# Low-Voltage Modulators for RFLICS

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# Outline

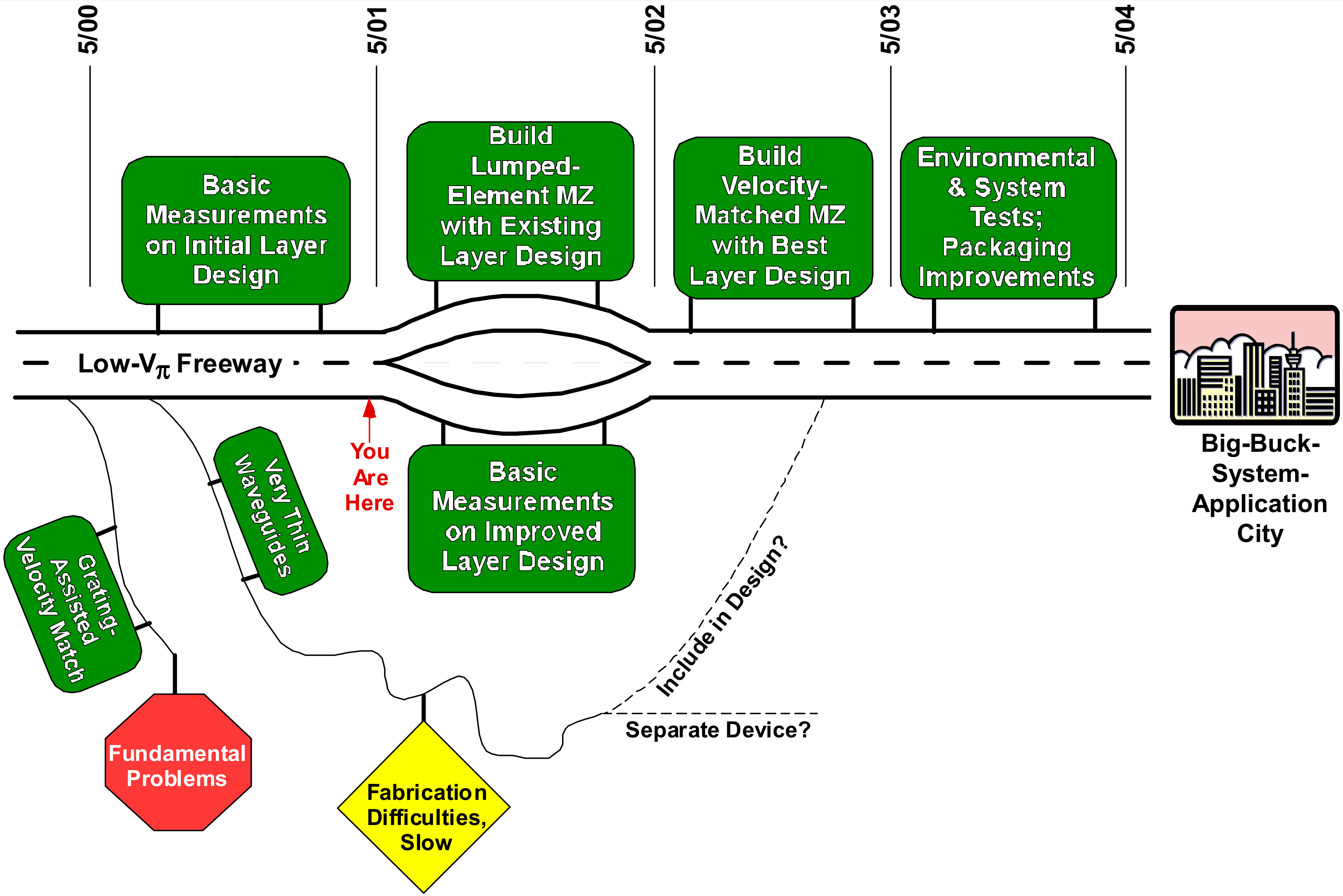
- Program objective & roadmap
- Semiconductor Electrorefractive Modulator
  - Structure and operation of primary design
  - Experimental results
- Summary: “Most significant accomplishment”

# Program Objective

- Program goal: Low-$V_\pi$ modulator
  - $V_\pi < 0.5$ V (at 50 GHz, from 50 ohms)
  - 50-GHz Bandwidth
  - Fiber-to-fiber loss <8 dB
  - Ability to meet practical linearity & environmental needs

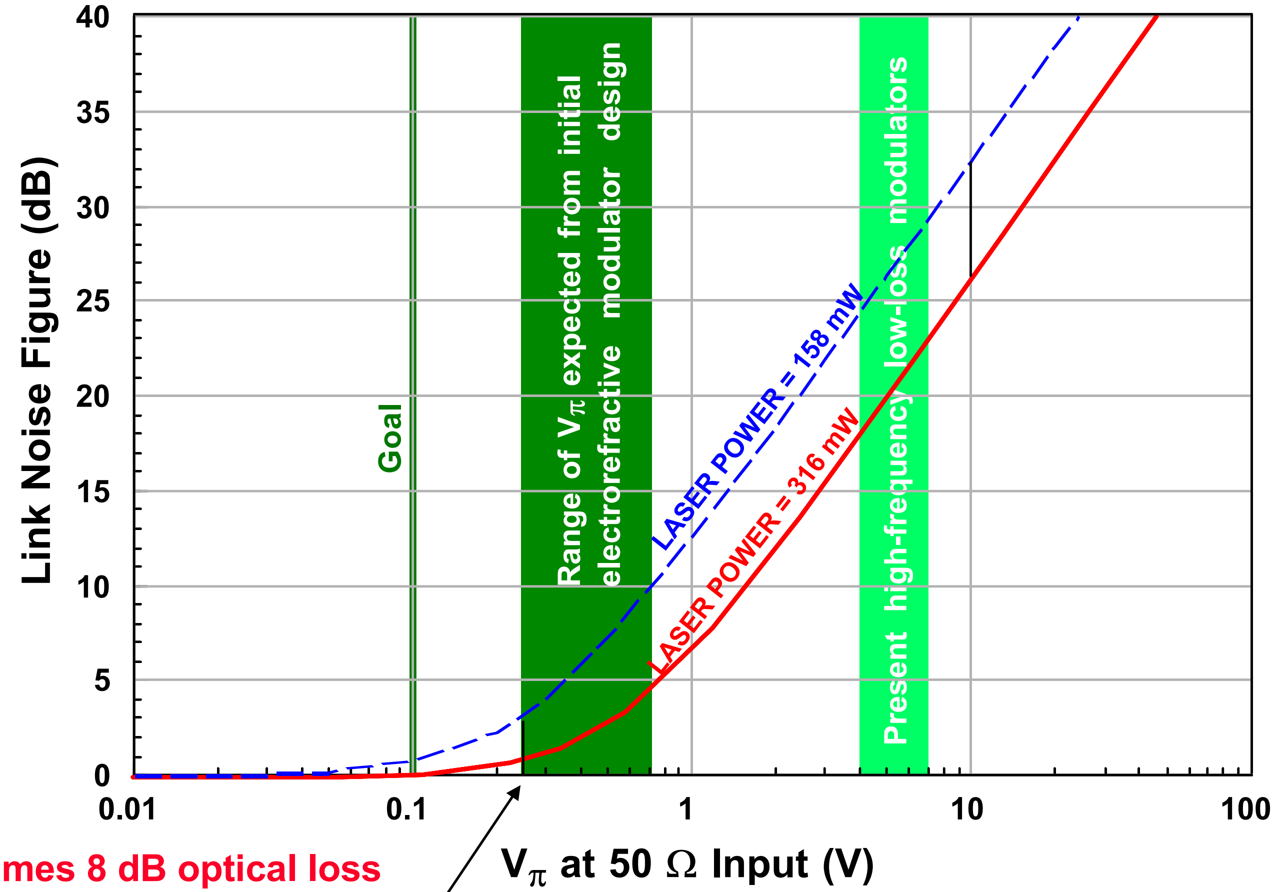
- Primary approach is III-V semiconductor Mach-Zehnder interferometer using electrorefraction + linear electro-optic effects

# Program Roadmap



# Motivation for Program Objective

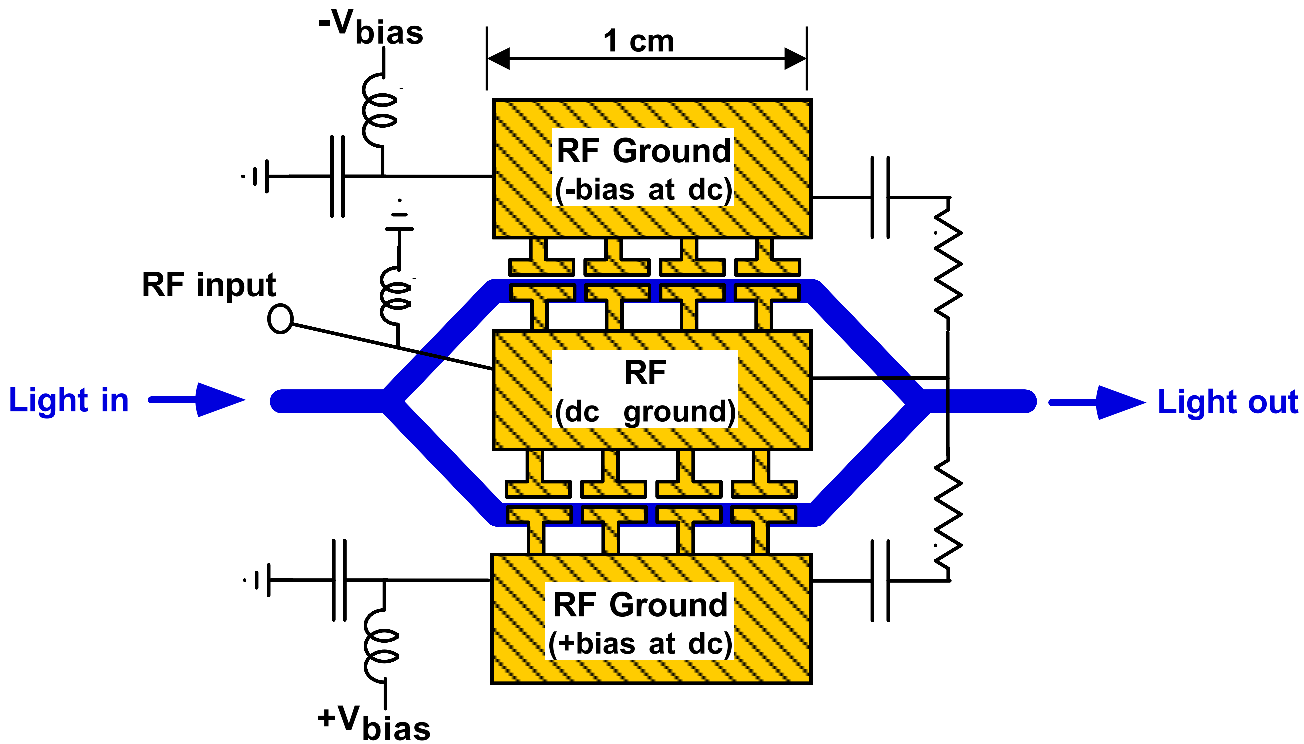
## Modulator that Enables Optical Links to Achieve <3 dB Noise Figure, without Electronic Preamplifiers




Plot assumes 8 dB optical loss

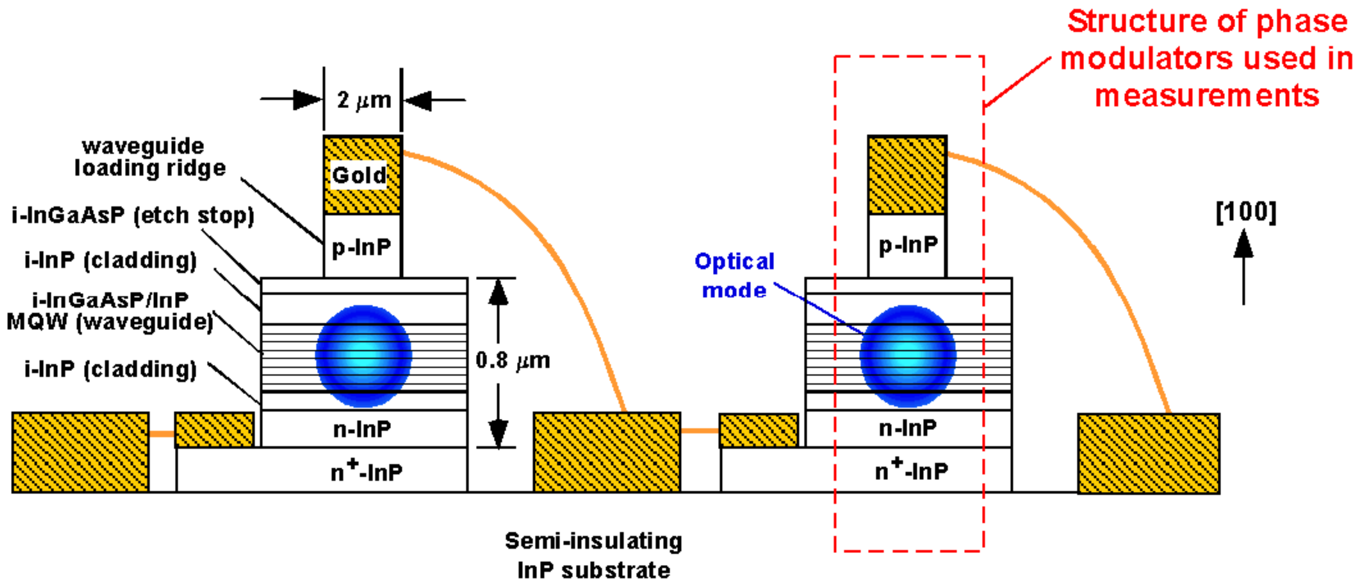
40-Gbit logic voltage

# Semiconductor Mach-Zehnder Modulator



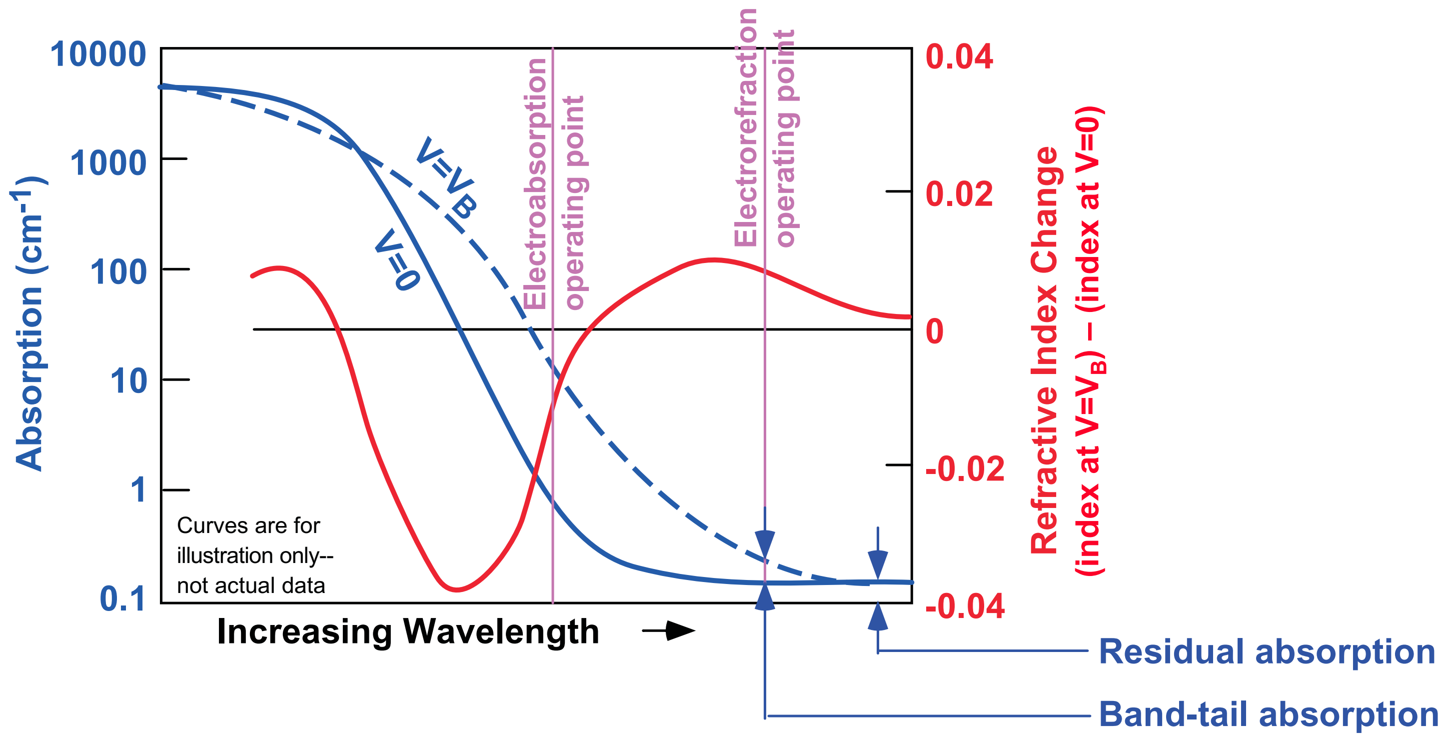

- Capacitively loaded line allows small electrode gaps with low microwave loss (6 dB/cm at 50 GHz projected)
- Optical losses are higher than lithium niobate, but acceptable
  - 2 dB per fiber/wg launch (demonstrated)
  - 4 dB/cm absorption loss (projected)

# Semiconductor Modulator Structure Details




- Doped layers cause applied voltage to appear across 0.8-μm waveguide layer
- Low-conductivity waveguide loading ridge need not be etched between sections
- Some design details need optimization
  - Thickness of i-InP cladding layer under p layer
  - Quantum well thickness and bandgap

# Electrorefractive Mechanism




— Residual absorption (waveguide scattering, free carrier absorption) can be engineered to be low

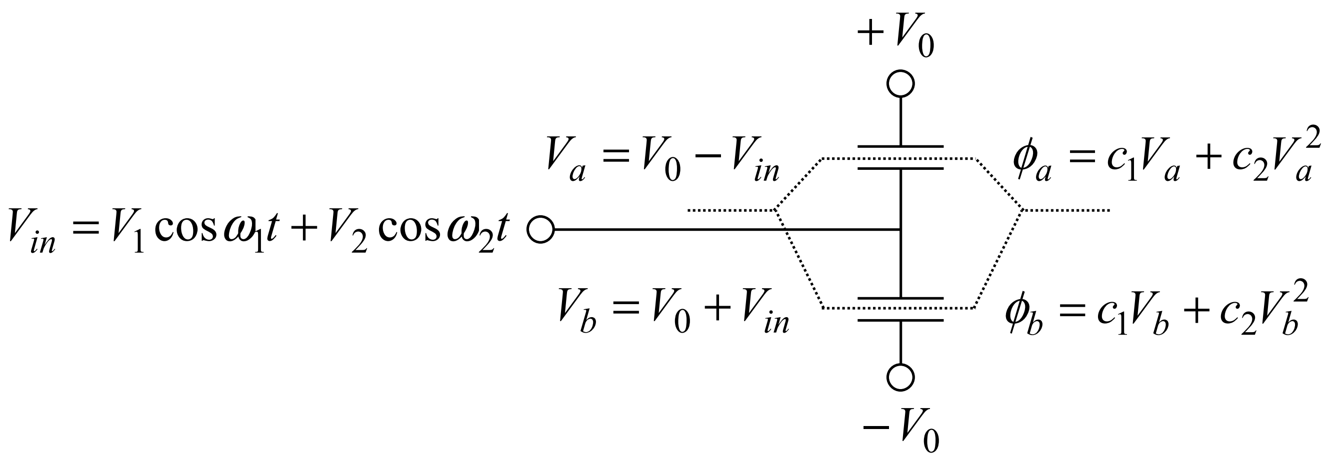
— Relative magnitude of band-tail absorption versus refractive index change is not well known

— Electrorefraction index change is quadratic in voltage; effective linear value is at 100 kV/cm bias

**Our goal for the electrorefraction MZ:**
**$V_\pi L$ product = 2.5 V-mm with absorption = 0.4 dB/mm**

**$n^3r$ = 275 pm/V (LN value is 312 pm/V), of which 80% is from electrorefraction**

# Linearity with Quadratic Electro-optic Effect



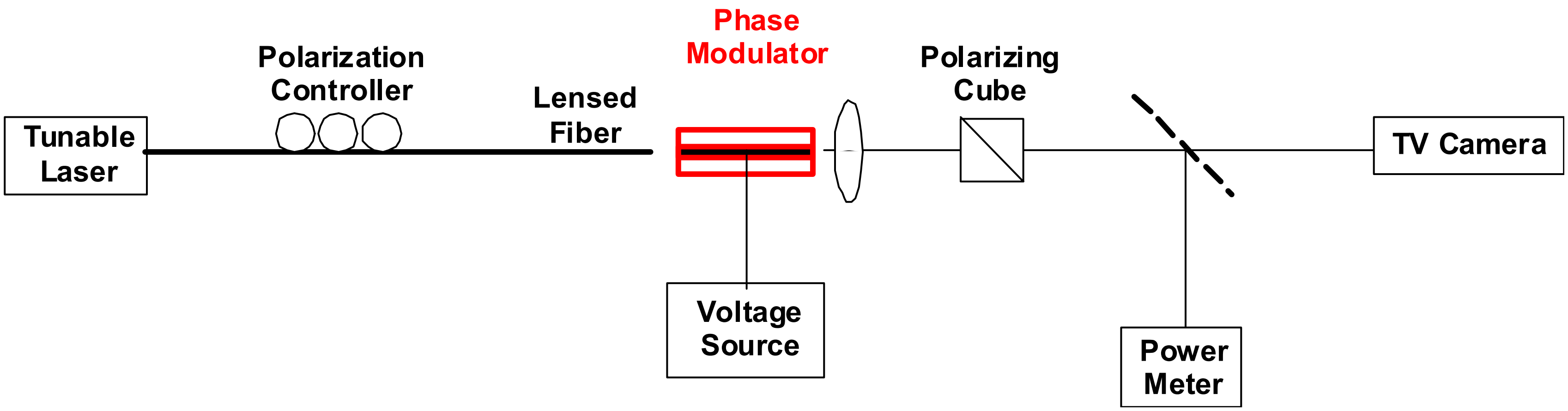

$$\phi_a = c_1\left(V_0 - V_1\cos\omega_1 t - V_2\cos\omega_2 t\right) + c_2\left(V_0 - V_1\cos\omega_1 t - V_2\cos\omega_2 t\right)^2$$

$$\phi_b = c_1\left(V_0 + V_1\cos\omega_1 t + V_2\cos\omega_2 t\right) + c_2\left(V_0 + V_1\cos\omega_1 t + V_2\cos\omega_2 t\right)^2$$

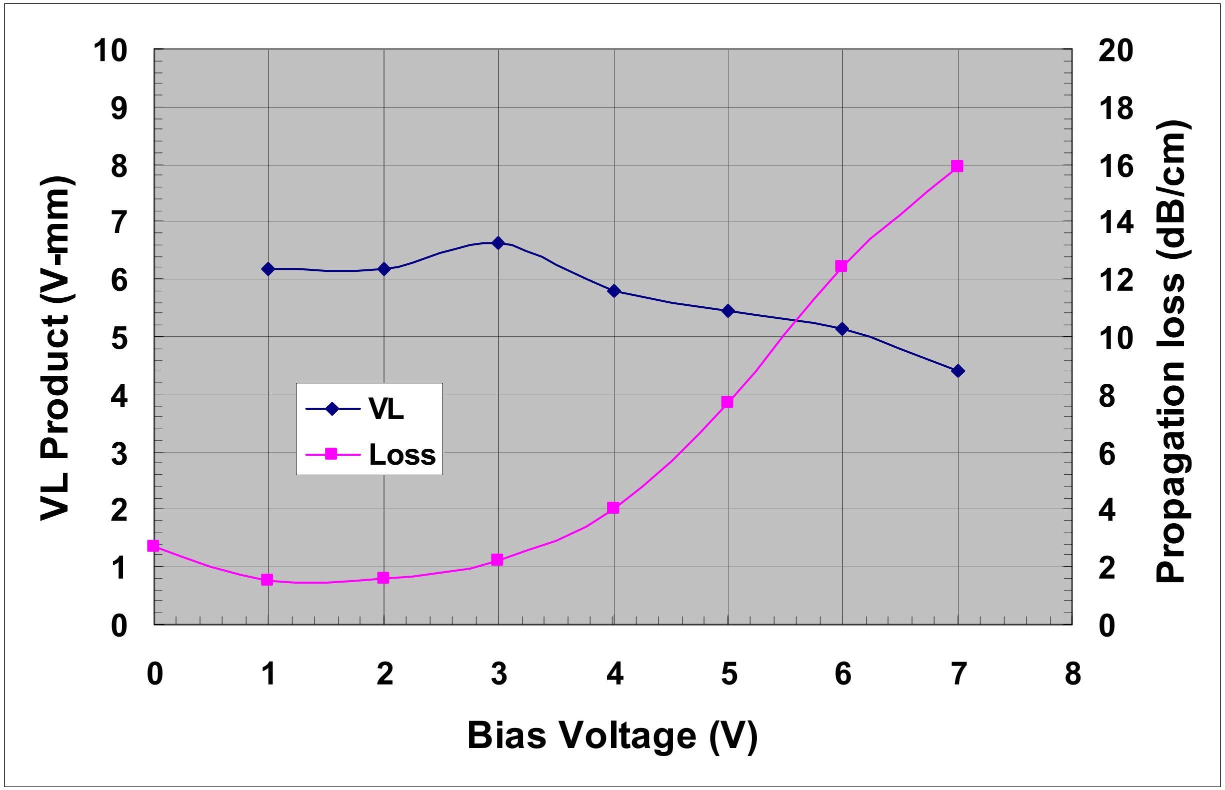
$$\phi_b - \phi_a = 2\left(c_1 + 2c_2 V_0\right)\left(V_0 + V_1\cos\omega_1 t + V_2\cos\omega_2 t\right)$$

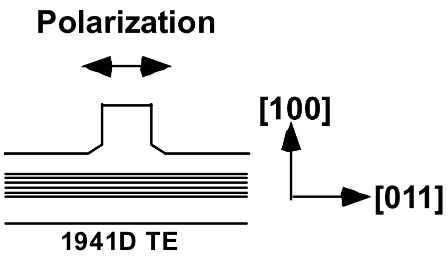
- **Phase modulation is just as linear as for purely linear electro-optic effect!**
- **BUT, this depends on perfect balance between arms**
  - **Practical implementation might be -20dB imbalance, giving 40dB suppression of extra nonlinearity**

# Diagram of Measurement Setup



# Loss and VL Product at 1500 nm



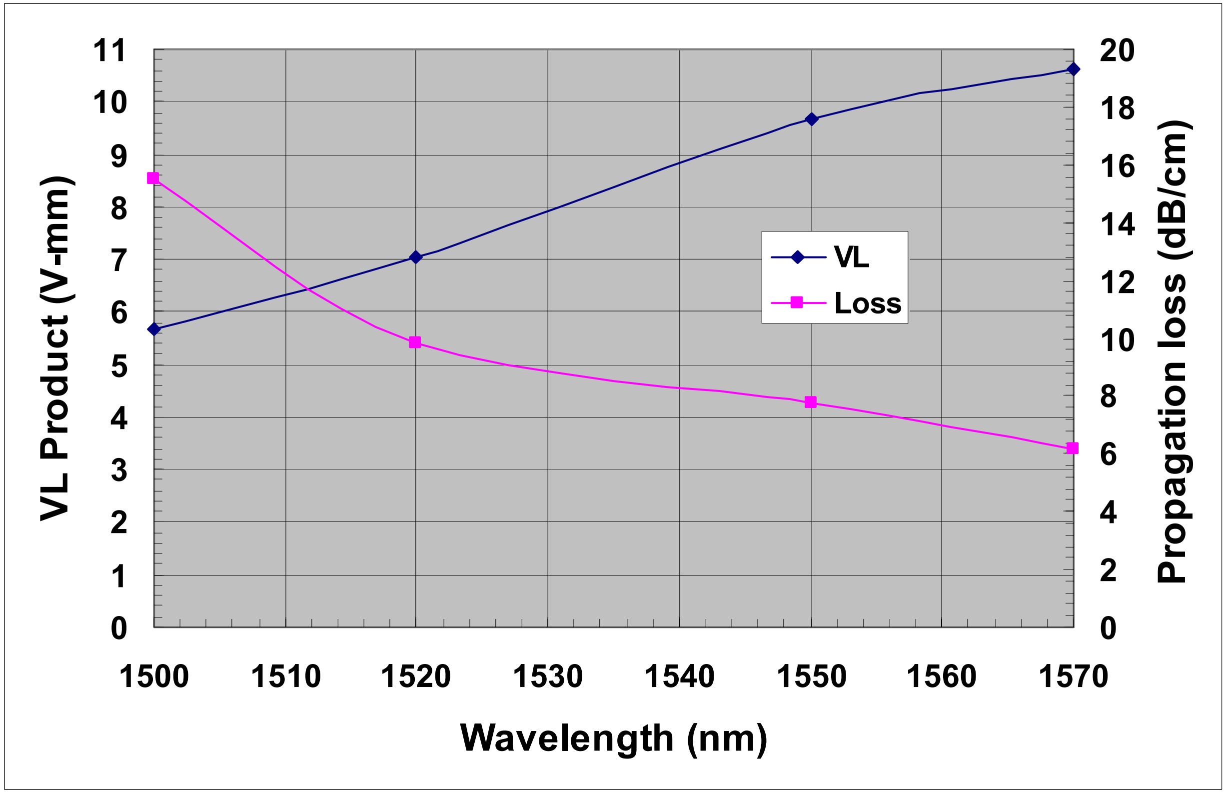



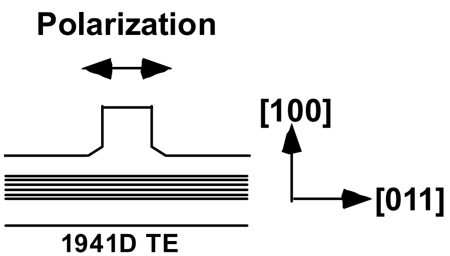

Photoluminescence wavelength is 1420 nm

- 5.8 V-mm with 4 dB/cm loss
- Best result (from same wafer as other samples with higher loss)

# Loss and VL Product vs Wavelength

## (VL product is for push-pull device)




Photoluminescence wavelength is 1420 nm

Loss & VL product measured at bias voltage of 6 V (typically)

- Linear electro-optic and electrorefraction effects add
  - Devices built using [011]-directed ridges and TE polarization show opposing effects, index change reaches zero at 1550nm
- [100] (TM) polarization shows smaller but nonzero effect
- 6 dB/cm loss may be background absorption due to p+ layer

# Most Significant Accomplishment

- Demonstrated basic electro-optic effect enabling MZ with $V_{\pi}$ of 0.6 V *before optimizing waveguide design*
  - Figure of merit* (transmission)/$V_{\pi}^2$ is 17x better than lithium niobate modulator even on this initial design

*Noise figure of shot-noise-limited analog link.
LN: $V_{\pi}$=4.0V, loss=4dB     Semiconductor: $V_{\pi}$=0.6V, loss=8dB