(Silicon) Photonic Integrated Circuit Ecosystem in India: Opportunities and Challenges

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Indian Institute of Science Bangalore at a Glance

#1 university (2016-2023)
#1 in research (2021-23)

#223 (2024), **#155 (2023)**
#1 in citations per faculty (2022-2023)
 # 1 in India (2023)

#201-250 World University Ranking (2024)
#**32** Asia University Rankings (**2024**)
#101-125th World Reputation Rankings 2023
#1 in India (2015-2024)

4500+ STUDENTS ON ROLL

2000+ PUBLICATIONS/YEAR

700+ COURSES

500+ FACULTY & SCIENTIFIC STAFF

Institution of Eminence (IoE) in July 2018 with more autonomy and additional matching funding (USD ~125 million for 5 years)

PIC research in India

- **Design research, primarily.**
- **Few places that can fabricate**
  - IISc Bangalore
  - IIT Madras
  - IIT Bombay

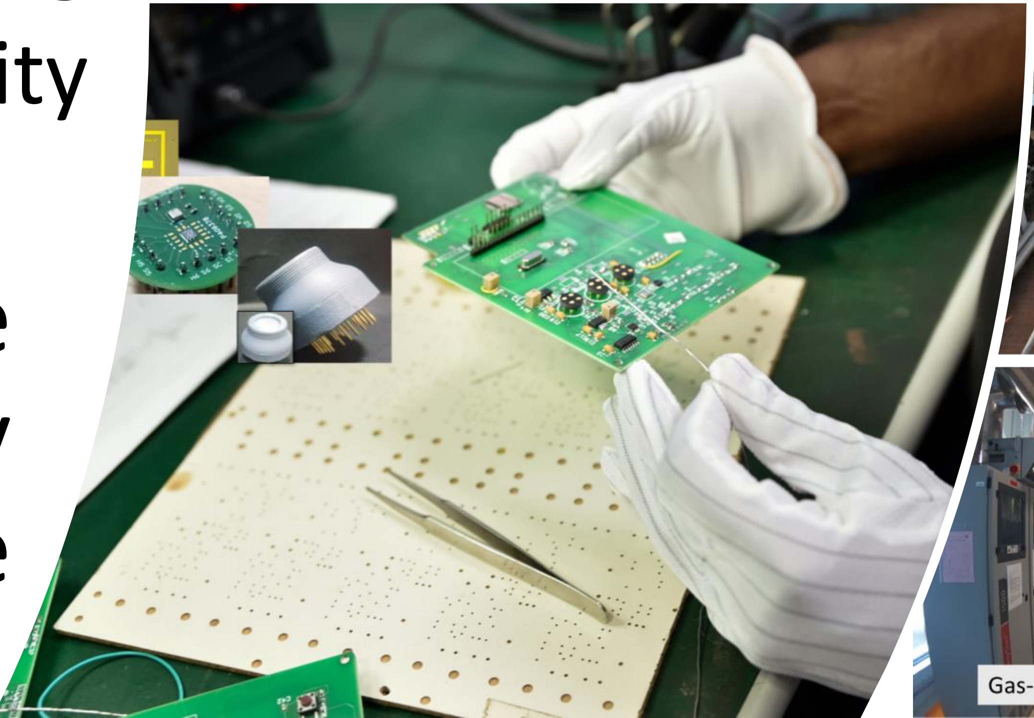
इंडिया सेमीकंडक्टर मिशन
India Semiconductor Mission

3.1. Compound Semiconductors / Silicon Photonics (SiPh) / Sensors (including MEMS) Fab / Discrete Semiconductors Fab

Description	Companies / Joint Ventures proposing to set up Compound Semiconductors / Silicon Photonics (SiPh) / Sensors (including MEMS)/ Discrete Semiconductors Fab in India for manufacturing High Frequency / High Power / Optoelectronics devices	
Technology	**Wafer Size**	**Capacity**
	150 / 200 mm or more	500 or more Wafer Starts / Month (in 100 mm equivalent)
Operational Experience	The applicant Companies / Joint Ventures should have the following experience: A. Own and operate a commercial Compound Semiconductors / Silicon Photonics (SiPh) / Sensors (including MEMS) Fab / Discrete Semiconductors Fab or Silicon Semiconductor Fab OR B. Own or possess licensed process technologies for the proposed Fab	
Capital Investment Threshold	Minimum Capital Investment of ₹100 crore (₹1 billion) for Compound Semiconductors / Silicon Photonics (SiPh) / Sensors (including MEMS)/ Discrete Semiconductors Fab	
Fiscal support from Government of India	50 % of Capital Expenditure	

RESEARCH INFRASTRUCTURES

Best integrated Fabrication/pilot-line, characterisation and packaging facility



Industrial scale facility utility infrastructure

NNfC (National Nano Fabrication Centre)

- A state-of-the-art semiconductor fabrication facility with over 70 high-end tools
- 14000 sq. ft facility class 100/1000 cleanroom
- Manned by 50 experienced staff and operates 24x7
- Capable of realizing features down to 10 nm on 4/6" Si, GaN, SiC, and III-V substates. Capable of prototyping and low-volume production of GaN, MEMS, photonics, and other more-than-Moore technologies.
- Open to national or international academia & industry.

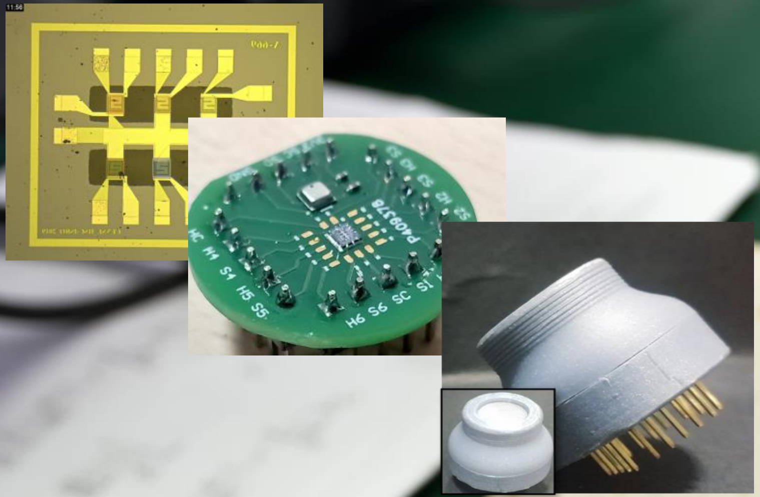
http://nnfc.cense.iisc.ac.in/content/equipment

MNCF (Micro and Nano Characterization Facility)

- More than 50 high-end equipment for electrical, mechanical, optical and material characterization
- 7000 sq. ft facility with precision-controlled environment
- Manned by 15 experienced staff and operates 24x7
- Open to national or international academia & industry
- Capable of defect tracking, advanced microscopy, electrical characterization, material screening, and thin-film measurements

http://mncf.cense.iisc.ac.in/facilities/

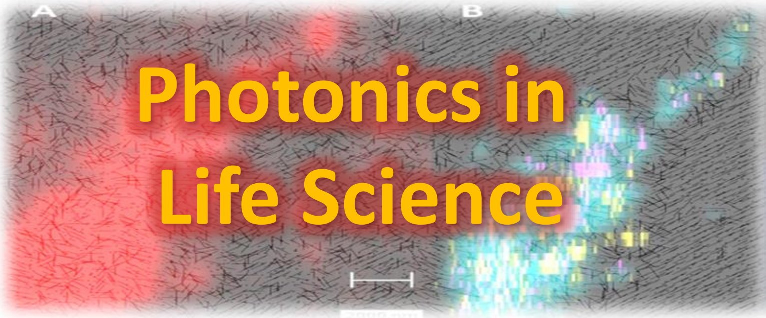
PASF (Packaging and System Facility)

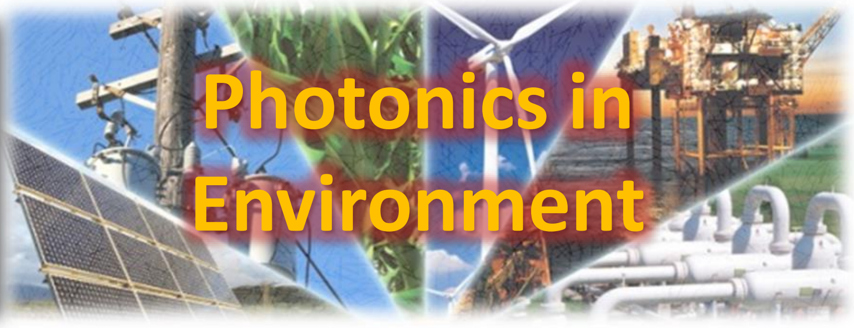


- 20 equipment for advanced packaging, including grinding, dicing, wire-bonding, flip-chip bonding, laser welding, etc.
- 2500 sq. ft facility in a class 10000 cleanroom
- Manned by 25 experienced staff
- Open to national or international academia & industry
- Capable of upto 20 services for electronic system design, die-attach, MEMS packaging, GaN packaging, PCB assembly, sensor calibration, and aerospace-grade testing

Photonics Integrated Circuits Research

CeNSE





Visible | **Near-IR** | **Mid-IR**

Material and Device

New material and device platform has to be created for each application area.
Scope for interesting material and device research

Integrated circuit

Circuit is application/platform specific and strongly technology limited
Novel circuit implementation strategy

System integration

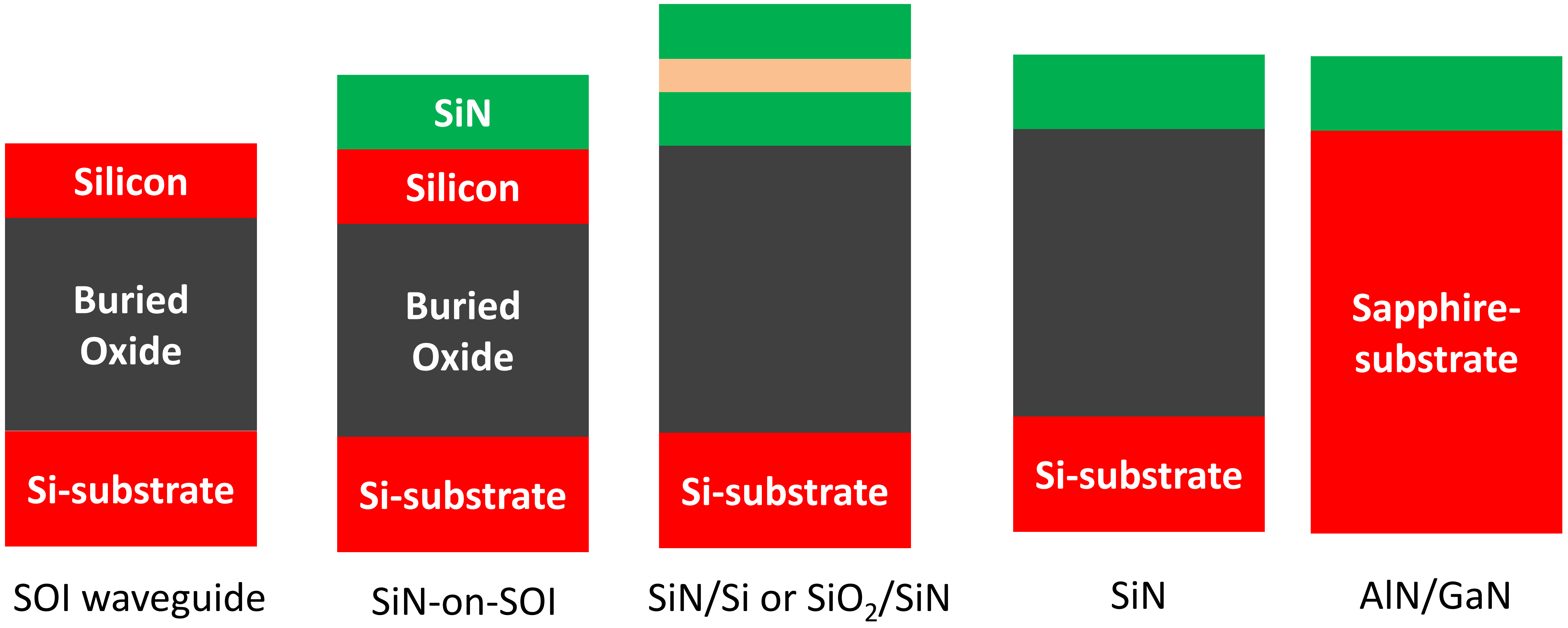
Technology demo requires a self-contained system with integrated discrete & circuit elements
Potential product demonstration.

Outline

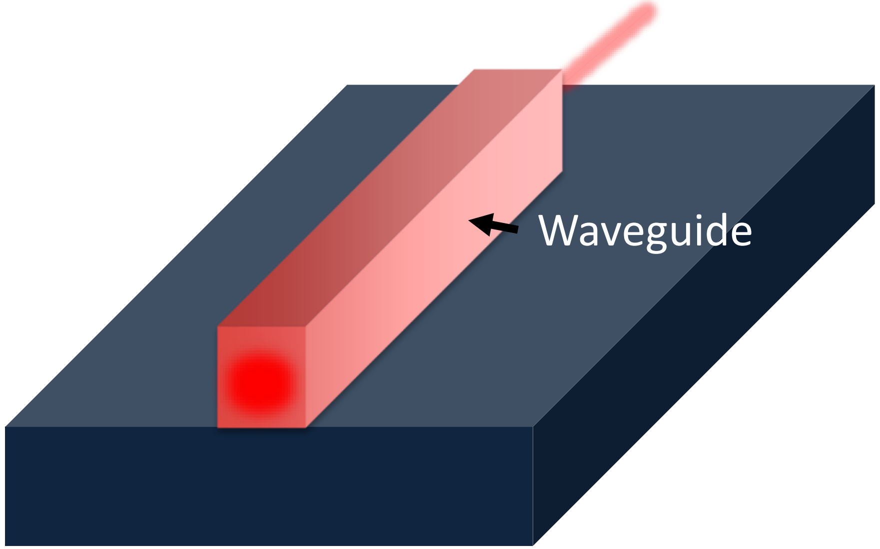
- **Waveguide platform**
- **Light modulators**
  - **Ferroelectric**
  - **Piezoelectric**
- **PIC-based sensor**
  - **Fluid**
- **Collaboration interest**
- **Academic programs**

Waveguide Platforms

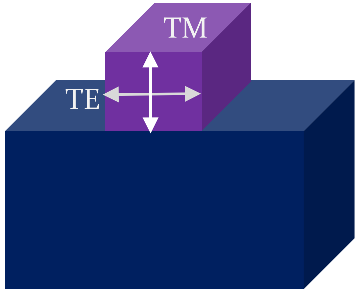
Waveguide platforms



Optical Waveguide

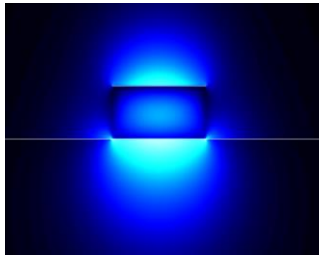


Wire Waveguide



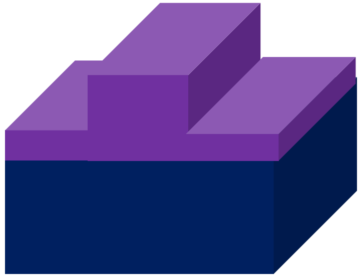
3D Structure

TE mode



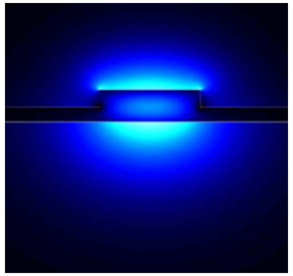
TM mode

Rib Waveguide



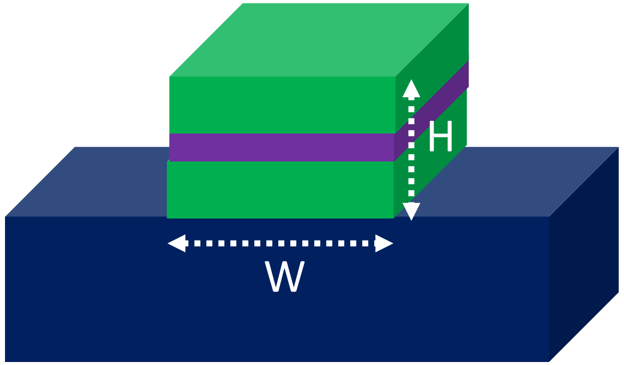
3D Structure

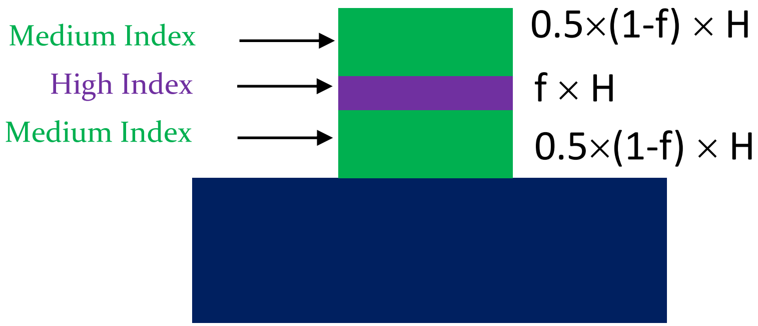
TE mode



TM mode

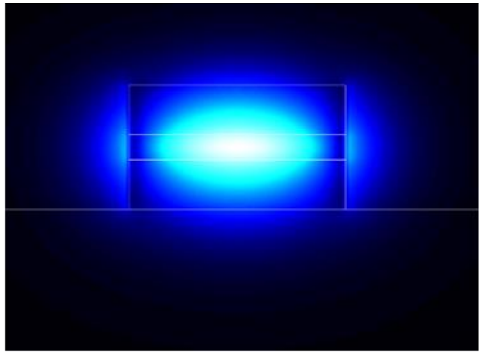
Sandwiched Hybrid Waveguide



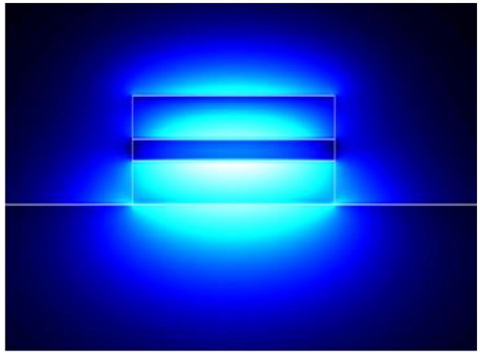


Cross Section

$$f = \frac{Thickness\ of\ High\ Index\ material}{Total\ Thickness\ ('H')}$$



TE mode

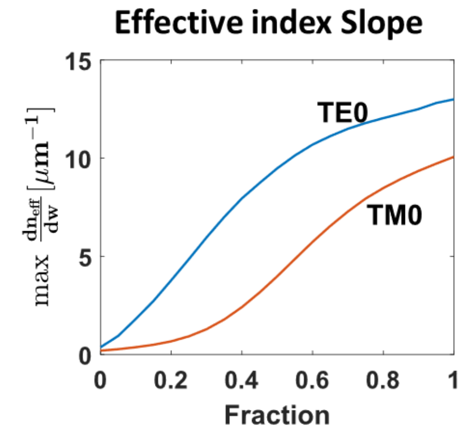


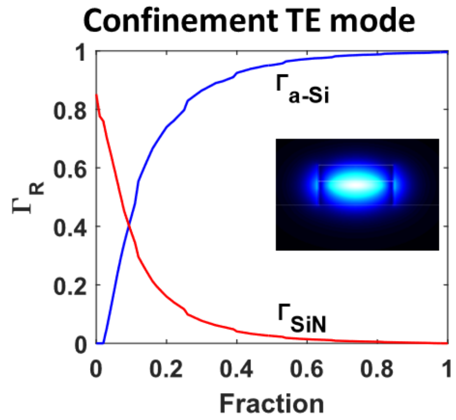
TM mode

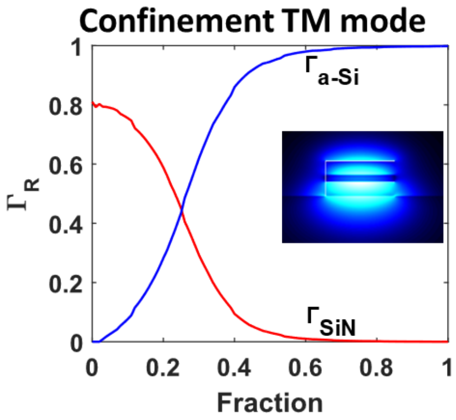
Rahul D., et. al., https://doi.org/10.48550/arXiv.2304.00748

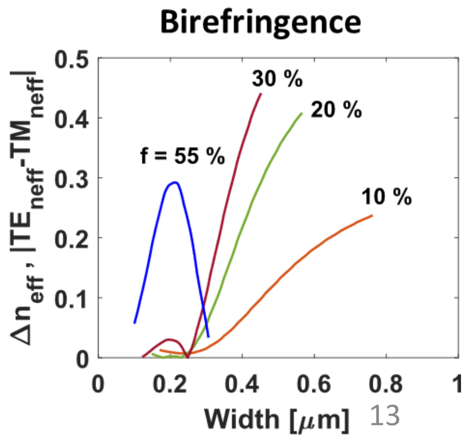
Optics Comm., vol. 550, 2024.

Fraction provides flexibility to control Effective Index, Confinement and Birefringence

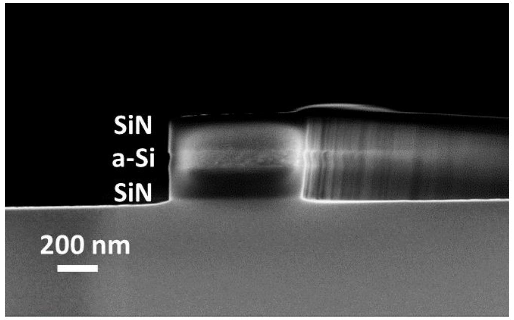


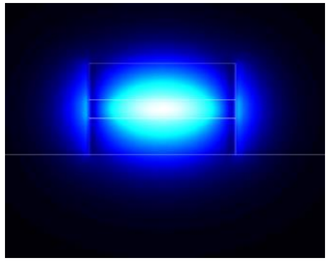




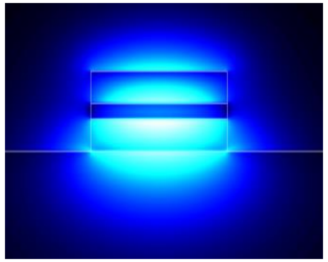


Polarization dependent Thermo-optic Response



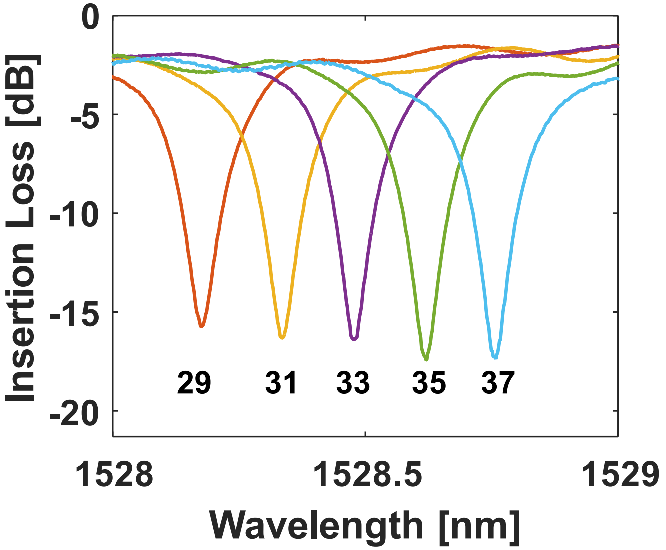


TE mode

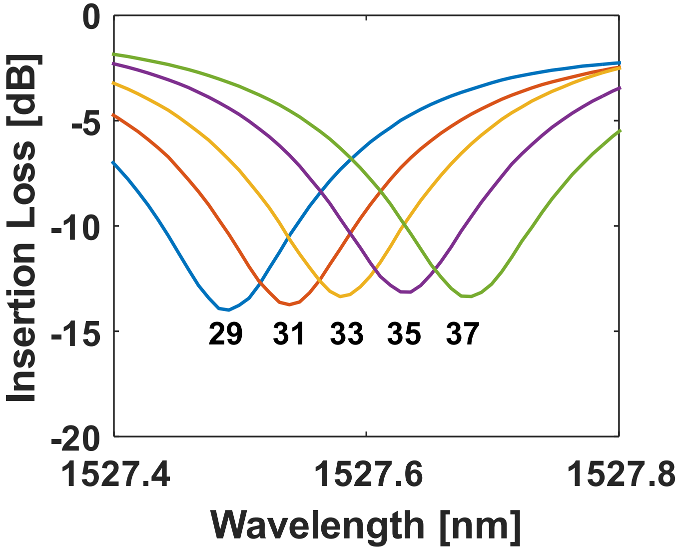


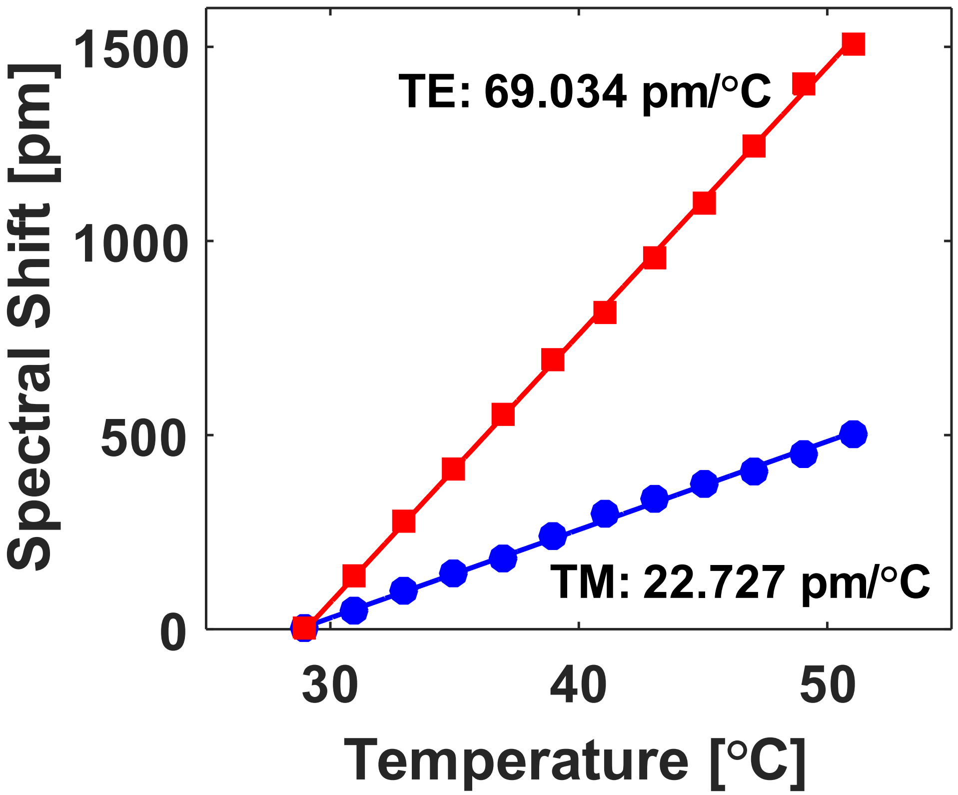
TM mode

TO shift: TE Mode



TO shift: TM Mode



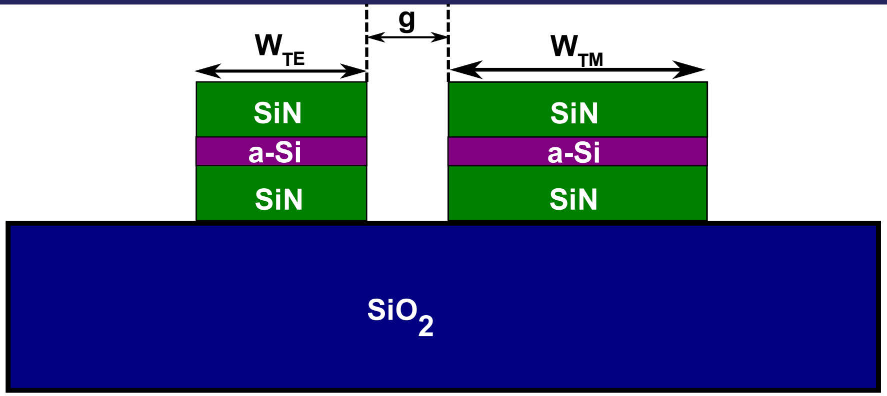


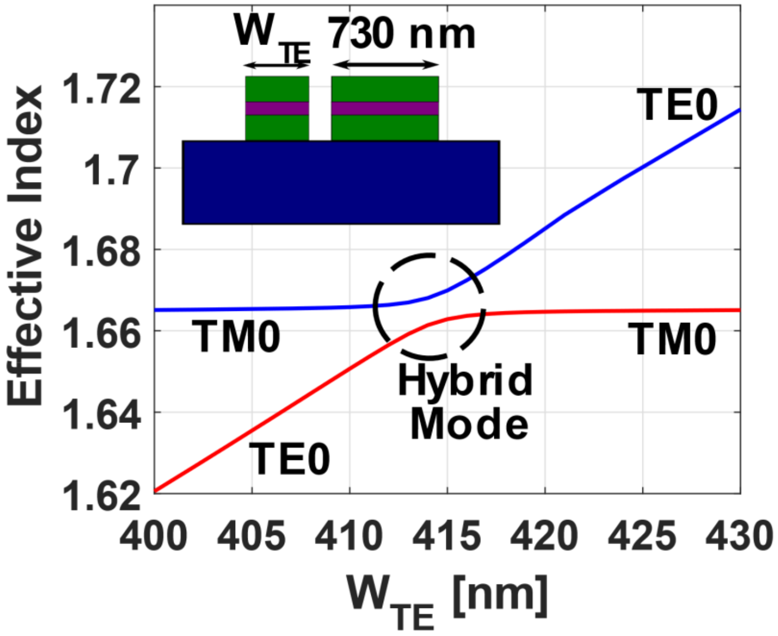
	a-Si	SiN
dn_{eff}/dT	1.528×10^{-4}	3.468×10^{-5}
TOC	2.05×10^{-4}	2.67×10^{-5}

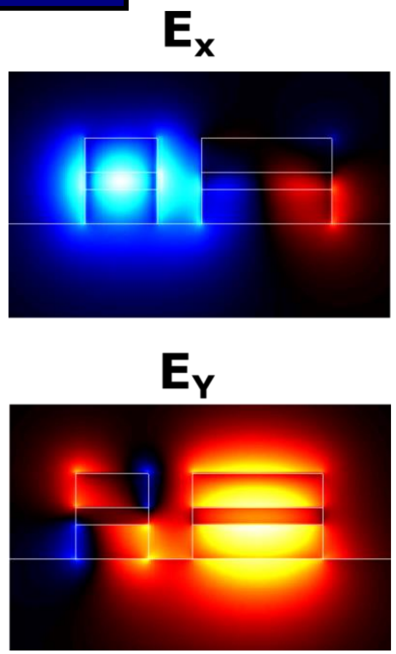
Rahul D., et. al., https://doi.org/10.48550/arXiv.2304.00748

Optics Comm., vol. 550, 2024.

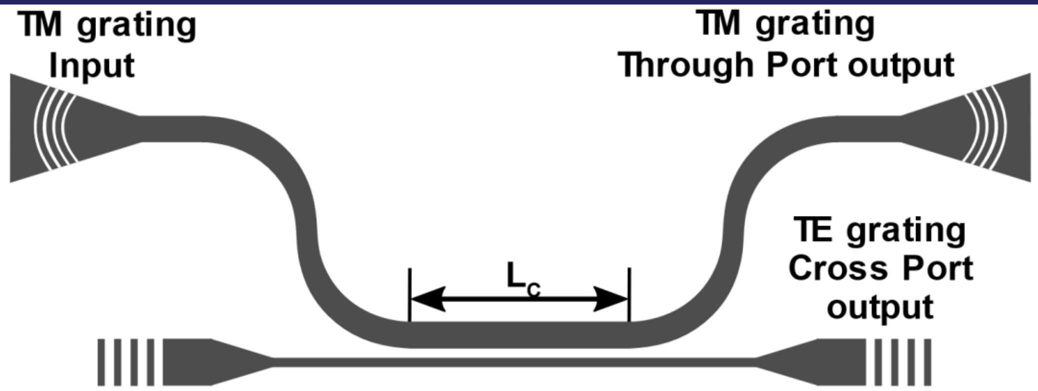
Polarizing directional coupler –
Potential application in Quantum Signal processing

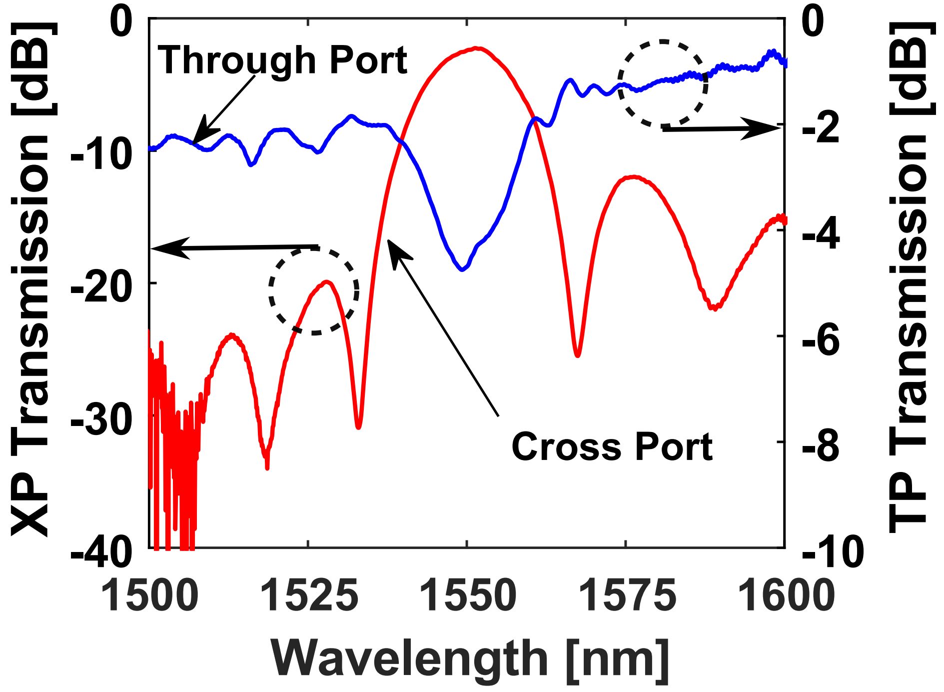






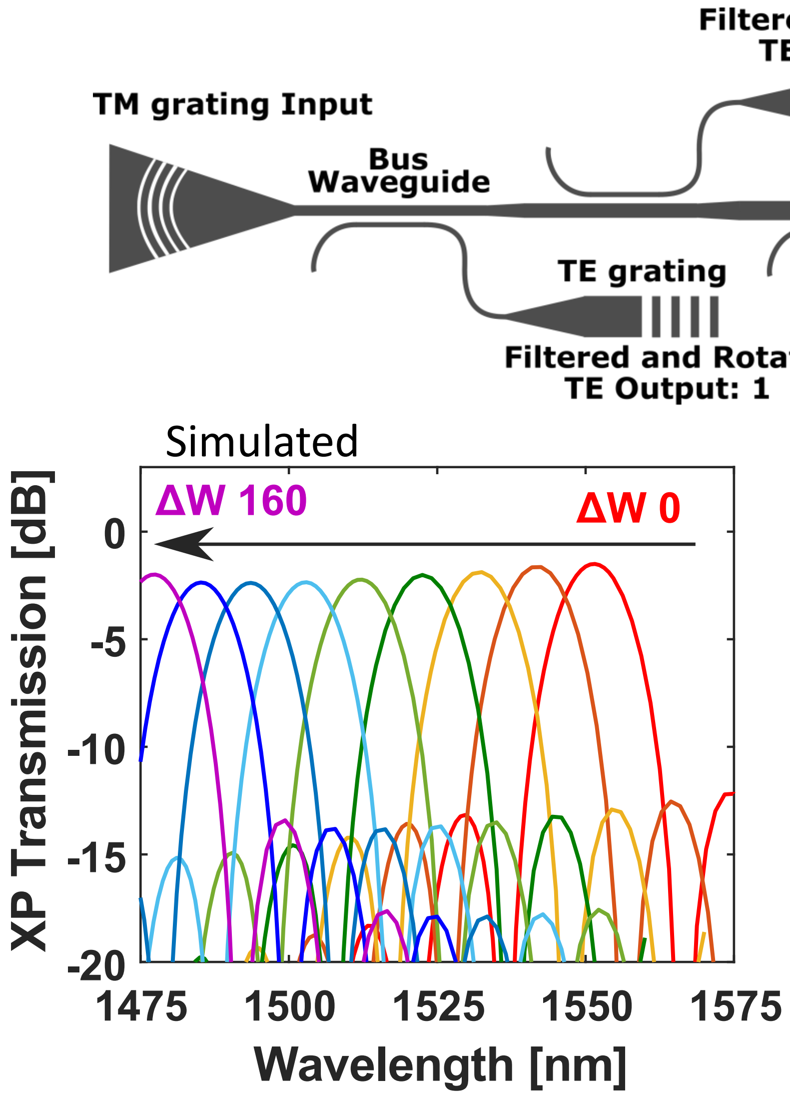
Optics Letters, vol. 36, p. 1059, 4 2011



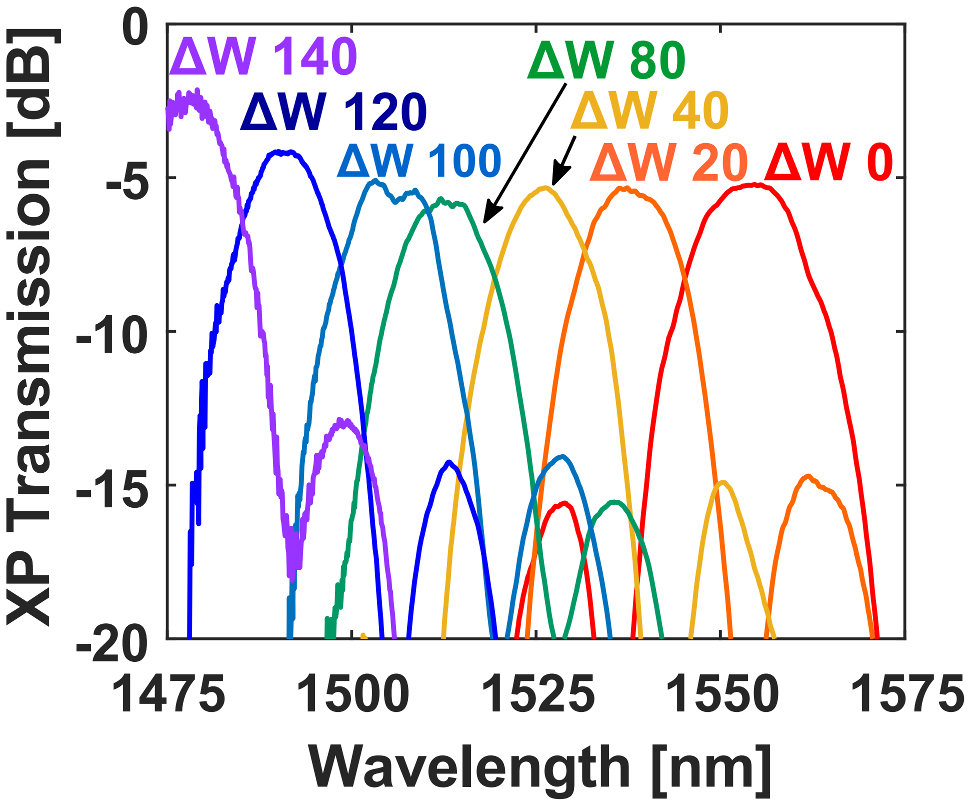


Optics Express, vol. 32, no. 8, pp. 13035-13047, 2024

Wavelength multiplexing selective pol. Rot.



Directional coupling waveguide width tuned spectral filter PR.



Optics Express, vol. 32, no. 8, pp. 13035-13047, 2024

Electro-Optic modulator

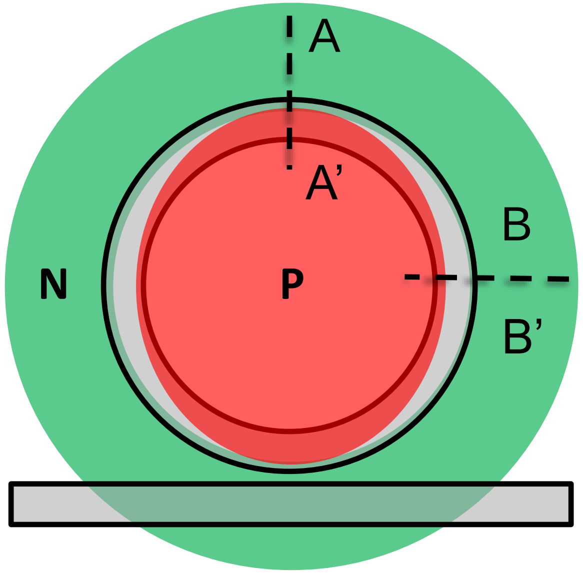
>45 GHz electro-optic bandwidth

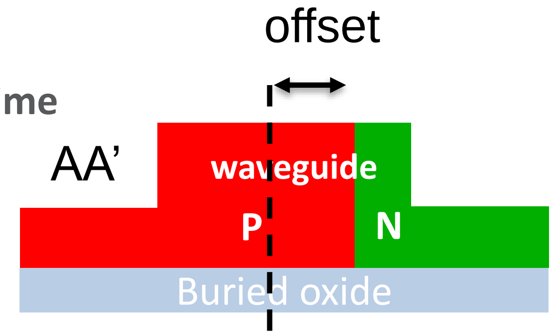
$$\frac{1}{f_{3-dB}^2} = \frac{1}{f_Q^2} + \frac{1}{f_{RC}^2},$$

$$f_{RC} = \frac{1}{2\pi RC}, f_Q = \frac{1}{2\pi\tau}, \tau$$ **– cavity photon life time**

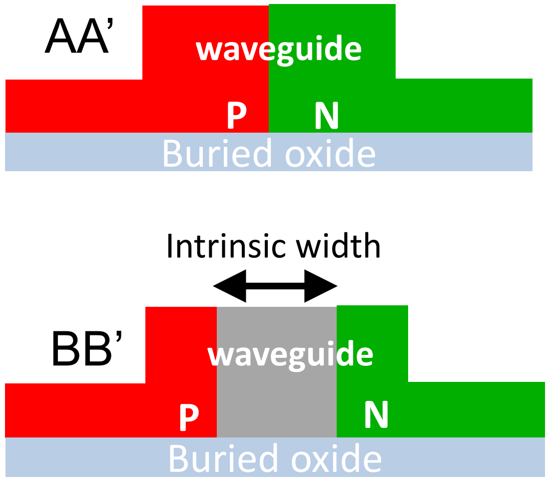
Techniques for improving bandwidth

1. Improve Q-factor
2. Improving R and C
3. R - increased doping concentration
4. C - introducing PIN junction



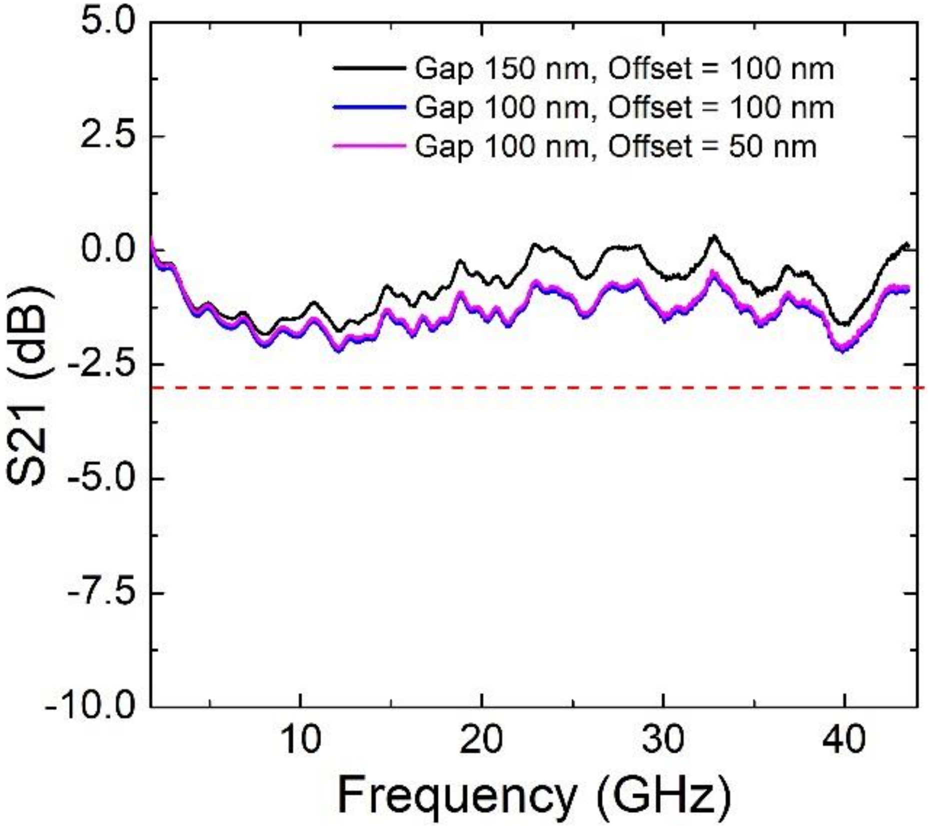


Krishnamoorthy A V et al., Optics Express (2009)



Ding J et al., Optics Express (2012)

Device fabricated through MPW

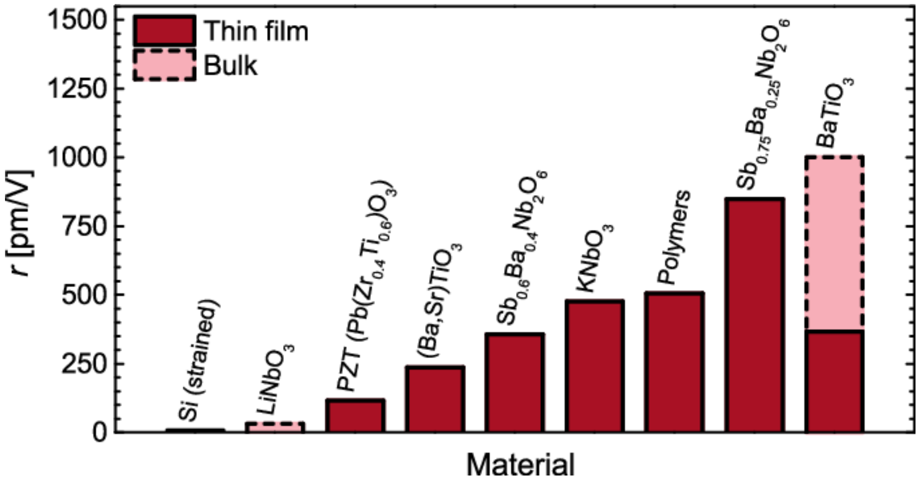


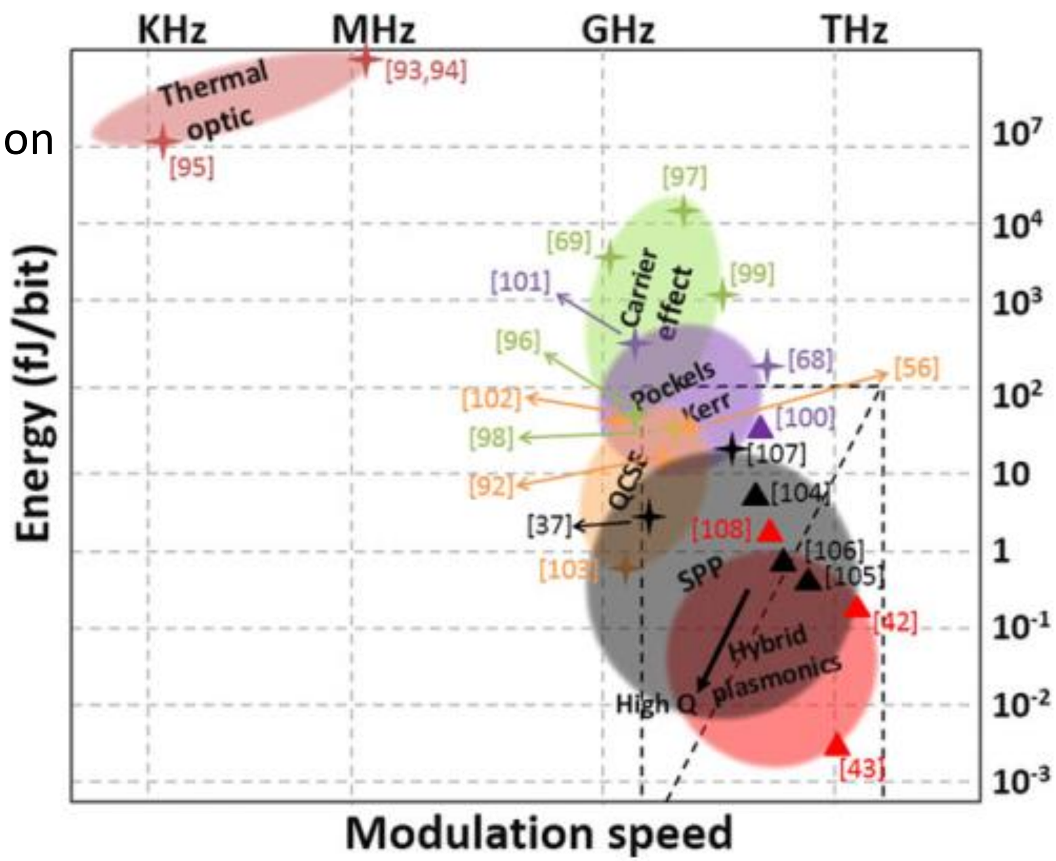
Accepted CLEO 2024

Beyond Silicon Electro-Optic Modulator

- Electro-optic (EO) (Pockels and Kerr, and carrier density effect)
  - Pockels and Kerr effect: - response time~ 100fs
  - Carrier density effect:- Carrier injection and carrier depletion
  - Materials: - Silicon, PZT, BTO, LNO

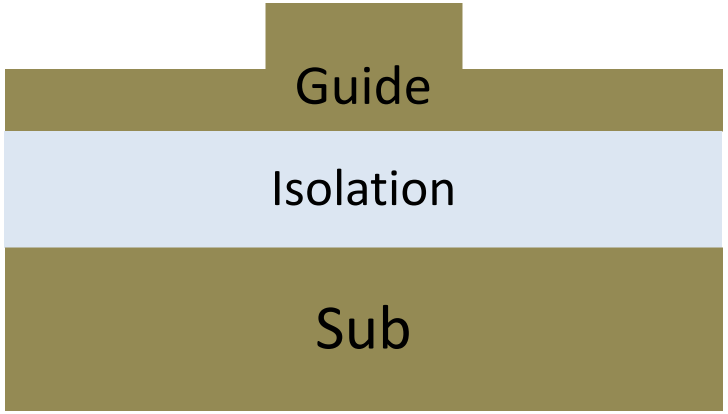
- Pockel's and Kerr effect
  - d_{33} values
    - LNO:- 33pm/V (bulk); 22pm/V(thin films)
    - PZT :- 300-700pm/V(PLZT- 1200pm/V)
    - BTO:- 300-800pm/V(~1000pm/V)

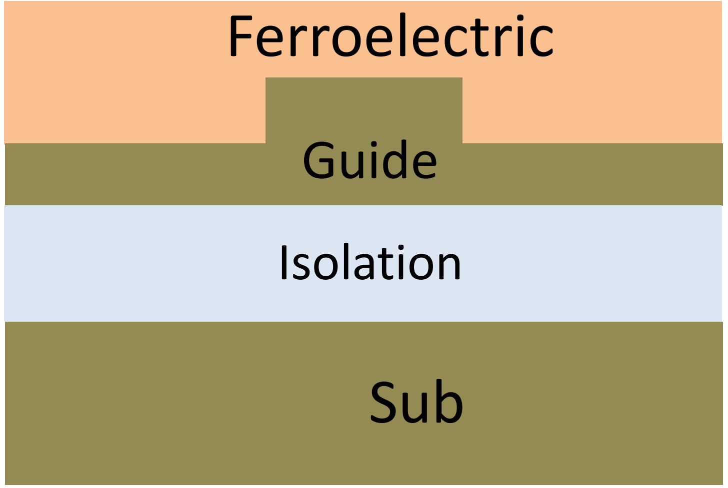




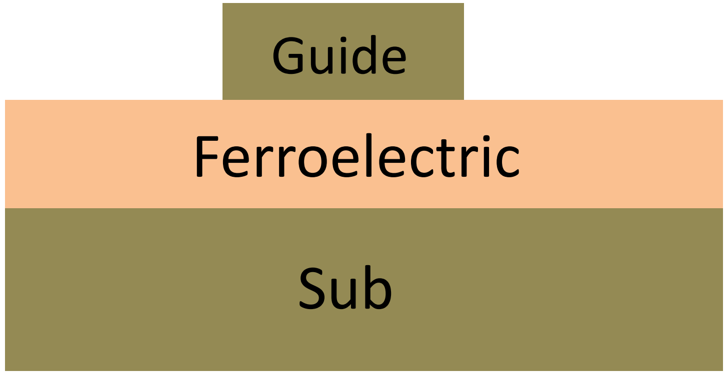
Liu, Ke, et al. Laser & Photonics Reviews 9.2 (2015): 172-194.
Abel S, et al., JLT, 2016.

Ferroelectric integration schemes for light modulation

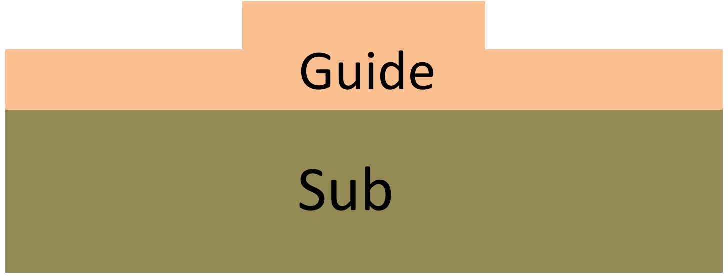




Cladding

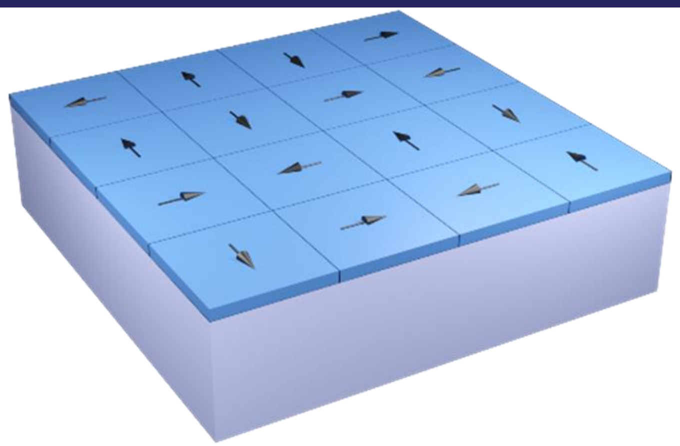


Loaded waveguide

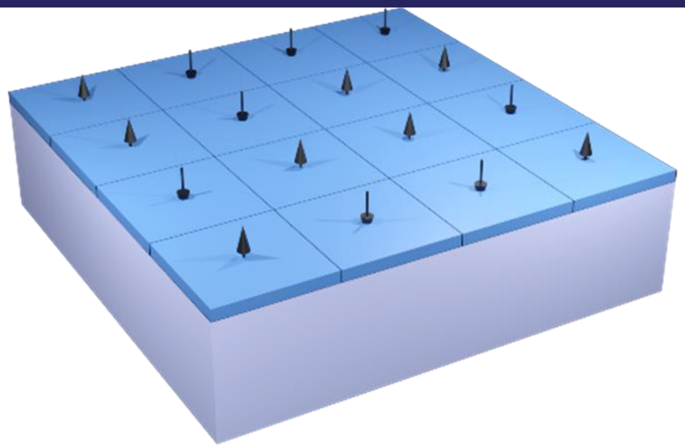


Patterned waveguide

Effect of ferroelectric domains on the EO property

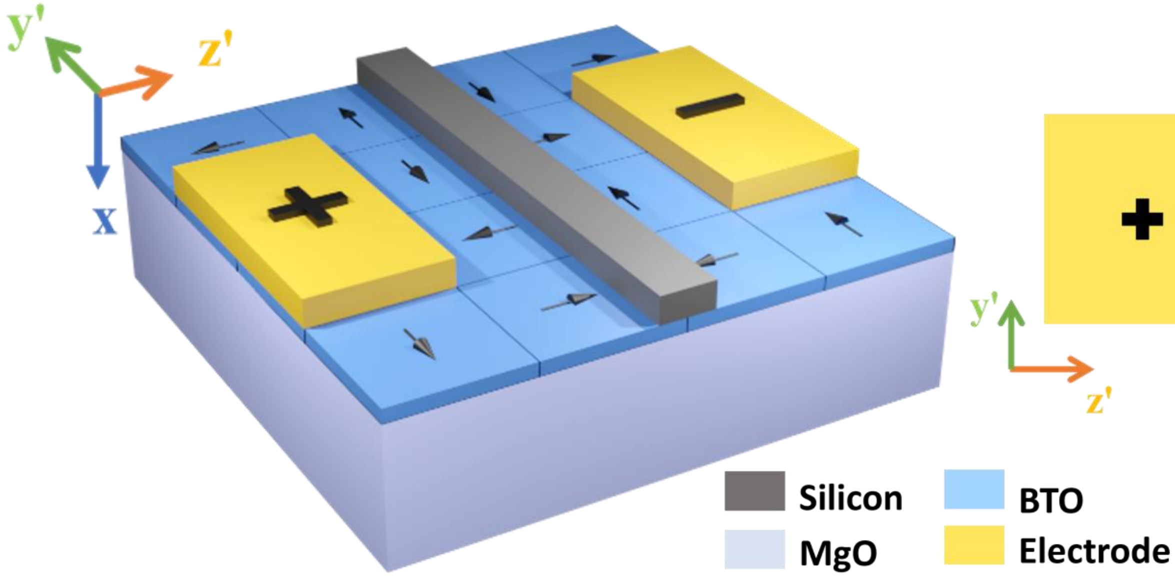


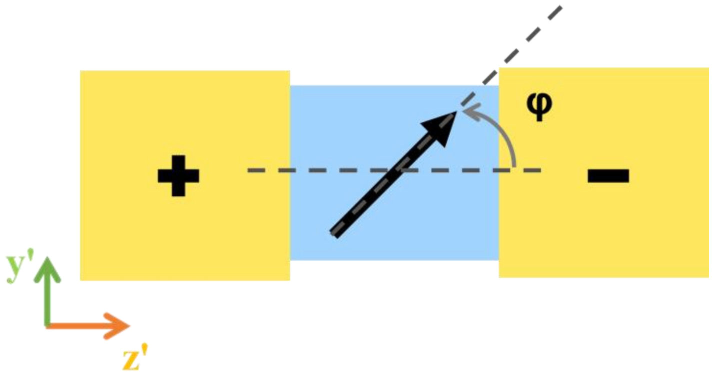
a-axis



c-axis

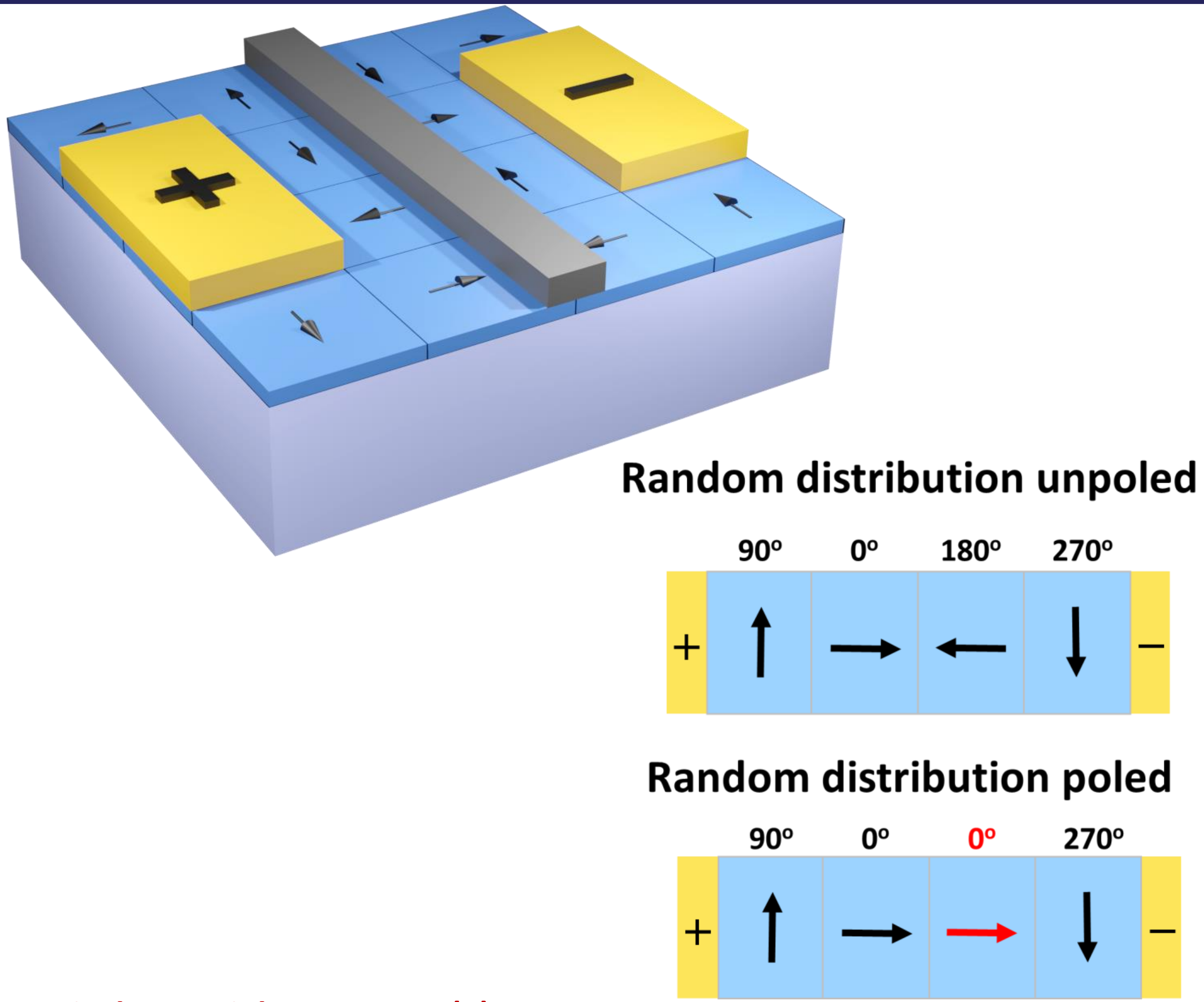
Loaded waveguide

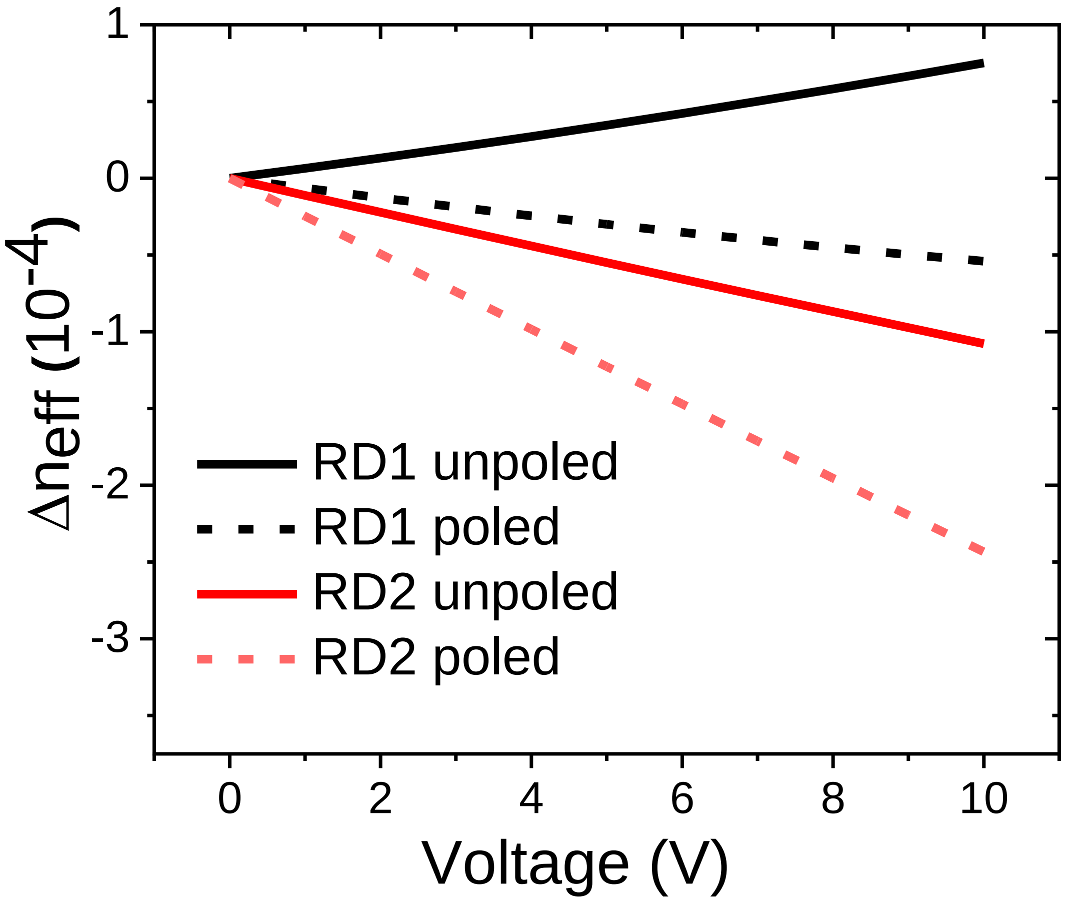




Optical Material Express, 13(4), 956-965, 2023.

Multi-domain system





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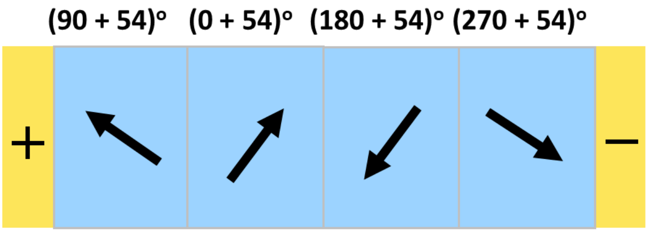
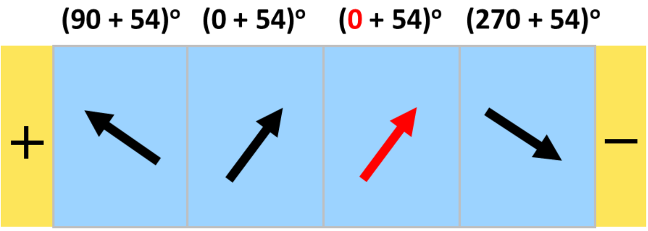
Multi-domain system -2

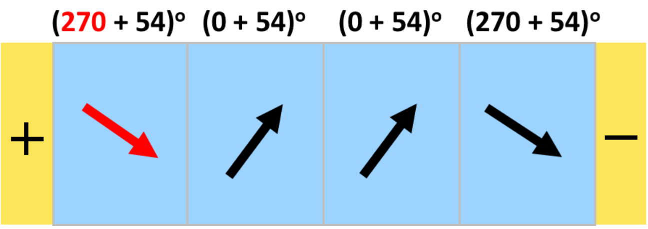
Random distribution unpoled
(RD unpoled)

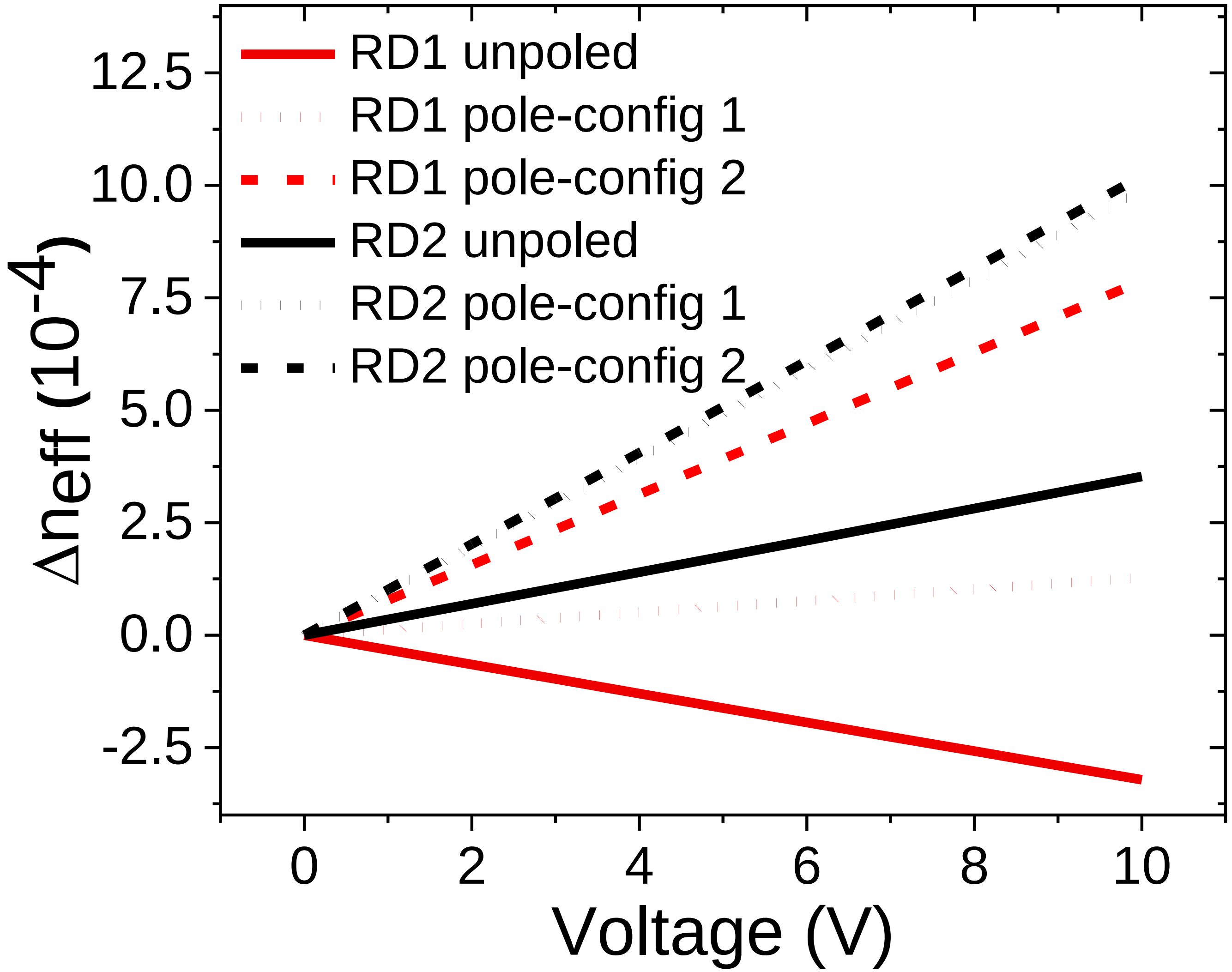


Random distribution poled configuration-1
(RD pole config-1)



Random distribution poled configuration-1
(RD pole config-2)





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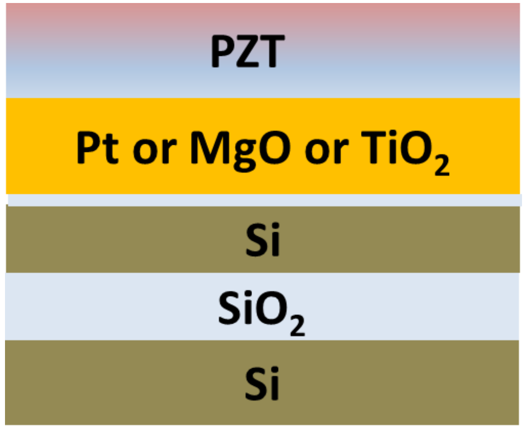
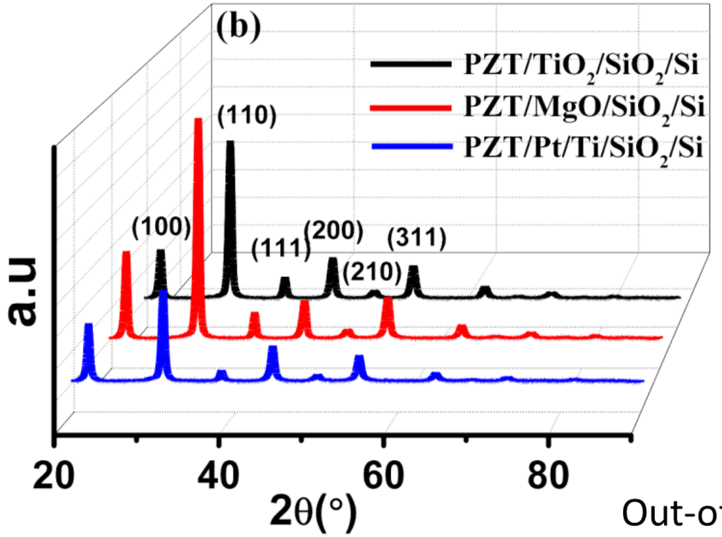
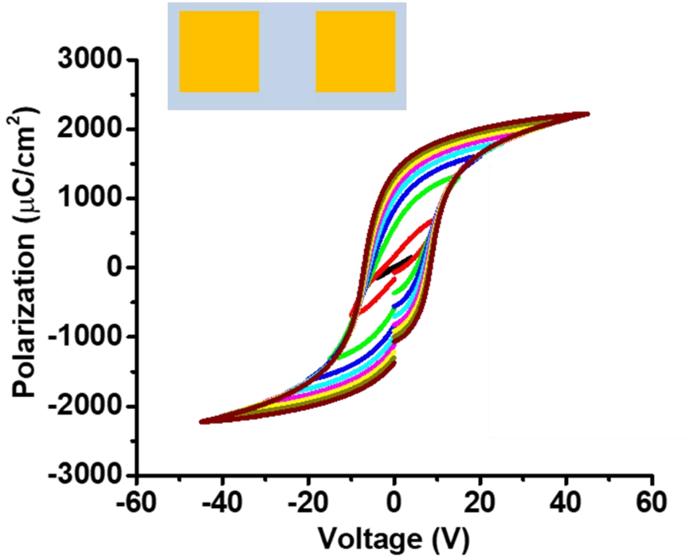
Lead zirconate titanate (PZT) on Si

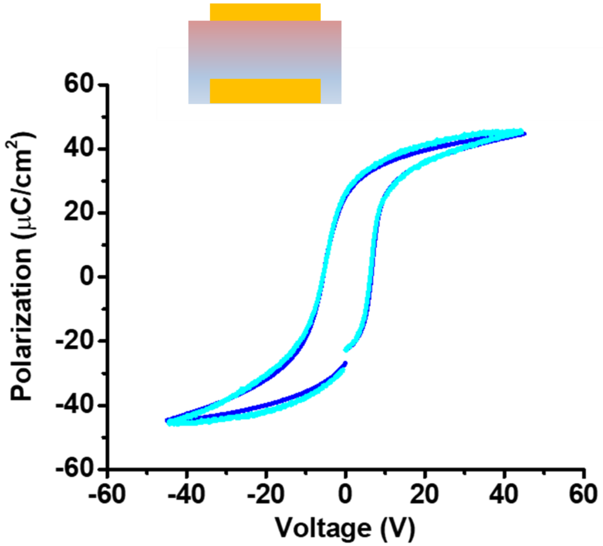




Inplane polarisation



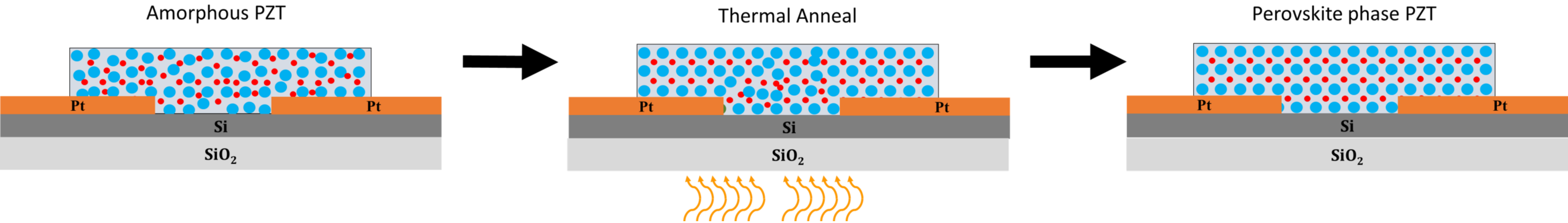
Out-of-plane plane polarisation

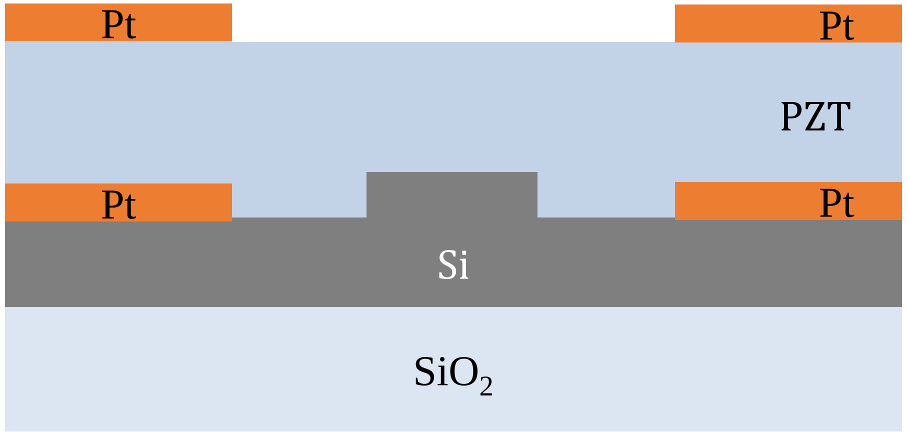


- **Perovskite phase achieved on metallic and dielectric buffer layers.**
- **Optically transparent: MgO and TiO2.**
- **Benchmark Platinum (on titanium).**

In-built polarization

Remote-epi with quadrature electrodes



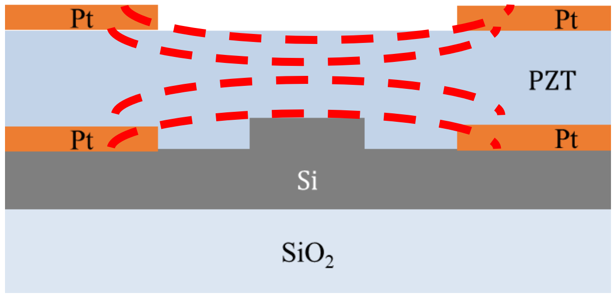


- **PZT-on-Si with in-plane and out-of-plane electrodes.**
- **Unlock maximum domains.**
- **Increase effective EO effect.**

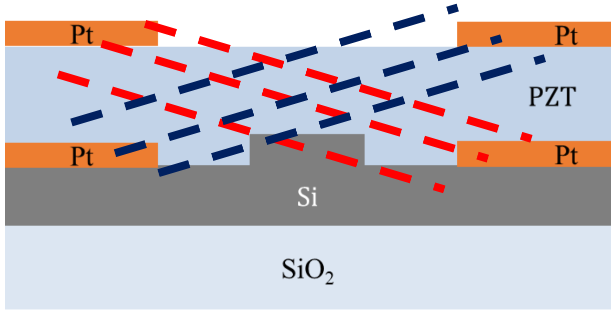
https://doi.org/10.48550/arXiv.2305.19174
https://doi.org/10.48550/arXiv.2305.19226
https://doi.org/10.48550/arXiv.2305.19126

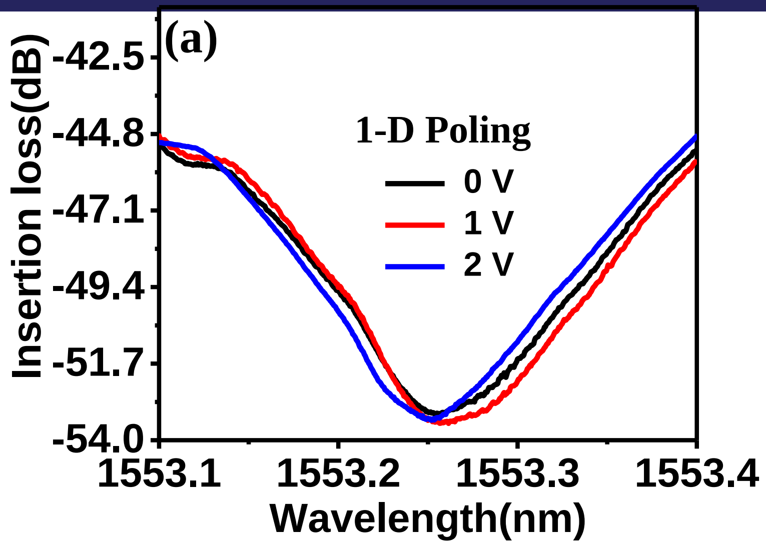
Effect of quadrature poling (3D poling)

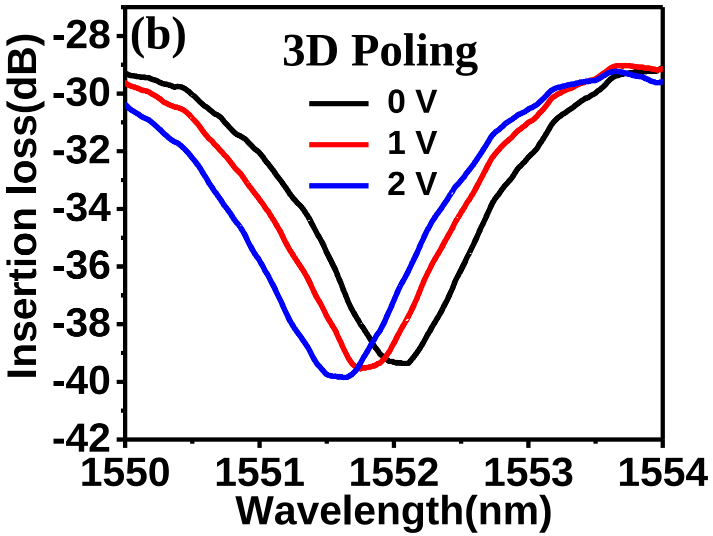
1D poling

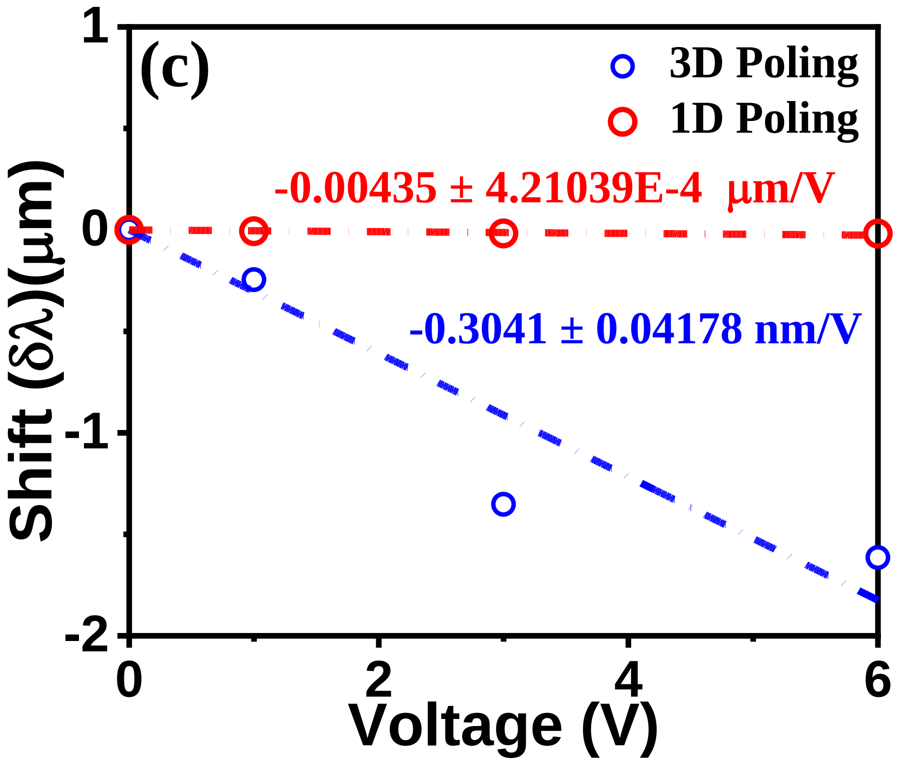


3D poling/Q-poling







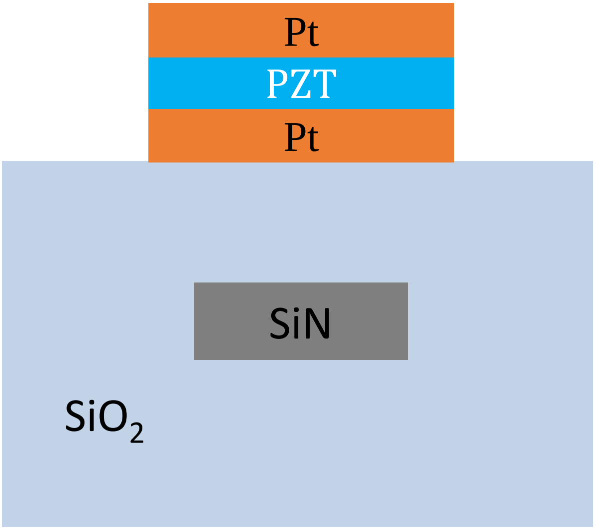


1D Poling: 4 pm/V

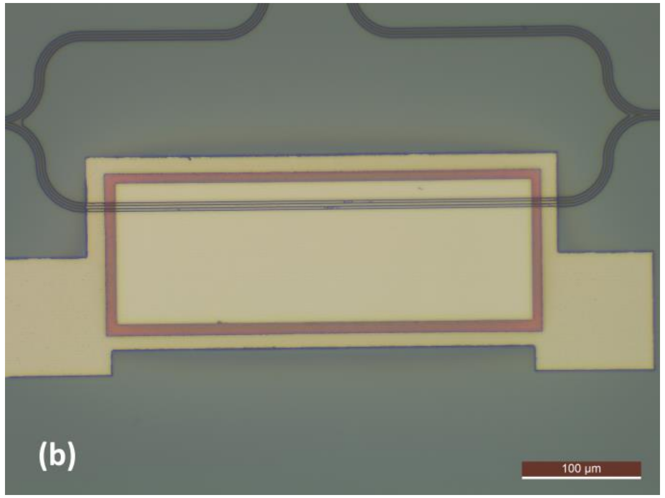
3D Poling: 304 pm/V

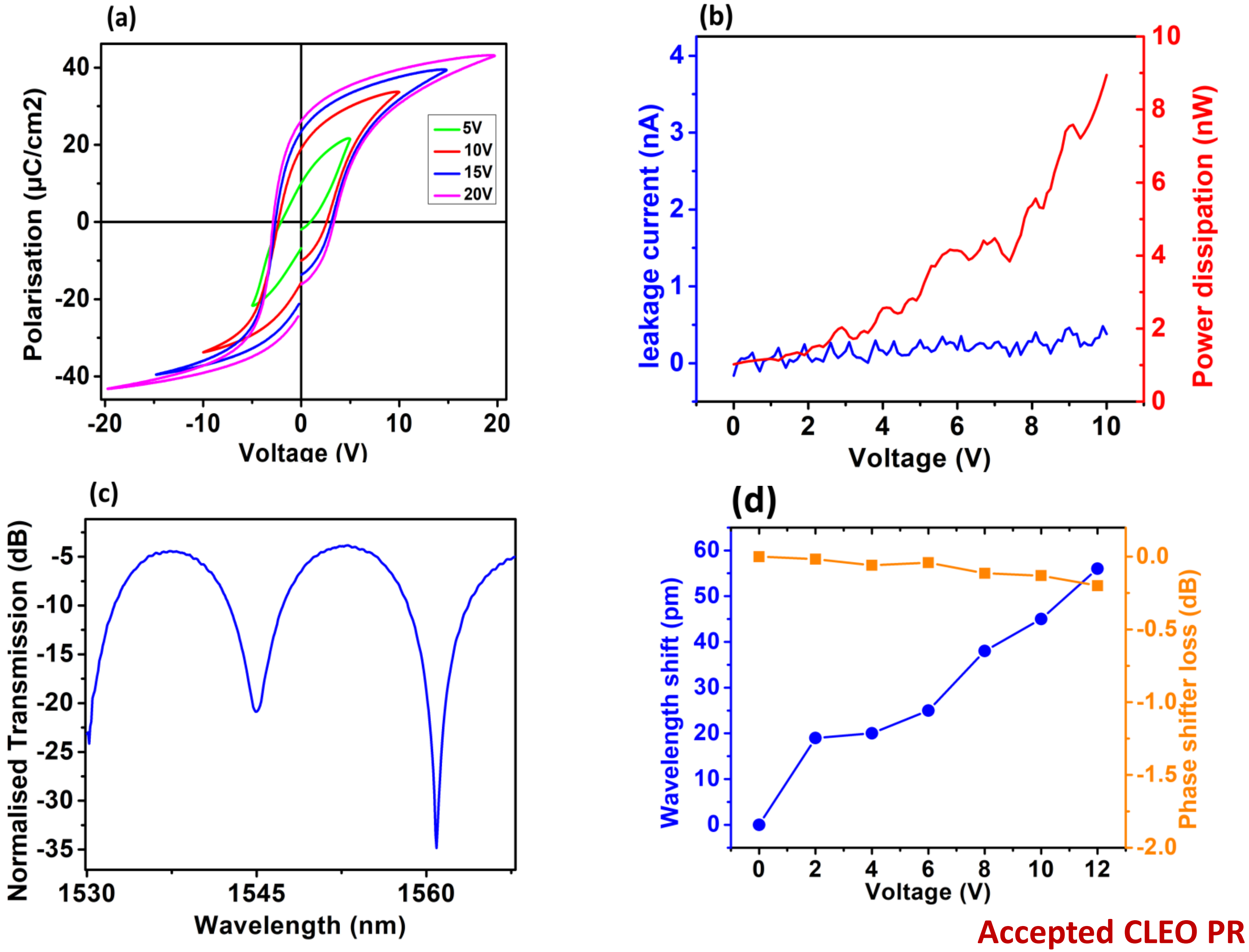
https://doi.org/10.48550/arXiv.2305.19174
https://doi.org/10.48550/arXiv.2305.19226
https://doi.org/10.48550/arXiv.2305.19126

Stress-optics using PZT on silicon nitride: Low power/loss phase shifter



PZT on SiN MZI

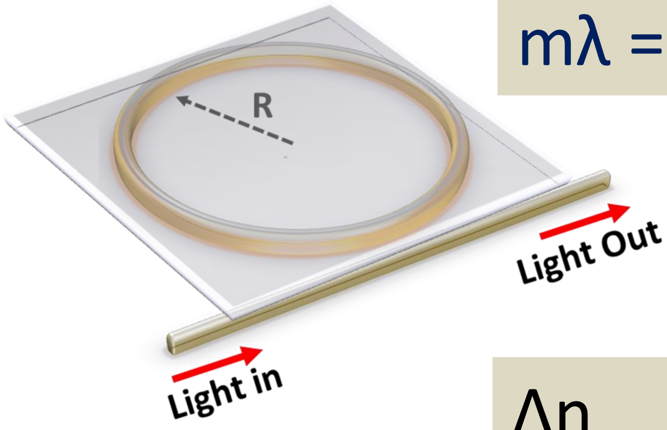




Accepted CLEO PR 2024

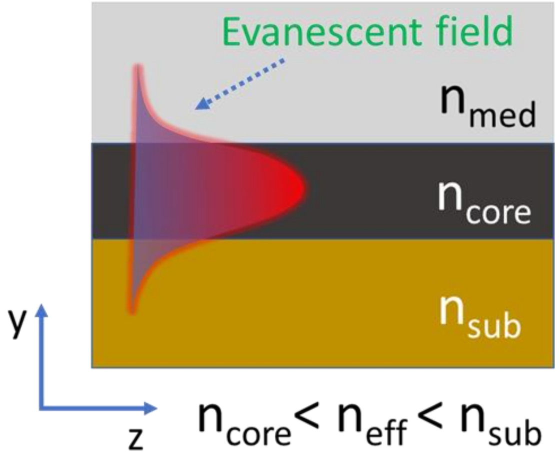
Sensor platform

Ring Resonator based Sensing

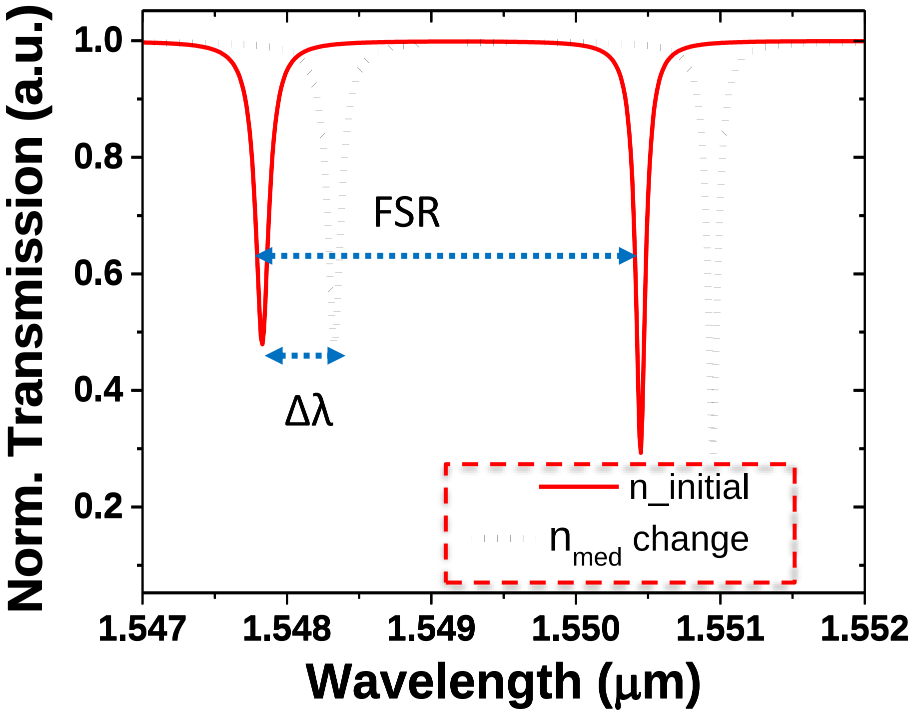


$$m\lambda = 2\pi \, n_{eff} \, R$$

$$\Delta n_{med} \rightarrow \Delta n_{eff}$$



$$n_{core} < n_{eff} < n_{sub}$$

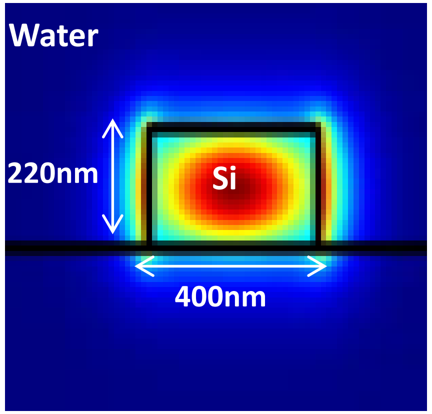


$$\text{Sensitivity} = \frac{\Delta\lambda}{\Delta n_{clad}} = \frac{\lambda_r}{n_g}\frac{\partial n_{eff}}{\partial n_{med}}$$

Slot waveguide offer higher light-matter interaction

- Higher interaction translates to higher sensitivity.
- ~50% Evanescent Field Fraction in slot waveguides for effective light-matter interaction.
- A double slot waveguide can offer relatively high sensitivity as its group index can be lower than that of a single slot waveguide.

Wire



EFF ~ 10-25%

$$S = \frac{\lambda_r \, dn_{eff}}{n_g \, dn_{clad}} = \frac{\Delta\lambda}{\Delta n_{clad}}$$

EFF - Evanescent Field Fraction
λ_r - Resonant wavelength
n_g – group index
n_{eff} - effective index
n_{clad} - Upper cladding index

IEEE Sensors, vol. 20, no. 11, pp. 5970 - 5975, 2020
IEEE Sensors Journal, vol. 23, no. 8, pp. 8360-8365, 2023

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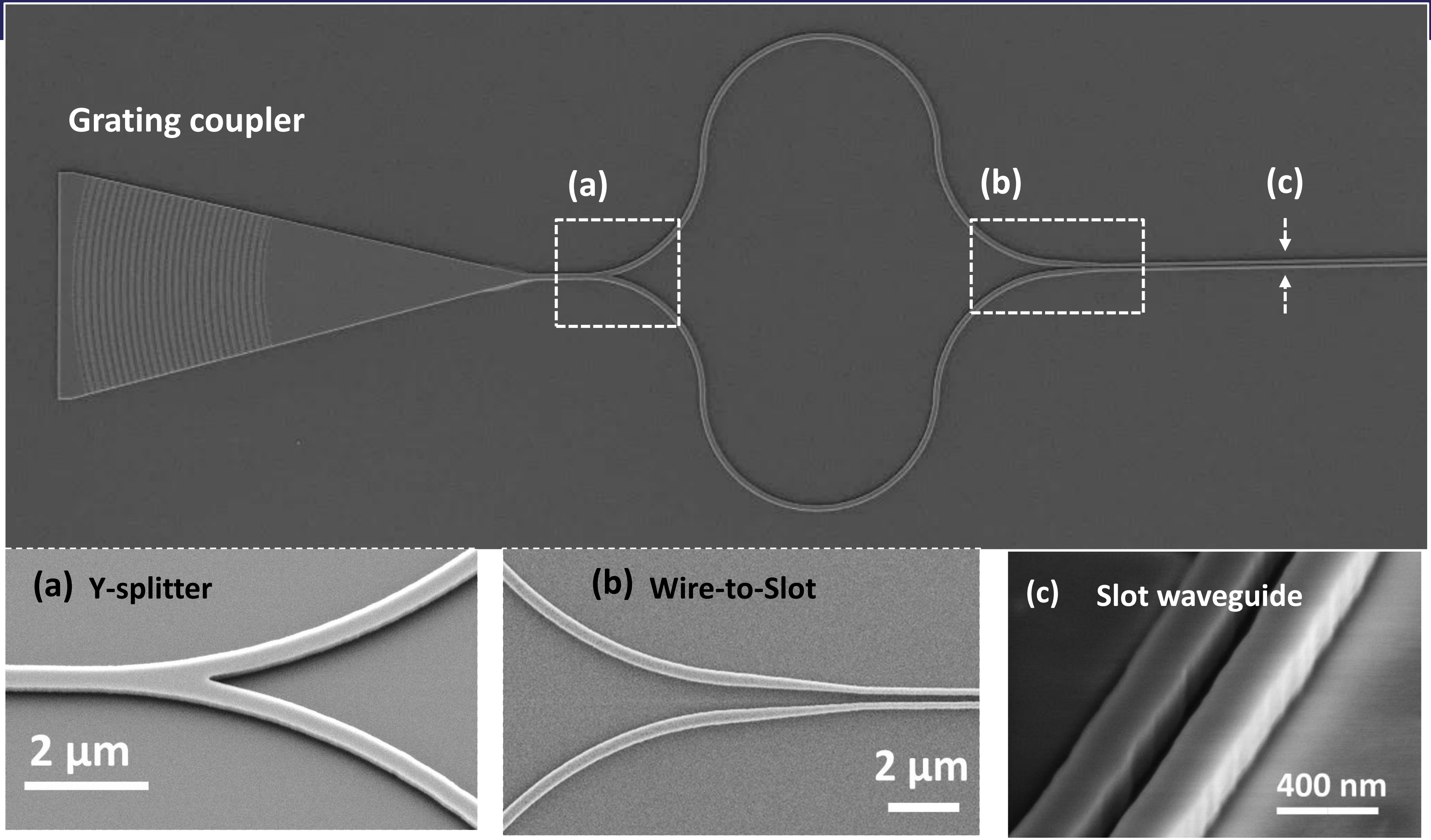
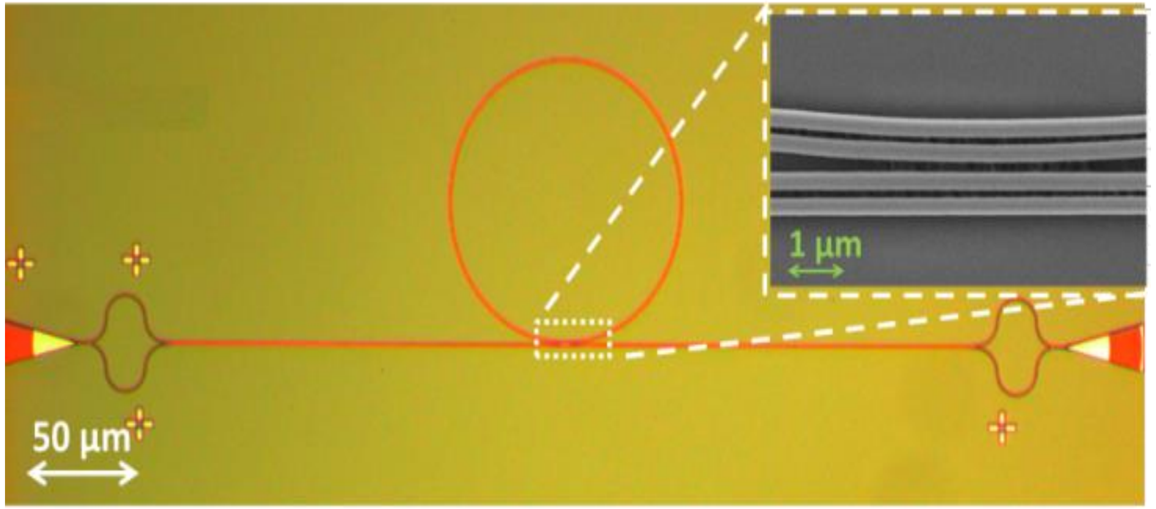
Fabricated device



J. of Micro/Nanolithography, MEMS, and MOEMS, 18(4), 043503 (2019).

Slot mode Excitation



Optical image of a slotted-ring resonator
(R = 60 µm; W_{slot} = 260 nm; gap = 140 nm)

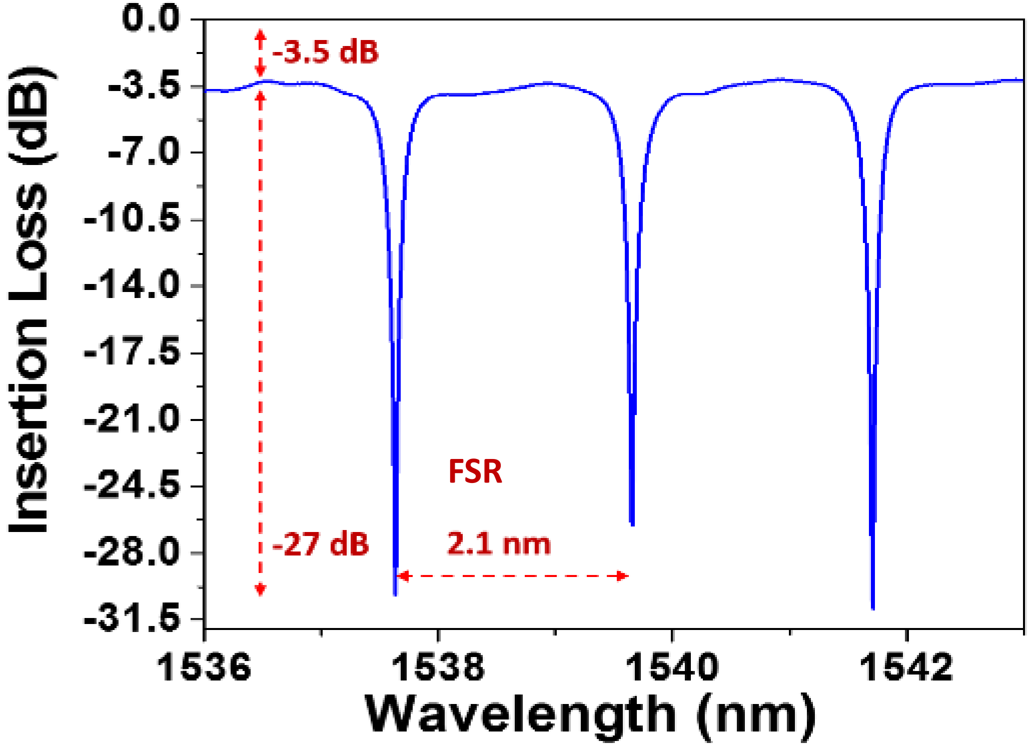
$$n_g = \frac{\lambda^2}{2\pi R * FSR}$$

$$n_g = 3.17$$

Simulated group index was 3.12.

R = Ring radius; FSR = Free spectral range
n_g= Group index; λ_r = Resonant wavelength

Spectral response slot ring resonator



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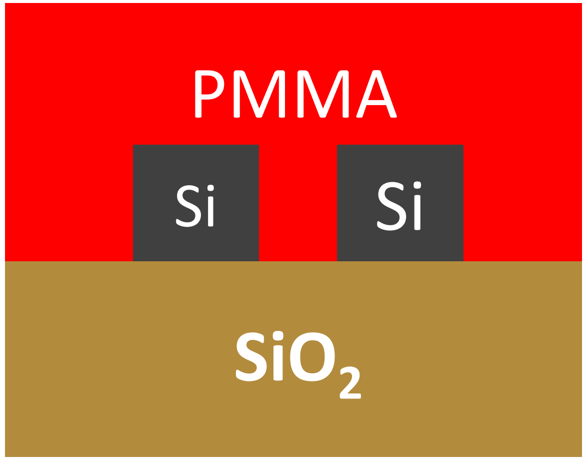
Temperature dependent study

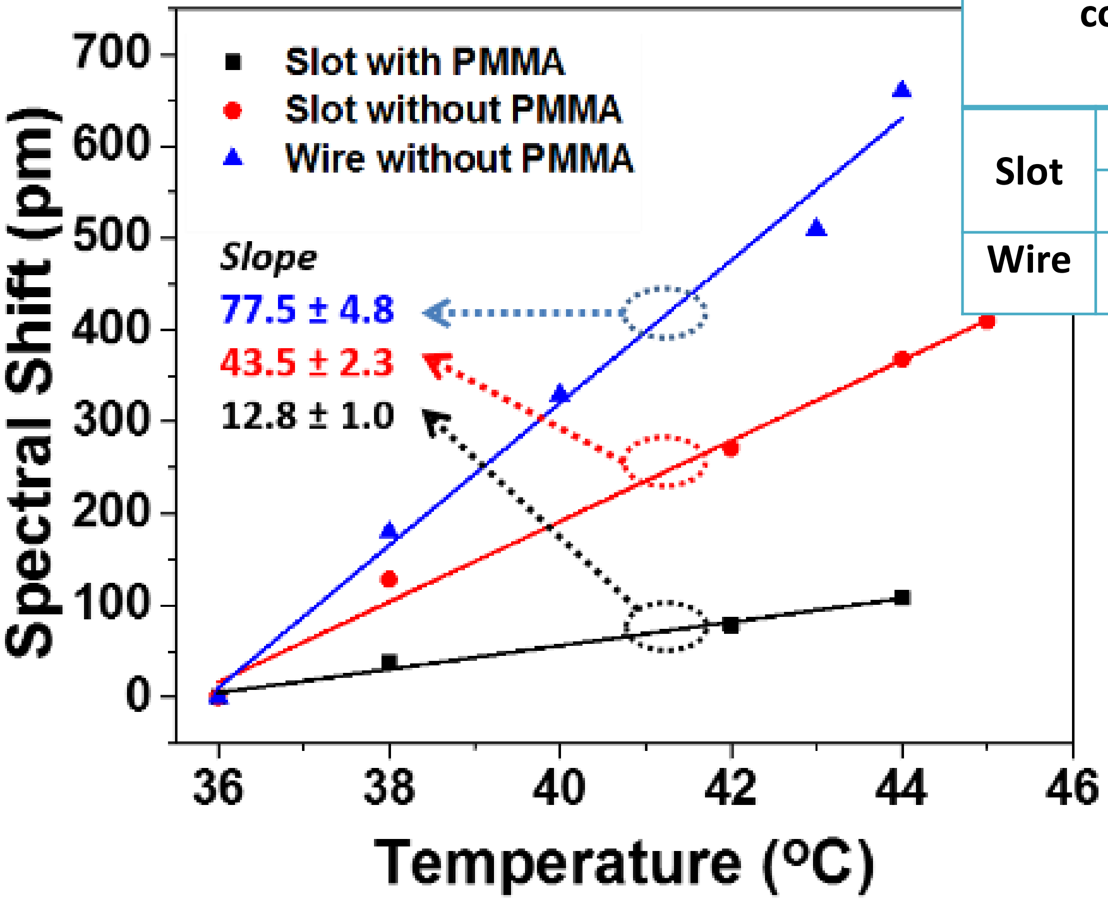


Thermo-Optic-Coefficient

$Si = 1.86 \times 10^{-4}$

$SiO_2 = 1.26 \times 10^{-5}$

$PMMA = -1.00 \times 10^{-4}$



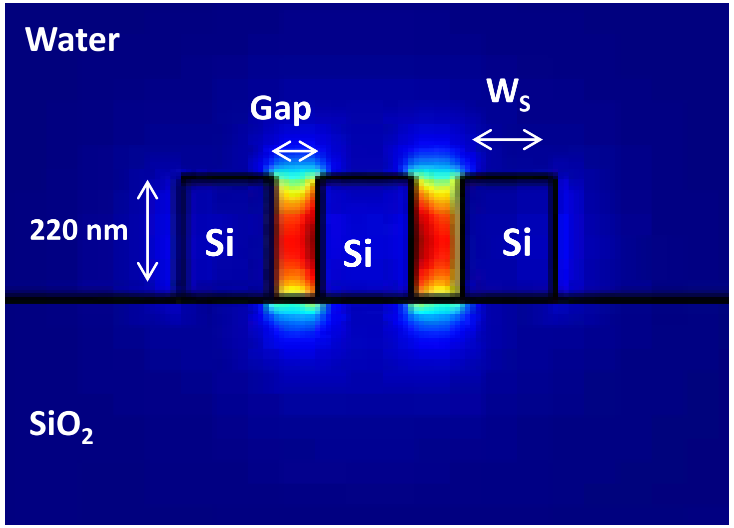
Waveguide configuration		$\frac{d\lambda_r}{dT} \approx \frac{dn_{eff}}{dT}\frac{\lambda_r}{n_g}$ [pm/°C]	
		Experiment	Simulation
Slot	With PMMA	12.8 ± 1.0	9.417
	Without PMMA	43.5 ± 2.3	44.46
Wire	Without PMMA	77.5 ± 4.8	77.74

Optics Express, vol. 26, no. 1, pp. 438-44, 2018.

S Feng *et. al.* Opt. Express, vol. 23, no. 20, p. 25653, 2015.

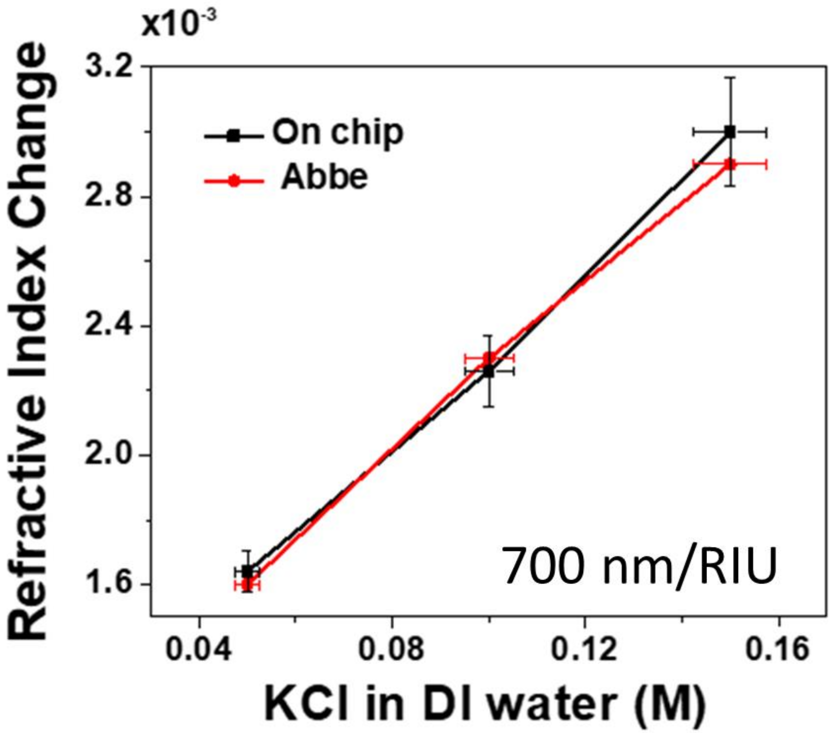
Estimation of Sensitivity

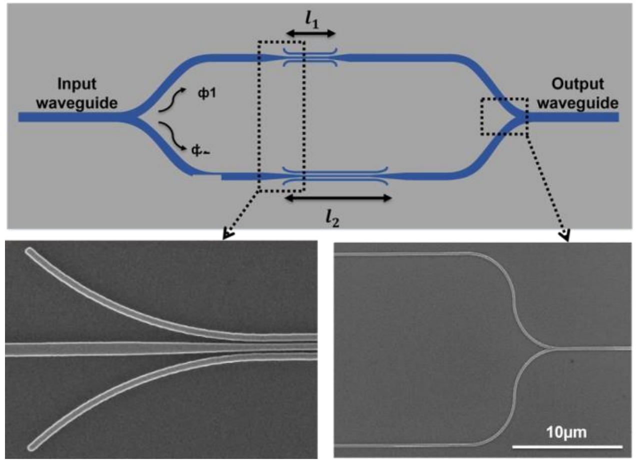
Double Slot

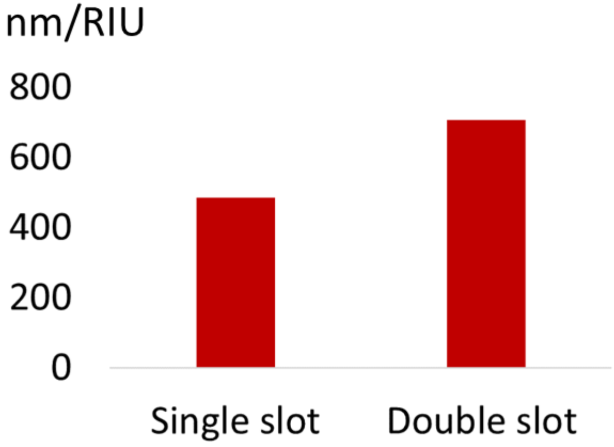


$$S = \frac{\lambda_r \, dn_{eff}}{n_g \, dn_{clad}} = \frac{\Delta\lambda}{\Delta n_{clad}}$$

S = 705 nm/RIU







IEEE Sensors Journal, 23(8), 8360, 2023.
Optics Express, vol. 26, no. 1, pp. 438-44, 2018.

Summary

Device	Waveguide	System resolution (δλ (pm))	Sensitivity (nm/RIU)	LOD (RIU)	Ref
MZI	Strip	NA	460 (2π)	3.0×10^{-5}	[1]
Ring	Strip	5	70	7.1×10^{-5}	[2]
	Slot	12.5	298	4.2×10^{-5}	[3]
		12.0	345	3.4×10^{-5}	[4]
	Slot	5.0	476	1.1×10^{-5}	[5]
PhC	Slot	NA	1538	7.0×10^{-6}	[6]
		NA	510	1.0×10^{-5}	[7]
Sub-wavelength grating	Strip	NA	666	NA	[8]
MZI	**Double Slot**	**5.0**	**700**	**7.1×10^{-6}**	**[9]**

1. Opt. Lett., vol. 33, no. 6, pp. 596–598, 2008.
2. Opt. Express, vol. 15, no. 12, pp. 7610–7615, 2007.
3. IEEE Photon. J., vol. 1, no. 3, pp. 197–204, 2009.
4. Proc. SPIE, vol. 8236, Feb. 2012, Art. no. 823620.
5. IEEE Sensors J., vol. 20, no. 11, pp. 5970–5975, 2020.
6. Appl. Phys. Lett., vol. 94, no. 6, Feb. 2009.
7. Opt. Lett., vol. 35, no. 15, pp. 2523–2525, 2010.
8. Opt. Lett. 39, 4442-4445 (2014).
9. IEEE Sensors Journal, 23(8), 8360, 2023

Collaboration interest – facility

- **Micro- and nano-fabrication facility**
- **Monolithic integration of materials**
- **Part-pieces to wafer-scale (6”) processing and testing**
- **PIC packaging (from 2025)**
- **Research HR exchanges**

FOCUS AREAS IN HETEROGENEOUS INTEGRATION AND ADVANCED PACKAGING

Semiconductor devices

- Heterogeneous integration
- 3D integration
- Enhanced reliability for automotive
- Flexible and biocompatible integration

RF devices

- High power RF device packaging
- RF system integration
- Enhanced reliability for harsh environment

MEMS sensor systems

- Heterogeneous integration with electronics
- Flexible and biocompatible platform
- 2.5D & 3D integration

Photon devices

- Photonic packaging
- Heterogenous integration

Running Programs: PhD & MTech

- As rank #1 institution, IISc attracts best students
- Deep hands-on process & integration expertise
- Focus on materials, device, packaging or photonics
- Industry projects & internships encouraged

Master degree in Semiconductor technology

PhD
- 5-year program
- >4Y thesis project

M. Tech. (Traditional)
- 2-year program
- 1-year thesis project
- Industry internship
- Conversion to PhD program

M. Engg. (Accelerated)
- 1-year program
- Course only, No thesis project
- Open to students from various field like materials, mechanical, chemical, etc.
- Industry point-upskilling
- Direct eligibility from top Indian Institutes

M. Tech. (Joint Taiwan)
- 1 Yr @Iisc+1 Yr in Taiwan
- Joint Degree
- 4 Taiwan universities
- National Taiwan University (NTU)
- National Chiao Tung Yang Ming University (NYCU)
- National Tsing Hua University (NTHU)
- National Sun Yat-Sen University (NSYSU)

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NSQF Certification in Semiconductor Technology

Electronics	Mechanical
Chemical	Materials
Applied Physics	Chemistry

Foundational Engineering (4Y degree)

+

Process Integration	**Unit-process**
Vacuum & Gas Handling	**Chemical & Gas Safety**
Equipment design & maintenance	**Modelling**

Certification Course(s)

=

- **Device design & modelling**
- **Design of experiments & loops**
- **Contamination, repeatability, and process control**
- **New unit processes**
- **Reactor and vacuum system design**
- **Metrology & defect analysis**
- **Device testing & reliability**
- **Facility support**
- **EHS & toxic gas handling**

Examples of Acquired Skills

1. Introductory course: 60-hour training for level 6.0 certification https://nqr.gov.in/qualifications/3809
2. Advanced course: 90-hour training for level 6.5 certification https://nqr.gov.in/qualifications/3808
3. Process-Engineer course: 160-hour training deep dive into one tool or module [in process]

NSQF-National Skills Qualifications Framework, Government of India

Models For Student Exchanges & Collaboration

MODE **1**

Summer research internships of undergraduate students (short-term 1 to 3 months)

MODE **2**

Student exchange between institutions for collaboration (short-term 6 months to 12 months)

MODE **3**

Joint supervision of Ph.D. students

Bilateral movement of IISc and collaborating institute graduate students (up to 18 months)

MODE **4**

Joint degree of Ph.D. students

Bilateral movement of IISc and collaborating institute graduate students (12-24 months)

SUCCESSFUL PARTNERSHIPS FOR JOINT PhD SUPERVISION

Initiated with several institutions across the world

TU-Delft (Netherlands), NTU (Singapore), Thales-CNRS (France), WSU, ANU, UoM (Australia), KTH (Sweden), Univ. of Manchester & UCL (UK), USC & Rice (USA)

SUCCESSFUL PARTNERSHIPS FOR JOINT PhD Degree

University of Melbourne, Australian National University, University of Manchester