Photonic Integration and Acousto-Optics in Aluminum Nitride

Siddhartha Ghosh

Microscale Acoustic and Photonic Systems Laboratory
Department of Electrical and Computer Engineering
Northeastern University
Boston, MA 02115
s.ghosh@northeastern.edu

NNCI Etch Symposium
University of Pennsylvania, Philadelphia, PA
April 22, 2022

Northeastern University

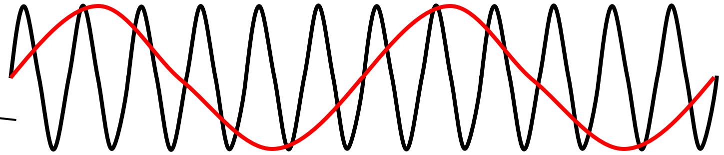
Outline

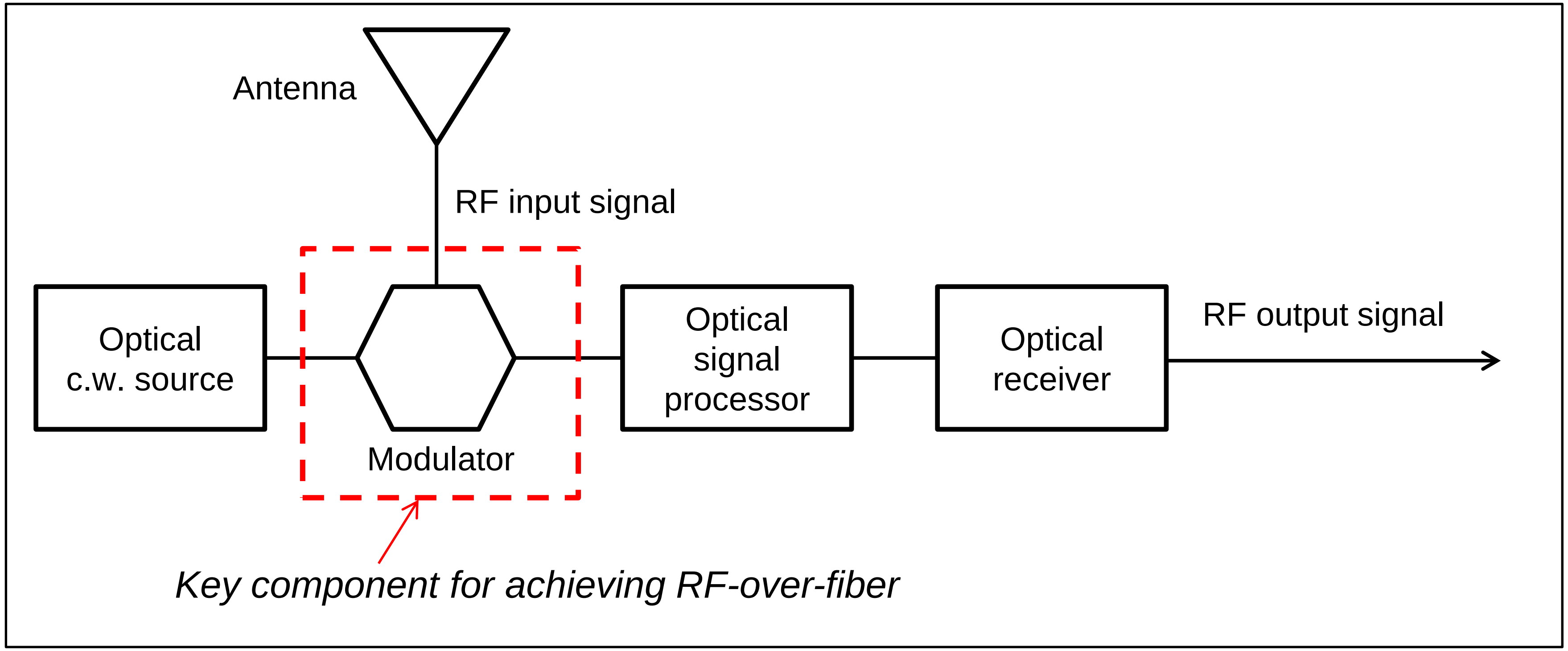
- **Motivation and background**
- **Material selection**
- **Light coupling in AlN**
- **Acousto-optic modulator**
- **200-mm process development**

Classical Applications in RF-Photonics

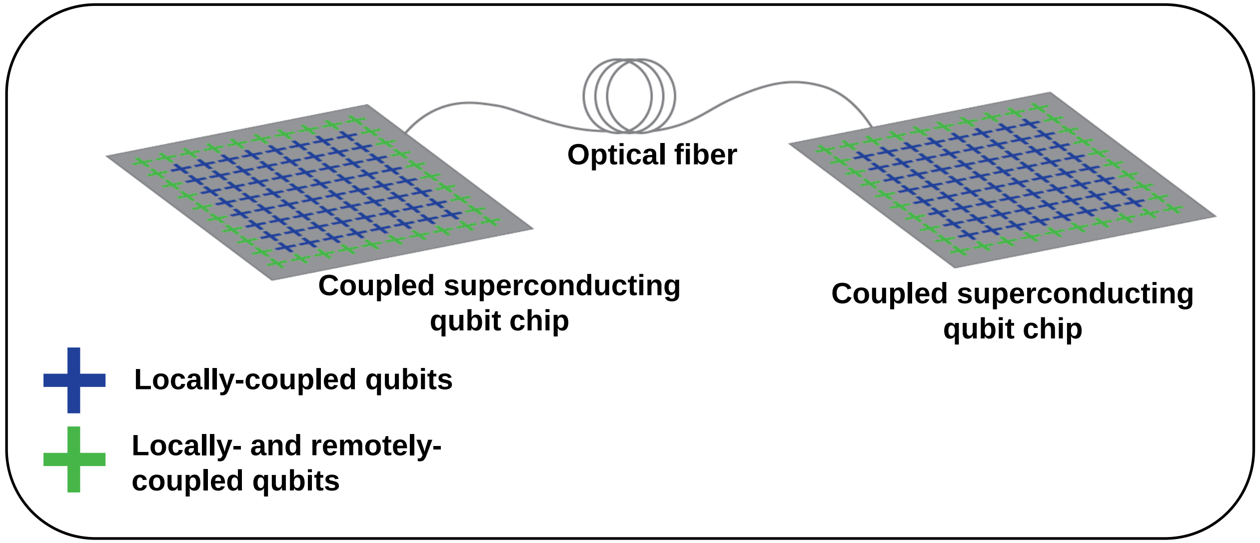
- **Optical links provide several advantages for controlling radio frequency (RF) signals in various communications applications**

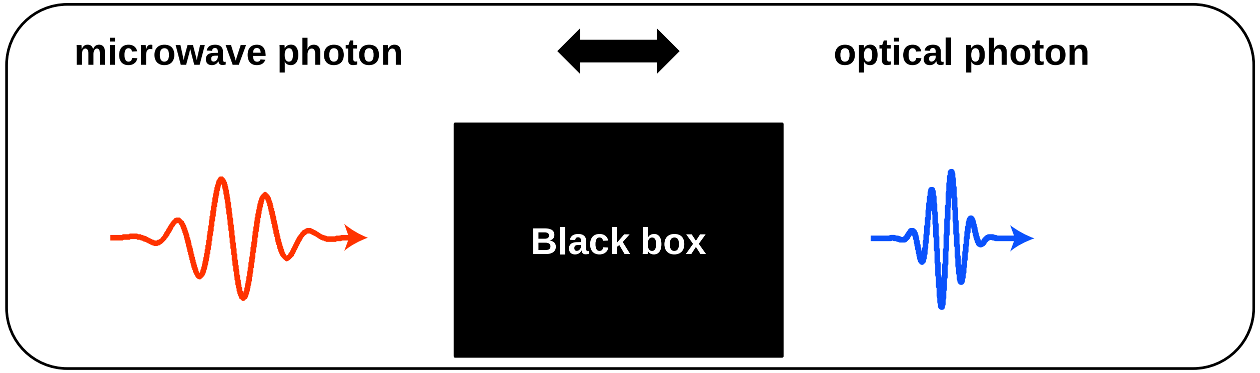
Use of light as a carrier:
✓ Increased channel capacity
✓ Frequency-independent low-loss delay lines





Coherent Microwave-to-Optical Conversion: A Quantum Interface



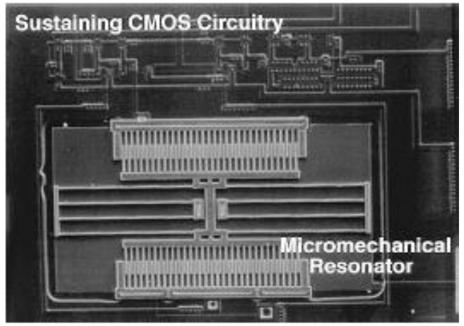


- Optical fibers can be used to transmit photons over long distances with very low loss
- Reversible coherent conversion between microwave and optical regimes can facilitate coupling of qubits in different cryostats
- Other applications include
  - Interface for components of a hybrid quantum system, e.g. a quantum network
  - High-bandwidth routing of control and readout signals from/into a cryostat
  - Optical detection of microwaves for radar, medical imaging, classical communication, navigation, etc.

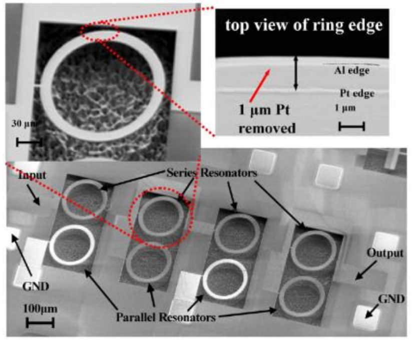
A quantum interface is an enabling technology for robust quantum computers and networks

MEMS for Integrated RF-Photonics

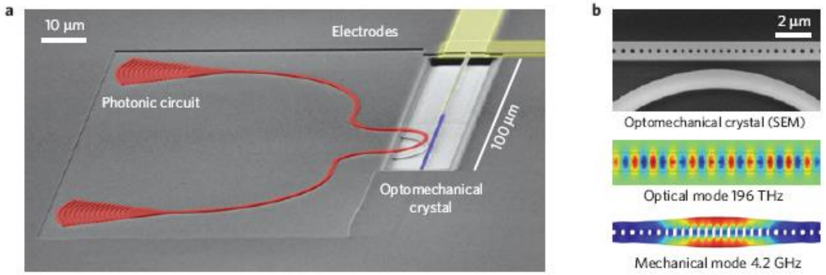
- **MEMS technology has been widely demonstrated for its compact filtering capabilities, CMOS compatibility and use in RF reference oscillators**



*Nguyen & Howe, JSSC **34**, 1999*



*Piazza et al., JMEMS **16**, 2007*



*Bochmann et al., Nat. Physics **9**, 2013*

- **Piezoelectric actuation offers:**
  - ✓ Scaling to higher/ multiple frequencies with lithographically-defined features
  - ✓ Strong electromechanical coupling
  - ✓ Low motional impedances/Matching to 50Ω electronics

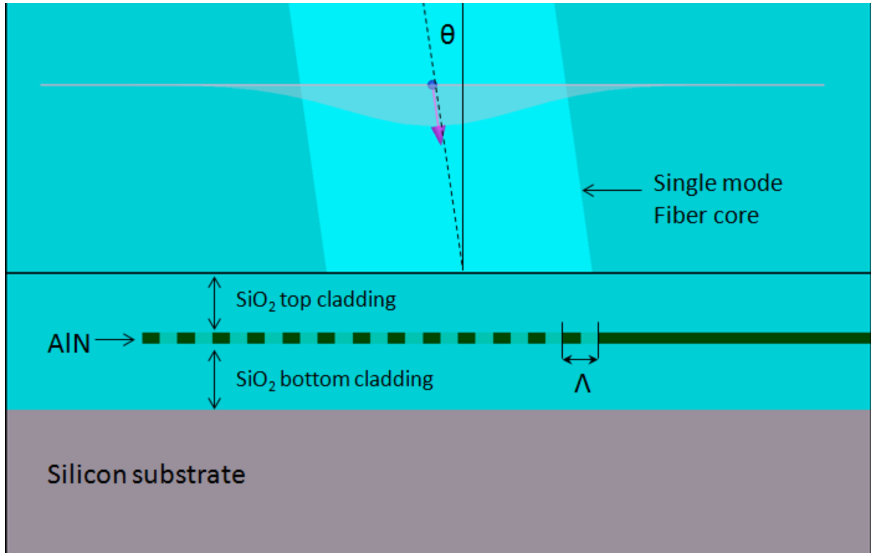
- **Advances in cavity optomechanics have produced highly sensitive detection techniques with useful applications in communications and fundamental science**

We seek to capitalize on these capabilities by creating devices that function in both the acoustic and optical domains

Integrated Photonic Material Options

Function / Property	III-V Compound Semiconductors (InP, GaAs, GaN)	Silicon (Si) + Germanium (Ge)	Silicon Dioxide (SiO_2) & Silicon Nitride (Si_3N_4)	Lithium Niobate ($LiNbO_3$)	Aluminum Nitride (AlN)	Polymers	Hexagonal Silicon Carbide (4H-SiC)
Efficient Light Emission	Direct Bandgap						
Efficient Light Detection							
Electro-Optic Modulation							
Electro-Absorption Mod							
Free-Carrier Modulation							
Thermo-Optic Modulation							
Piezoelectric							
Acousto-Optic Modulation							
Low-Loss Passives							
Efficient Nonlinearities	2nd & 3rd order	3rd order	3rd order	2nd & 3rd	2nd & 3rd	2nd & 3rd	2nd & 3rd
High-Power Handling							
Monolithic Electronics							
Foundry Compatible							

Grating Coupler Design

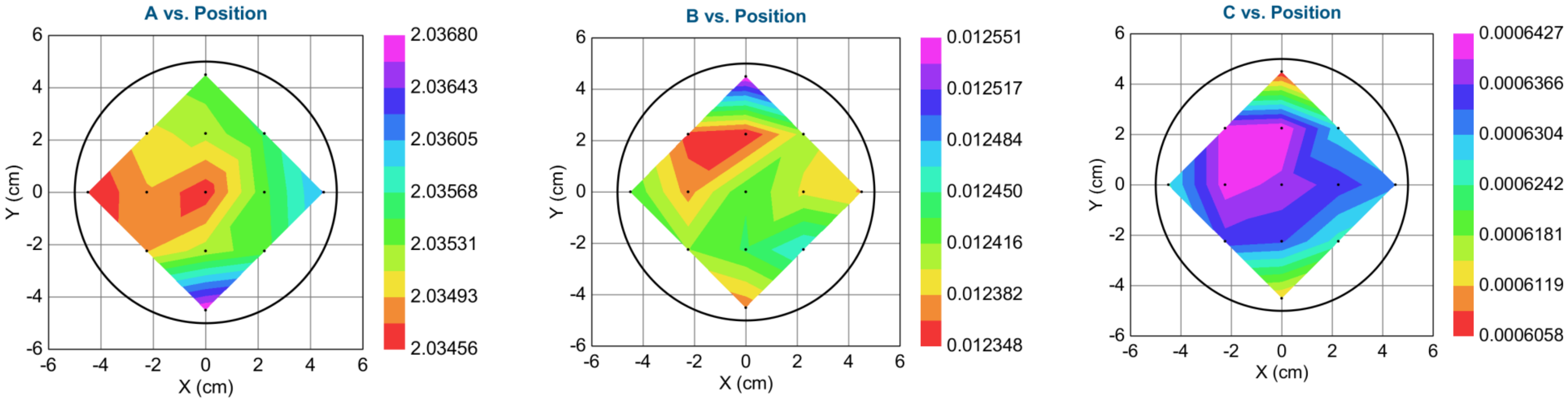


Approximate grating pitch from Bragg condition:

$$\frac{1}{\Lambda} = \frac{n_{eff}}{\lambda} - \frac{n_o}{\lambda}\sin\theta$$

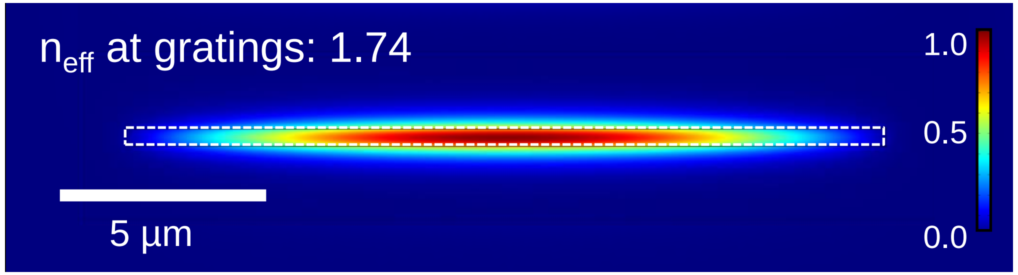
Fix: $\theta = 8^\circ$, t_{AlN} = 400nm, SiO_2 cladding, λ = 1550 nm

Polycrystalline AlN: 400nm thick



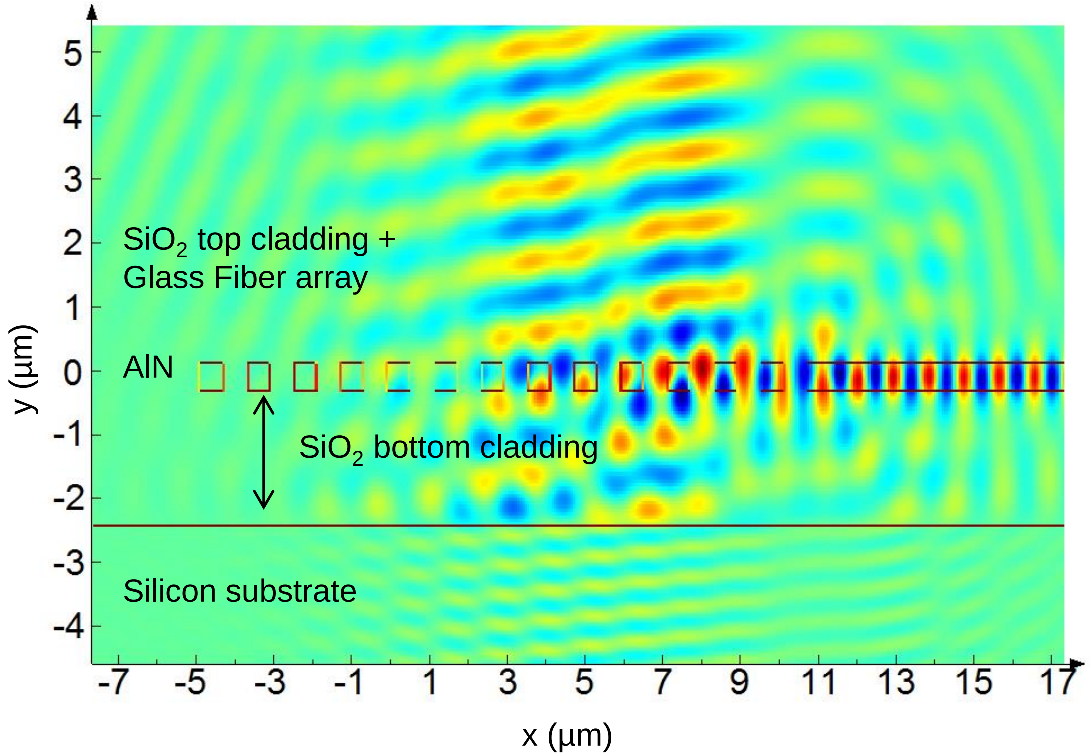
A=2.0353 ± 8.03x10^{-4}
B=0.0124 ± 2.39x10^{-4}
C=0.0006 ± 3.28x10^{-5}

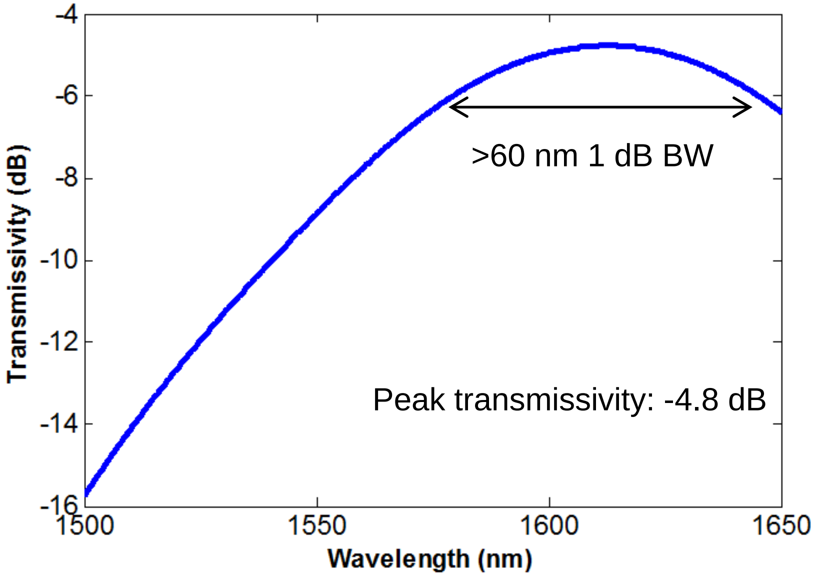
Grating Coupler Simulation



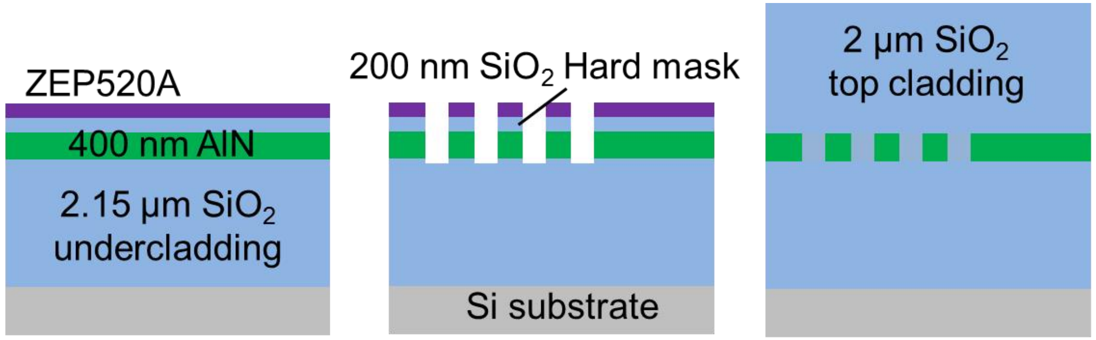
n_{eff} (average) = 1.6, Λ = 1.2 µm

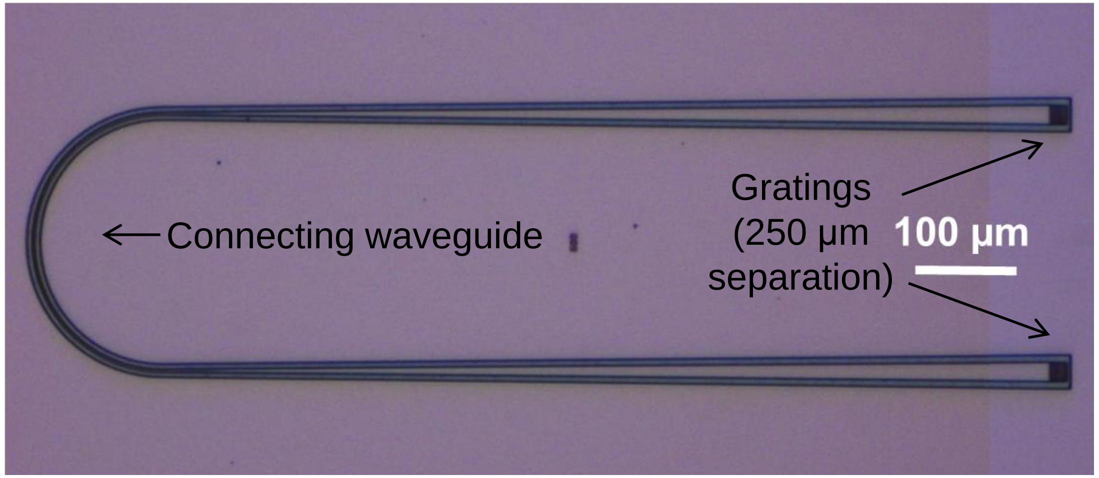
Cladding layers: 2.15 µm & 2.0 µm

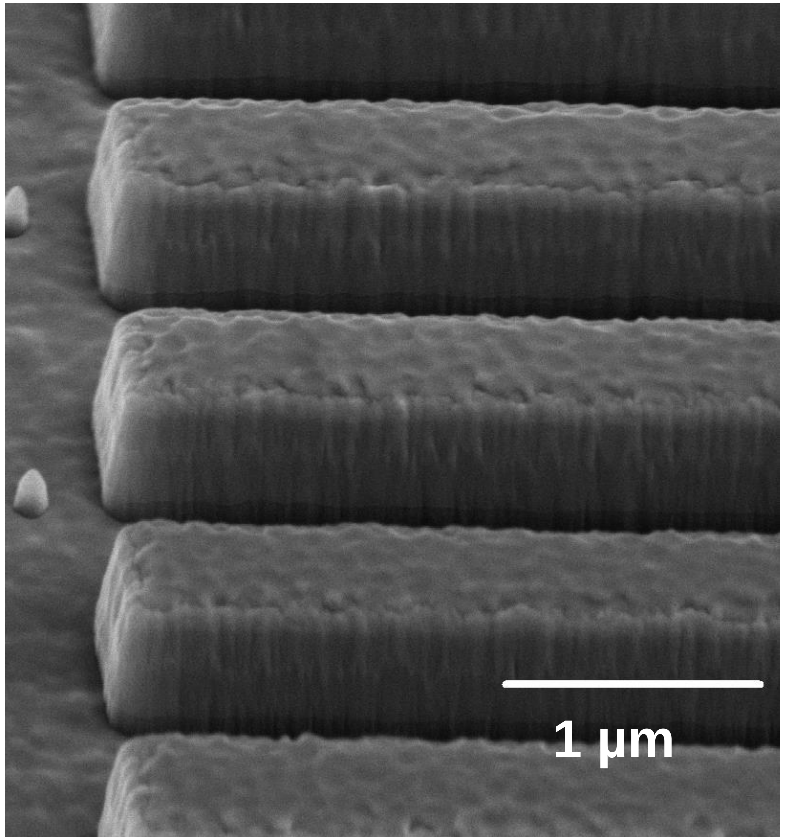




Fabrication

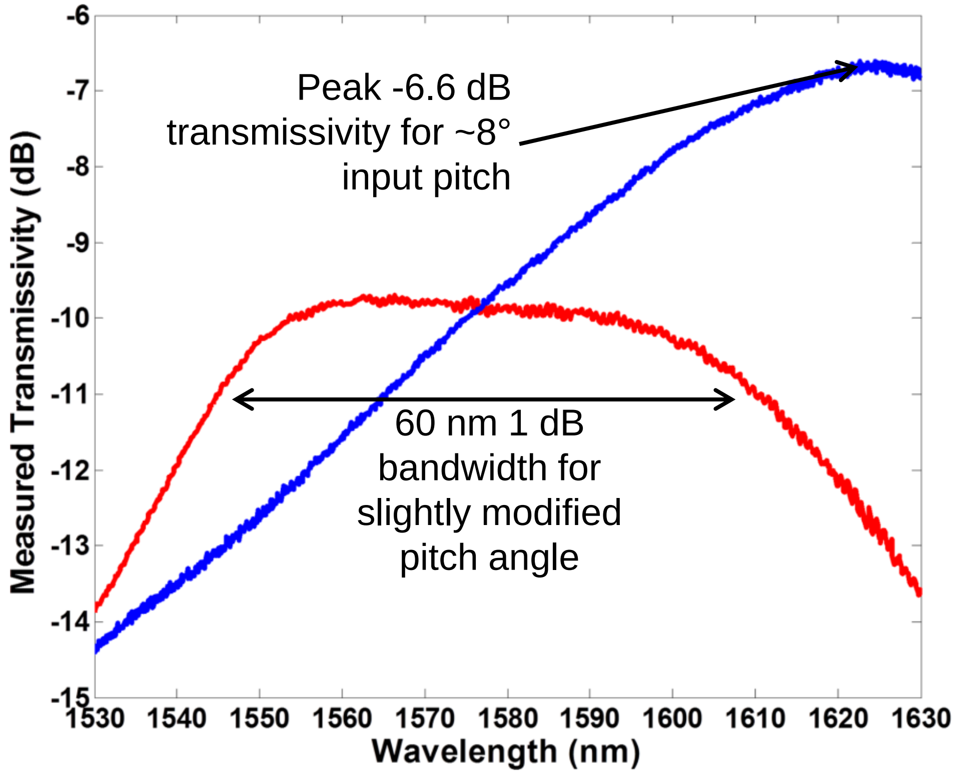


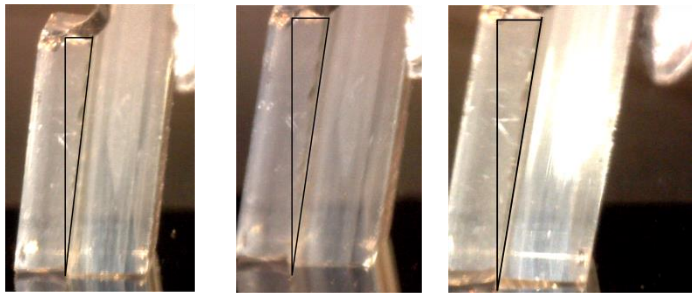




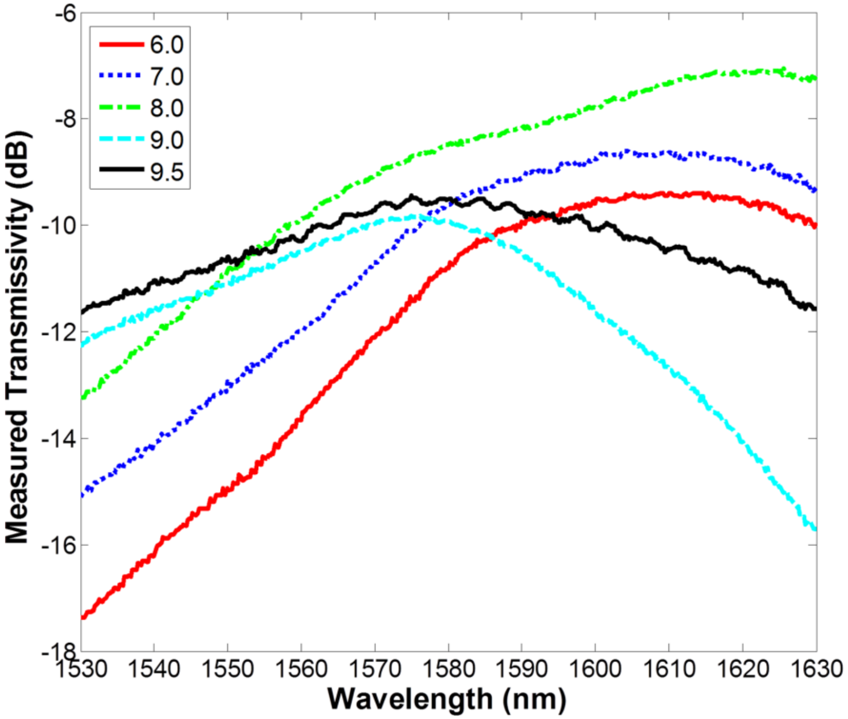
AlN etch – Plasmatherm Versaline	
RF Power	125 W
ICP Power	400 W
Pressure:	5 mT
Cl2 flow:	25 sccm
BCl3 flow:	5 sccm
Ar flow:	70 sccm
Temperature:	25C electrode 120C lid 70C liner 120C spool

Grating Measurements

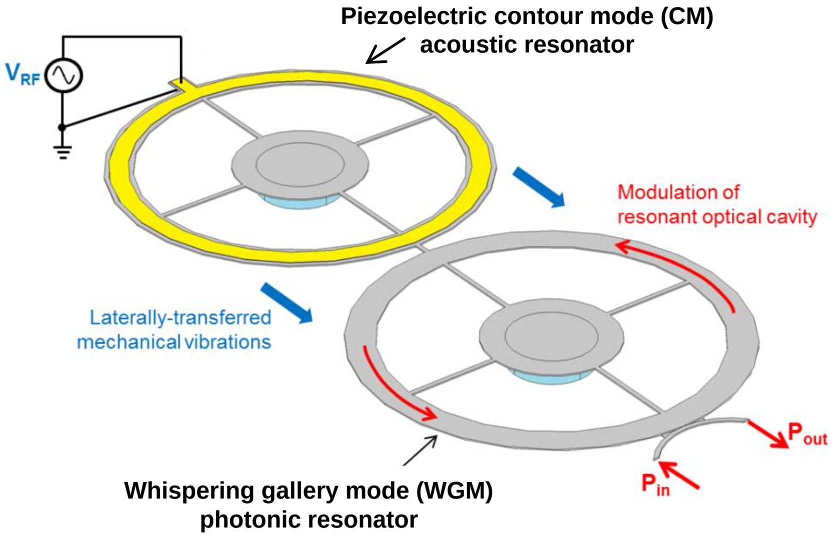


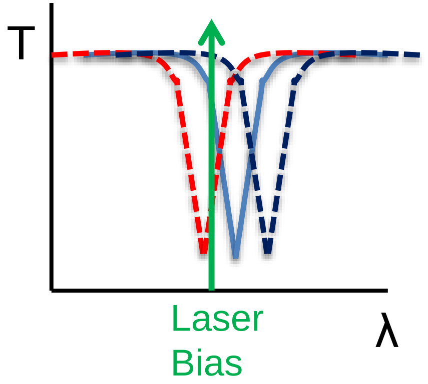


Varying pitch angle (8° initial):



Acousto-Optic Modulator – Concept



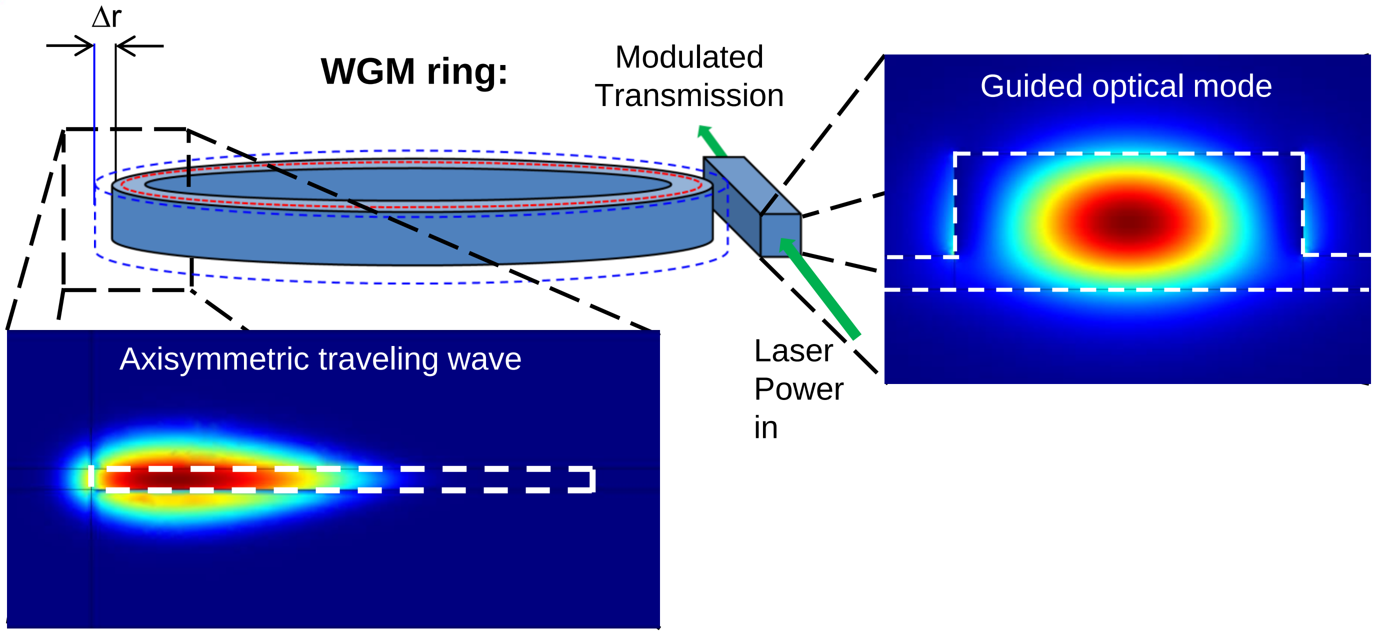


- **Piezoelectric actuation generates perturbations to the optical resonance condition:**

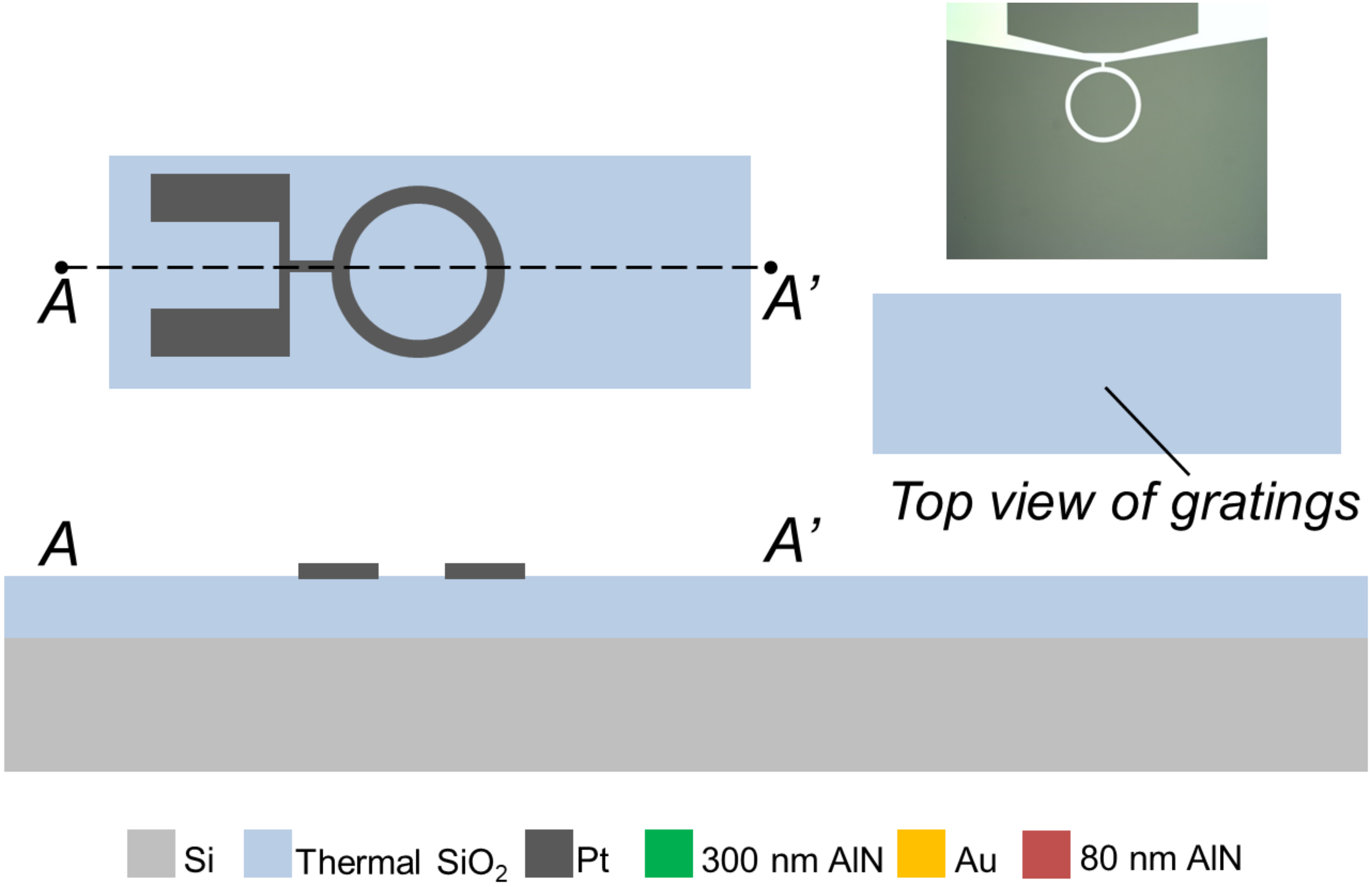
$$m\lambda_o = n_{eff} \cdot 2\pi R$$

- **Optical intensity modulation of the output given by:**

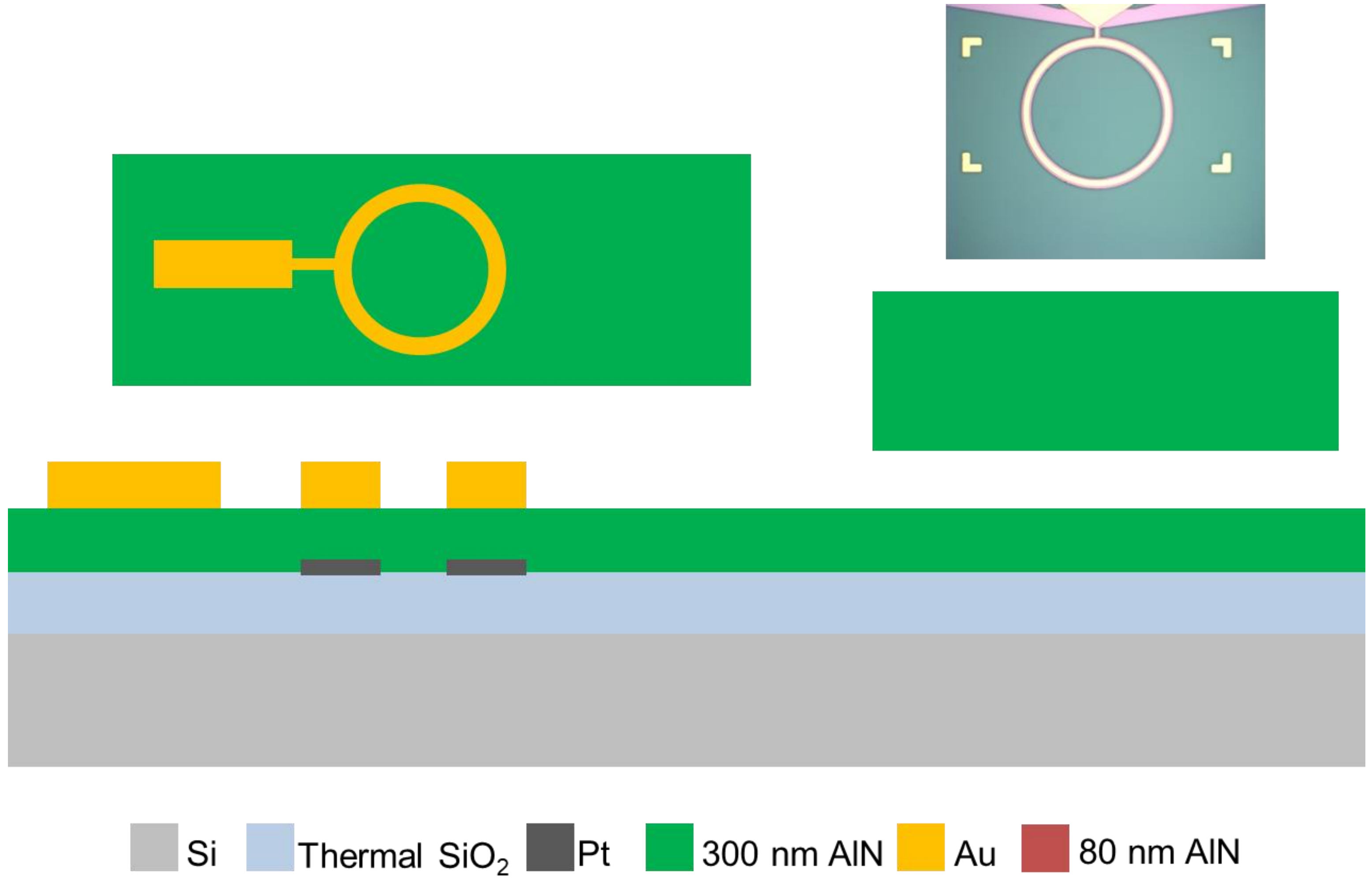
$$P_{\mathrm{mod}} = \frac{dT}{d\lambda} \cdot \frac{d\lambda}{dr} \cdot \Delta r \longleftarrow \Delta r = \eta_{om} V_{rms}$$



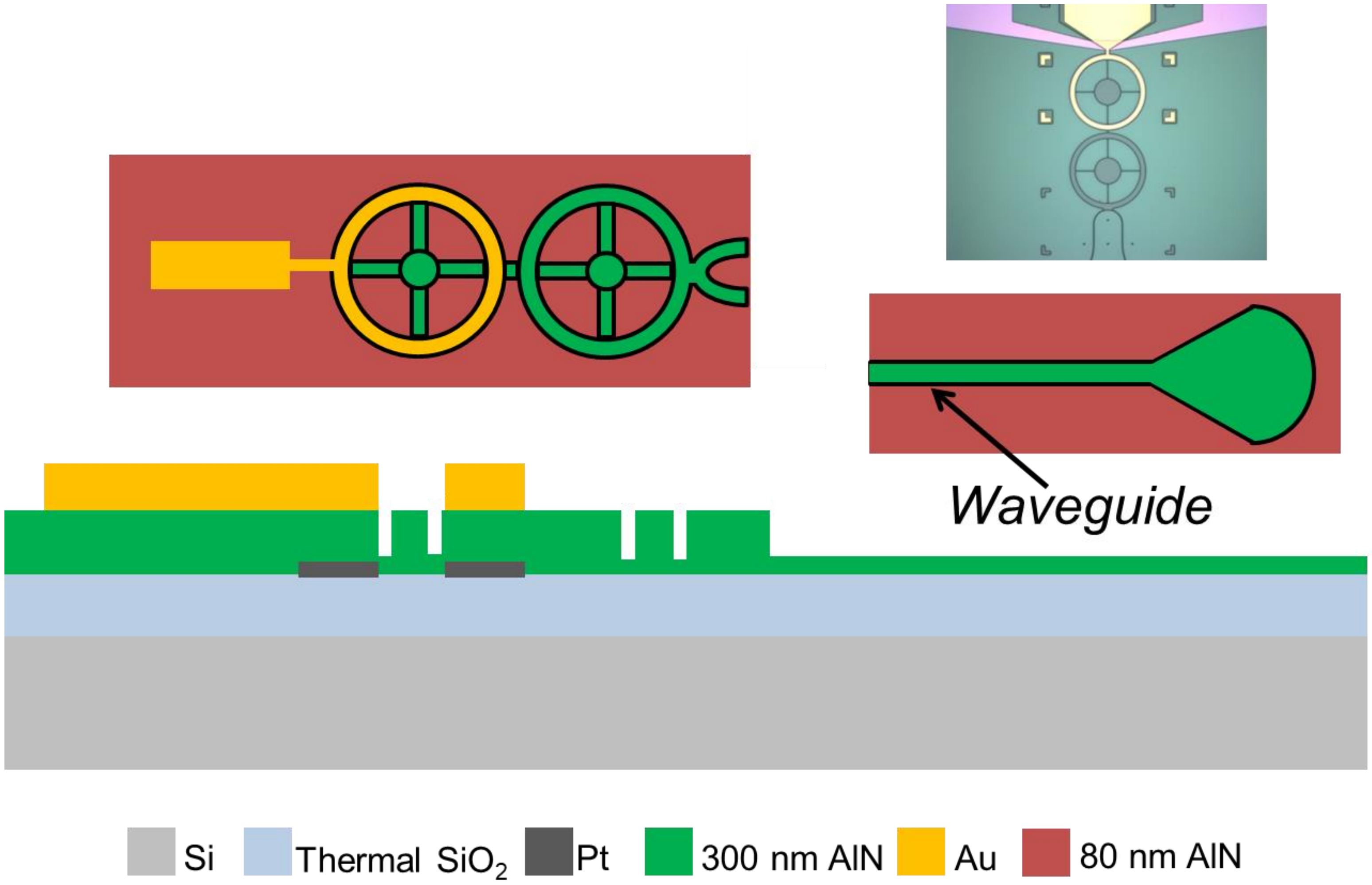
Lift-off for Pt Bottom Electrodes on Thermally Oxidized HR Wafer



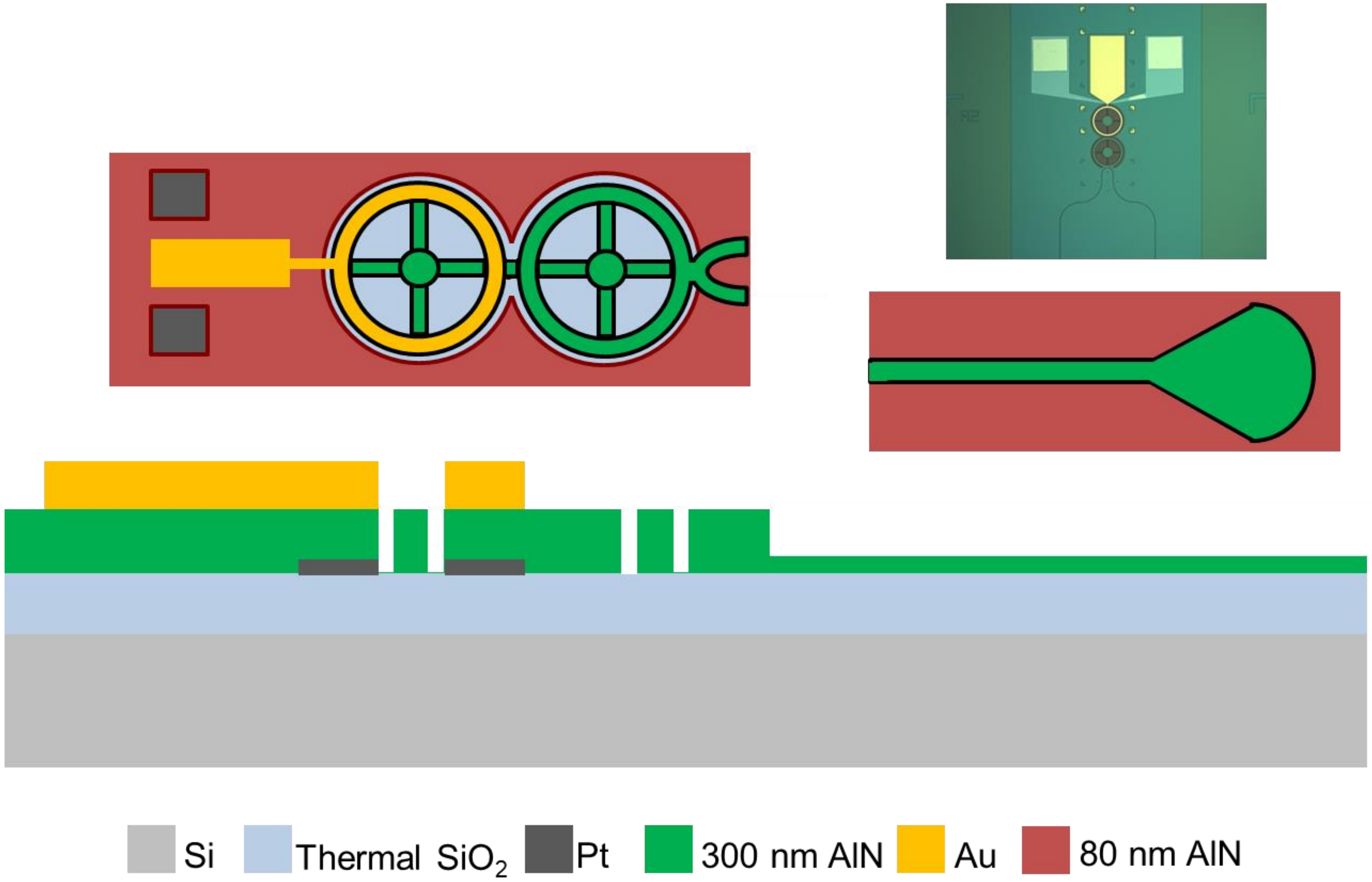
300 nm AlN Deposition & Lift-off for Au Top Electrodes



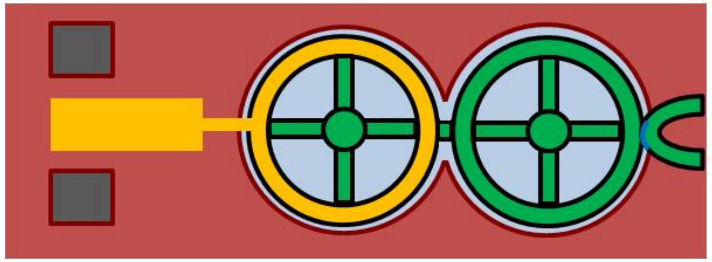
1st AlN Partial Etch: Define Large Features (Resonators, Waveguides)

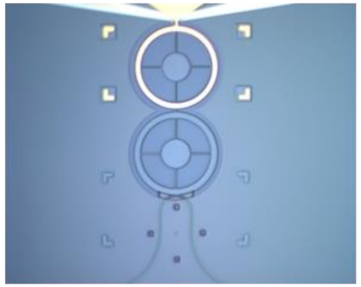


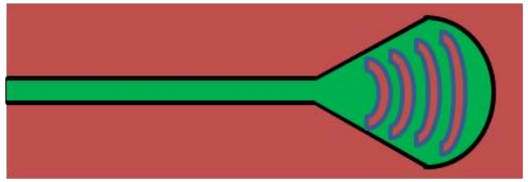
Define Vias (to bottom Pt) and Release Windows – Etch through AlN

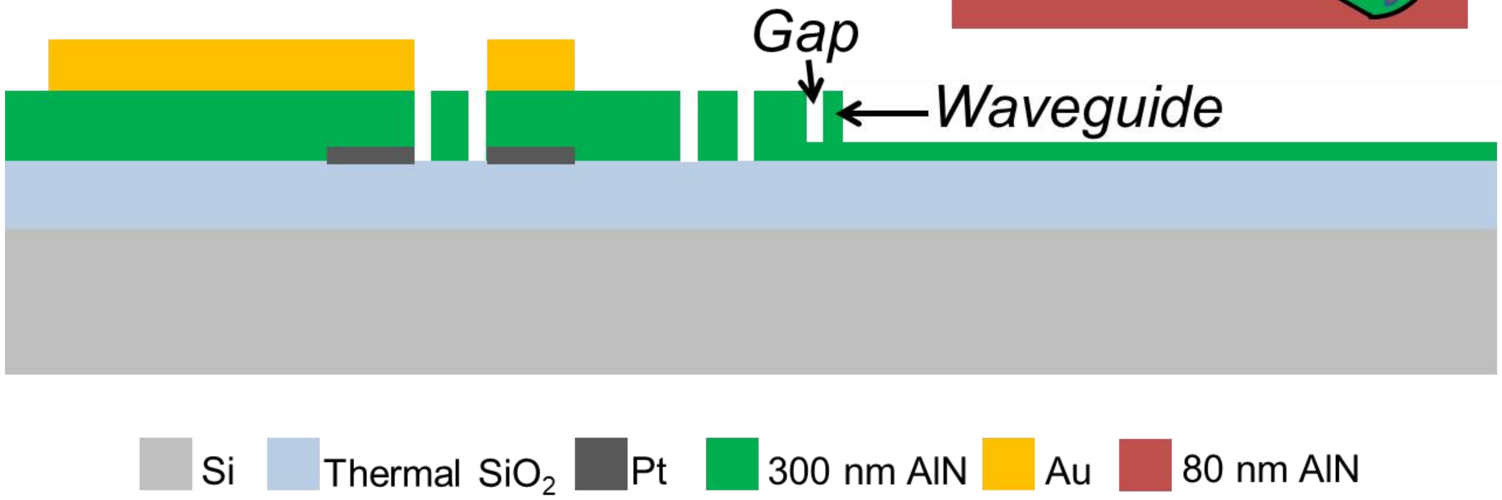


E-beam Lithography of Gaps and Gratings + 2nd Partial etch

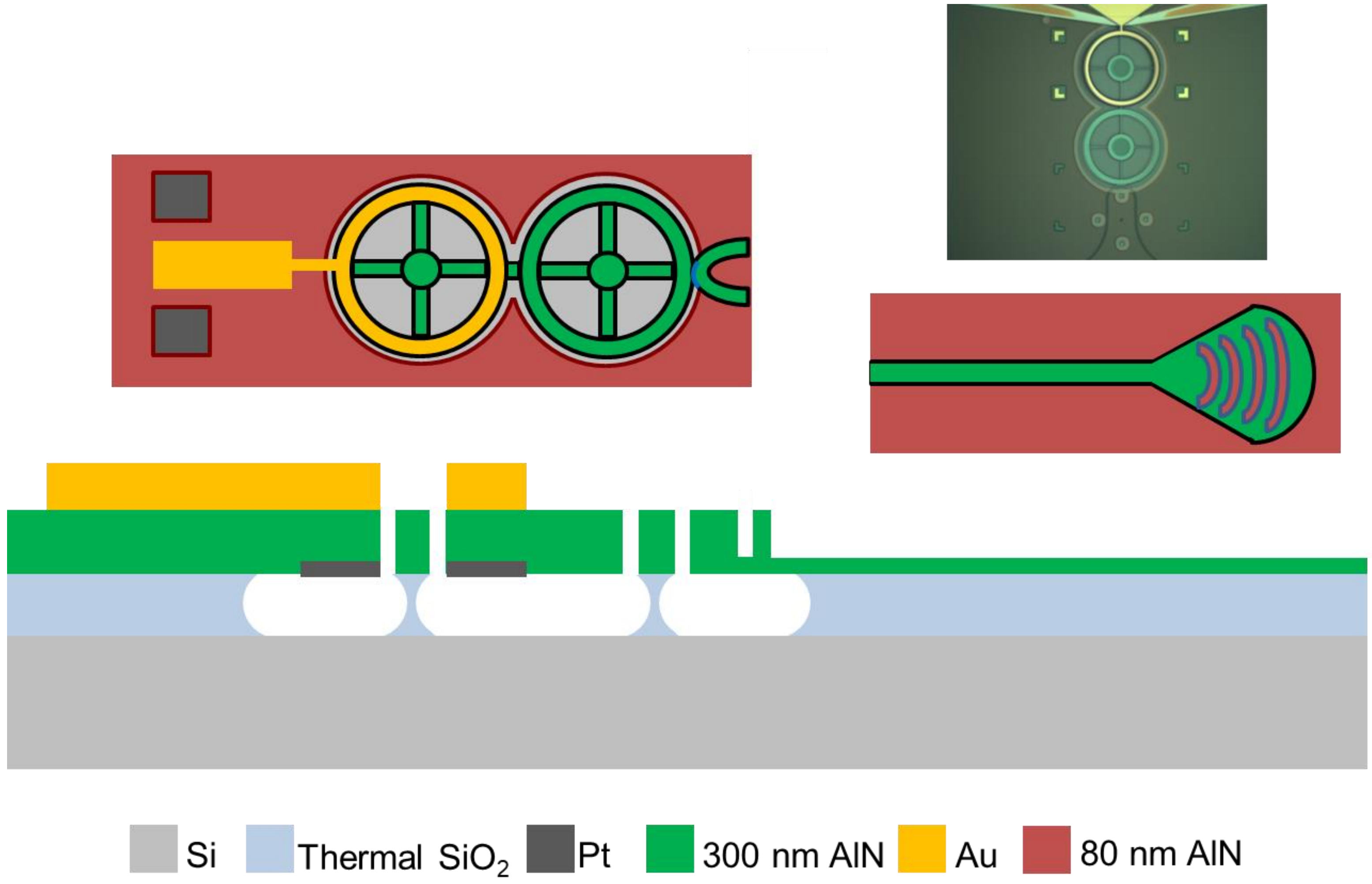




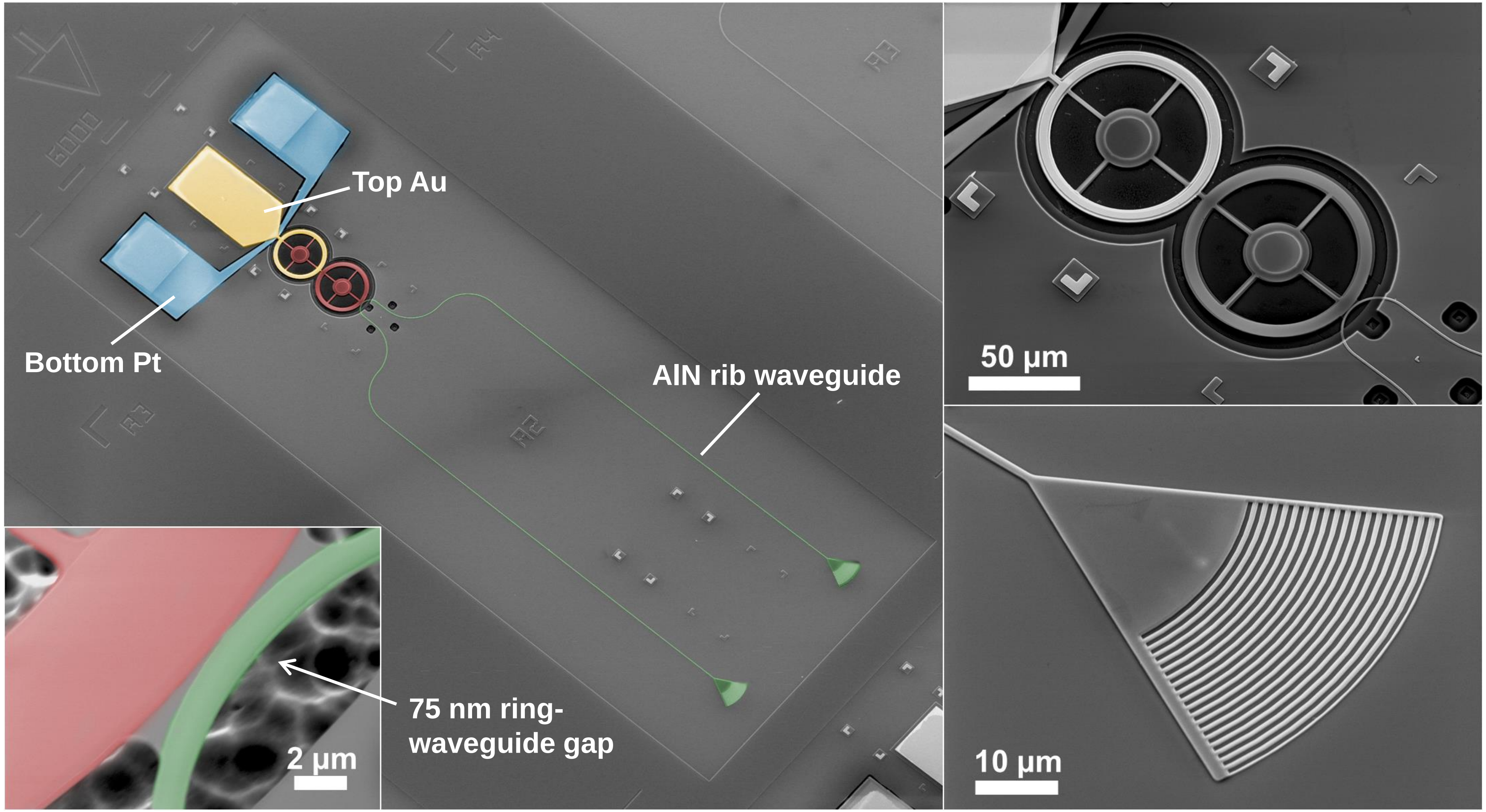




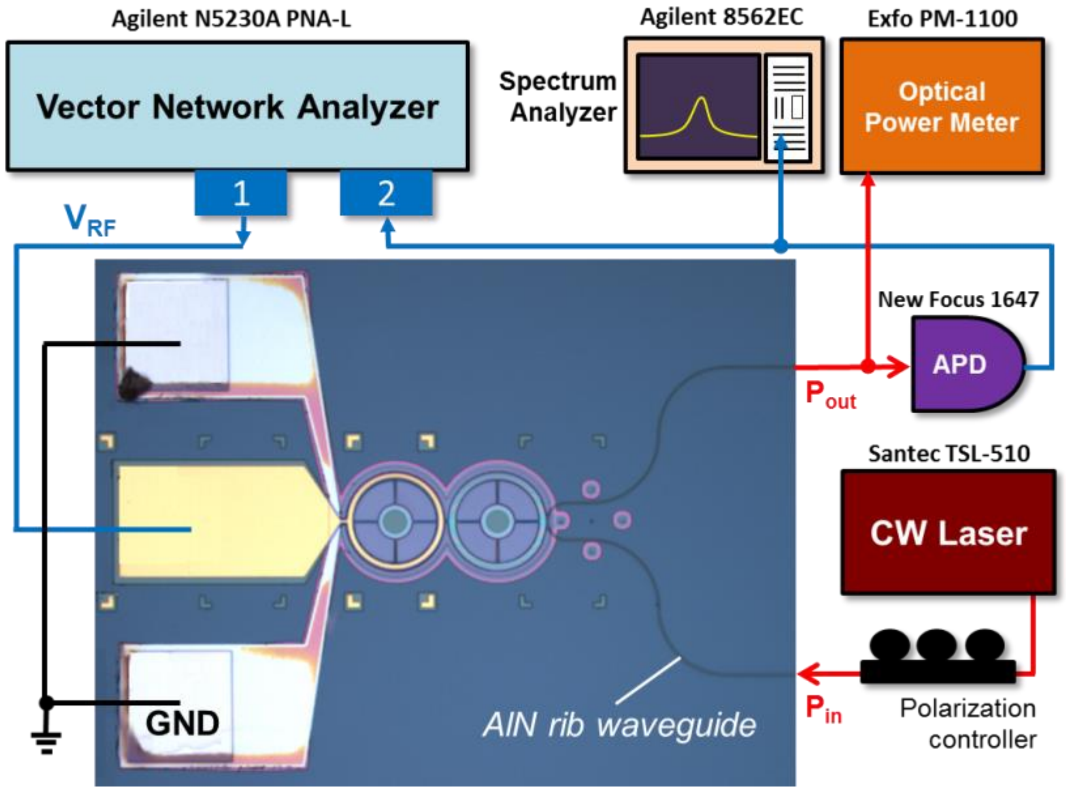
Vapor HF Release of CMR and WGM Resonators



Integrated Modulator Device



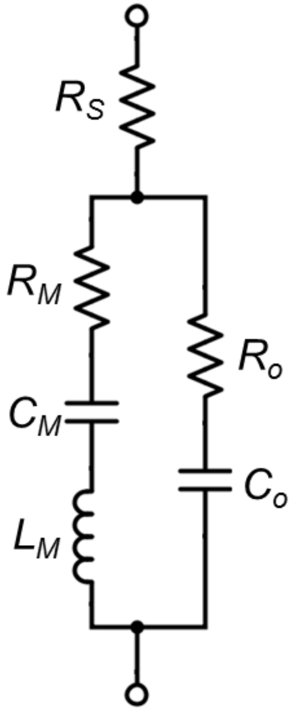
Acousto-Optic Modulator Characterization

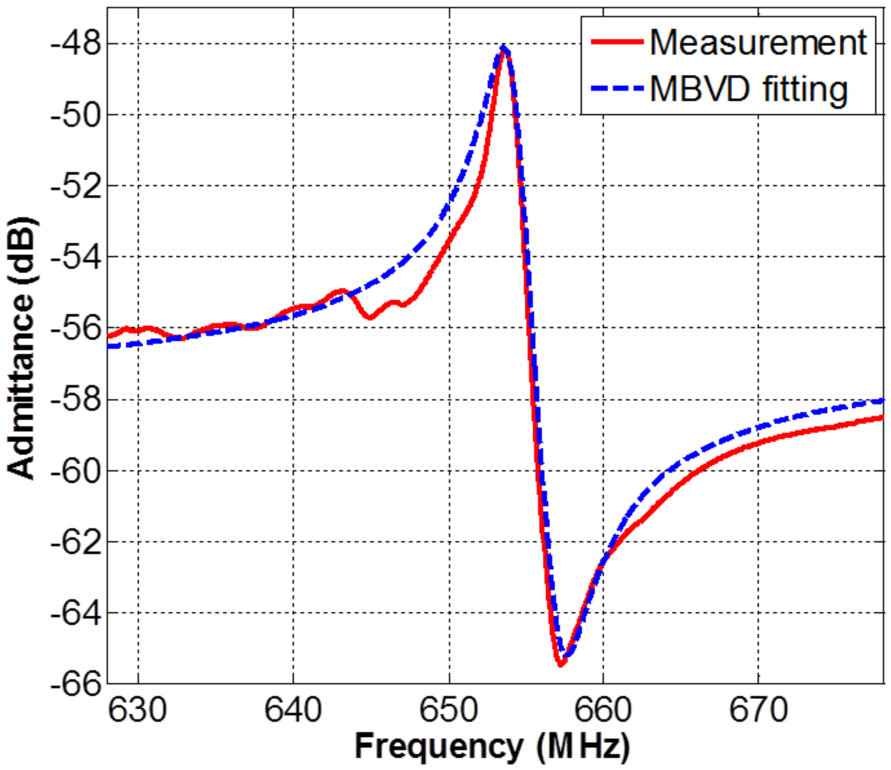


- Device characterization is done for both types of resonator
- Acoustic resonator tested with RF ground-signal-ground probes to extract S_{11} parameters
- Optical resonator tested with fiber array
- Simultaneous probing for electro-optomechanical characterization (via S_{21} or Spectrum Analyzer)

Acoustic Resonator Response

- **Modified Butterworth van Dyke (MBVD) equivalent circuit model:**

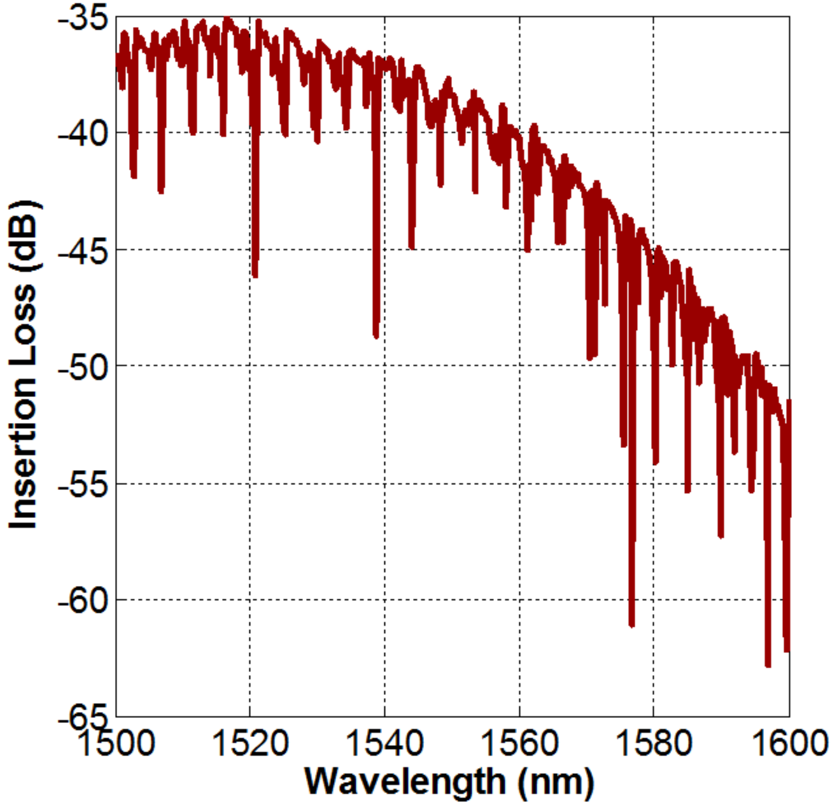


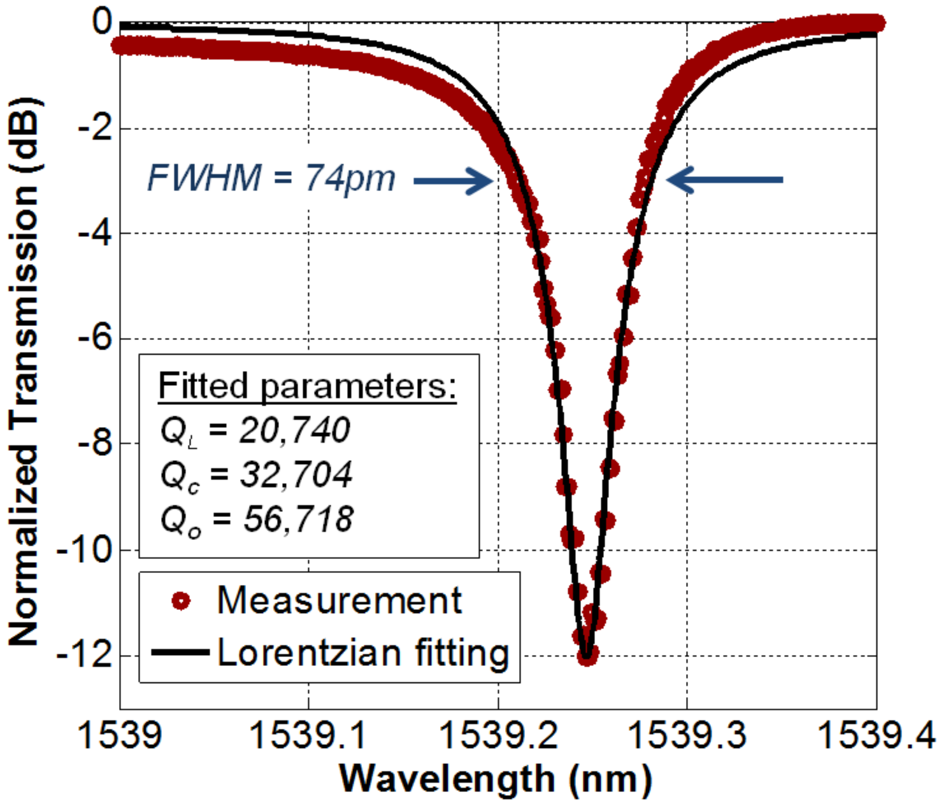


<u>Fitted parameters:</u>

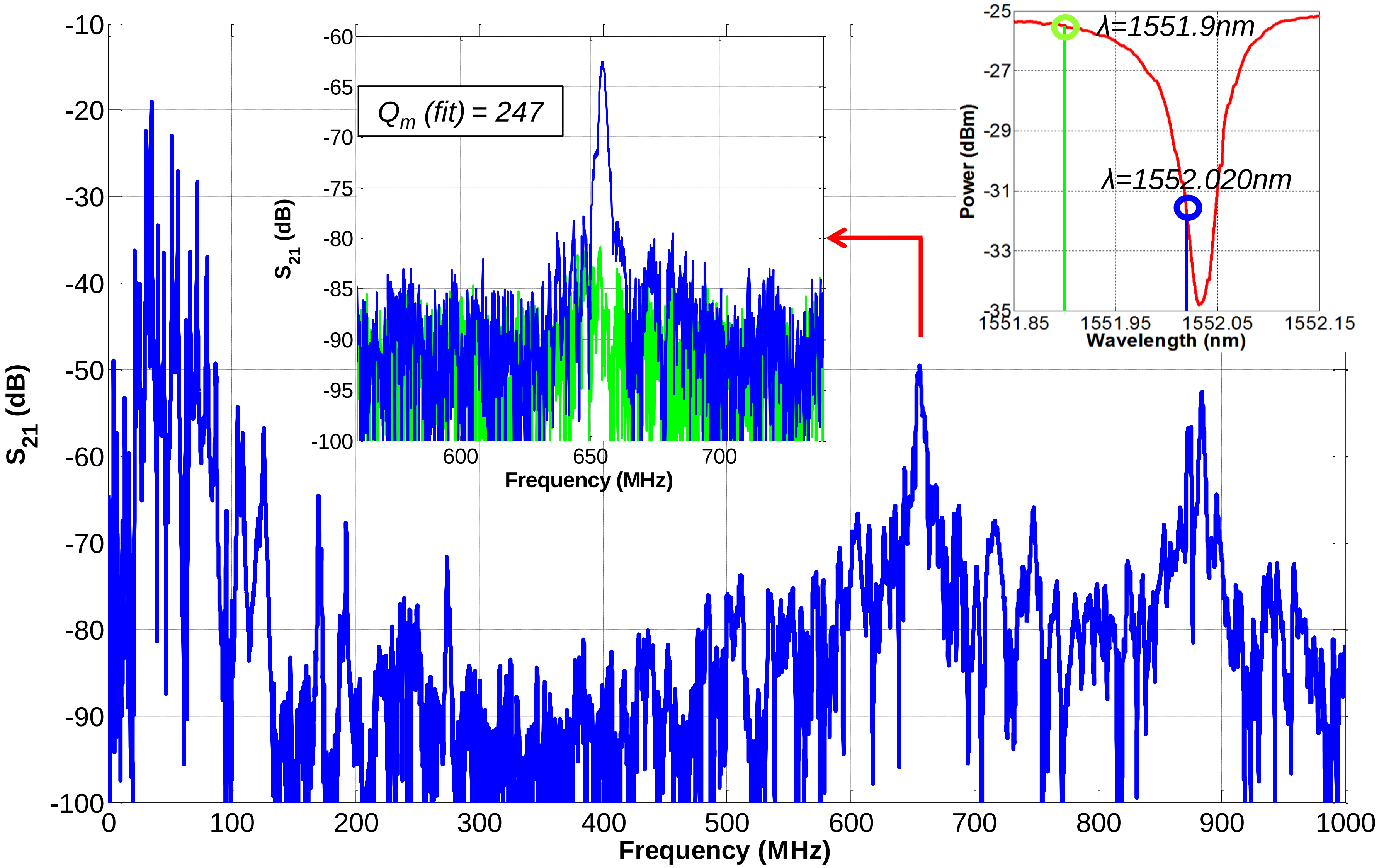
f_o = 653.96 MHz
Q_{mech} = 270
k_t^2 = 1.16%
R_S = 68 Ω
R_M = 220 Ω
C_M = 3.24 fF
L_M = 18.22 uH
R_o = 100 Ω
C_o = 345 fF

Photonic Resonator Response





Forward Transmission (S_{21}) – Electro-Optomechanical Measurement

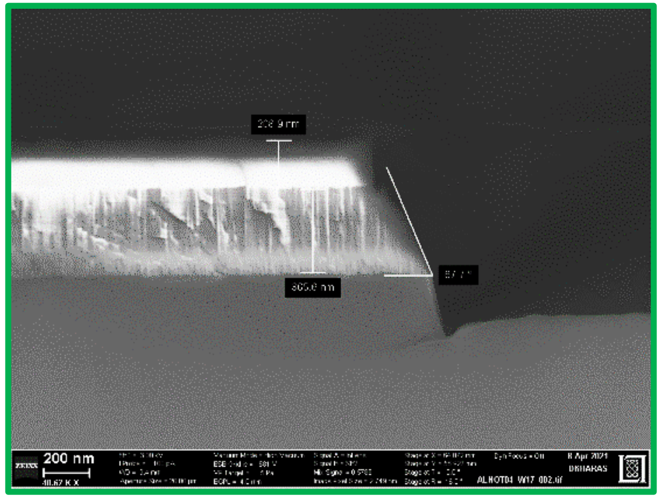


Northeastern University

200-mm wafer processing – etch development

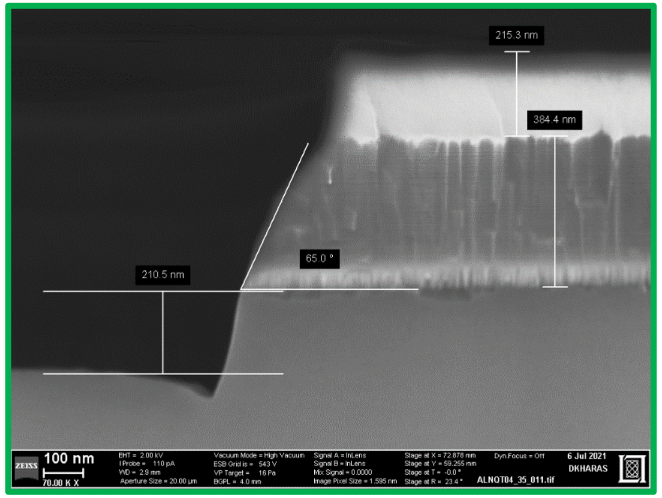
Applied Materials Centura Metal Etch

	Variables:	Best Condition:
ICP Power (W)	{1000, 1200}	1000
Bias Power (W)	{100, 125}	125
Pressure (mTorr)	{4, 6, 15}	6
Cl2 flow (sccm)	{0, 40, 82, 120}	120
BCl3 flow (sccm)	{0, 10, 20, 58, 100}	10
Ar flow (sccm)	{0, 20, 40, 80}	40
Total flow (sccm)	{100, 160, 170, 180, 220}	170
Etched Result:	Angle	~65°

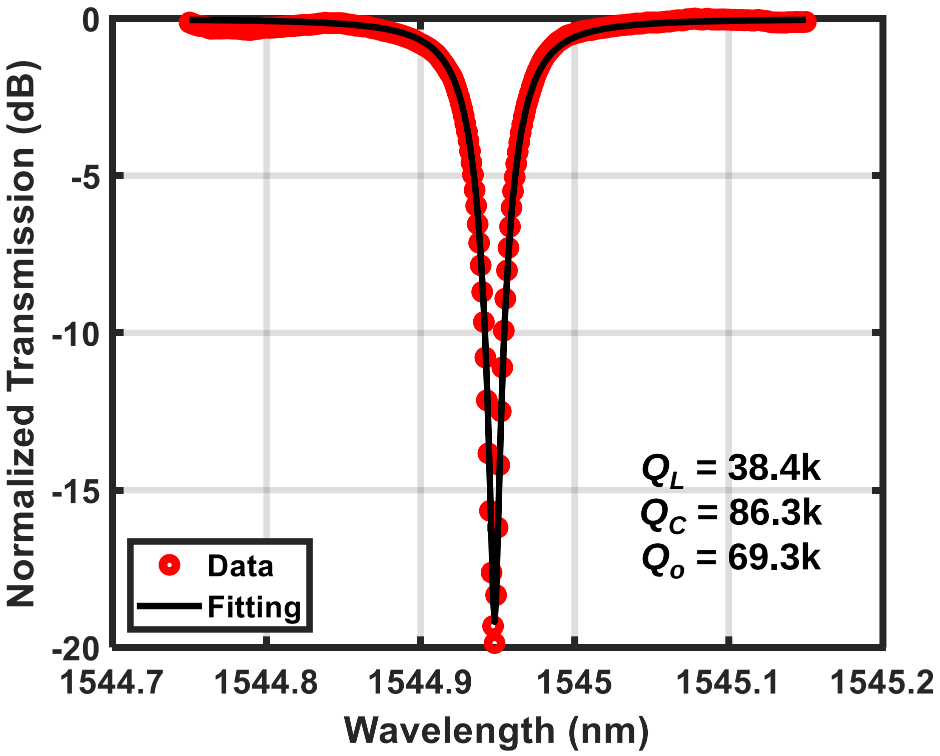


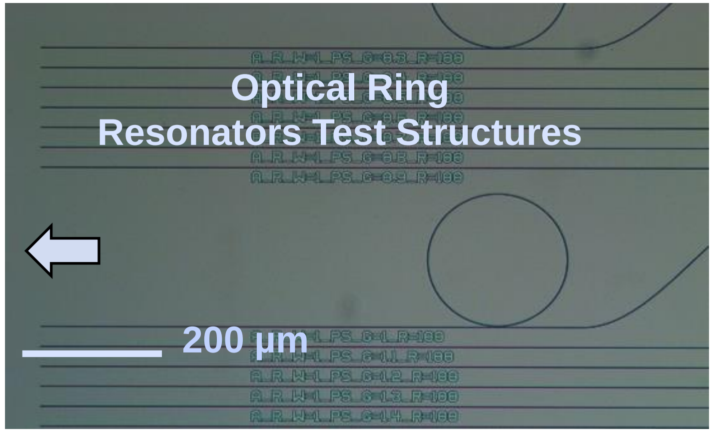
SAMCO Metal Etch

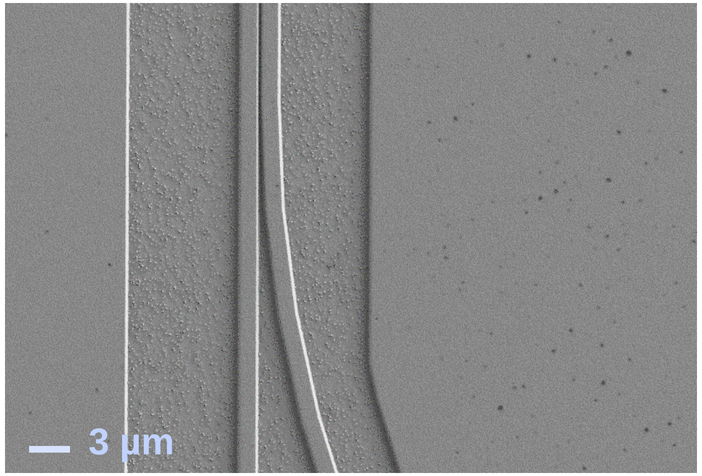
	Variables:	Best Condition:
ICP Power (W)	{600}	600
Bias Power (W)	{200}	200
Pressure (Pa)	{0.4, 0.7, 1.1}	0.4
Cl2 flow (sccm)	{14, 20, 30, 40, 65, 90}	40
BCl3 flow (sccm)	{0, 5, 10, 15, 40}	10
Ar flow (sccm)	{0, 6, 10, 15}	0
Total flow (sccm)	{20, 30, 35, 40, 50, 115}	50
Etched Result:	Angle	~65°

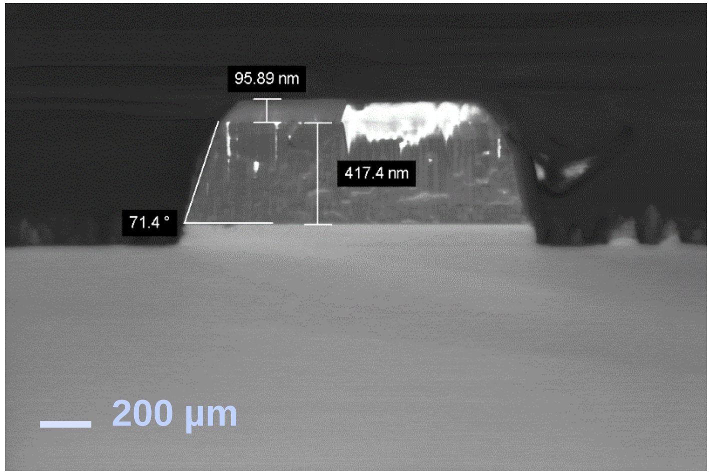


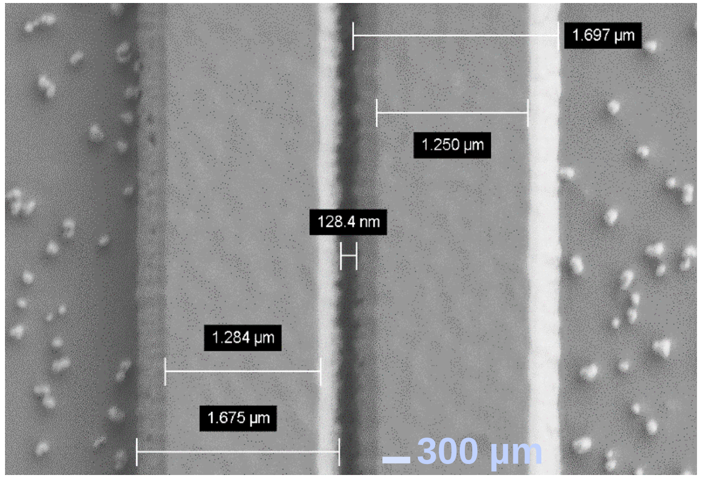
Initial Optical Ring Resonator Measurements











Target Q achievable through:
5-10X enhancement for disk resonator geometries
2-3X improvement from etching optimization

Conclusions

- **AlN is an excellent platform for photonic integration targeting applications in RF-Photonics as well as quantum information processing**

- **Low-loss gratings and waveguides have been demonstrated with sputtered AlN thin films**

- **Piezoelectric and photonic resonators are successfully co-fabricated to demonstrate displacement-based acousto-optic modulators**

- **Further improvements to processing will enable microwave-to-optical frequency converters in 200-mm platform**

Acknowledgements

Carnegie Mellon University:

- Prof. Gianluca Piazza
- Matt Moneck
- Norm Gottron
- James Rosvanis
- National Science Foundation (NSF ECCS-1201659)

Northeastern University:

- Jack Guida
- Michele Pirro
- Prof. Matteo Rinaldi

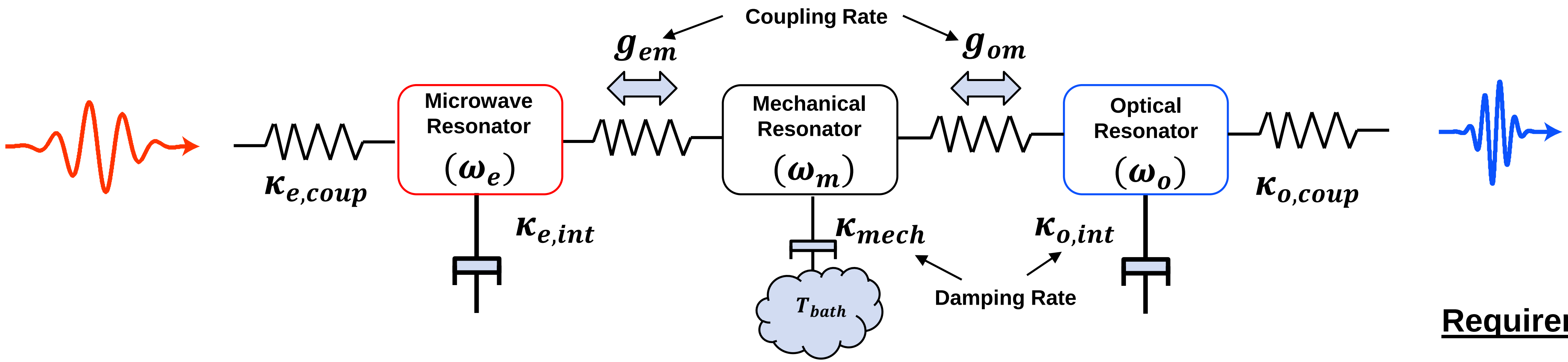
MITLL Quantum Transducer team:

- Dave Kharas
- Danna Rosenberg
- Alex Medeiros
- Matt Cook
- Cyrus Hirjibehedin
- Paul Juodawlkis

Thank you!

Supplementary

Optical-to-Microwave Photon Conversion



Efficiency

$$\eta_e = \frac{\kappa_{e,coup}}{\kappa_{e,coup} + \kappa_{e,int}} \qquad \eta_{mech} = \frac{4C_{em}C_{om}}{(C_{em} + C_{om} + 1)^2} \qquad \eta_o = \frac{\kappa_{o,coup}}{\kappa_{o,coup} + \kappa_{o,int}}$$

Bandwidth

$$\Gamma_{em} = \frac{4g_{em}^2}{\kappa_{e,coup} + \kappa_{e,int}} \qquad \Gamma_{om} = \frac{4g_{om}^2}{\kappa_{o,coup} + \kappa_{o,int}}$$

Cooperativity

$$C_{em} = \frac{\Gamma_{em}}{\kappa_{mech}} \qquad C_{om} = \frac{\Gamma_{om}}{\kappa_{mech}}$$

Requirements

$\kappa_{coup} \gg \kappa_{int}$

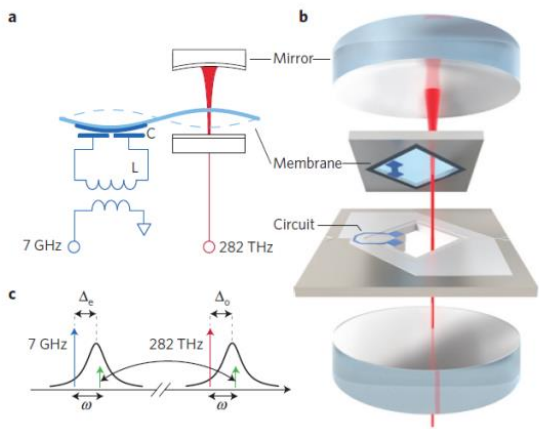
Large g

$\kappa_{mech} \ll \Gamma$

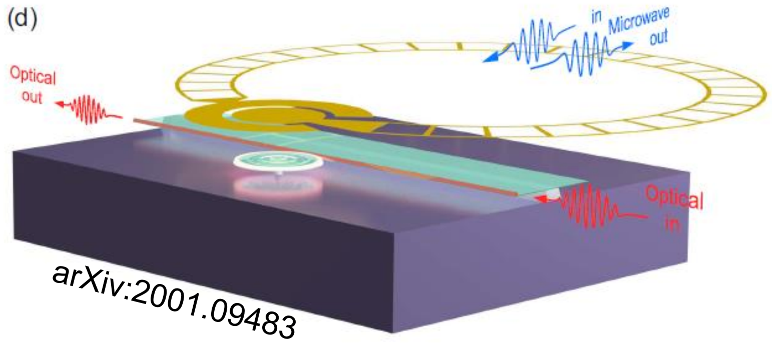
High-efficiency, high-bandwidth, low-noise conversion requires overcoupled resonators, strong coupling between resonators, and low resonator losses

Overview of Recent Work

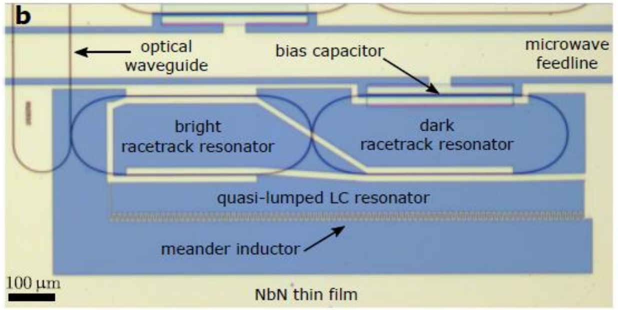
Electro-static optomechanical



Piezo optomechanical



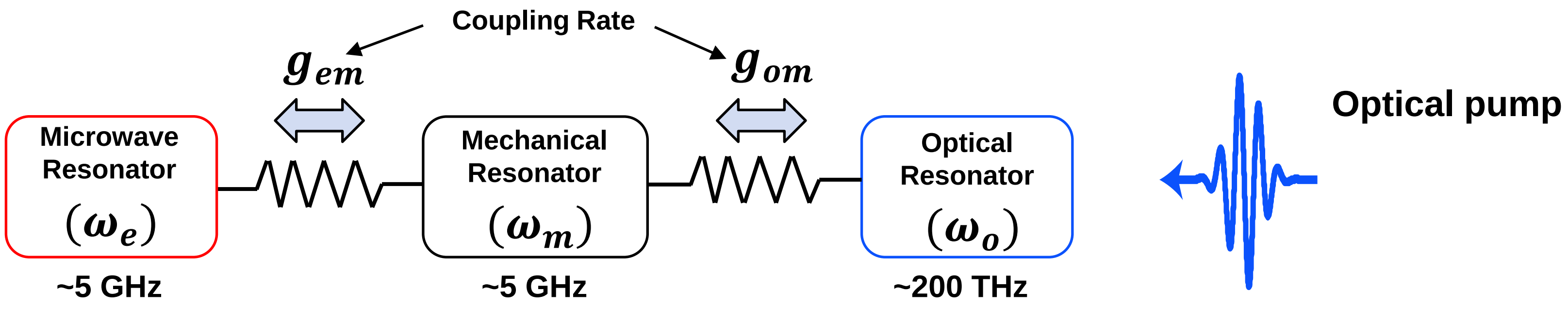
Electro-optic



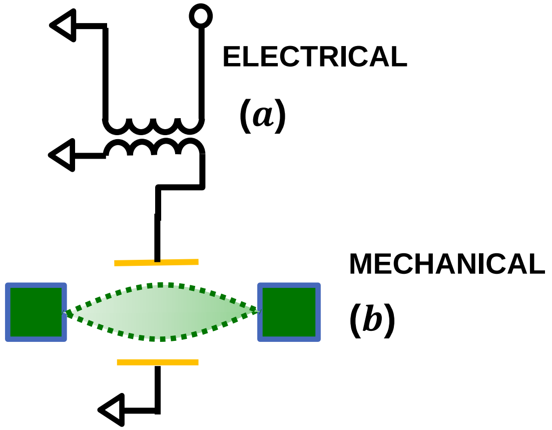
	Electro-static	Piezo-based	Electro-optic
Efficiency	47% [1]		
Coupling strength g_0	few Hz [1]	10's kHz to MHz [2,3,4]	100's Hz [5,6]
Noise			
Scalability			

1. Higginbotham et al, Nature Physics (2018)
2. Han et al, arXiv (2020)
3. Forsch et al, Nature Physics (2020)
4. Mirhosseini et al, Nature (2020)
5. Fan et al, Science Adv. (2018)
6. Holzgrafe et al, arXiv (2020)

Piezo-mechanical and Opto-mechanical Coupling



Piezo-mechanical coupling



- Same frequency for mech. and elec. resonators
- Native beamsplitter interaction that swaps an excitation between the two resonators

Opto-mechanical coupling

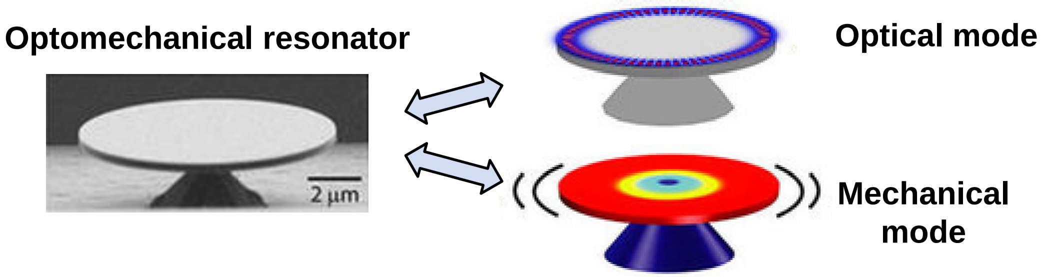


Image adapted from: https://www.nist.gov/news-events/news/2013/08/wideband-wavelength-conversion-using-cavity-optomechanics

- Requires pump to get beamsplitter interaction
- Coupling rate can be tuned with power
- Low $g_{0,om}$ combined with optical losses can lead to high thermal occupation, leading to noise

Material Properties

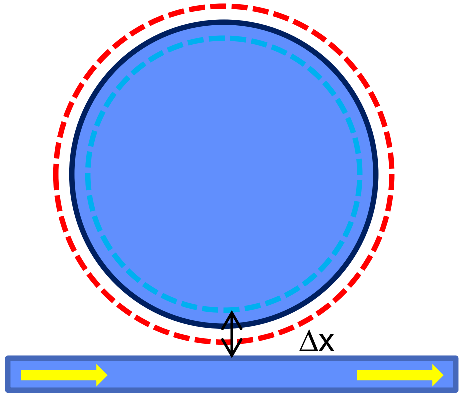
AlN as a photonic material: CMOS integrable, piezoelectric, elasto-optic effects, with low optical losses

	Si	SiO_2	Si_3N_4	GaAs	GaN	$LiNbO_3$	AlN
Index (1550 nm, Ordinary)	**3.47**	**1.45**	**~2.0**	**3.37**	**2.31**	**2.21**	**~2.04**
Bandgap	**1.12 eV**	**8.9 eV**	**5.1 eV**	**1.43 eV**	**3.4 eV**	**4.0 eV**	**6.2 eV**
Optical losses (α) in integrated structure	**0.3 dB/cm** ***Waveguide*** ***(Cardenas et al., 2009)***	**0.007 dB/cm** ***Microtoroid resonator*** ***(Polman et al., 2004)***	**0.055 dB/cm** ***Ring resonator*** ***(Gondarenko et al., 2009)***	**0.5 dB/cm** ***Waveguide*** ***(Inoue et al., 1985)***	**0.65 dB/cm** ***Waveguide*** ***(Stolz et al., 2011)***	**2.03 dB/cm** ***Disk resonator*** ***(Wang et al., 2014)***	**0.6 dB/cm** ***Ring resonator*** ***(Xiong et al., 2012)***
Piezoelectric	☒	☒	☒	d_{31} = 0 d_{33} = 0 d_{14} = -2.7 pC/N	d_{31} = -1.9 pC/N d_{33} = 3.7 pC/N	d_{31} = -1 pC/N d_{33} = 6 pC/N (Z-cut)	d_{31} = -1.98 pC/N d_{33} = 4.98 pC/N
Elasto-Optic	☒	☒	☒	p_{11} = -0.026	p_{11} = -0.086* (estimated)	p_{11} = -0.026	p_{11} = -0.10* (estimated)

***S. Yu. Davydov, *Semiconductors* **36**, 41-44 (2002); G. Bu, et al., *Appl. Phys. Lett.* **85**, 2157 (2004).**

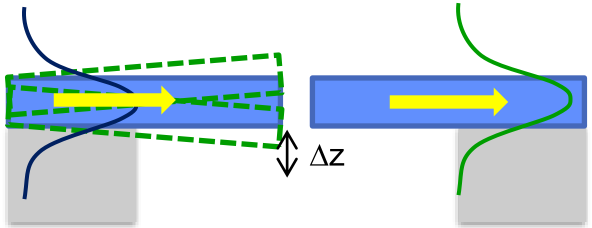
Modulation of Mechanically-Actuated Structures

i) Mechanical displacements perturbing WGM resonator



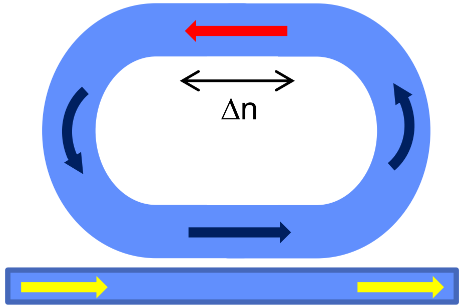
$$\Delta T(x,n) = \frac{\partial T}{\partial x}\Delta x$$

ii) Mechanical displacements perturbing waveguide end-coupling



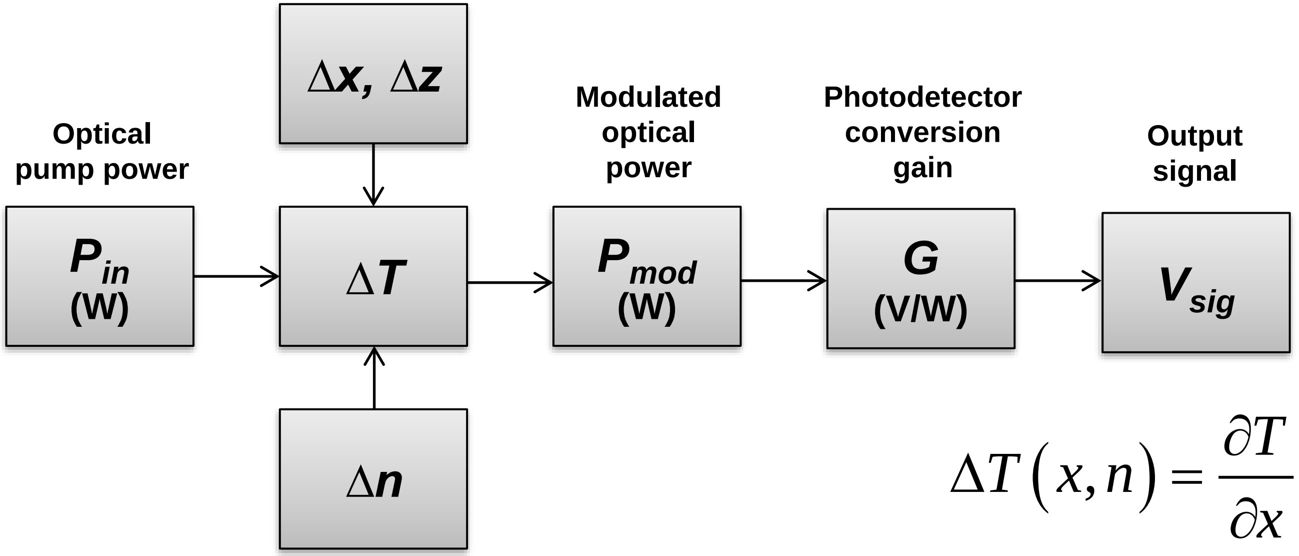
$$\Delta T(z,n) = \frac{\partial T}{\partial z}\Delta z$$

iii) Strain-induced refractive index changes



$$\Delta T(x,n) = \frac{\partial T}{\partial n}\Delta n$$

Optomechanical Modulation Model

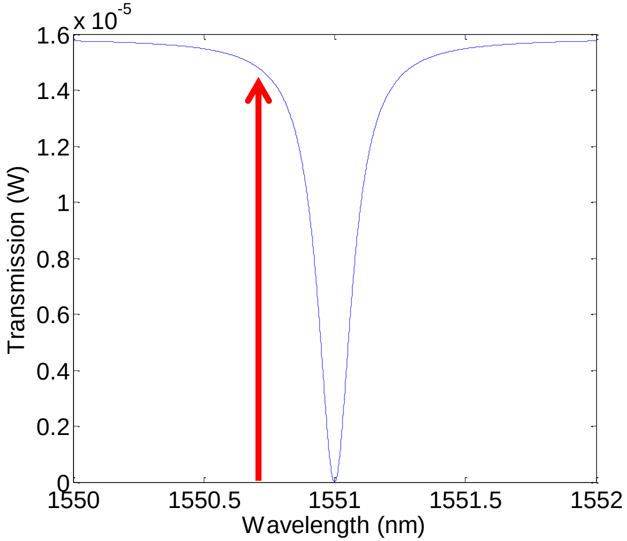


$$\Delta T\left(x,n\right)=\frac{\partial T}{\partial x}\Delta x+\frac{\partial T}{\partial n}\Delta n=\frac{\partial T}{\partial \lambda}\left(\frac{\partial \lambda}{\partial x}\Delta x+\frac{\partial \lambda}{\partial n}\Delta n\right)$$

Fit data to Lorentzian:
P_{trans} = Insertion loss
Γ = FWHM

$$T\left(\lambda\right)=P_{trans}\left(1-\frac{\Gamma^2}{4(\lambda-\lambda_o)^2+\Gamma^2}\right)$$

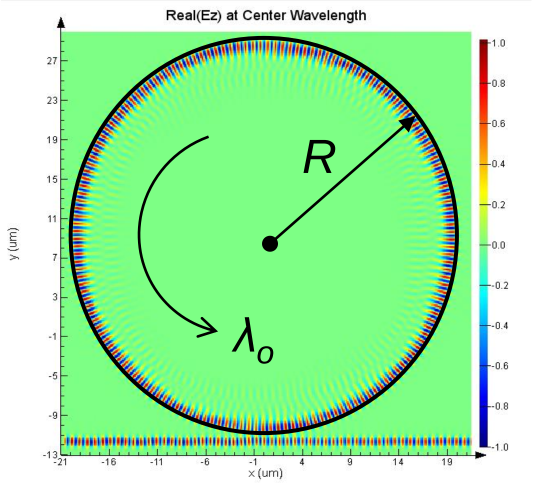
$$Q_L=\frac{\lambda_o}{\Gamma}$$



Bias laser with blue-cavity detuning and assume maximum slope of cavity Lorentzian:

$$\frac{dT}{d\lambda}=\frac{P_{trans}8\Gamma^2(\lambda-\lambda_o)}{[4\left(\lambda-\lambda_o\right)^2+\Gamma^2]^2}$$

Displacement and Refractive Index Based Modulation



Resonance condition:

$$n_{eff}\,L = m\lambda_o$$

$$n_{eff}\,(2\pi R) = m\lambda_o$$

$$n_{eff}\,2\pi\left(R + \Delta r\right) = m(\lambda_o + \Delta\lambda)$$

$$\frac{d\lambda}{dr} = \frac{\lambda_o}{R} = g_{om\lambda}$$

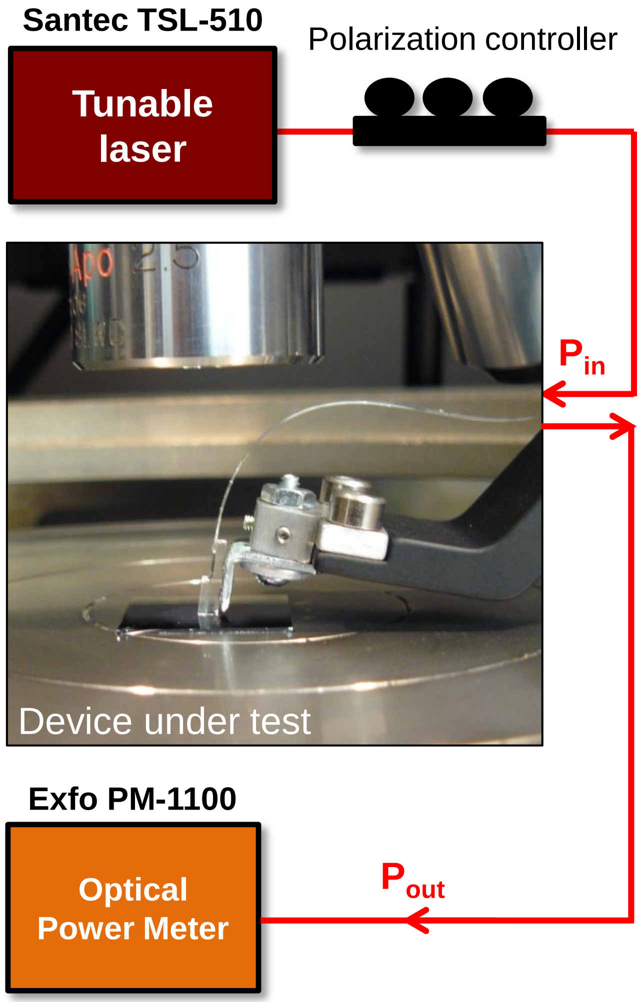
Where dr is produced by piezoelectrically induced displacements

$$(n_{eff} + \Delta n_{eff})2\pi R = m(\lambda_o + \Delta\lambda)$$

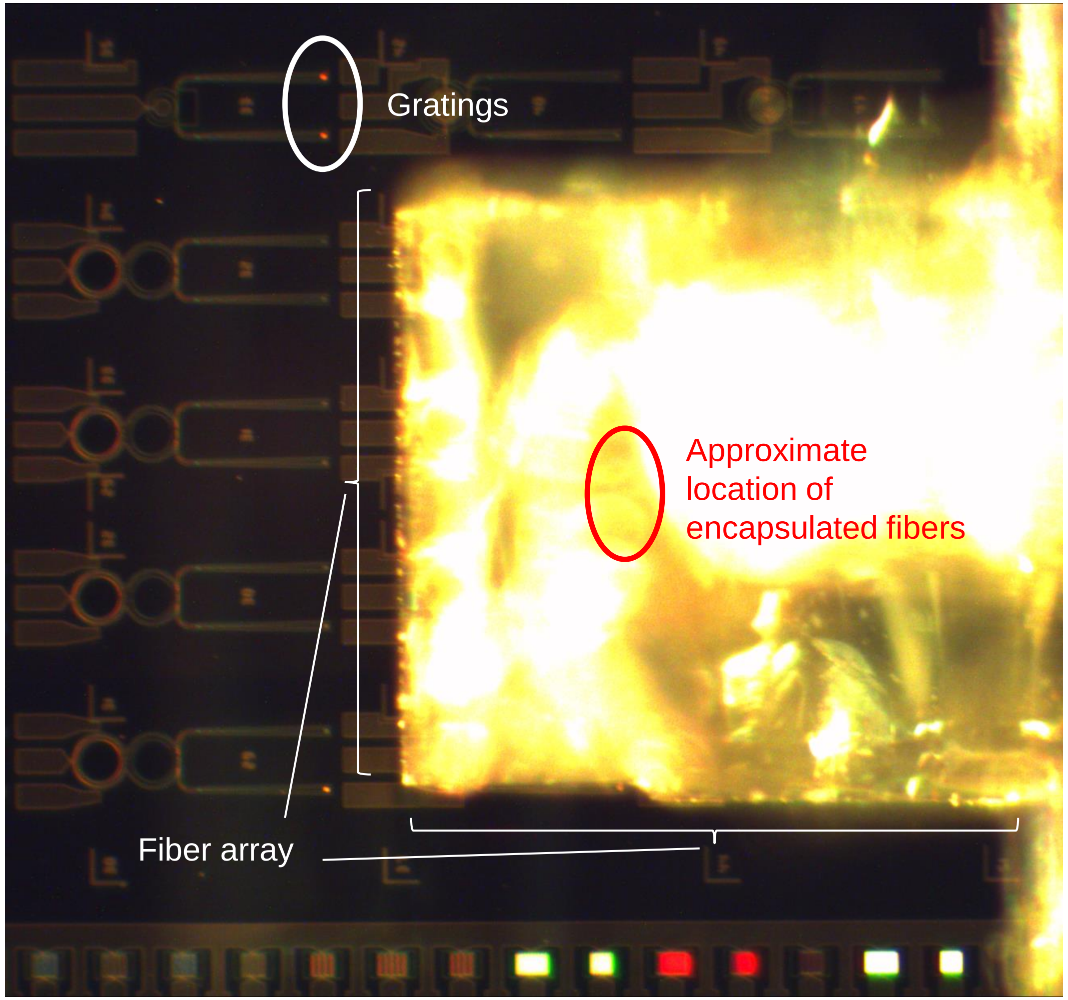
$$\frac{d\lambda}{dn_{eff}} = \frac{\lambda_o}{n_{eff}}$$

Where dn_{eff} is produced by piezoelectrically generated strain

Test Setup

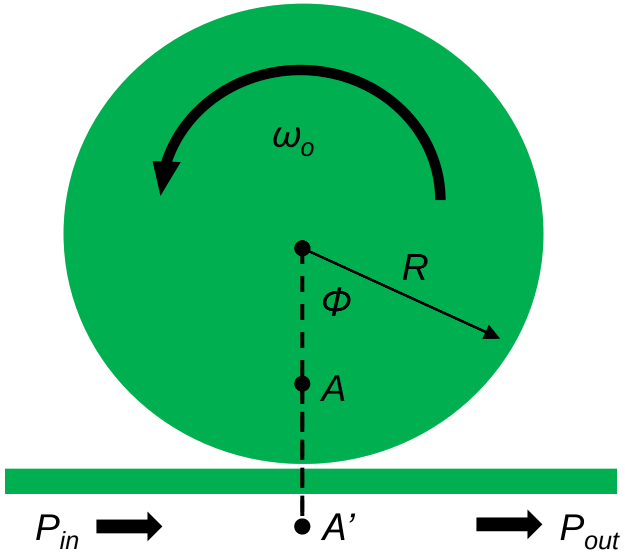


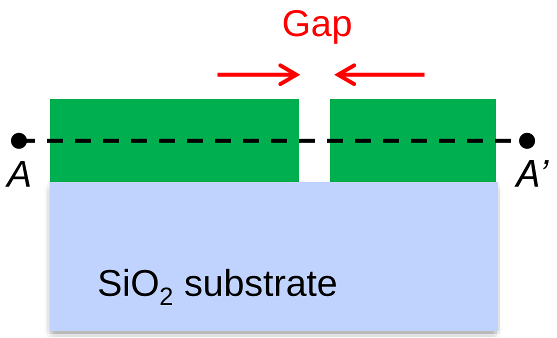
Santec TSL-510
Tunable laser
Polarization controller
P_{in}
Device under test
Exfo PM-1100
Optical Power Meter
P_{out}



Gratings
Approximate location of encapsulated fibers
Fiber array

Photonic Resonator Coupling





Waveguide-Resonator coupling:

$$T(\omega) = \frac{P_{out}}{P_{in}} = \left| \frac{\frac{j2(\omega-\omega_o)}{\omega_o} + \frac{1}{Q_o} - \frac{1}{Q_c}}{\frac{j2(\omega-\omega_o)}{\omega_o} + \frac{1}{Q_o} + \frac{1}{Q_c}} \right|^2 \quad \& \quad \frac{1}{Q_L} = \frac{1}{Q_o} + \frac{1}{Q_c}$$

Regimes of operation:

i) $Q_c > Q_o$: Undercoupled

ii) $Q_c = Q_o$: Critically coupled ←

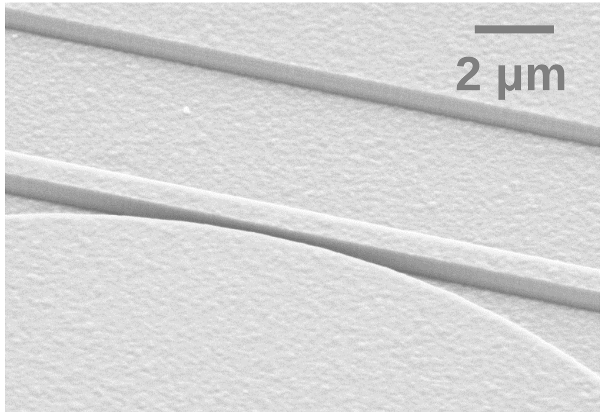
iii) $Q_c < Q_o$: Overcoupled

Attenuation losses:

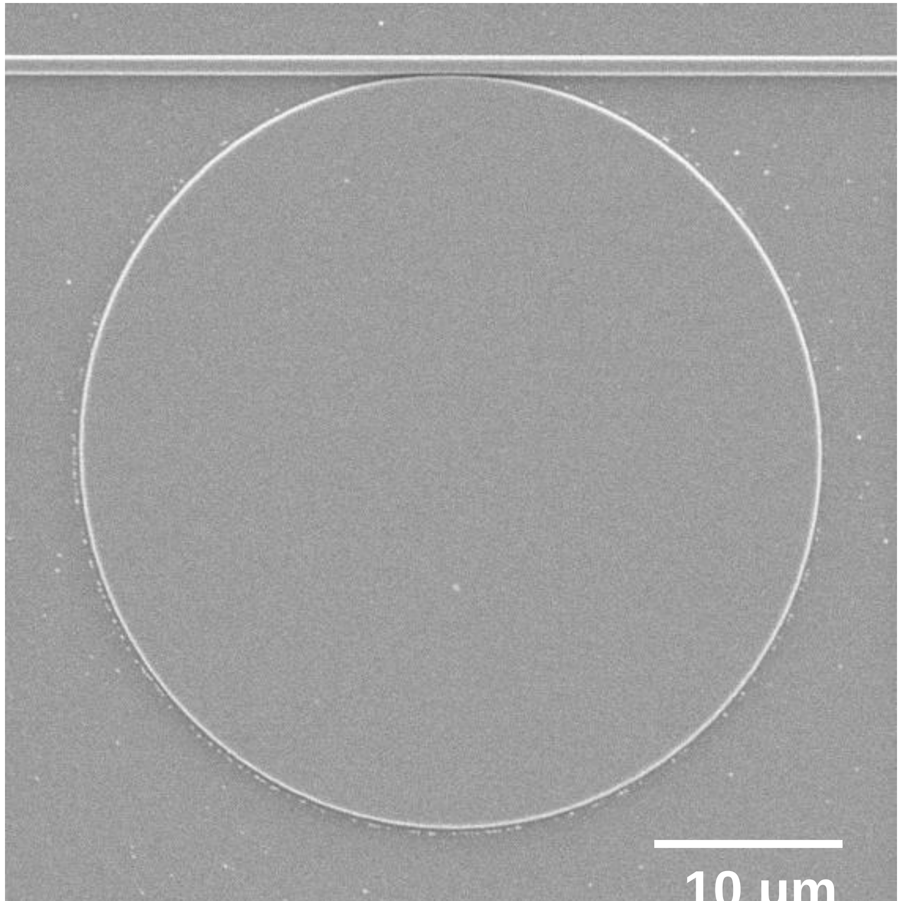
$$n_g \approx \frac{{\lambda_o}^2}{(FSR)(L)} \longrightarrow Q_L = \frac{1}{2} Q_o = \frac{\pi n_g}{\lambda_o \alpha_{disk}}$$

Vary Gap Widths to Microdisks

Fix: R = 20 µm, Bus WG = 850 nm,
Gap: 50 nm – 700 nm in 50 nm increments

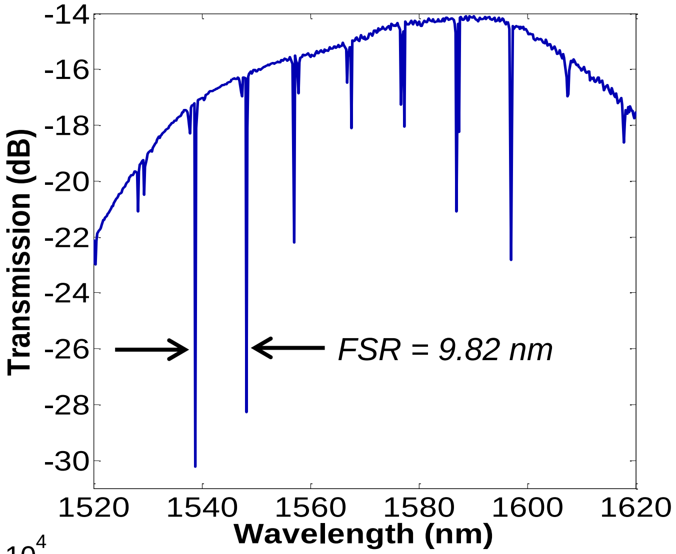


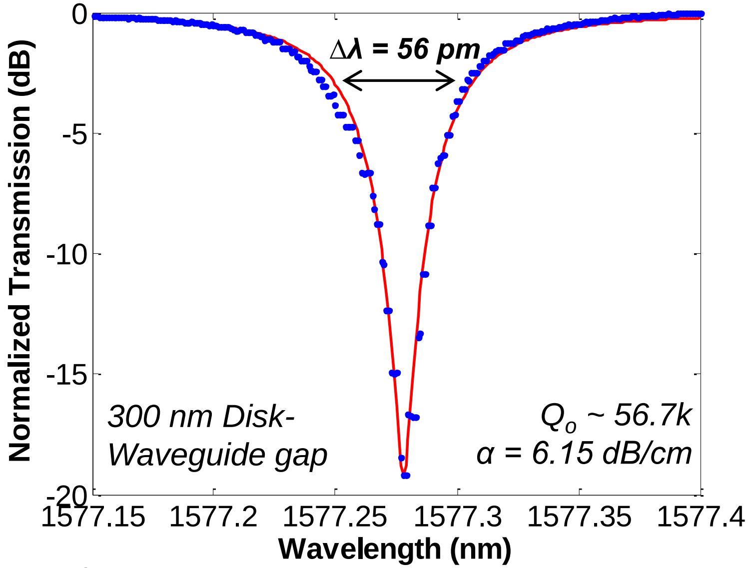
200 nm Disk-Waveguide gap

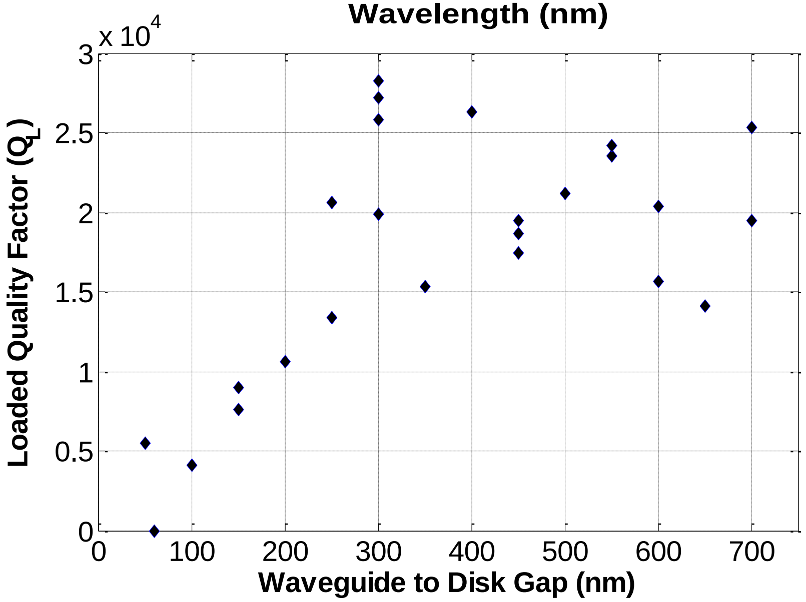


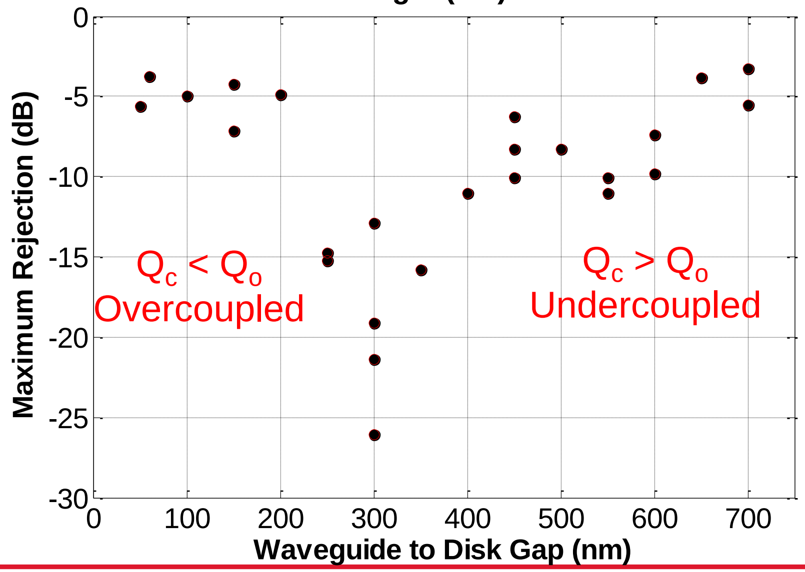
20 µm radius microdisk

Experimental Results





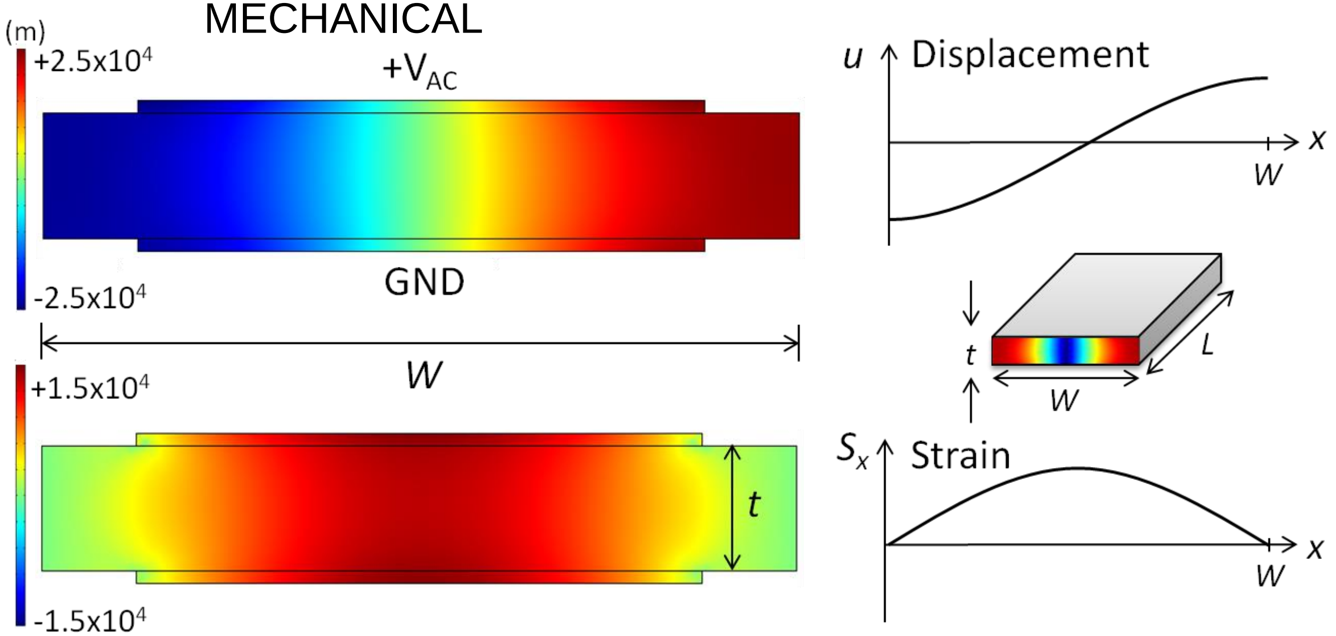




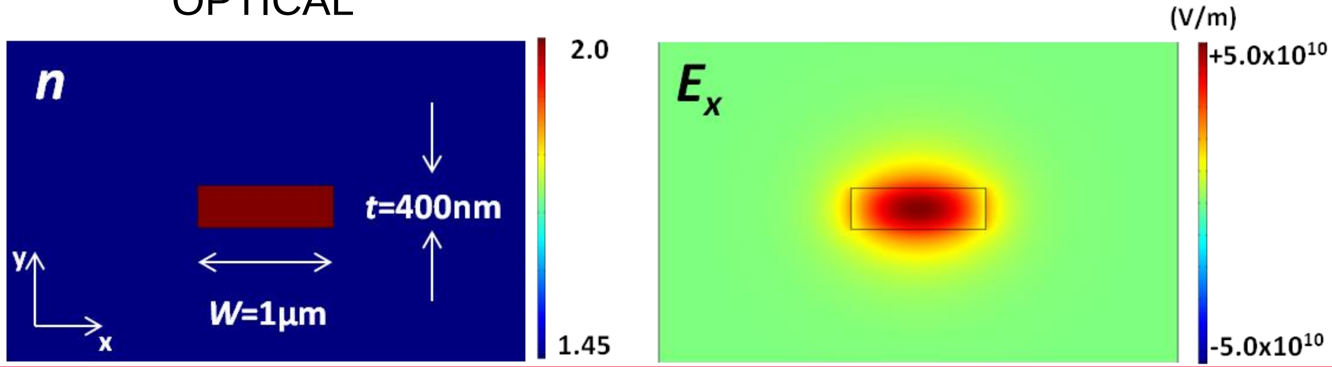
Elasto-optic modulation

- **Consider a thin rectangular plate cross-section:**

MECHANICAL



OPTICAL



"Single finger" contour mode resonator (CMR)

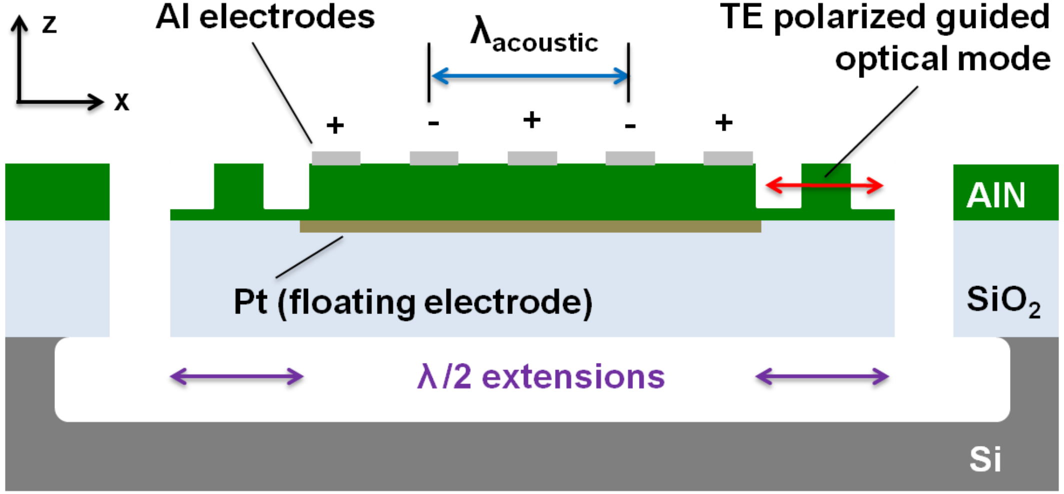
↓

<u>OVERLAP:</u>
Strain → Δn via elasto-optic (*p*) coefficients

↑

Guided in waveguides, or photonic resonator

Device geometry



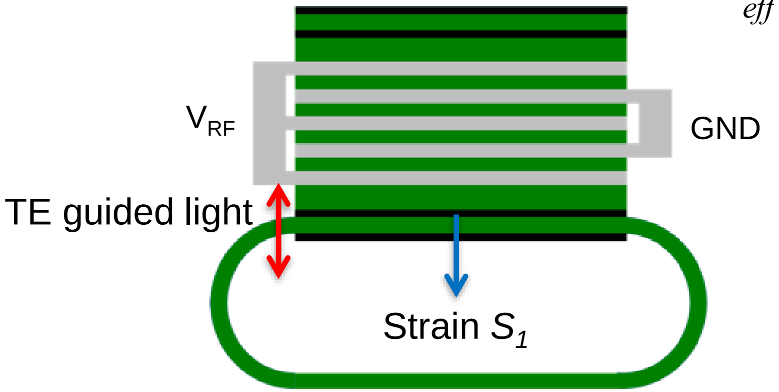
- **Extended CMR generates lateral strains (*S_1*)**
- **Refractive index change for TE mode**
  - **AlN p_{11} = -0.1*:**

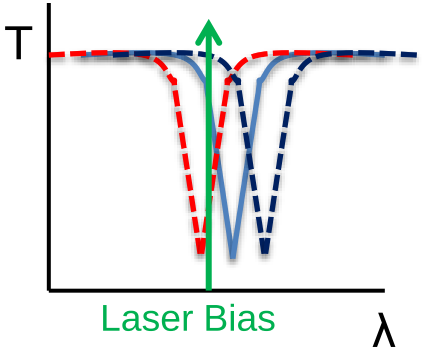
$$\Delta n_1 = -\frac{1}{2} n_1^3 p_{11} S_1$$

*****Davydov, Semiconductors **36**, 2002*

- **Enhance sensitivity to strain by incorporating waveguide into a photonic racetrack resonator:**

$$n_{eff}(2\pi R + 2L_A) = m\,\lambda_o$$

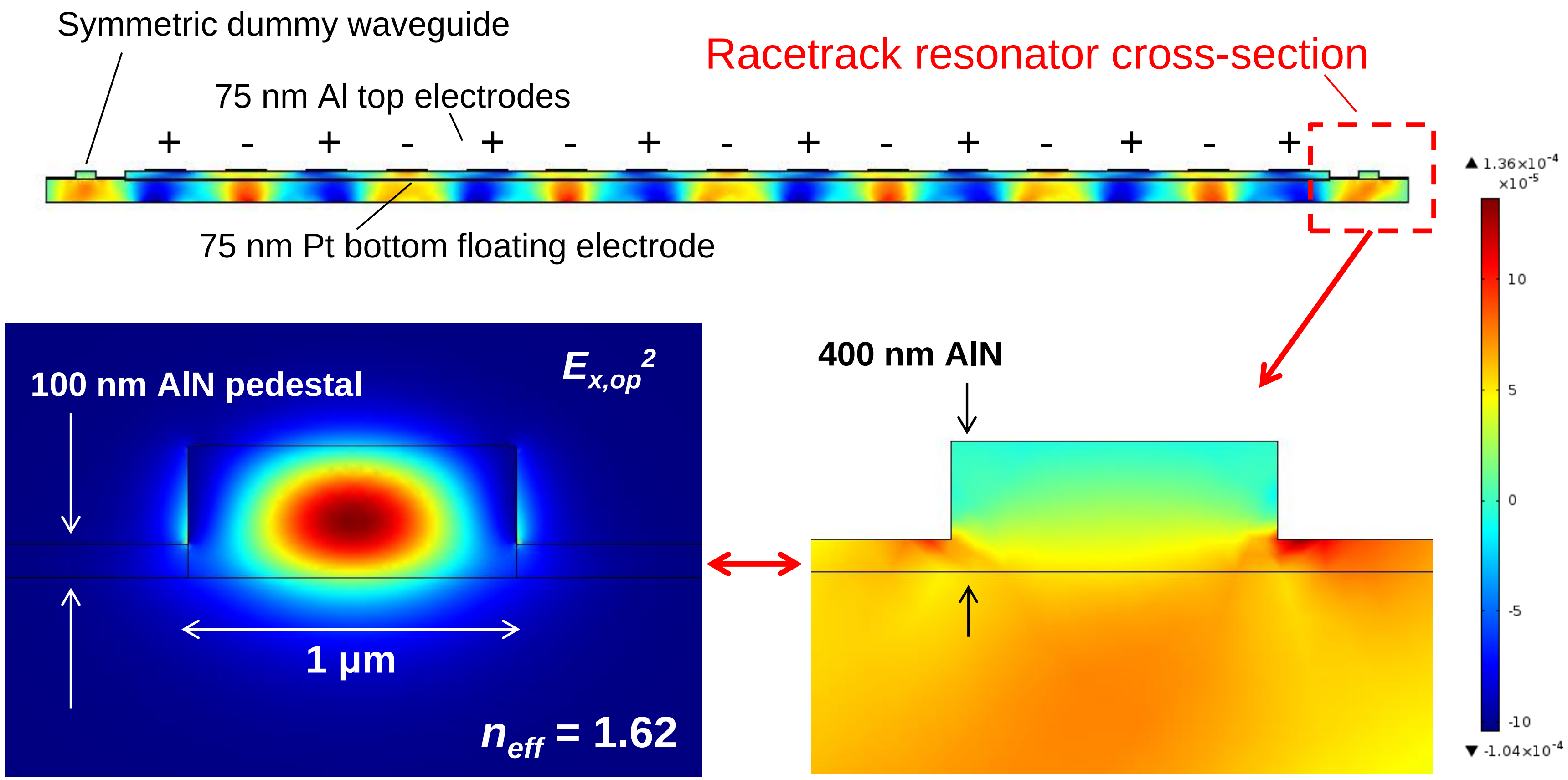




- **Optical intensity modulation:**

$$P_{mod} = \frac{dT}{d\lambda} \cdot \frac{d\lambda}{dn_{eff}} \cdot \Delta n_{eff}$$

Optical mode overlap

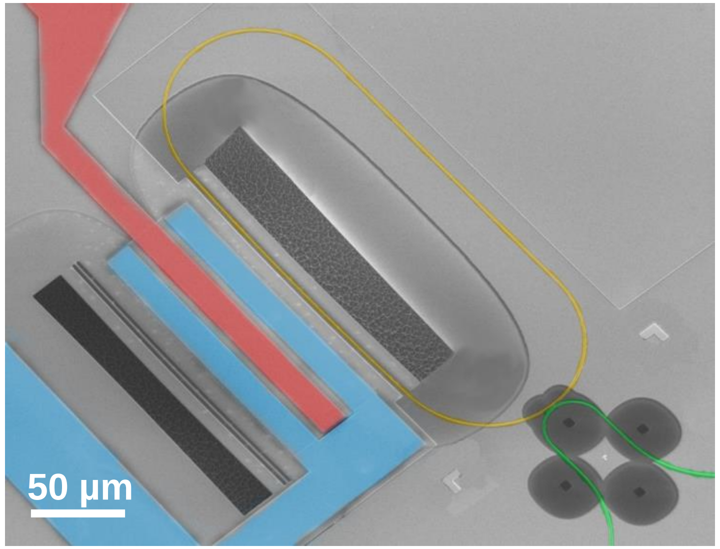


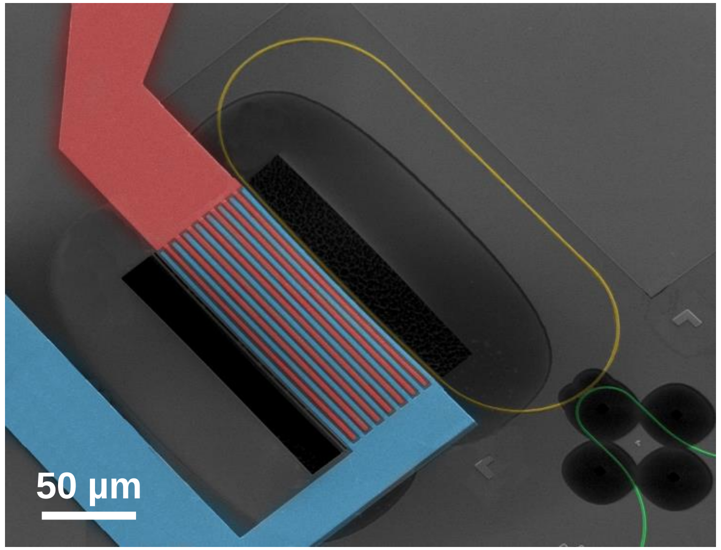
GUIDED OPTICAL MODE

LATERAL STRAIN (S_{XX})

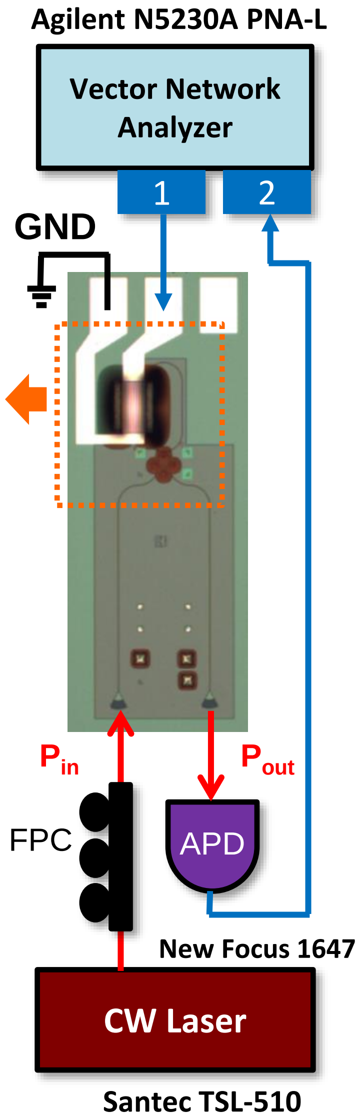
- **Estimation of effective strain:** $S_{1,eff} = \dfrac{\iint S_1 E_{x,op}^2 \, dxdz}{\iint E_{x,op}^2 \, dxdz}$

Fabricated devices and characterization

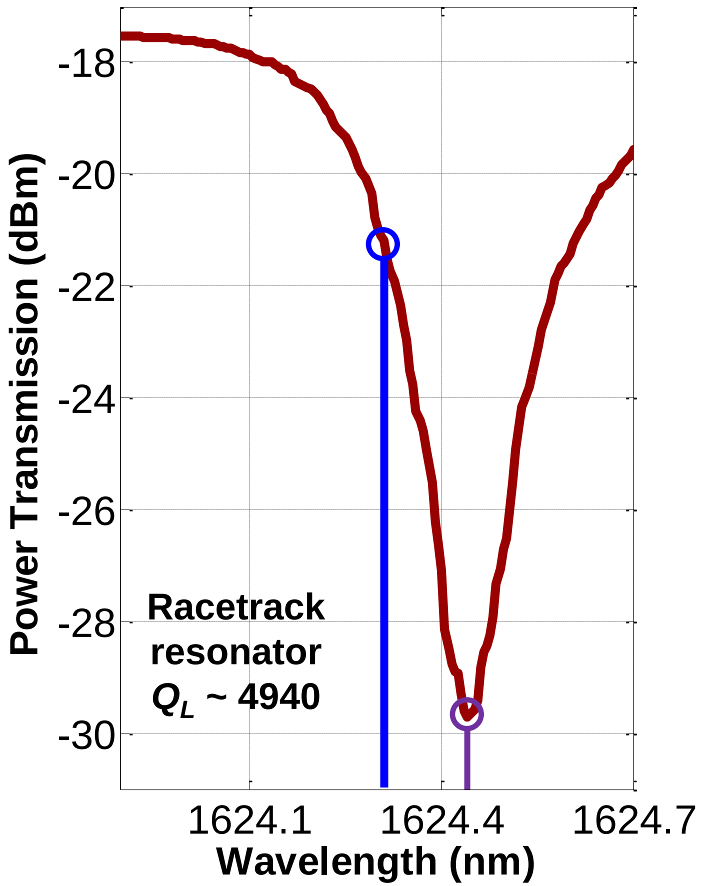


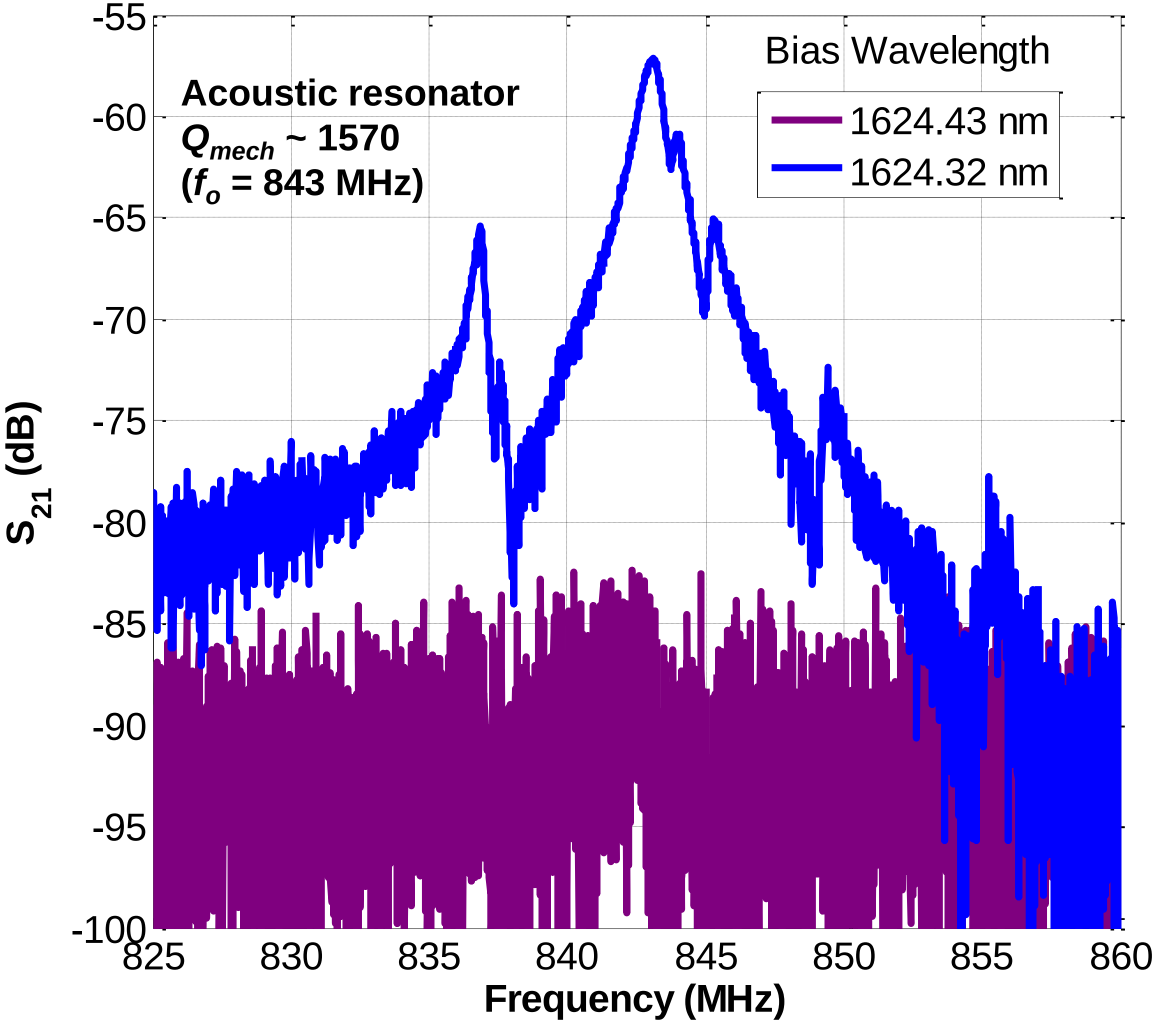


- Similar processing and testing procedure to displacement-based modulator
- Acoustic resonators fabricated with λ = 40 µm and λ = 8 µm
- Design is extendable to smaller wavelengths (higher frequencies) of interest for microwave-optical conversion



S_{21} elasto-optic device response

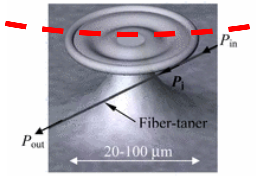




Optomechanical Device Actuation

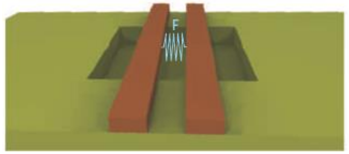
Optical

- *Radiation Pressure*



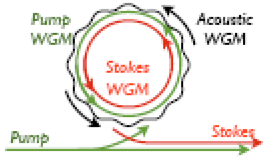
K.J. Vahala et al.

- *Gradient Force*



D. Van Thourhout et al.

- *Electrostriction*



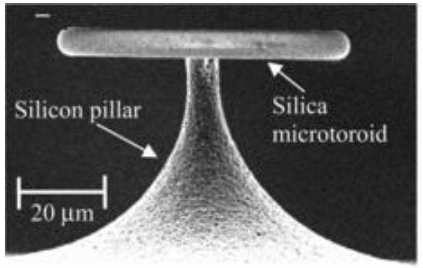
T. Carmon et al.

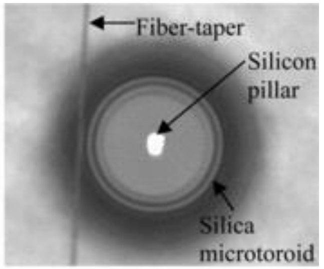
Electrical

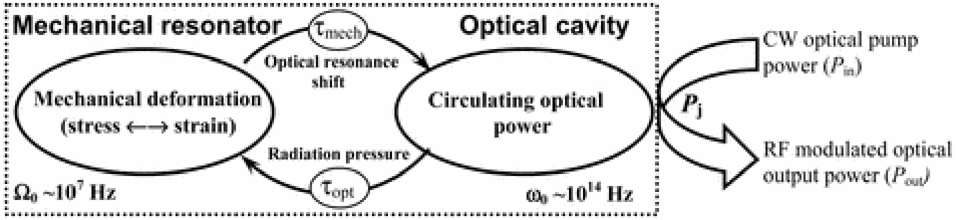
- *Electrostatic*
- *Piezoelectric*

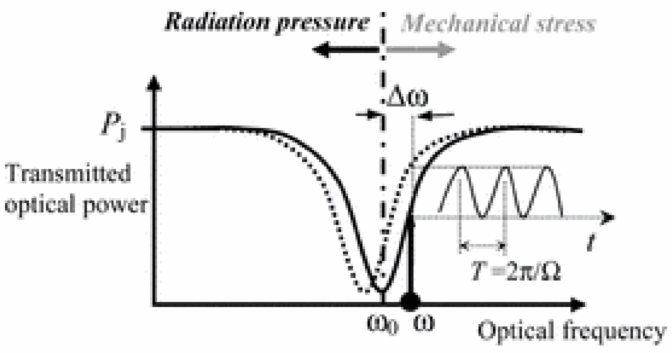
i) Radiation Pressure Driven:

*Silica microtoroid optomechanical oscillator (Hossein-Zadeh et al., Phys. Rev. A **74**, 2005):*

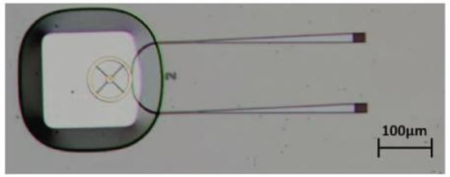


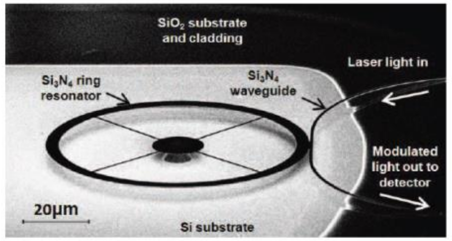


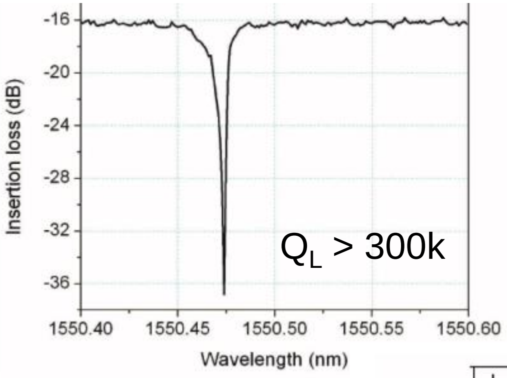


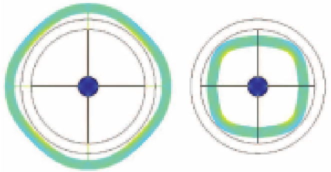


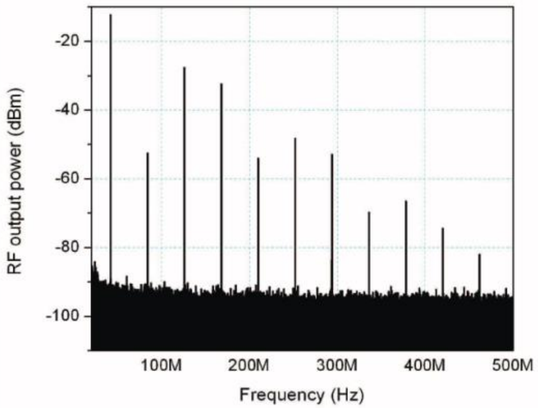
*Silicon nitride optomechanical oscillator (Tallur et al., Opt. Express **19**, 2011):*





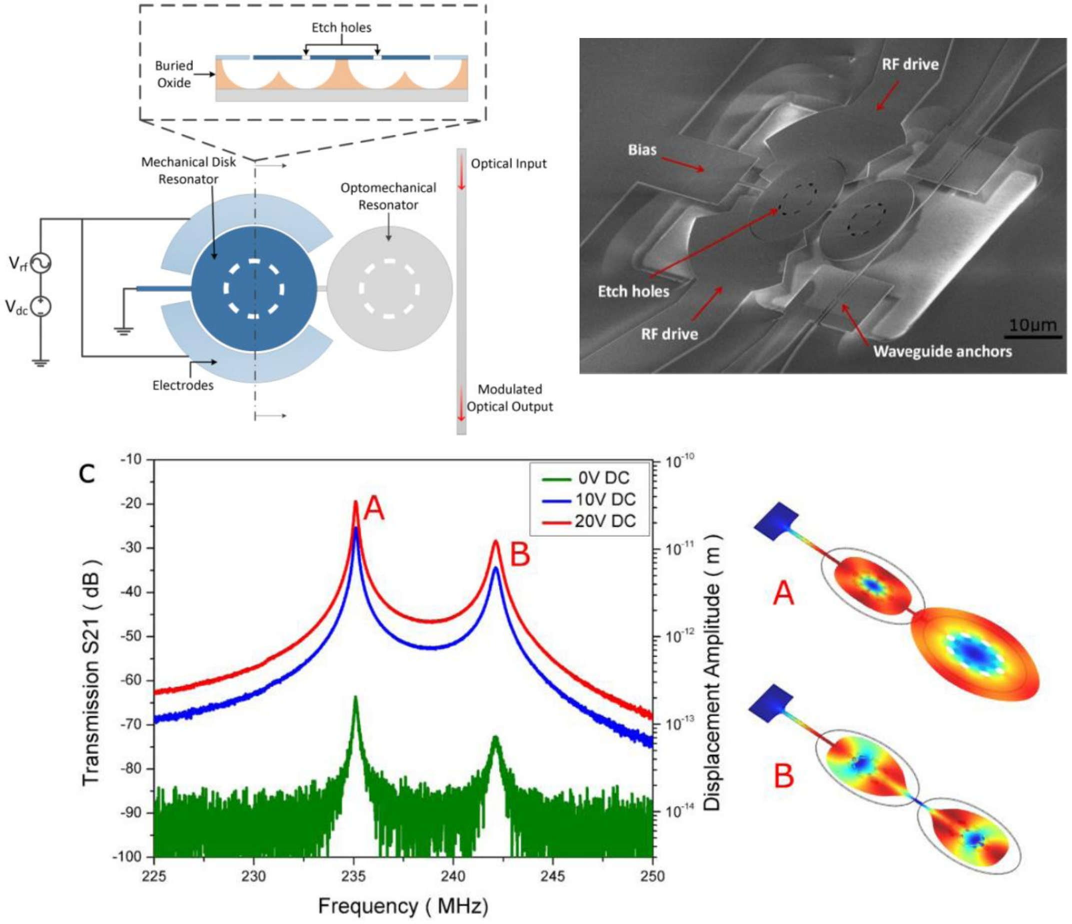






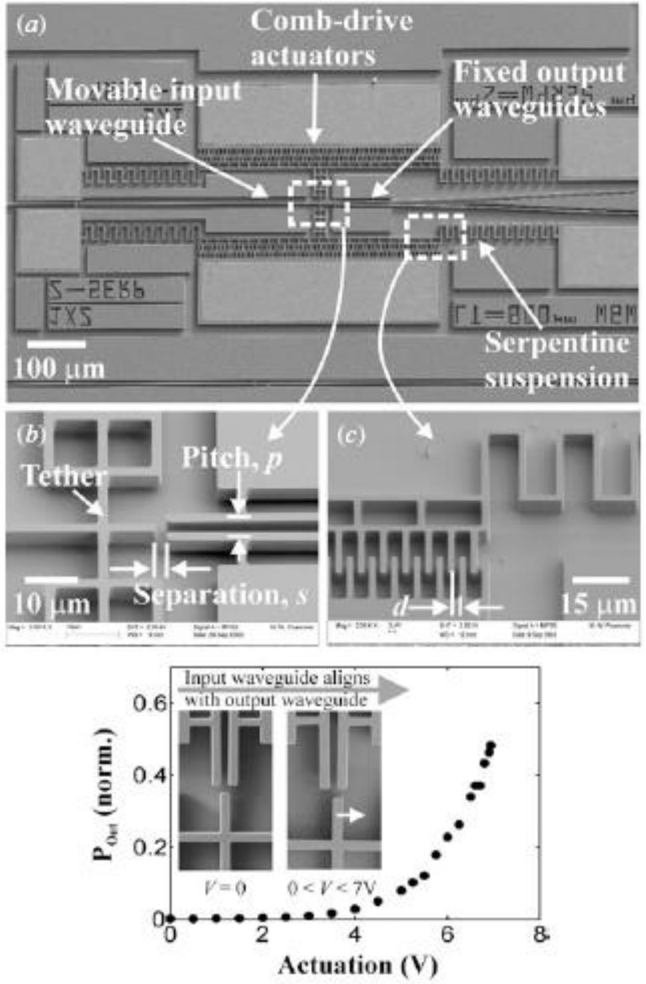
ii) Electrostatically Driven:

Silicon microdisk resonators
(Sridaran & Bhave, Opt. Express ***19****, 2011):*



Difficult to scale >1GHz

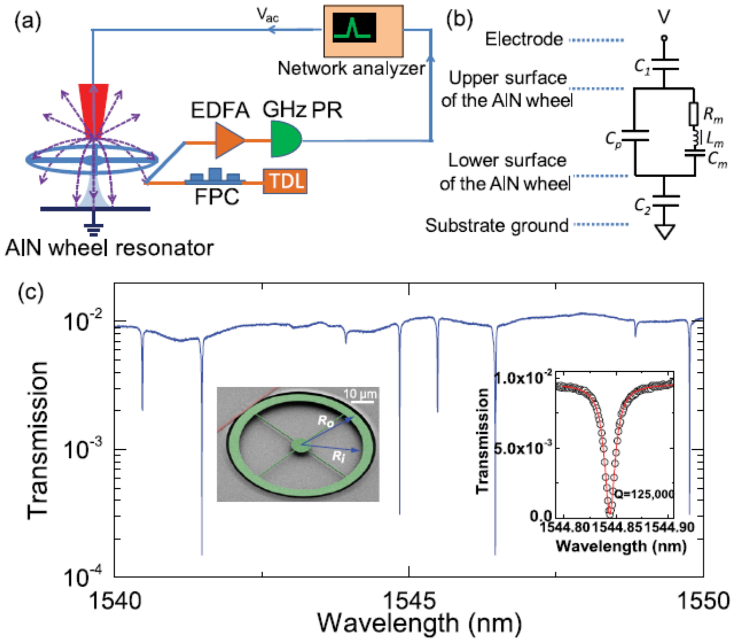
End-coupled Indium Phosphide Waveguides
(Preussner et al., J. Micromech. Microeng. ***16****, 2006):*

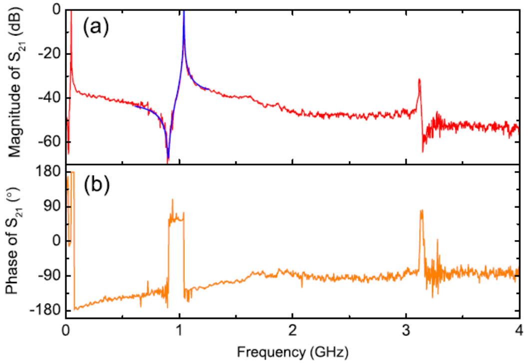


Carnegie Mellon

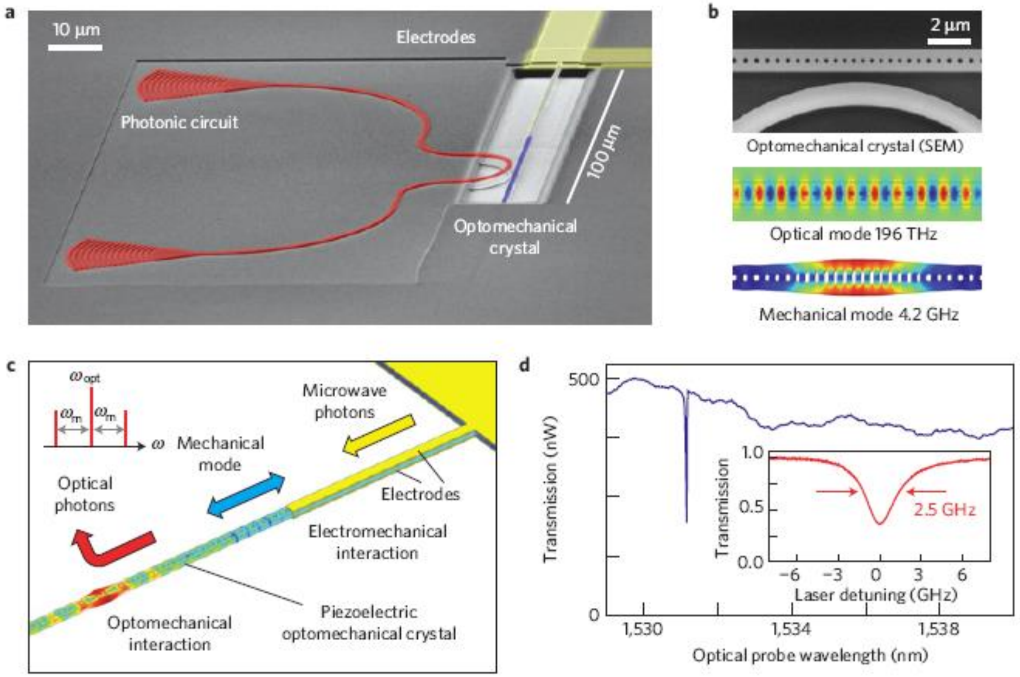
iii) Piezoelectrically Driven:

AlN ring actuated with suspended RF probe:
(Xiong et al., Appl. Phys. Lett. ***102****, 2013):*



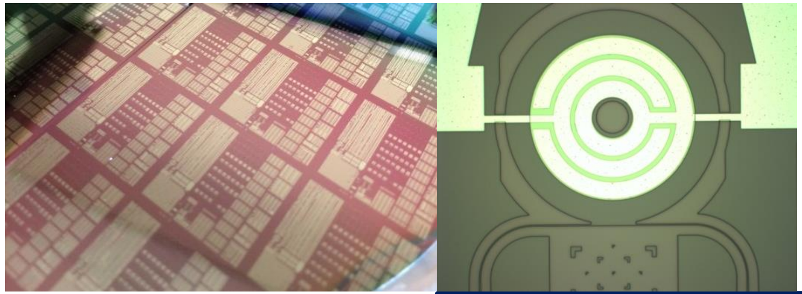


AlN optomechanical crystal:
(Bochmann et al., Nat. Physics ***9****, 2013):*

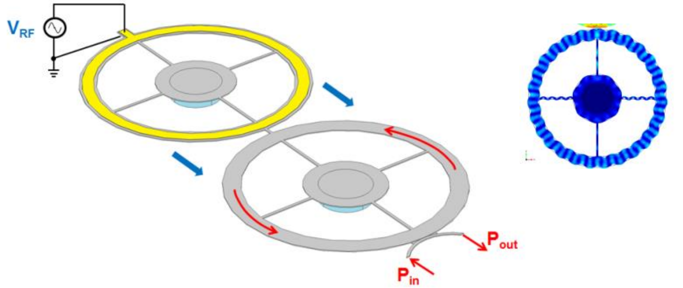


Development Overview

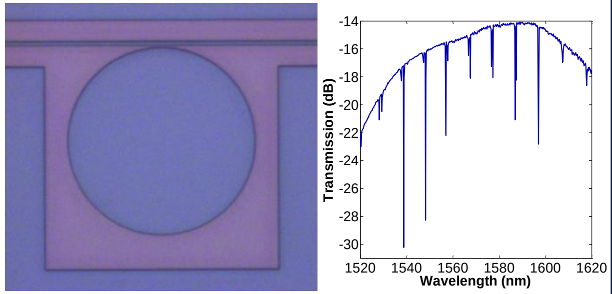
(III) *Fabrication process development*



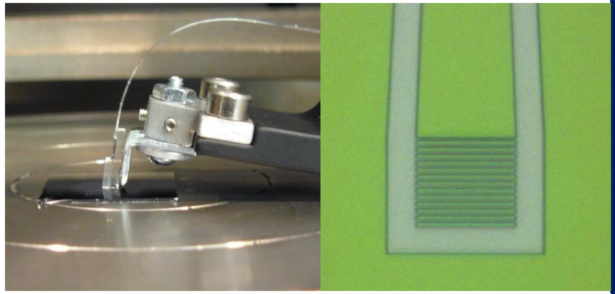
(IV) *Piezoelectric acousto-optic modulator*



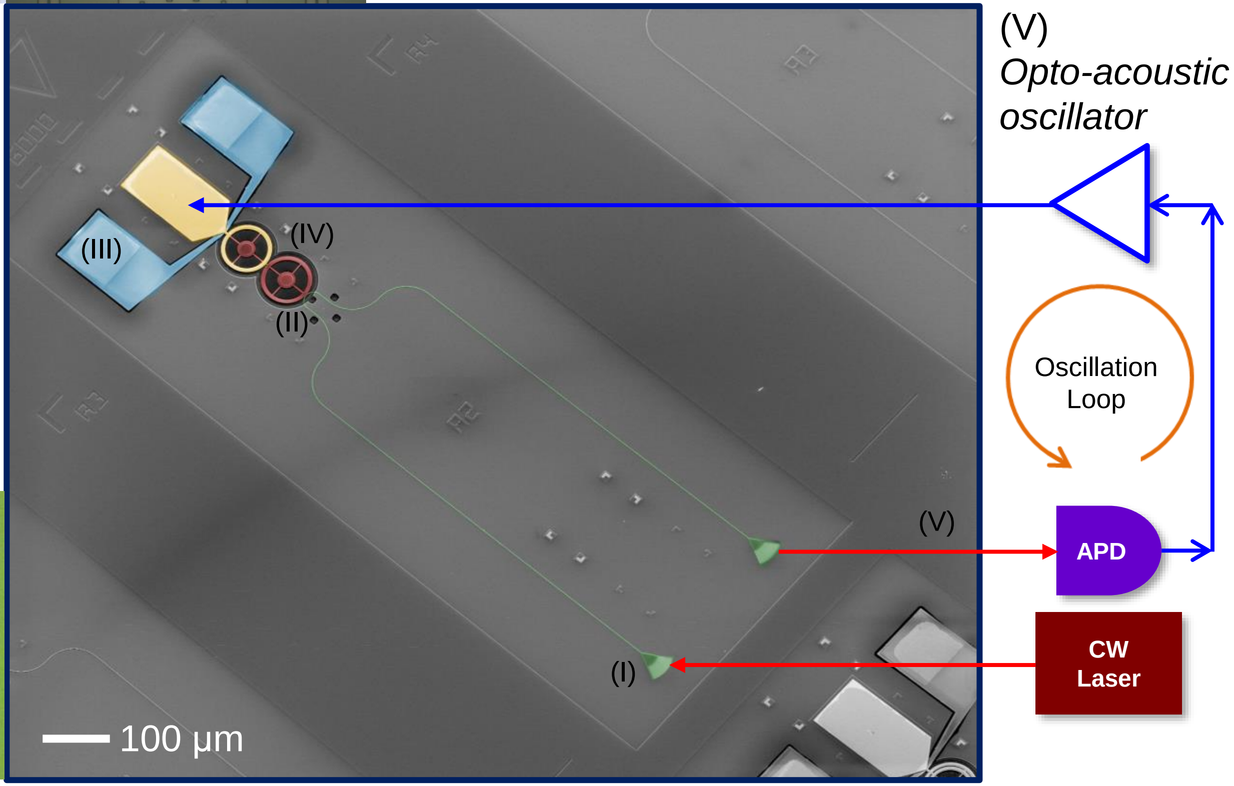
(II) *Photonic resonator*



(I) *AlN grating coupler*

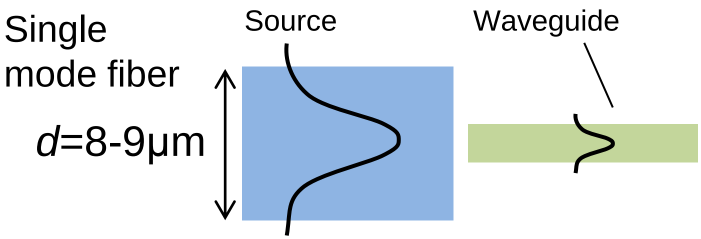


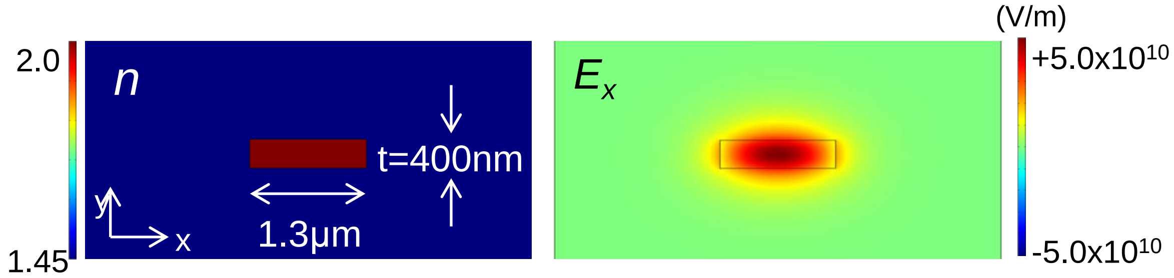
(V) *Opto-acoustic oscillator*



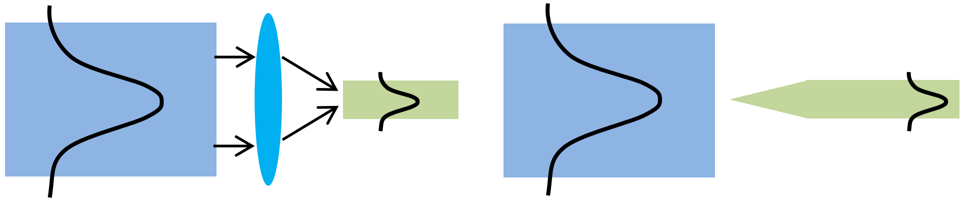
Carnegie Mellon

Light Coupling

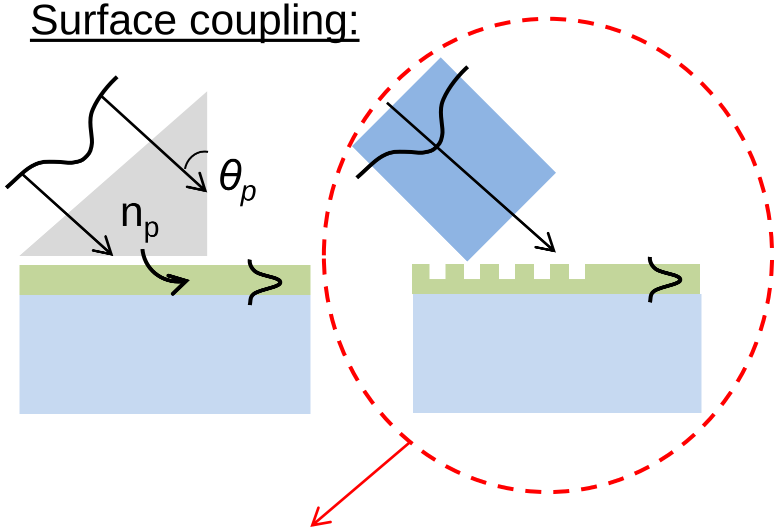


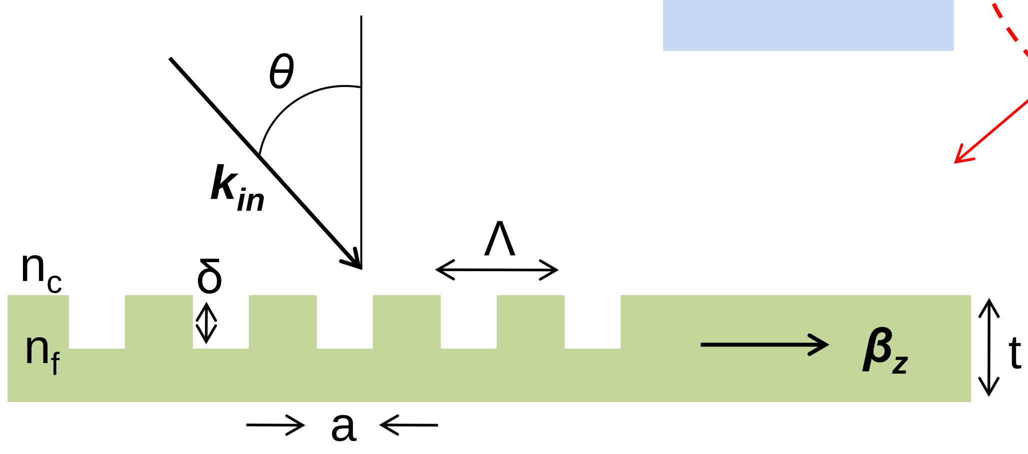


Edge coupling:



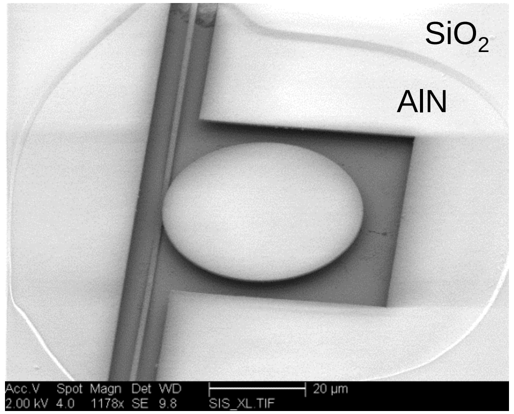
Surface coupling:

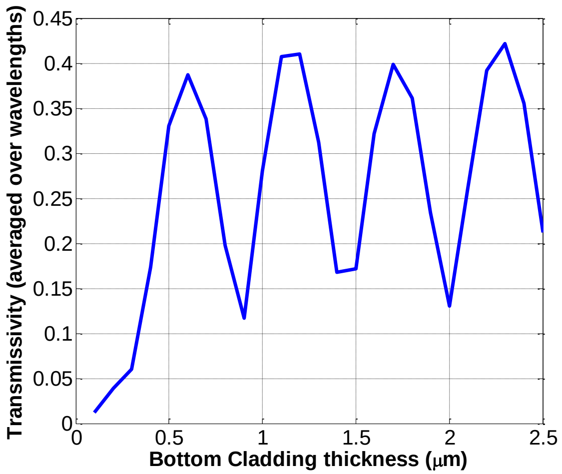


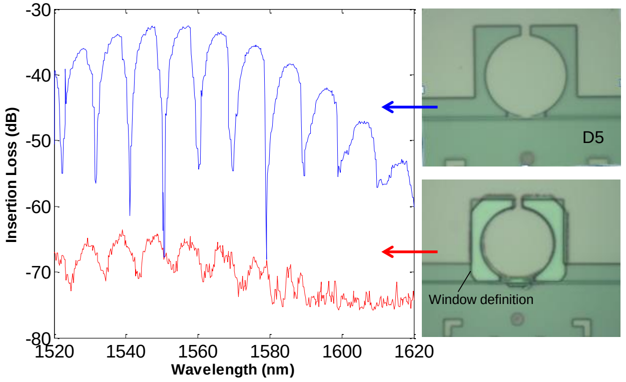


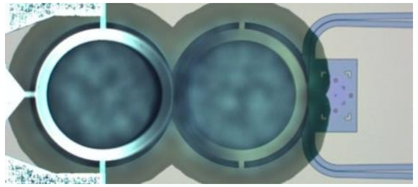
Integration Challenges

- **Oxide etching and release**

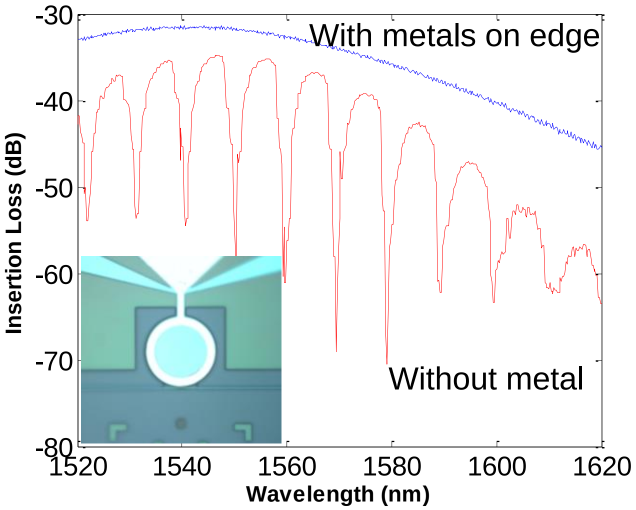


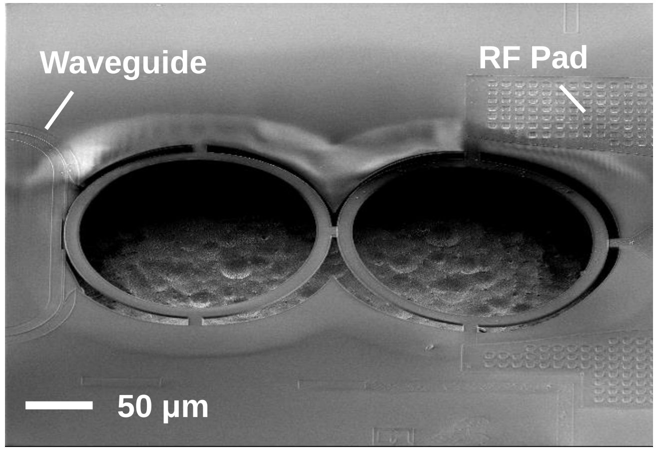


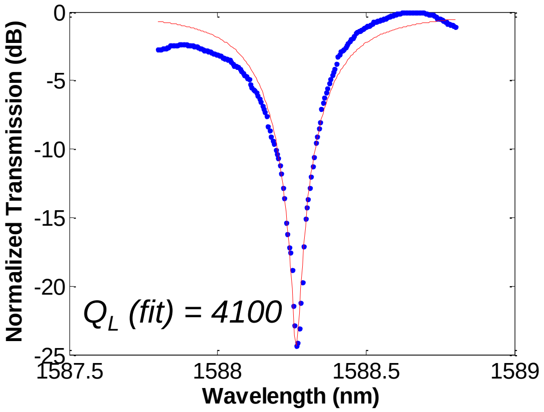




- **Electrode patterning and AlN etching**

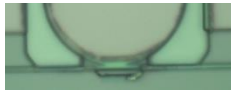


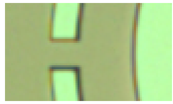


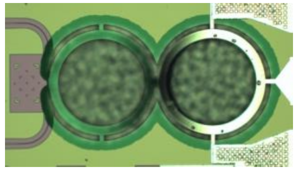
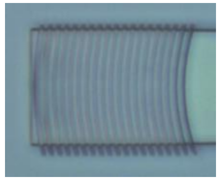
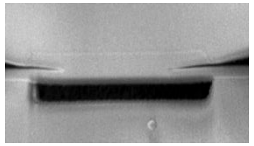


Carnegie Mellon

Process Modifications – Partial Etch Method

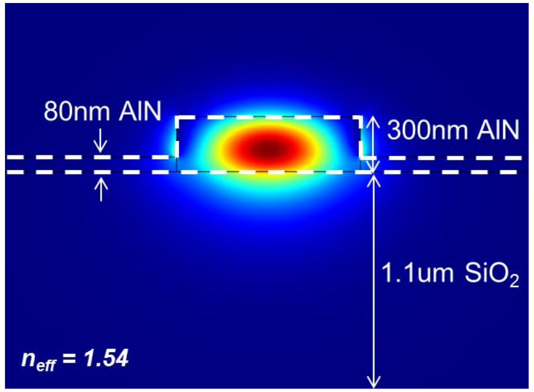




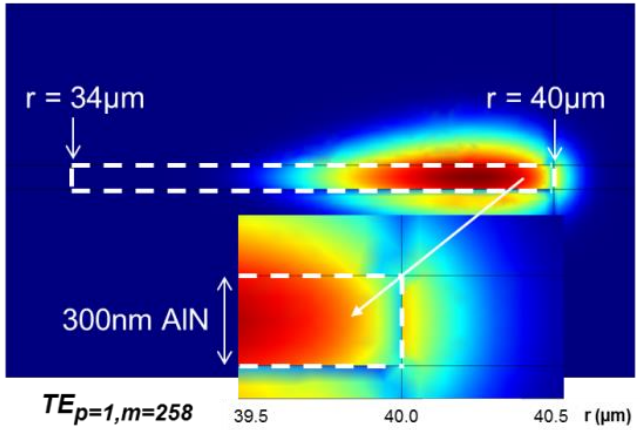




Identified Issue:	Solution:
Release window	Complete release with HF etch – using partially etched AlN as a hard mask
Metals	Primary focus on Dual-Ring or Dual-Disk structures (separated excitation)
Anchors	Change anchor points – increase number symmetrically, but reduce width
Buckling	Use a curved/recessed waveguide at the point of approach [cannot have more than 40 µm suspension]
Stress	Removal of oxide with wet release should relieve uncontrolled stress in oxide & use a thicker top metal to ensure step coverage
Oxide removal	Partial etch will keep gratings protected; Wet release at the end will automatically remove any PECVD oxide (if required as a hard mask)
WGM Coupling	Performing release in a single step at the end with HF avoids any effects from release window; May need to focus on the use of sub-100nm gaps

- Fix 300 nm AlN thickness
- Select partial etch slab thickness for rib waveguides and gratings: 80 nm



- Set WGM R_{out} = 40 µm, and thick ring width = 6 µm



Power Sweeping – Peak Modulation

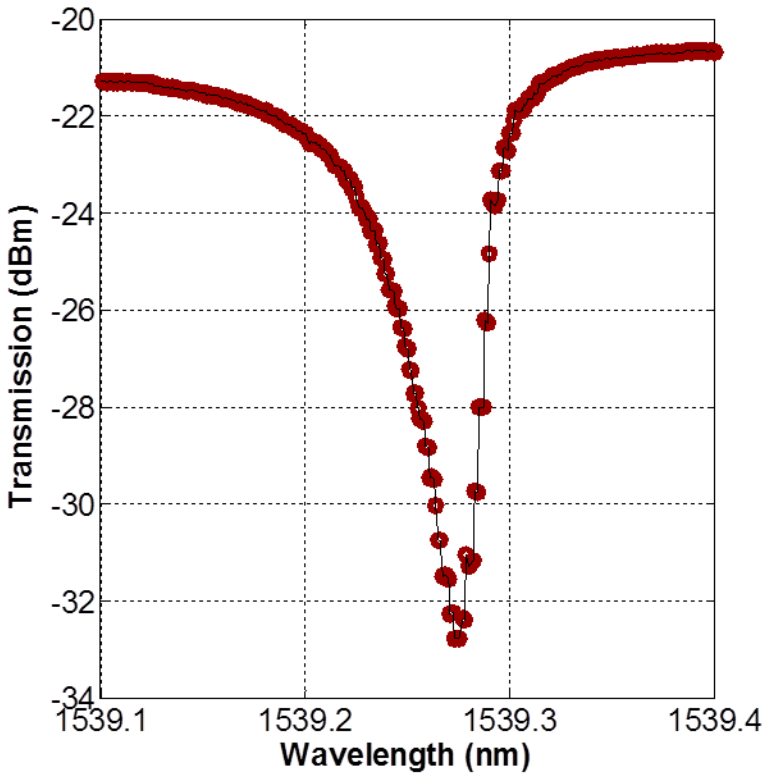
- VNA operated in CW at $f_{res,mech}$, Output on spectrum analyzer
- Increase Δr with applied P_{rf}

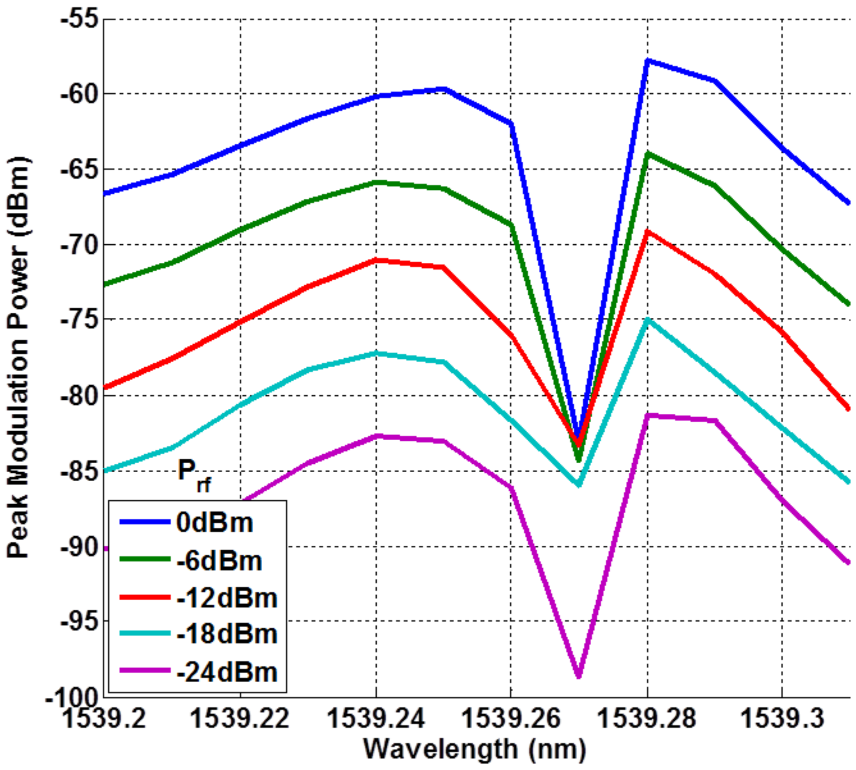
Optical:

$$P_{\mathrm{mod}} = \frac{dT}{d\lambda} \cdot \frac{d\lambda}{dr} \cdot \Delta r \longrightarrow$$

Electrical:

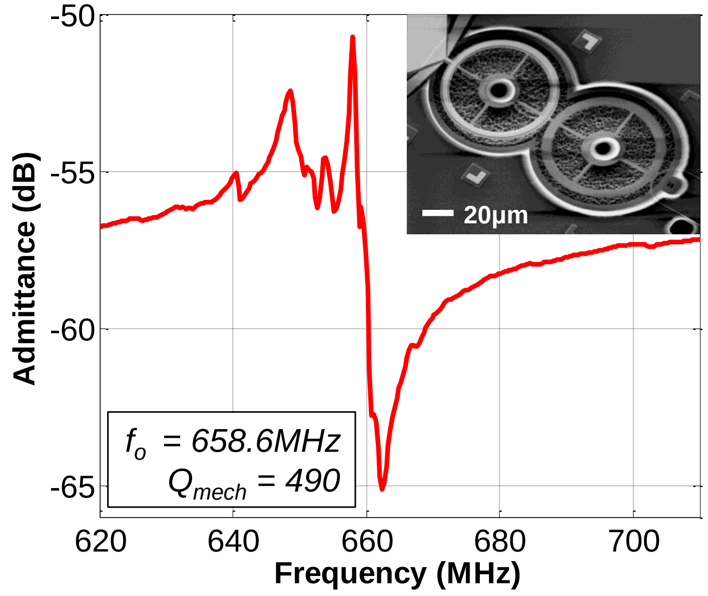
$$P_{sig} = \frac{(P_{\mathrm{mod}} \cdot G)^2}{Z_o}$$

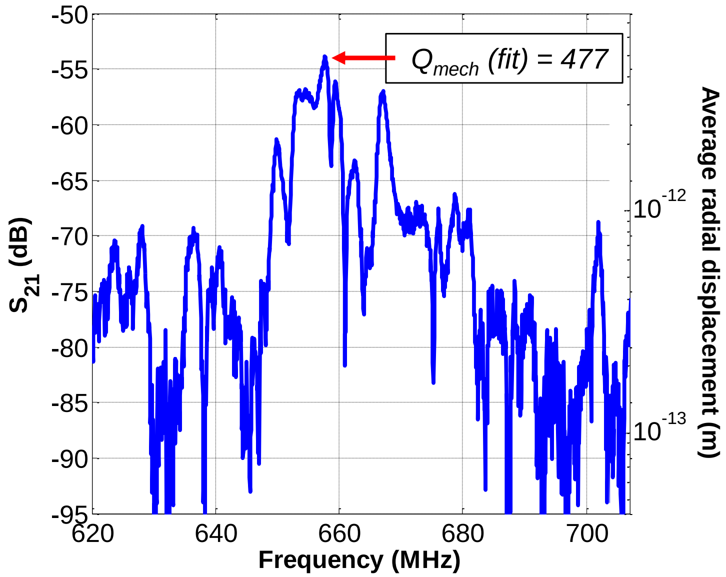


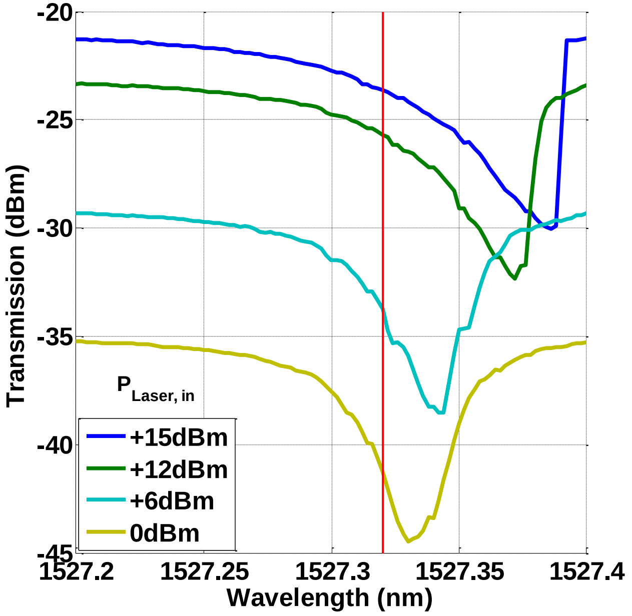


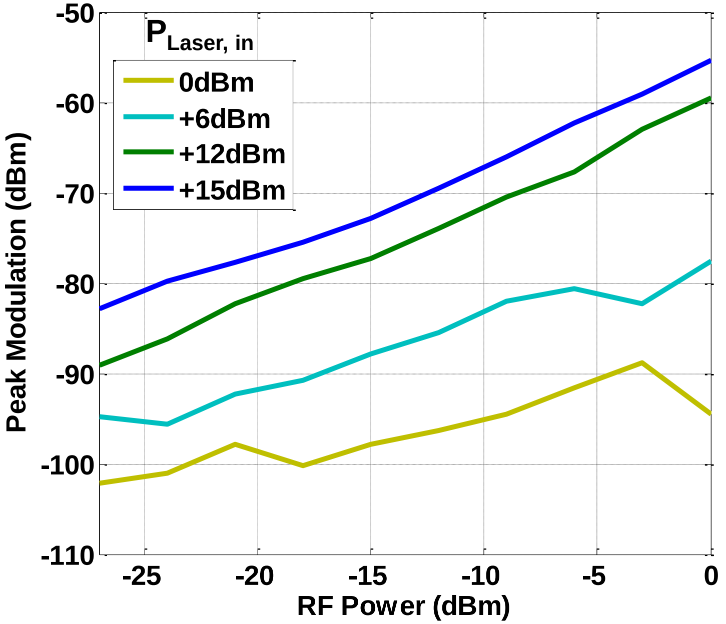
Carnegie Mellon

Additional XeF_2 Release

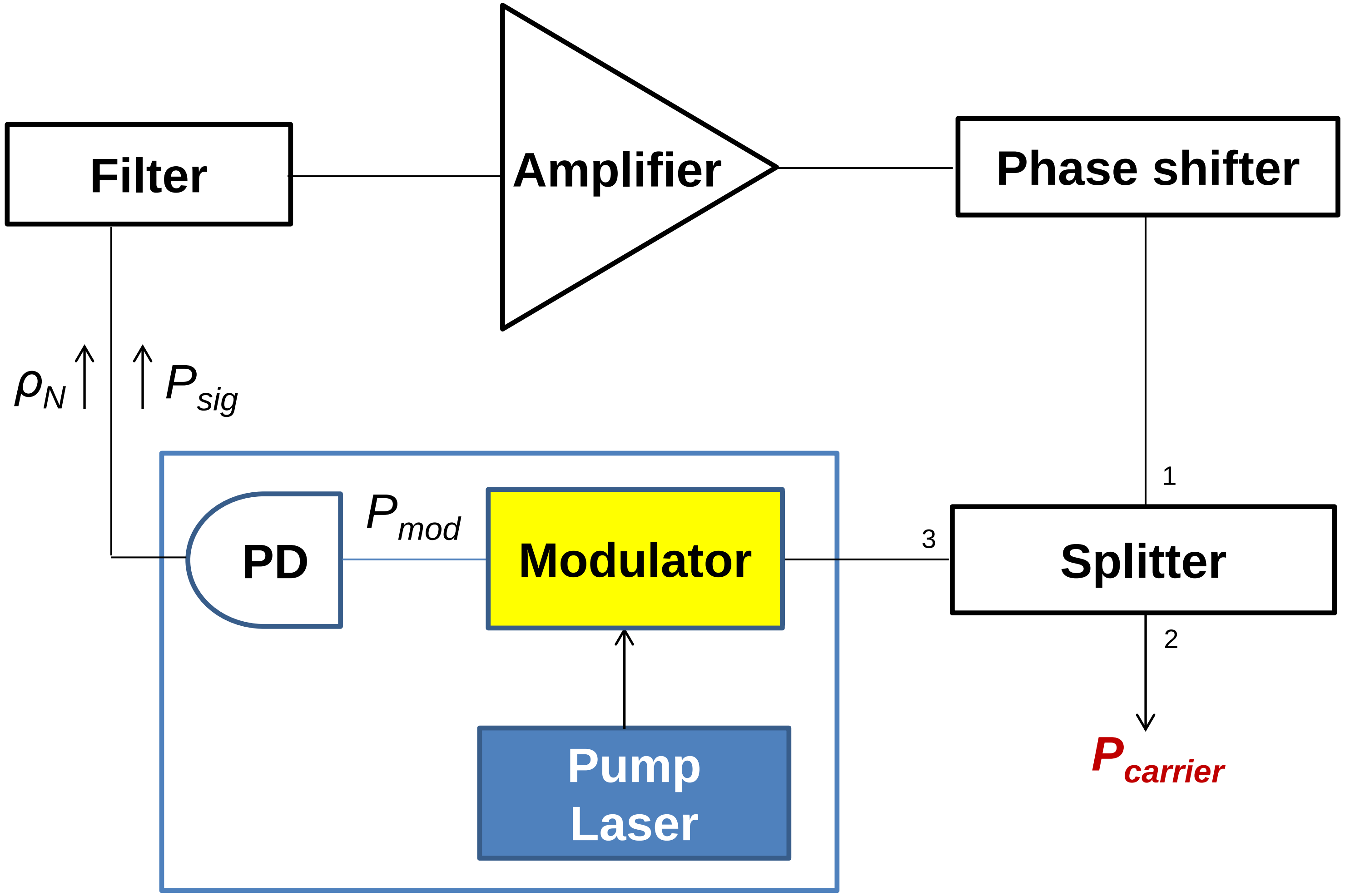






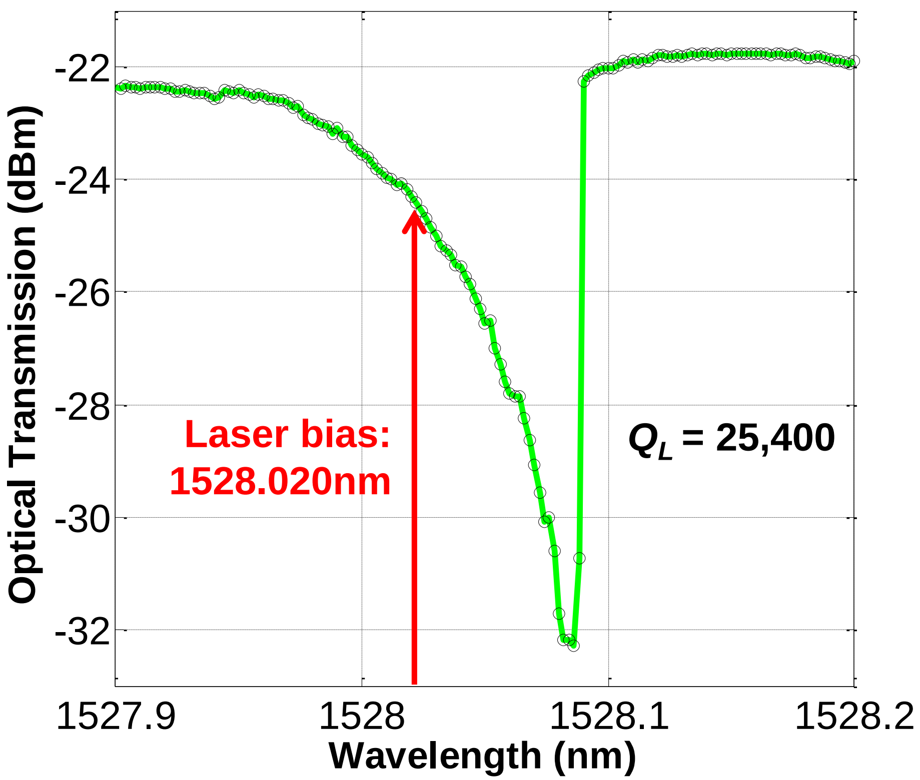


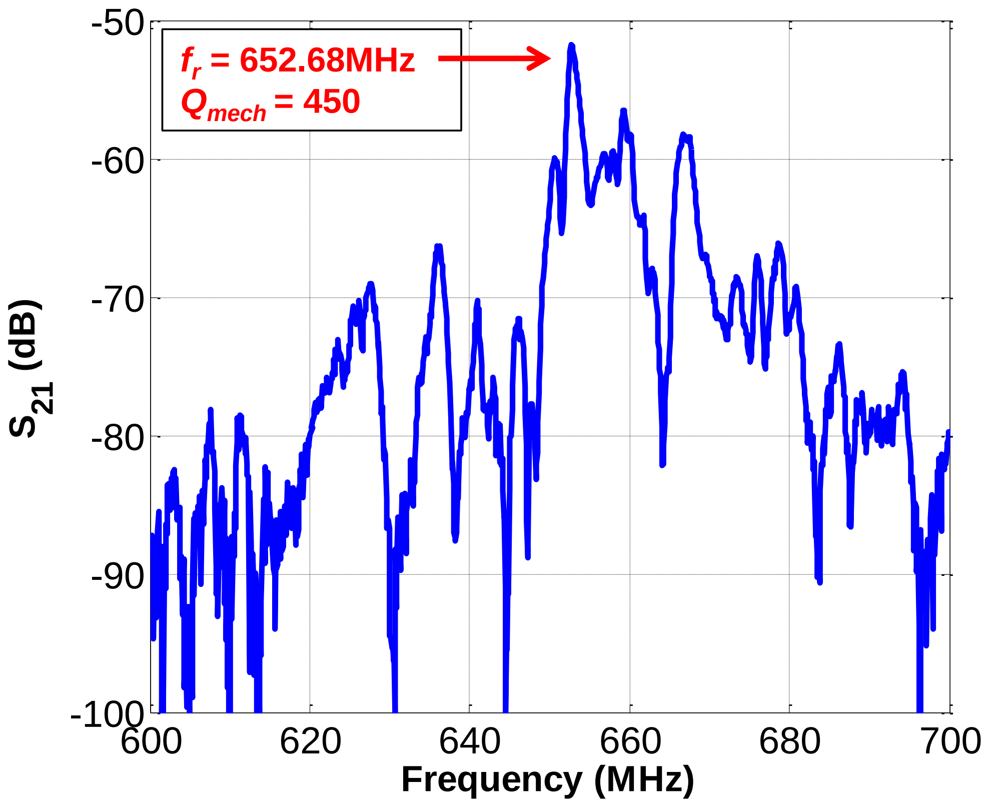
Opto-Acoustic Oscillator Loop



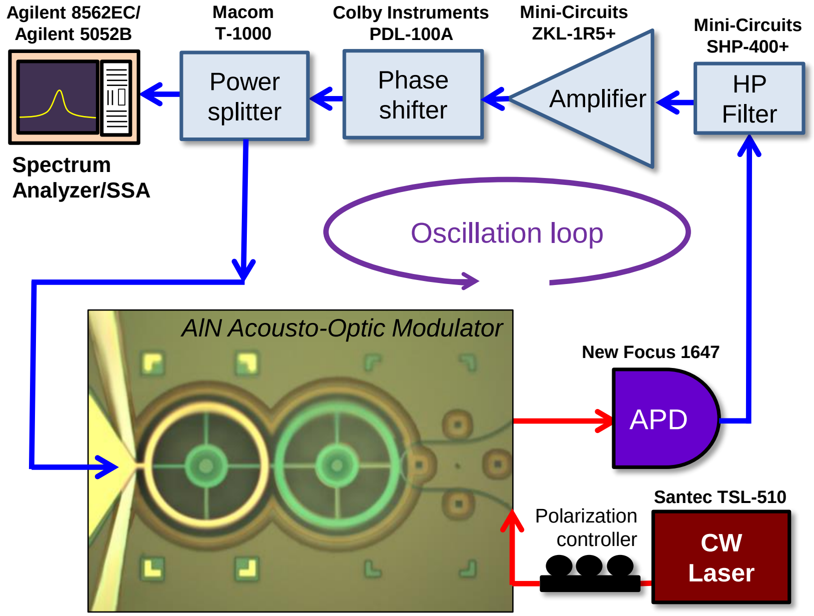
Carnegie Mellon

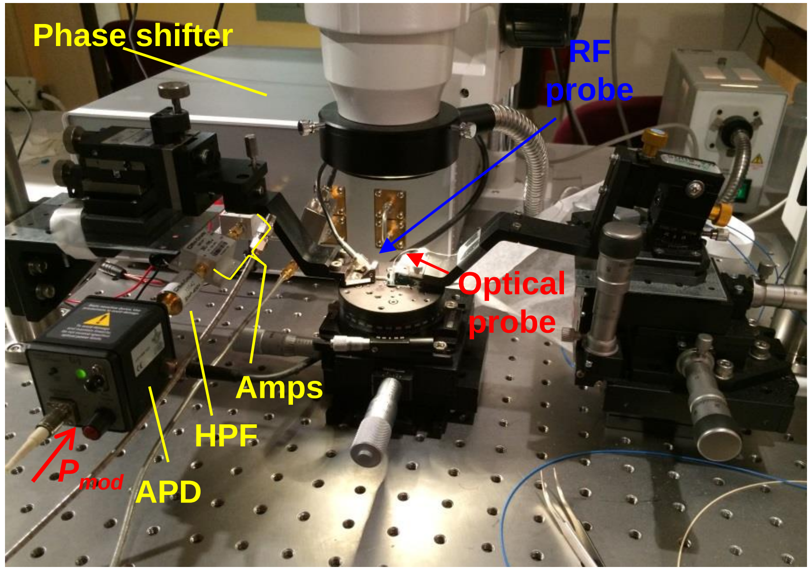
Operating conditions

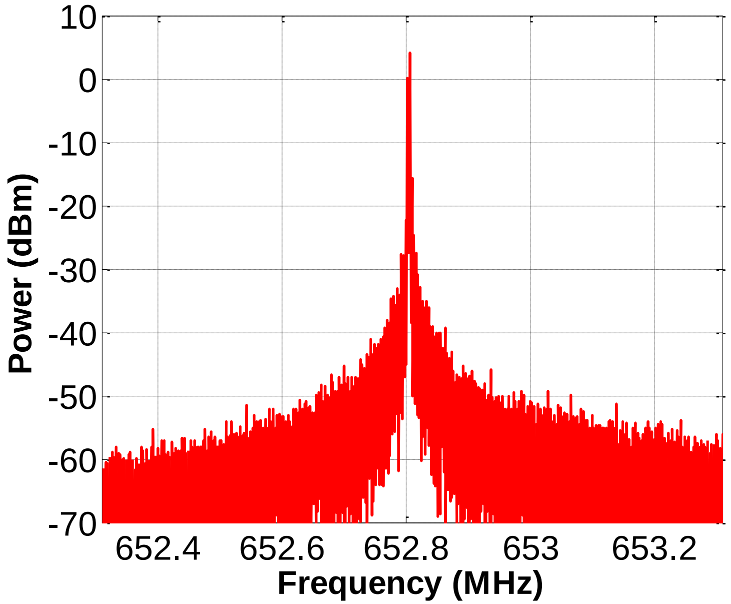




Opto-Acoustic Oscillation





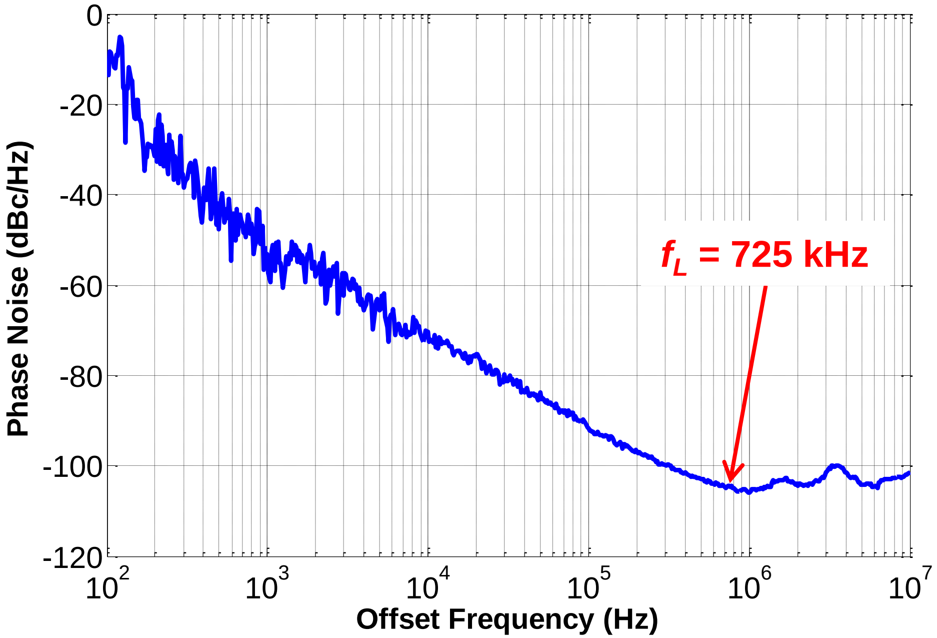


- **Circuit built with coaxial SMA components satisfies Barkhausen criteria**
- **Gain provided by 2 cascaded RF amplifiers, producing a net gain of ~66 dB**
- **High Pass Filter (HPF) used to exclude low frequency spurious modes in S_{21} transmission**

Carnegie Mellon

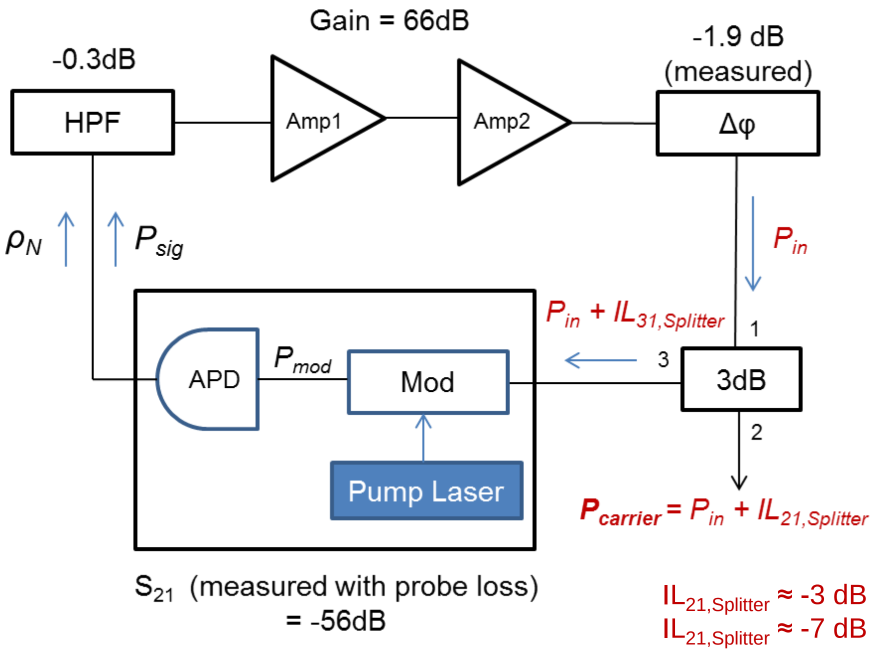
Phase Noise Measurement

Phase noise measured for $f_{carrier}$ = 652.8 MHz with $P_{carrier}$ = +6.51 dBm



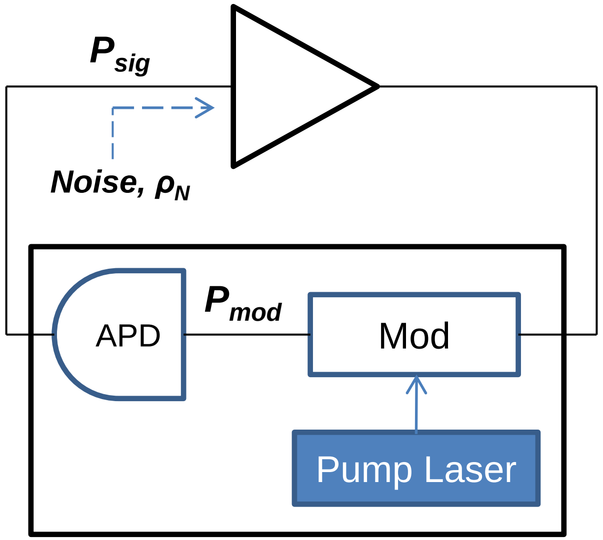
- **10kHz offset = -72 dBc/Hz**
- **Noise floor = -106 dBc/Hz**
- **Leeson corner frequency: $f_L = (f_{carrier}/2Q_{mech}) \approx$ 725 kHz (matches experiment)**

Schematic of the loop as tested:



- **Individual components were measured for loss contributions**
- **Some additional losses present in the connections – but this provides us an estimate for P_{sig}**

Phase Noise Model



- **Starting from the Leeson formula:**

$$S_\varphi(f) = \left[1 + \frac{1}{f^2}\left(\frac{\upsilon_o}{2Q_{mech}}\right)^2\right] S_\psi(f)$$

- **Describe $S_\psi(f)$:**

$$S_\psi(f) = \frac{\overline{v_n^2}/\Delta f}{\overline{v_{sig}^2}} = \frac{\left(1/2\right)\rho_N R_{PD}}{P_{sig} R_{PD}} = \frac{\rho_N}{2P_{sig}}$$

- **ρ_N is the additive noise, originating at the photodetector:**

$$\rho_N = Thermal\ noise + Shot\ noise + Laser\ RIN$$

$$\rho_N = (4k_B T \cdot NF) + (2eMF_A\sqrt{P_{sig}R_{PD}}) + (N_{RIN}P_{sig})$$

Where:

- k_B: Boltzmann's constant
- T: Ambient temperature
- e: electron charge
- M: APD multiplication factor
- F_A: APD excess noise factor
- R_{PD}: APD load resistor
- N_{RIN}: Laser Relative Intensity Noise
- NF: Amplifier Noise Factor
- A: Amplifier Gain

Main Contributions to Phase Noise

- Using losses in the loop, estimate: P_{sig} = -54.29 dBm

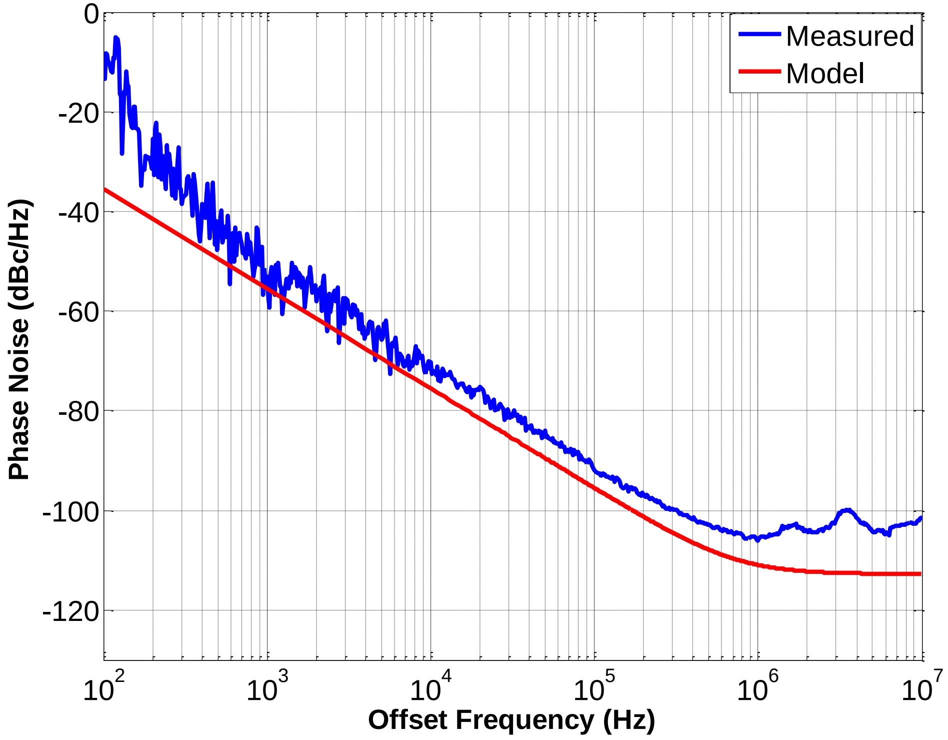
- Assuming: T = 293K
  NF = 3.05dB
  F_A = 5 (New Focus 1647)
  $F_A = M^x$ (x~0.7 for InGaAs)
  R_{PD} = 50Ω
  N_{RIN} = -145 dB/Hz for Laser (Santec TSL-510)

- Evaluation of ρ_N contributors:

$$Thermal = 3.26\times10^{-20}\ \text{W/Hz}$$

$$Shot = 6.88\times10^{-21}\ \text{W/Hz}$$

$$RIN = 1.17\times10^{-23}\ \text{W/Hz}$$



- Net $\rho_N = 3.95\text{x}10^{-20}$ W/Hz, producing a noise floor of -113 dBc/Hz
- Low photocurrent generated by P_{sig} causes thermal noise contribution to dominate

Modulator Analytical Transfer Function

- **Description of modulation capability:**

$$P_{\text{mod}} = \frac{dT}{d\lambda} \cdot \frac{d\lambda}{dr} \cdot \Delta r$$

$$= P_{trans} H_{cav} \cdot g_{om\lambda} \cdot \eta_{om} V_{rms}$$

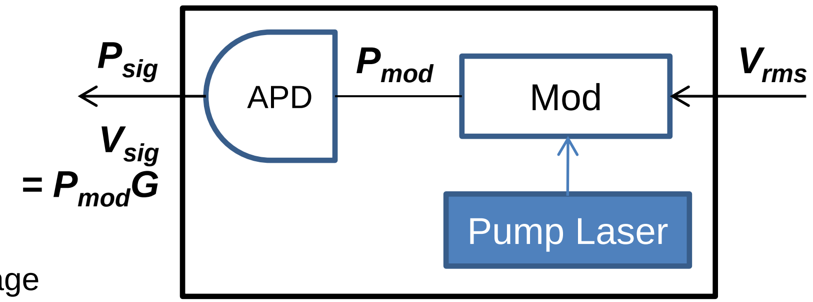
Transmission losses

Transfer function

Optomechanical coupling

Piezo-optomechanical transduction

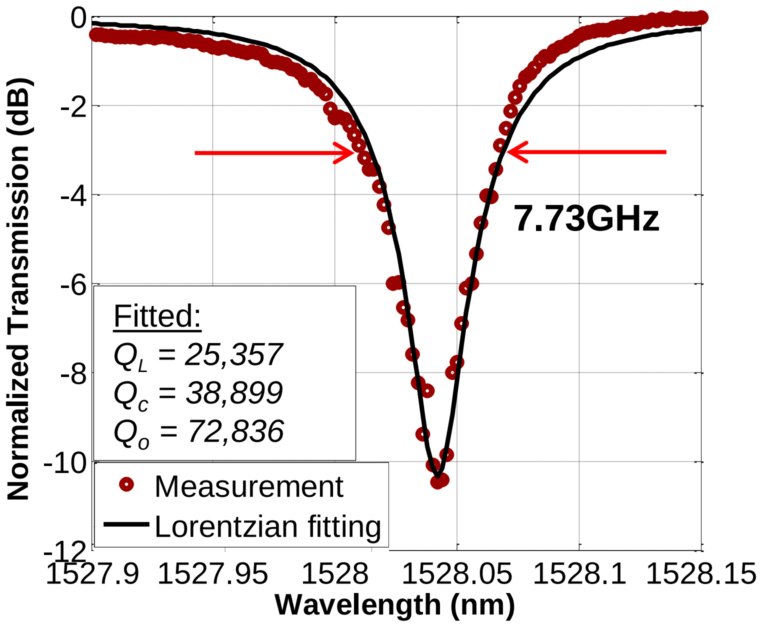
Input voltage



$$H_{cav} = \frac{8\Gamma^2(\lambda - \lambda_o)}{[4(\lambda - \lambda_o)^2 + \Gamma^2]^2}$$

$$g_{om\lambda} = \frac{\lambda_o}{R_{out}}$$

- **Device tested for P_{trans} at a level of -22dBm**
- **For our WGM resonator, Γ = 60 pm**



- **We can extract a simplified expression for S_{21} of the modulator (G = APD gain):**

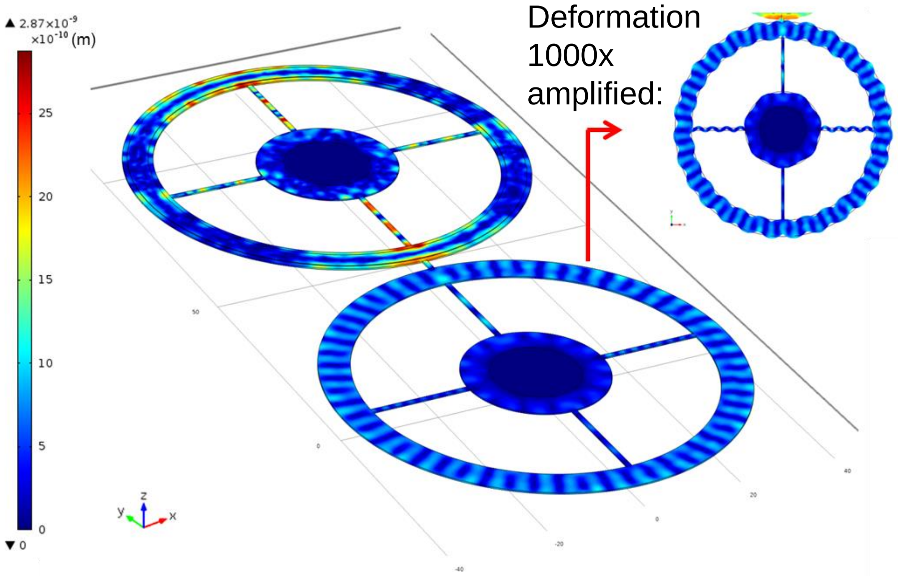
$$S_{21,dB} = 20\log\left(P_{trans} H_{cav} g_{om\lambda} \eta_{om} G\right)$$

- **For the measured S_{21} = -56dB, this yields η_{om} = 26 pm/V**

Carnegie Mellon

Piezo-Optomechanical Transduction Capability

- **FEM simulations confirm the η_{om} transduction capability is diminished due to mismatch in the modes of the CM and WGM rings**
- **This produces displacement in the WGM ring, in which Δr does not correspond to that of the radial contour mode, but rather generates an average displacement Δr_{avg}**



- **By re-designing the ring geometries to exploit the electromechanical coupling (η) in the CMR:**

$$\eta = 2d_{31}E_{eq}\left(2\pi R_{avg}\right)$$

- **Fully coupled into WGM:**

$$\Delta r = Q_{mech}\left(\frac{F_{piezo}}{m_{eff}\Omega_{mech}^2}\right) = Q_{mech}\left(\frac{2d_{31}E_{eq}\left(2\pi R_{avg}\right)V_{rms}}{m_{eff}\Omega_{mech}^2}\right)$$

- **Resulting in effective η_{om} capability:**

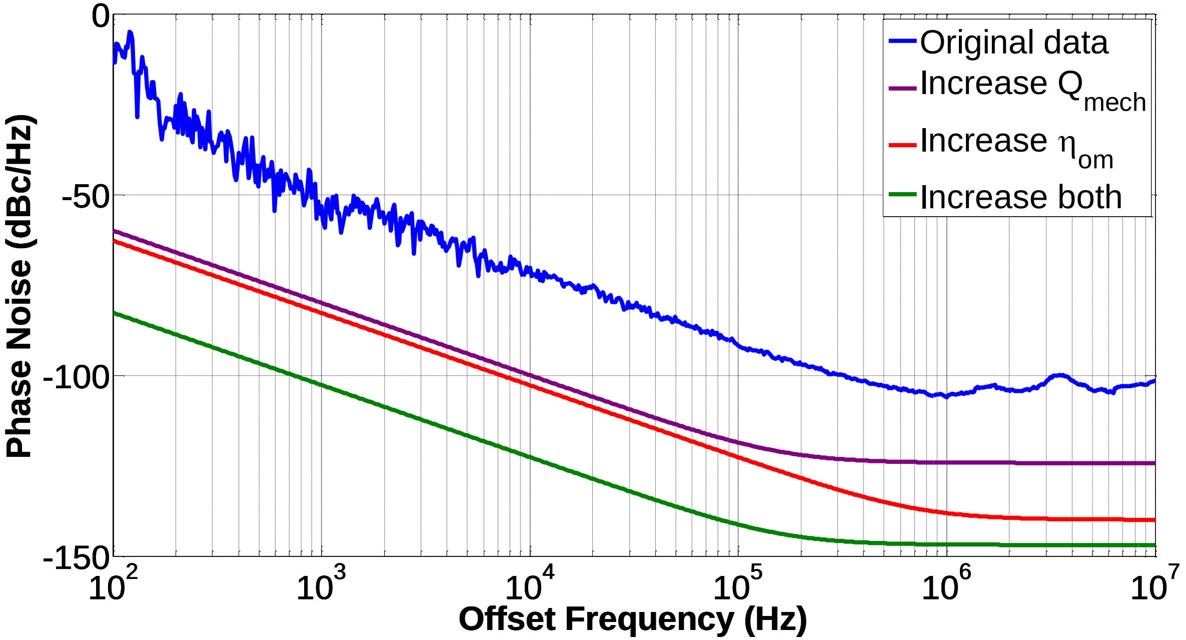
$$\eta_{om} = Q_{mech}\left(\frac{4\pi d_{31}E_{eq}R_{avg}}{m_{eff}\Omega_{mech}^2}\right)$$

2-3 orders of magnitude higher than that currently produced

Carnegie Mellon

PN Expectation with Improvements to η_{om}

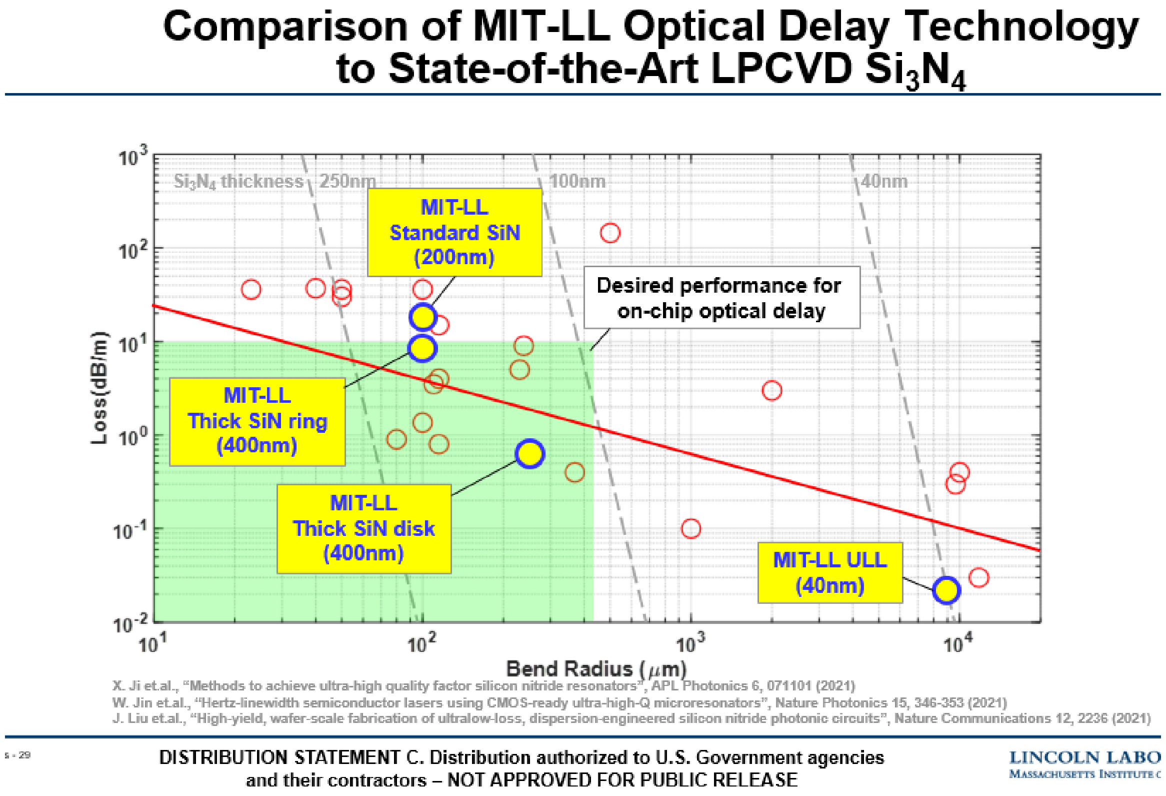
- All other factors remaining the same (Q_{opt} = 25,000, Optical transmission losses, $P_{carrier}$, Mismatch losses at input), compute η_{om}

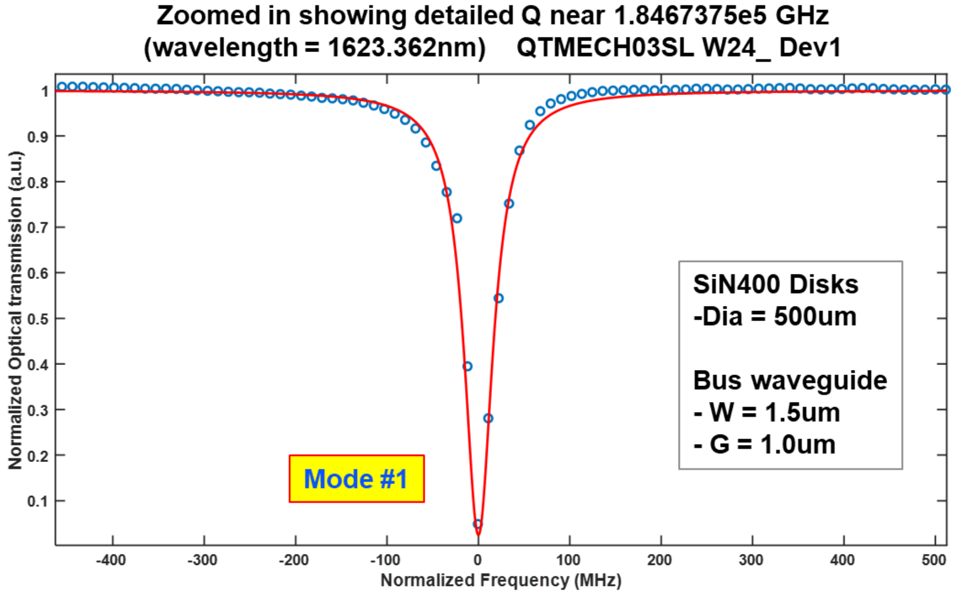


	Initial			
η_{om} P_{trans} G Q_{mech} P_{sig} Noise floor ρ_N Dominant contribution	26 pm/V -22.5 dBm 14,000 V/W 450 -54.2 dBm -113 dBc/Hz Thermal			

- Improvements in the S_{21} can also be attained by tuning a host of parameters:
  - P_{trans} (determined by gratings)
  - Q_{opt} – Generate S_{21} gain
  - 50Ω matching

Optical resonators using 400 nm thick LPCVD SiN

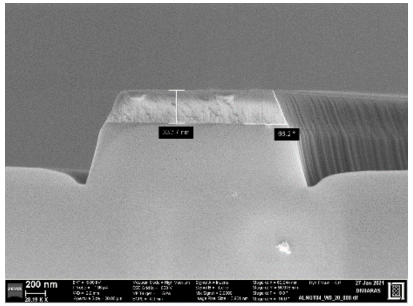




Mode #	Q bus-disk	Q unloaded	FSR (GHz)	ng
1	8.3943e6	11.542e6	100.06	1.90739

EB-ALNWG01

- Etched several wafers using an oxide hard mask and EB-ALNWG01 Aluminum Nitride etch.
  - Wafer 0 (AlNQT03 -20) & ALNQT04 wafers 1 & 4,
- 300-400nm Aluminum Nitride sputtered by OEM group
- 300 nm oxide hard mask needed
- Patterning using JSR 500nm resist w 65nm BARC
- Oxide open using EBA-SIPWGOX28 (15 sec Barc etch, and 50 sec Oxide etch)
  - Etch was developed as part of the IONPH008X aluminum oxide improvement DOE, where we tried to have an oxide opening ethch with good JSR selectivity and reduced polymer formation.
  - OX ER ~6.7nm/sec, JSR ER ~4.1nm/sec

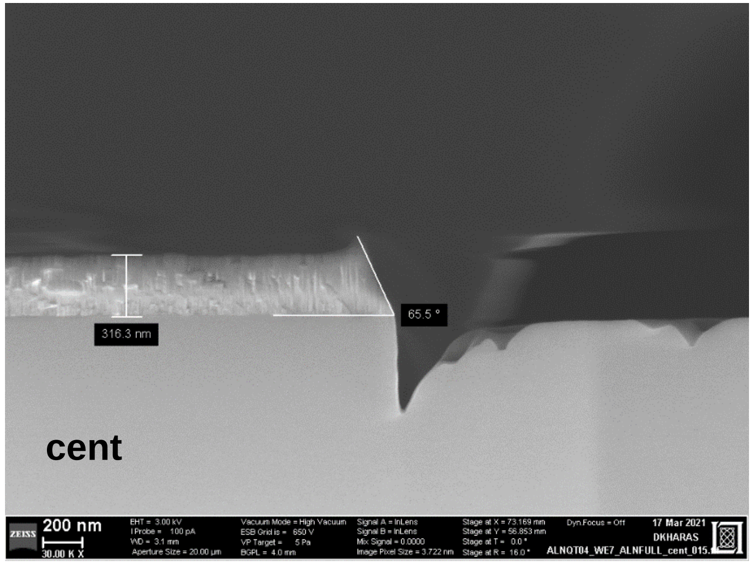


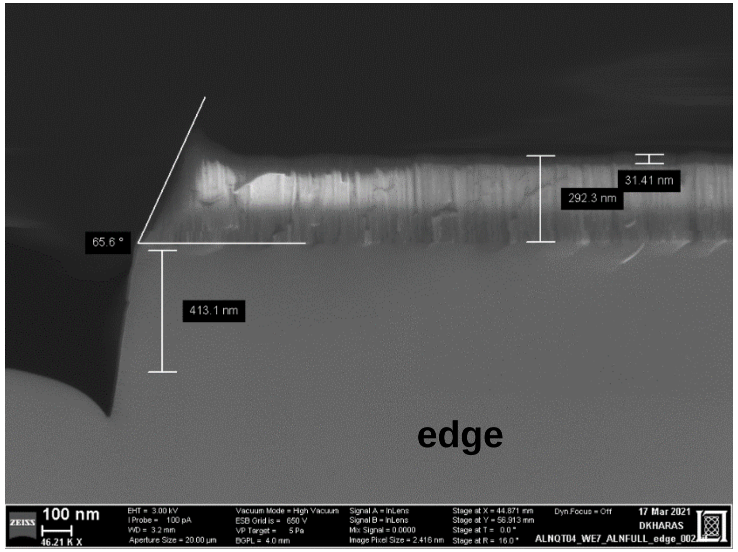
- Aluminum Nitride etch EB-ALNWG01
  - Etch seems to slow down with time and not clear at the bottom
  - Etch is sloped 65 deg, shows micro trenching at edges
  - Accelerated etch into silicon is seen.
  - Etch is not uniform across the wafer surface-some evidence of polymer residues on surface. Mottled surface appearance in places, perhaps where oxide hard-mask thickness variability on the surface or polymer residues?
  - ALN ER ~1.65-2.4 nm/sec
  - Ox HM ER ~1.3 nm/sec

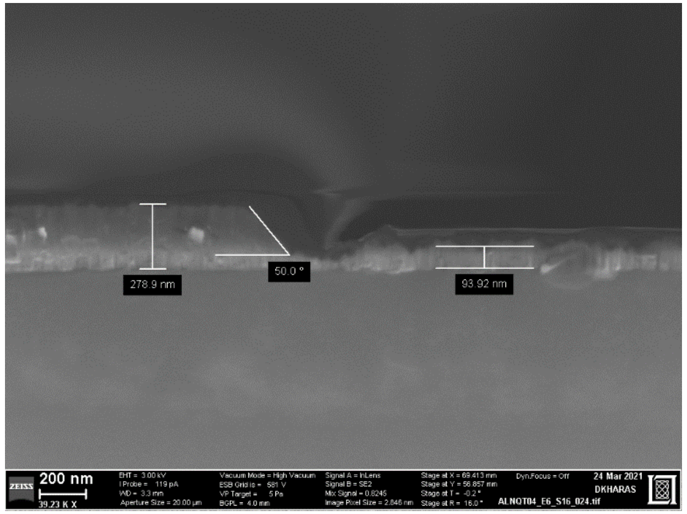
EB-ALNWG02

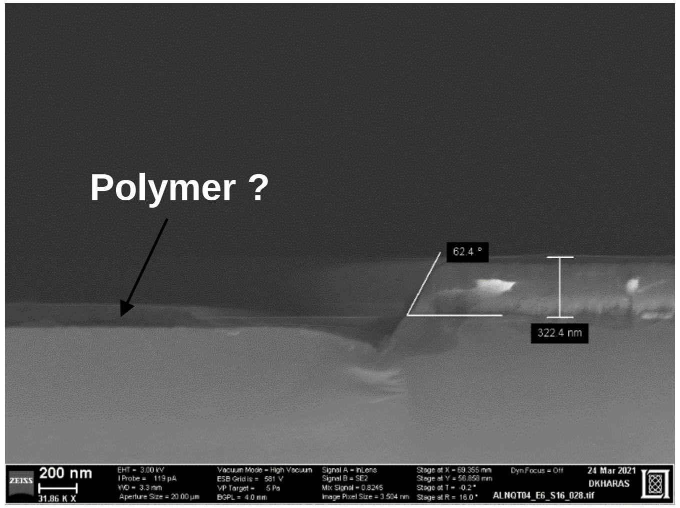
- Etched several wafers using an oxide hard mask and EB-ALNWG01 Aluminum Nitride etch.
  - ALNQT04 wafers 16, 17 (ALNQT03 E6, E7) and ALNQT04 w3,
- Wafers were had ALN deposited at Northeastern University, and wafer 3 had OEM ALN.
- 200 nm oxide hard mask used on wafer 16 and 17, but insufficient used 300 nm sequel oxide on wafer 3
- Patterning using JSR 500nm resist w 65nm BARC
- Oxide open using EBA-SIPWGOX28 (15 sec Barc etch, and 35 sec Oxide etch)
- Aluminum Nitride etch EB-ALNWG02
  - Etch seems to slow down with time and not clear at the bottom
  - Etch is sloped 65 deg, shows micro trenching at edges
  - Accelerated etch into silicon is not seen to the same extent as 01 etch
  - OEM and NE ALN appear to etch at different rates,
  - NE ALN etched at ~2 nm/sec,
  - OEM ALN ER ~1.4 -1.9 nm/sec
  - Ox HM ER ~1.36 - 1.6 nm/sec
  - Resist consumption rate ~ 3.3 nm/sec (averaged across all steps)

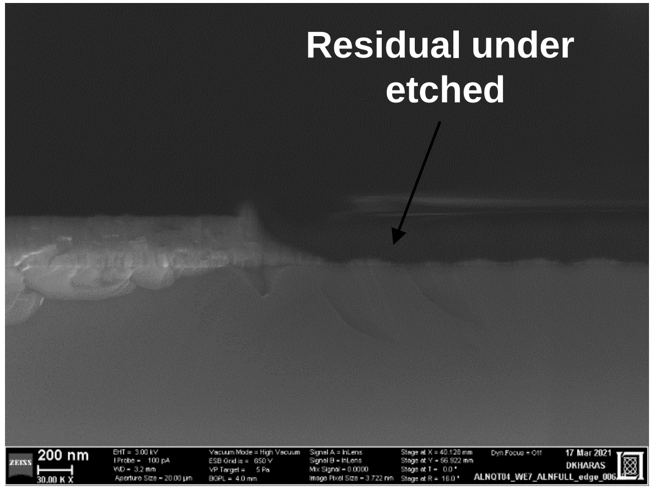
ALNWG02 x-SEM and optical











Variable Etch depth And color

Northeastern University

AlN baseline etch recipe – EB-ALNWG01

EB-ALNWG01.rcp

File Help

Step:	Step 1	Step 2	Step 3	Step 4
StepName:	STAB1	TIN-TI	MAIN	DECHUCK
Chamber Selection:	-B---------	-B---------	-B---------	-B----12345
Step end control:	By Time	By Time	By Time	By Time
Maximum step time:	10.0 seconds	5.5 seconds	180.0 seconds	5.0 seconds
Endpoint Selection:	No Endpoint	No Endpoint	External Endpoint	No Endpoint
EndpointParams:			Algorithm ID: 3 Min Endpoint Time: 100 Secs	
Pressure Control:	Servo to xxx mTorr	Servo to xxx mTorr	Servo to xxx mTorr	No Pressure Control
Pressure:	10 mTorr	10 mTorr	6 mTorr	mTorr
Bias Power:	0	100	125	0
RFMode:	0	0	0	0
DC Bias Limit:	-1000 to 0	-1000 to 0	-1000 to 0	-1000 to 0
Source Peak Power:	0 W	1200 W	1000 W	0 W
Process Position:	N/A	N/A	N/A	N/A
Temperature:	14.0 °C	14.0 °C	14.0 °C	1.0 °C
Gas1:	BCL3 0	BCL3 0	BCL3 20	N2-20 10
Gas2:	CL2 80	CL2 80	CL2 120	
Gas3:	N2-20 0	N2-20 0	N2-20 0	
Gas4:	ARB 40	ARB 40	ARB 40	

Ideas to try for improving sidewall angle

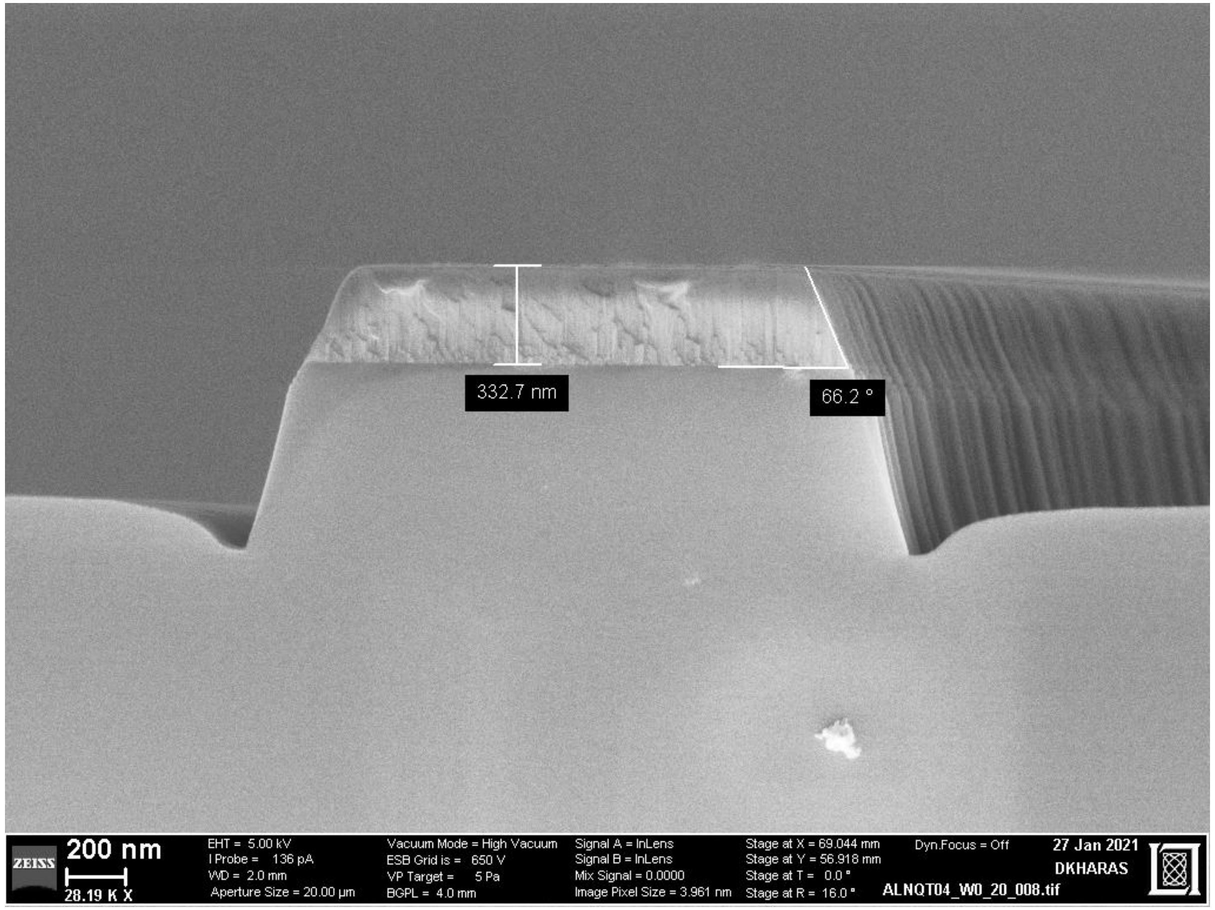
- **Low chamber pressure (maybe can try 4 mT if the plasma can stabilize)**
- **High ICP power**
- **Changing the Cl2/BCl3 blend (typically higher flow on BCl_3 than Cl_2, blended in seems to help the etch rate and selectivity for III-V's)**
- **Minimizing Ar flow unless we have a lot of re-deposition on the substrate (Ar is physical and might hurt the SiO2 selectivity)**

Recipe 1: EB-ALNWG01

Main etch: (1/27/21)

- **6 mT**
- **1000 W source (ICP)**
- **20 sccm BCl3**
- **120 sccm Cl2**
- **40 sccm Ar**
- **125 W bias**

- **Wafer: AlNQT04_W0 (slot 20)**



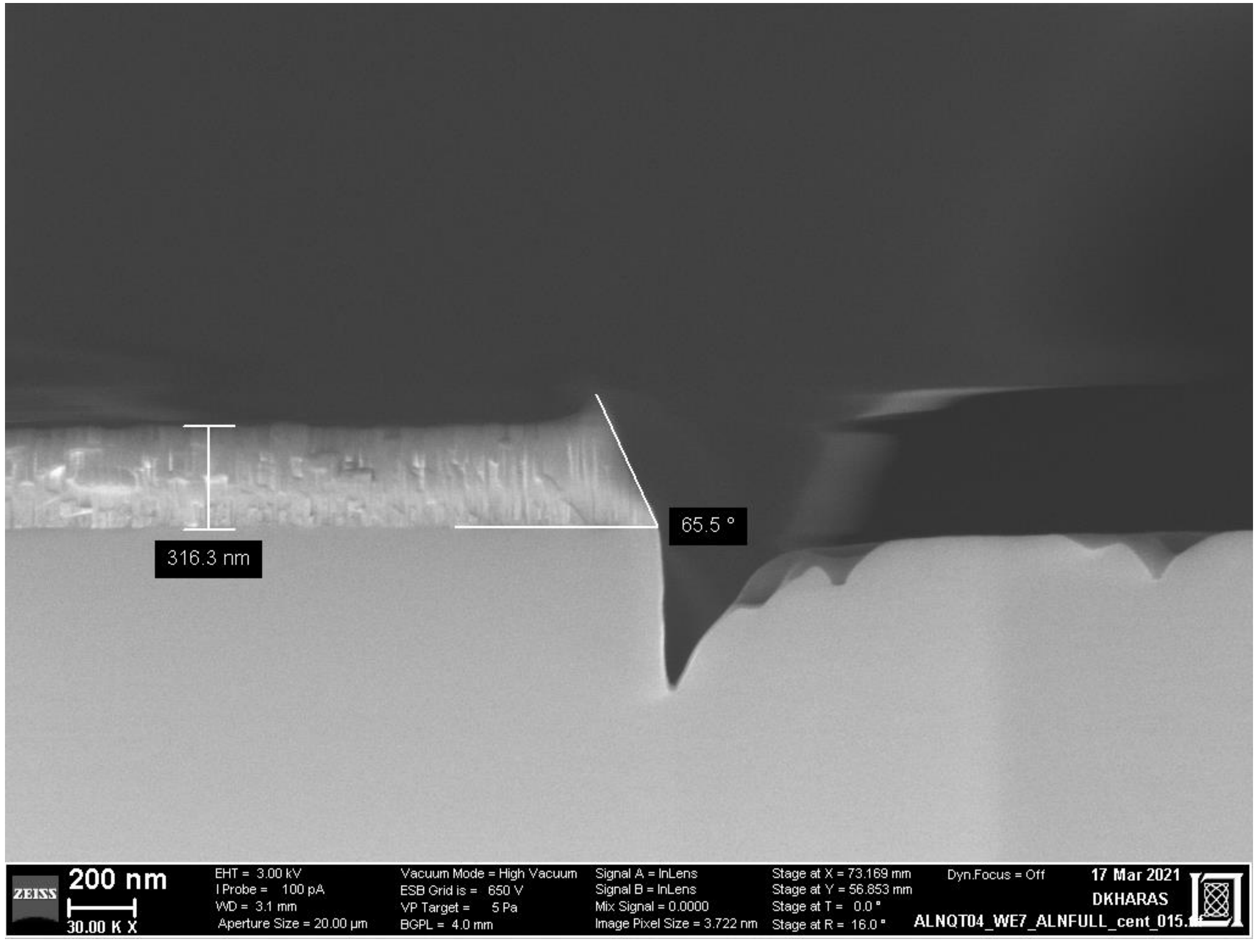
Recipe 2: EB-ALNWG02

Main etch: (2/3/21)

- **4 mT**
- **1200 W source (ICP)**
- **20 sccm BCl3**
- **80 sccm Cl2**
- **40 sccm Ar**
- **125 W bias**

- **Lower pressure, higher power → no effect on slope, negative impact on selectivity**

- **Wafer: AlNQT03_E7**



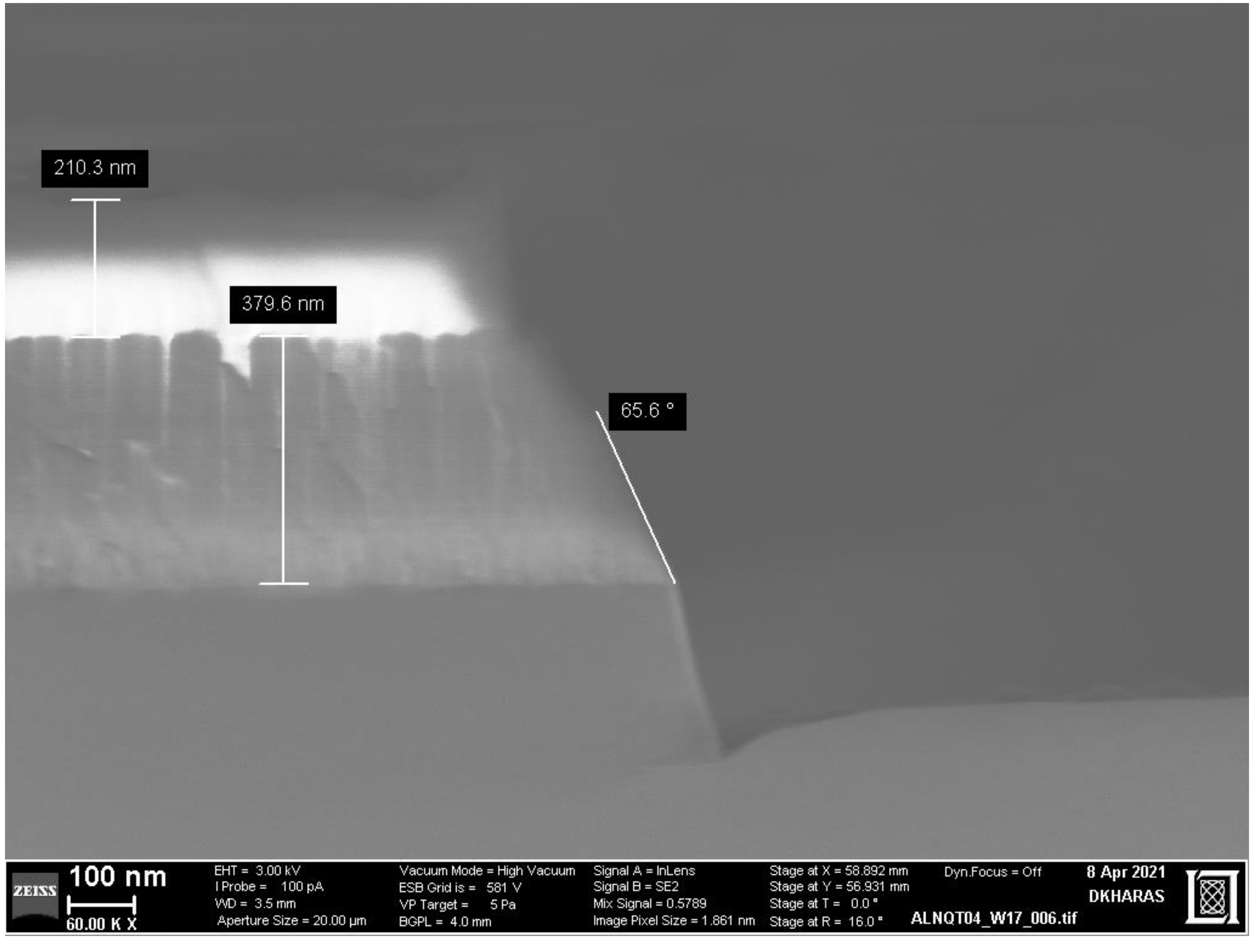
Northeastern University

Recipe 3

Main etch: (4/2/21)

- **6 mT**
- **1000 W source (ICP)**
- **10 sccm BCl3**
- **120 sccm Cl2**
- **40 sccm Ar**
- **125 W bias**

- **Wafer: AlNQT04_W17**

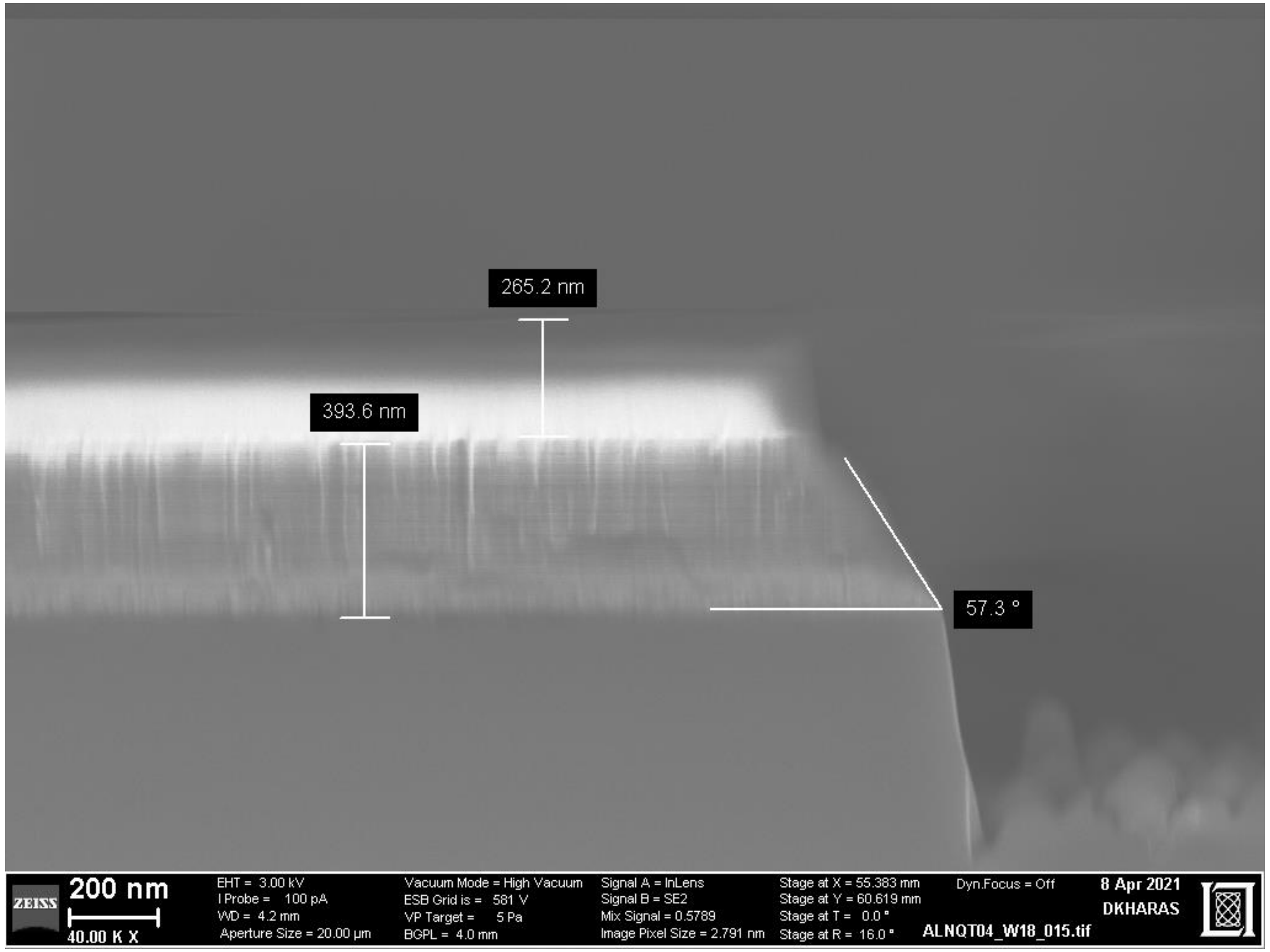


Recipe 4

Main etch: (4/2/21)

- **6 mT**
- **1000 W source (ICP)**
- **0 sccm BCl3**
- **120 sccm Cl2**
- **40 sccm Ar**
- **125 W bias**

- **Wafer: AlNQT04_W18**



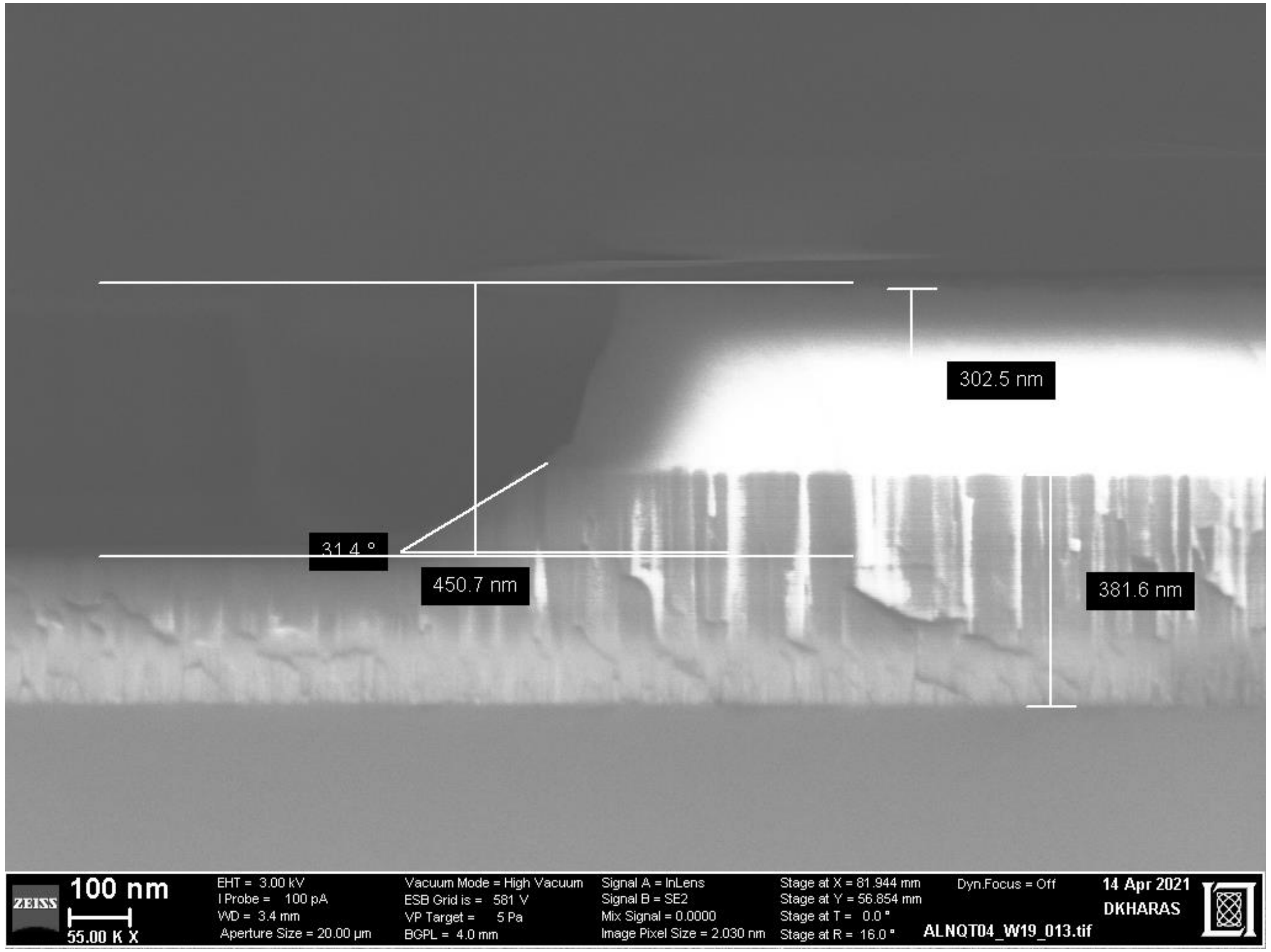
Recipe 5

Main etch: (4/15/21)

- **6 mT**
- **1000 W source (ICP)**
- **58 sccm BCl3**
- **82 sccm Cl2**
- **40 sccm Ar**
- **125 W bias**

Adapting from Al in C400:

- **Bias – 250** **ICP – 250**
- **Pressure - .4Pa** **Pos – 100%**
- **Cl2 – 14sccm / AR – 6sccm / BCl3 – 10sccm**



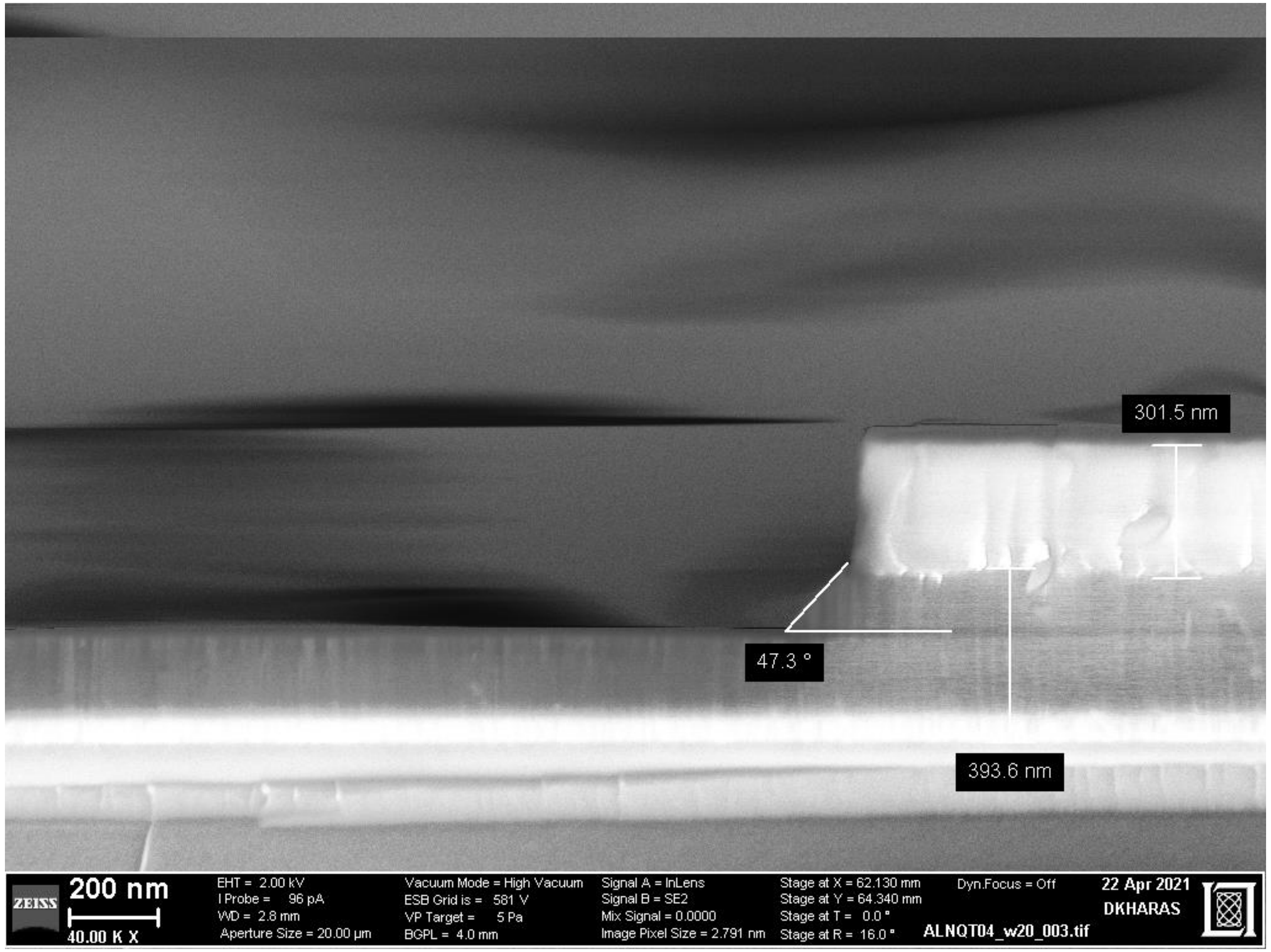
- **Wafer: AlNQT04_W19**

Recipe 6

Main etch: (4/22/21)

- **6 mT**
- **1000 W source (ICP)**
- **20 sccm BCl3**
- **40 sccm Cl2**
- **40 sccm Ar**
- **125 W bias**

- **Wafer: AlNQT04_W20**



Recipe 7

Main etch: (4/26/21)

- **15 mT**
- **1000 W source (ICP)**
- **20 sccm BCl3**
- **120 sccm Cl2**
- **40 sccm Ar**
- **125 W bias**

- **Wafer: AlNQT04_W21**

AMAT Etch Trials grouped by Variable

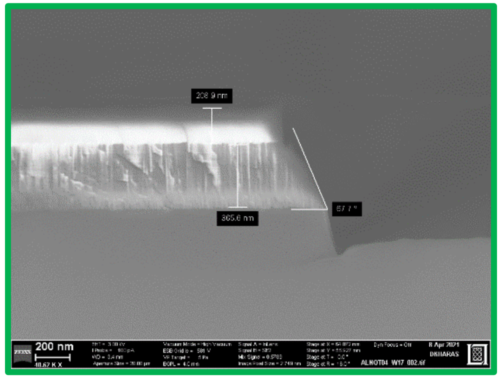
Appled Materials Centura Etcher

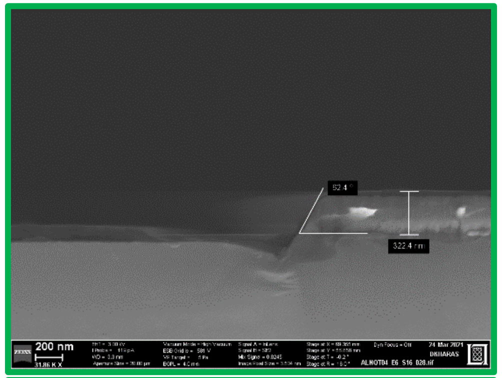
			fixed power, reduced BCl3		reduced Cl2, increasing BCl3			Higher Argon flow	
Wafer ID	wafer 1,4	26	17	18	20	19	27	26	B23
Recipe variant	WG01 POR	POR	WG01_V1	WG01_V2	WG01_V4	WG01_V3	EB-ALOX36	POR	WG01_V7
ICP	1000	1000	1000	1000	1000	1000	1200	1000	1000
BIAS	125	125	125	125	125	125	100	125	125
Press	6	6	6	6	6	6	4	6	6
Cl2	120	120	120	120	40	82	0	120	120
BCl3	20	20	10	0	20	58	100	20	20
Ar	40	40	40	40	40	40	0	40	80
total flow	180	180	170	160	100	180	100	180	220
Cl2/BCL3 ratio	6	6	12		2	1.41		6	6
etch angle	66	50.4	66	57	47	39	47	50.4	57
etch time	120	50	100	100	50	50	70	50	50
depth	160	228	380	397	134	163	63	228	245
			etched through	etched through					
Etch rate		4.56	3.80	3.97	2.68	3.26	0.90		4.90
				worse	higher BCL3 worse				

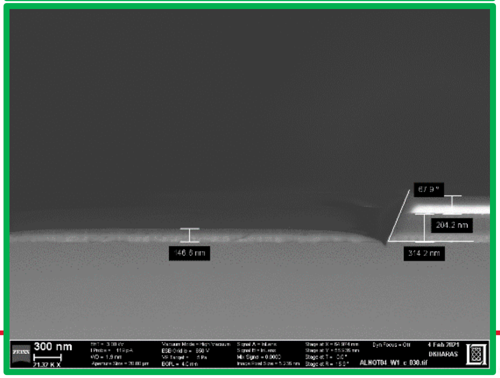
			Increase P	decrease P	resist only etching, elliminate impact of oxide etch byproducts		
Wafer ID	wafer 1,4	26	21	E6,E7	30	31	32
Recipe variant	WG01 POR	POR	WG01_V5	WG02	POR	WG01_V10	WG01_V11
ICP	1000	1000	1000	1200	1000	1000	1000
BIAS	125	125	125	125	125	100	200
Press	6	6	15	4	6	6	6
Cl2	120	120	120	80	120	100	120
BCl3	20	20	20	20	20	10	20
Ar	40	40	40	40	40	20	40
total flow	180	180	180	140	180	130	180
Cl2/BCL3 ratio	6	6	6	4	6	10	6
etch angle	66	50.4	47	66	58	45	40
etch time	120	50	50	25	45	45	45
depth	160	228	263	53	145	130	220
Etch rate	1.33	4.56	5.26	2.12	3.22	2.89	4.89
		WGOX14	reduces etch angle	maintains etch angle	resist only	resist only	resist only
					7.4	8.4	4.8
					0.44	0.34	1.02

	variables	Best Condition
ICP	1000, 1200	1000
BIAS	100, 125	125
Press mtor	4, 6,15	6
Cl2	0,40,82,120,	120
BCl3	0,10,20,58,100	10
Ar	0,20,40,80	40
total flow	100,160,170,180,220	170
angle		65 deg

			higher Bias	lower bias	higher bias and icp
Wafer ID	wafer 1,4	26	B22	B25	B24
Recipe variant	WG01 POR	POR	WG01_V6	WG01_V9	WG01_V8
ICP	1000	1000	1000	700	1200
BIAS	125	125	200	50	200
Press	6	6	6	6	6
Cl2	120	120	120	120	120
BCl3	20	20	20	20	20
Ar	40	40	40	40	80
total flow	180	180	180	180	220
Cl2/BCL3 ratio	6	6	6	6	6
etch angle	66	50.4	57	56	59
etch time	120	50	50	100	50
depth	160	228	350	253	338
Etch rate	1.33	4.56	7.00	2.53	6.76

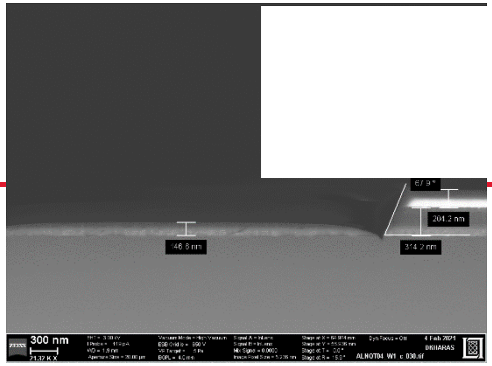
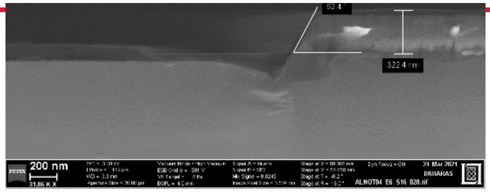
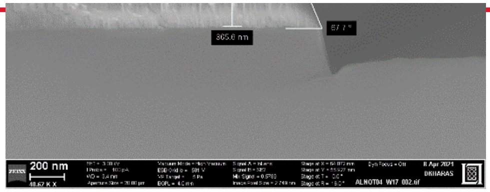
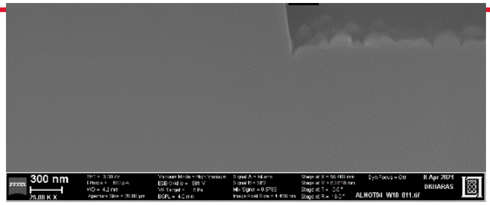
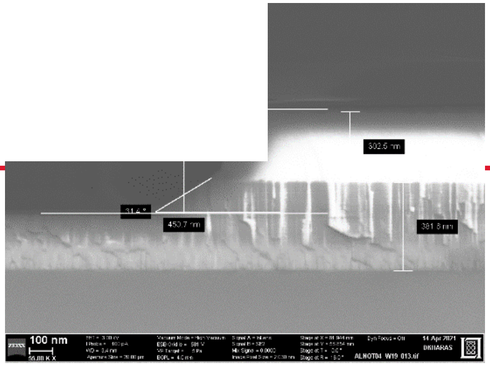
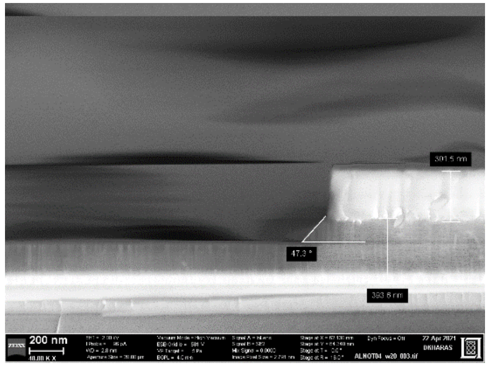
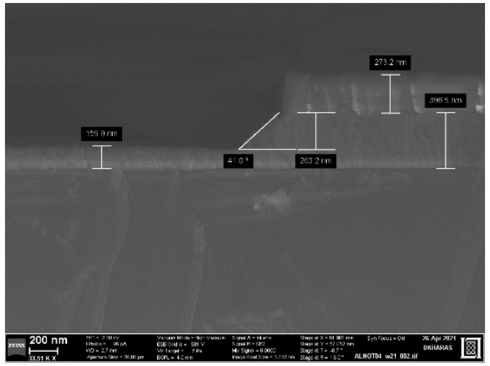
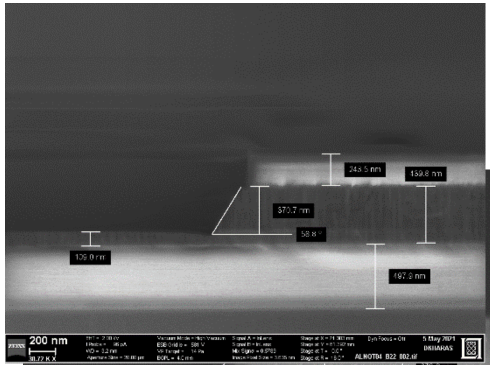
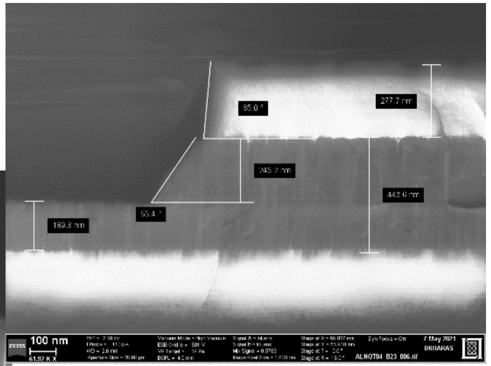
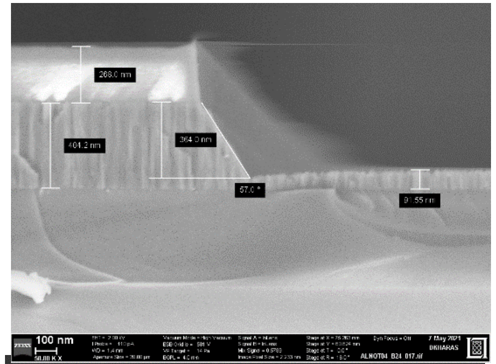
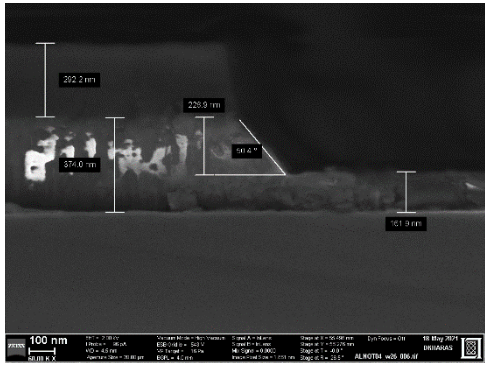
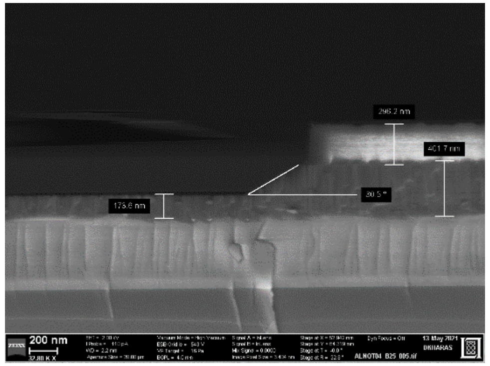
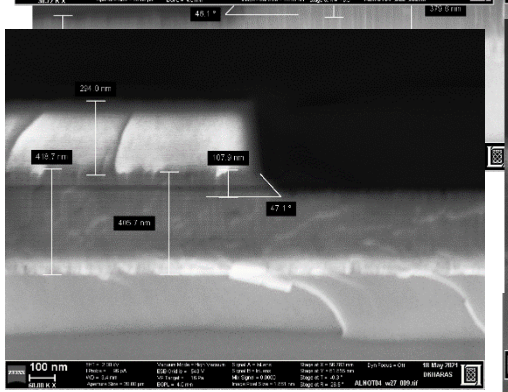
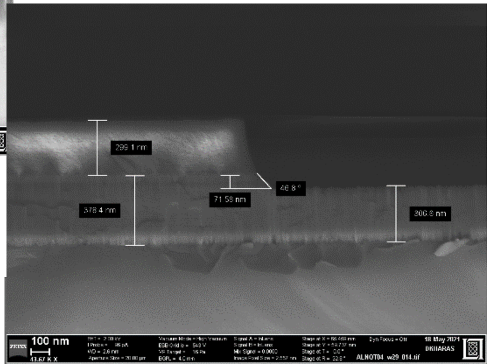


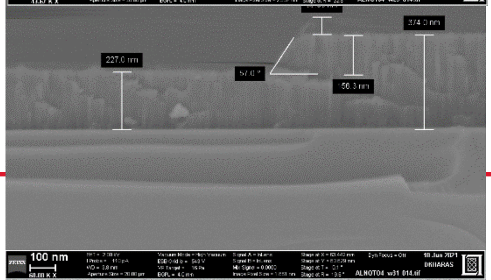




Northeastern University

AMAT Etch Variants (refer to wafer id)



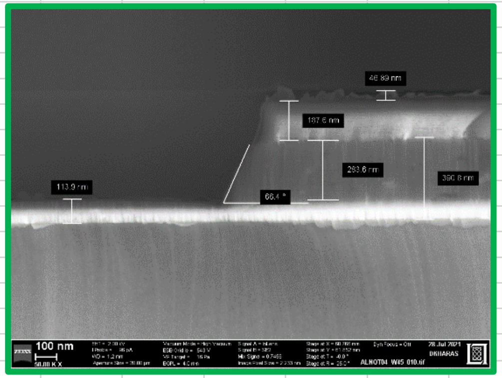
SAMCO Etch Trials grouped by Variable

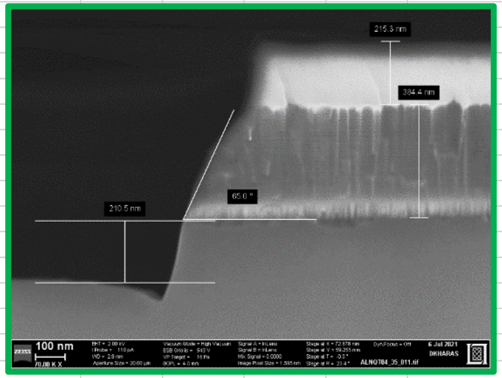
SAMCO Metal Etcher

Notes on the table:
- Wafers 33, 35, 34, 36: higher BCl3 worse angle; reduced total flow better angle (33: 1st; 35: shorter time)
- Wafers 38, 41, 44, 45: lower pressure slightly better; reduced Ar dilution; reduced BCl3
- Wafer 42 (with the unlabelled wafer before it): incresed Bcl3 worse
- Wafers 41, 42 (last group): Higher Presssure worse angle

Wafer ID	33	35	34	36	38	41	44	45		42	41	42
Recipe variant	72 Samco	74 sam	73 sam	73 sam	74 sam	74	77	77	72	76	74	76
ICP	600	600	600	600	600	600	600	600	600	600	600	600
BIAS	200	200	200	200	200	200	200	200	200	200	200	200
Press	0.7 PA	0.7 PA	0.7 PA	0.7 PA	0.4	0.4	0.4	0.4	1.1	1.1	0.4	1.1
Cl2	90	90	65	30	14	40	20	20	20	40	40	40
BCl3	15	15	40	5	10	10	0	0	10	0	10	0
Ar	10	50	10	0	6	0	0	0	0	0	0	0
total flow	115	155	115	35	30	50	20	20	30	40	50	40
Cl2/BCL3 ratio	6	6	1.625	6	1.4	4			2		4	
etch angle	58	52	47	64	53	64	53	60	30	48	64	48
etch time	90	50	50	50	50	50	50	50	50	50	50	50
depth	385+30	381+162	207	216	152	245	200	200	186	250	245	250
Etch rate	4.6	10.9	4.1	4.3	3.0	4.9	4.0	4.0	3.7	5.0	4.9	5.0
Oxide HM BT Recipe	WG0X14 50	WG0X14 51	WG0X14 5	WG0X14 38	WG0X14 38				WG0X14 3	WG0X14 38		WG0X14 38
Oxide HM thickness	300	301	300	200	200				200	200		
AlN/RES												

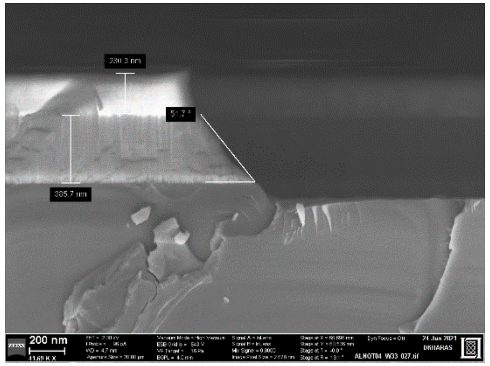
	variables	Best Condition	
ICP	600	600	
BIAS	200	200	
Press pa	0.4, 0.7, 1.1	0.4	
Cl2	14,20,30,40,65,90	40	20
BCl3	0,5,10,15,40	10	0
Ar	0,6,10,15	0	
total flow	20, 30,35,40,50,115	50	20
angle		65 deg	

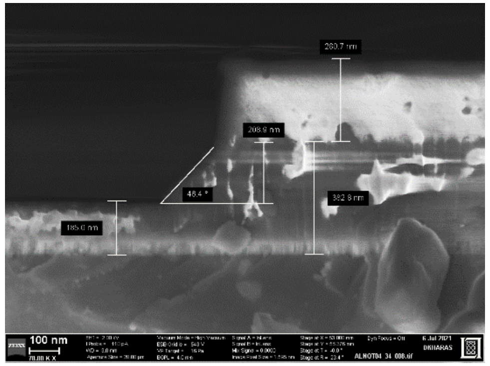


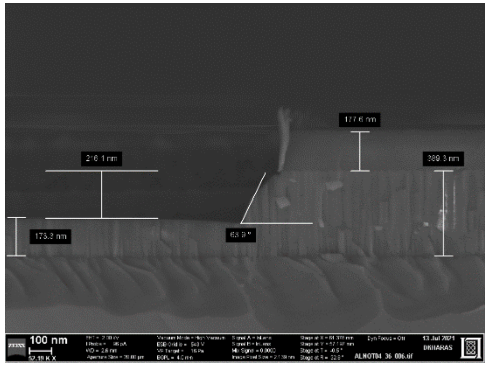


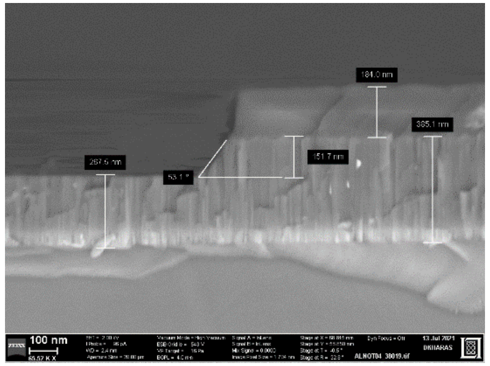
Northeastern University

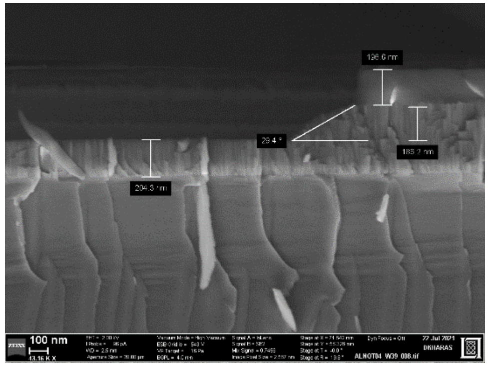
SAMCO Etch Variants

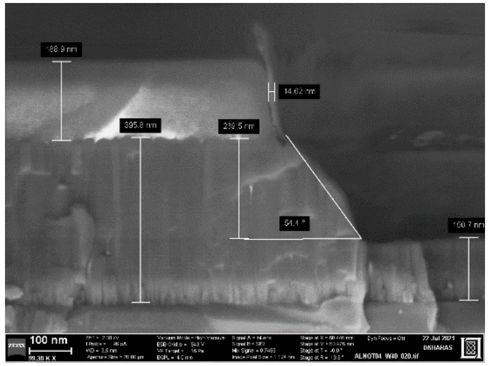


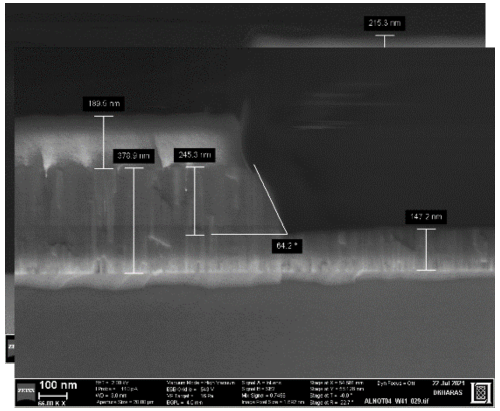


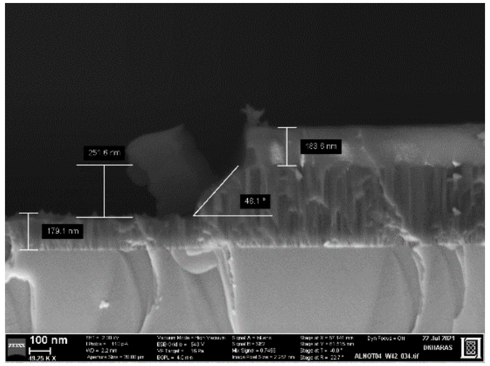


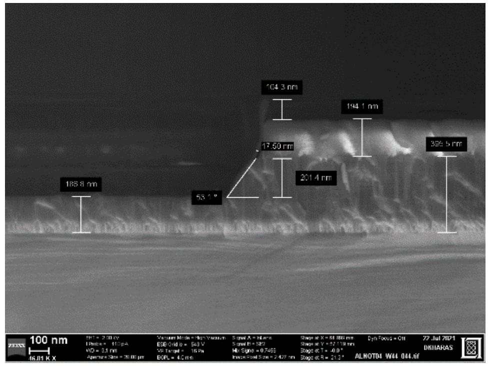


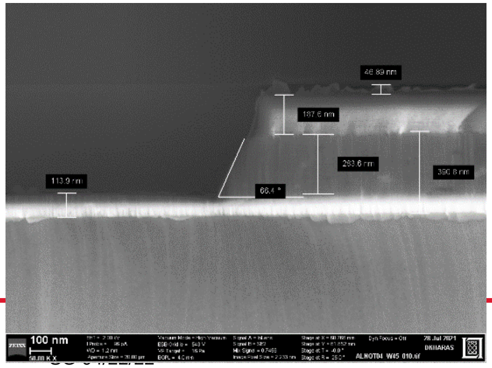


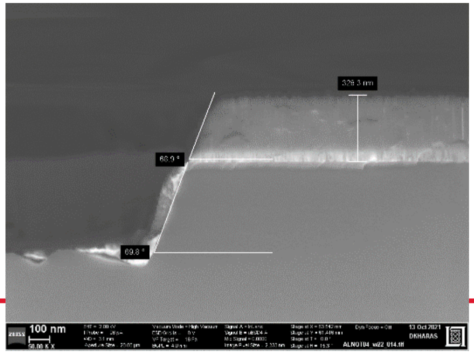




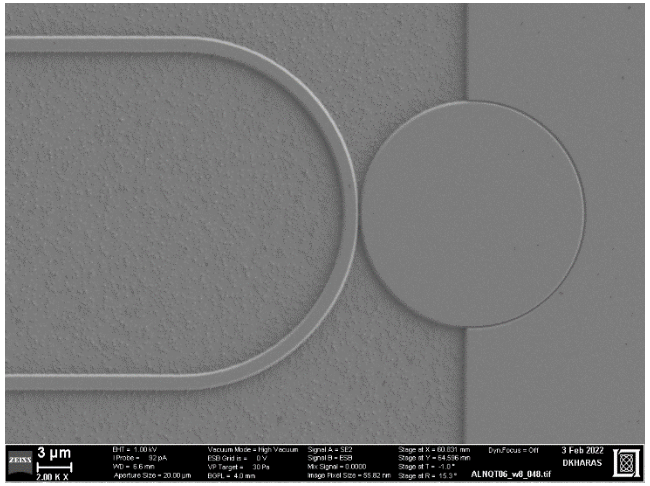


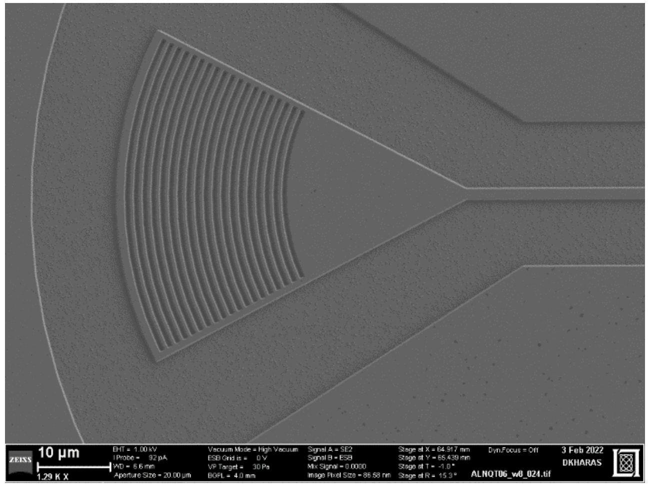


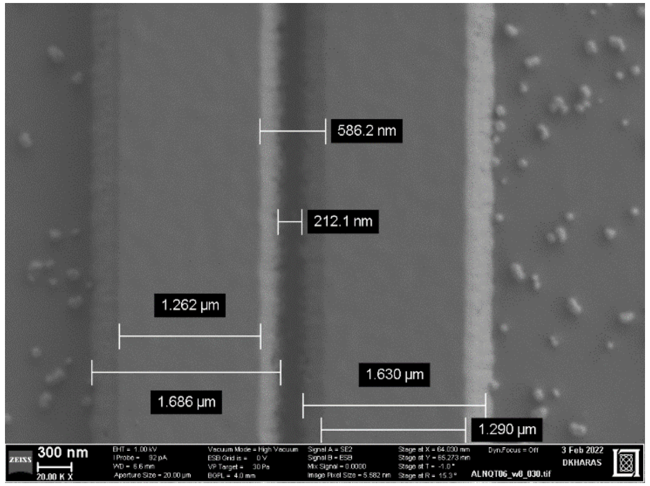


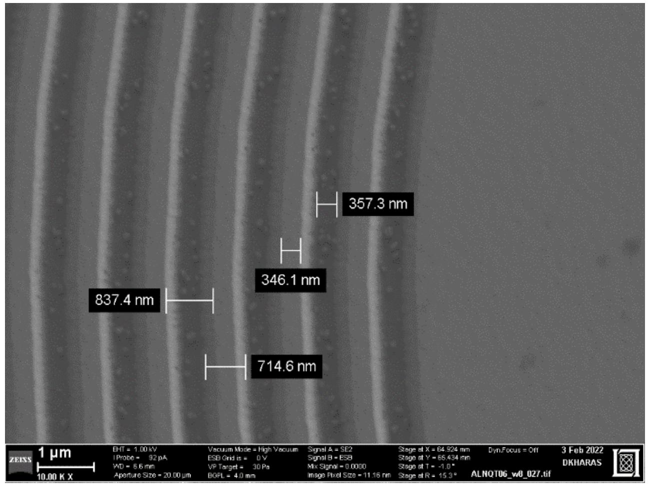


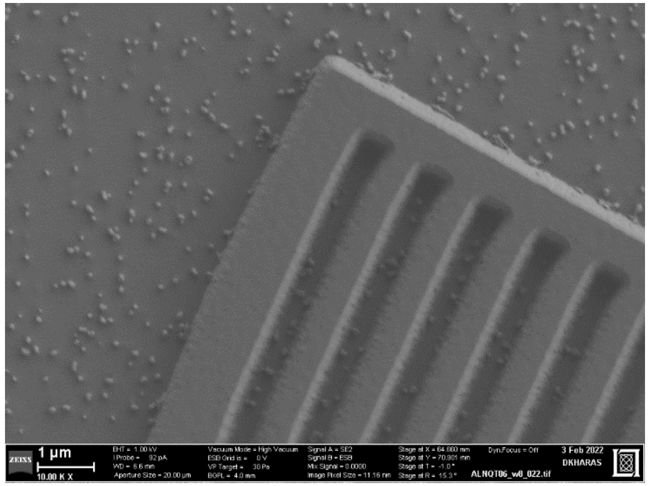
Group 1 ALNQT06 wafer 8 AlN Photonics SEM

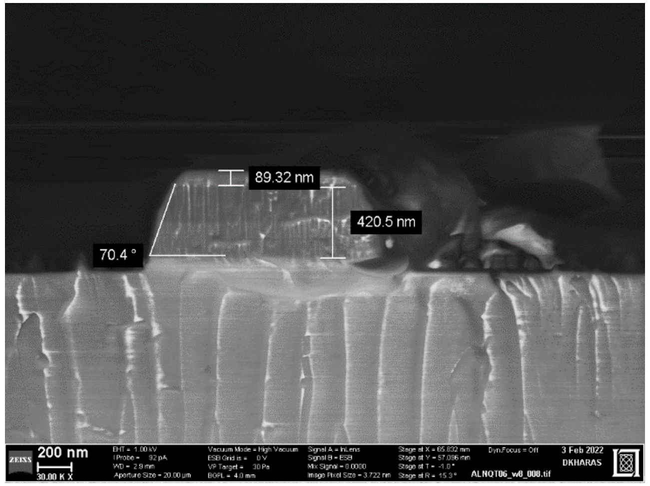






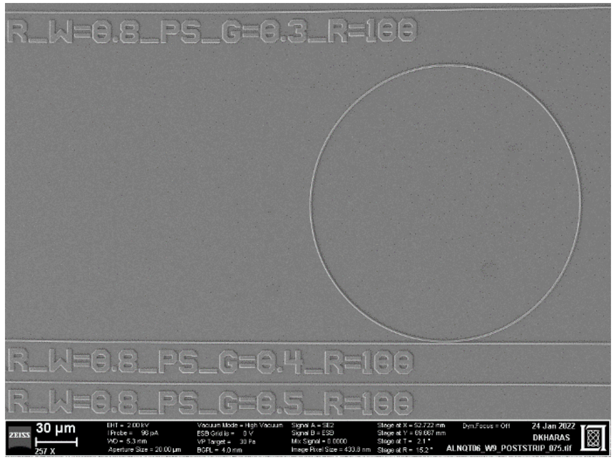


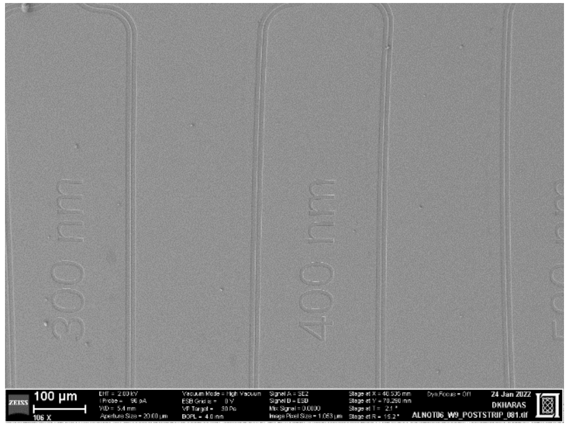


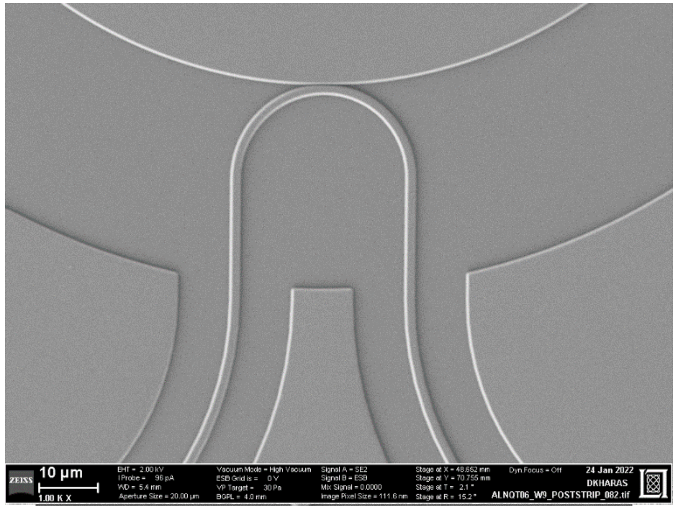


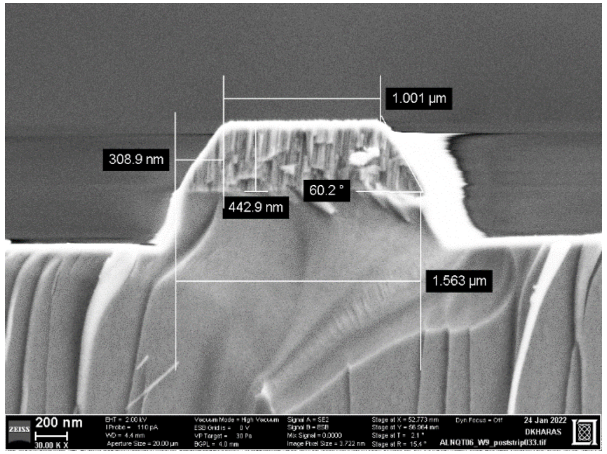
\\LIfs\div8\GROUPS\G89\G89MEMBERSHARE\Programs\Quantum Interface\QT Fab Lots (ML)\ALNQT06\Fab Images _SEM and Optical

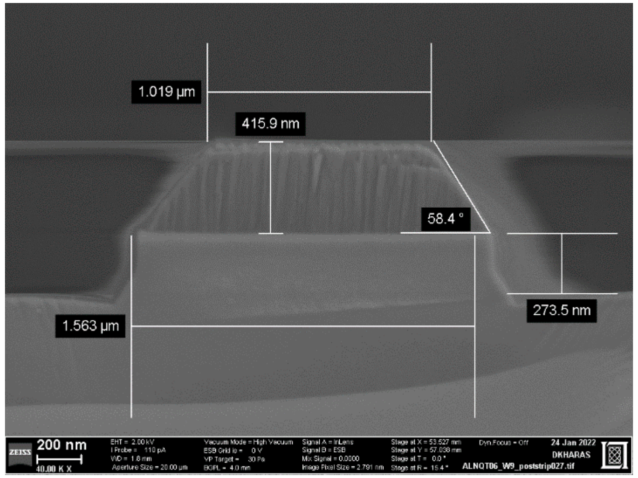
Group 1 ALNQT06 wafer 9 AlN Photonics SEM

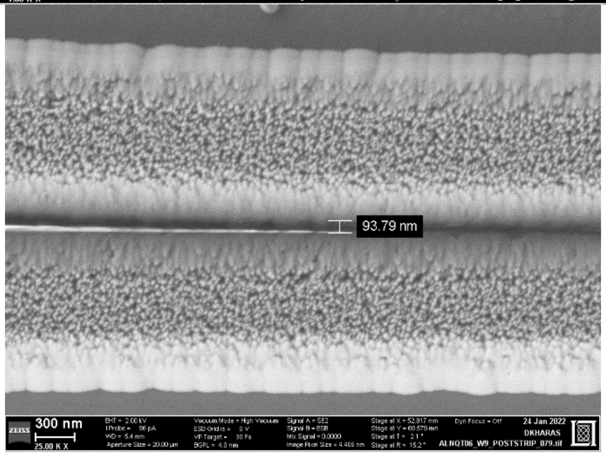










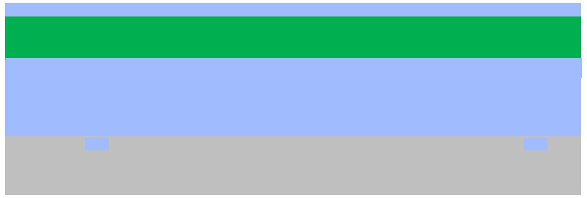


\\LIfs\div8\GROUPS\G89\G89MEMBERSHARE\Programs\Quantum Interface\QT Fab Lots (ML)\ALNQT06\Fab Images _SEM and Optical

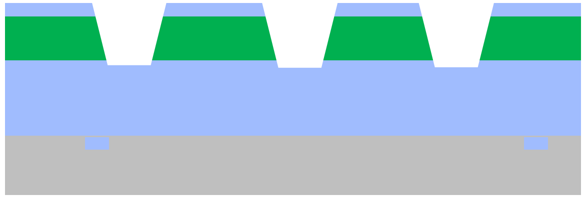
Task 1. Aluminum Nitride Photonics ML Fabrication

1. Alignment mark pattern and Si etch and deposit bottom oxide

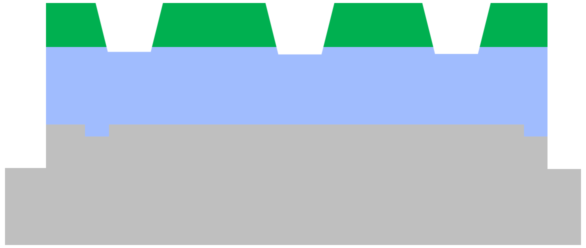
2. Sputter 400 nm Aluminum Nitride (external to ML) and deposit oxide hardmask



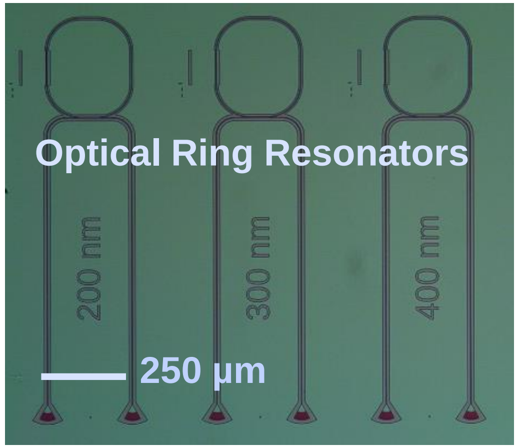
3. Pattern AlN WG layer, etch oxide HM, AlN

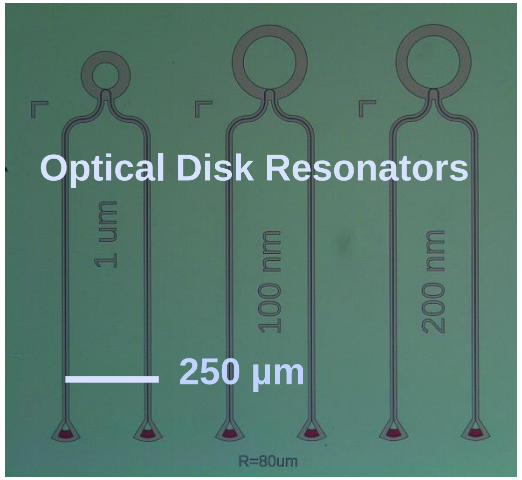


4. Remove excess oxide hardmask, and pattern and etch a deep facet to enable fiber coupling testing

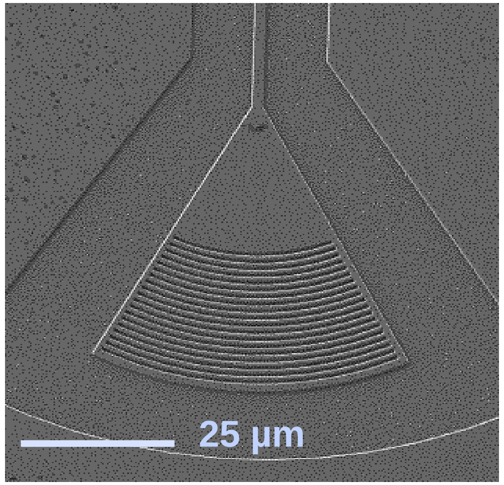


Si substrate PECVD SiO_2 AlN





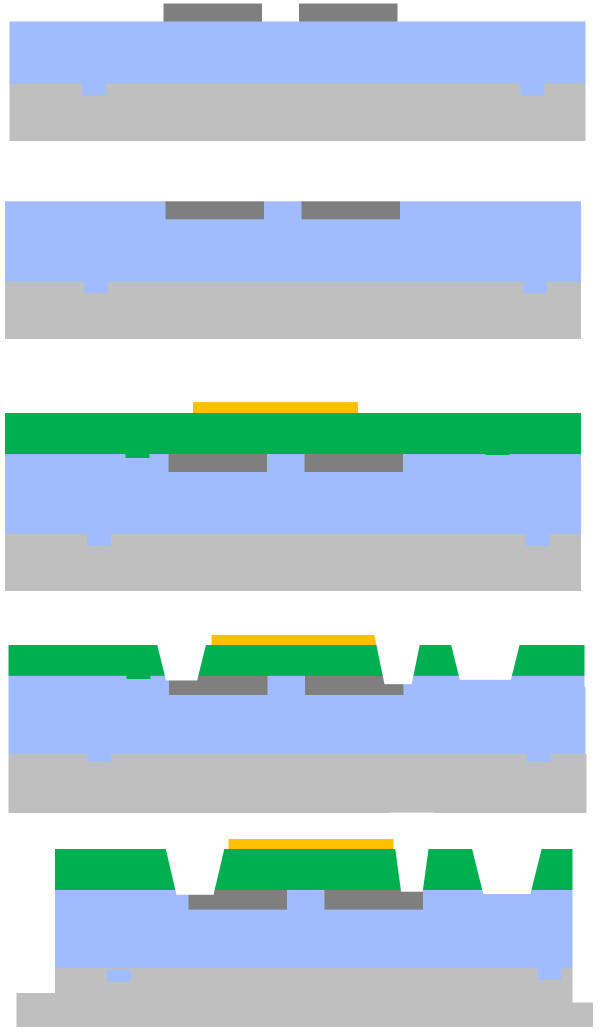
Vertical grating coupler



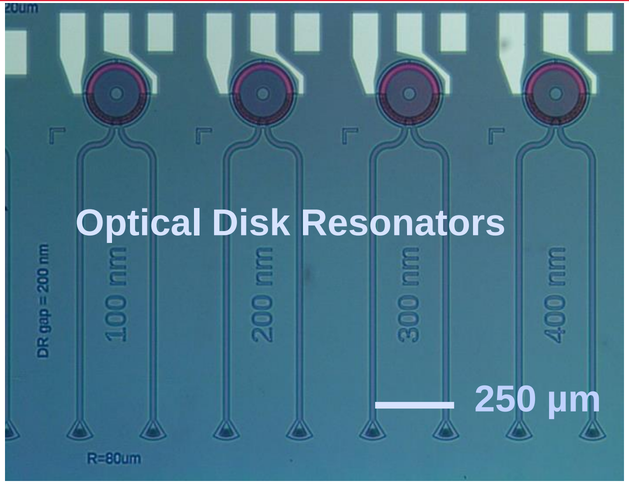
Ring and Disk optical resonators have been fabricated

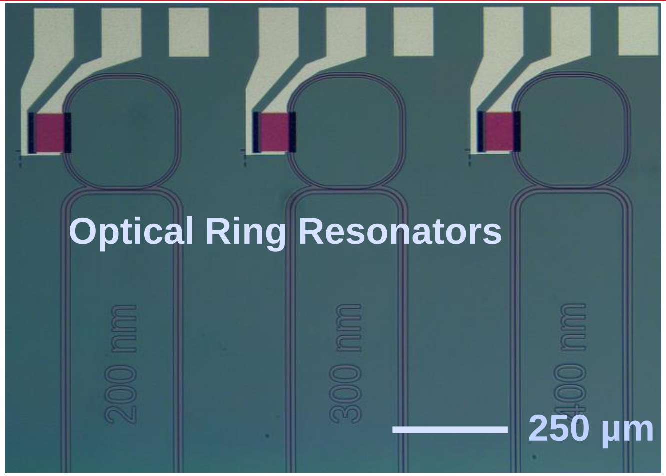
Task 2: AlN Optomechanical Resonators

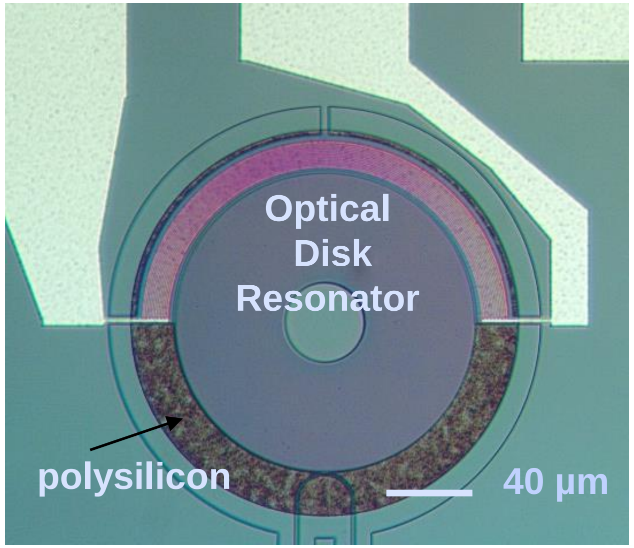
1. **Deposit bottom clad oxide, dep polysilicon release layer, pattern**
2. **Cap release layer with oxide and CMP flat**
3. **Sputter AlN and Al electrode metal, pattern etch metal electrode.**
4. **Pattern AlN Waveguide**
5. **Deep Facet Pattern and etch.**

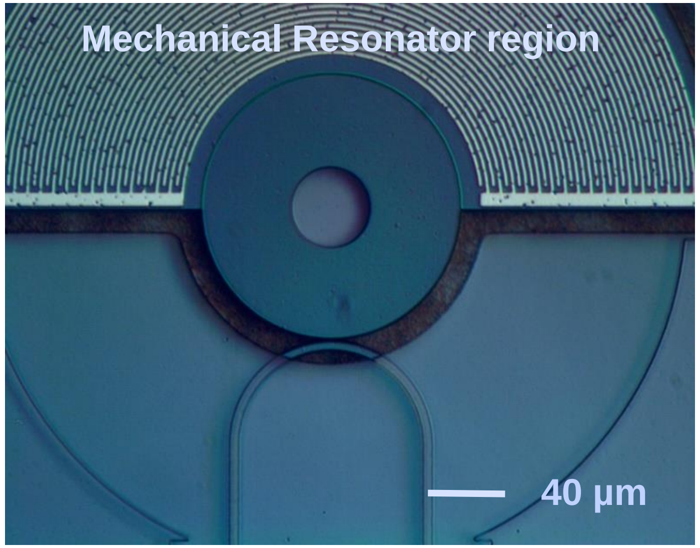


Si substrate **Polysilicon** **PECVD SiO_2** **AlN** **Top metal**









Northeastern University