Integrated Digital Optical Vector Modulator for Analog Optical Signal Processing

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Outline

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- Objective
- Methodology
- Critical Components
- Potential Applications
- Program Schedule

Objective:

Design and demonstration of a frequency agile all-optical vector modulator with broad microwave frequency tuning range, low close-in phase noise and fast switching capability of phase and amplitude of synthesized waveform using all-optical signal processing techniques.

Traditional Microwave Vector Modulator and Arbitrary Waveform Generator

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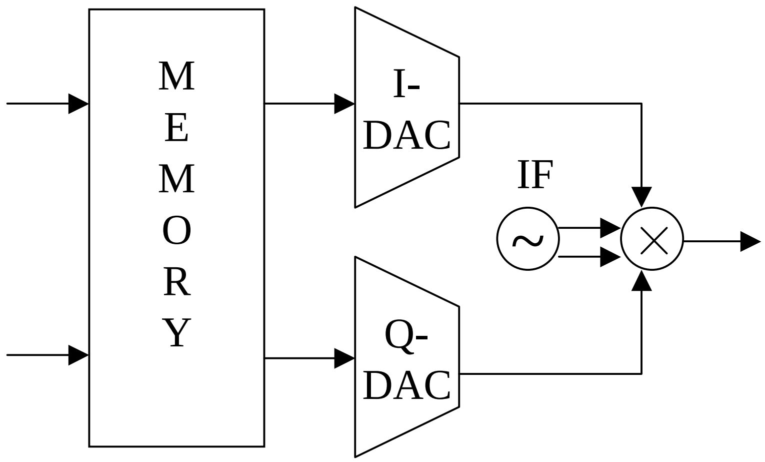
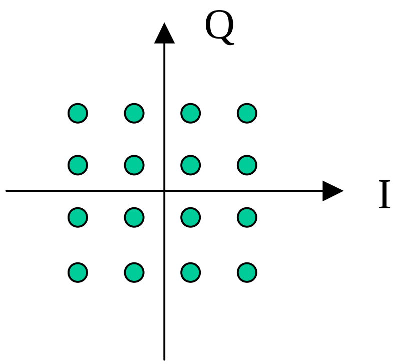
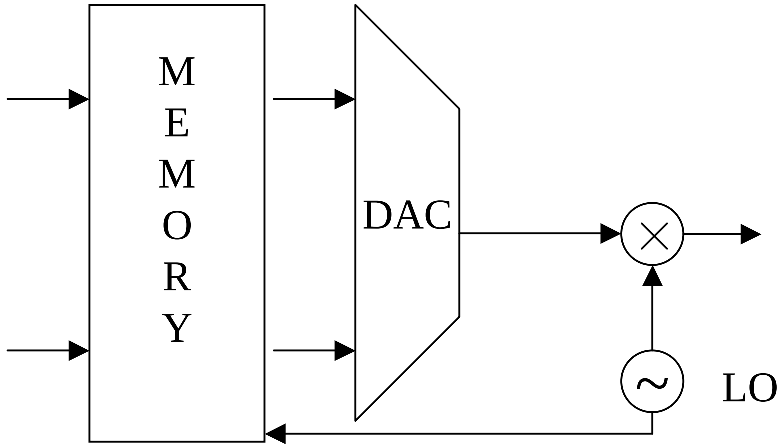
Analog Vector Modulator





Direct Digital Synthesizer



Implementation of All-Optical Waveform Generator

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- broad tuning range of carrier frequency

  => remote optical heterodyne technique

- fast switching time among various phase and amplitude states

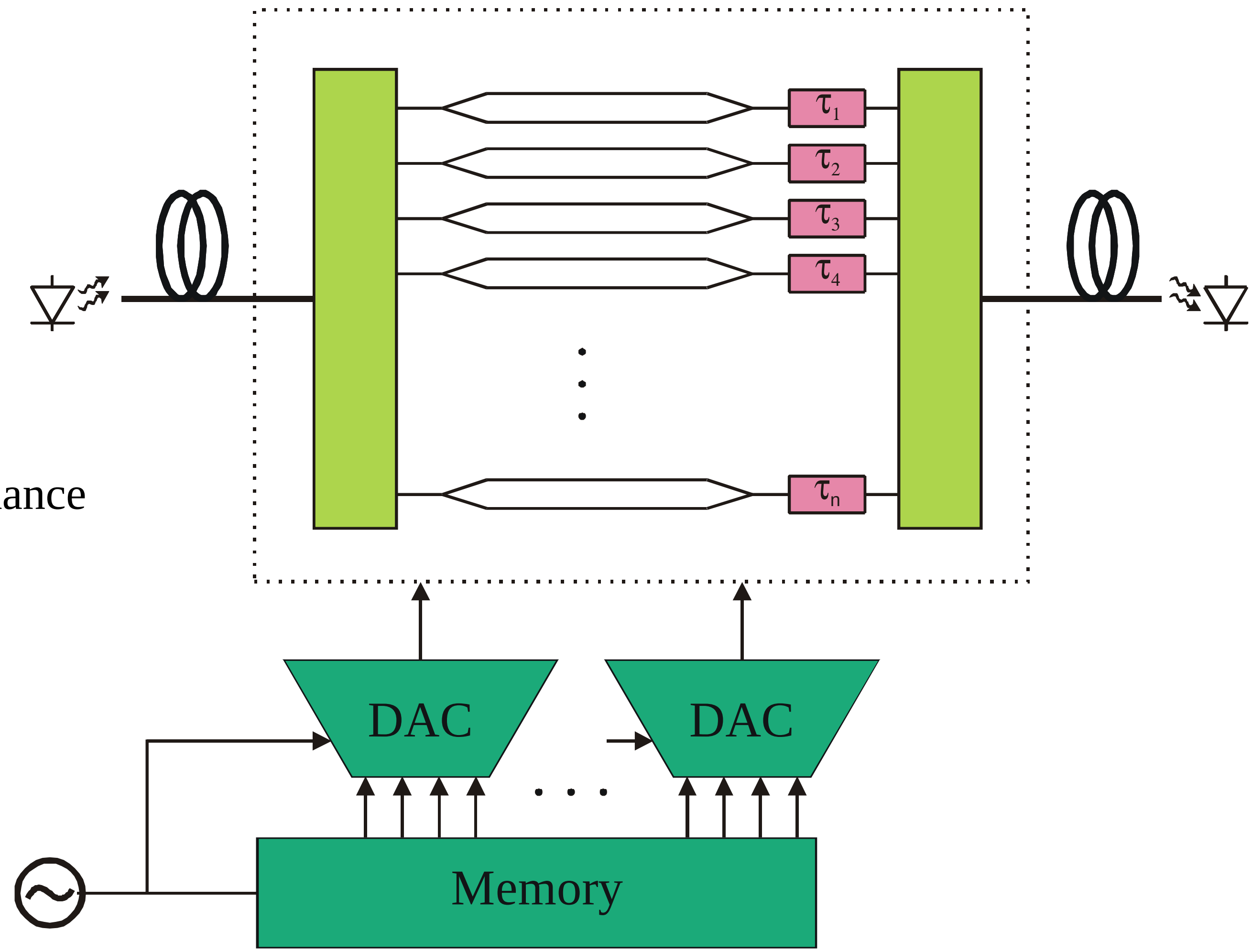
  => MZ interferometer with high speed optoelectronic phase shifters and optical delay lines

- integrated on InP substrate

- low close-in phase noise

  => optoelectronic phase-locking loop

Commonly Used Optical Technique for AWG



Problems:

- limited by DAC performance speed, resolution
- Modulator linearity

Concept of Optical Vector Modulator

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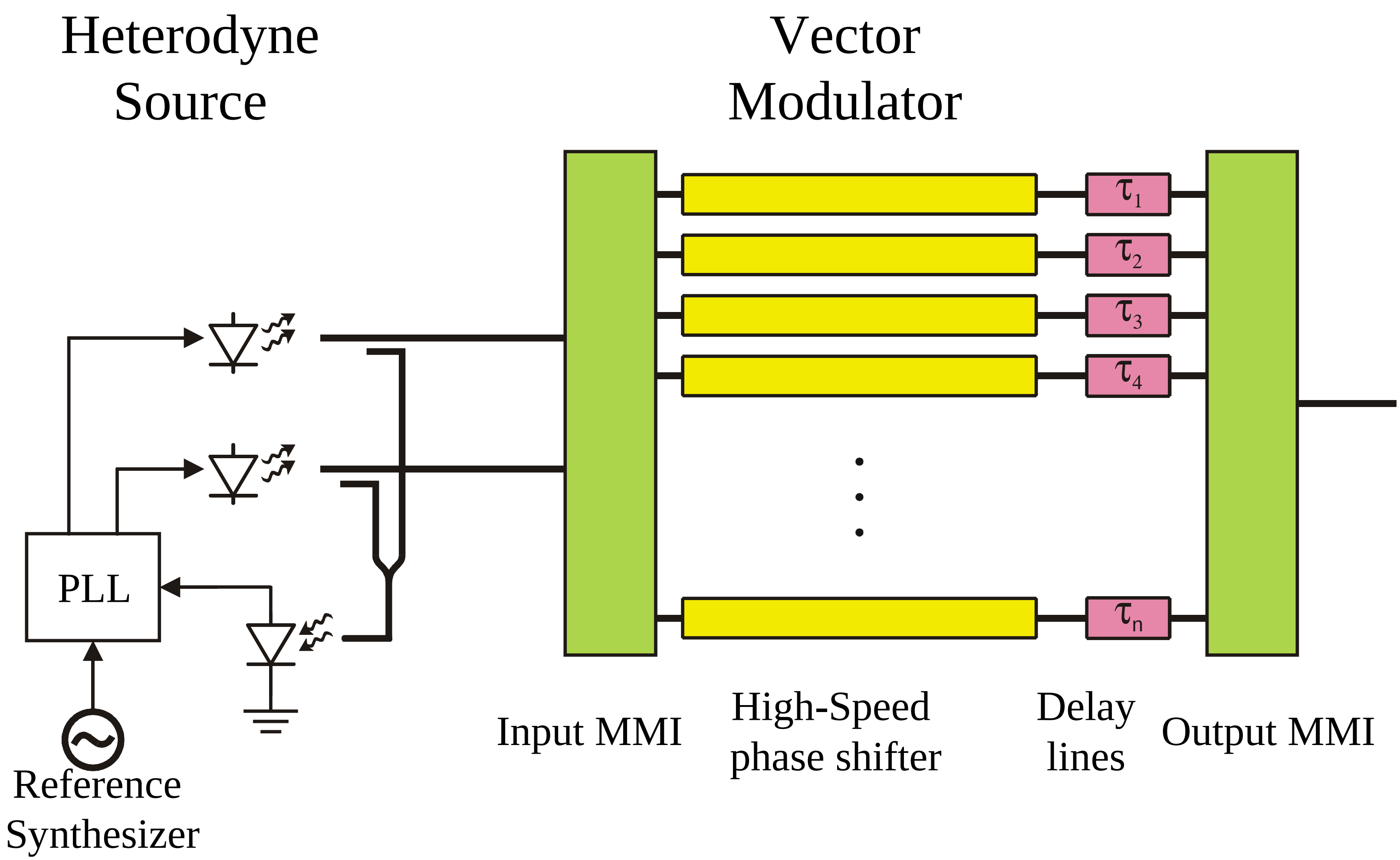

Heterodyne Mixing of two Lasers

- Laser #1: $E_1(t) = \sqrt{P_1}\cos(2\pi\nu_1 t + \varphi_1)$
- Laser #2: $E_2(t) = \sqrt{P_2}\cos(2\pi\nu_2 t + \varphi_2)$
- Photodiode current: $i(t) = R\cdot\overline{(E_1(t)+E_2(t))^2}$

$$i(t) = R\cdot\left(P_1 + P_2 + 2\sqrt{P_1 P_2}\cos(2\pi f\, t + \Delta\varphi)\right)$$

- Difference frequency: $f = \nu_1 - \nu_2$
- Microwave phase: $\Delta\varphi = \varphi_1 - \varphi_2$

ν_1, ν_2 optical frequencies, f microwave difference frequency

Two-tone Heterodyne SNR Budget

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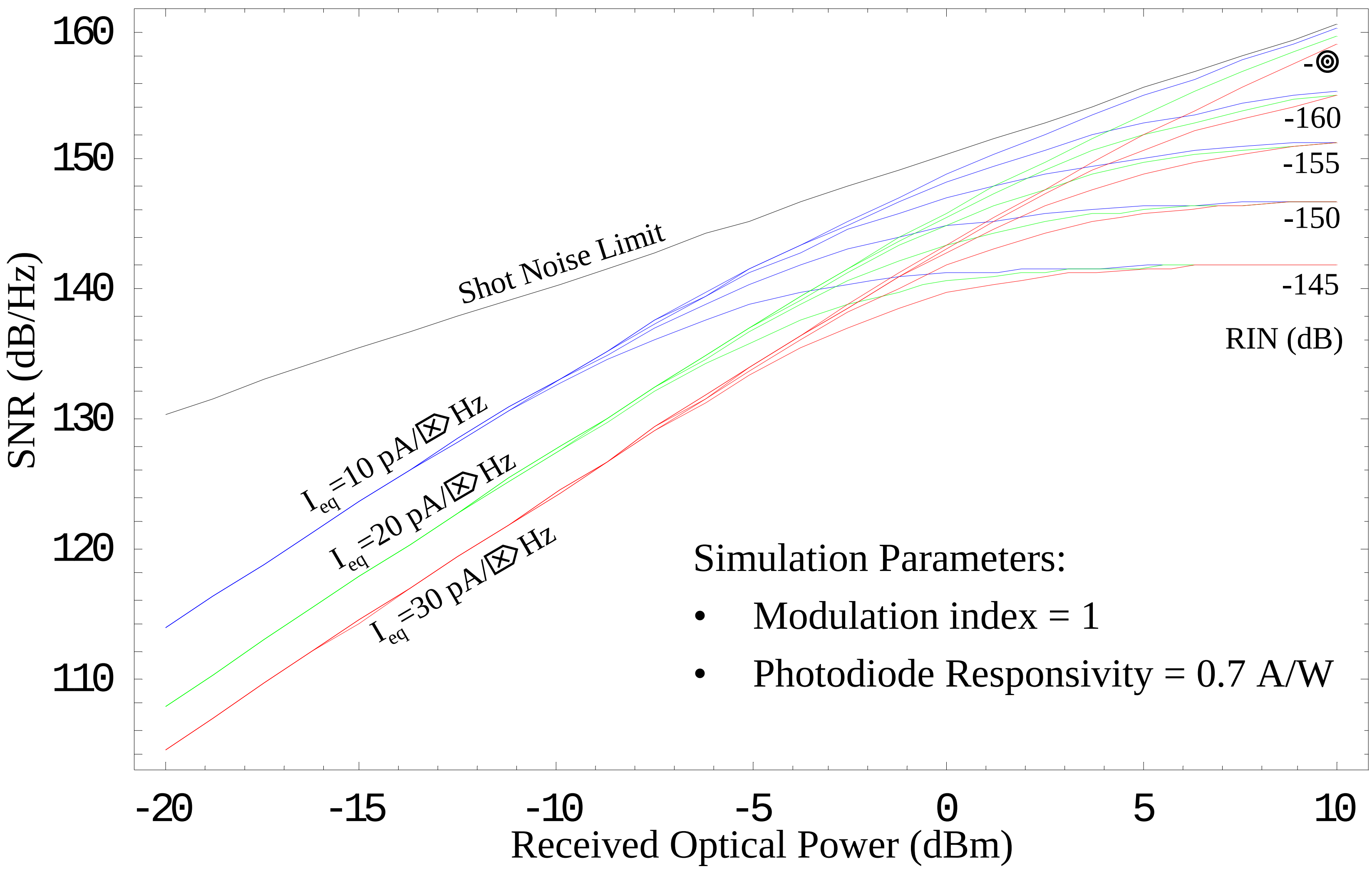

Layout Example of Integrated Optical Vector Modulator

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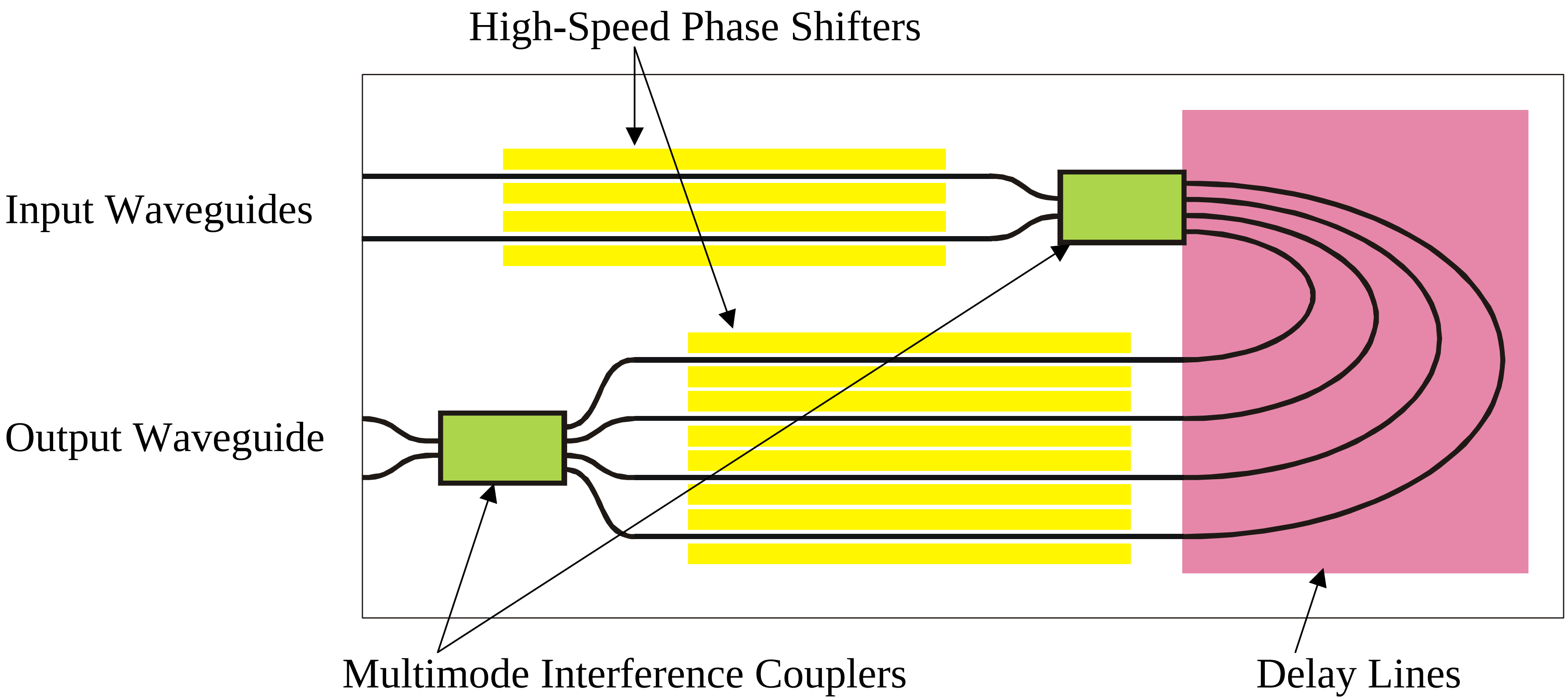

Resulting Phasor States with Four Branches (Simulation)

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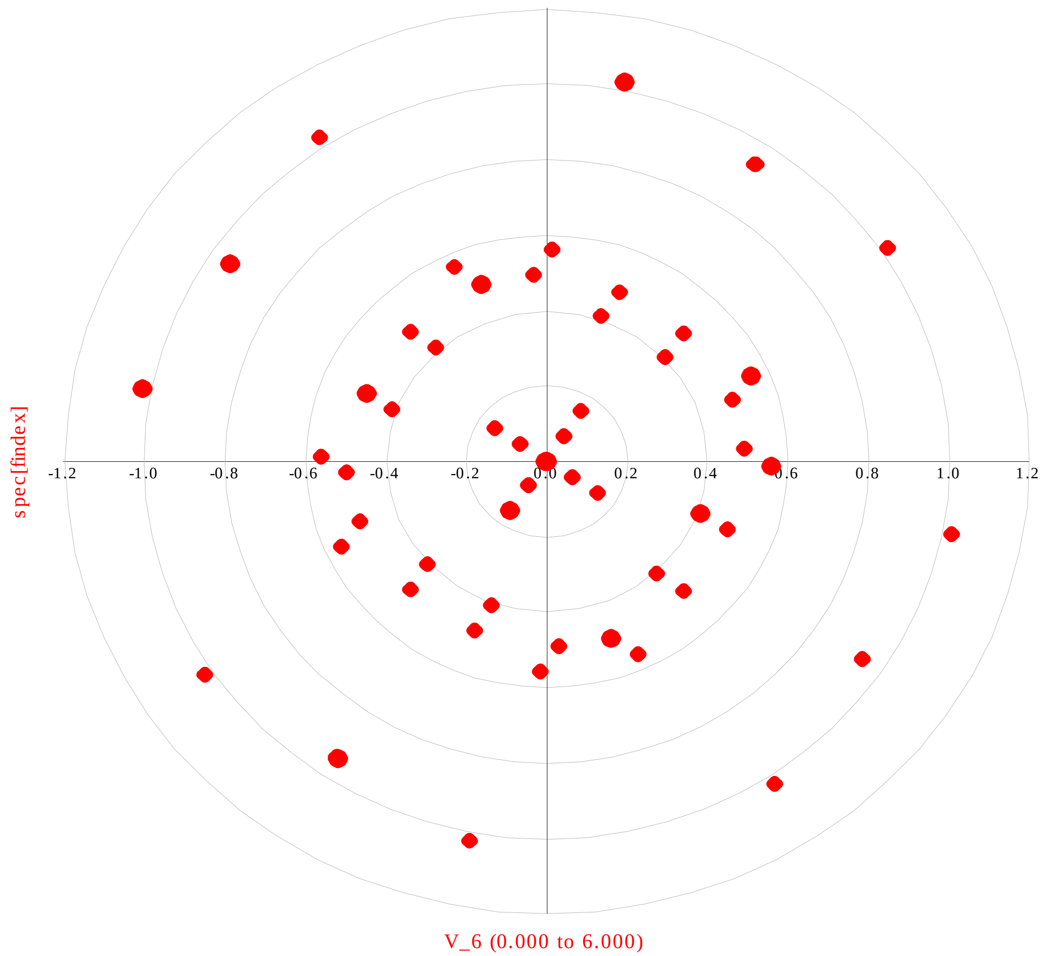
- Input/Output Frequency: 10 GHz
- Modulator driven with 6 binary signals, $V_{pp}=V_{\pi}$
- Relative delay: 0, 6.25 ps, 12,5 ps and 18.75 ps
- Phase/amplitude of states can be optimized by:
  - Adjusting delay
  - Adjusting DC-offset
  - Adjusting voltage swing



More States by Using More Branches and Orthogonal Delays

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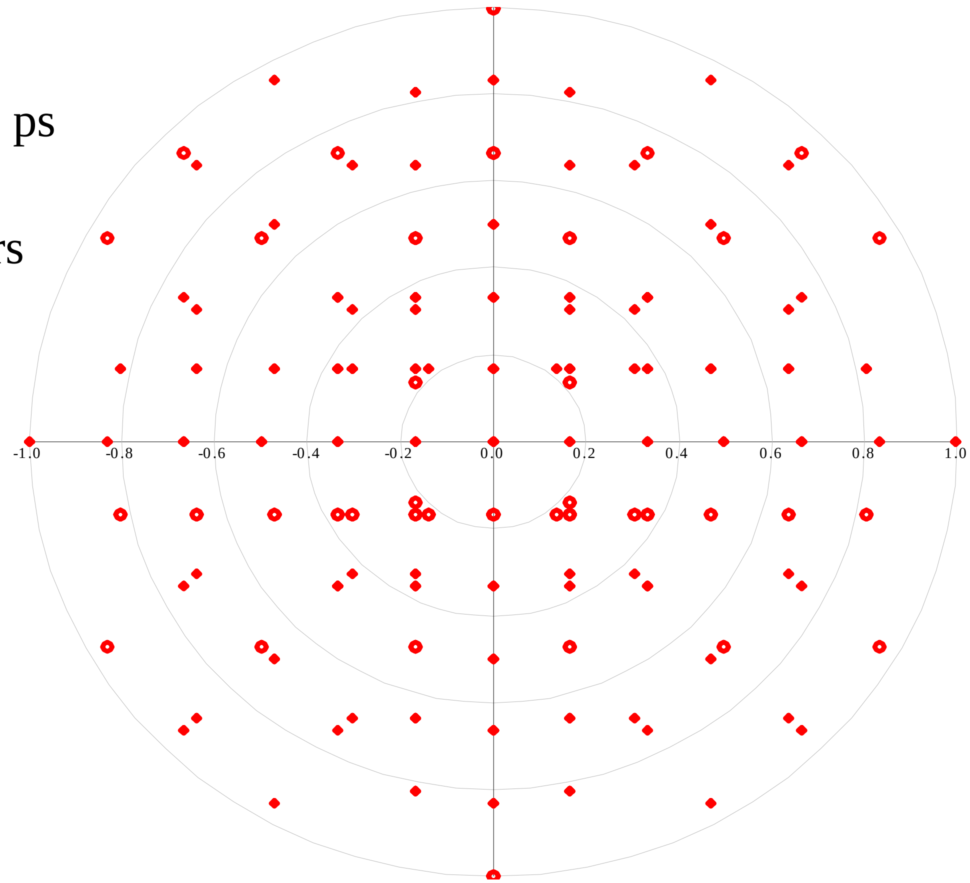
- 8 Branches
- Paired delays of 0, 6.25 ps, 12.5 ps and 18.75 ps
- 85 randomly addressable phasors



Electro-Optic Phase Modulator Material Systems

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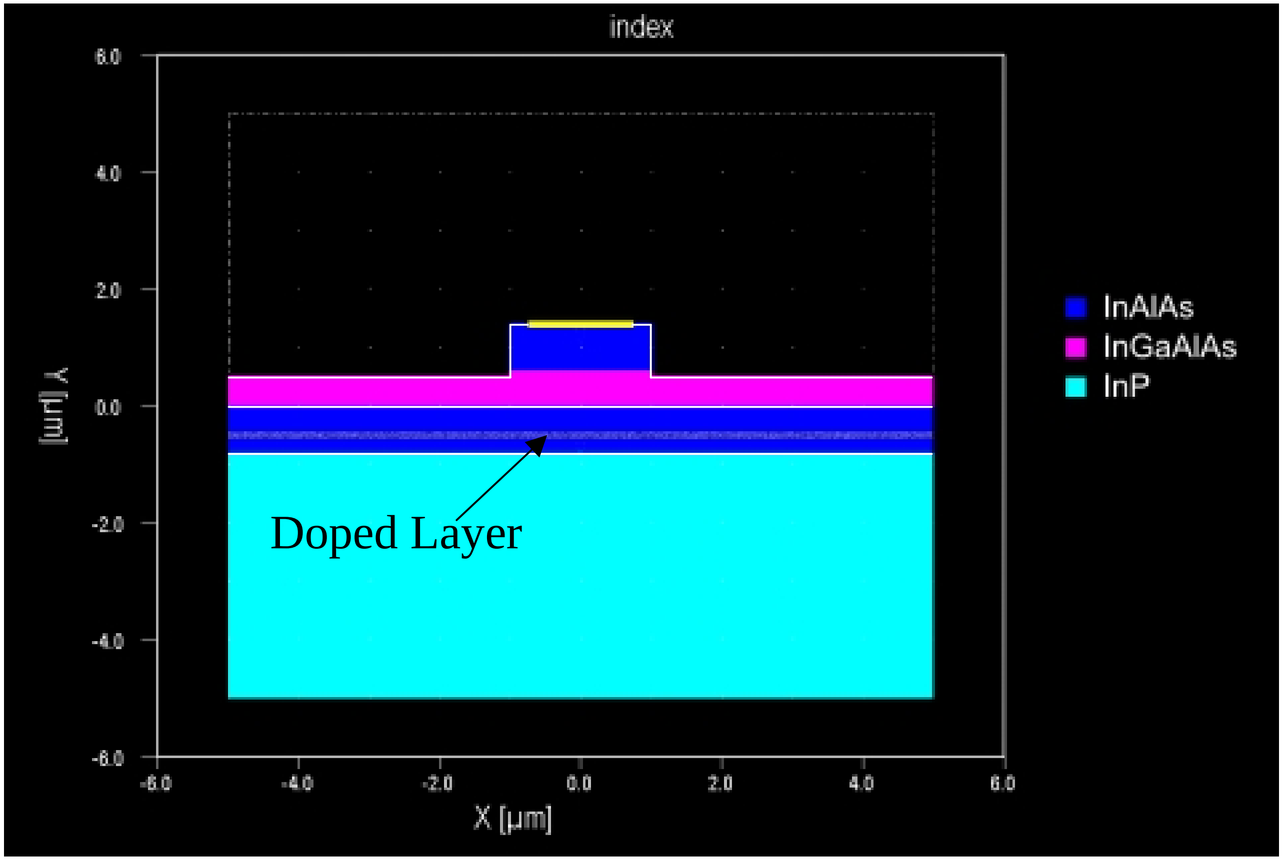
- Lithium Niobate
  - Tight bends not possible. Large physical dimensions.
  - Low fiber-coupling loss
  - Environmental, stability and frequency-response problems

- III-V Semiconductor – InP or GaAs-based
  - High power handling capability
  - Excellent stability
  - Can make tight bends
  - Monolithic integration
  - Efficient and fast

- Electro-Optic Polymers
  - Pre-poled waveguides allow microstrip configuration
  - Low drive power, high bandwidth
  - Not mature yet

InP-based Waveguide (Phaseshift Section)



Cross-section

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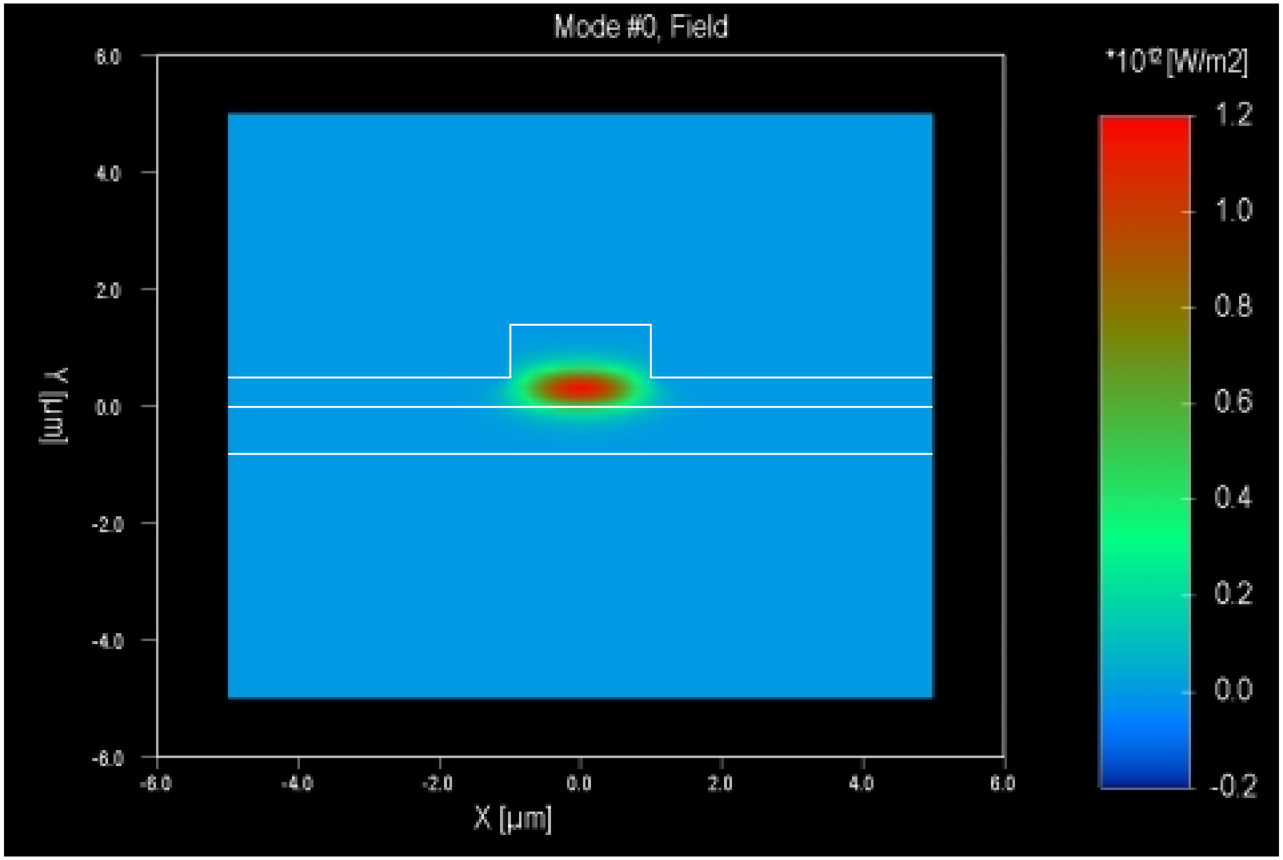
InP-based Waveguide (Phaseshift Section)



Optical Mode

InP-based Waveguide (Phaseshift Section)

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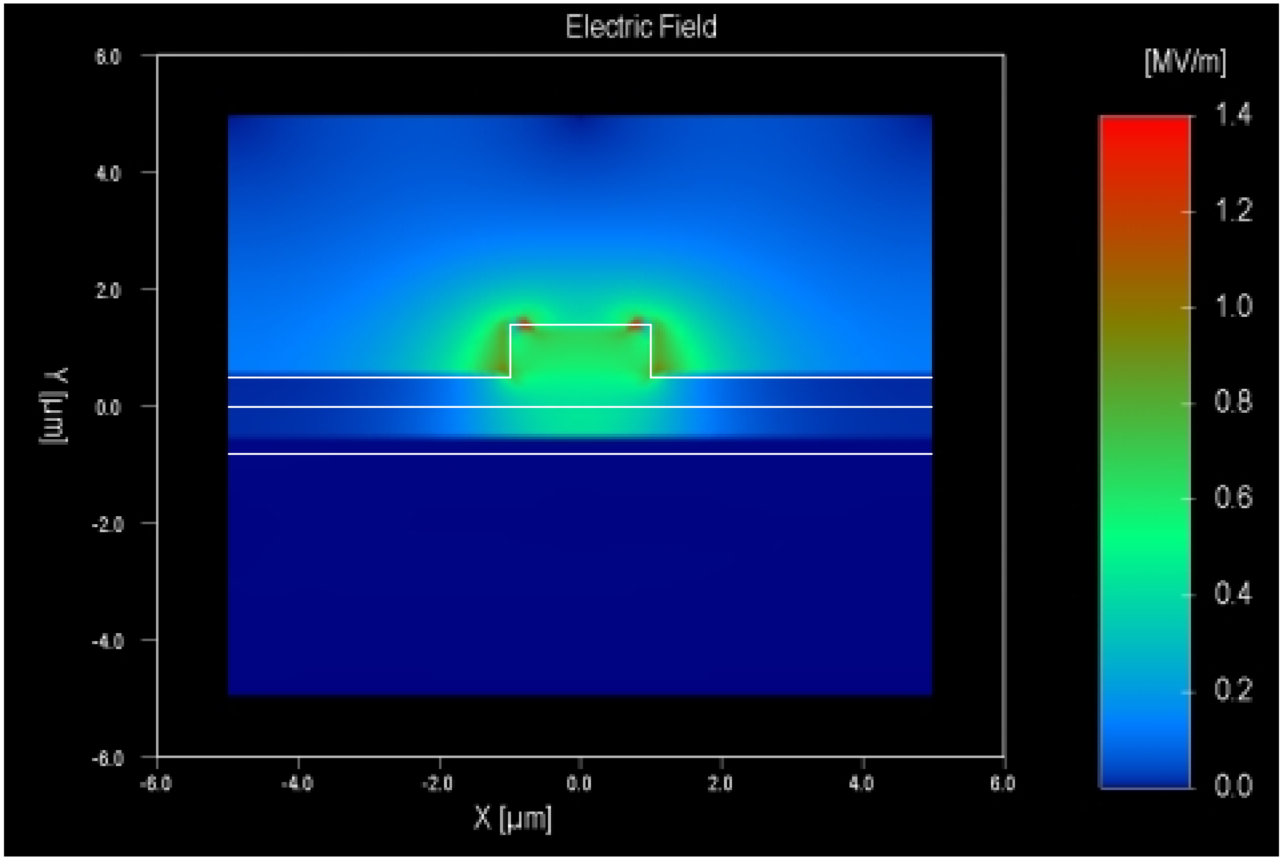

Electrical Field

InP-based Waveguide (Phaseshift Section)

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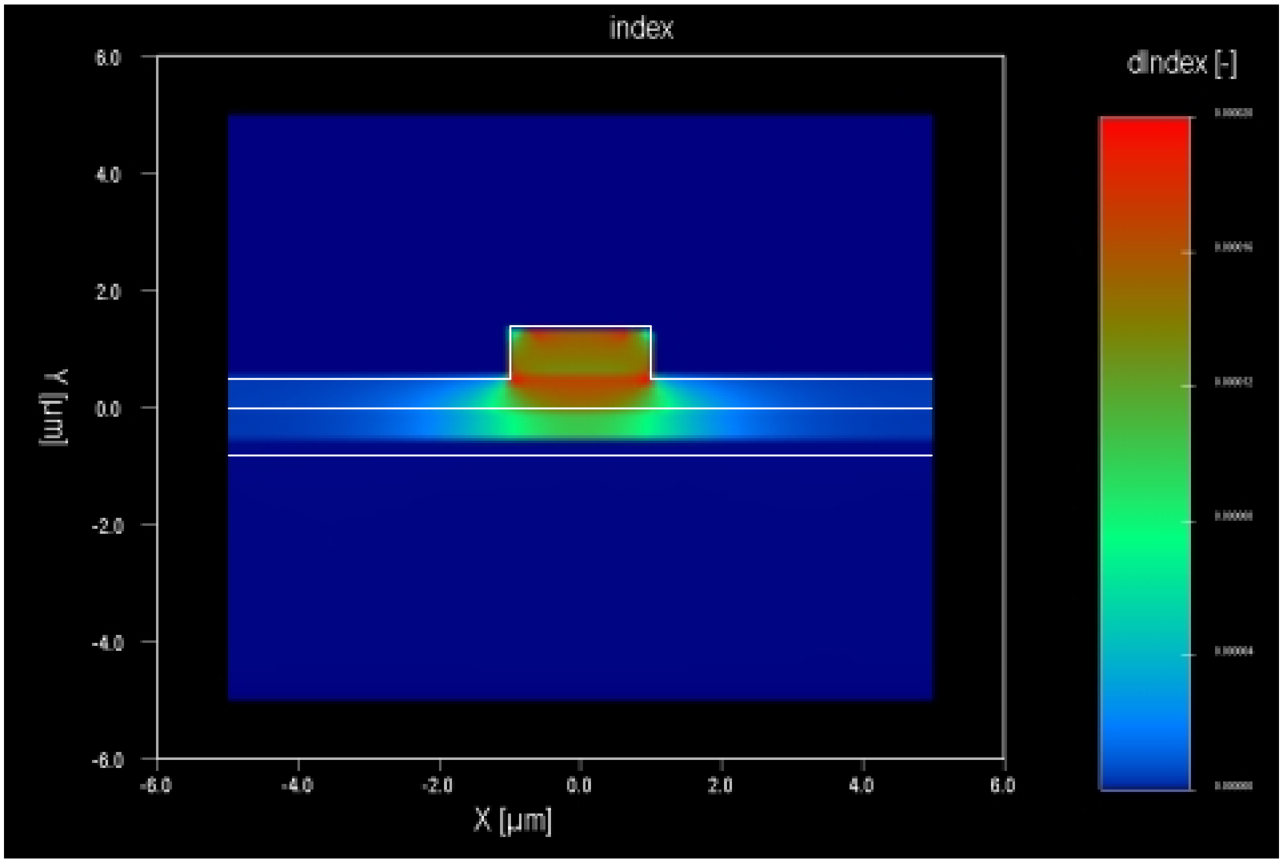


Index Change

Traveling-wave Electrodes

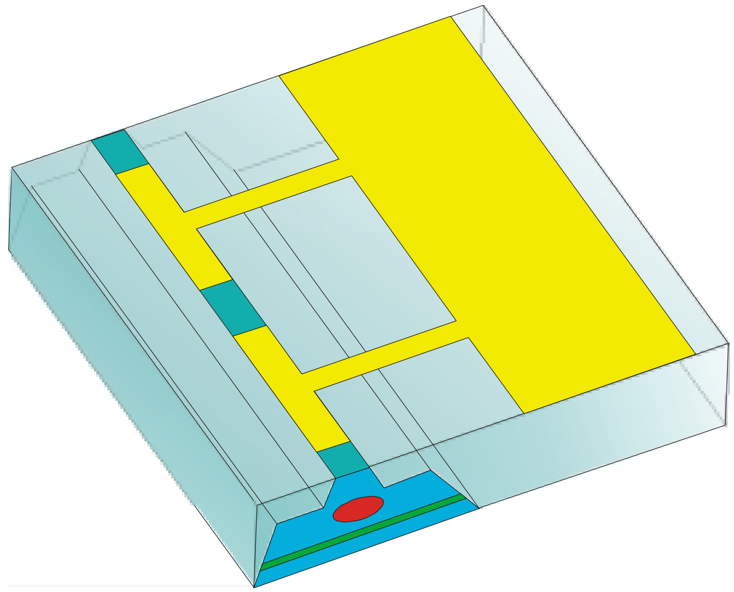
High-Speed operation of phase shifter requires:

- Velocity-match of co-propagating optical and electrical wave
- Electrodes with low frequency-dependent loss

➢ Microstrip too lossy due to the small dimensions

➢ Coplanar electrodes are not velocity matched, as $n_{opt} \approx \sqrt{2} n_{el,eff}$

Solution: **Capactively Loaded Transmission-Line**



Applications of Optical Vector Modulator

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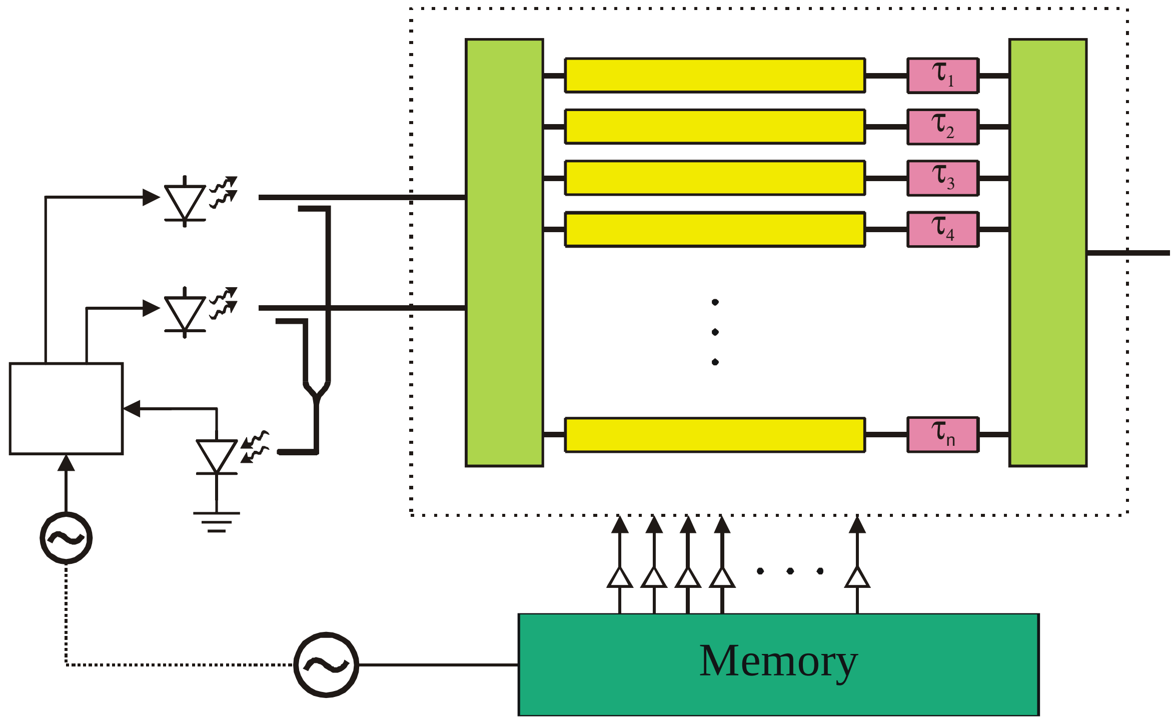
- High-data-rate wireless/wireline communication
- Beam-steering of phased-array antennas
- Optical signal processing/filtering
- Arbitrary waveform generation

Application in Arbitrary Waveform Generation

- Optical phase shifters are driven with binary signal from memory
- Data rate equals sampling rate
- Waveform synthesized by states of vector modulator



Application in Arbitrary Waveform Generation

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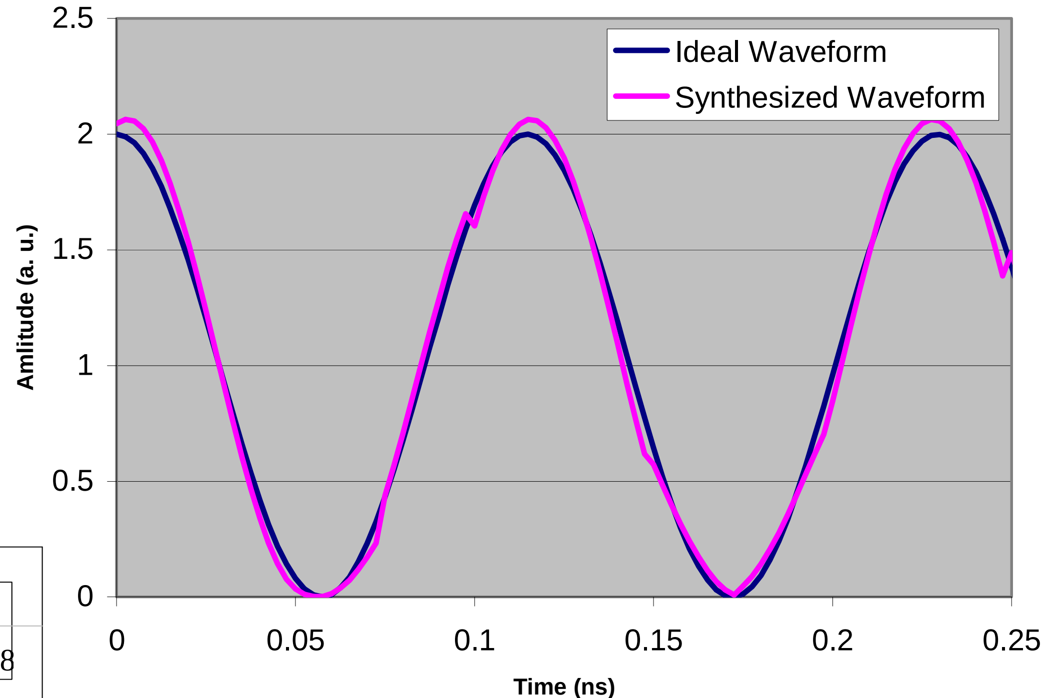
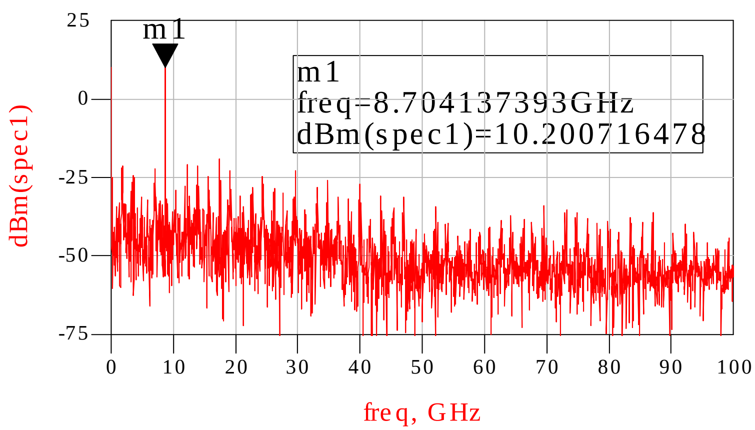
- Input Frequency: 10 GHz
- Sampling Rate: 40 GHz
- Synthesized Waveform: 8,704,137,393 Hz, 0 deg





System Parameters

Architecture	•Optical synthesizer: Two tunable lasers, phase-locked with optical PLL •Optical vector modulator: High speed optical phase modulators and delay lines to vector-modulate RF-signal
Aggregate update rate	10 Gbit/s
Full-scale output power	–5 to 0 dBm optical
SNR	Less than 140 dB/Hz @ 0dBm P_{in}, 20 pA/⌧Hz receiver noise
SFDR	Expected to be receiver-limited
Equivalent Number of Bits	About 2 bits less than the addressable number of bits
Number of bits	Start with 6 bits, increase to 10 to 14 bits
Clock Source	Commercial synthesizer
Clock frequency	10 GHz
Laser description	Two phase-locked external cavity tunable lasers
Average power	5 –10 dBm CW
RIN of Laser	better than -145 dB/Hz
SNR impact of laser noise	7 dB

System Parameters (cont)

Memory and DAC architecture	No DAC necessary, Data source: commercial 10 Gbit/s pattern generator
Modulator type	InP-based application-specific optical vector modulator
Input electrical signal	5V
Amplifier to be used	Datacom modulator driver
Modulator electrical input impedance	50 Ohm
Input optical power	5-10 dBm, can handle much higher power
Modulation depth	20 – 25 dB
Modulator bandwidth	10 GHz, 3dB electrical
Modulator linearity	NA – Digitally addressed modulator
Modulator control signals	Each input bit requires adequate DC-offset control
Optical insertion loss for zero input signal	10 dB

Program Tasks

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Task 1.1 InP Modulator for High Resolution All Optical Vector Modulators Engineering and Fabrication.

Task 1.2 Integrated High Speed InP All optical Vector Modulator.

Task 2.1 All Optical Waveform Generator Subsystem.

Task 2.2 Optical Microwave Synthesizer with opto-electronic PLL.

Vertical InP RIE/ICP Dry etching

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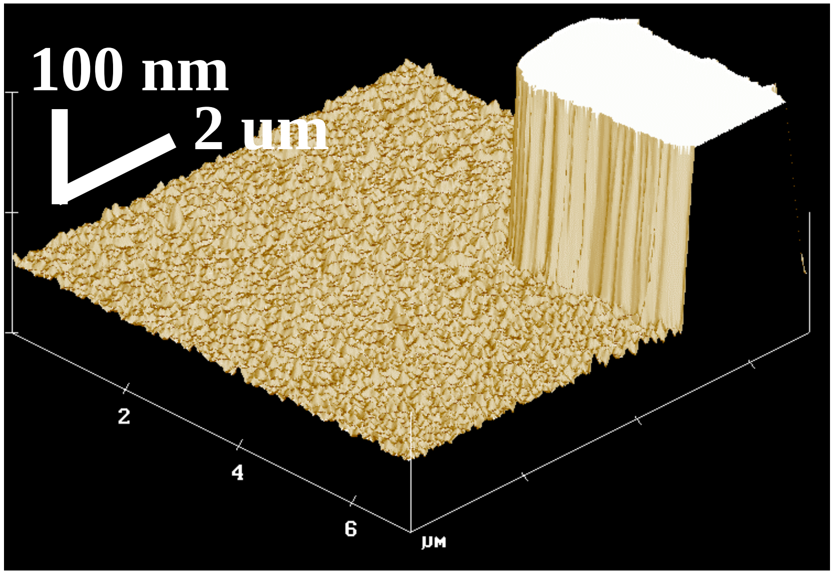
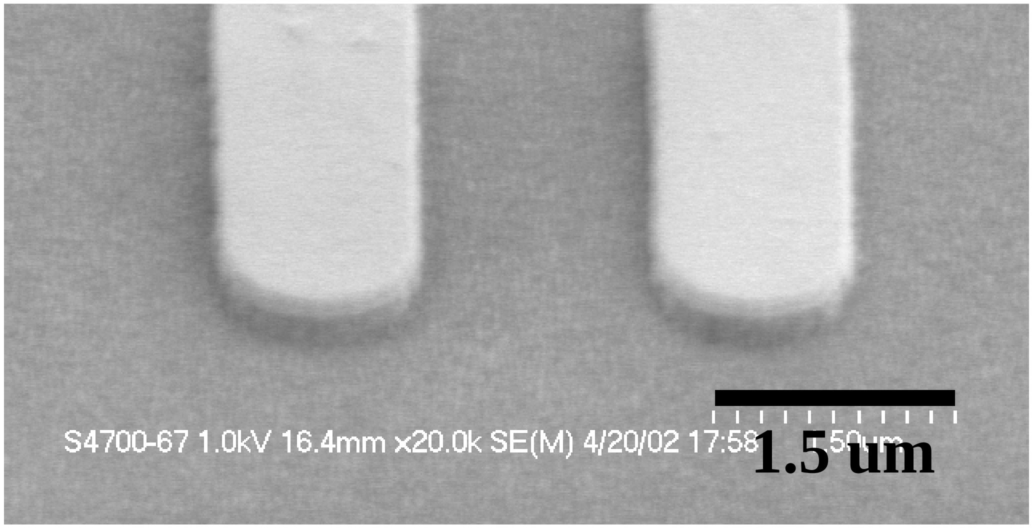
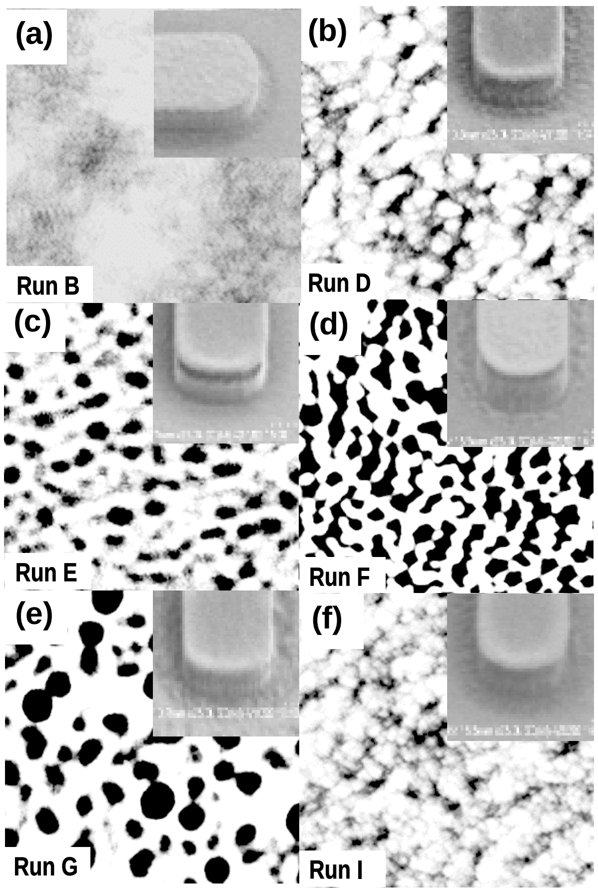
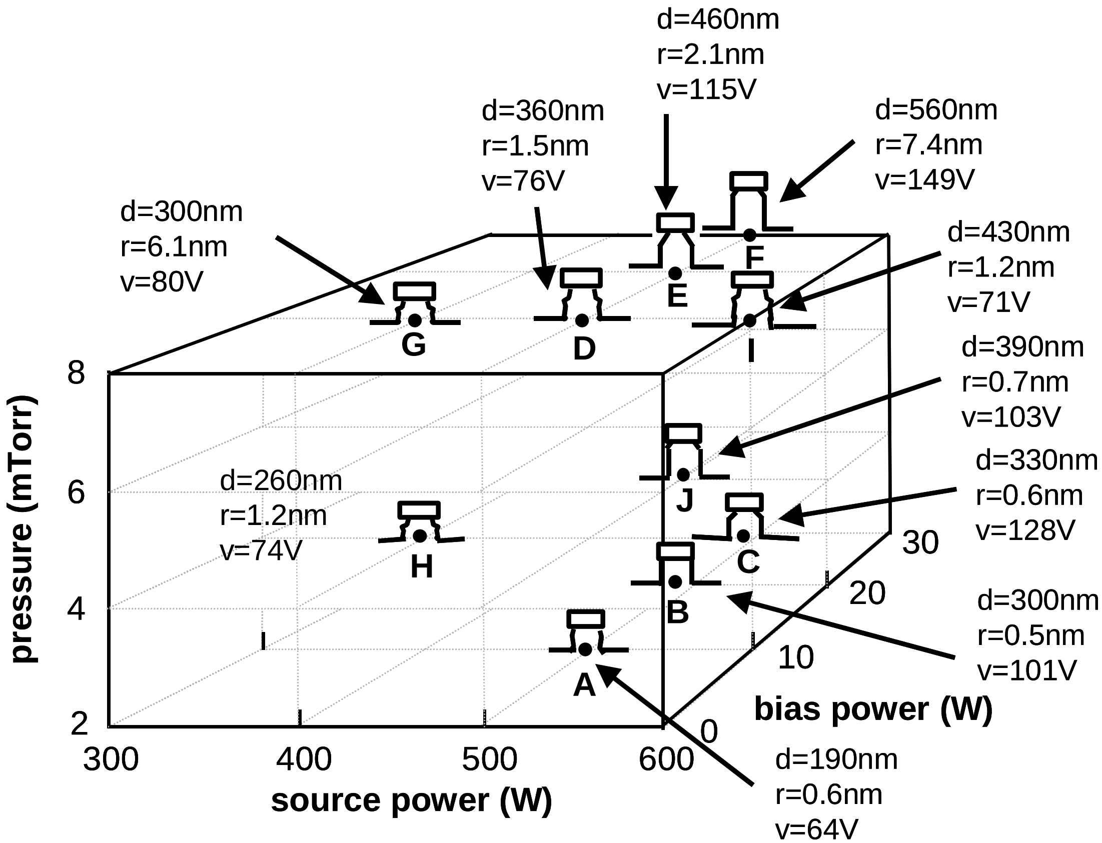




Sidewall angle 90º
RMS roughness 25Å

Dry Etch Process for InP Waveguide





Etching depth: 1.1um
RMS roughness: 6 nm

Summary

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All-optical vector modulator:

- Synthesize amplitude and phase of RF-subcarrier
- Digitally addressing of phasor states without DAC

Technology

- InP-based phase modulator based on electro-optic effect
- Opto-electronic phase-locked laser source

Applications for Arbitrary waveform generation:

- Optical vector modulator in conjunction with optical microwave source
- Sampling rate equals to the bitrate of digital signal