Novel coupling of on-chip optical elements through PBG crystals to achieve ultra-high performance optical source and filters for analog optical signal processing

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Outline

- Opto-Electronic Oscillator (OEO)
- Ultra high Q silica micro-resonators with (whispering gallery modes) WGM
- Lithium niobate and semiconductor microresonators:
  - ? Tunable filters and modulators
- Quasi-phase-matching by PBG (Photonic Band Gap):
  - ? A versatile coupling method for wide range of waveguides and resonators
- Advanced optical amplifier/modulator chips with direct coupling to resonator

? High performance Opto-Electronic Oscillator (OEO)

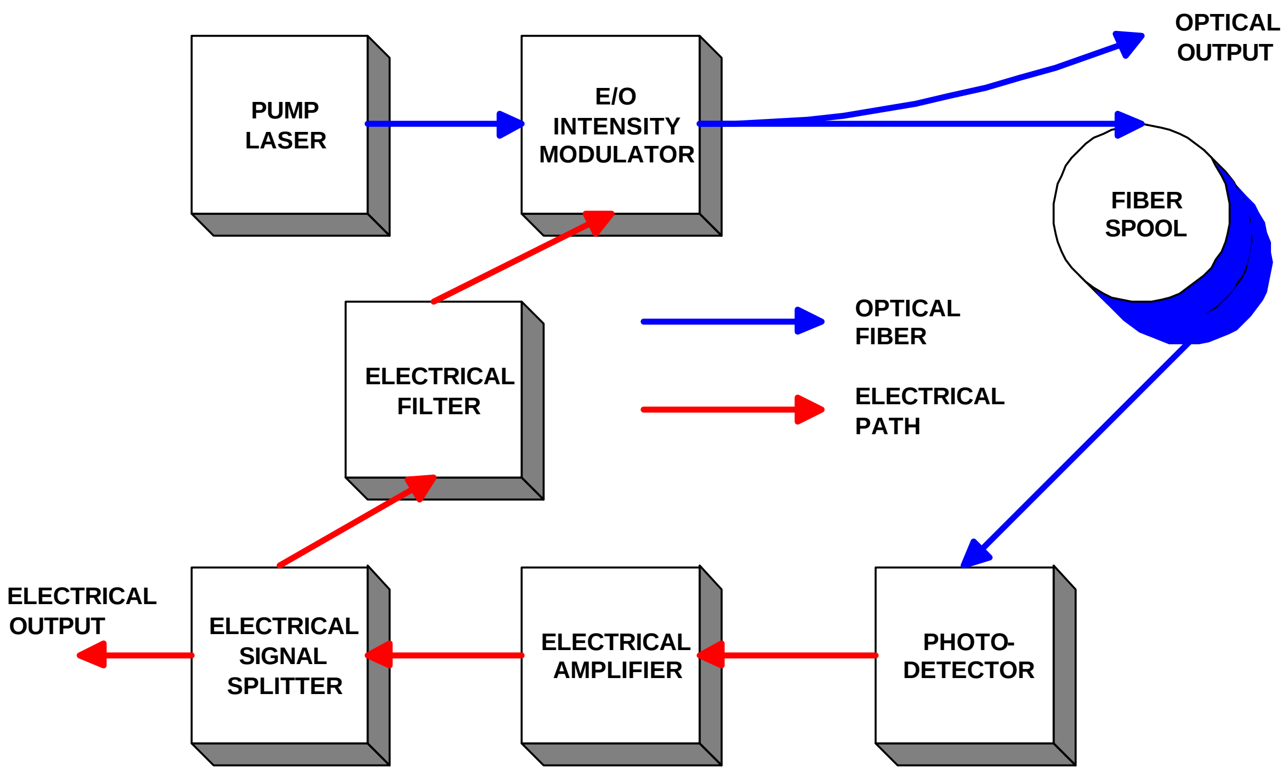
Project Team

- Vladimir Ilchenko, Ph.D.; PI OEwaves
- Professor Dan Dapkus; Co-I USC
- Professor John O'Brien; Co-I USC
- Dmitri Kossakovski, Ph.D.; OEwaves
- Kouros Sariri; OEwaves
- Danny Eliyahu; Ph.D. OEwaves
- Lute Maleki, Ph.D.; Project Consultant

Motivation

- High performance analog signal processing
  - Ultra-low noise references
  - Ultra-high Q, tunable, optical-domain RF filters
  - High performance modulators for optical processing of analog signals
- High performance radar application and processing for diverse environmental conditions
  - Low phase noise pulse Doppler and wideband waveforms
  - Ground based, airborne, shipboard
  - Doppler processing with low clutter induced noise
  - Fast reaction time defense

Background:the Basic OEO Technology



Important Characteristics of the OEO

- **High spectral purity** due to long optical storage time provided by the fiber in a closed loop.

- The quality factor (Q) is proportional to the oscillation frequency, leading to **noise level performance that is *independent* of frequency**.

- The **mode spacing** is related to the inverse of loop trip time: $? \frac{c}{n ?L}$

  where c is the speed of light, n is the fiber refractive index and L is the fiber length.

Important Characteristics of current OEO architecture

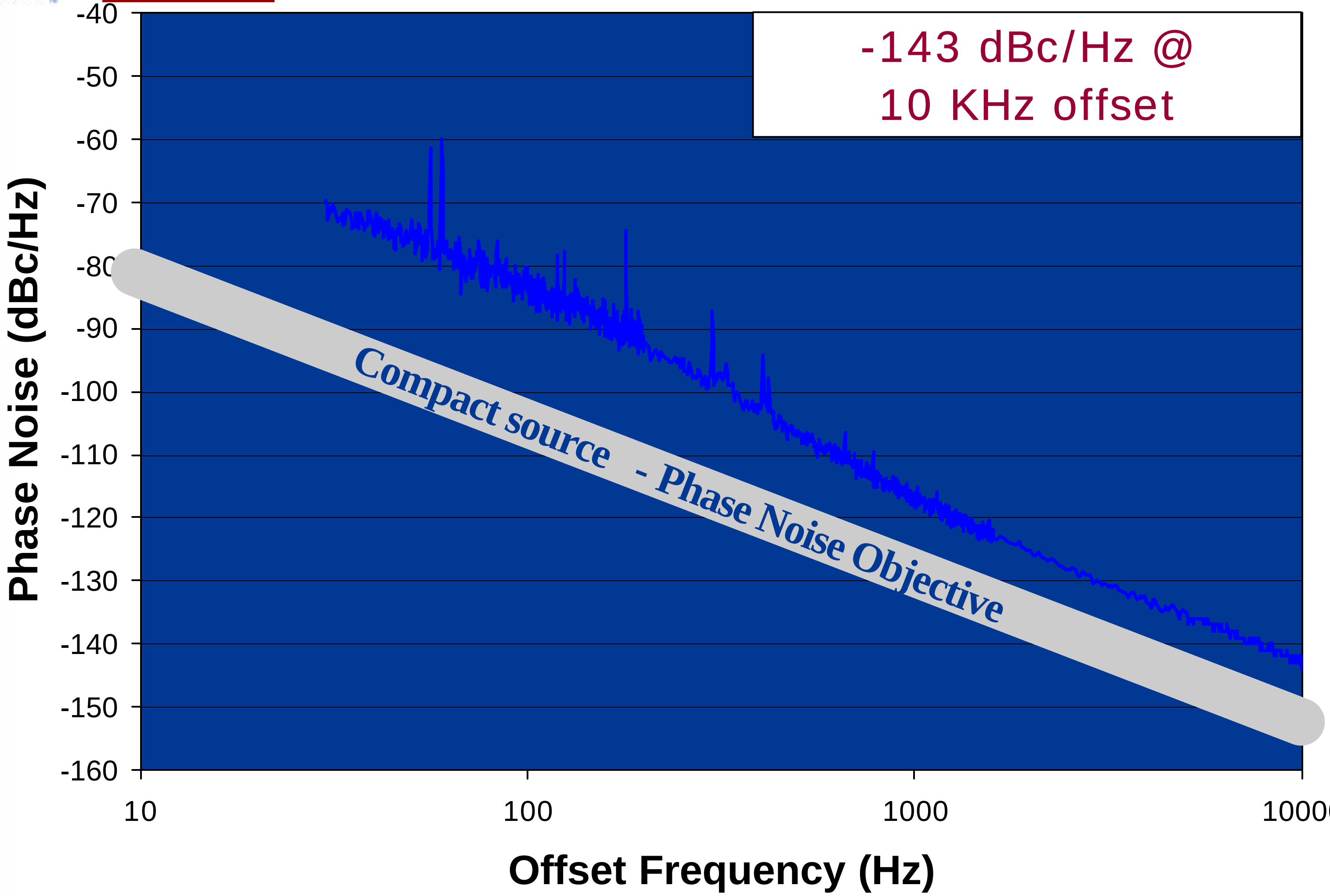
Discrete component based bench-top unit performance (10 GHz) :

- Phase Noise:
  -143 dBc/Hz @ 10 KHz offset
- Spurious Level: -105 dBc
- Harmonics: -40 dBc
- Output Power: >10 dBm
- Size 10?10?4 in

Features:

- Thermal stabilization
- External reference locking
- Integrated power-up sequencer
- Lock indicator
- PLL Variable Loop Bandwidth
- Electronic Coarse Tuning
- Electronic Fine Tuning

OEO: Free Running Phase Noise
(10 GHz oscillator)



Technical Objectives

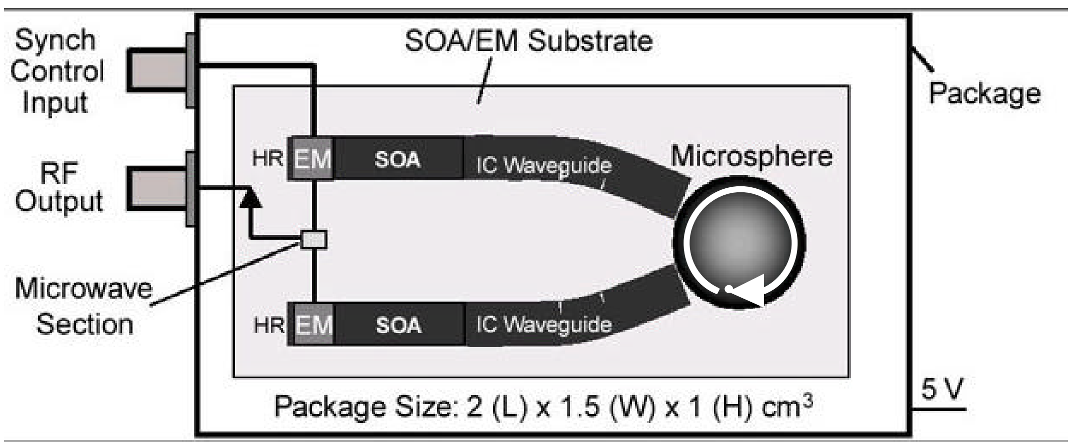
Miniature Opto-electronic Oscillator (MOEO)

OEO Assembly

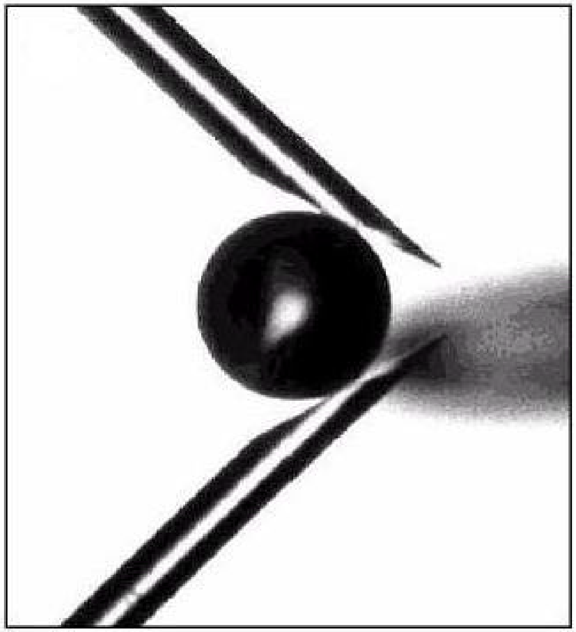
- **Fabricated devices will be assembled in the OEO** configurations and tested for performance.
- **Microresonators** will be integrated by OEwaves with the devices fabricated at USC.
- The **microwave segment** of the OEO circuit will be designed and implemented with discreet components for 40 GHz operation.
- **The coupling and the microwave circuit designs will be optimized to achieve high spectral purity performance (-150dBc/Hz @ 10kHz, 10GHz carrier)**.

Advanced Micro-Opto-Electronic Oscillator

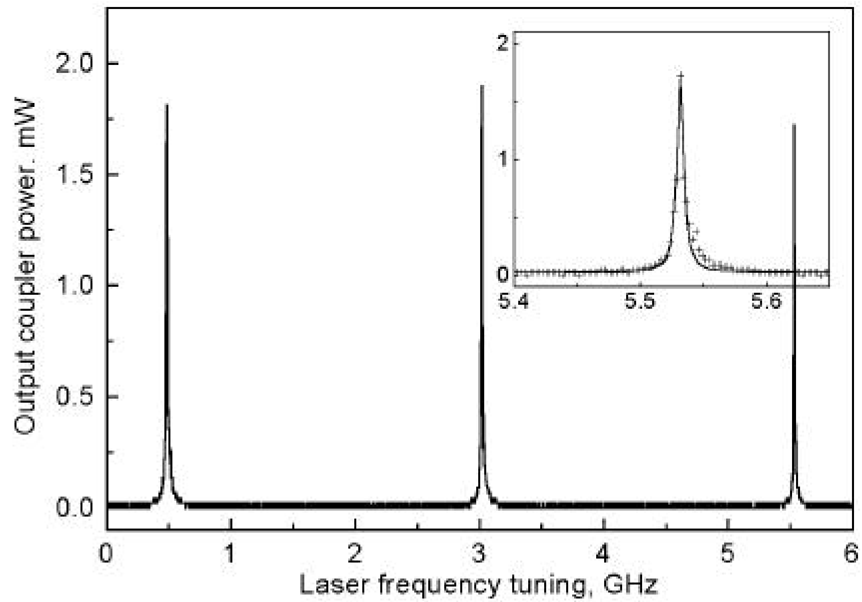
Monolithic Semiconductor Optical Amplifier - Electroabsorption Modulators and microresonator



Pre-existing state of the art in microresonator: WGM in Microsphere

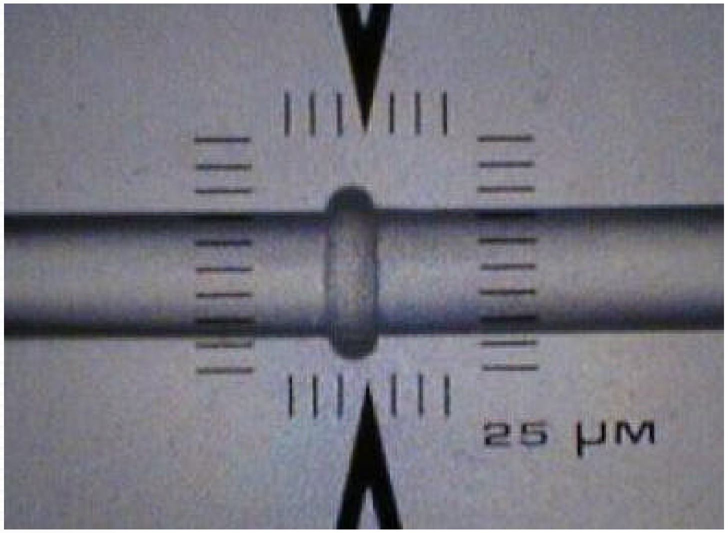


V.S. Ilchenko et al., Opt. Lett. 24 (1999) p. 723

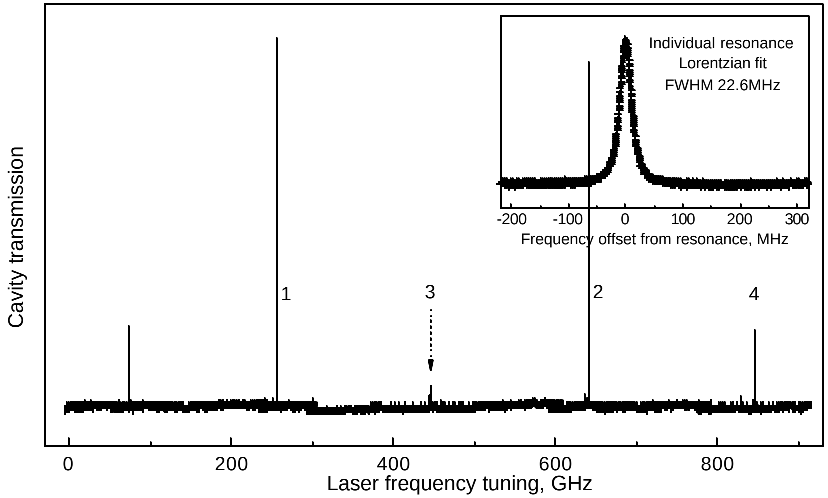


Hard to control mode spacing defined by eccentricity

Pre-existing state of the art in microresonator: Microtoroidal resonator



V.S. Ilchenko et al., Opt. Lett. 26 (2001) p. 256



Solution for reproducible manufacturability: Toroidal resonator
Mode spacing defined by diameter. Quasi-single mode closed waveguide.
Diameter 160?m, FSR 400GHz

X-Band Microresonator

A consistent fabrication technology has to be developed to reproducibly obtain FSR in the microwave band and $Q>10^9$.

For the X-band (12GHz) resonator diameter has to be ~5mm

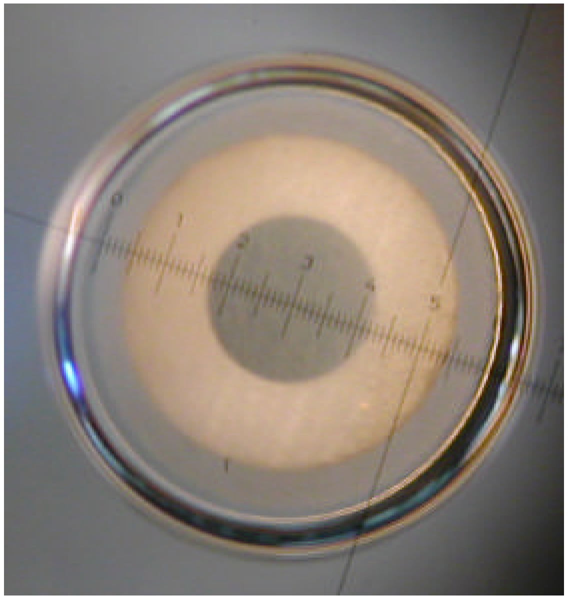
Basic elements:

- Prefabricate cylindrical silica preforms
- Post-processing

Main challenge:

To obtain high $Q>10^9$ comparable to long fiber delays

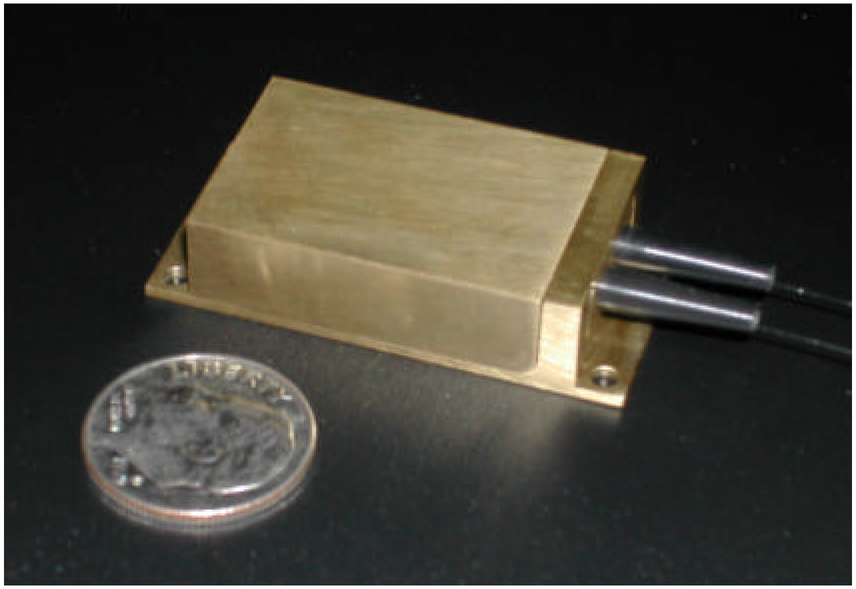
Fabrication of High Q Resonator with FSR in microwave band



Toroidal Resonator.

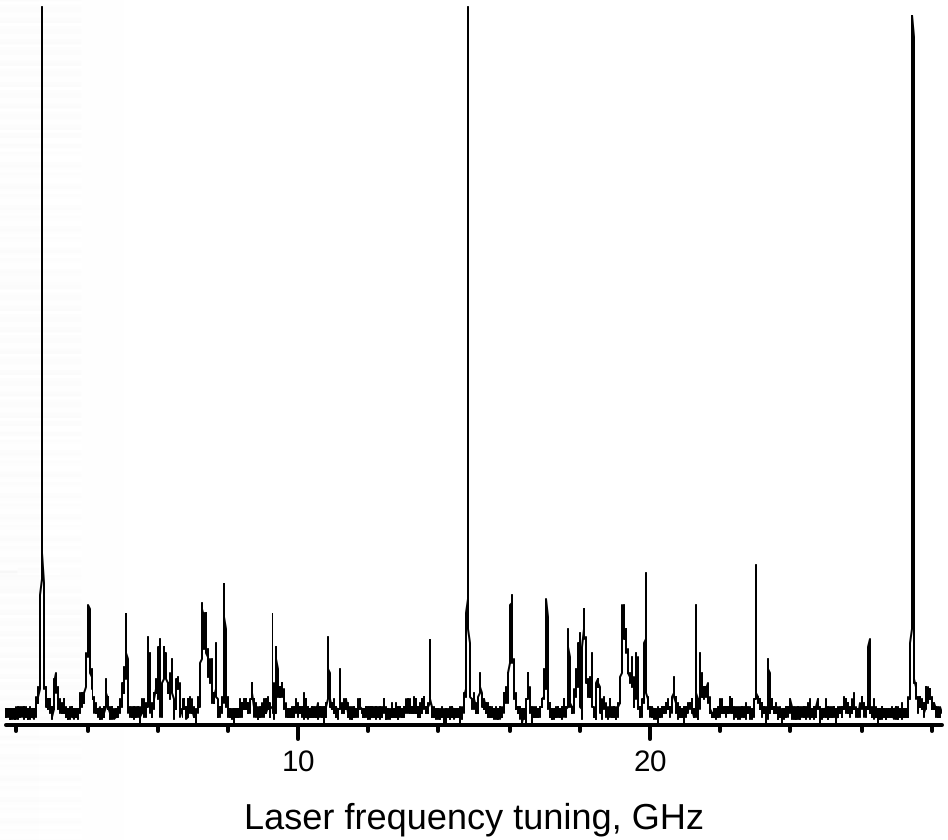
Results: High Q resonator. Diameter~5.5mm, FSR~12.5GHz.

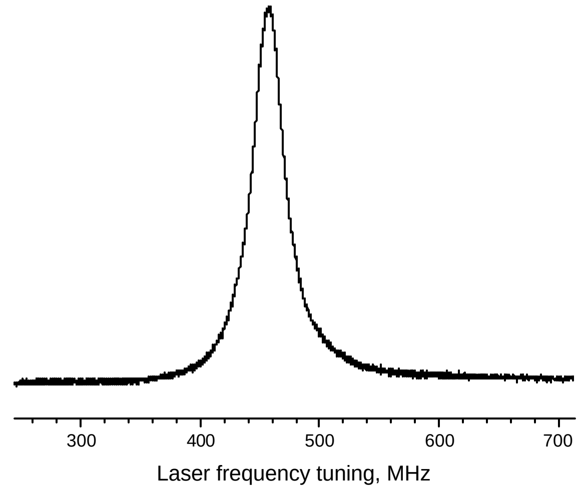
Manufacturing and packaging of High Q Silica Resonator



Resonator packaging
In-house made resonator to ensure stability, precision etc.

Transmission Spectra of Packaged Resonator





Packaged resonator characteristics:

FSR=12.64 GHz
$Q=10^7 - 10^8$
Insertion loss 4.5 dB

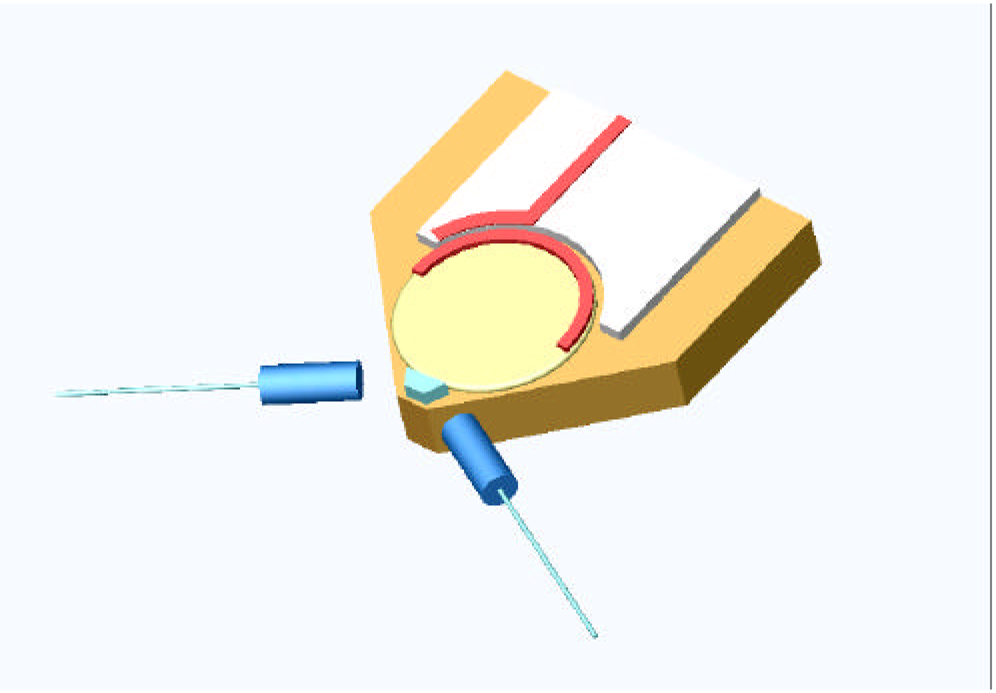
Improvements: fabrication procedure, cleanliness of outsourced preforms and packaging.

High Q Lithium Niobate Toroidal resonator for tunable filters and microwave modulators

Filter/Modulator

Tunable Resonators

Objective: Design and fabricate lithium niobate resonators with microstrip electrodes, using polishing techniques.



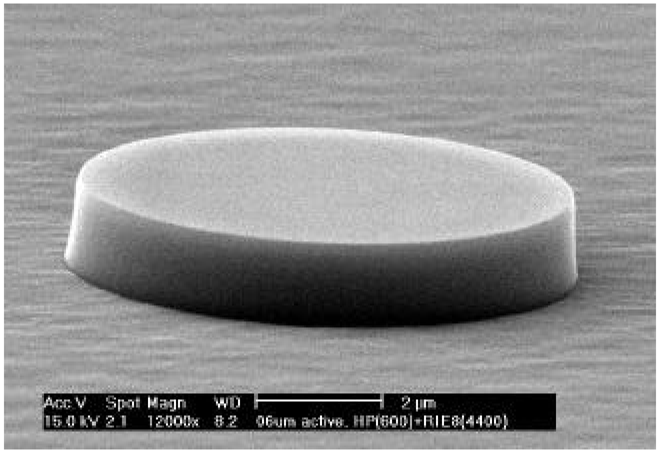
Tunability is achieved by applying external electrical field

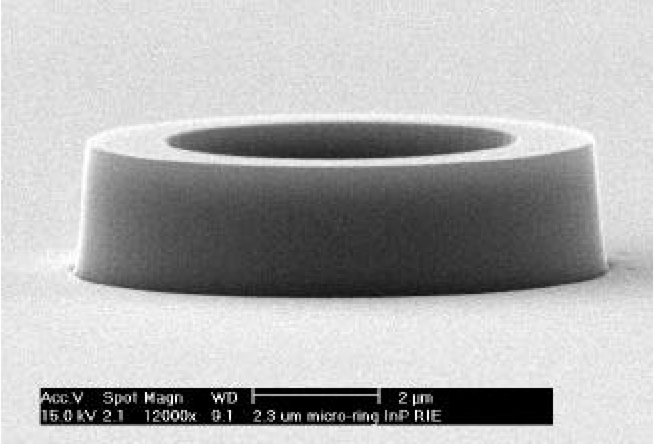
High Q Lithium Niobate Toroidal resonator for tunable filters and microwave modulators

Tunable Filter/Modulator Projected Performance:

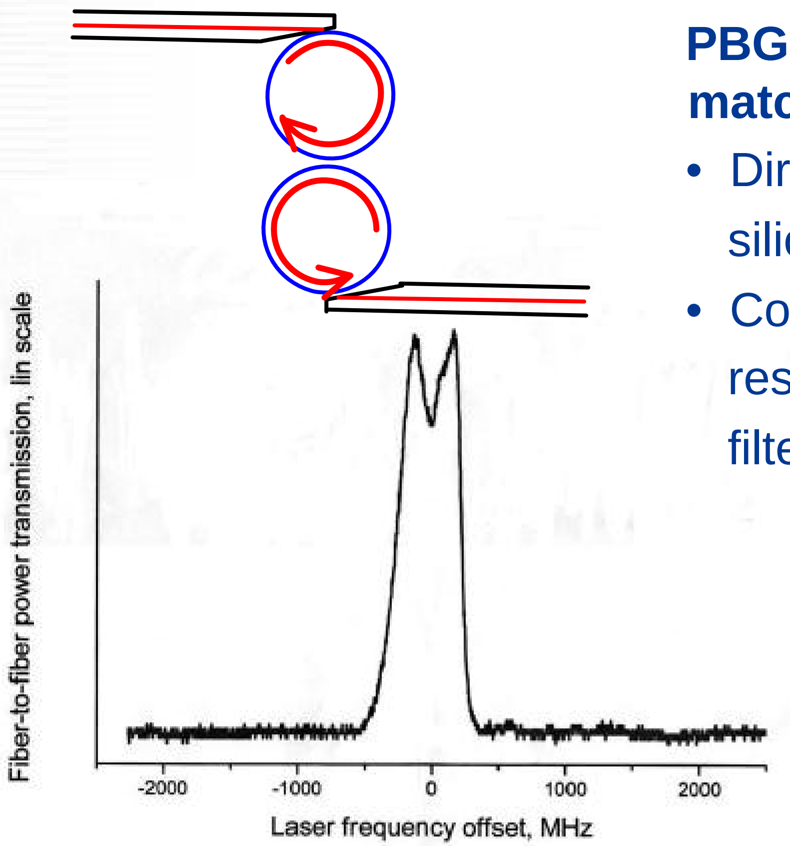
- FSR at X-Band
- Tuning range of >10GHz
- High Q, $>10^7$

Semiconductor micro-resonator



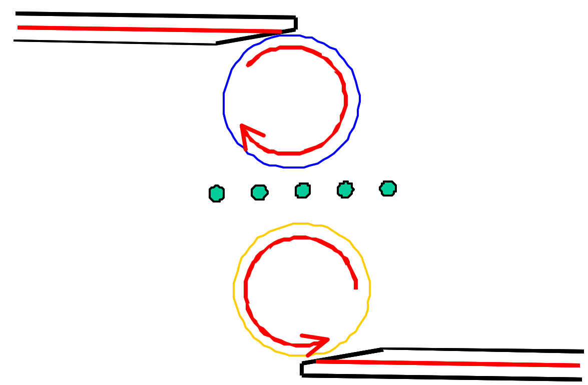


Synthesis of tunable high order filters and arbitrary waveguide and resonator coupling

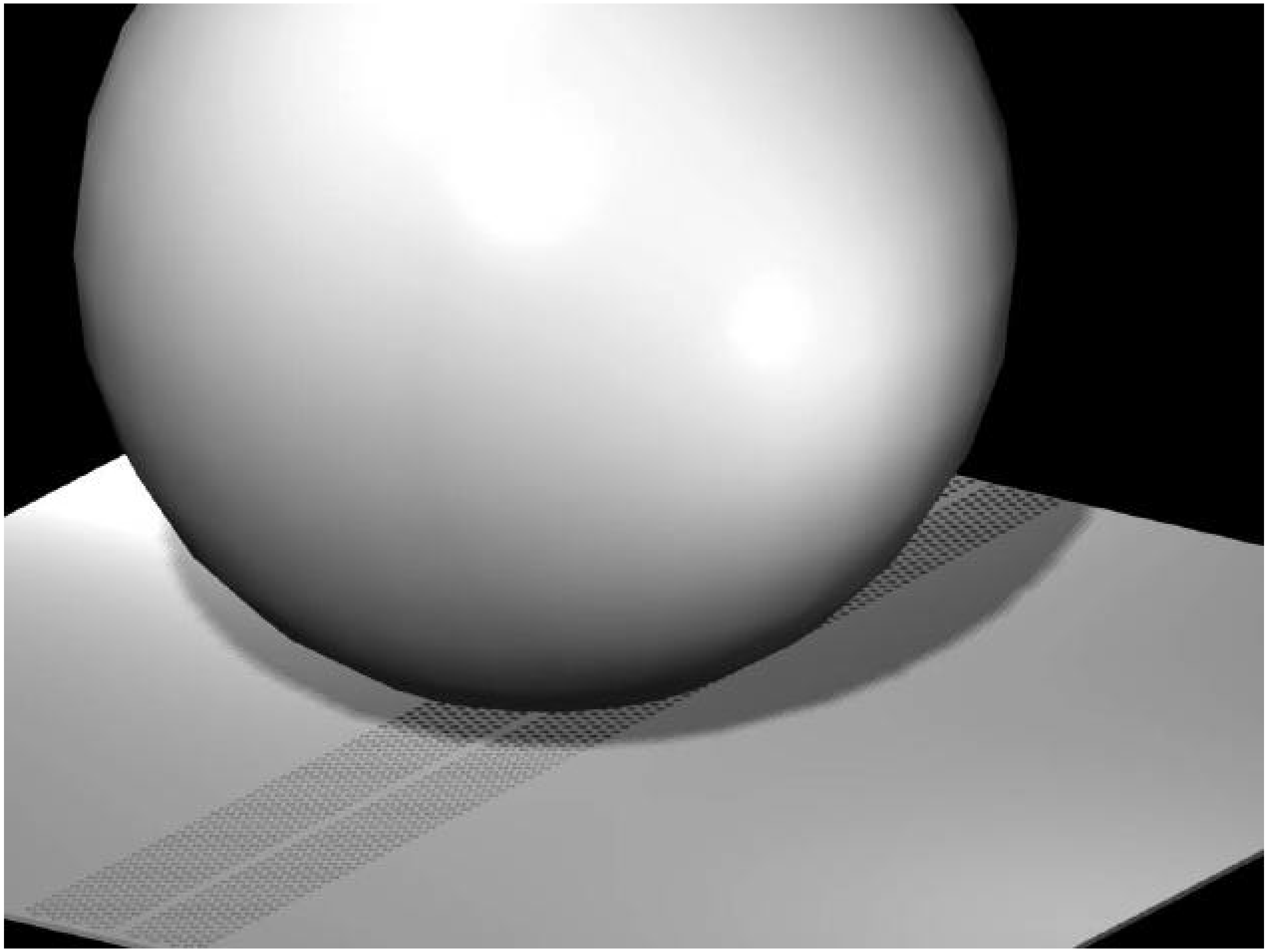


PBG as a generalized tool for quasi-phase matching of waveguides and resonators:

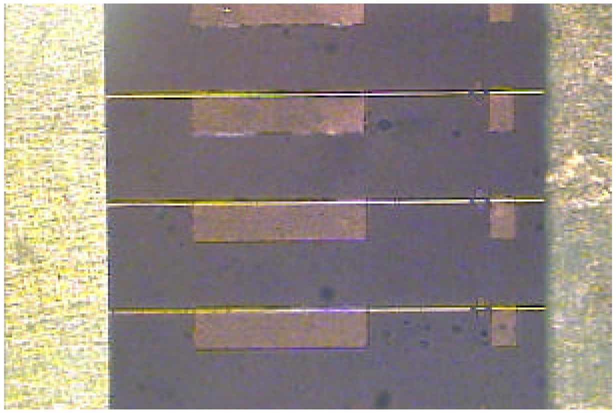
- Direct coupling of arbitrary waveguide to high-Q silica and tunable $LiNbO_3$ resonators
- Coupling of different material WGM resonators for obtaining multipole/tunable filter functions



PBG-assisted waveguide coupling to the resonator



Advanced SOA/EAM: A core for on chip high performance OEO

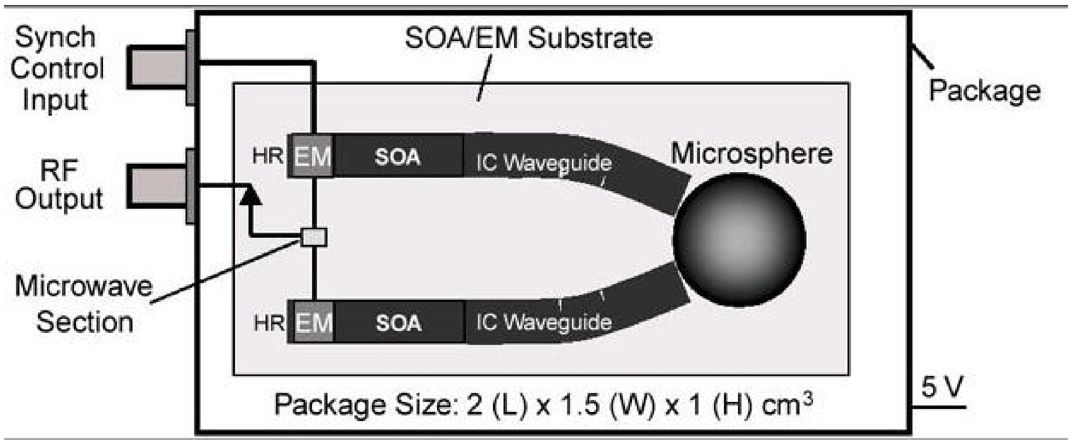


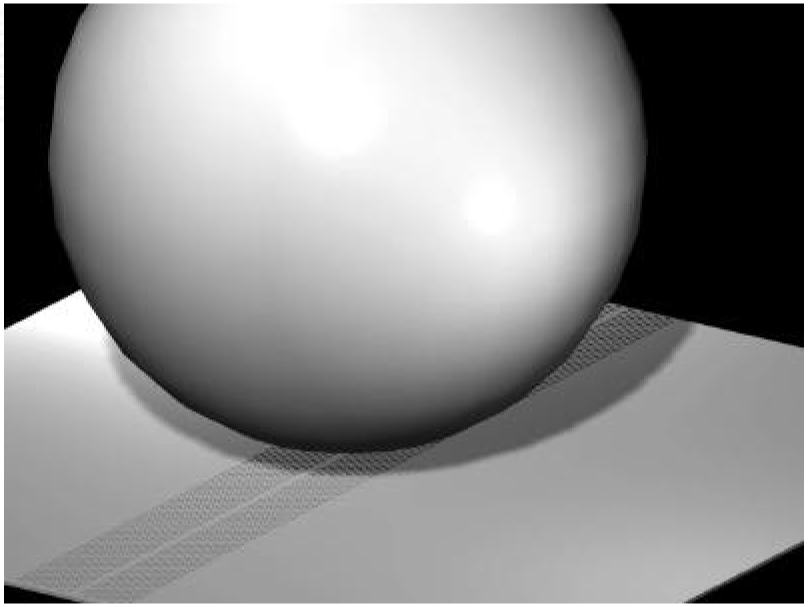
1 mm

- High gain (15dB)
- High power (10mW)
- Improved modulation efficiency
- Minimal coupling loss:
  - ? Direct coupling to micro-resonator is required.

Advanced Micro-Opto-Electronic Oscillator

Monolithic Semiconductor Optical Amplifier - Electroabsorption Modulators and microresonator

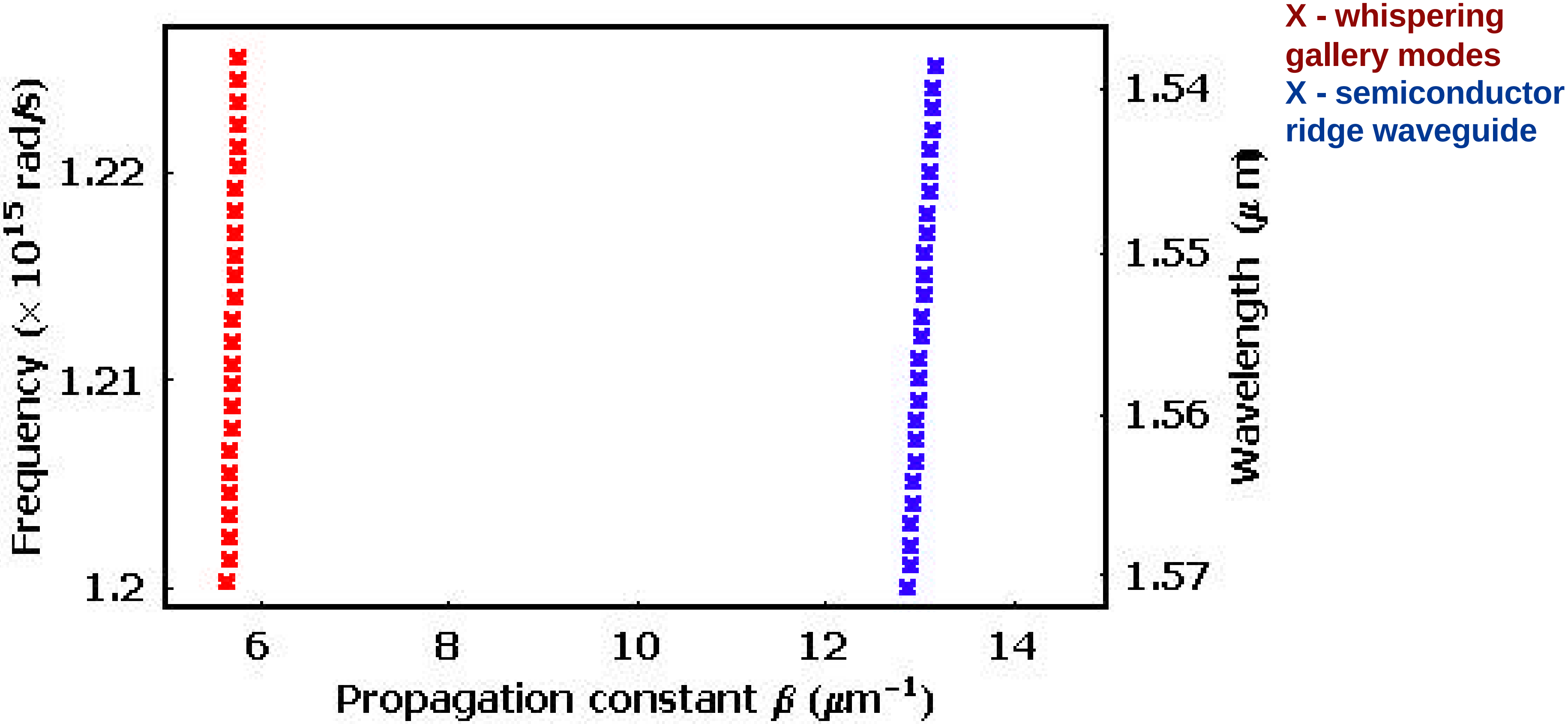




•The microsphere modes that are most often of interest are the whispering gallery modes which are confined near the surface of the sphere. (These modes are characterized by small radial mode number, large angular mode number, and l~m.)

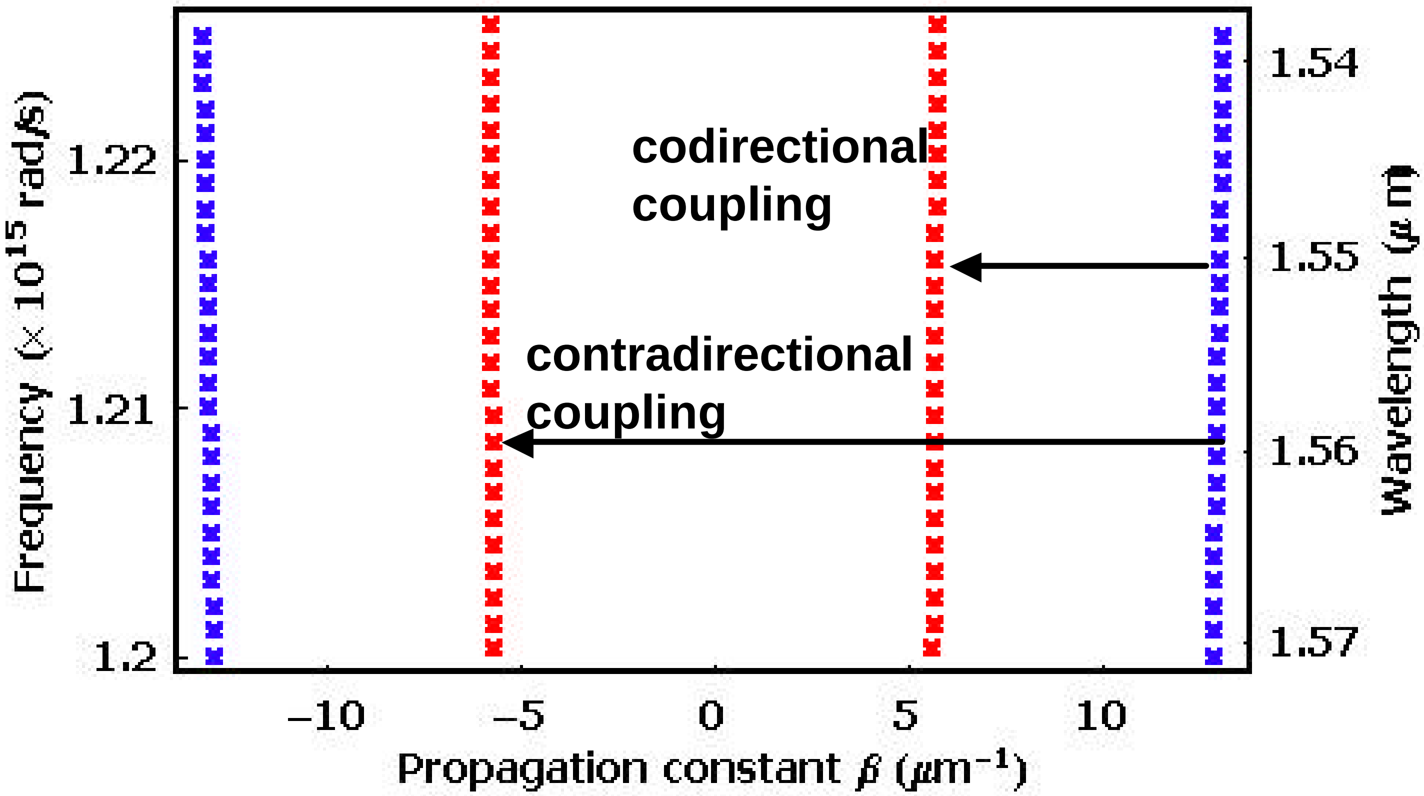
•To efficiently excite these modes, the propagation constant of the excitation must match the propagation constant of the whispering gallery mode inside the microsphere.

Dispersion relations for a semiconductor ridge waveguide and silica microsphere whispering gallery modes.

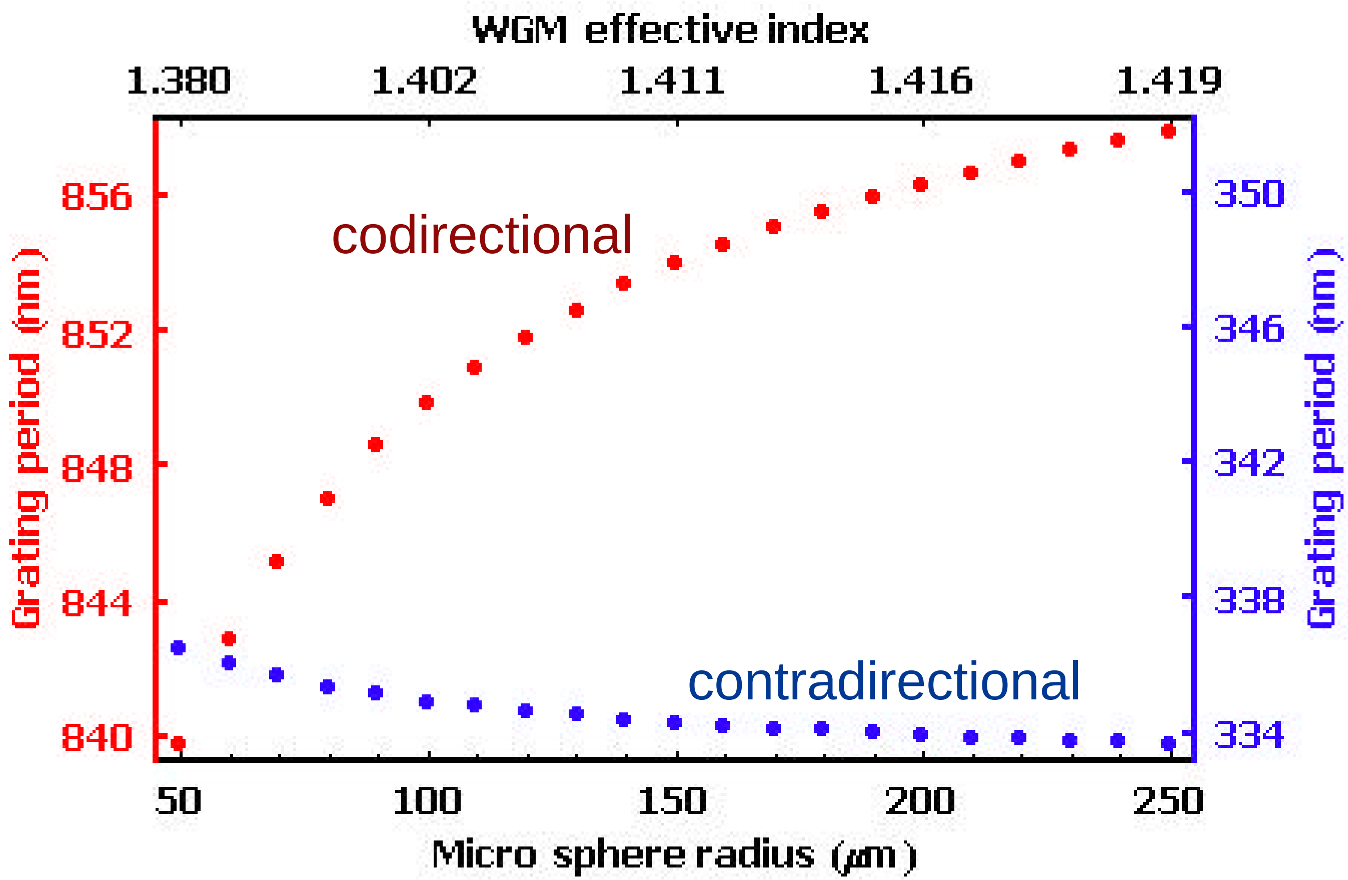


There is a significant phase mismatch between the whispering gallery modes and the ridge waveguide modes. This can be compensated for by including a grating element.

Grating Choices and Trade-offs



Quasi-Phase Matching Grating Period for the Two Cases



Technical Questions and Challenges

Codirectional vs. contradirectional coupling

contradirectional coupling:

appears to be insensitive to sphere radius

has a shorter grating period allowing the phase matching to be narrow band

Reduce the coupling between the semiconductor waveguide mode in the grating section and the substrate radiation modes

Approach to Coupling Design and Demonstration

- Design the quasi-phase matching gratings using analytical methods

- Simulate and verify the design using three-dimensional FDTD to calculate the coupling using a scaled version of the microsphere and the grating element

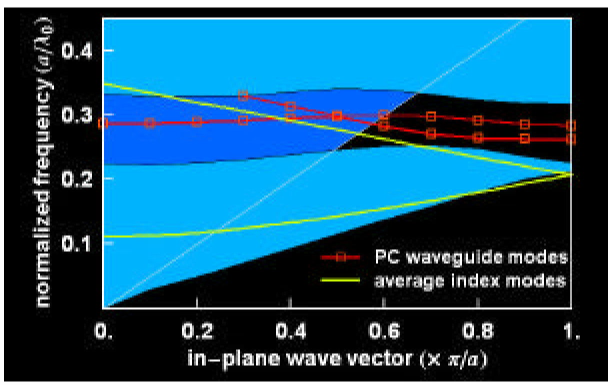
- Fabricate grating and test.

Numerical Tools
Finite-Difference Time-Domain

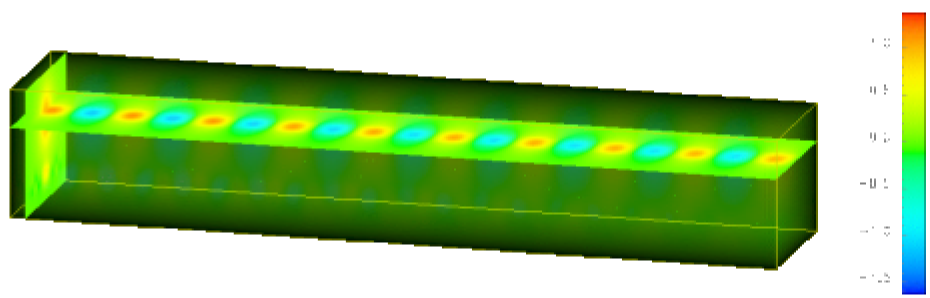
- Maxwell's equations solved as difference equations on a grid
- Dispersion relations obtained by Fourier transform techniques
- Can calculate power lost due to radiation

Finite Element Method

- Method of weighted residuals applied to wave equation (generalized eigenvalue problem $\underline{O}_1\underline{E} = ?^2\underline{O}_2\underline{E}$)
- Eigenvalues and dispersion relation solved for directly



Bandstructure and dispersion relations



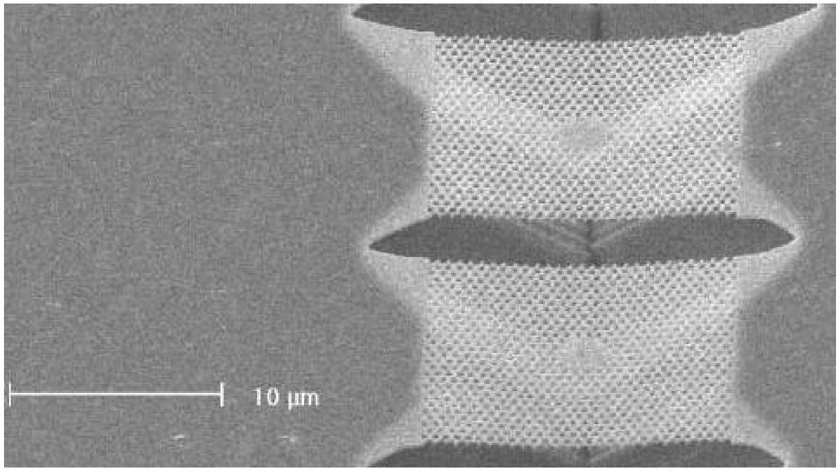
Two and three-dimensional field calculations

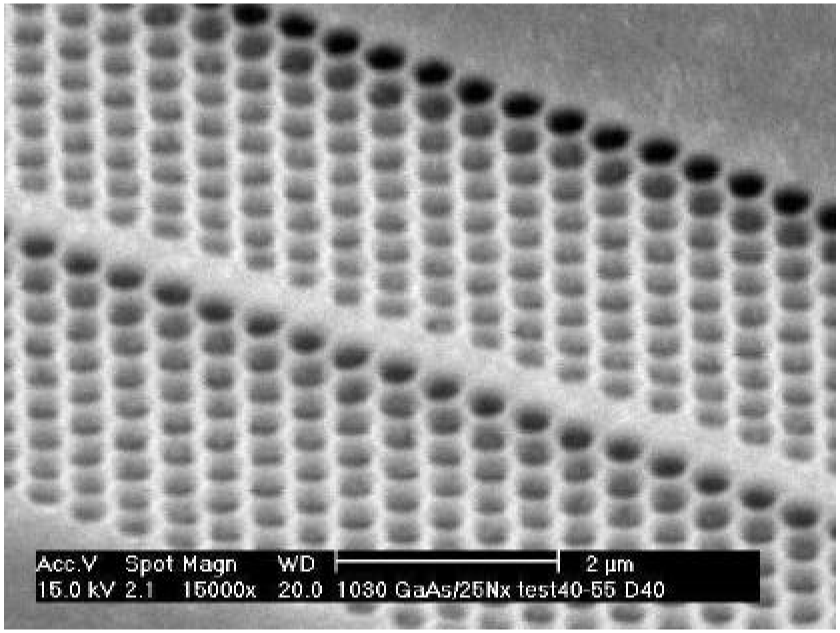
Nanofabrication

- Si_xN_y and Cr/Au mask deposition

- Pattern defined by e-beam lithography in 2% pmma.

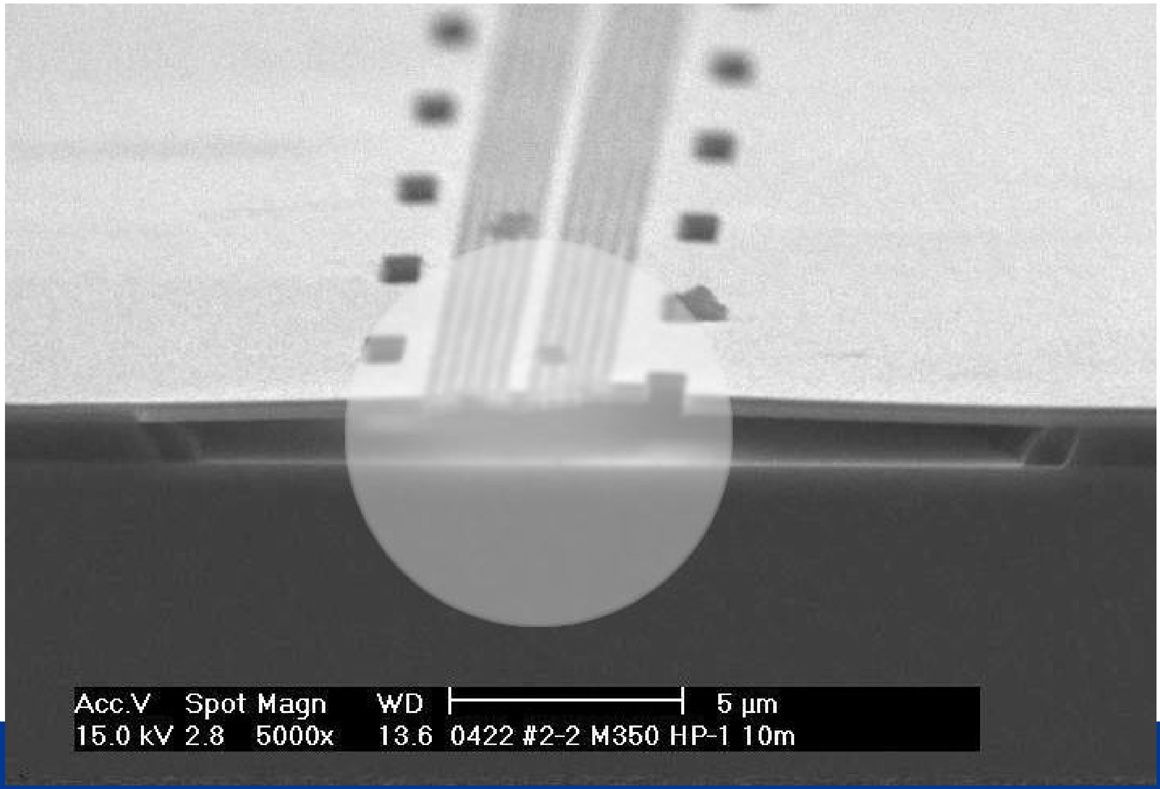
- Pattern transfer by Ar^+ ion beam mill, RIE etch, and ECR etch



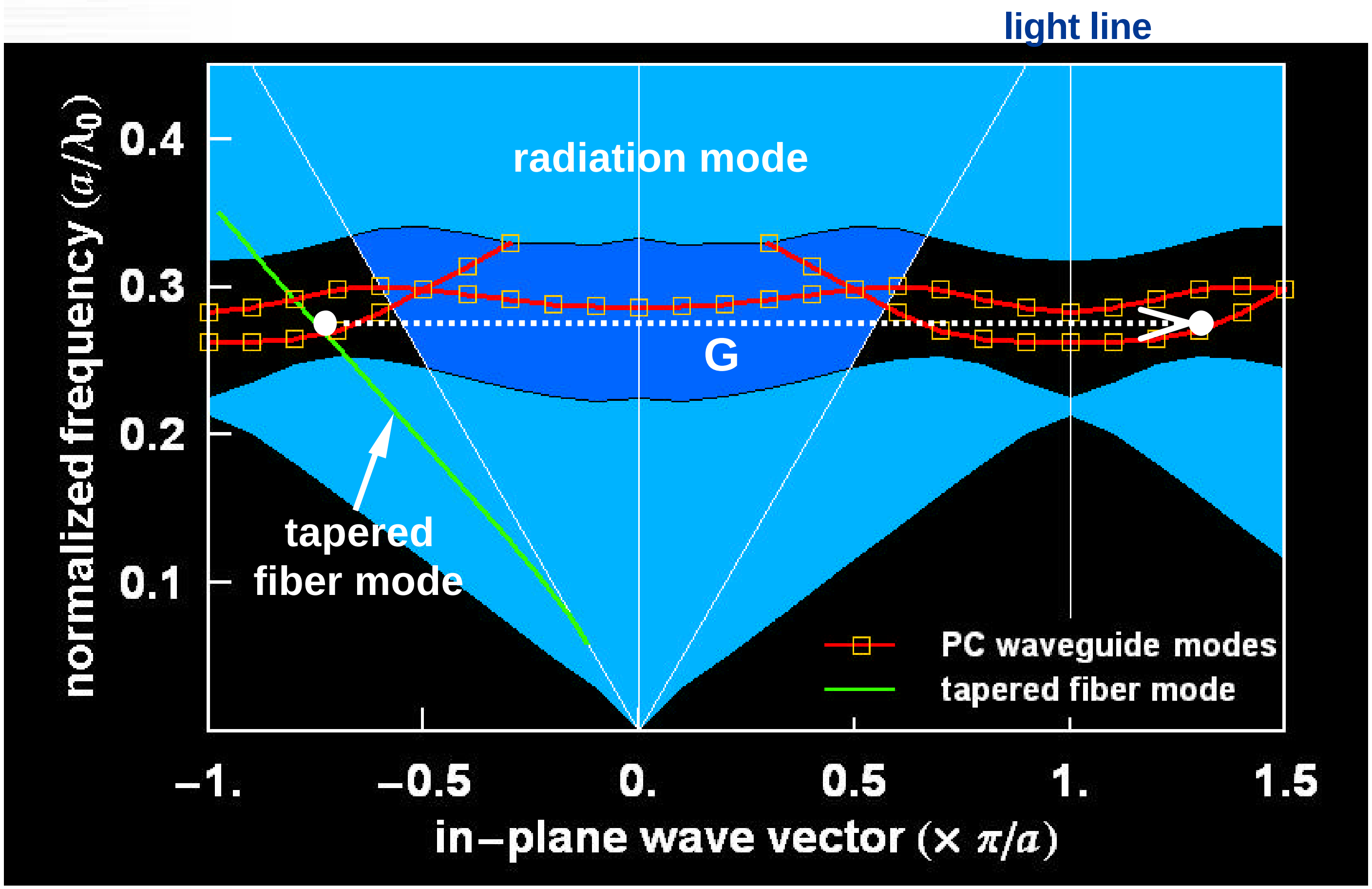


Example of Grating-Assisted Coupling: Optical Fiber to Photonic Crystal Waveguides

•Photonic crystal defect waveguides are important for integrated optical devices
•Input coupling from fiber to photonic crystal defect waveguide is one of the major obstacles



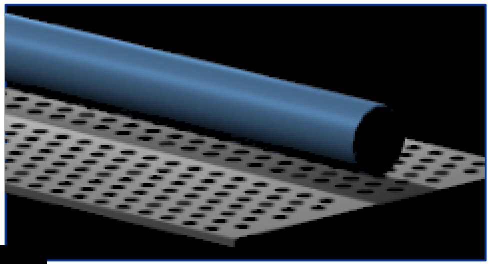
Phase Matching



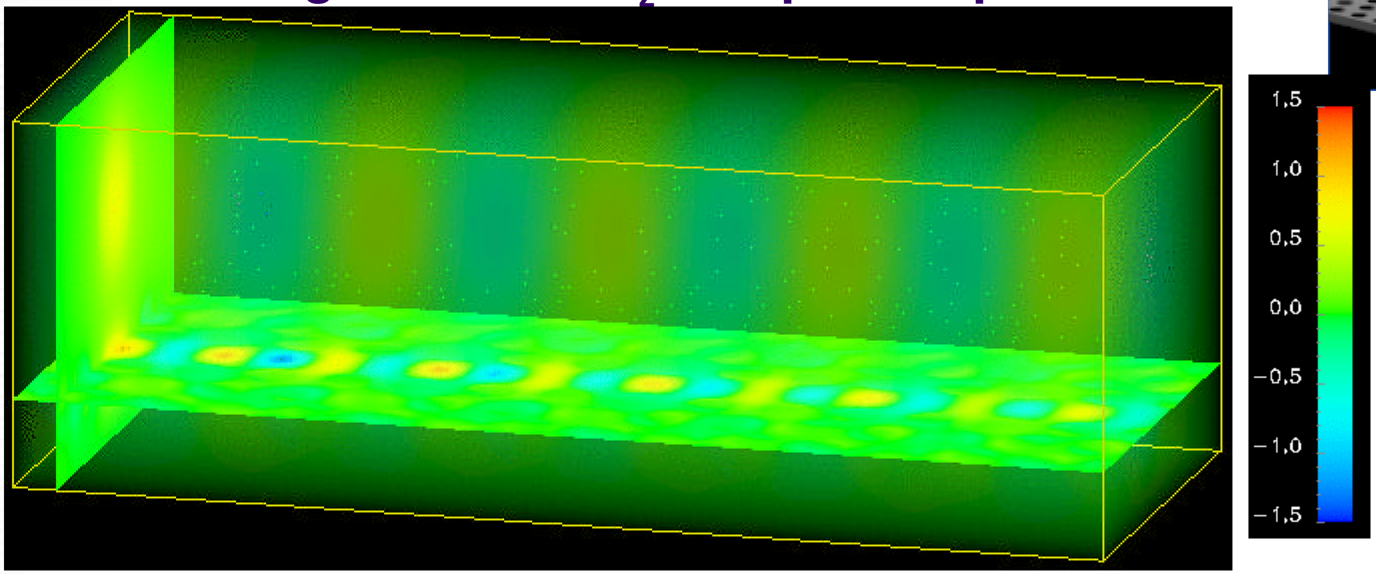
$$H_z \; ? \; f_0 e^{i? z}$$
$$? \; f_{?1} e^{? iGz} e^{i? z}$$
$$? \; f_{?2} e^{? 2iGz} e^{i? z}$$
$$? \ldots$$

Photonic bandstructure of the defect waveguide and the tapered fiber in extended Brillouin zone

Simulation Results



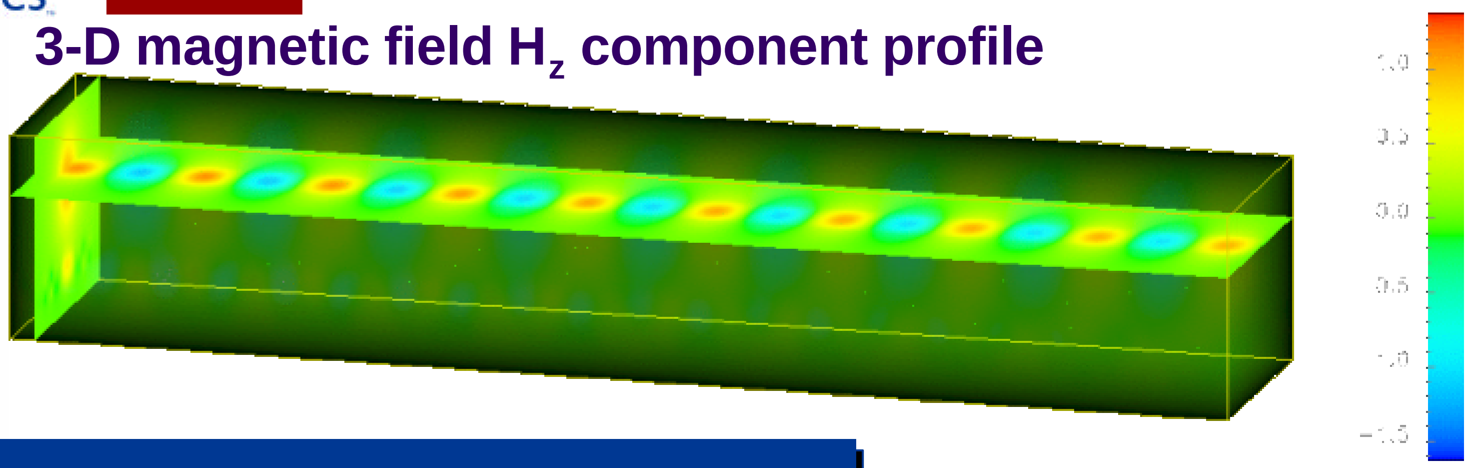
3-D magnetic field H_z component profile

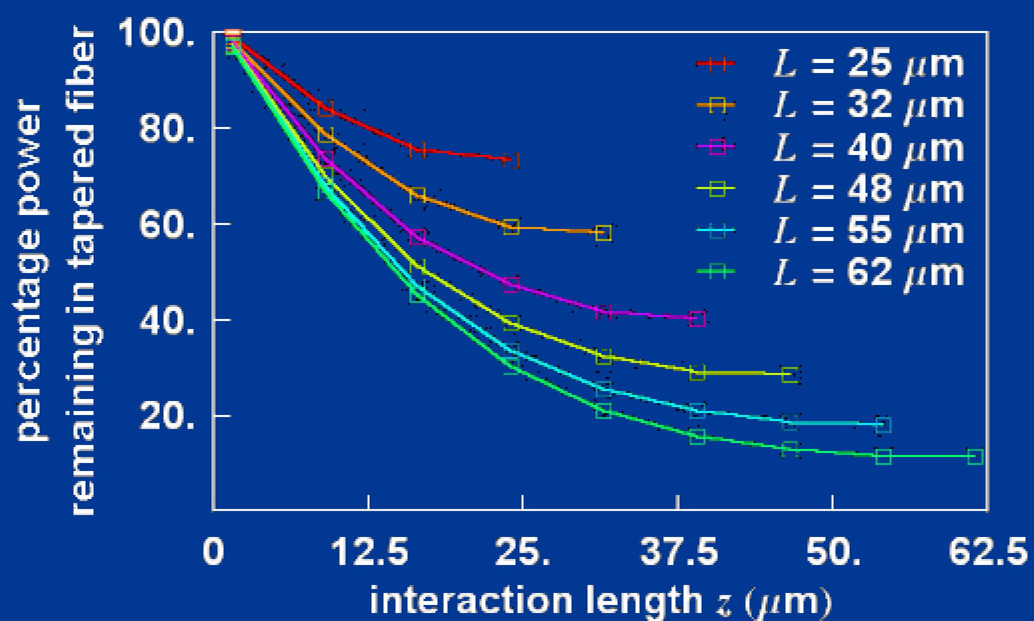


- **> 90% peak coupling efficiency for < 100 ? m interaction length at 1550 nm**

Simulation Results

3-D magnetic field H_z component profile





$$I_f(z) = I_f(0)\frac{\cosh^2\left[|\kappa|(L - z)\right]}{\cosh^2|\kappa L|}$$

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  - ? **Tunable filters and modulators**
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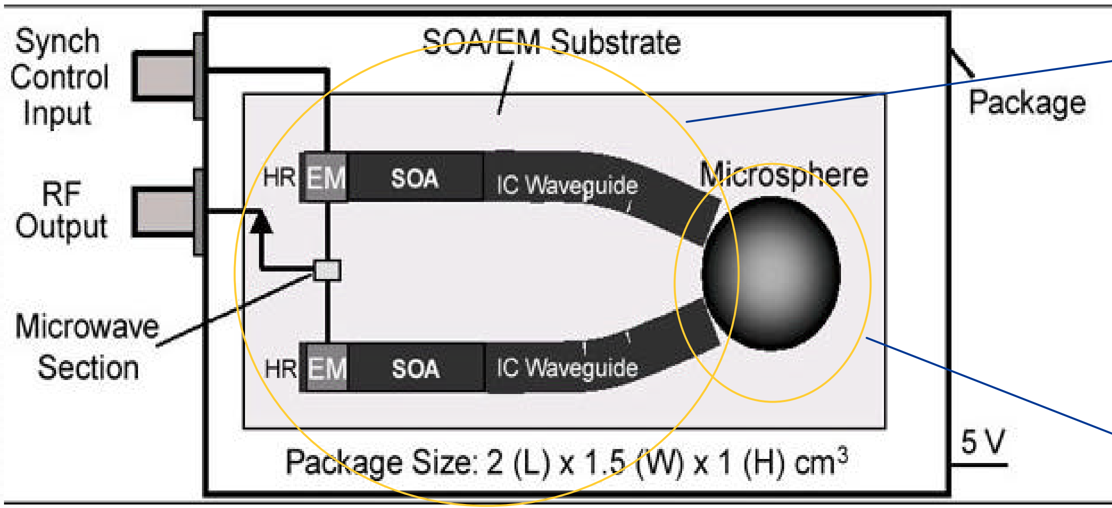
? **High performance Opto-Electronic Oscillator (OEO)**

Program Tasks



Integrated SOA/EAM PIC with Passive Waveguide

High Q Semiconductor Resonator?

Integrating microresonator on SOA/EAM substrate (with integrated waveguide):

- **eliminates the internal fiber coupling**
- **dramatically reducing size, power consumption, and manufacturing cost**

SBIR and AOSP Program Tasks

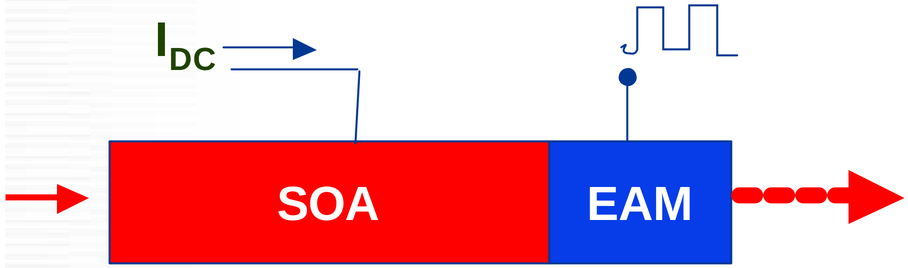
SBIR Program

- Develop SOA/EAM for Modelocked Laser
- Build Prototypes for Evaluation
- Transfer Design to Industry Partner
- Develop Dispersion Compensated Active Region Design for Wide Spectral Range Operation

AOSP

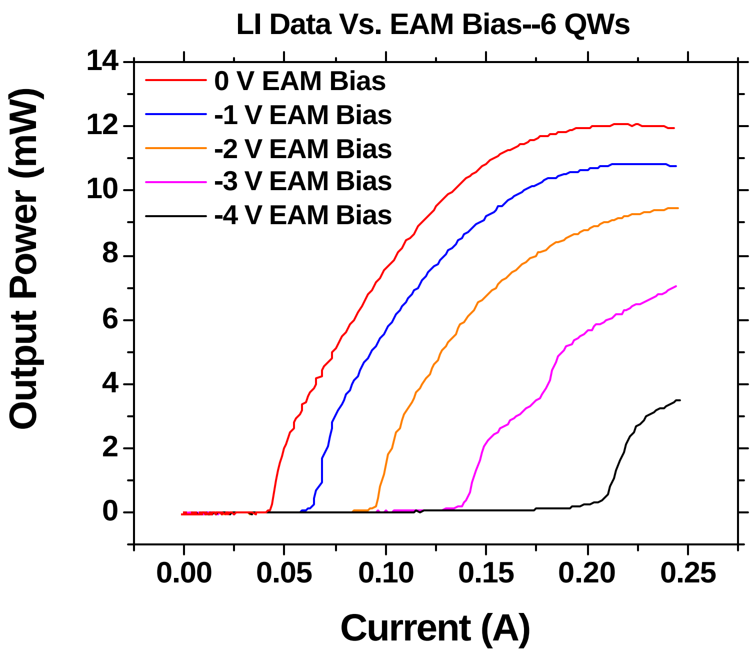
- Develop SOA/EAM for OEO
- Build Prototypes For Evaluation
- Develop Angled Facet Etching to Optimize Coupling
- ✍ Develop High Q Semiconductor Microresonator

SOA / EAM By Selective Growth



- •Compensate for coupling losses
- •Tailor chirp characteristics
- •Provide round trip gain in external cavity devices

Two Section Laser / EAM



Section-to-section resistance: 10K?

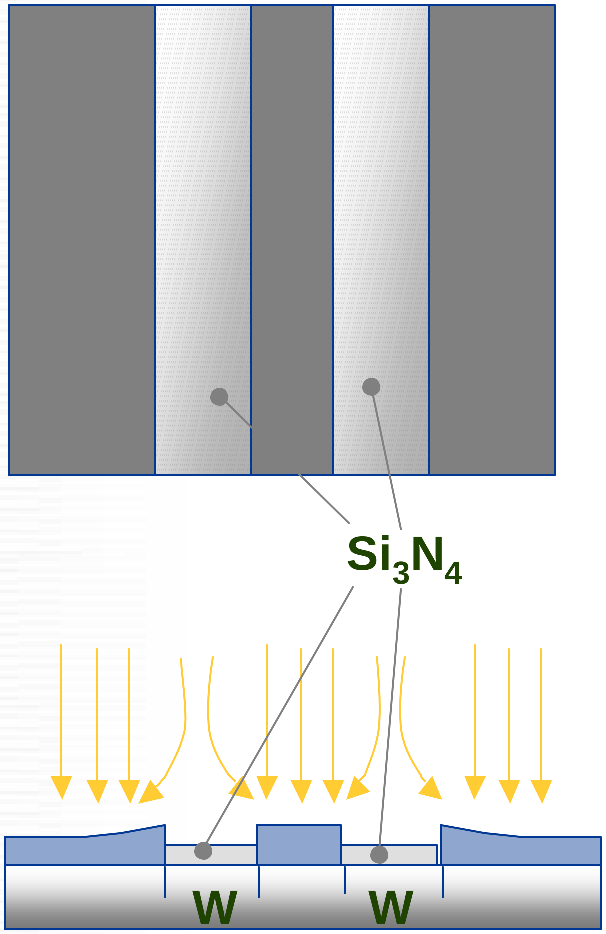
<u>Single Section Device:</u>

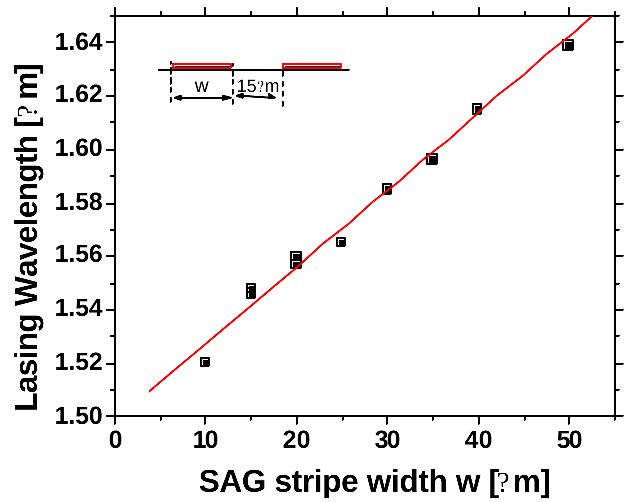
J_{th}: 140 A/cm^2/well (L=680? m, W=3? m)

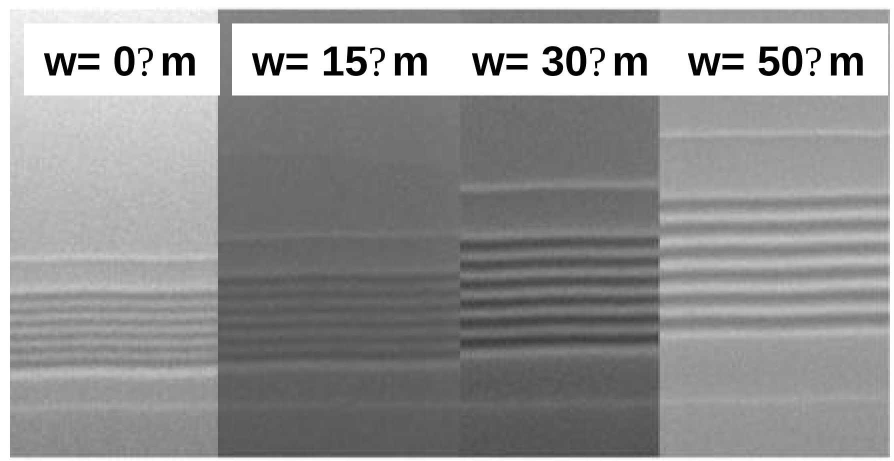
Series Resistance: 6?

Peak Wavelength: $?_o$=1542 nm

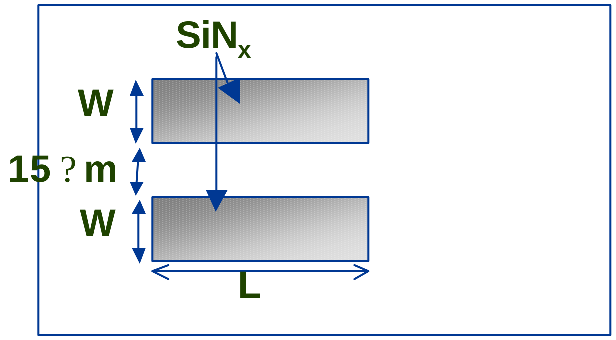
Selective Area Growth Rate Enhancement



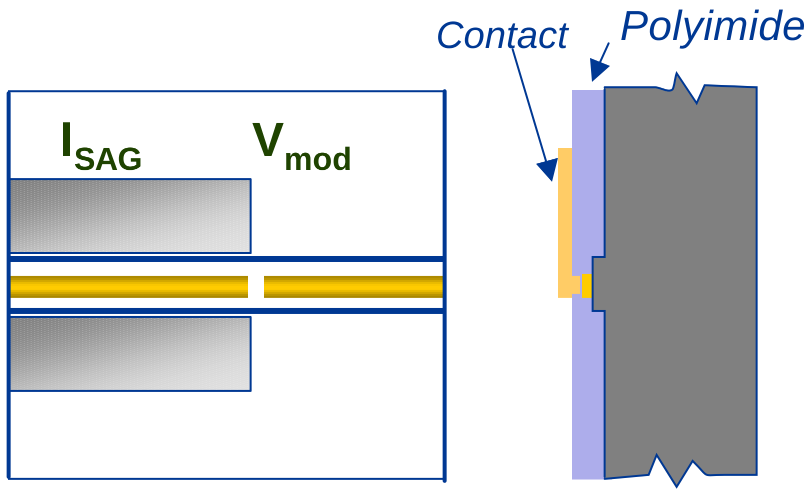




SOA/EAM Processing



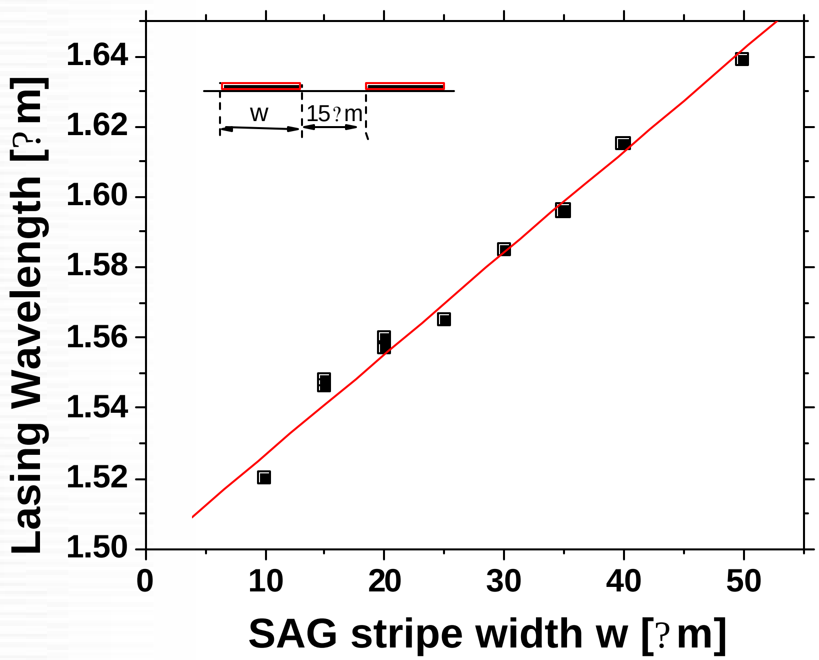
Growth Mask

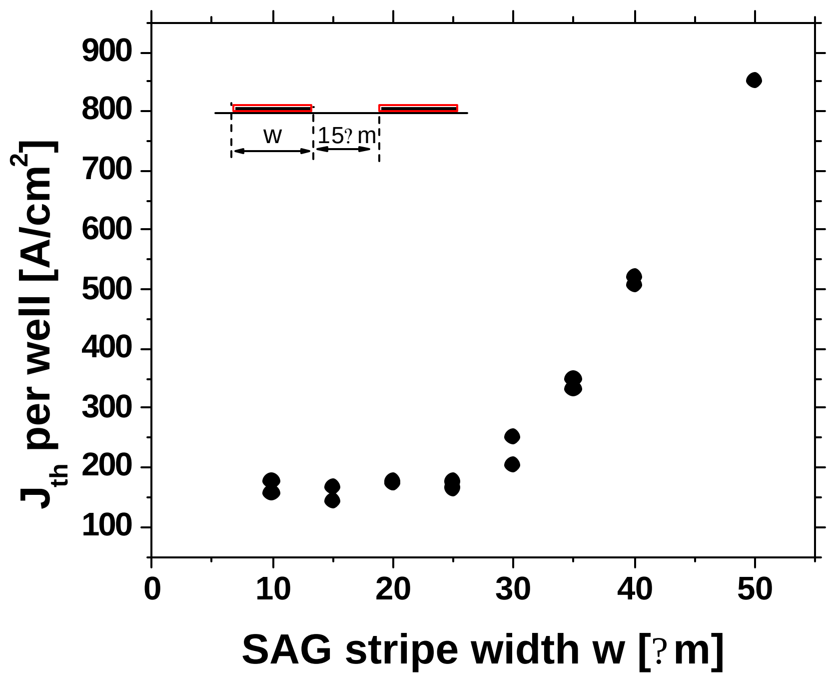


Cleave and AR Coat

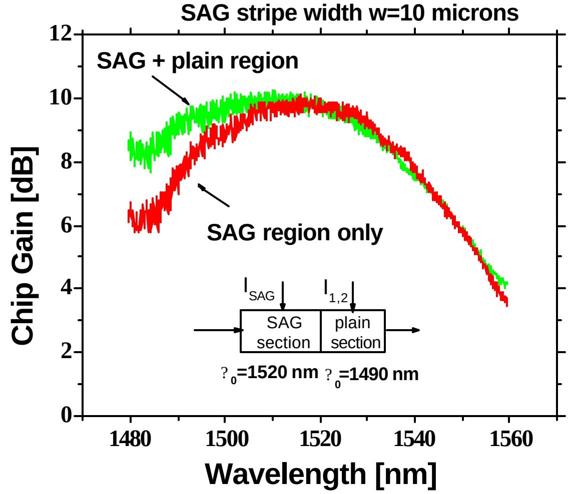
Device Process

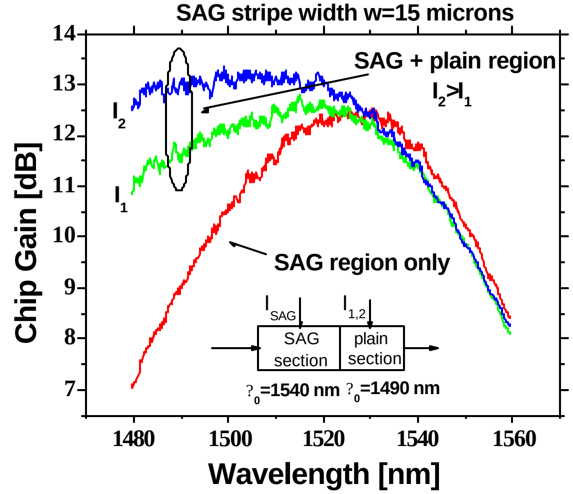
Selectively Grown Laser Active Regions

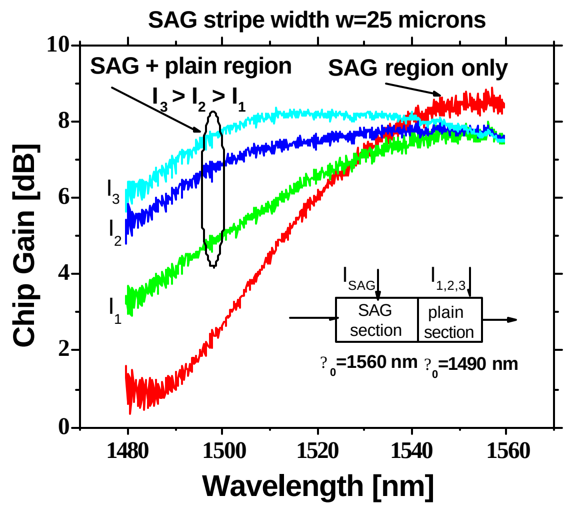


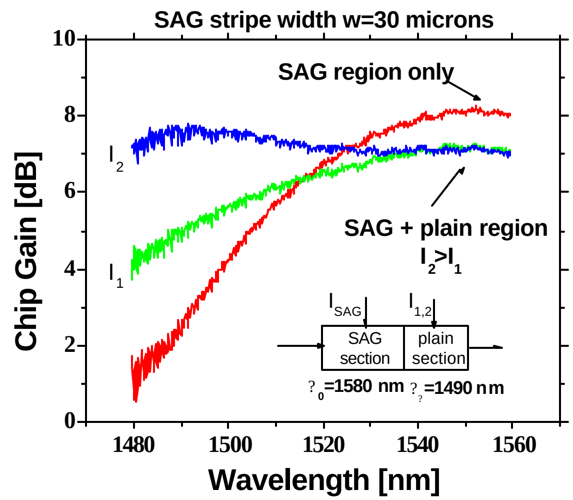


2 Section Amplifier Gain Spectra vs. SAG Stripe Width

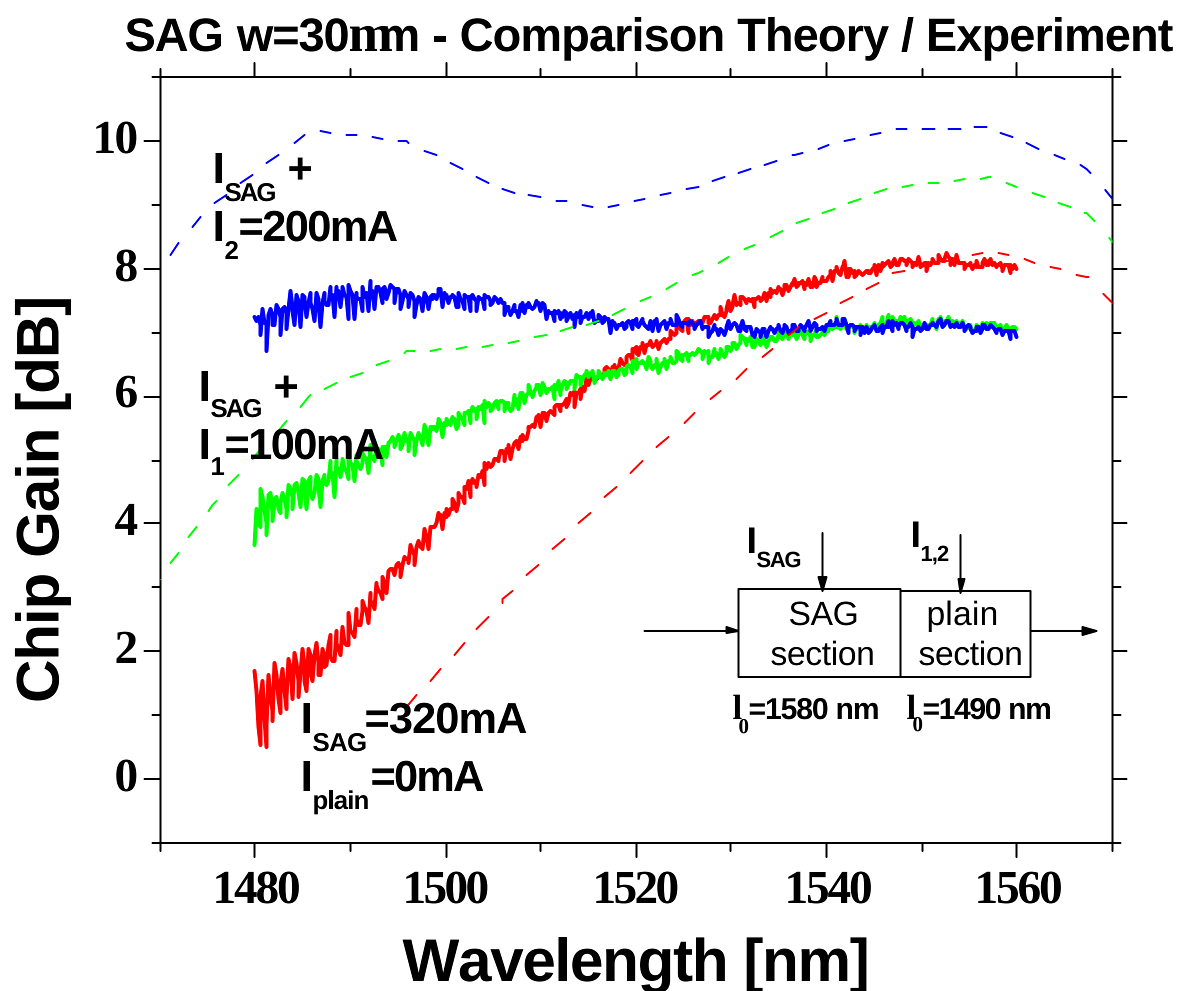






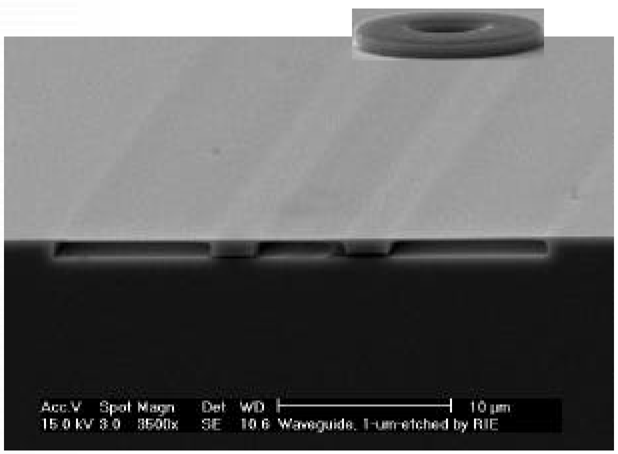


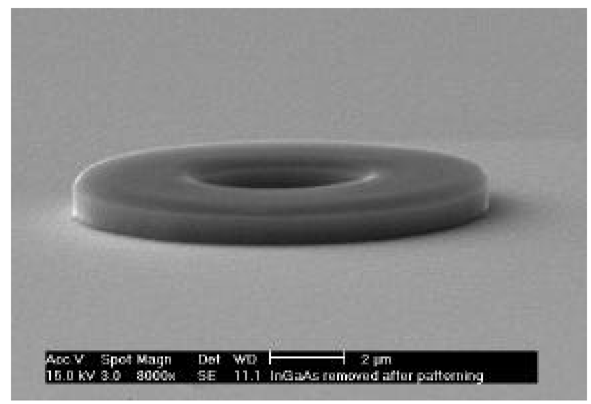
Two Section Amplifier – Comparison with Theory



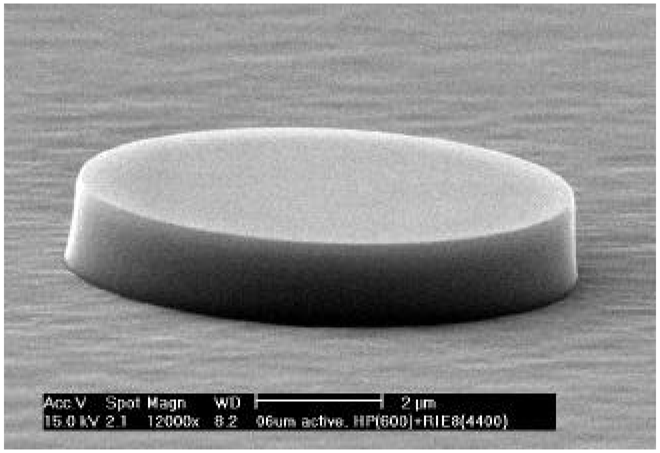
Vertically-Coupled Semiconductor Microresonators

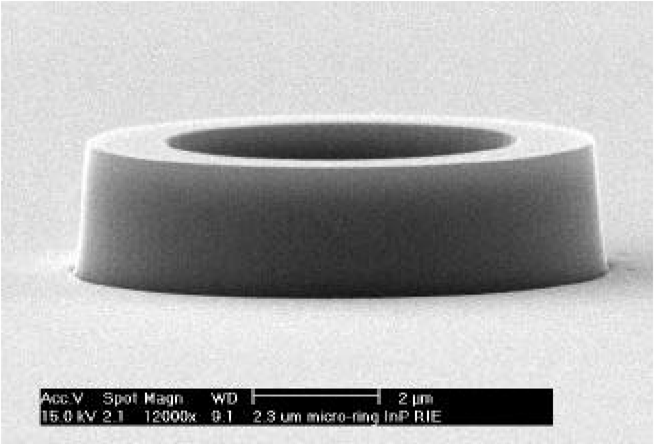
- Epitaxial Growth
- Waveguide Definition
- Wafer Bonding
- Substrate Removal
- Resonator Definition

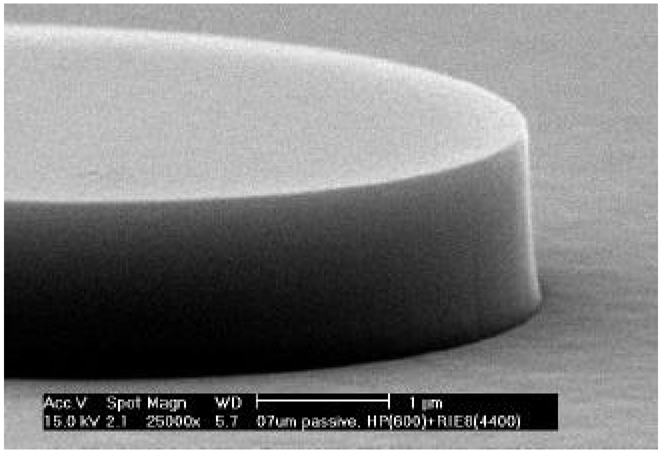


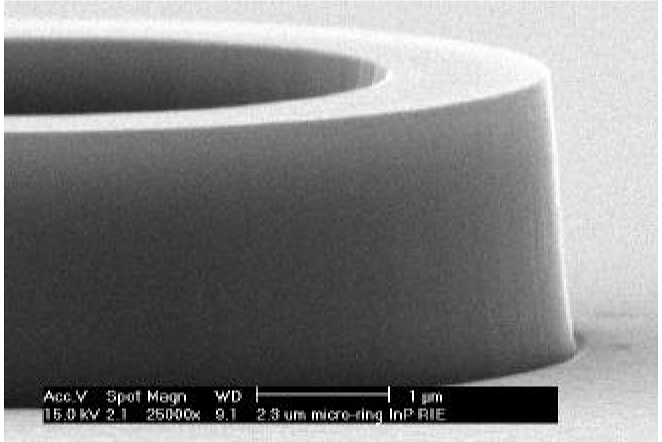


High Q Resonators

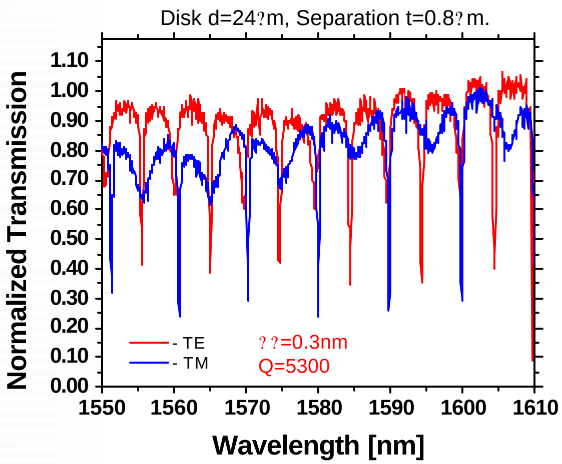


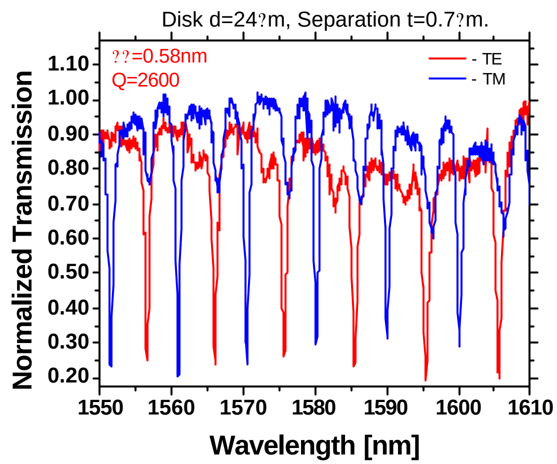


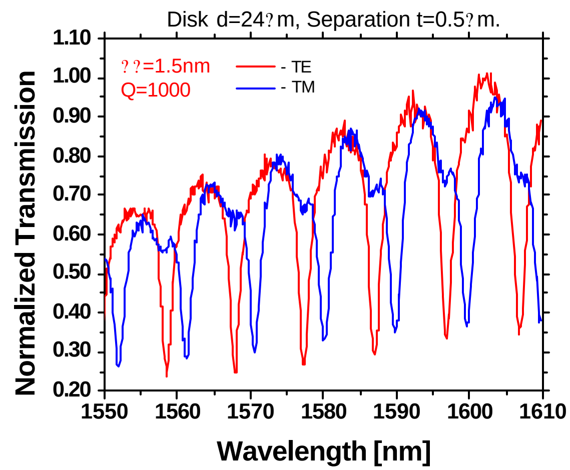


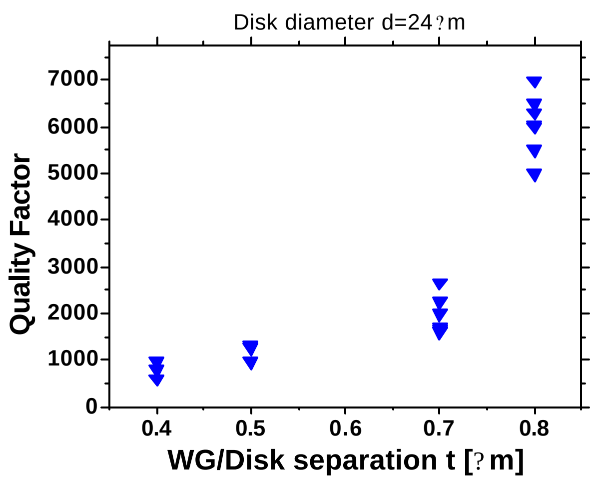


Coupling Limited Q's

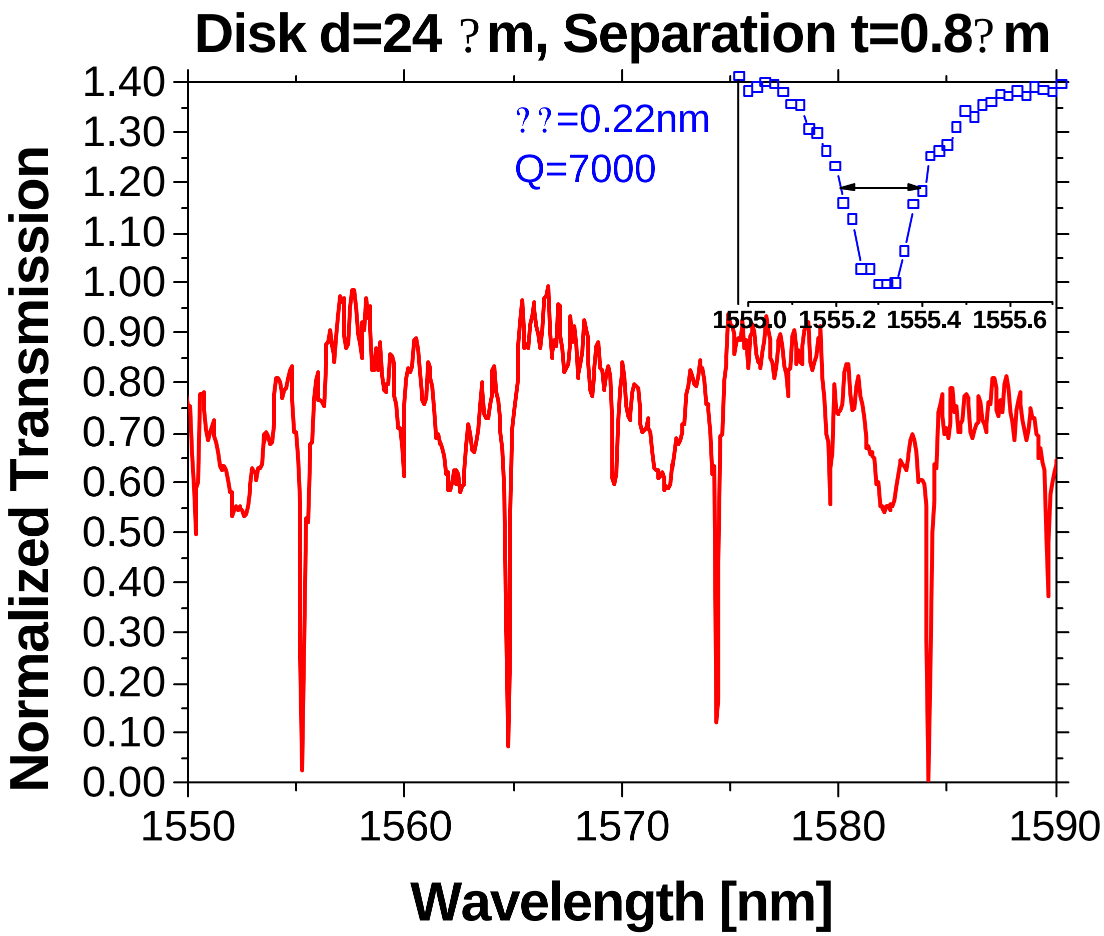






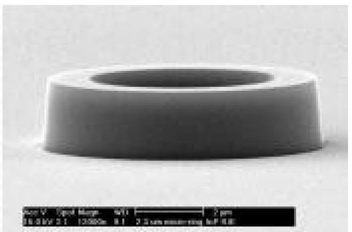


0.22 nm Linewidth Resonator



High Q Semiconductor Resonators

Air Isolated Resonators



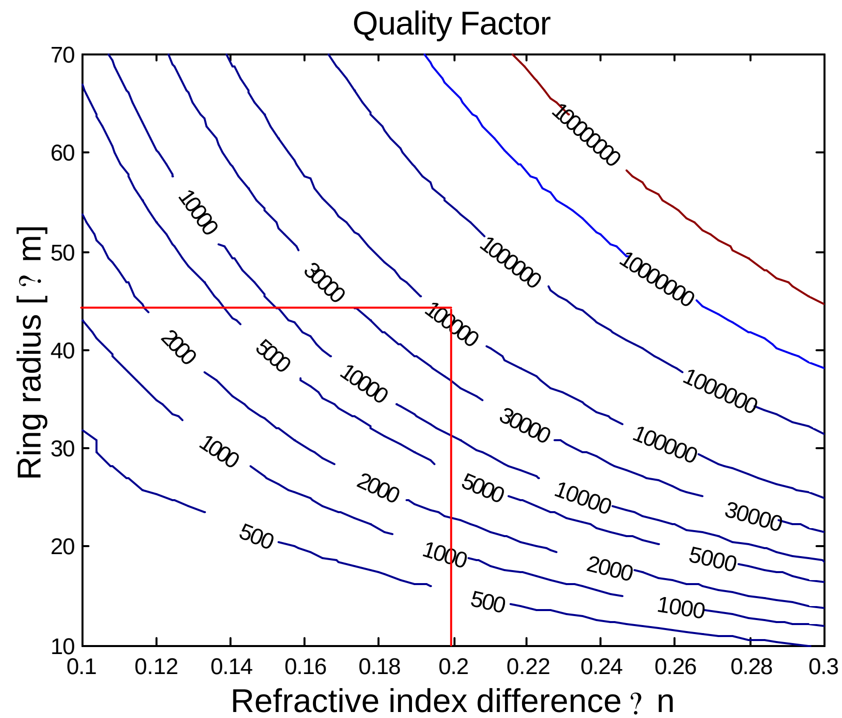
- Q's as high as 12,000
- Limited by
    - Coupling
    - Radius
    - Confinement

$$\frac{1}{Q_{tot}} ? \underset{i}{?} \frac{1}{Q_i} ? \frac{1}{Q_{in}} ? \frac{1}{Q_{out}} ? \frac{1}{Q_{scat}} ? \frac{1}{Q_{abs}} ? \frac{1}{Q_{bend}}$$

$$Q_{in,out} ? \frac{2?^2 R n_e}{?_o ?^2_{input}}$$

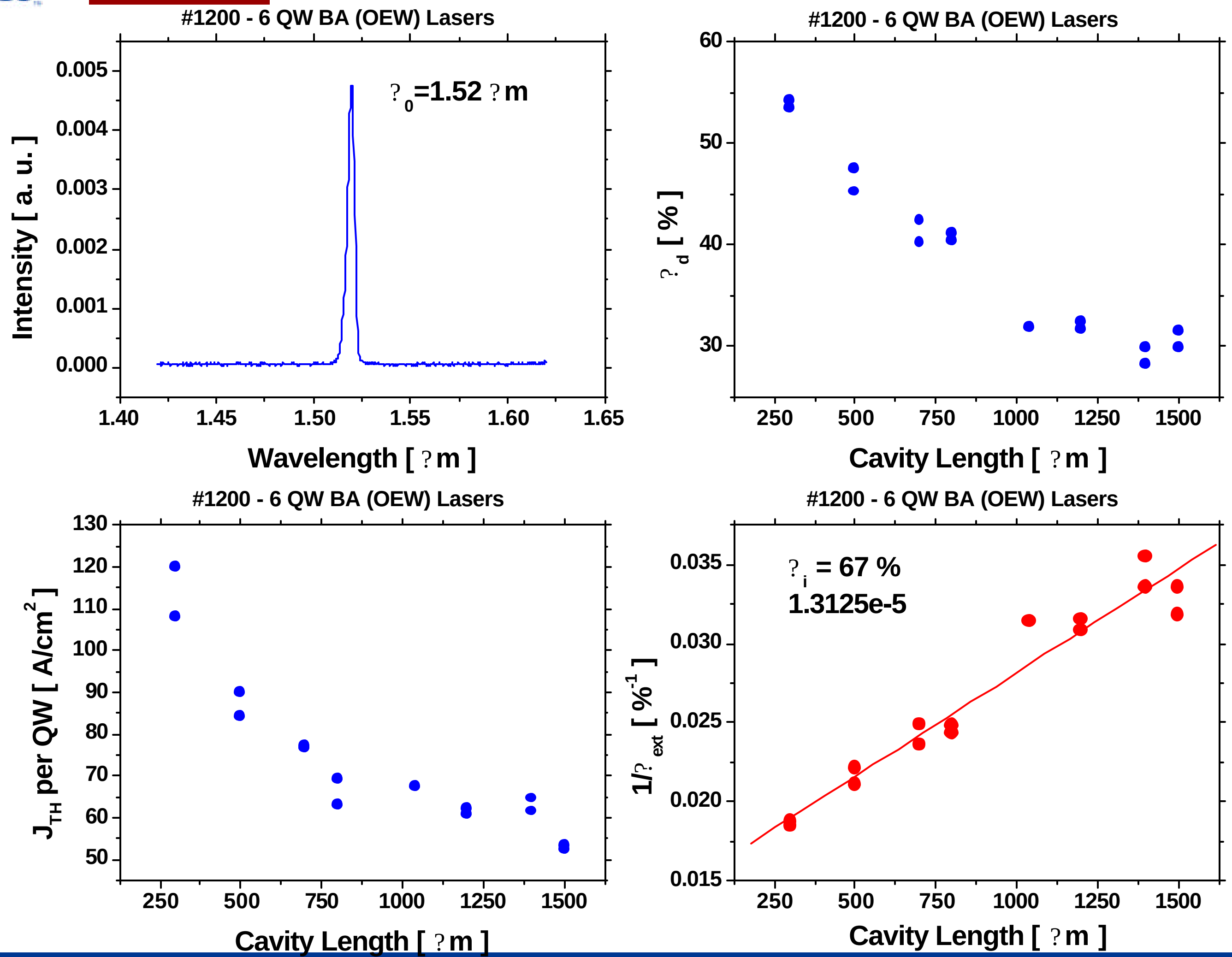
$$Q_{abs} ? \frac{? n_e}{?_{mode} ?_o}; \quad Q_{scat} ? \frac{? n_e}{?_{scat} ?_o}; \quad Q_{bend} ? \frac{? n_e}{?_{bend} ?_o}$$

$$?_{scat} : \left|M_{ij}\right|^2 : \left|n_g^2 ? n_c^2\right|^2$$

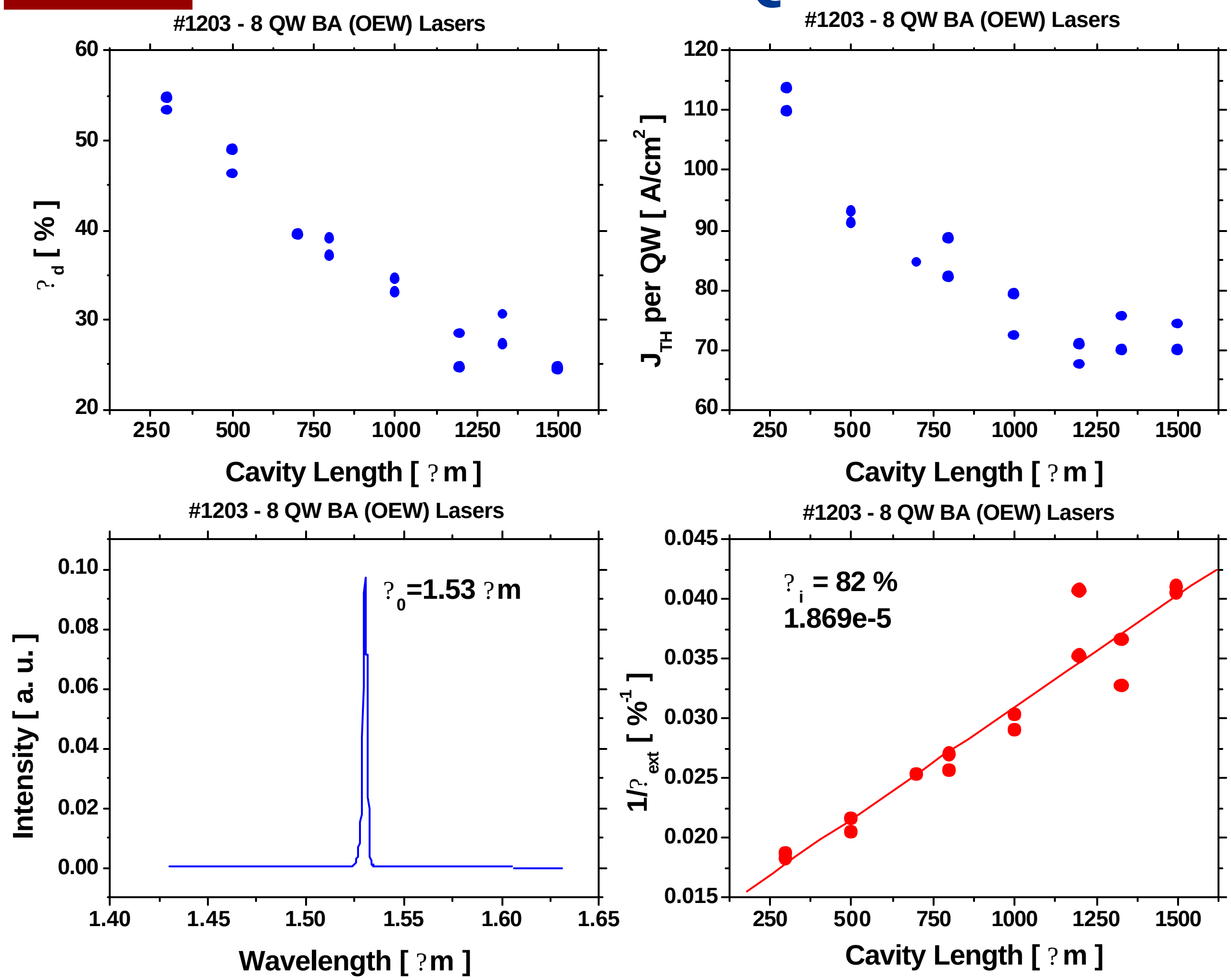


Bending-loss-limited Q contours plotted as a function of the index difference between the guide and cladding in a BH ring resonator and the ring radius. The solid lines mark a reasonable design point for a very high Q resonator.

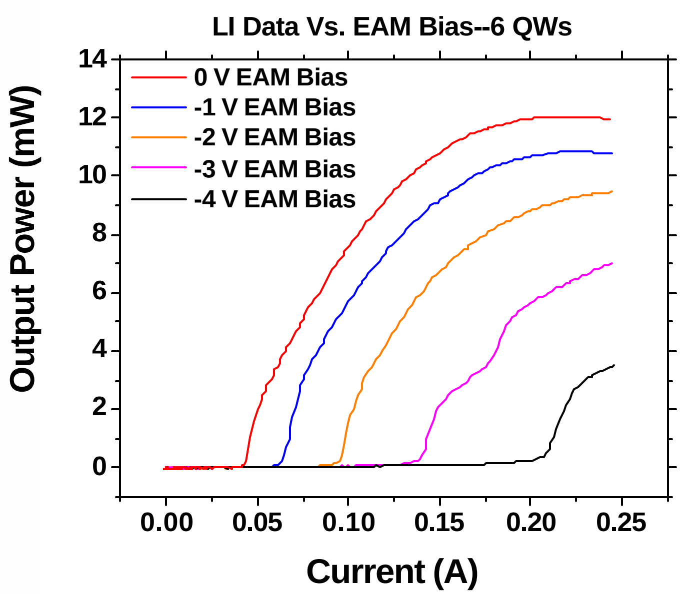
OEwaves BA Lasers – 6 QW's

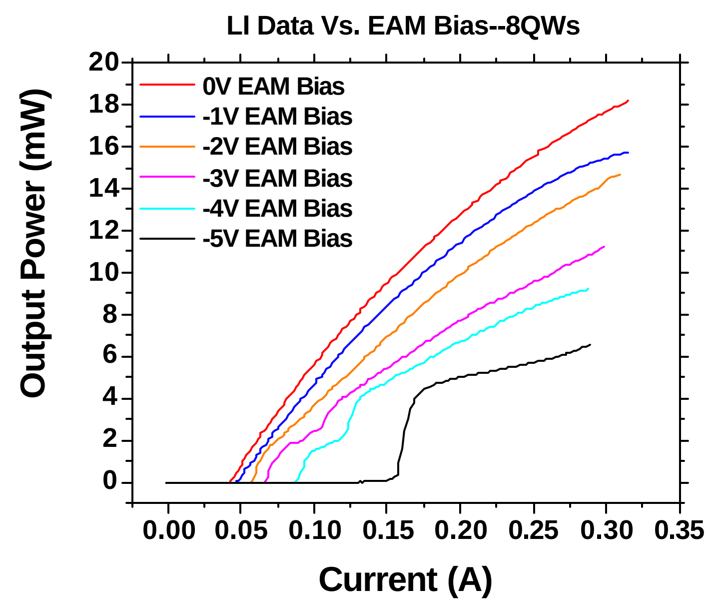


OEwaves BA Lasers – 8 QW



SOA / EAM Operated as Laser – Recent Results





Section-to-section resistance: 10K?

Single Section Device:

J_{th}: 140 A/cm^2/well (L=680? m, W=3 ? m)
Series Resistance: 6?
Peak Wavelength: ?$_o$=1542 nm

Section-to-section resistance: 10K?

Single Section Device:

J_{th}: 185 A/cm^2/well (L=680? m, W=3? m)
Series Resistance: 6 ? ?
Peak Wavelength: ?$_o$=1528 nm

Summary

New technologies will be developed to facilitate high performance photonic microwave oscillators and photonic tools for microwave analog signal processing.