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ENZ Optical Modulators

PRESENTED BY

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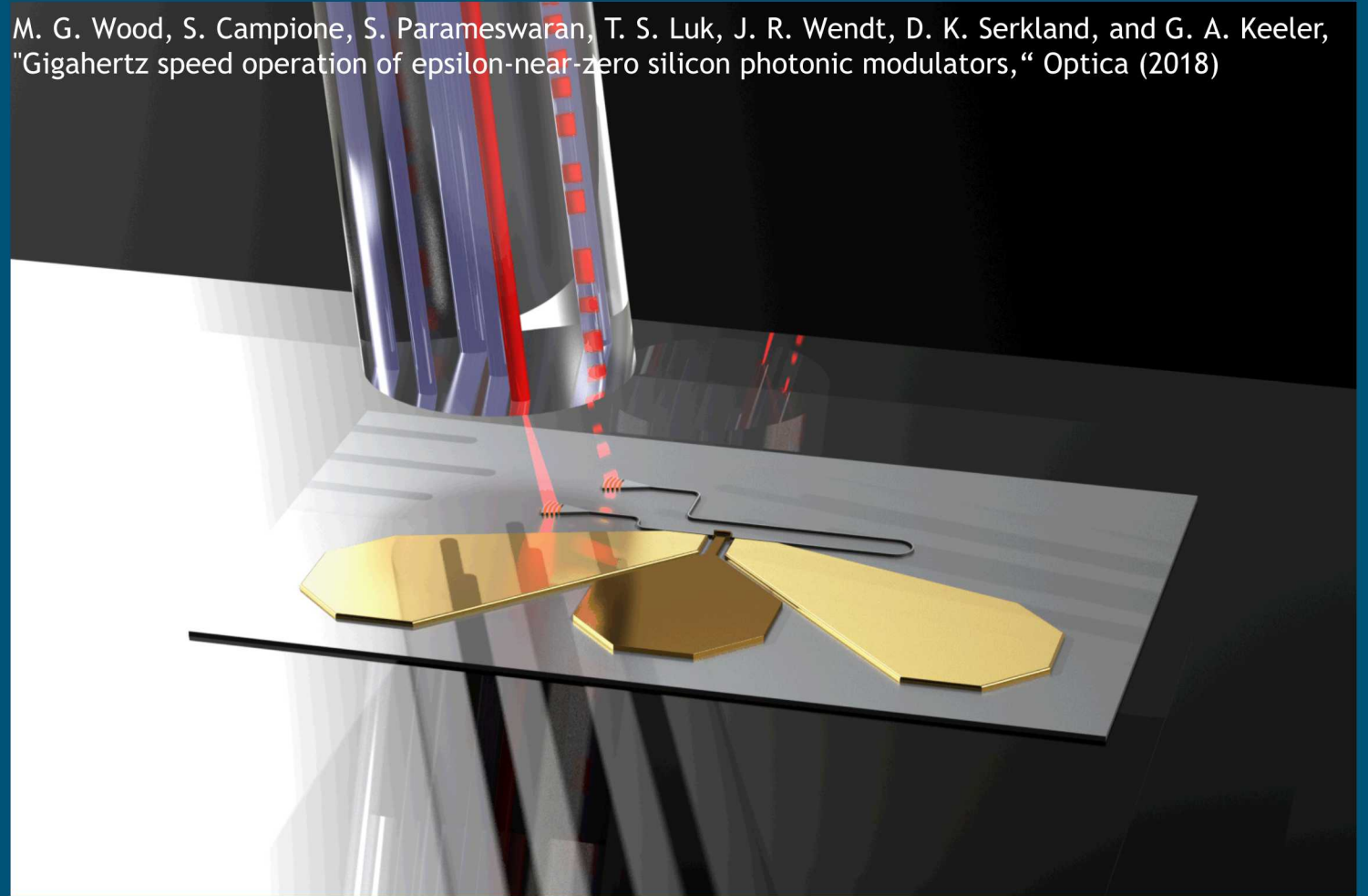
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M. G. Wood, S. Campione, S. Parameswaran, T. S. Luk, J. R. Wendt, D. K. Serkland, and G. A. Keeler, "Gigahertz speed operation of epsilon-near-zero silicon photonic modulators," *Optica* (2018)



Metrics for optical modulators

Modulation Performance:

Modulation efficiency - Modulated power divided by unmodulated power

Extinction ratio - OFF/ON ratio of the transmission

Modulation frequency response - frequency at which the transmission is dropped by 3dB

Energy efficiency:

Insertion loss

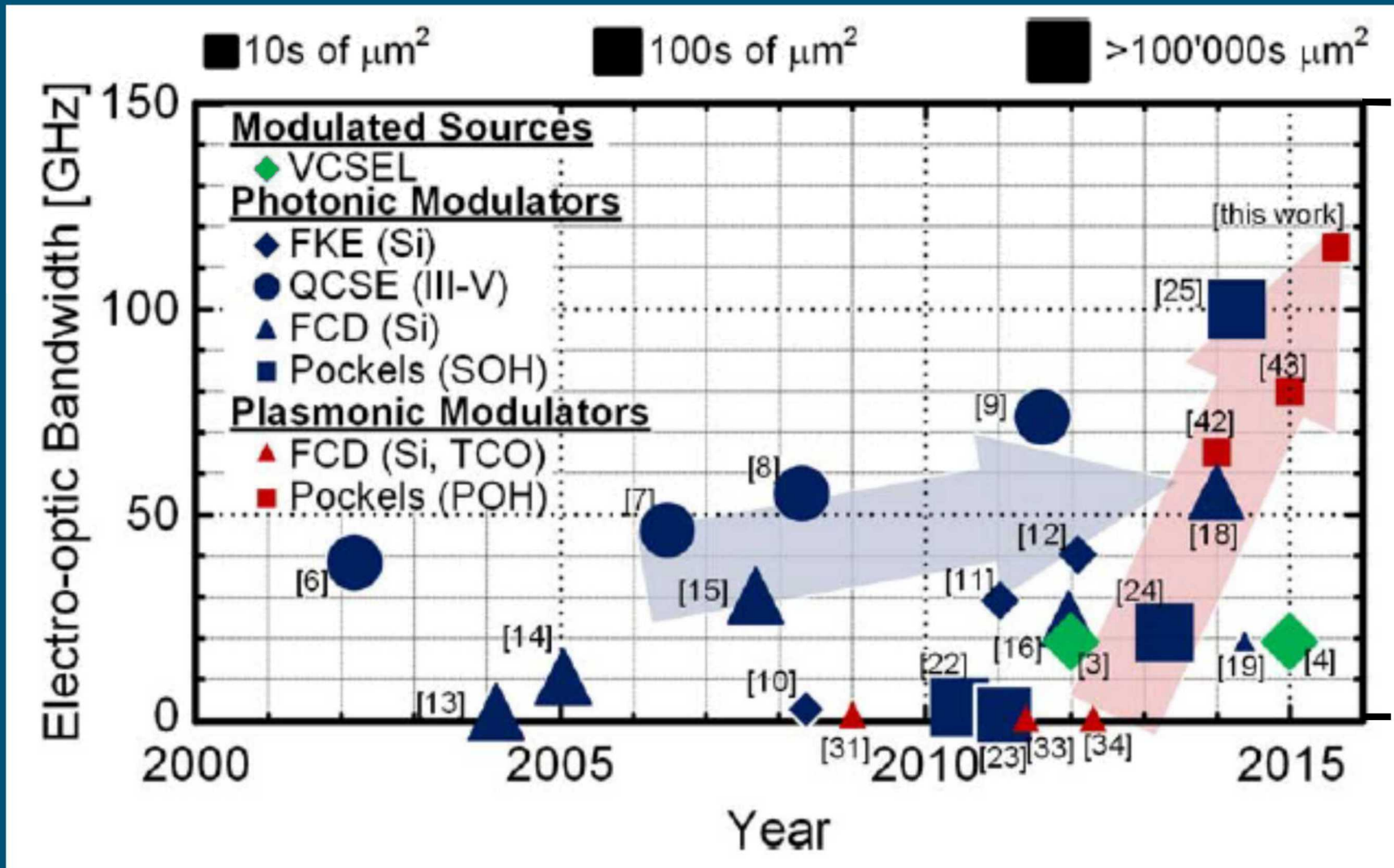
Energy cost in modulation (Energy/bit)

Size trade-off:

Modulation per unit length (dB/ μm)

Voltage-length product (Vcm)

Photonic modulator Synopsis



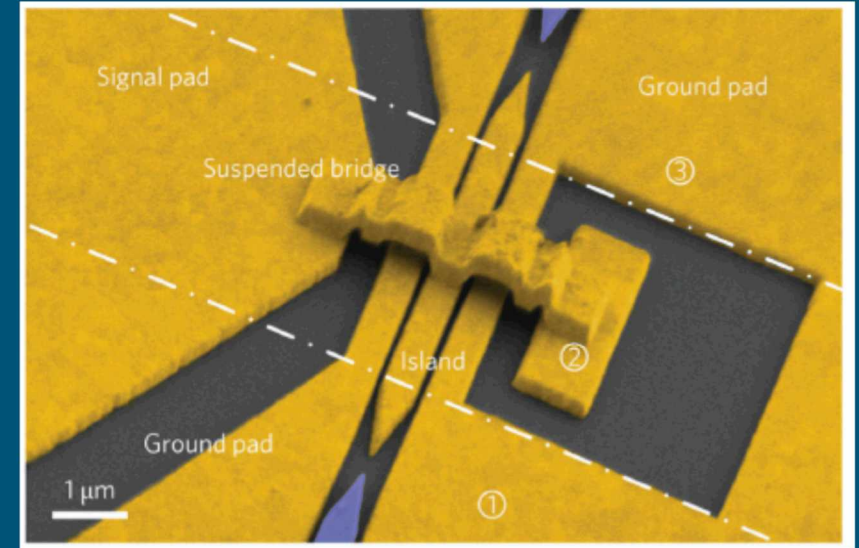
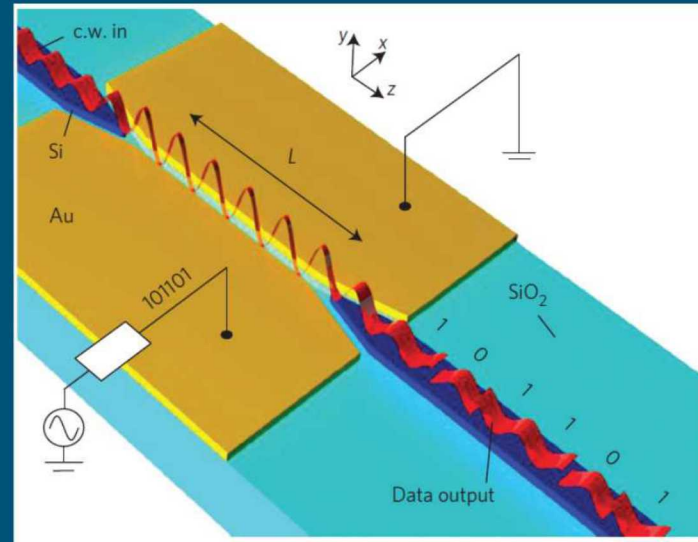
ENZ
2018

2020

Plasmonic Organic Hybrid modulator scheme

Plasmonic-Organic-hybrid (Kerr effect) modulator

- 170GHz most recently
- 0.004 volt.cm
- 25 fJ/b
- Extinction ratio 26 dB
- FOM' 0.095 rad/dB/V



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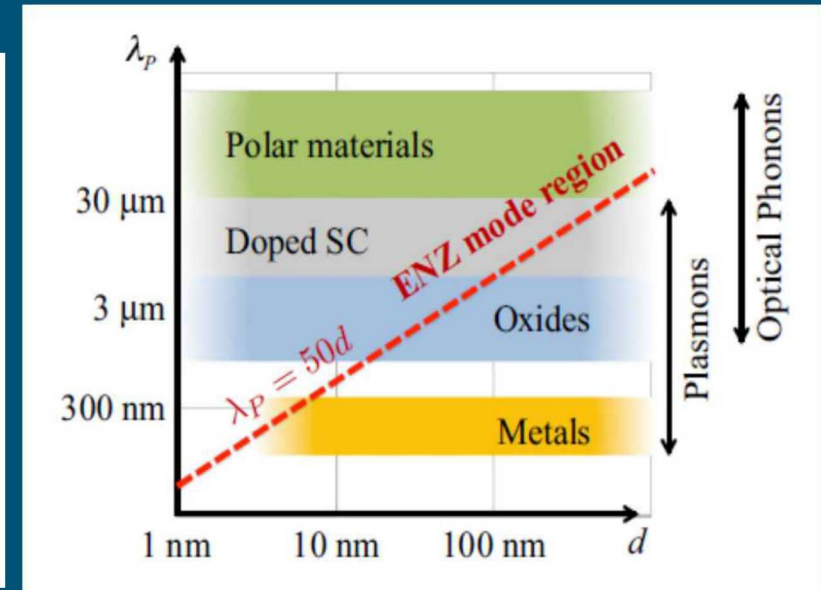
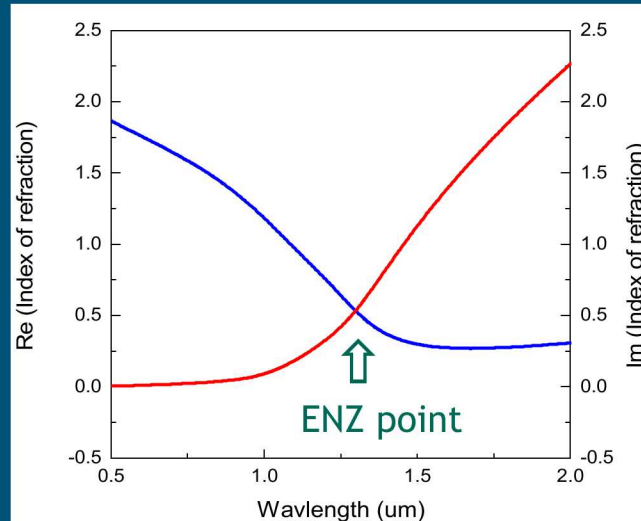
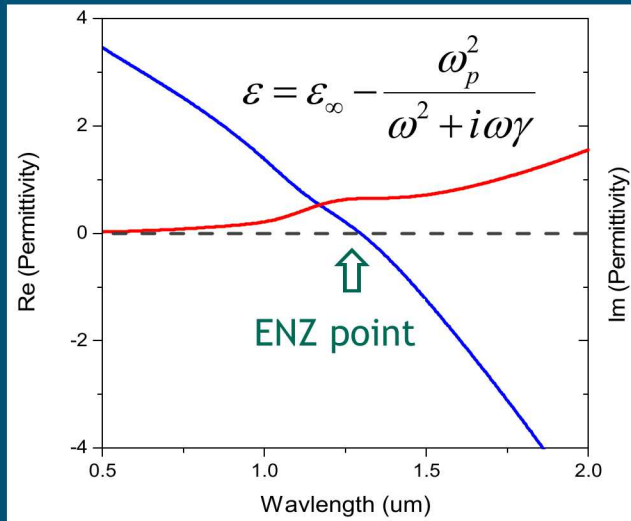
What are Epsilon-Near-Zero(ENZ) materials?

Natural:

Almost free charges:

$$\epsilon = \epsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}$$

$$\omega_{ENZ} = \sqrt{\frac{\omega_p^2}{\epsilon_{\infty}} - \gamma^2}$$



Bound charges:

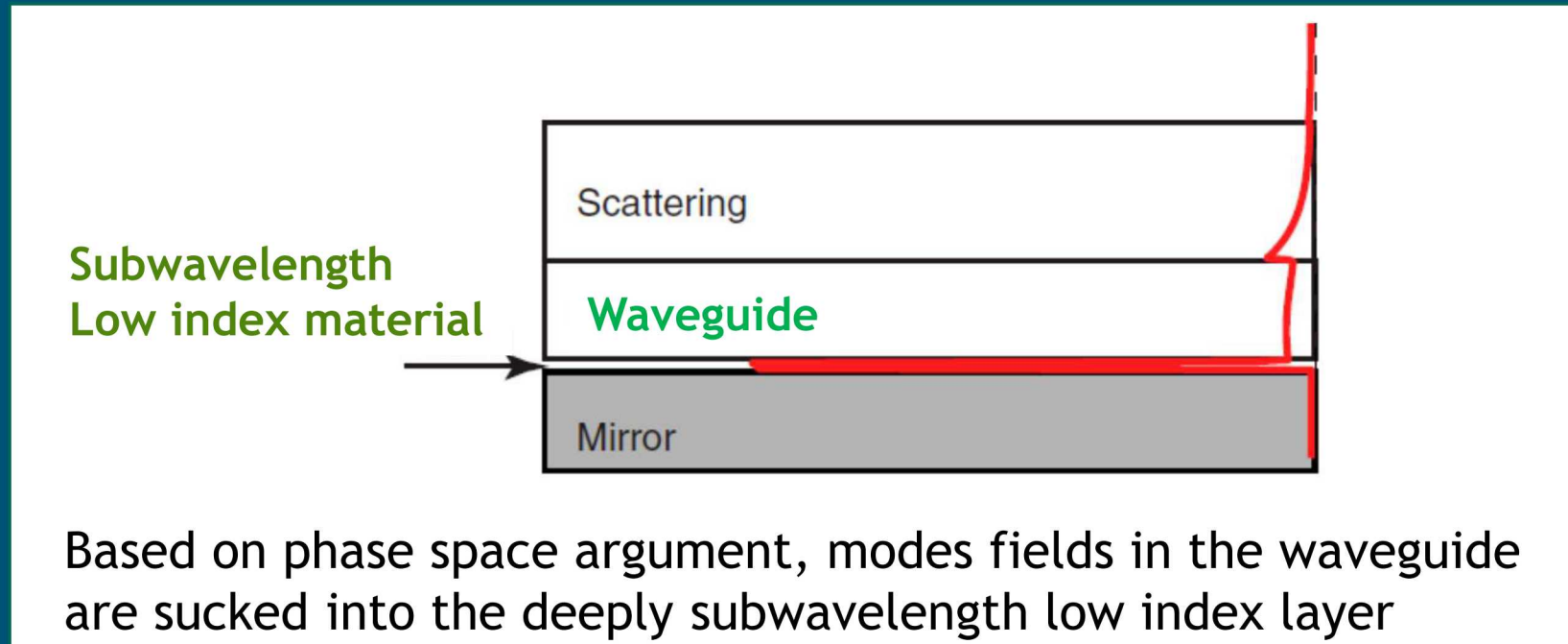
$$\epsilon = \epsilon_{\infty} + \frac{\Omega_p^2}{\omega_{TO}^2 - \omega^2 + i\omega\gamma}$$

$$\omega_{ENZ} = \omega_{LO} = \sqrt{\omega_{TO}^2 + \frac{\Omega_p^2}{\epsilon_{\infty}}}$$

Metamaterial:

Effective zero permittivity - engineered plasmonic and dielectric resonances

Mode confinement in low index material

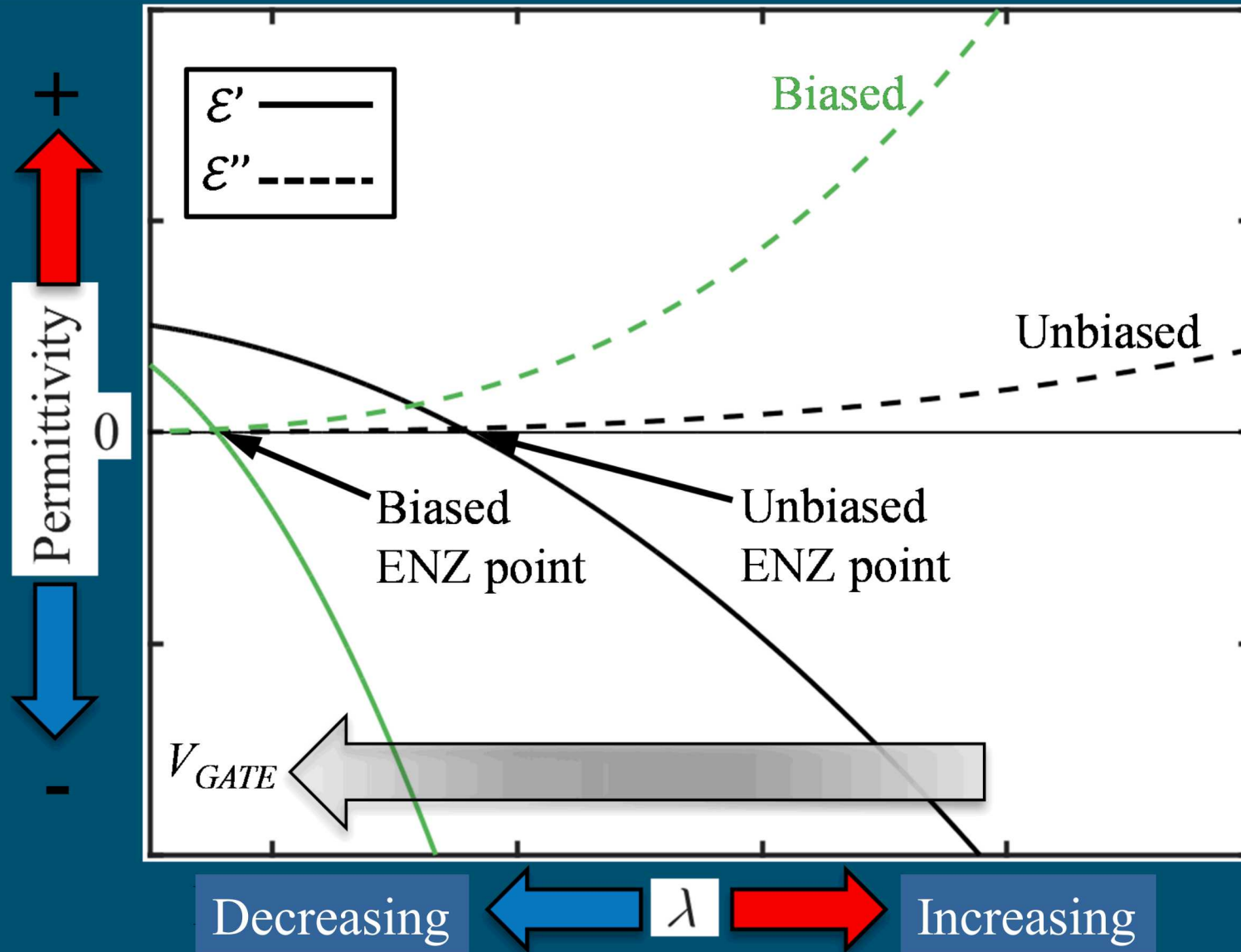


Optical Modulator Applications

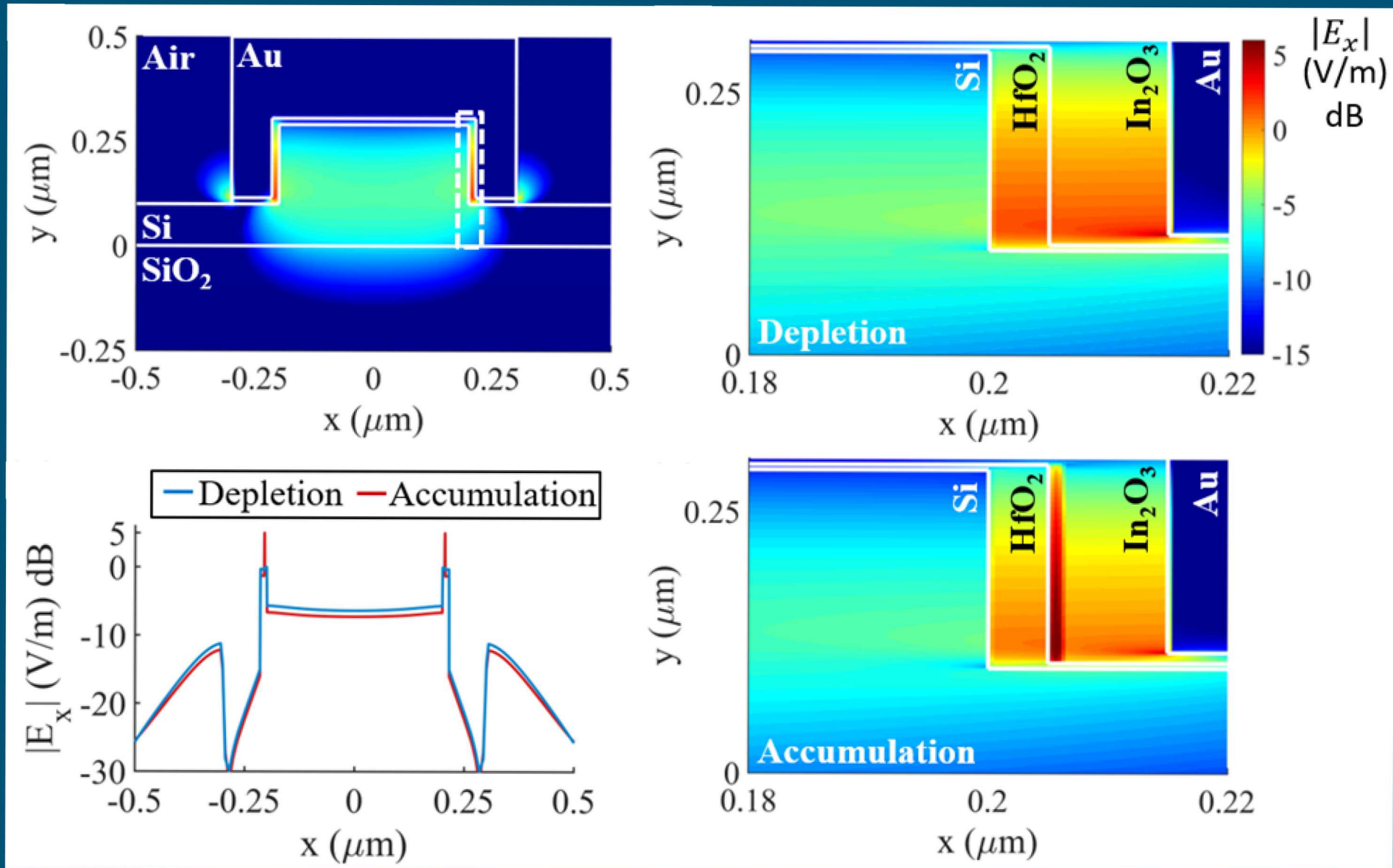
- Use the ENZ material as the low index layer.
- Modulate carrier density of the low index layer to modulate the waveguide field.

ENZ modulator

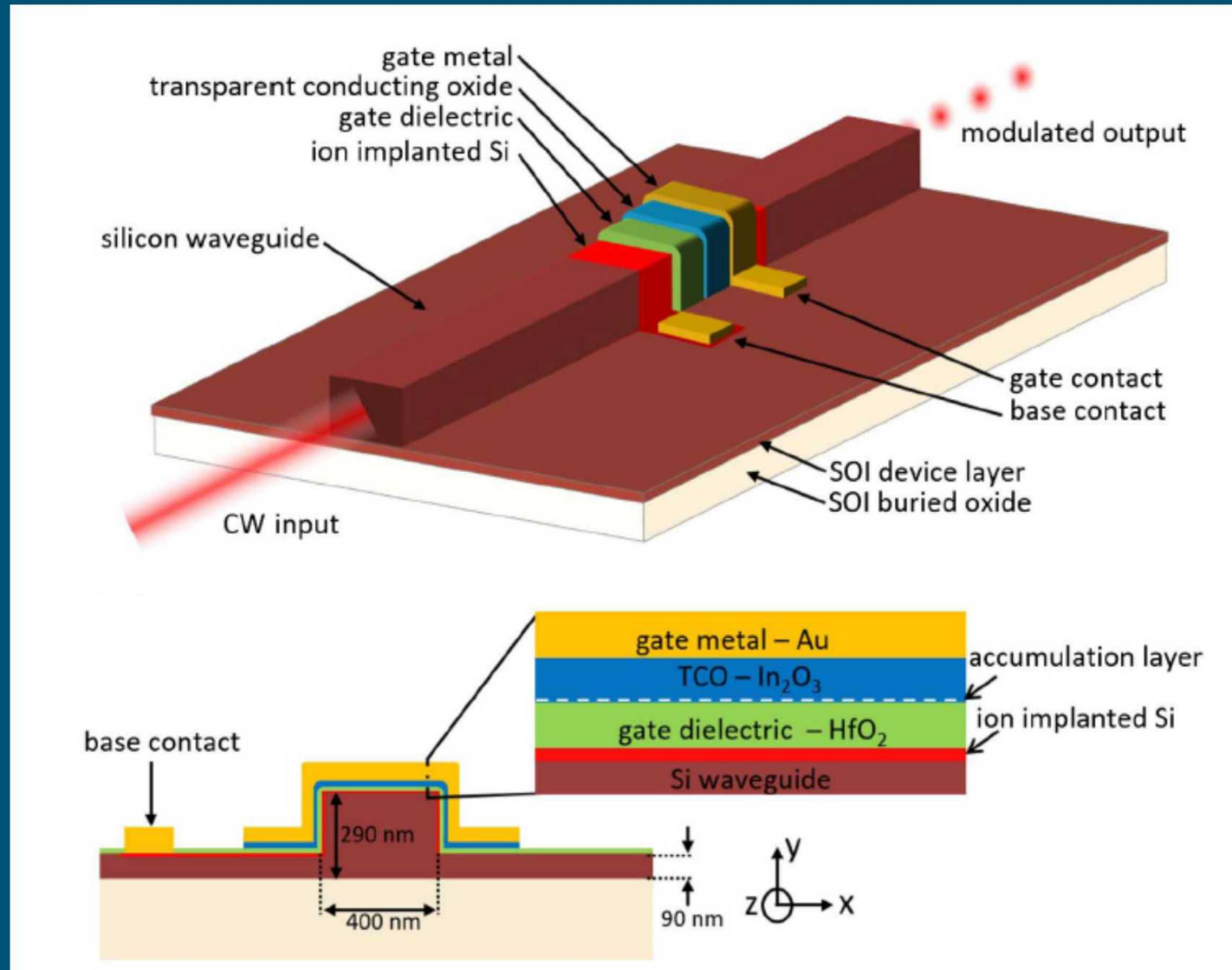
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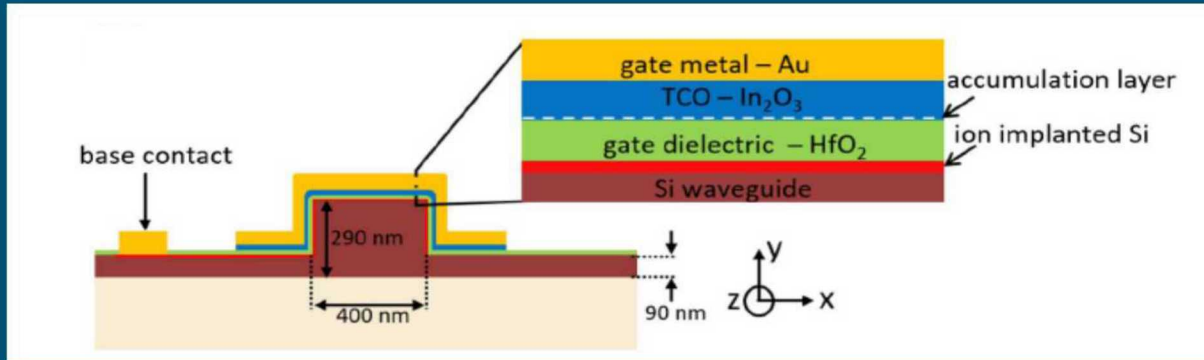
Optical mode profile



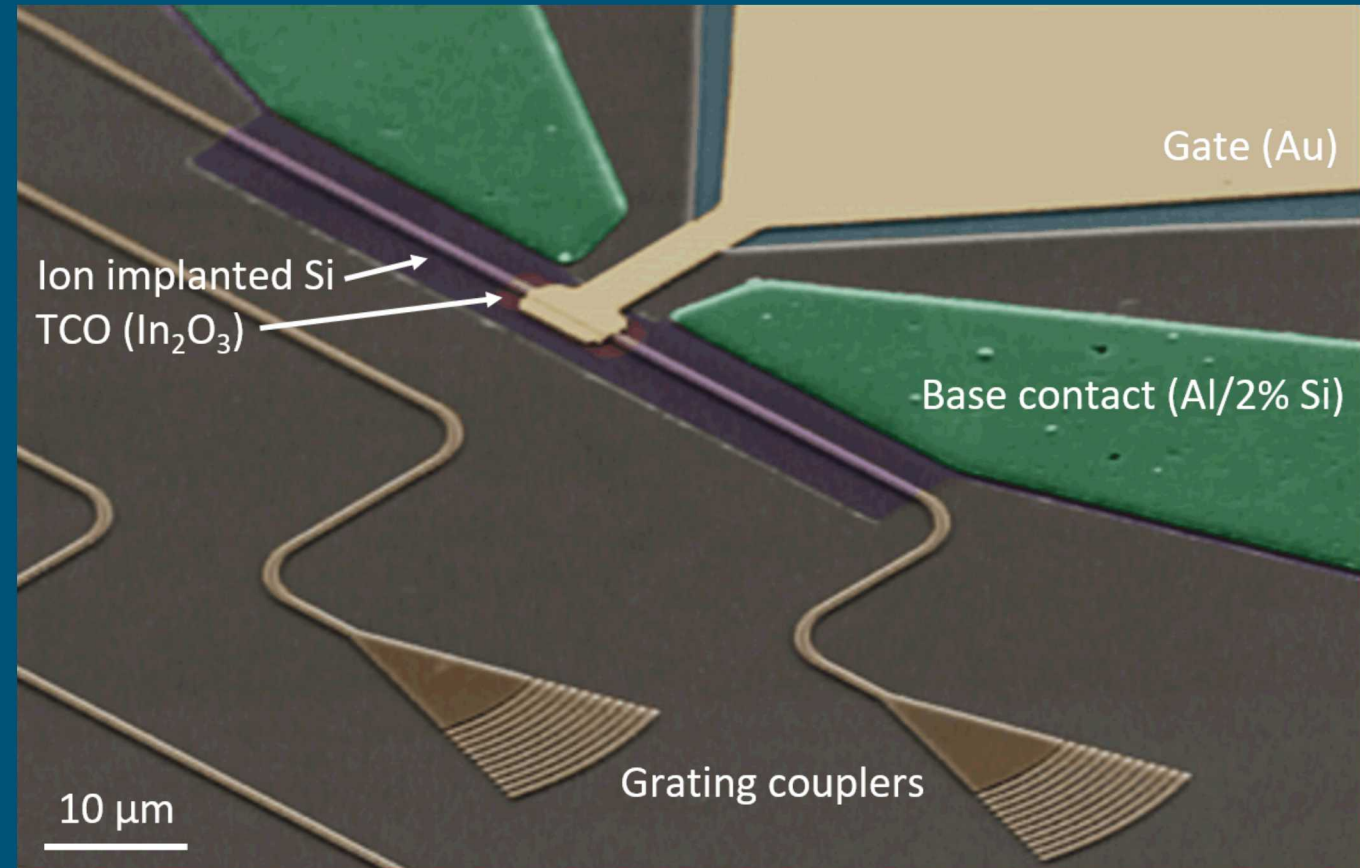
ENZ optical modulators structure



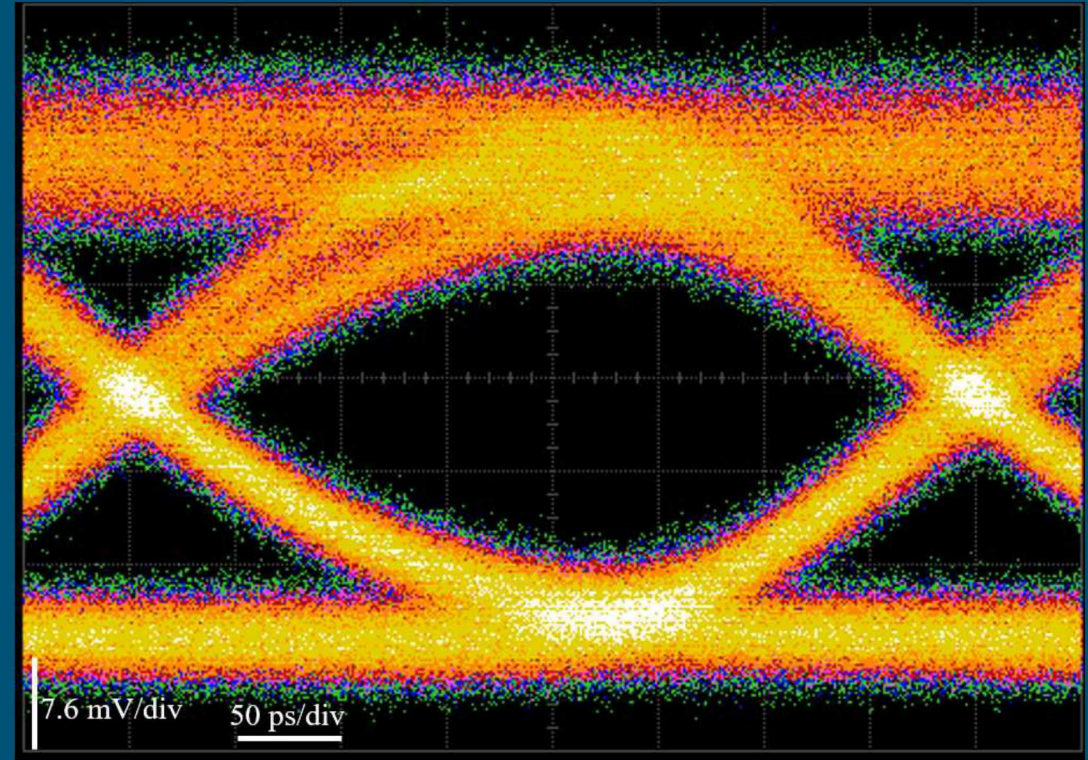
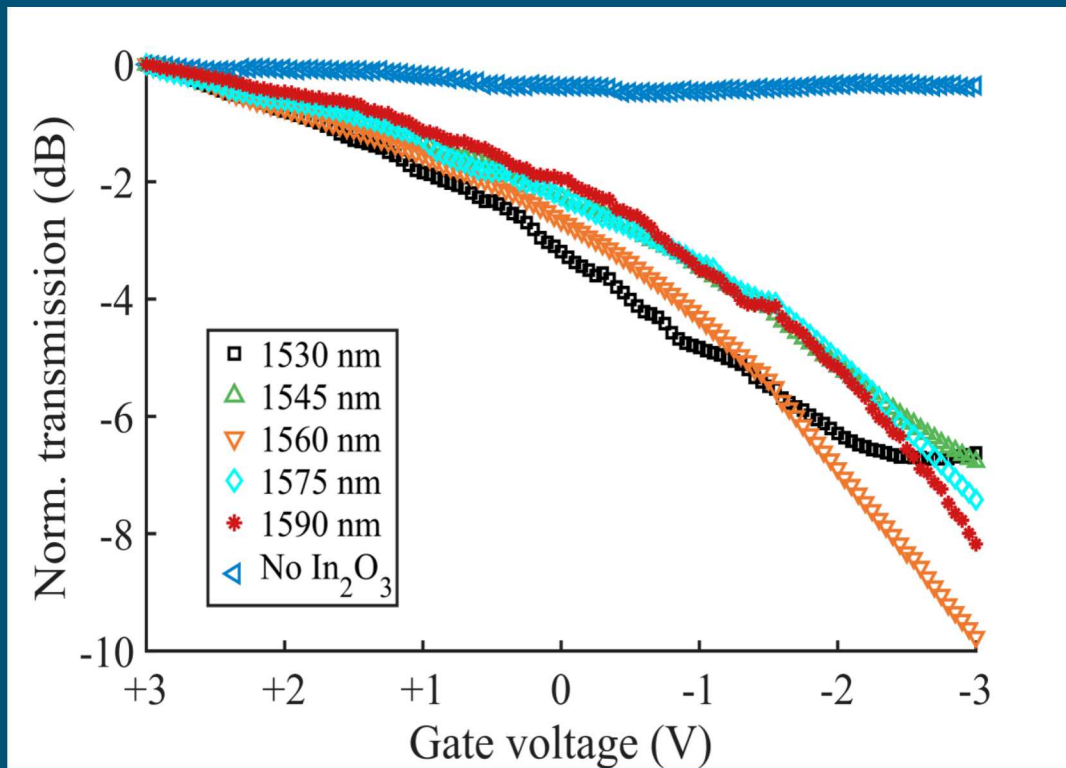
1st Generation In_2O_3 ENZ absorption modulator



CMOS compatible
 Free space coupling through grating
 Silicon waveguide: 290x400nm
 TCO: In_2O_3 10nm
 Gate oxide: Hafnia 5nm
 Length: 4 μm



Gigahertz In_2O_3 ENZ optical modulators



Bandwidth 1530-1590nm

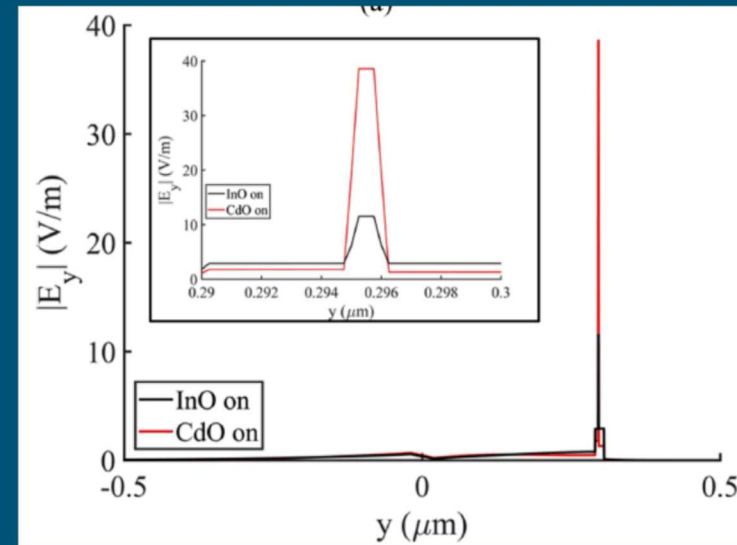
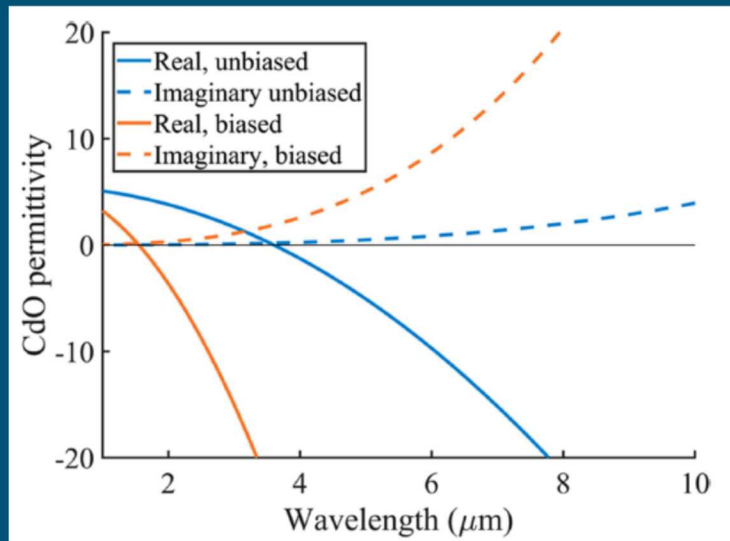
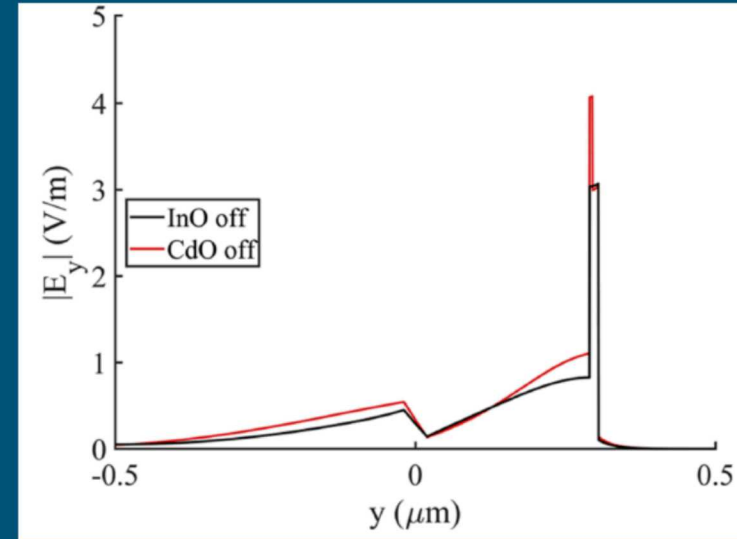
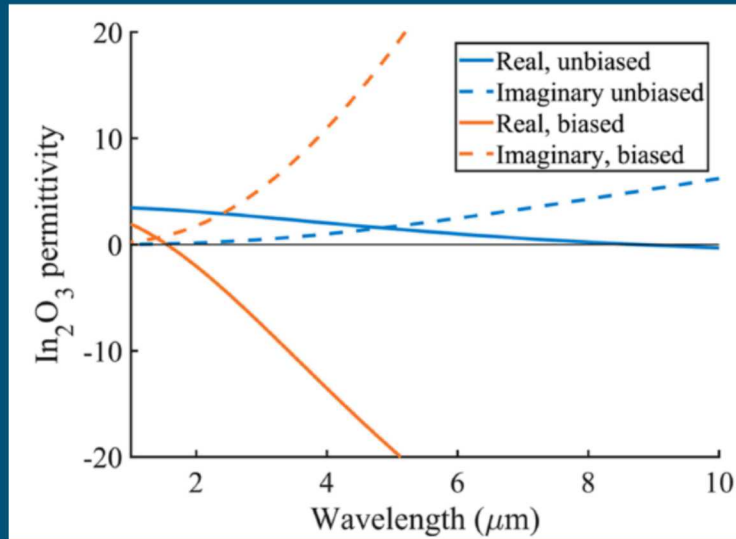
Speed: 2.5 Gb/s, RC limited

Extinction ratio: 6.5 dB in 4 μm for $6V_{pp}$ (1.6 dB/ μm)

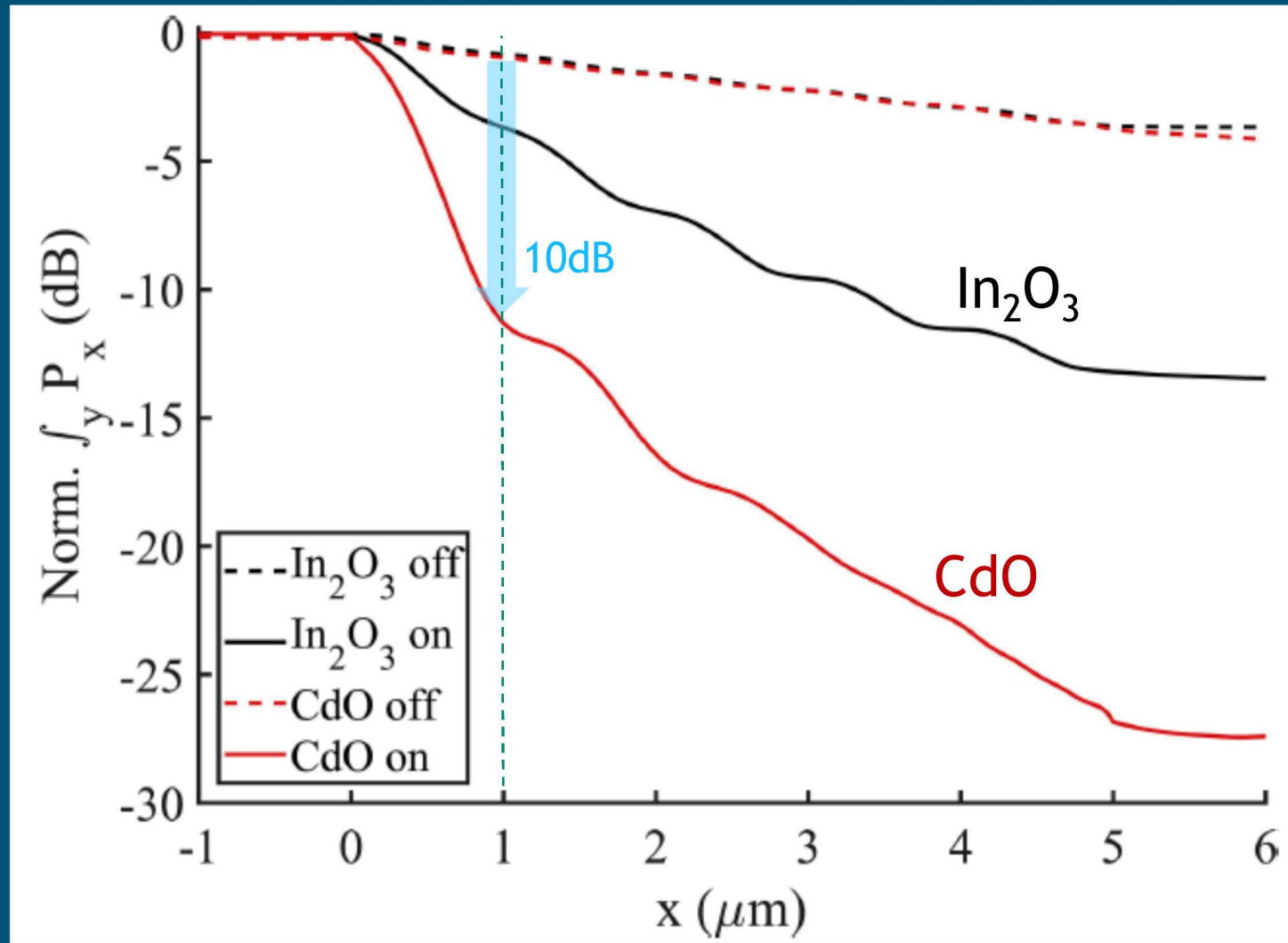
Drive voltage $2V_{pp}$

Absorption modulator: In_2O_3 and CdO

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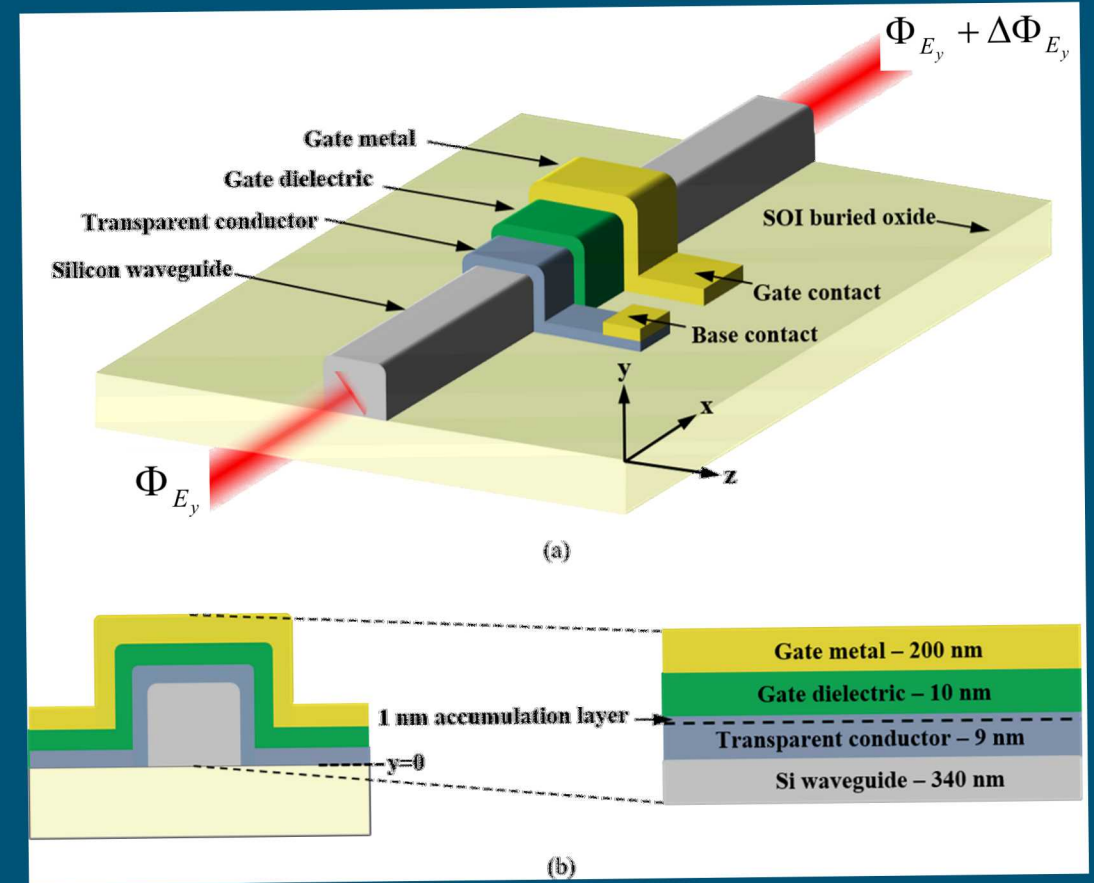
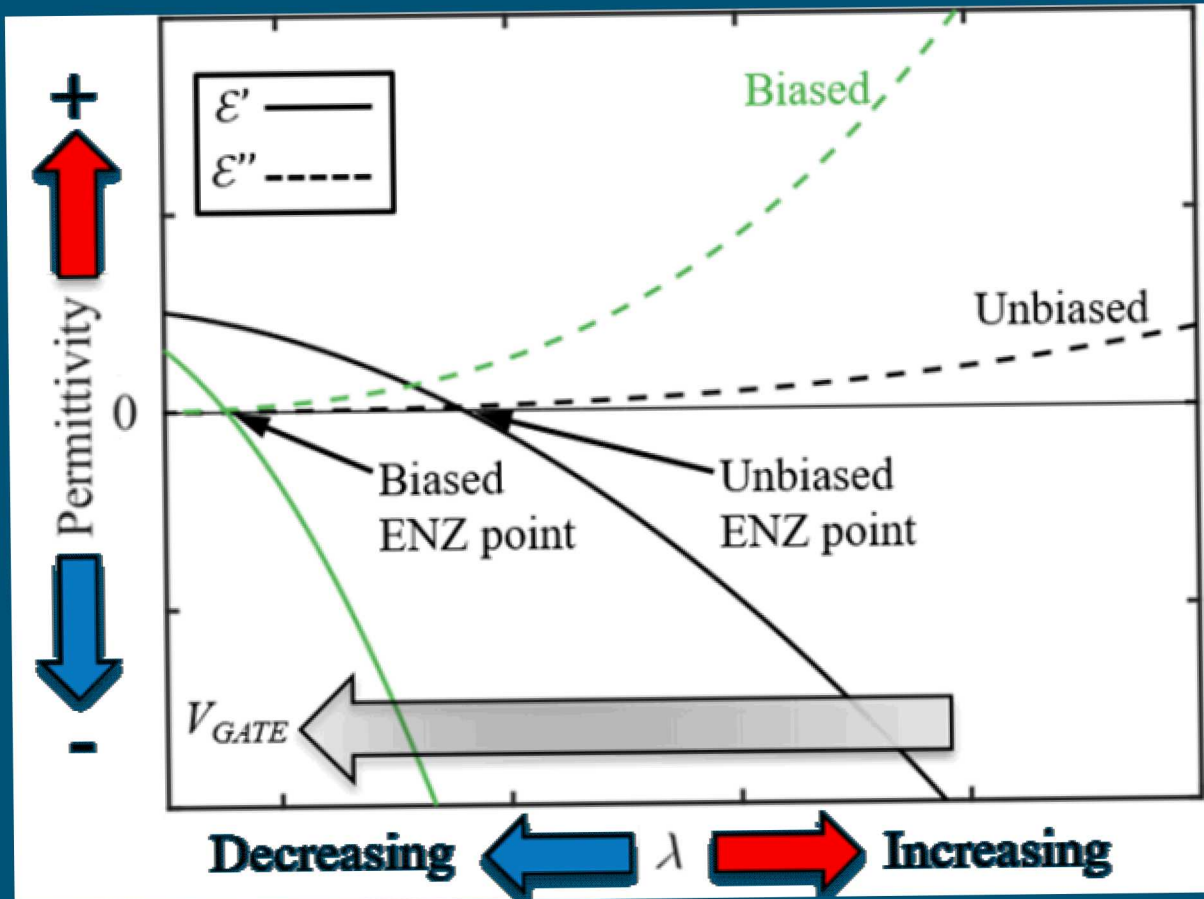


Absorption modulator: In_2O_3 and CdO

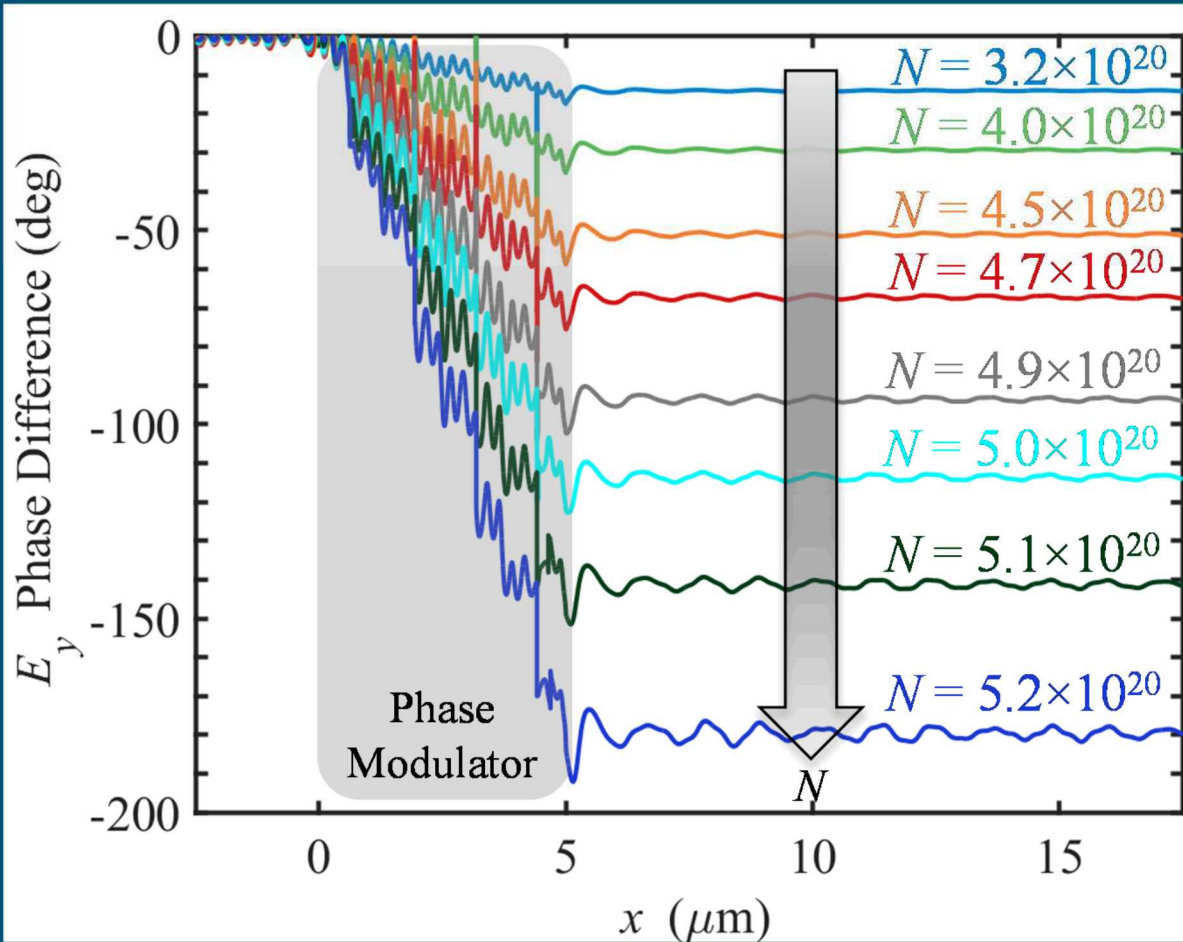


ENZ Phase modulator

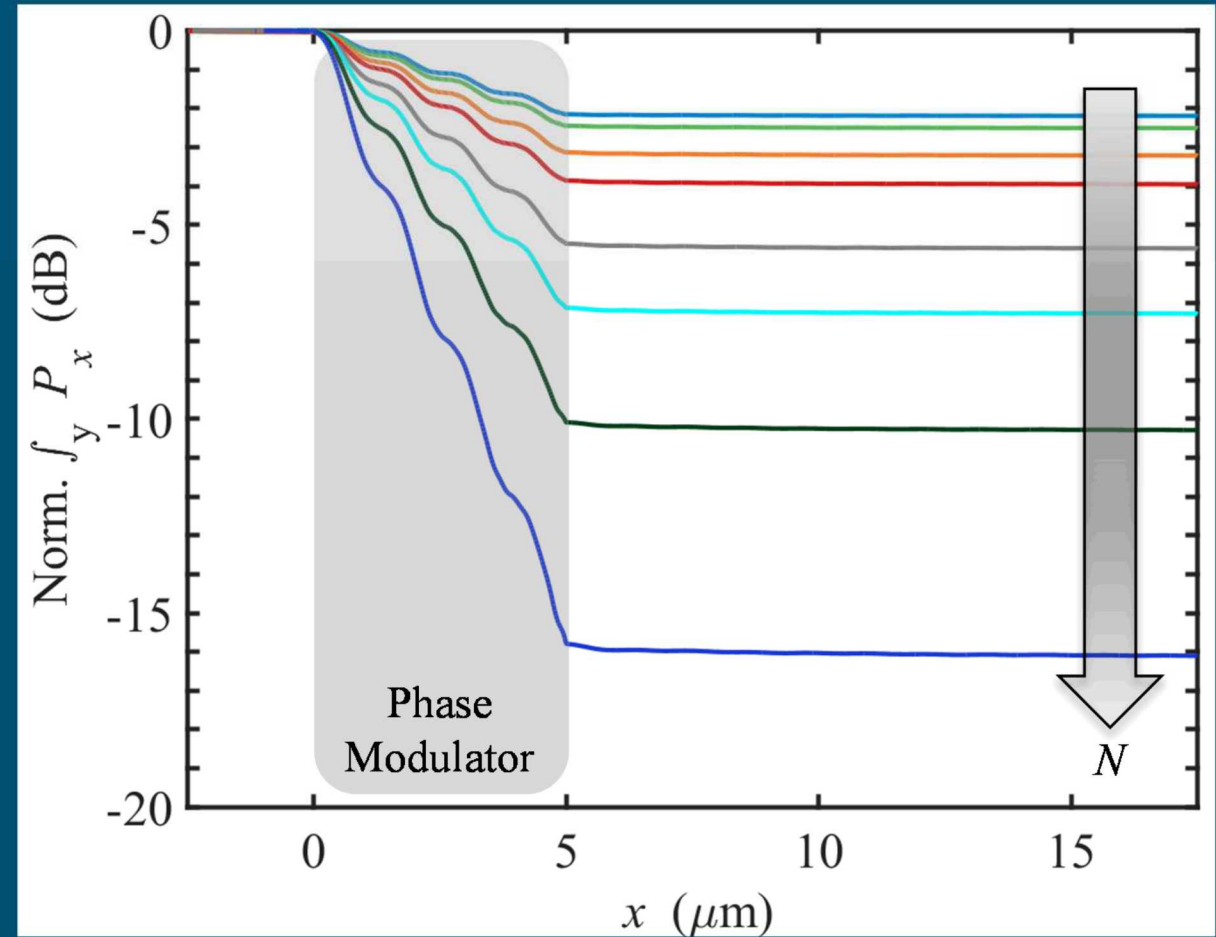
15



CdO phase modulator

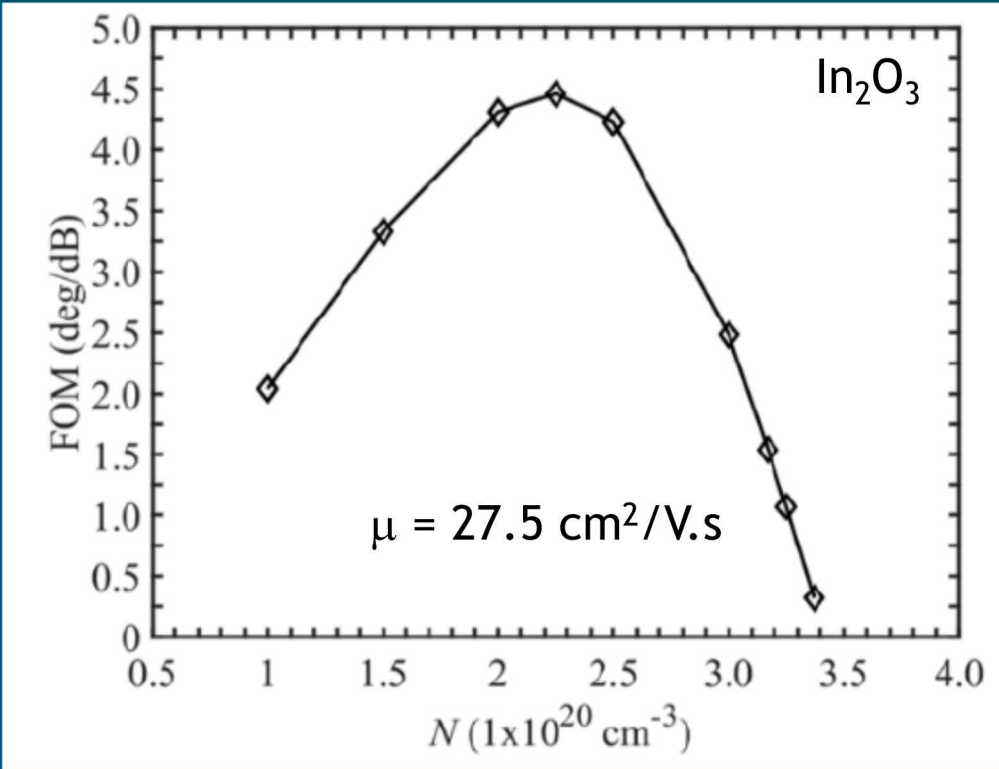


(a)

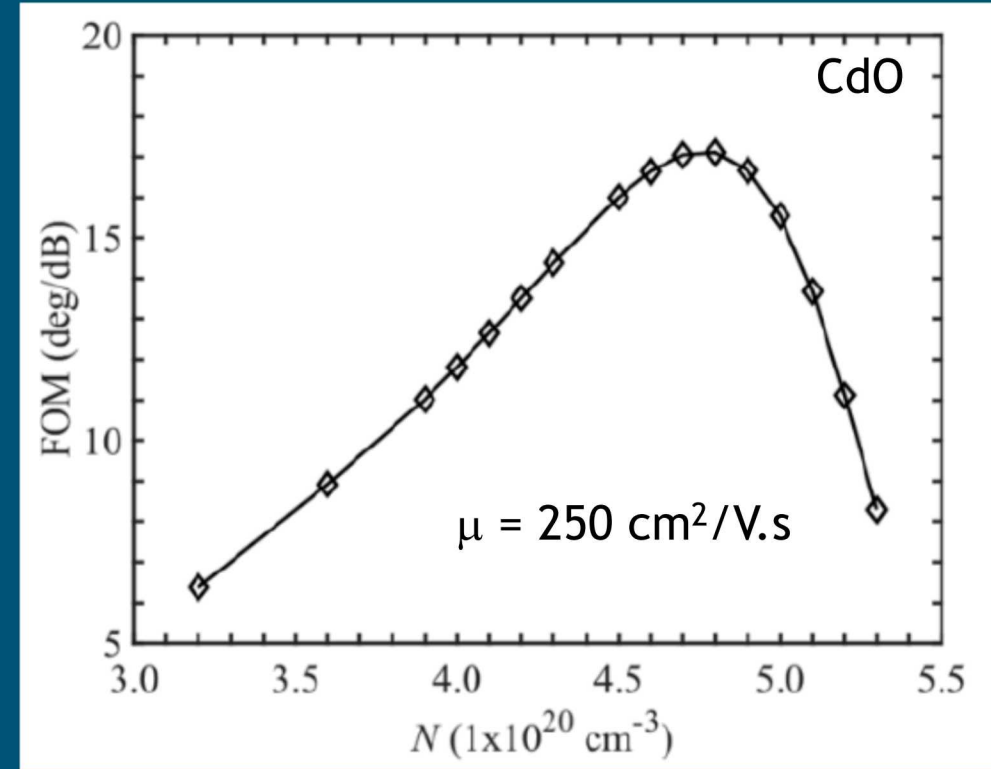


(b)

Comparison of In_2O_3 and CdO as phase modulator

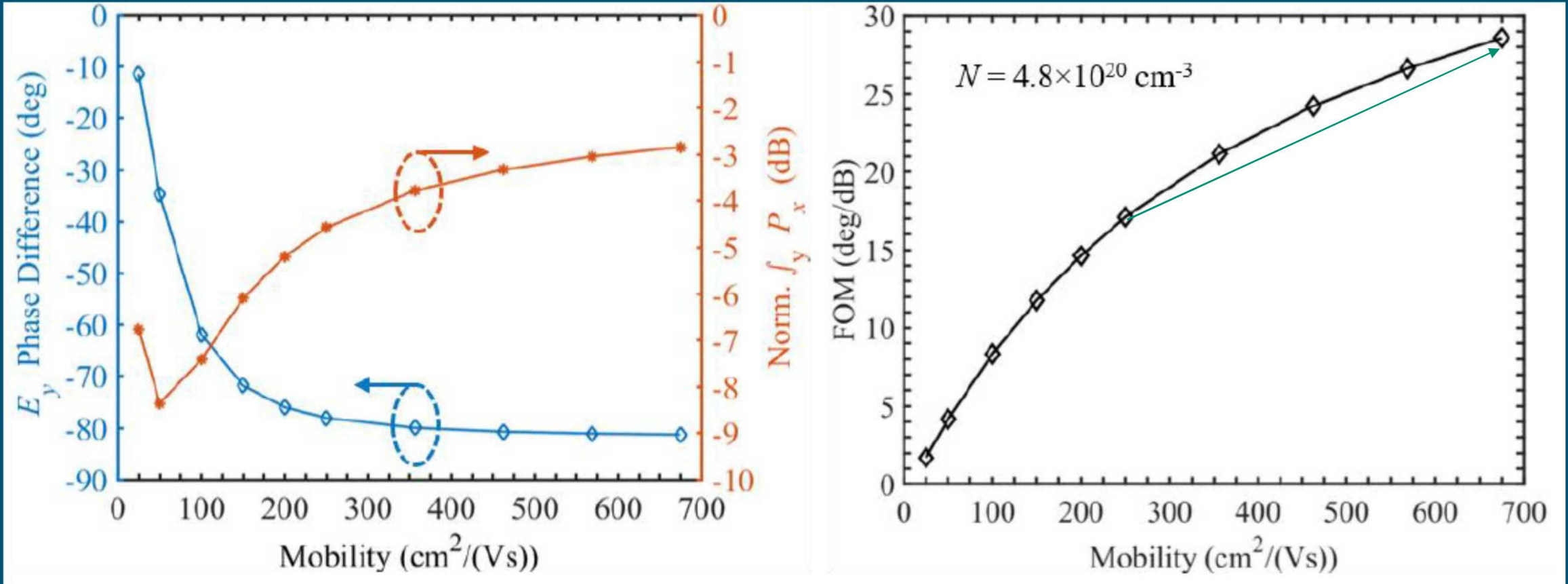


$V = 2.5 \text{ V}$, $L = 20 \mu\text{m}$
 $(VL)_\pi = 0.005 \text{ V.cm}$
 $(\text{Loss})_\pi = 40 \text{ dB}$
 $\text{FOM}' = 0.03 \text{ rad/dB/V}$



$V = 4.3 \text{ V}$, $L = 11.5 \mu\text{m}$
 $(VL)_\pi = 0.005 \text{ V.cm}$
 $(\text{Loss})_\pi = 10.52 \text{ dB}$
 $\text{FOM}' = 0.069 \text{ rad/dB/V}$

High mobility oxide impact



Summary

Absorption modulator	In2O3	CdO
Waveguide length (um)	4	1
Extinction (dB/um)	2.5	10
Capacitance (fF)	44	11
Bandwidth (GHz)	450	1800
Energy per bit (fJ)	400	100

Phase modulator	CdO	Plasmonic Organic Hybrid
Waveguide length (um)	10	5
Capacitance (fF)	110	5
Bandwidth (GHz)	180	1350
Energy per bit (fJ)	700	20
$(VL)_\pi$ [volt.um]	50	40
FOM [rad/dB/V]	0.07	0.095

CdO is a superb absorption modulator

CdO can be a viable phase modulator

- Without the stability issue of organic material.
- Simpler to fabricate.

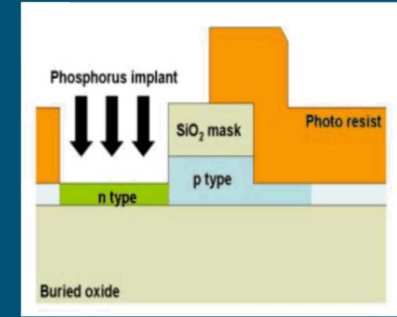
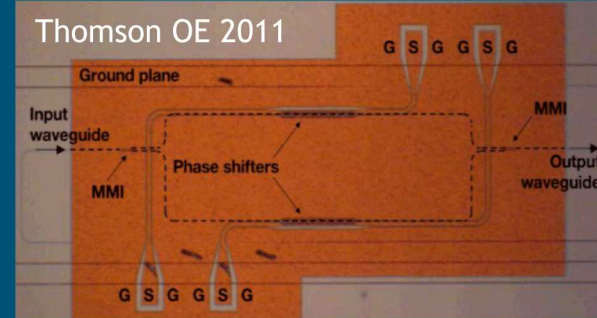
End



Selected modulator approaches

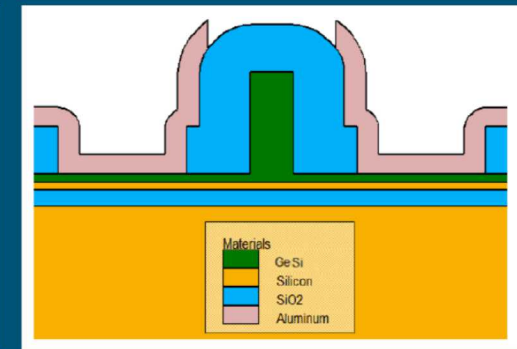
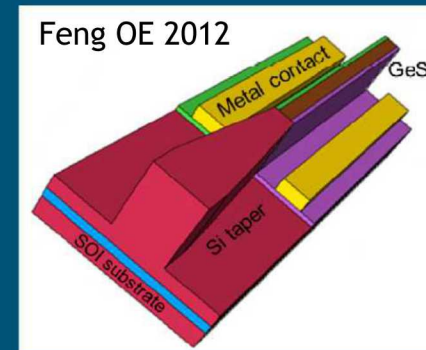
Plasma dispersion (carrier depletion in a pn junction) modulator

- 10 dB extinction
- 0.004 dB/ μm modulation, 0.0016 dB/ μm loss
- 40GHz
- 2.7 volts, half-wave modulation 2.7 volt.cm
- 2-5.3 pJ/bit



Electro-absorption (Franz-Keldysh effect) modulator

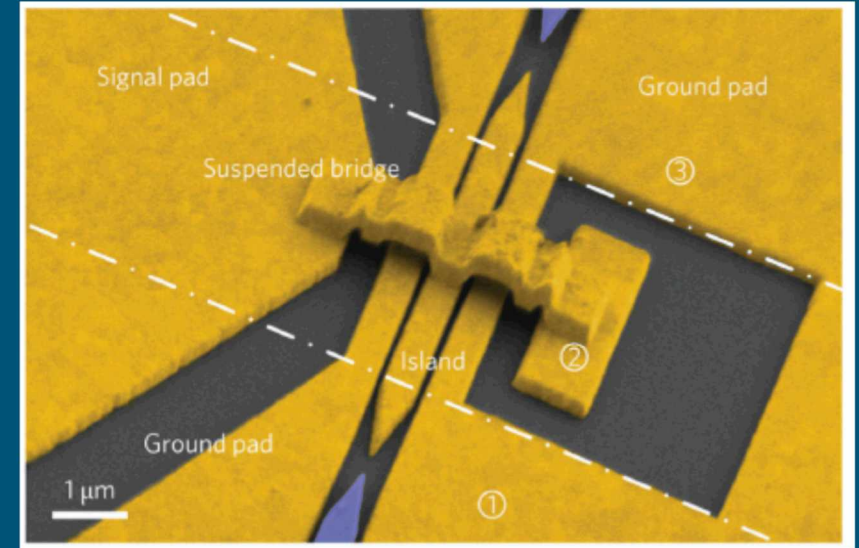
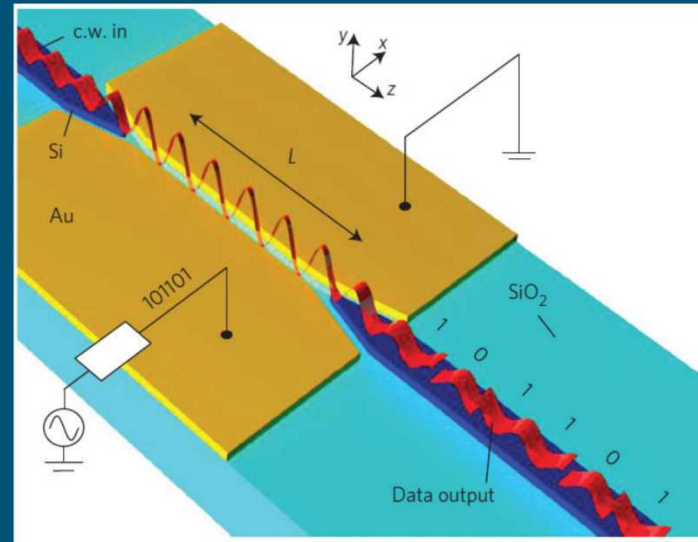
- 6 dB extinction
- 2.8 Volt, 3 μm



Plasmonic Organic Hybrid modulator scheme

Plasmonic-Organic-hybrid (Kerr effect) modulator

- 170GHz most recently
- 0.004 volt.cm (0.001 Volt.cm possible)
- 25 fJ/b (sub fJ/b possible)
- Extinction ratio 26 dB
- FOM' 0.095 rad/dB/V



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BER image from Wikipedia

