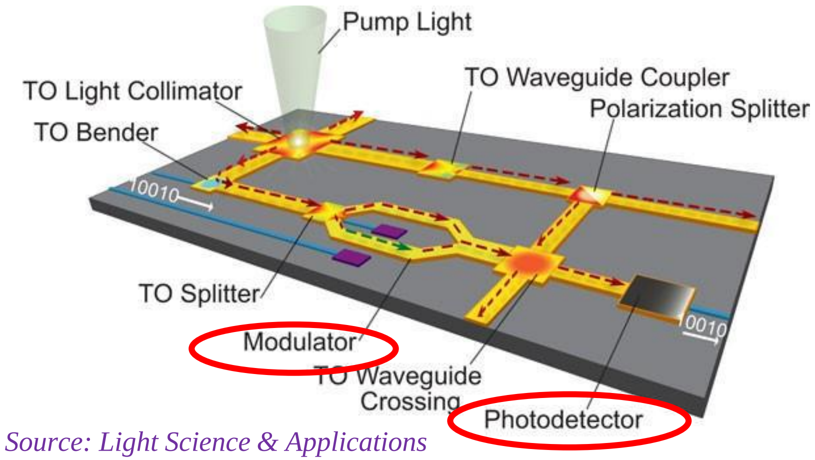
Integrated Photonic Devices

Photonics is the science and technology of generating, controlling, and detecting photons

Photonic Integrated Circuit



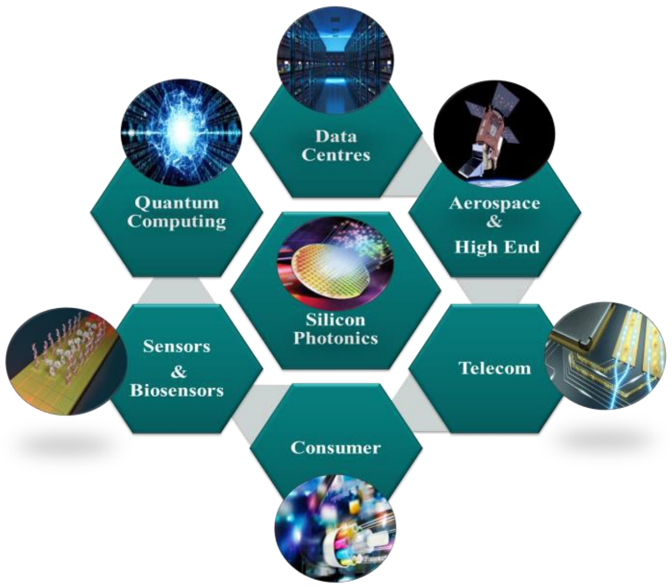
Source: Light Science & Applications

Why Photonics…????

- Improved EM interference immunity
- Increased bandwidth
- Expanded frequency division multiplexing
- Expanded multiple switching
- Small size and lower power consumption
- Improved optical alignment

Photonics and electronics integrated circuits are complementary and not competitive…!!!!

Silicon Photonics



Smart Integration of Electronics and Photonics

(Enable each technology to play to its strength)

CMOS's Density and ability to perform complex processing

+

Photonics outright speed and transmission capacity

Silicon photonics delivers all the components necessary to facilitate the transmission and reception of data

Why..??

Standard CMOS silicon-based fabrication techniques:

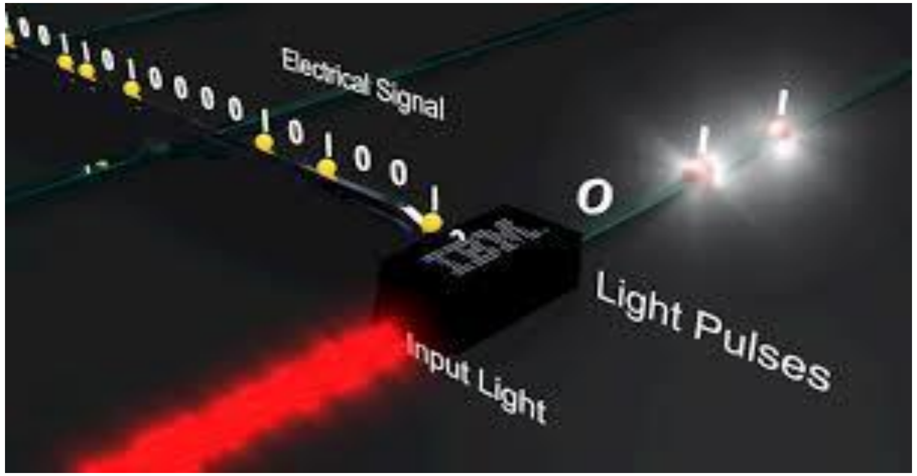
- Produces high volume, low cost components
- Integrate components at manufacturing stage removing need of expensive assembly of devices

Ref:

1. P. Cheben et.al., "Subwavelength integrated photonics," ***Nature***, vol. 560, no. 7720.
2. H. W. Hübers, "Terahertz technology: Towards THz integrated photonics," ***Nat. Photonics***, vol. 4, no. 8, pp. 503–504, Aug. 2010.
3. M. U. Khan et.al., "Photonic integrated circuit design in a foundry fabless ecosystem," ***IEEE J. Sel. Top. Quantum Electron.***, vol. 25, no. 5, Sep. 2019.
4. M. Paniccia, "Integrating silicon photonics," ***Nature Photonics***, vol. 4, no. 8. Nature Publishing Group, pp. 498–499, Aug. 2010.

Optical Modulator

An optical modulator is a device which can be used for manipulating a property of light (intensity, phase, etc..)



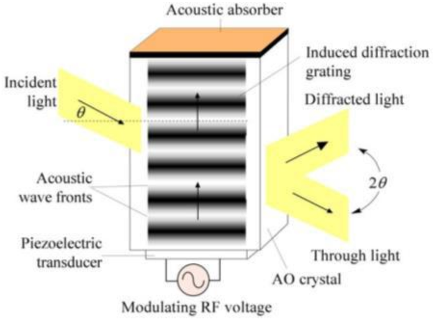
Source: www.semiwiki.com

Why Modulation…????

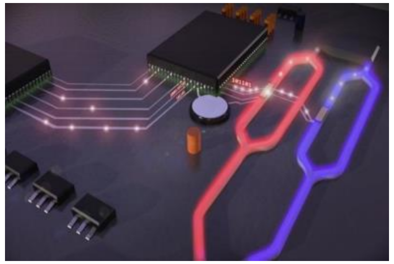
- Embedding the information on the optical carrier for data security
- Workhorses of the internet
- Enabling modern data communications
- Maximizing bandwidth
- Growth of smart cities
- Implementation of Internet of Things (IoT)
- Self-driving cars
- Telemedicine adoption

Optical Modulator

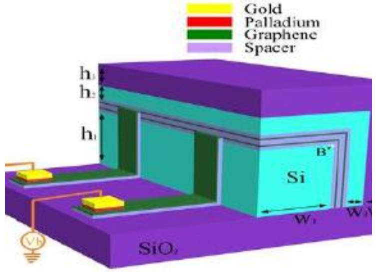
- **Acousto-optic Modulator**
- **Electro-optic Modulator** → **Phase**
- **Electro-absorptive Modulator** → **Intensity**



Source: Beam Q Laser



Source: Physics.org

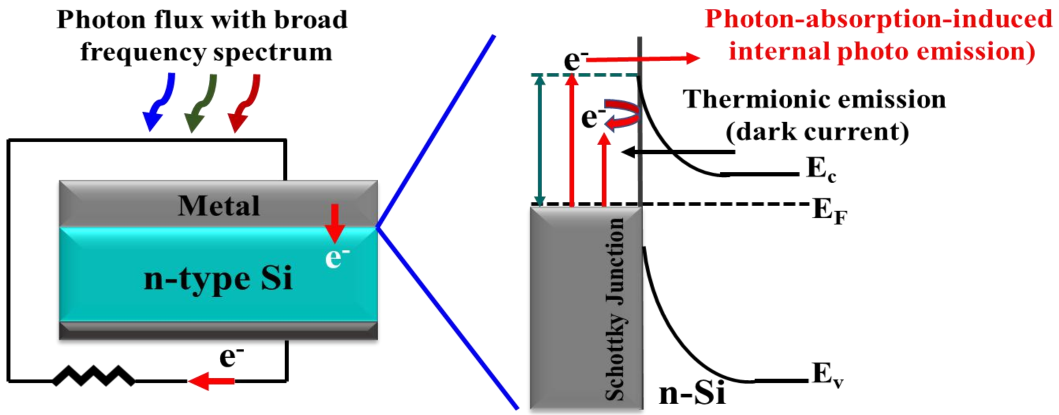


Source: Nature.com

Ref:

1. M. Lipson, "Guiding, modulating, and emitting light on Silicon - Challenges and opportunities," ***J. of Lightwave Technol.***, vol. 23, no. 12, 2005.
2. G. T. Reed et.al., "Silicon optical modulators," ***Nature Photonics***, vol. 4, no. 8. , Aug. 2010.
3. C. E. Png et.al., "Optical phase modulators for MHz and GHz modulation in silicon-on-insulator (SOI)," ***J. Light. Technol***., vol. 22, no. 6, Jun. 2004.
4. C. K. Tang et.al., "Highly efficient optical phase modulator in SOI waveguides," ***Electron. Lett***., vol. 31, no. 6, Mar. 1995.
5. R. A. Soref and B. R. Bennett, "Electrooptical effects in silicon**," *IEEE J. of Quantum Electronics***, vol. 23, no. 1., 1987.

Silicon based Sub-bandgap Photodetector



Internal Photoemission (IPE)

- Metal-semiconductor Schottky junction for infrared detection
- Optical excitation of electrons in the metal to the energy greater than the Schottky barrier height

(ϕ_{SBH} <Photon Energy)

- Transports the electrons to the conduction band of the semiconductor

Drawback of Metal/n-Si Schottky junction-based Photodetector

- ***Low responsivity and quantum efficiency:*** Metal reflects most of the light of wavelength above 1100 nm
- Thin metal layer: high series resistance as well as poor adhesion
- ***Momentum imbalance:*** reflection of excited charge carriers in place of emission
- Incoming light excites the carriers which lie far below the fermi level
- Difficult for the charge carrier to cross the metal-semiconductor potential barrier

How to Overcome..??

✓Replacing metal with transparent conducting oxides (TCO's)

✓TCO's: Indium Tin Oxide (ITO) => most potential candidates to replace metal in Schottky photodetectors

✓IPE: **ϕ_{SBH} <Photon Energy;**

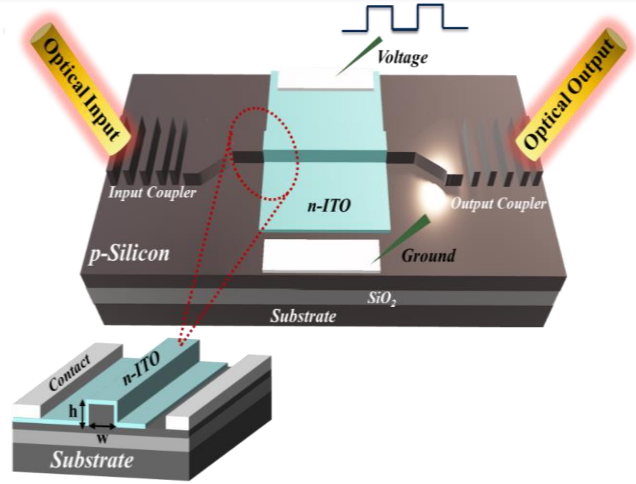
ϕ_{SBH} (ITO/n-Si)=0.45 eV < 0.8 eV

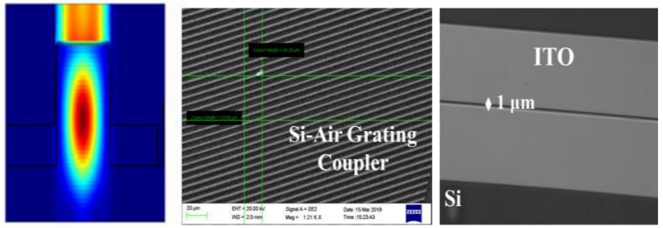
✓ ITO with good carrier concentration integrated with Si

Ref:

1. S. Muehlbrandt *et al.*, "Silicon-plasmonic internal-photoemission detector for 40 Gbit/s data reception," ***Optica,*** vol. 3, no. 7, Jul. 2016.
2. M. Casalino et.al., "Silicon resonant cavity enhanced photodetector based on the internal photoemission effect at 1.55 μm: Fabrication and characterization," ***Appl. Phys. Lett.***, vol. 92, no. 25, Jun. 2008.
3. M. Alavirad et.al., "High-responsivity sub-bandgap hot-hole plasmonic Schottky detectors," ***Opt. Express***, vol. 24, no. 20, Oct. 2016.
4. B. Desiatov et.al., "Plasmonic enhanced silicon pyramids for internal photoemission Schottky detectors in the near-infrared regime," ***Optica***, vol. 2, no. 4, Apr. 2015.

Optical Modulation in Composite Waveguide based on Si-ITO Heterojunction





$$\Delta n = \frac{-e^2\lambda_0^2}{8\pi^2 c^2 \varepsilon_0 n}\left(\frac{N_e}{m_{ce}^*} + \frac{N_h}{m_{ch}^*}\right) \;\&$$

$$\Delta\alpha = \frac{e^3\lambda_0^2}{4\pi^2 c^3 \varepsilon_0 n}\left(\frac{N_e}{\mu_e (m_{ce}^*)^2} + \frac{N_h}{\mu_h (m_{ch}^*)^2}\right)$$

$$\Delta\phi = 2\pi \Delta n_{eff} L_\pi / \lambda_0$$

$$\alpha = 4\pi k_{eff}/\lambda$$

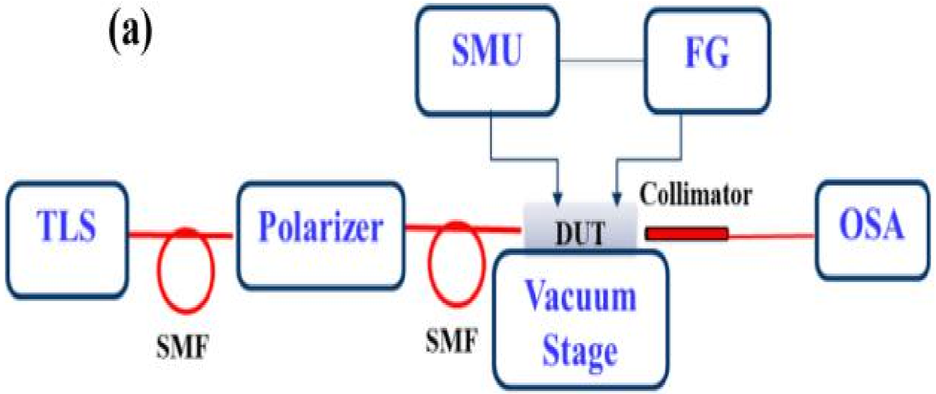
$$ER = 4.343[\alpha(0) - \alpha(V)]L$$

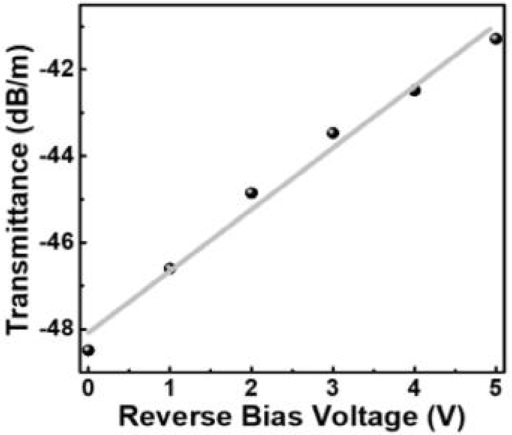
Characterization of Si-ITO Heterojunction

Carrier Concentration: 0.89×10^{19} /cm^3	Carrier Concentration: 5.02×10^{19} /cm^3	Carrier Concentration: 1.57×10^{20} /cm^3

- ITO Deposition at different oxygen partial pressure (3.5 sccm to 0.5 sccm) ➔ in order to vary carrier concentration
- Deposition Technique: Ion Assisted e-beam deposition

Measurement of Modulation Characteristics



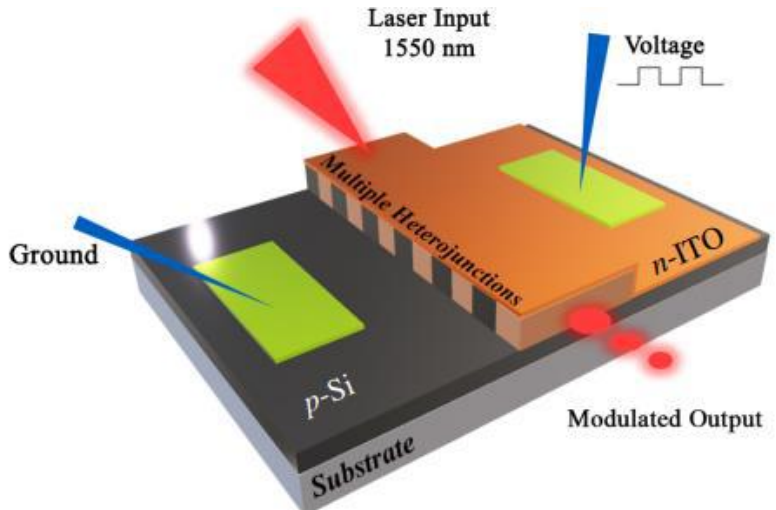


Findings

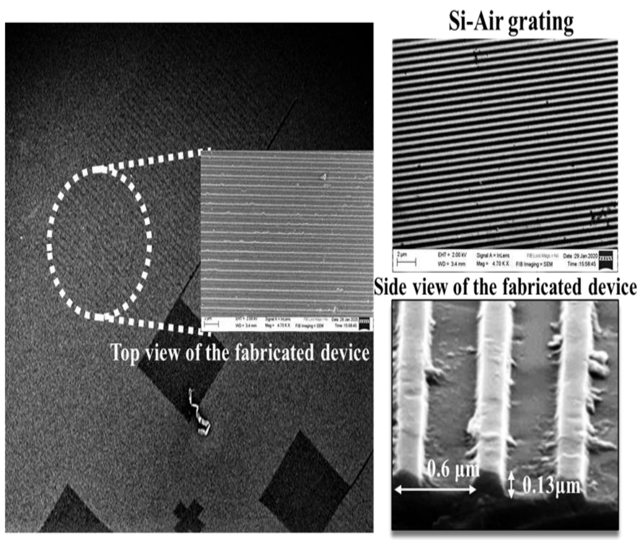
- Increase in transmittance with increasing reverse bias voltage
- **Extinction Ratio:** 7 dB for 1 mm long device
- Potential for phase modulation and photodetection

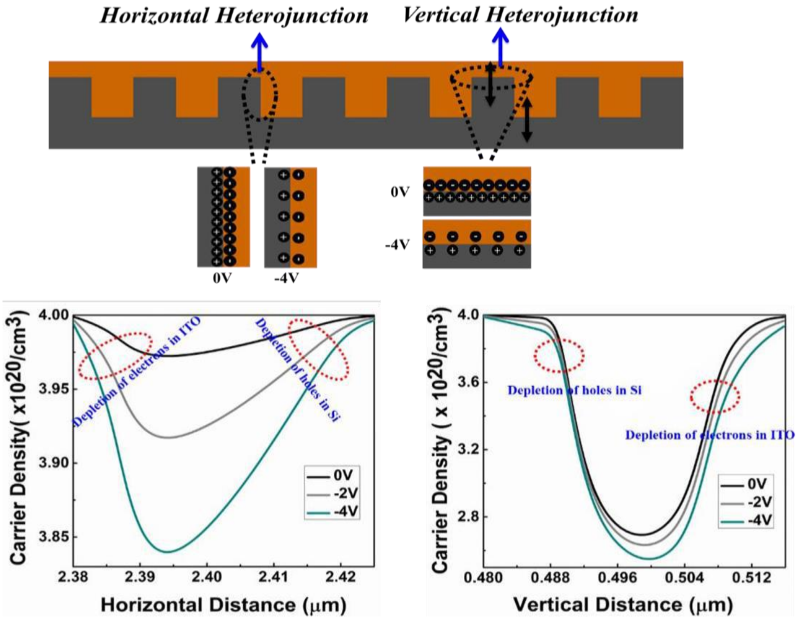
S. Rajput et. al., Journal of Lightwave Technology, vol. 38, no. 6, pp. 1365-1371, March 2020. (I.F.-4.7

Optical Modulator based on Distributed Heterojunctions



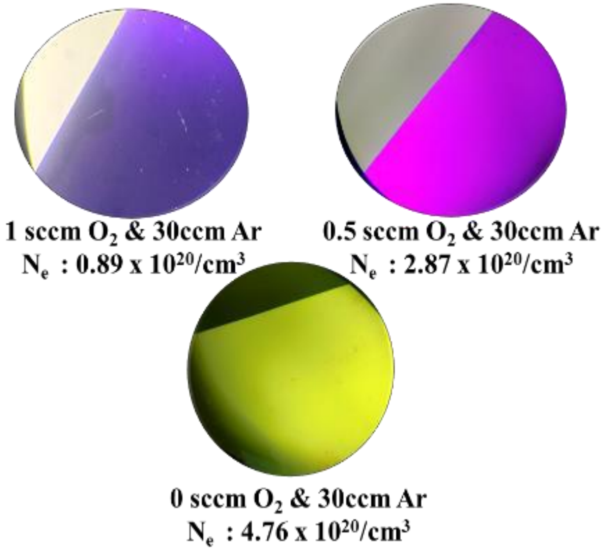
Enhanced light matter interaction

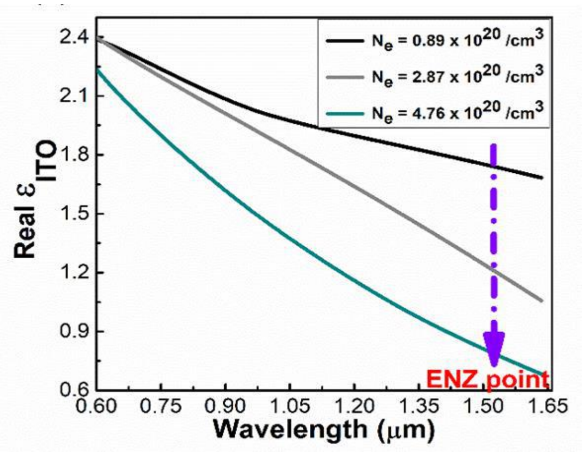


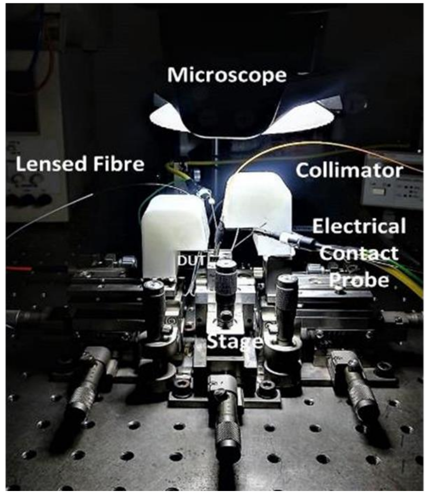


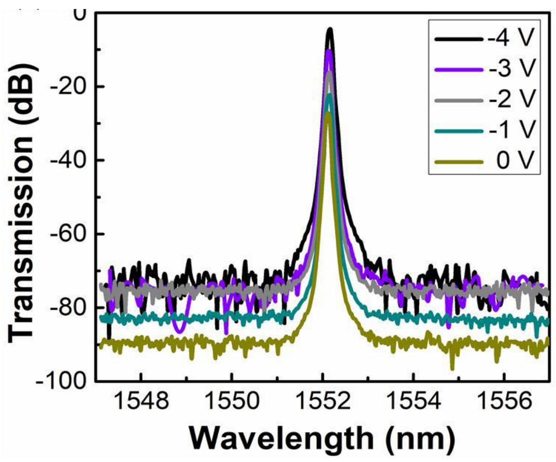
Analysis of Epsilon Near Zero Condition

Optoelectronic Measurements



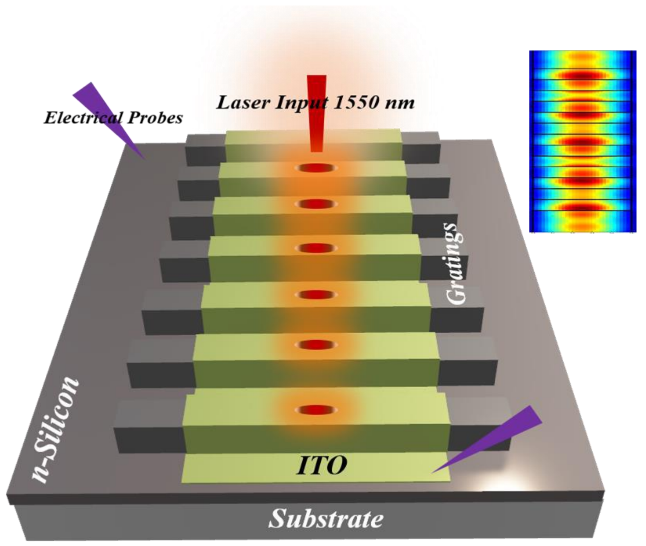


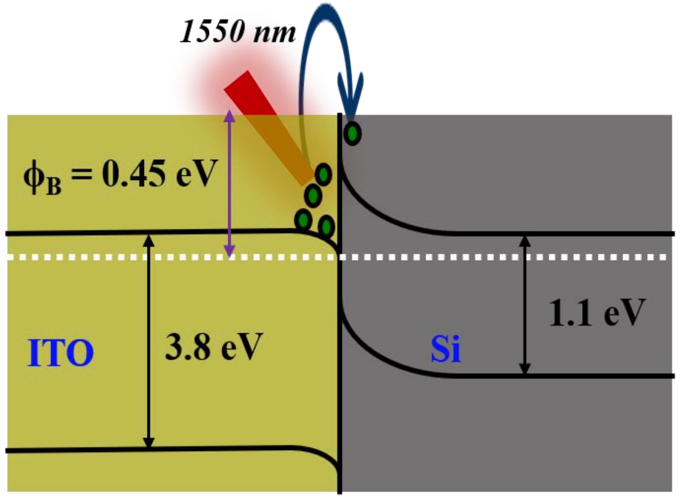


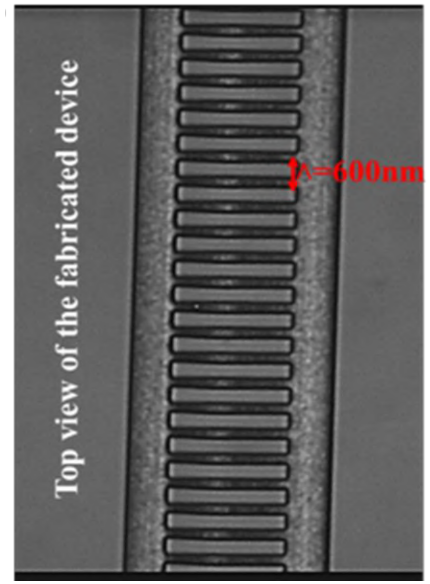


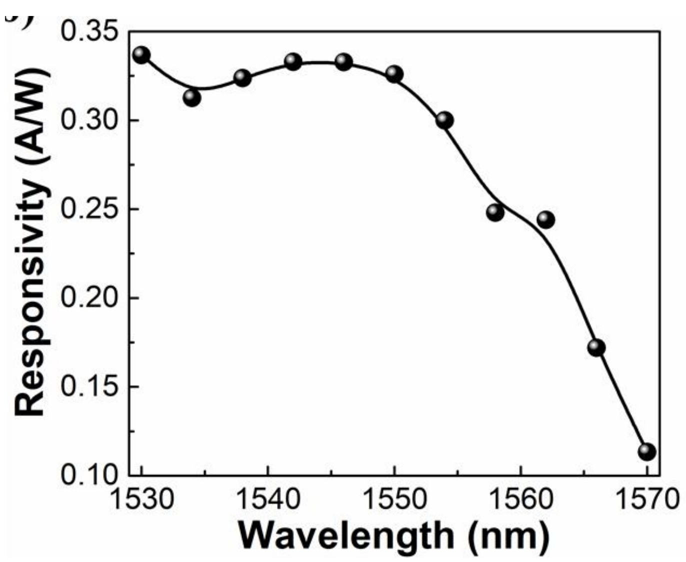
S. Rajput et. al., Physical Review Applied, vol. 15, no. 5, pp. 54029, May 2021. (I.F.-4.985)

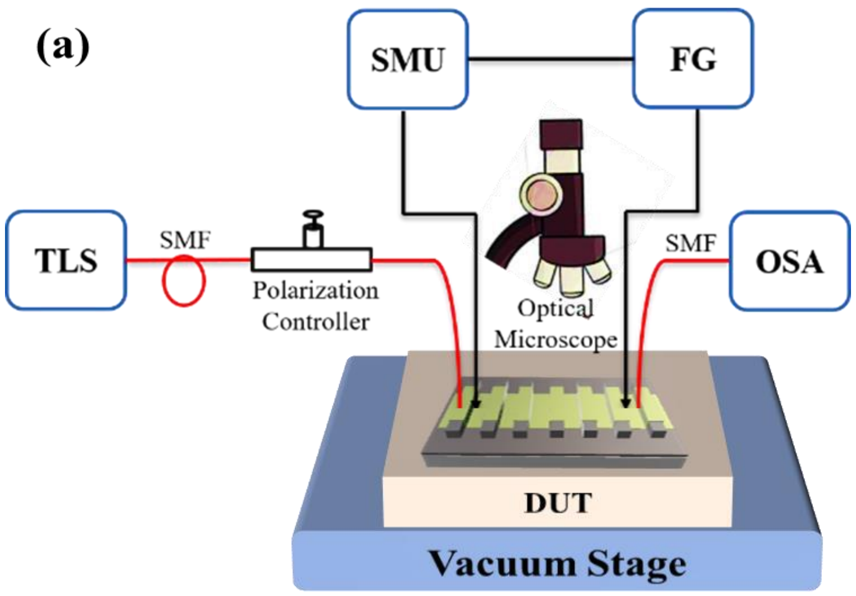
Photodetector using Sub-bandgap Transition in Si-ITO Heterojunction



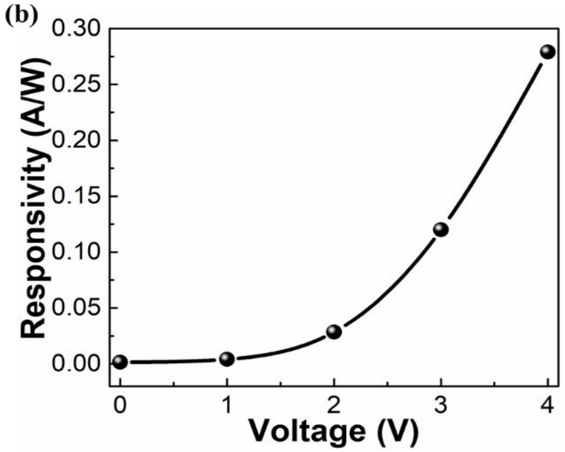




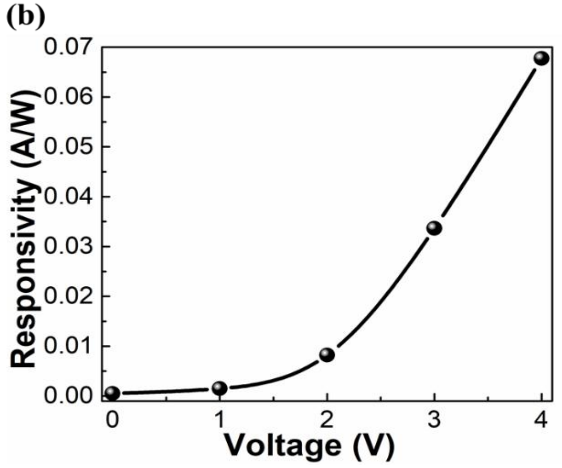




Si-ITO Distributed-Heterojunction

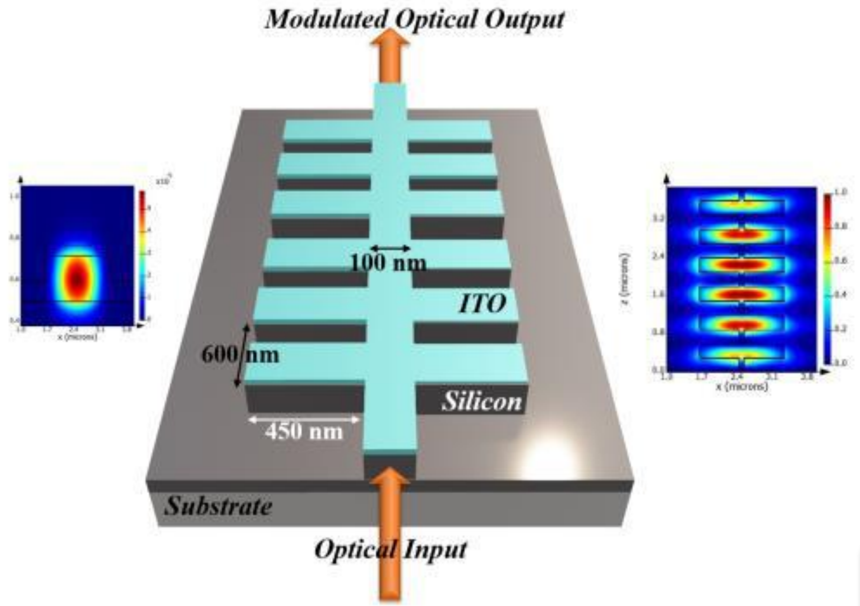


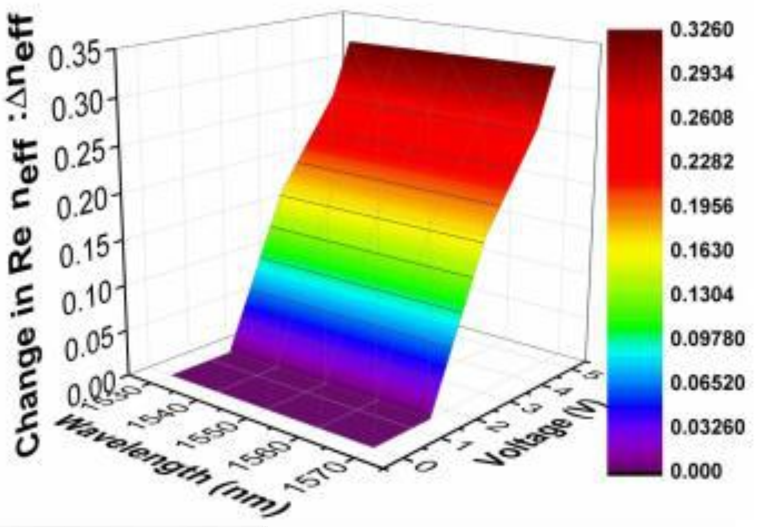
Si-ITO Planar-Heterojunction

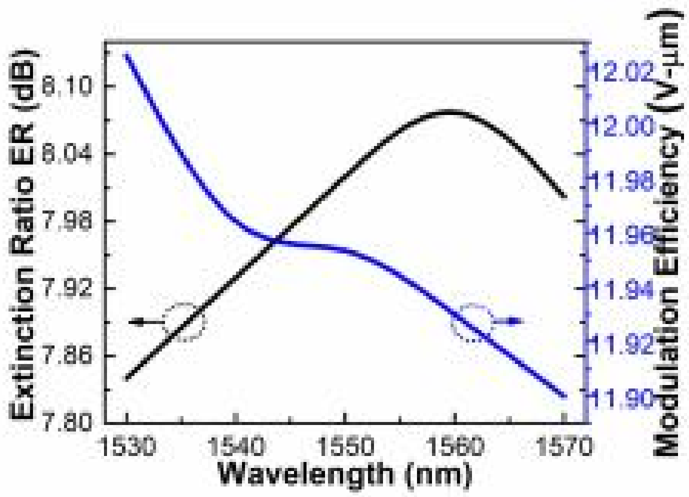


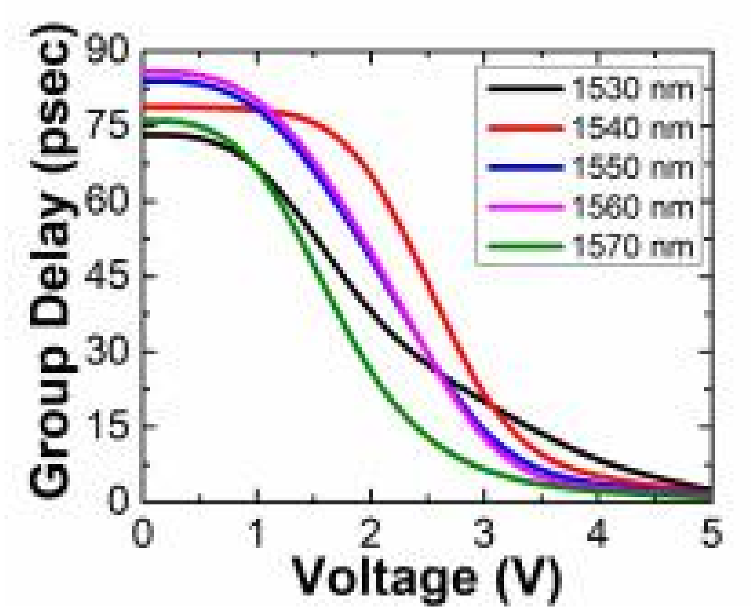
S. Rajput et. al., Journal of Lightwave Technology, vol. 39, no. 21, pp. 6886-6892. (I.F.-4.439)

Optical Modulator based on Si-ITO Grating Embedded Rib Structure







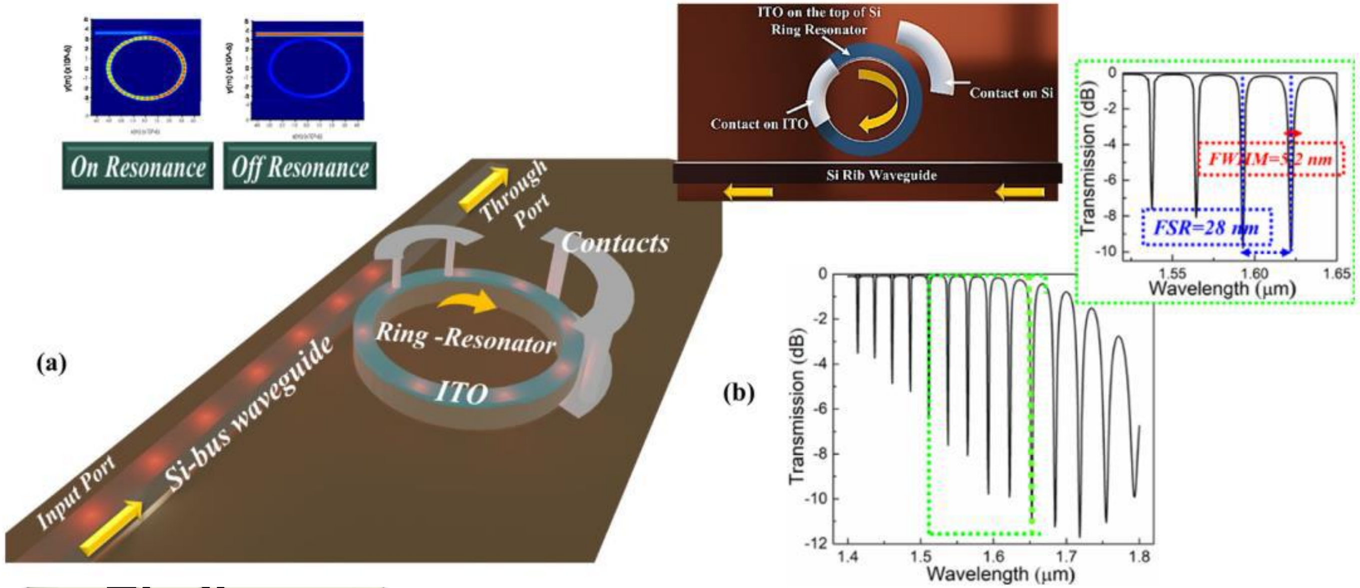


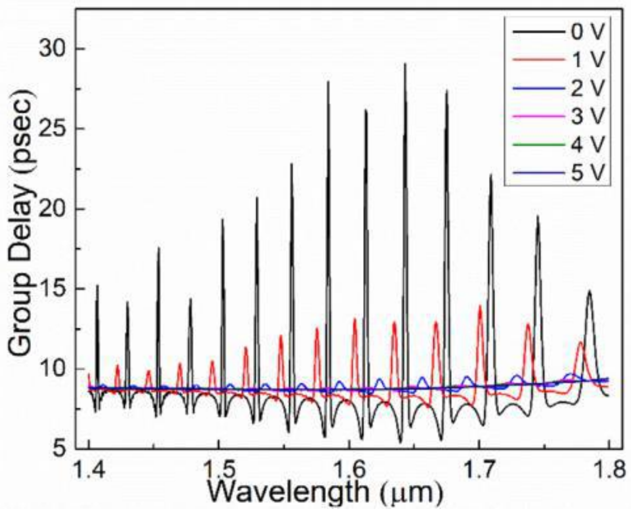
Findings

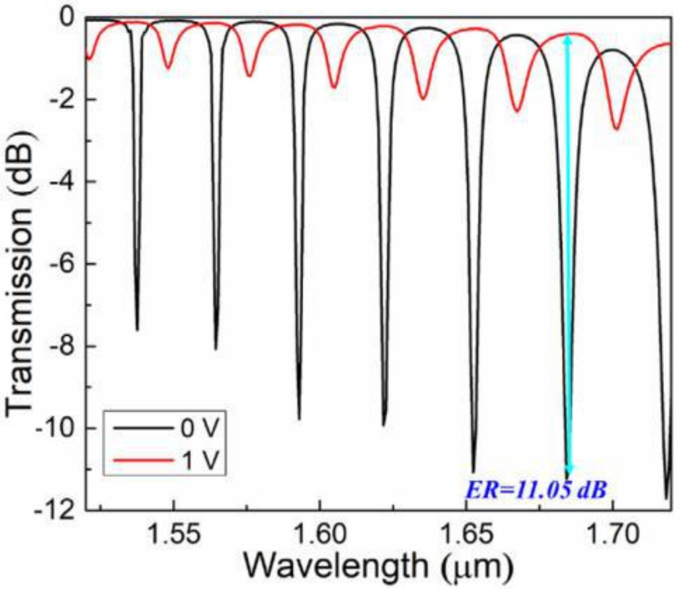
- Slow-light effect arising from the optical confinement in the small mode volumes increases the light-matter interaction and yields a larger group delay
- ITO's electrical tuning along with larger group delay ➔ efficient slow light enhanced optical modulation
- Extinction-ratio over 8 dB (for 10 μm long device)
- Modulation efficiency $V_\pi L$ around 12 V-μm for 1530 -1570 nm wavelength
- Active control of slow light
- Electrical tuning in group delay of 82 ps

S. Rajput et. al., Optics Letters, vol. 46, no. 14, pp. 3468-3471, June 2021. (I.F.-3.56)

High Extinction Ratio and Low Voltage Ring Modulator based on Si-ITO Heterojunction







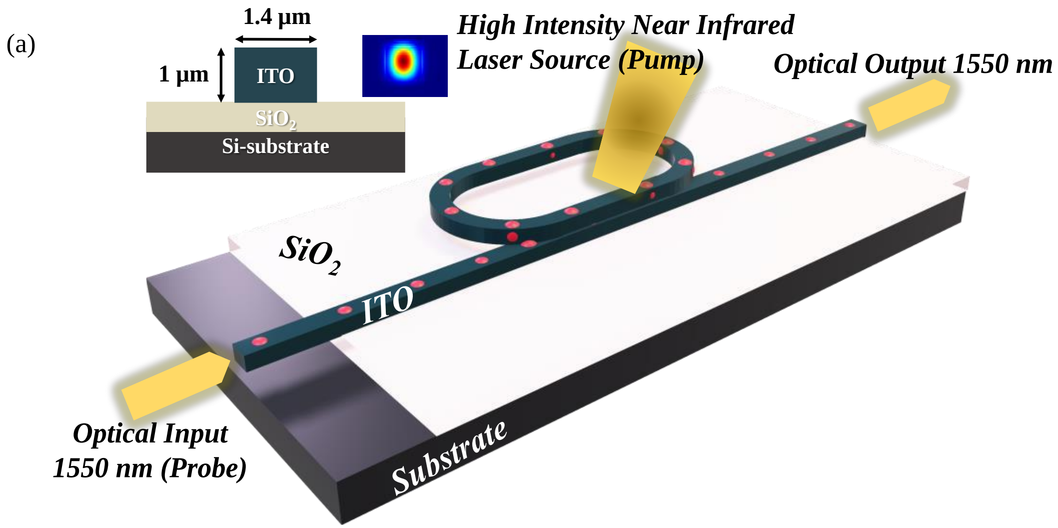
Findings

- The resonance condition shifts because of the ENZ state, and the transmission at the ring resonator's through port changes dramatically.
- Extinction ratio (ER) of 11 dB at a low forward bias of 1 V with a low energy consumption of 2.6 fJ
- Fulfills the non-trivial demand of an optical network
- Ring modulator with a high extinction ratio at low driving voltage outperforms conventional waveguide-based modulators in terms of energy efficiency

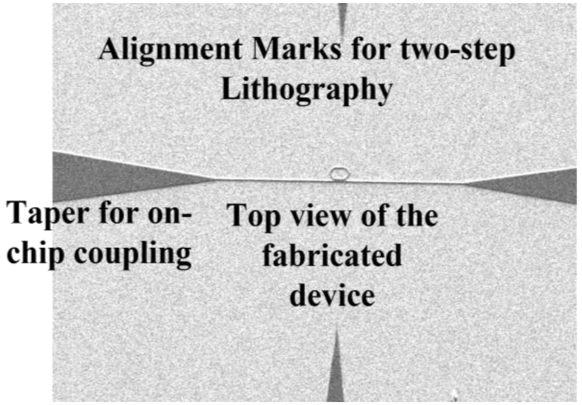
S. Rajput et. al., Optics Comm, vol. 545, pp. 129562, May 2023. (I.F.-2.3)

All Optical Modulation in ITO Ring Resonator employing ENZ state

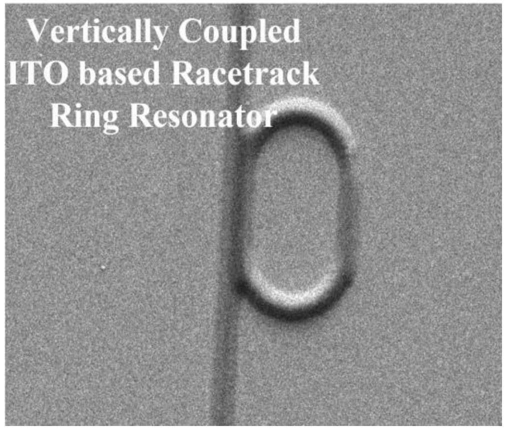
(a)



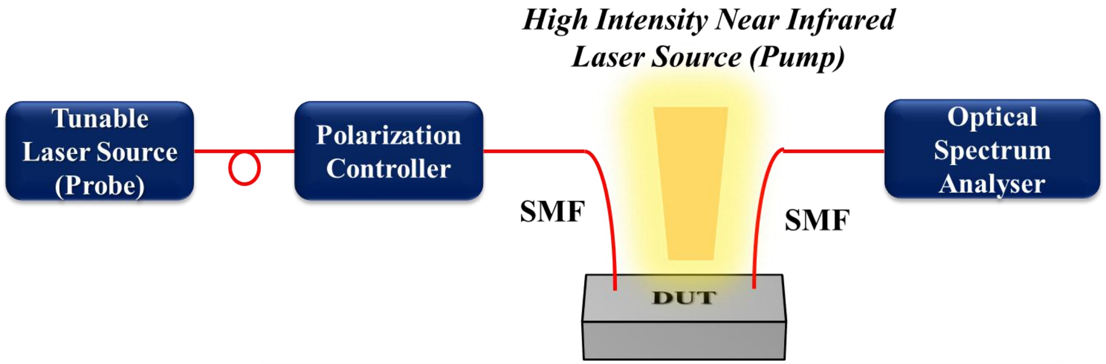
(b)

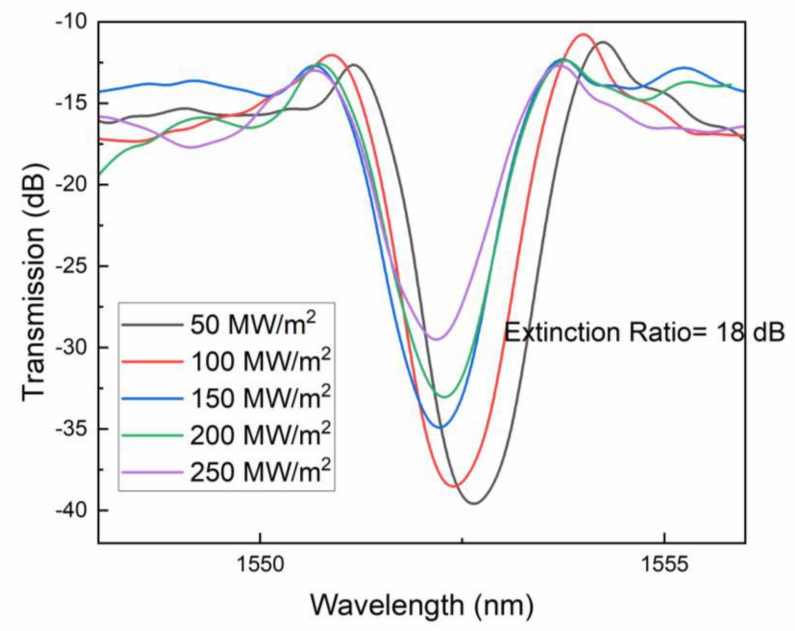


(c)



All-Optical Measurements





S. Rajput et. al., Nature Scientific Reports, vol. 13, 18379, October 2023. (I.F.-4.6)

Research Expertise

Design & Simulation:	Nanofabrication	Measurement & Testing
Lumerical Mode, FDTD, Charge Transport Solver	**Lithography:** Maskless Lithography & Electron beam Lithography	Optical fiber and electrical probe system
Fimmwave/Fimprop	**Etching:** Reactive Ion Etching & Wet Etching	**Thin-film measurement and characterization** (Ellipsometry, XRD, XRR, Hall Effect, Spectroscopy)
GSolver	**Deposition:** Sputtering, Ion-Assisted e-beam Deposition	**Electro-optic measurement** (modulation depth, speed, I-V, Tx line, etc.).
Klayout, LEdit and Clewin for Mask designing of Nanodevices		**Imaging:** SEM, AFM, Confocal & Optical microscopy

- **Hands on experience with cleanroom facilities at RRCAT Indore**
- **Lab development and maintenance for lithography facility at IIT Indore**
- **Hands on experience with cleanroom facilities at the Quantum Nanofabrication Centre (QNC), University of Waterloo**
- **Global Foundries Exposure CMC Microsystems and AIM Photonics**