Advances in Optical Modulators for Analog Communications

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Outline

Introduction: Analog/Digital Applications

External Optical Modulator for fiber-optic link and performance figure of merit

Technological trend for high performance MZM modulators

Summary

The Wideband Optical Modulator

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Analog Optical Transmission

- The lack of a highly efficient (<1 V V_{π}=half-wave voltage), wideband (>100 GHz) optical modulator has long frustrated microwave photonics for use in military antenna applications

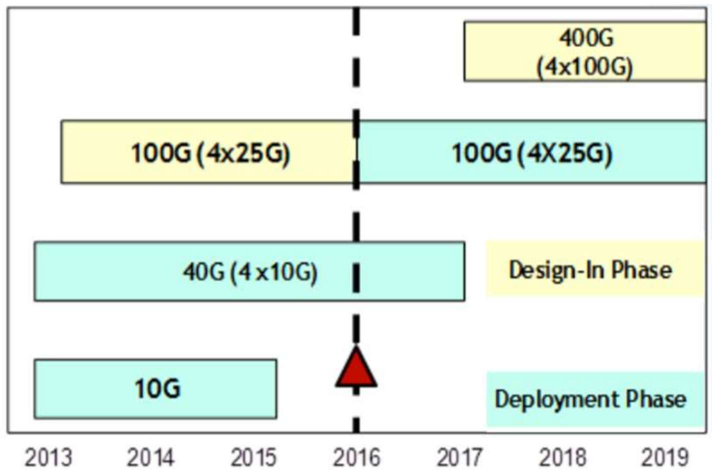
Digital Optical Transmission

- Commercial network capacity scaling (data center/cloud) is driving the need for 100G+ data links with minimal power consumption
- The non-existence of a highly efficient (<1 V V_{π}), wideband (>100 GHz) optical modulator now thwarts commercial optical networks as well

The Market Place

Commercial Metro and Data Center networking:

IEEE P802.3bs 400 Gb/s Ethernet Task Force



Data Center

- $1.6B GbE/10/40/100G transceiver in 2014, 10%CAGR for 2014-2018
- Expanding rapidly

Metro 100G

- $4B metro 100G by 2018; <$500M in 2014, inflection point in 2015

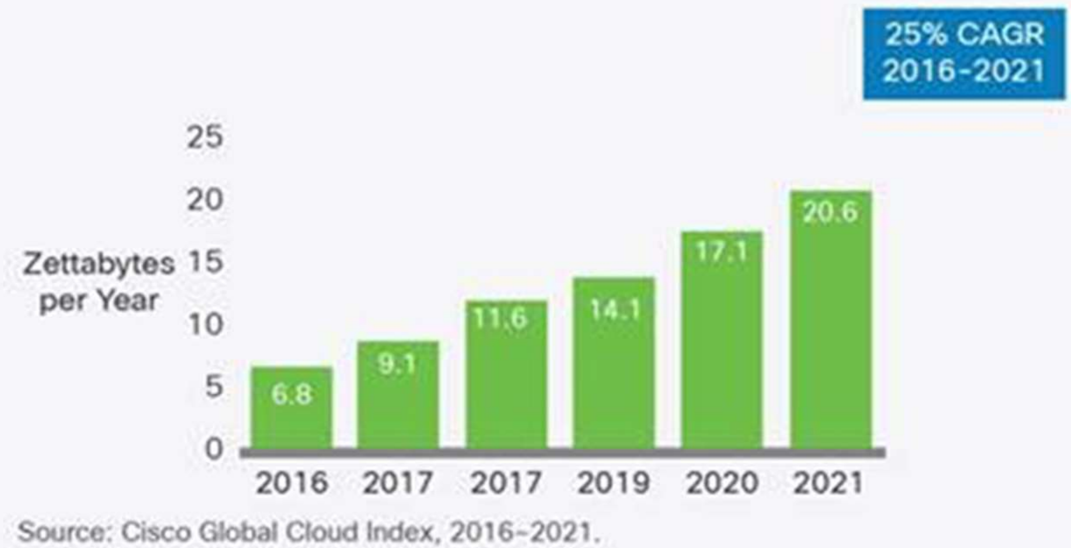
Fiscal	Q3/2014	Q4/2014	Q1/2015	Q2/2015	Q3/2015
Revenue	$294m	$306m	$327.6m	$297m	$306.3m

Finisar quarterly report: growth due to 40/100Gb transceivers for data center and wireless applications

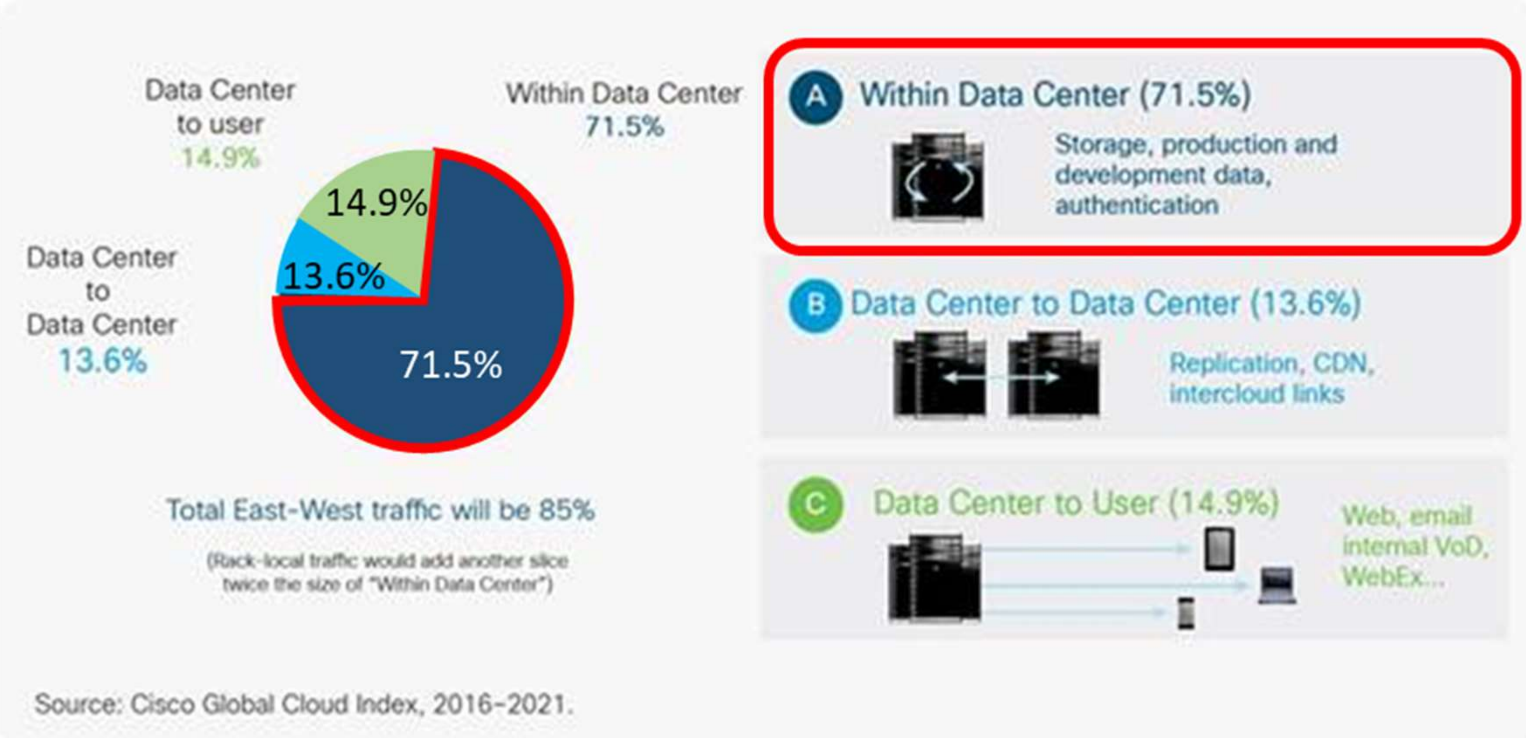
Military Platform RF Networking & Signal Processing:

Small (<< $1B) but critically important US military market to provide wideband antenna/sensor interconnects and mixed-signal networking aboard air, land and sea platforms. Modulator performance will bring dramatic change to these RF systems.

Update …



25% CAGR
2016-2021
25
20
Zettabytes per Year 15
10
5
0
6.8
9.1
11.6
14.1
17.1
20.6
2016
2017
2017
2019
2020
2021
Source: Cisco Global Cloud Index, 2016-2021.



Data Center to user 14.9%
Within Data Center 71.5%
Data Center to Data Center 13.6%
14.9%
13.6%
71.5%
Total East-West traffic will be 85%
(Rack-local traffic would add another slice twice the size of "Within Data Center")
A Within Data Center (71.5%)
Storage, production and development data, authentication
B Data Center to Data Center (13.6%)
Replication, CDN, intercloud links
C Data Center to User (14.9%)
Web, email internal VoD, WebEx...
Source: Cisco Global Cloud Index, 2016-2021.

Analog RF Photonics

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- **RF Signal Distribution –** Antenna Remoting
- **Front-End RF Signal Processing**

Optical Technology Advantages

- **Distance-bandwidth product improves RF performance for broadband transmission**
  - Low loss (0.2 dB/km), low frequency dependence
  - Design freedom in antenna location, cable routing, receiver location
- **Cabling size and weight**
  - Reduced cable weight, diameter, bend radius
- **Signal Isolation**
  - No cross talk between cables / EMI resistant
- **Design flexibility/scalability**
  - Change sensor/transmitter/receiver without changing fiber
  - Wavelength Division multiplexing
- **Unprecedented Time-Bandwidth Product (TBWP) Processors**

Main Takeaways:

High Performance RF Photonic Links *Reduces* the dependence on Front-End Electronics

***E-O modulator* is the key for achieving Low Noise Figure, High Dynamic Range, Wideband Photonic Links common in these applications**

RF over Fiber (RFoF) Links & Signal Processing Outlook

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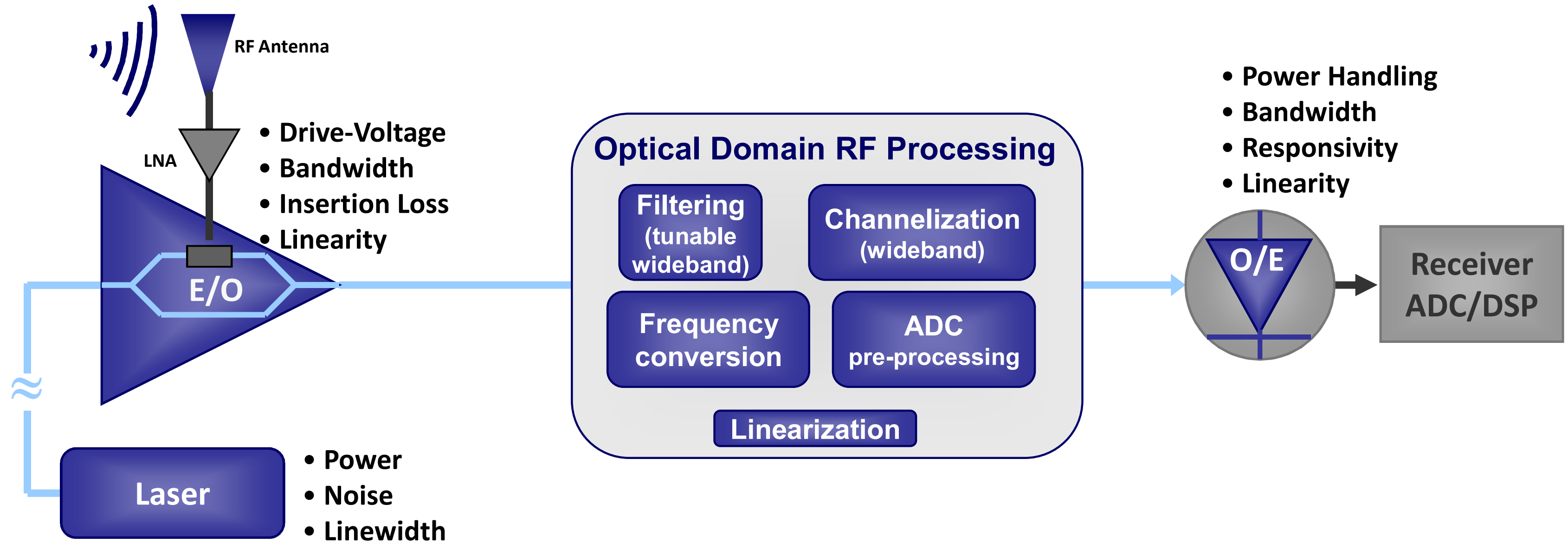
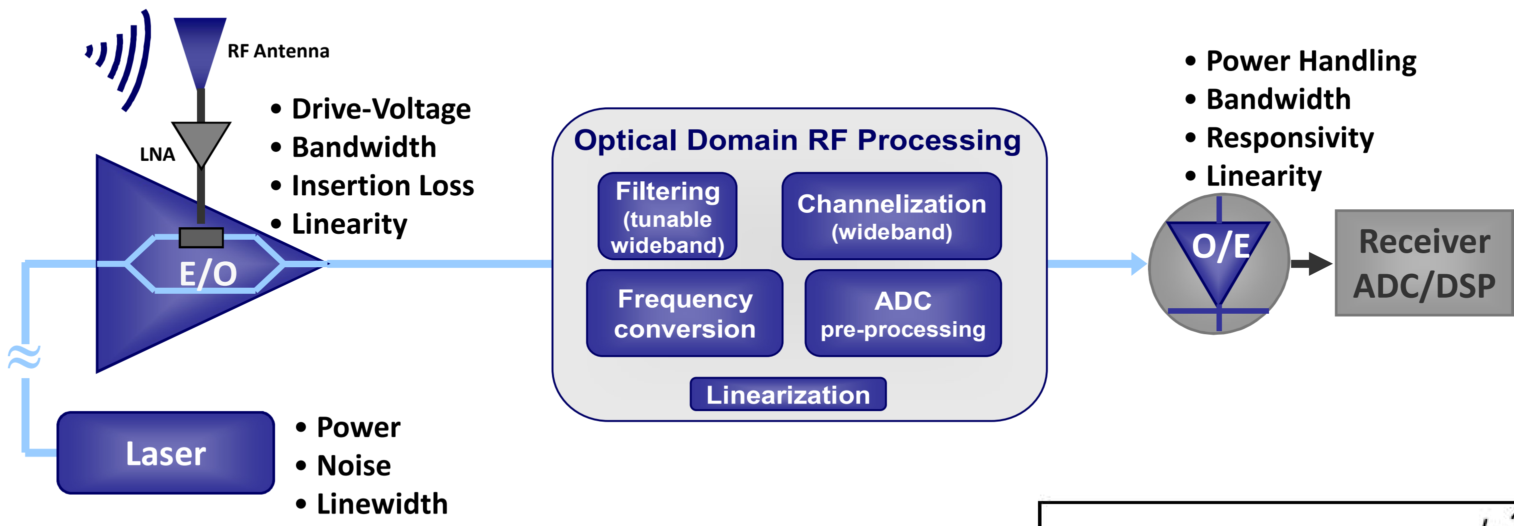


- **Gradual Laser, Modulator & Detector Improvement for Analog Operation**
- **Modulator limits RF link Noise Figure (NF) and Spurious Free Dynamic Range (SFDR)**

Yesterday	***Today***	***Tomorrow***
Amp-less RFoF Link	**Amp-less RFoF Link**	**Amp-less RFoF Link**
NF: >30 dB — **20 GHz**	NF: ~15 dB — **50 GHz**	NF: <5 dB — **100 GHz**
SFDR: 110 dB-Hz$^{2/3}$	SFDR: 120 dB-Hz$^{2/3}$	SFDR: 130 dB-Hz$^{2/3}$

Important Analog Link Parameters



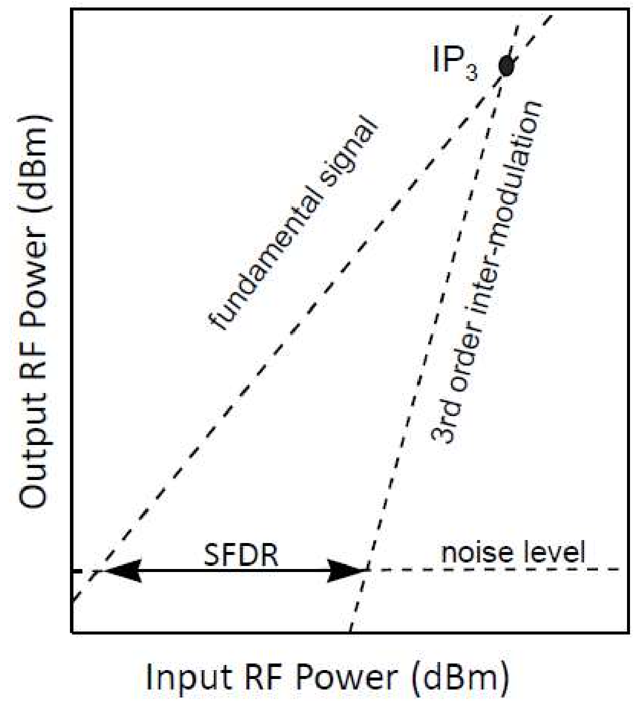
1. RF link Gain:

$$\frac{\text{RF power output}}{\text{RF power input}}$$

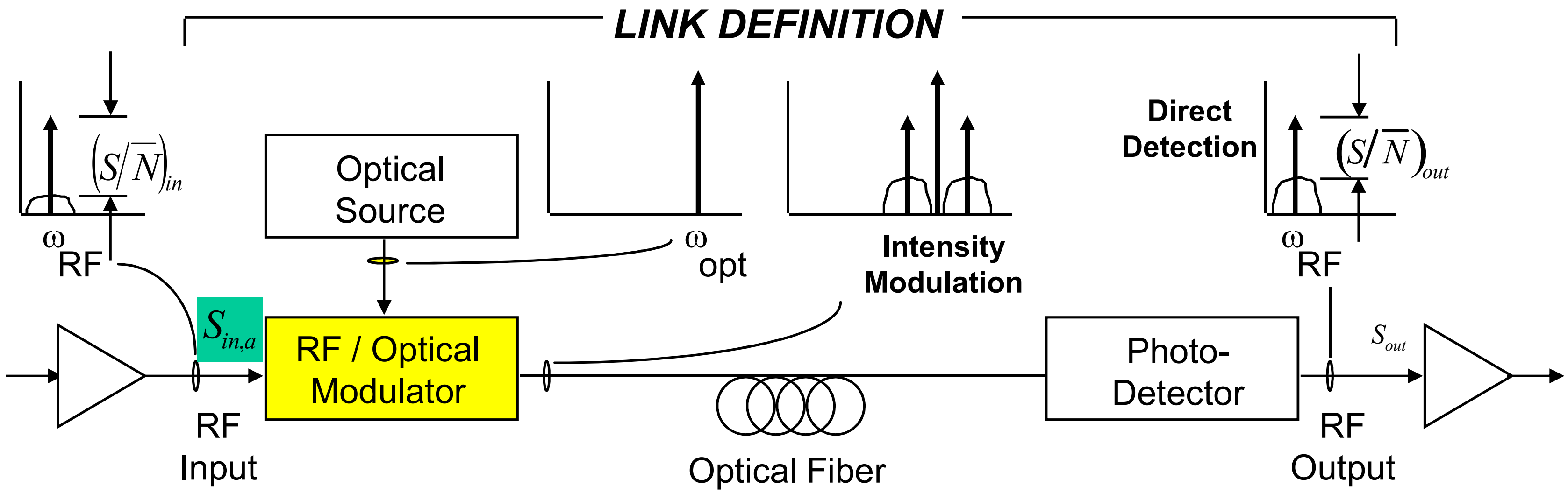
2. Noise Figure:

$$\frac{\text{Input SNR}}{\text{Output SNR}}$$

3. Spurious free dynamic range: RF Power Range (dB) above noise and inter-modulation distortions



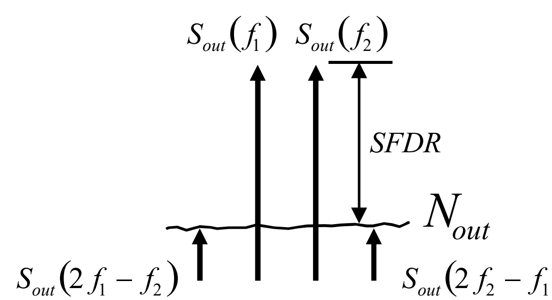
Intensity Modulation/Direct Detection Analog Fiber Optic Link*



$$G = \frac{S_{out}}{S_{in,a}}$$

$$NF \equiv 10 \log \left[\frac{(S/\overline{N})_{in}}{(S/\overline{N})_{out}} \right], \text{ where } \overline{N}_{in} \equiv kT, \quad \text{and } T = 290°\text{K } *$$

$$SFDR \equiv \frac{S_{out}(f_1)}{S_{out}(2f_2 - f_1)} \quad \text{at } S_{in} \text{ for which } S_{out}(2f_2 - f_1) = N_{out}$$



* "IRE Standards on Methods of Measuring Noise in Linear Twoports, 1959," *Proc. IRE*, **48**, No. 1 (Jan 1960), pp. 60-68. Courtesy of Charles Cox

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External Optical Modulator for fiber-optic link and performance figure of merit

Technological trend for high performance MZM modulators

Summary

External Optical Modulator Requirements

Ideal Modulator: low V_π (< 1 V);
high linearity;
low optical insertion loss;
high saturation power;
low polarization sensitivity;
reliable.

Link Gain:

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

where:
t_{ff} = fiber-to-fiber optical insertion loss of the modulator
R_{in} = the modulator drive impedance,

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

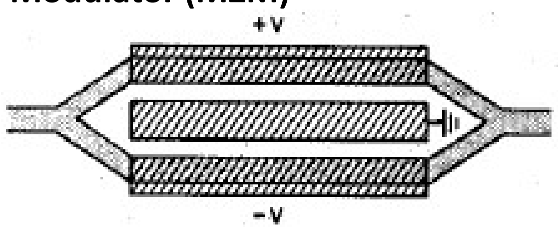
L_f = optical loss in the fiber

R_d = the photodetector responsivity
R_{out} = the detector load impedance

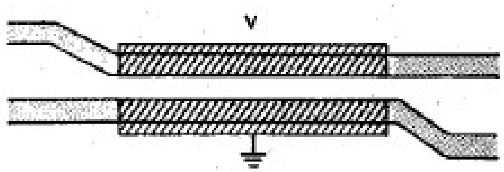
Optical Modulator Technology Choices

Popular Modulator Types

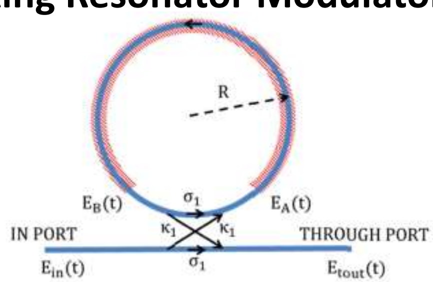
Y-Branch Interferrometric Mach-Zehnder Modulator (MZM)



Directional Coupler Modulator (DCM)



Ring Resonator Modulator



Electroabsorption Modulator (EAM/EML)

Material Choices

- Lithium Niobate
- III-V semiconductor
- Silicon
- Polymer
- Graphene; Nanowires
- Plasmonic

Electrode Choices

- Lumped Electrode
- Traveling Wave Electrode
- 50 Ω Terminated
- Unterminated

Performance Parameters of Interest

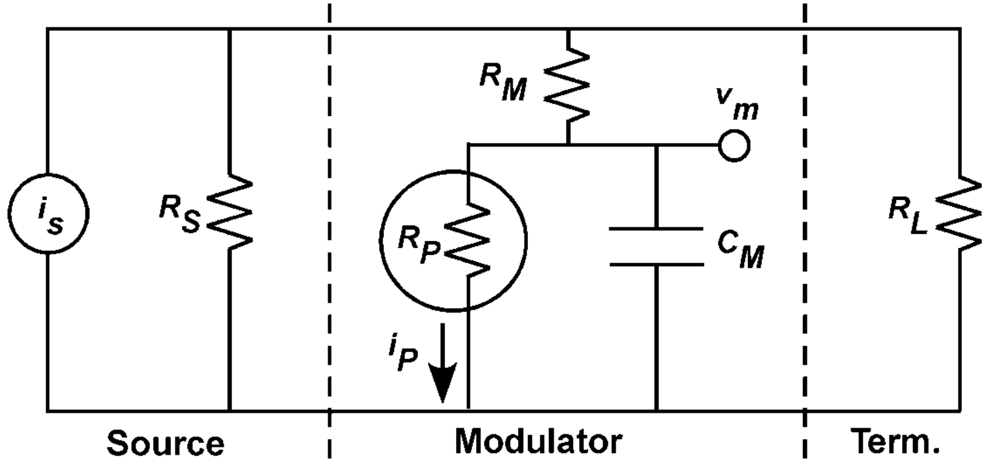
- Modulation Bandwidth
- Sensitivity (V_π)
- Optical Insertion Loss
- Extinction Ratio
- Optical Bandwidth
- Power Handling
- Thermal Stability
- Form Factor

The goal is to develop low-loss E-O modulators with a performance parameter:

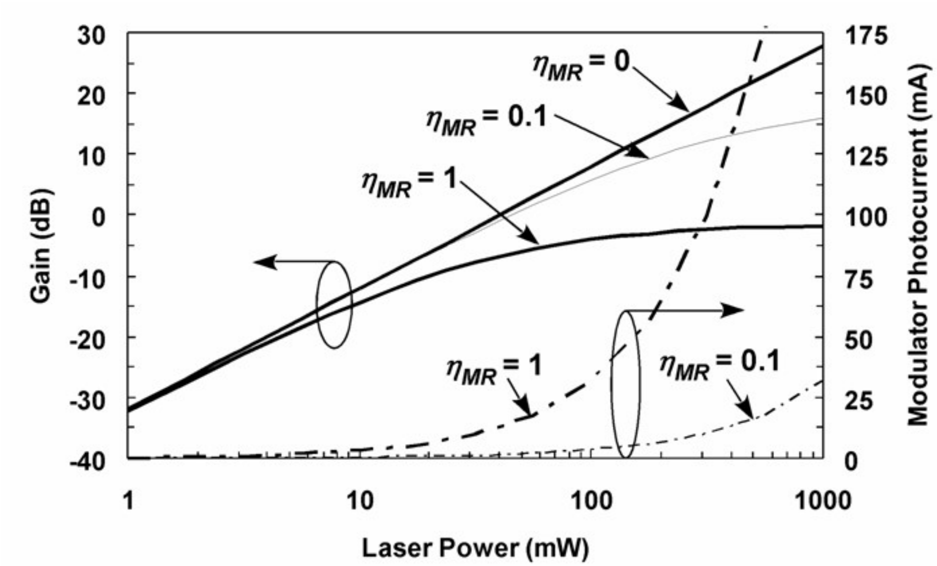
$$M_{PF} = BW(GHz, 3dBe)/V_\pi(V)$$

Analog Fiber Link: Gain Limitation of EAM modulator

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

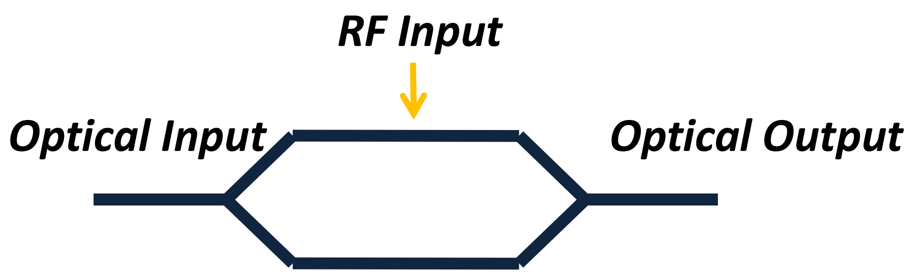


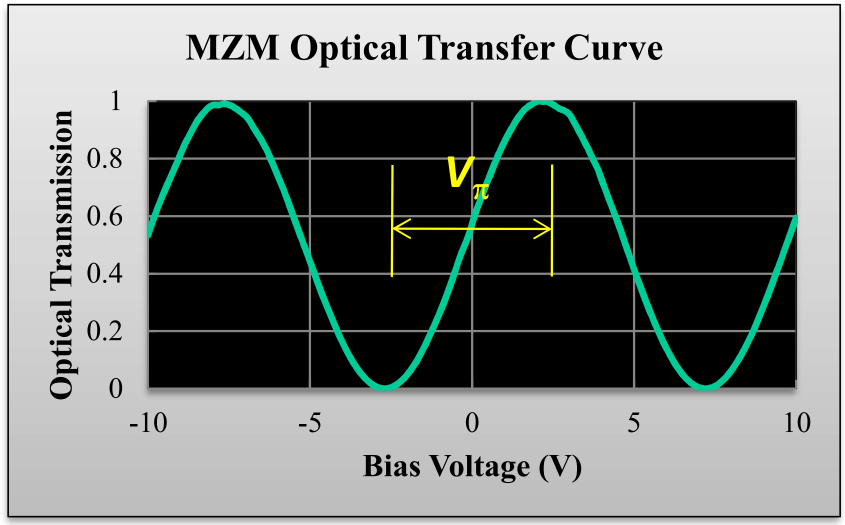
G. Betts et al, *PTL* 2007



MZM Based E-O Modulator

Electrooptic Modulator





Popular materials for Electro-optic Modulator:

(a) Lithium Niobate
(b) Semiconductor
(c) Polymer (large electro-optic coefficients)

E-O Modulator Technology Outlook

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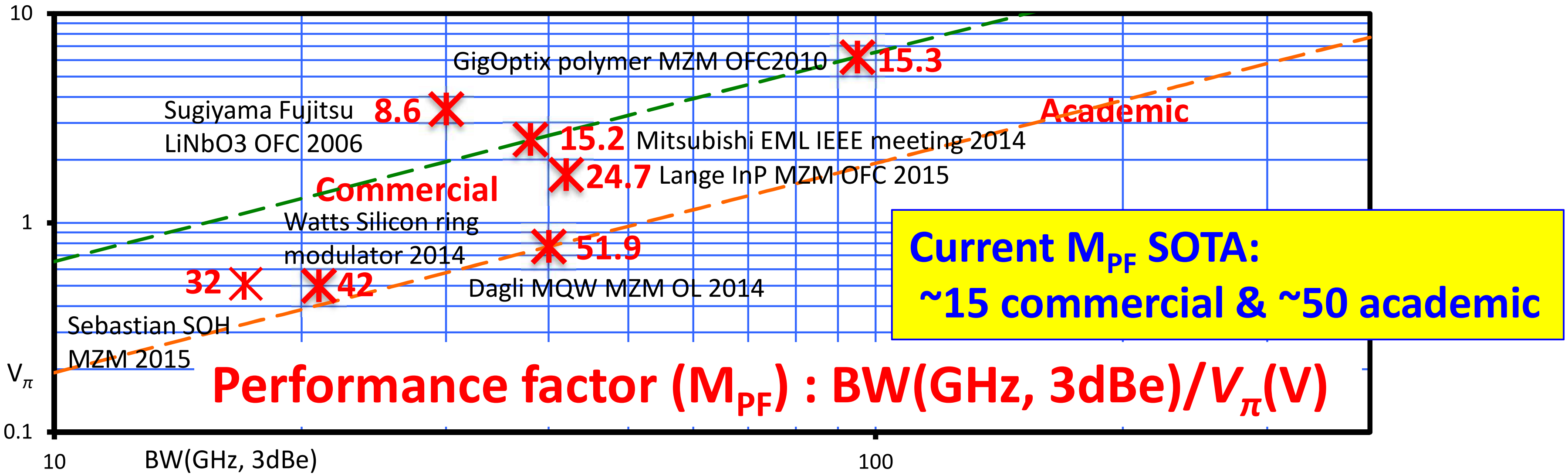
Lack of high performance wideband optical modulator

- **Drive Voltage:** ~2V today (sub volt is highly desired or required)
- **Bandwidth:** 30-40GHz today (~100GHz is desired for > 100Gb/s)
- **Transmitter driver power:** $P \propto V_{\pi}^2$, dominating power consumption
- **$V_{\pi} \propto$ BW:** more bandwidth results in higher drive voltage



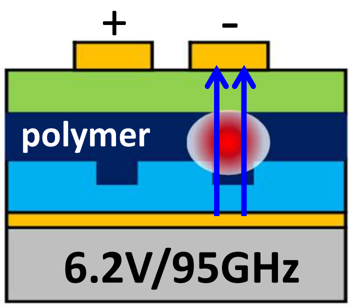
SYSTEM IMPACTS: Small M_{PF} modulators result in:
- **High noise figure broadband analog links**
- **High power consumption digital data centers**
- **Reduced resolution and efficiency LIDAR**

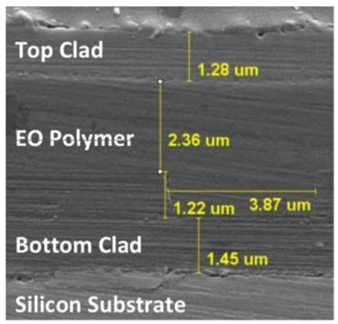
Performance Limitation Analysis

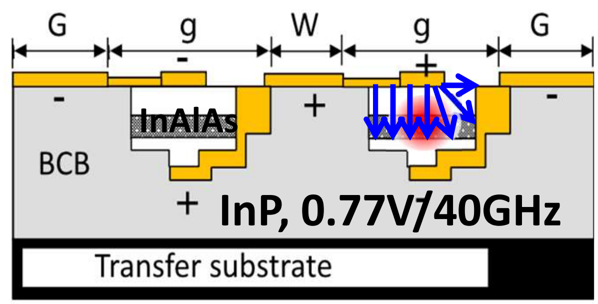
Exemplary MZM modulators with respect to M_{PF}

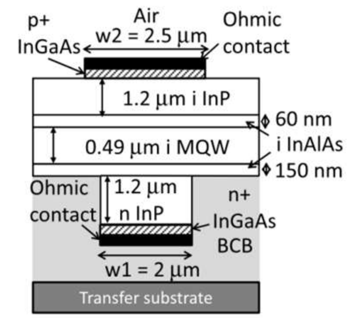
$$V_\pi = \frac{\lambda \times d}{2 \times {n_{eo}}^3 \times r \times \Gamma \times l}$$

$$C_s = \frac{{n_{eo}}^2 \times \epsilon_0 \times g \times l}{d} \times 2$$









Polymer-MZM, M_{PF}=15.3

- **High *r* :** 100pm/V (*r : relevant EO coef.*)
- **Large V_π:** 6.2V, *l*=0.37cm, d=6.3µm
- **n_{eo}:** 1.7
- **Moderate C_s:** > 2 x 0.058 pF
- **Traveling-wave for speed**

InP-MZM, (Dagli et al) M_{PF}=51.9

- **Low *r* :** 8.2pm/V
- **Long device length:** 0.77V, *l*=1cm, d=2µm
- **n_{eo}:** 3.3
- **Large C_s:** 2 x 1.2pF
- **Traveling-wave for speed**

Commercial (M_{PF}~15) | Today's Best | **Laboratory (M_{PF}~50)**

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GaN Nanowire MZM Modulator

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Motivation for using Nanowires

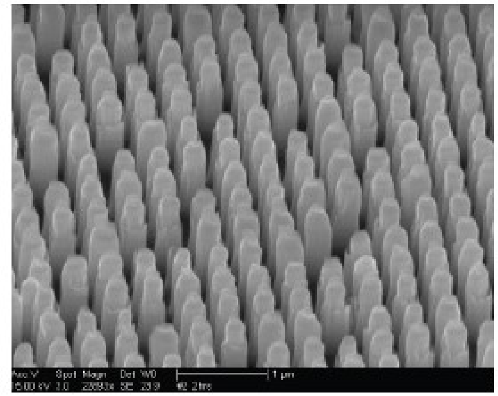
1. Potential for small V_π

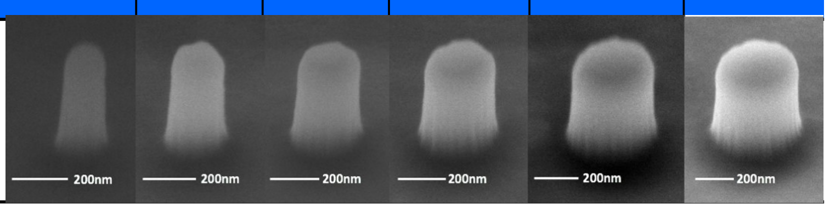
$$V_\pi = \frac{\lambda}{n_e^3 r_{XX}} \frac{d}{l}$$

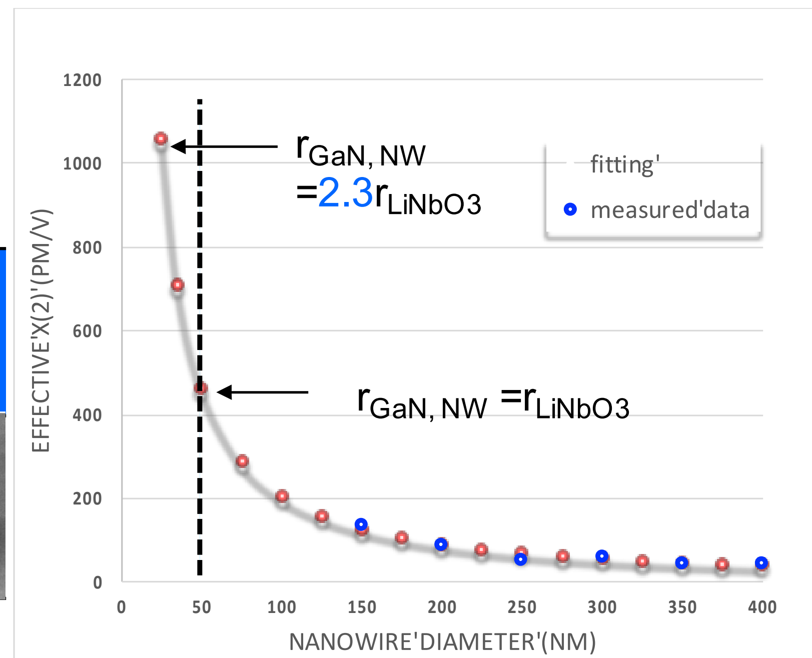
2. High second harmonic susceptibility:

$$r_{31} = \frac{2\chi_{31}^{(2)}}{n_0^4} \propto \frac{\sqrt{I_{2\omega}}}{n_0^4 E^2}$$

GaN Nanowires array

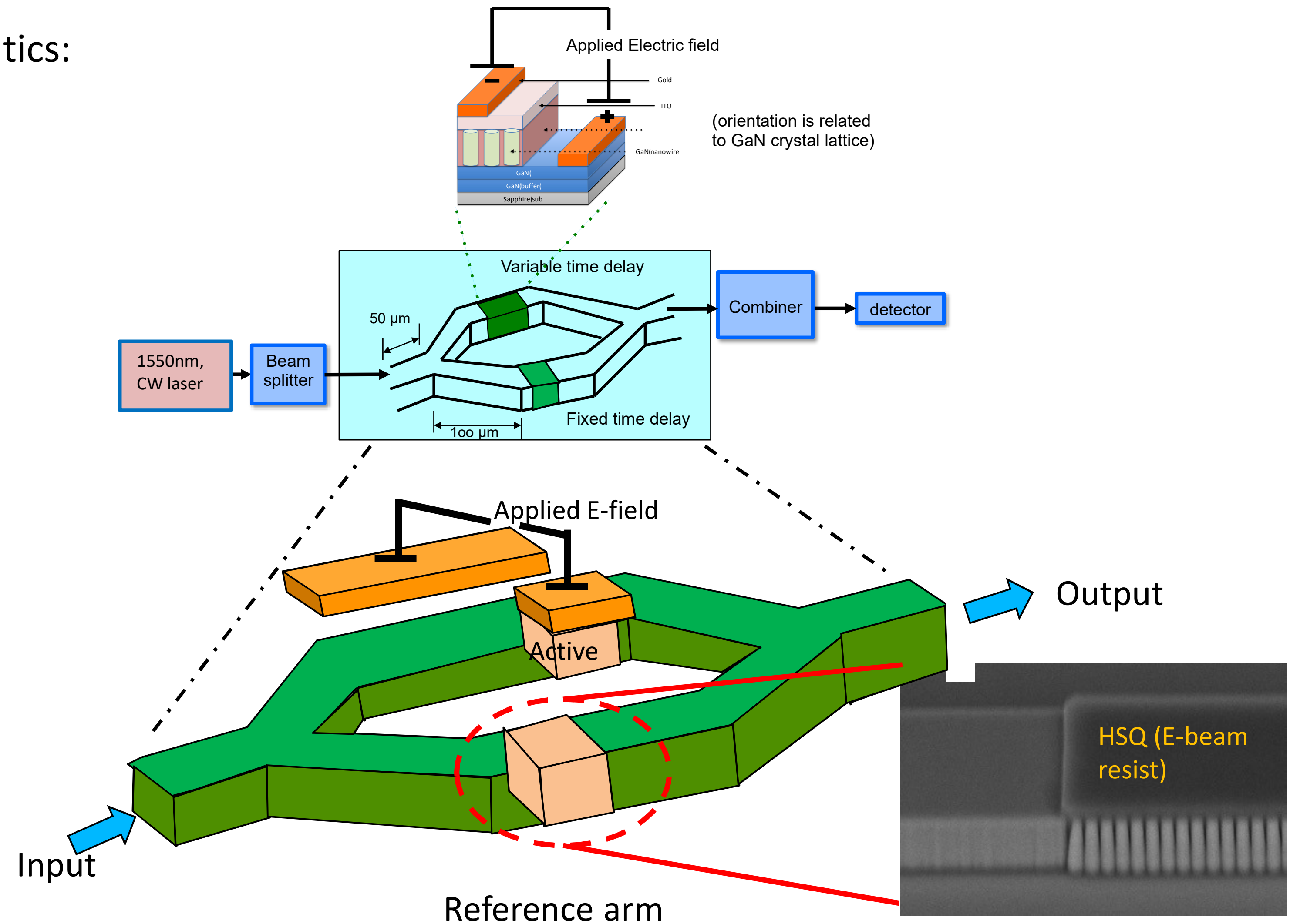


Nanowire diameter (nm)	150	200	250	300	350	400
SEM						



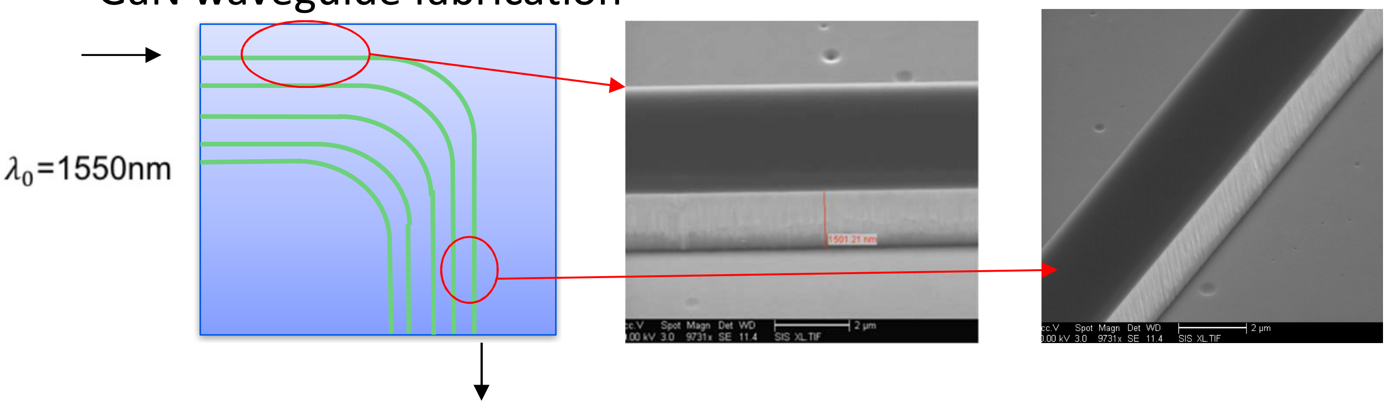
GaN nano-pillars MZM design

Device Schematics:

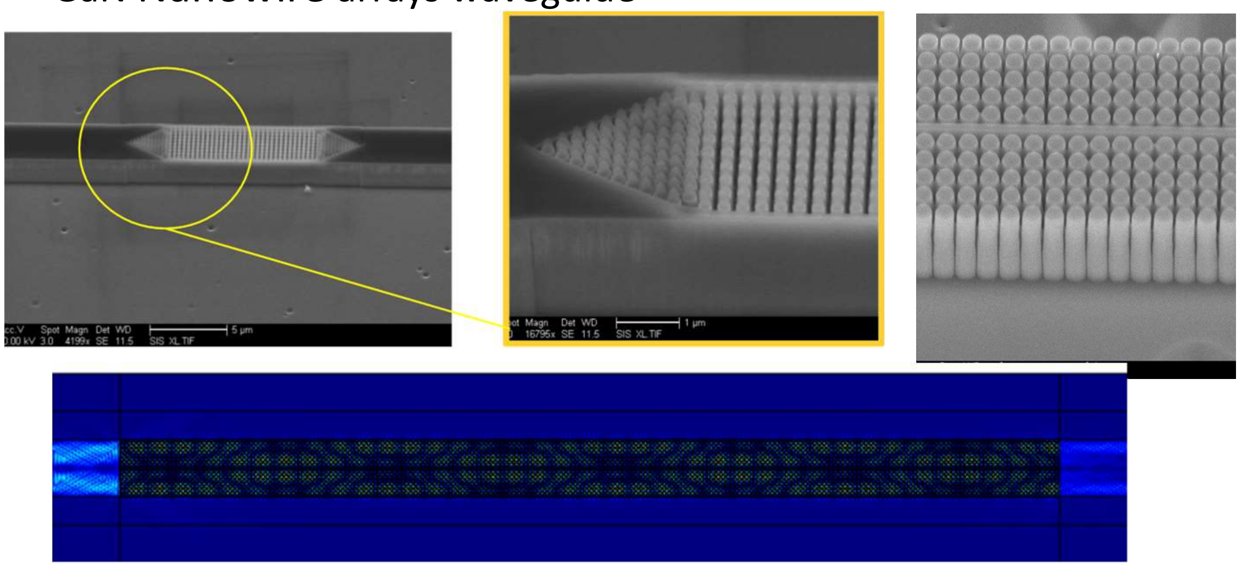


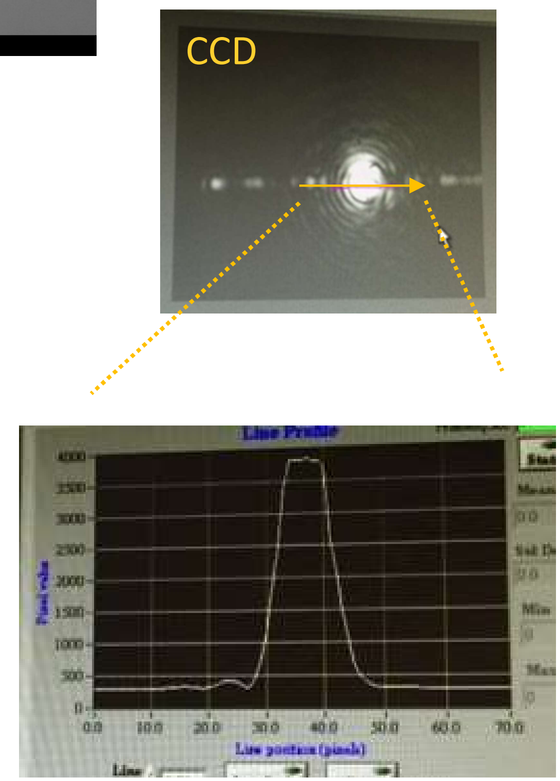
On-going GaN Nanowire Waveguide Modulator

- GaN waveguide fabrication



- GaN Nanowire arrays waveguide





Propagation characteristics of dielectric filled GaN nano pillar arrays consistent with EM-mode simulation

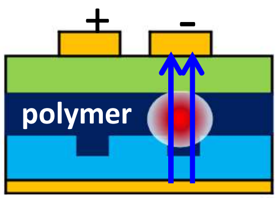
Slotted Waveguide Geometries

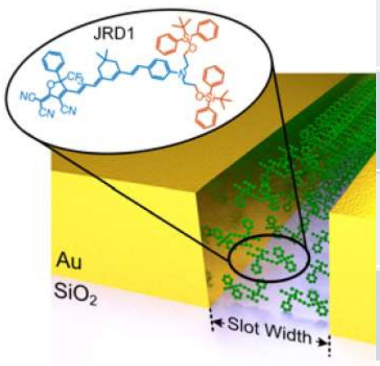
By inserting a narrow slot (Prof. M. Lipson et al, Columbia U, USA) in the waveguide and apply a E-field across it, one can obtain efficient EO modulation if the slot is filled with an active EO material such as EO-polymer, provided:

(1) Good modal overlap between the high E-field region and the optical mode;
(2) The total waveguide length will not lead to excessive propagation loss.

How narrow is narrow? This has to do with the drive voltage or equivalently, V_π consideration. For conventional MZM with a slotted arm, there is an optimization between the drive voltage, optical insertion loss, and bandwidth. The bandwidth can be separately optimized in travelling wave electrode configuration.

Comparison of Electro-optic MZMs



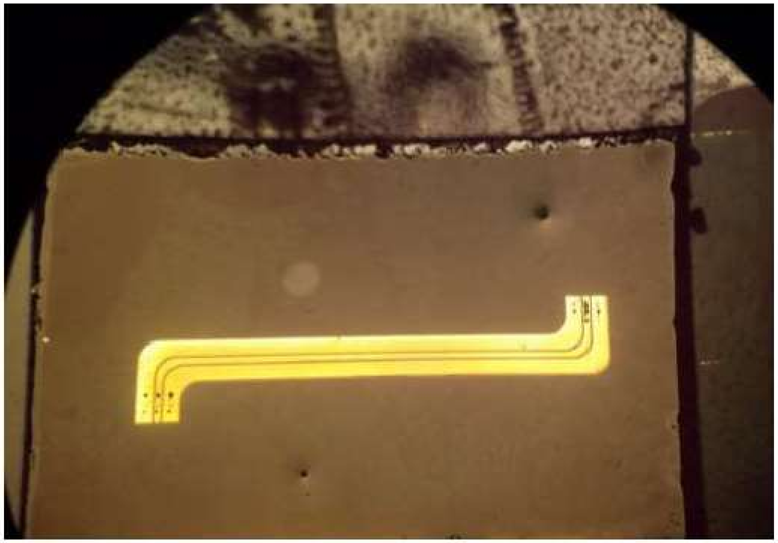


Type	Polymer	r_{33} (pm/V)	$V_{\pi}L$ (Vcm)	α (dB/cm)	BW (GHz)
$LiNbO_3$ (Oclaro)	NA	30	37.4 (4.5V x 8.3 cm)	0.2	40
$LiNbO_3$ on Si [10]	NA	32.2	7.1	NA	NA
Polymer	SEO-125	80-250 [1-4]	1.26 - 13	1.5	40-100
Hybrid Si slot + polymer	SEO-125	1230 [5]	2.82		15
Plasmonic Hybrid Si + Polymer [6]	DLD-164 [Dalton]	137 [7] 180 [6]	0.06	4000	73
Hybrid TiO_2 slot WG + Polymer [8]	NA	144	0.8	5	Not tested
Hybrid Si slot WG + Polymer [9]	DLD-164	180	NA	NA	NA

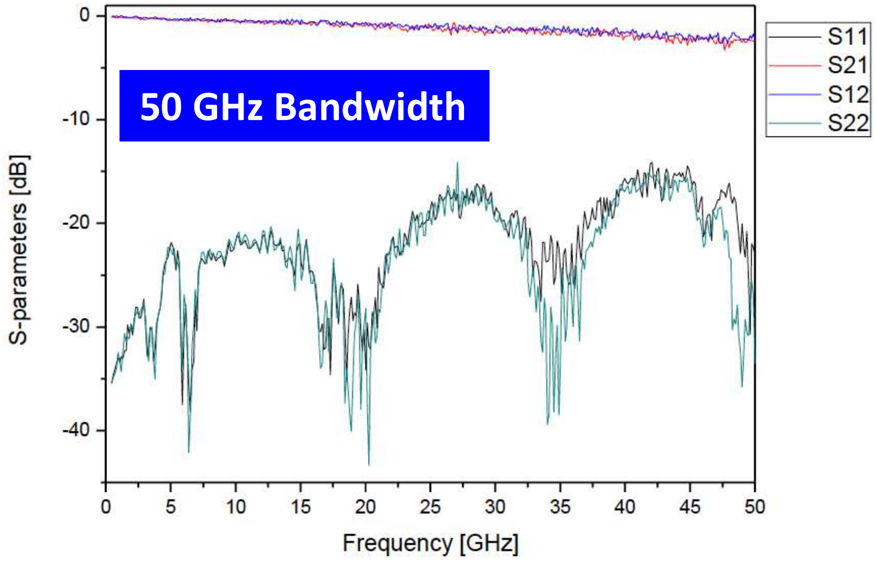
[1] Y. Enami et al., Appl. Phys. Lett., 91, 093507, 2007
[2] Y. Enami et al., AIP advances, 1, 042137, 2011
[3] R. Palmer et al., J-LT, 16, 2726, 2014
[4] Y. Enami et al., Opt. Ex., 22, 30191, 2014
[5] Xinyu Zhang et al., Arxiv, 2015
[6] L. Muffner et al, Nature Photon., 9, 529, 2015
[7] Chem. Mater., 26, B72-B74, 2014
[8] Feng Qiu et al., Scientific Reports, 5, 5861, 2015
[9] S. Koeber et al., Light: Sci. & Appl., 4, e255, 2015
[9] A. J. Mercante et al., Opt. Lett., 41, 867, 2016

MZM Polymer Modulator on Glass

Pre-poled high E-O coefficient polymer film



Electrical Performance



- **High speed, low loss modulator design**
- **Handled high optical power (> 50 mW)**
- **Quick turnaround fabrication & service packaging**
- **Low cost manufacturing**
- **Performance scalable with improved polymers**

(Courtesy of N. Peyghambarian, U. of Arizona)

Silicon Slot Polymer Selection

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E-O Material Comparison

Effect	Electro-Optic Effect		Free Carrier Plasma Dispersion Effect
Material	**LiNbO3**	**EO Polymers**	**InP, GaAs**
V_p dependence	$V_\pi = \frac{\lambda d}{n^3 r_{ij} L\Gamma}$ Fast effect, femtoseconds for polymers.		$V_\pi = f(\lambda, n, L, V_{bias}, \Gamma, T, N, P)$ The effect limits the modulation speed, bandwidth, <30G.
Refractive index (*n*) (@1550nm)	X-cut: 2.15 Z-cut: 2.21	1.7	3.2
EO Coefficient (r_{33}) (pm/V)	30	90	29

Initial modulator designs and demonstration incorporate E-O polymer with modest r_{33} (80-90 pm/V) and proven environmental stability **(Telcordia qualified M3 polymer)**

Commercial SEO 120 and M3 Polymer Material Comparison

SEO 120 polymer brings 25% V_π reduction over M3 polymer

Developmental slot polymer (JRD1) ** shows r_{33} = 160 pm/V, 2x that of M3 polymer

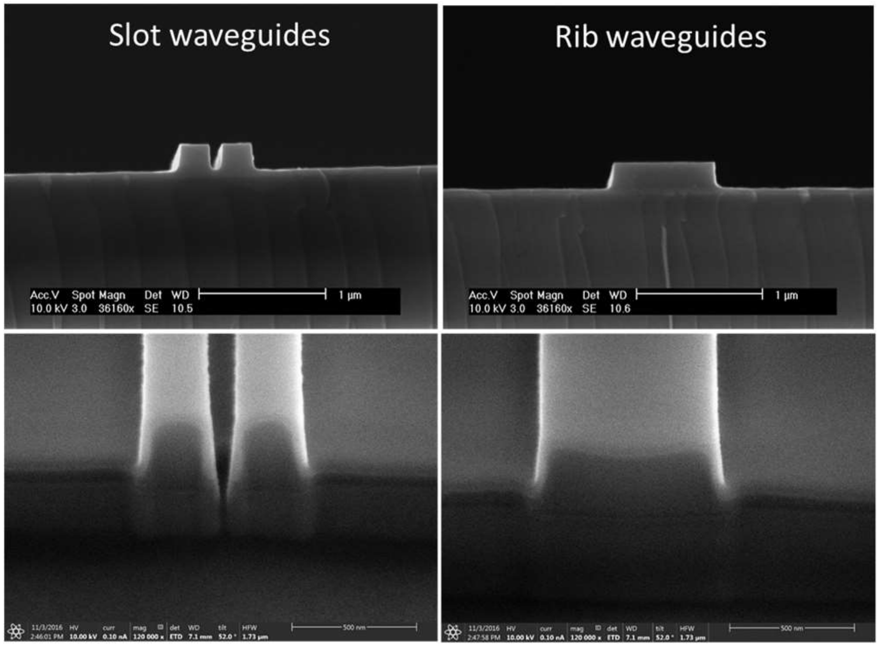
	SEO 120	M3 (LXM3)
E-O coefficients, r_{33}	123pm/V @1300nm; 100pm/V@1550nm	87-107pm/V@1300nm 74-91pm/V@1550nm
Refractive indices. (unpoled)	n_o=1.636 @1550nm n_e=1.681 @1550nm	n_o=1.675 @1550nm n_e=1.691 @1550nm
Optical loss :	1.0 dB/cm @1550nm	1.5 db/cm @1550nm
Operational Temp	RT to 85^{0}C	RT to 85^{0}C
T_g		163-170^{0}C
Poling E-field(V/um)		110-140
Power handling		Max 100 mW
Price	$2000 /1 gram	$2500/1 gram $4200/2 gram
Stability		25 year at 85^{0}C

**** UW/German JRD1 work; Optics Express 25, 2627 (2017)**

Inorganic E-O Material Candidates

Pre-BTO deposition

Post-BTO deposition

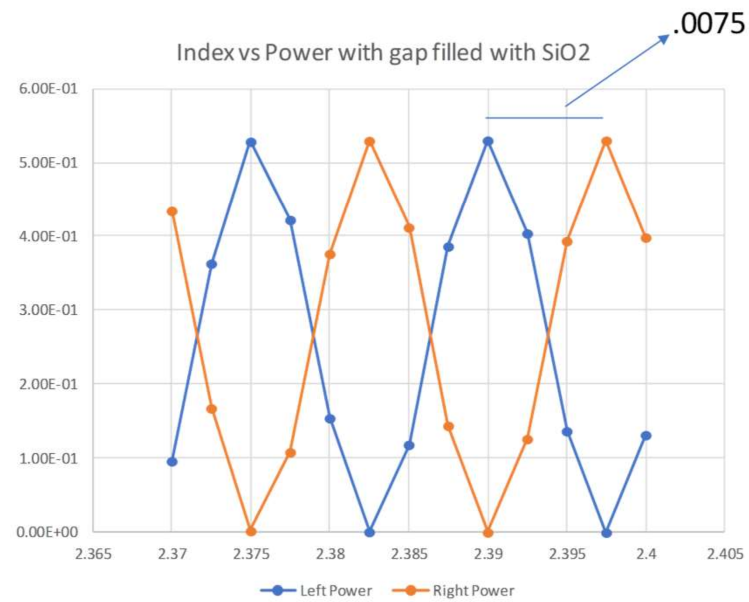


BTO (Barium Titanate): Candidate for E-O slot material

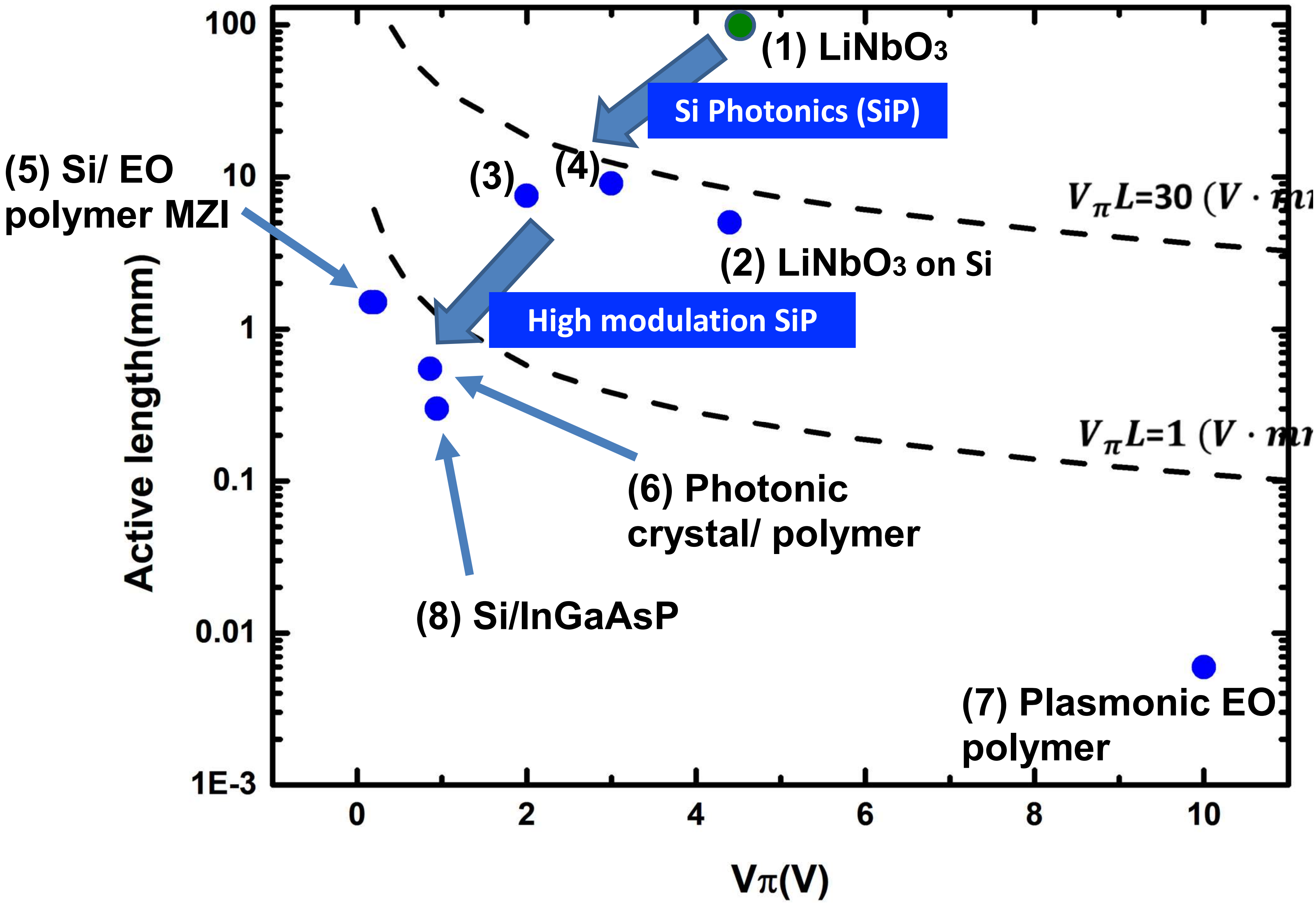
Dimensions:
Entire Piece 700 microns long
Gap: 500 microns long, 100nm wide
Walls are 260nm x 330nm, index is 3.48
It is surrounded by SiO2 with index 1.46

Width of Wall	V_π
10nm	12.3
20nm	7.60
30nm	3.98
40nm	1.81
50nm(filled)	1.09

d=100nm, n180=.0075
r=100pm/v, n=2.4



Results from Professor Shaya Fainman's group



(1) LiNbO3
Si Photonics (SiP)
(3)
(4)
(5) Si/ EO polymer MZI
(2) LiNbO3 on Si
High modulation SiP
(6) Photonic crystal/ polymer
(8) Si/InGaAsP
(7) Plasmonic EO polymer
$V_\pi L$=30 (V · m
$V_\pi L$=1 (V · m
100
10
1
0.1
0.01
1E-3
0
2
4
6
8
10
Active length(mm)
Vπ(V)

Summary

In this talk, we have

- presented the roles of optical modulators in analog and digital applications
- introduced a performance figure of merit, M_{ph}, for the optical modulators
- surveyed the commercial and laboratory modulators
- examined some MZM structures and nonlinear materials
- discussed the nanopillar and nanoslot MZMs and pointed out the advancement required to achieve large M_{ph}

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