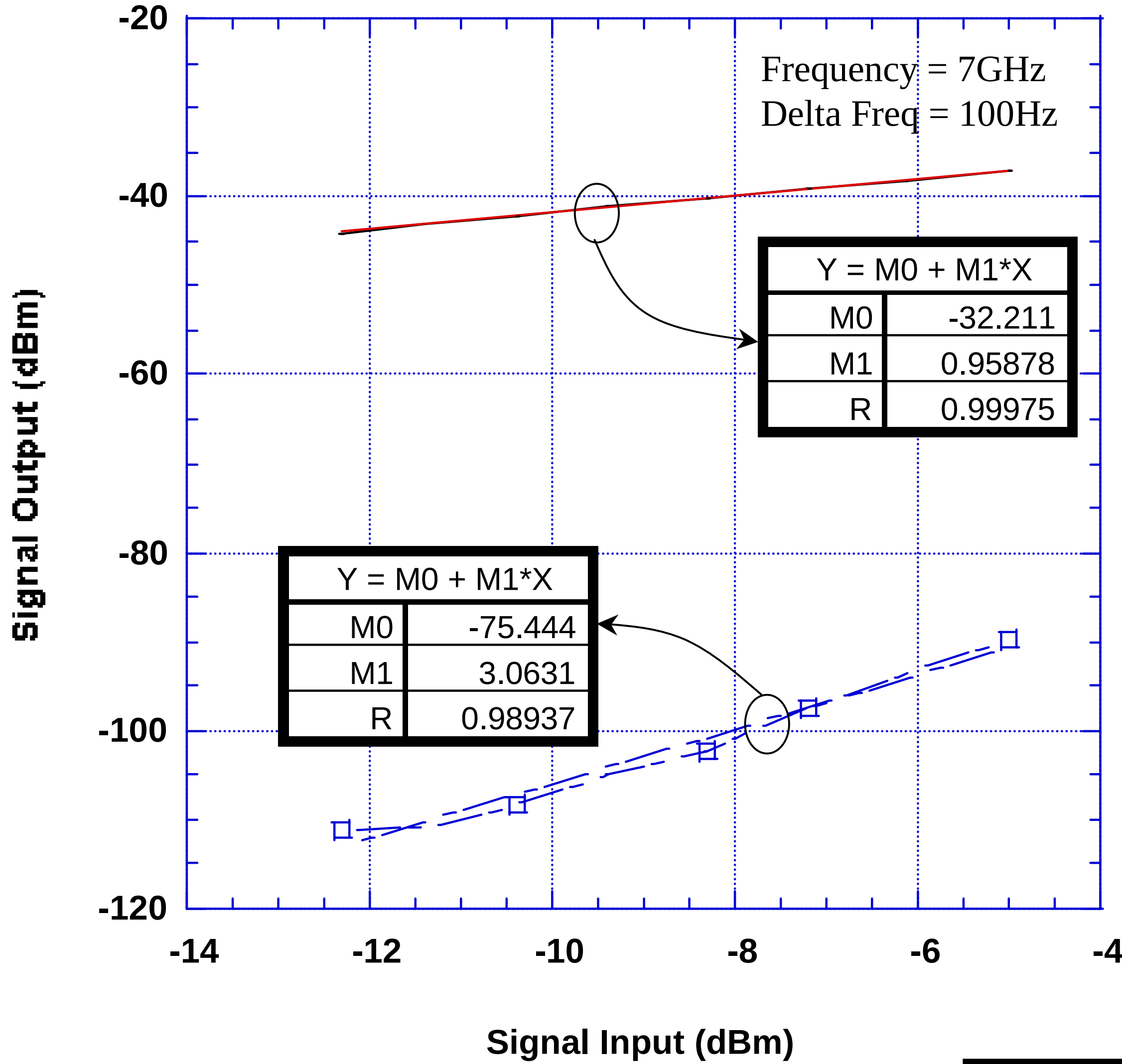
# PSI Noise/IM Test Set



# 3rd Order IM Measurements
## External Modulation Link

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# Outline

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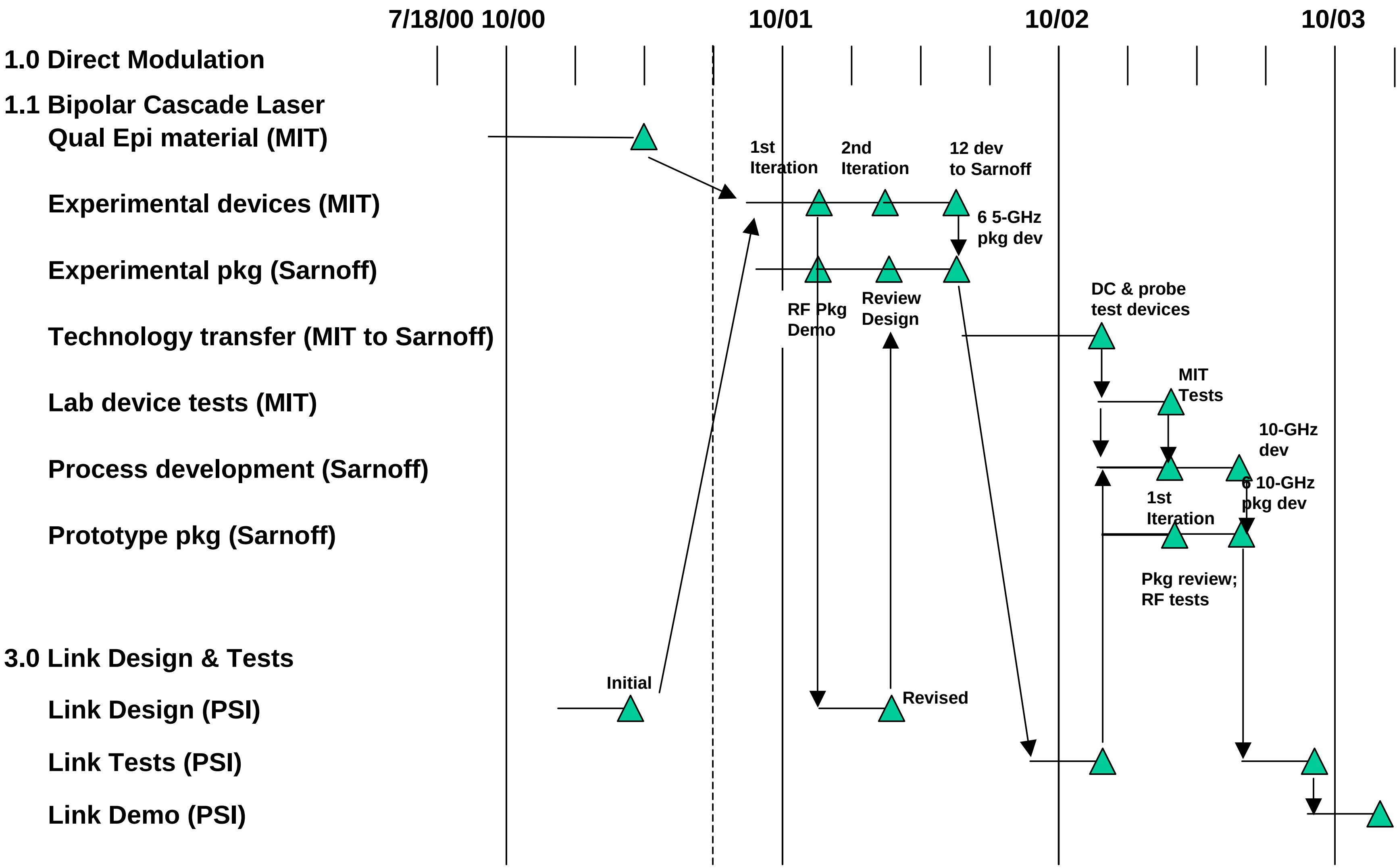
# Summary

- **Cascade Laser for Direct Modulation Links**
  - **Validated model of low-wavelength tunnel junction measurements in GaAs is being used to design 1.55 μm devices in InP**
  - **ARROW waveguide design is being applied to solve fiber coupling issue**
  - **Fiber-coupled effective quantum efficiency of 150% predicted for 3-laser cascade**
  - **Detuned loading and injection locking yield very high bandwidth (demonstrated 28 GHz) and low chirp**
- **Resonant Modulators for External Modulation Links**
  - **Investigating several designs to exploit Columbia crystal ion slicing technique**
  - **So far, all resonant structures have yielded efficiency-bandwidth tradeoffs inferior to traveling-wave MZs**
  - **Sarnoff cascaded traveling-wave FP concept is being investigated as a solution (however implementation is challenging)**
  - **Structures that combine resonance with guide/antiguide effects may yield alternative solutions**

# Most Significant Accomplishment

- **Demonstration:**
  - 28 GHz direct modulation of resonant-modulation laser with zero adiabatic chirp and very low dynamic chirp

# Program Roadmap
## Cascade Laser

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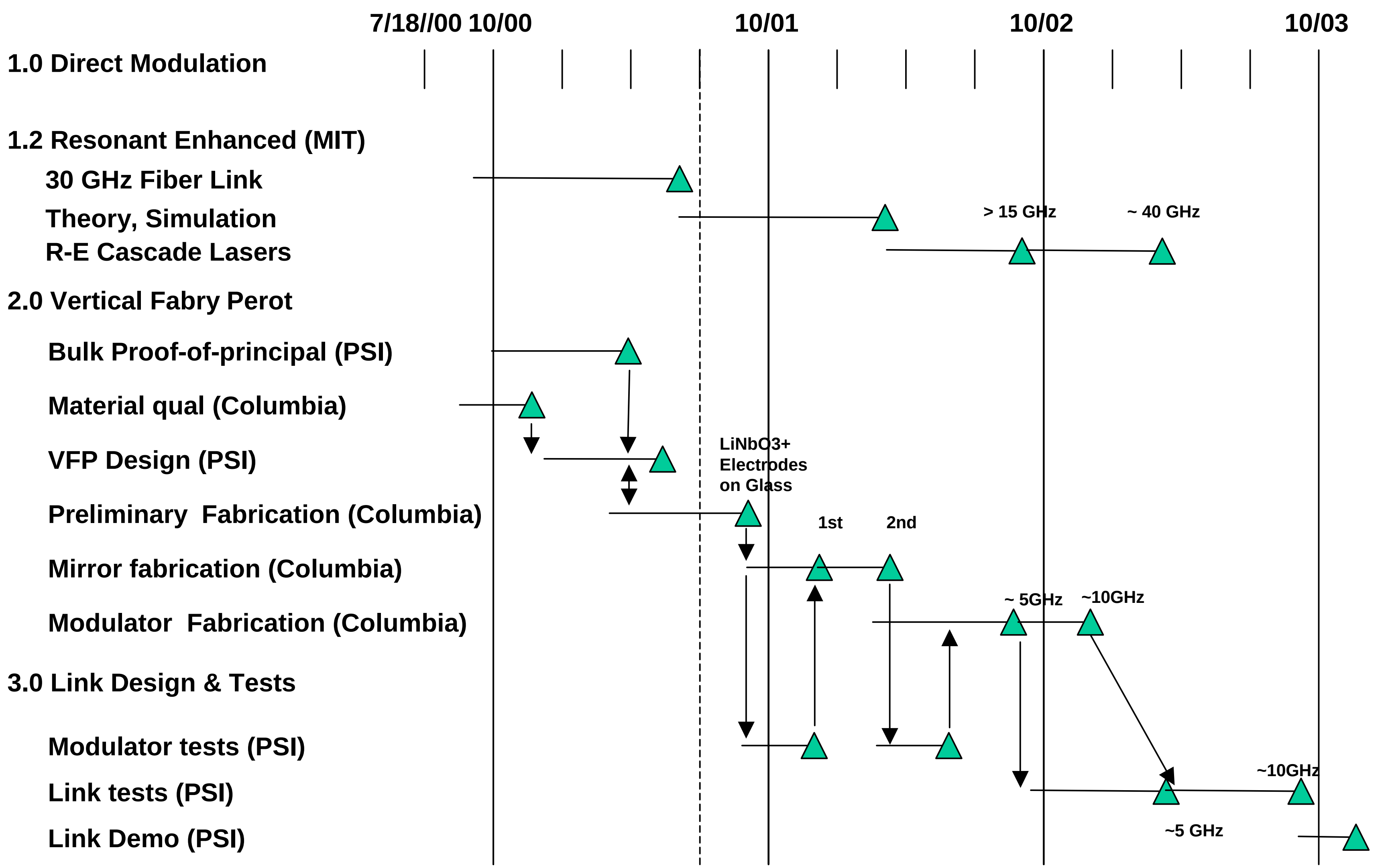
# Program Roadmap

## Resonantly Enhanced & External Modulation

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