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Photonic Integrated Circuit for Channelizing RF Signals

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CLEO, San Jose, CA

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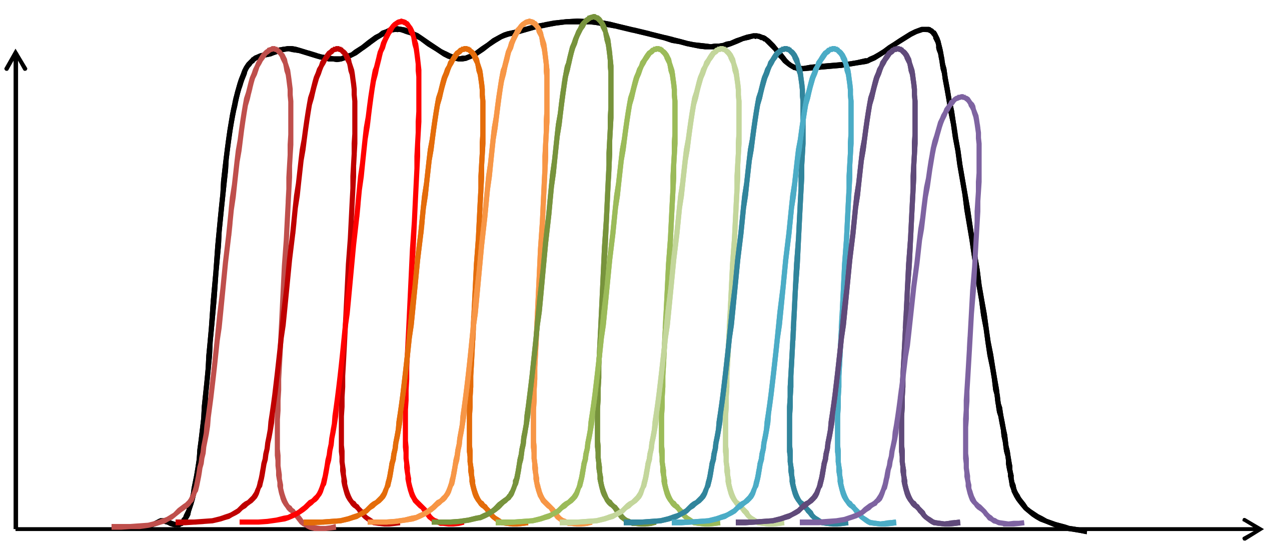
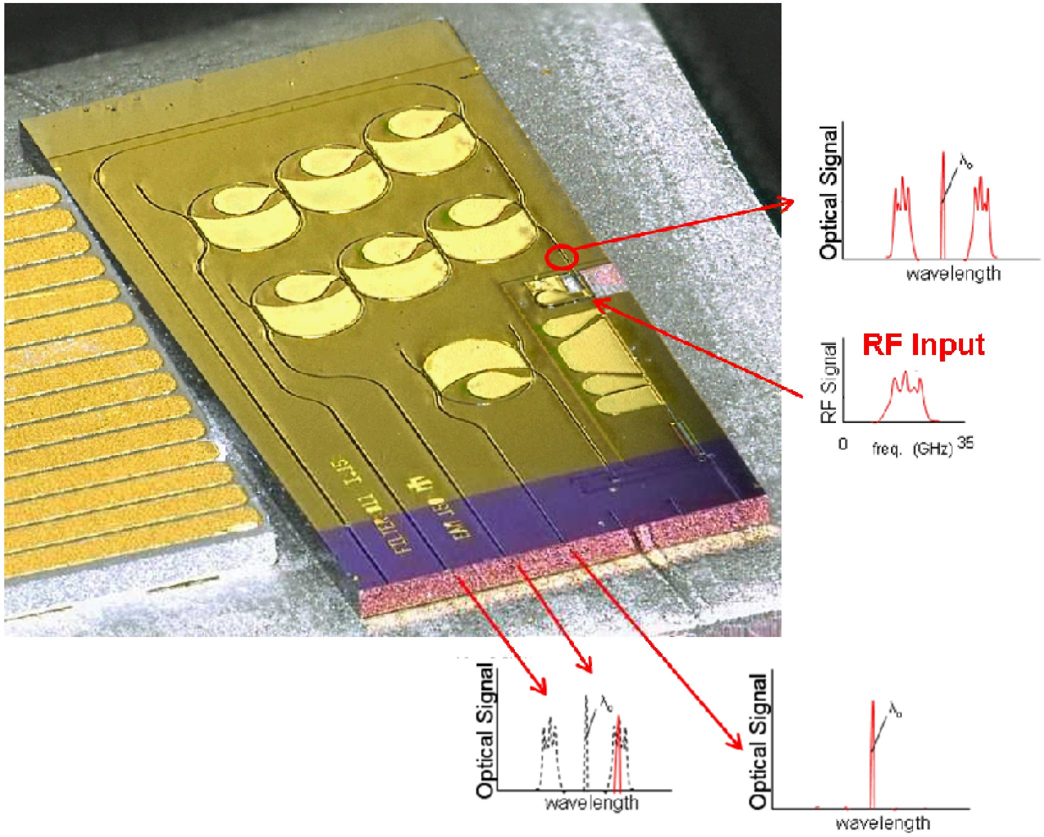
Motivation

- Electronic digital signal processing is limited for wideband RF signals
  - Wideband signals have to be channelized to passbands of a few GHz
  - They are then down-converted to frequencies compatible with A-to-D converters
  - Electronic channelizers are physically large and have fixed frequency characteristics
    - Limiting the application space



Monolithic RF Channelizing PIC

- Why optical RF channelizing?
  - Low SWaP
  - Wide bandwidth (1-50 GHz)
  - Made possible by InP-based photonic integrated circuits (PICs)
- Channelize RF signals for further analysis
- Monolithic integration enables compact, highly functional photonic integrated circuits (PICs)
- Tunable filters enable accurate placement across the frequency band



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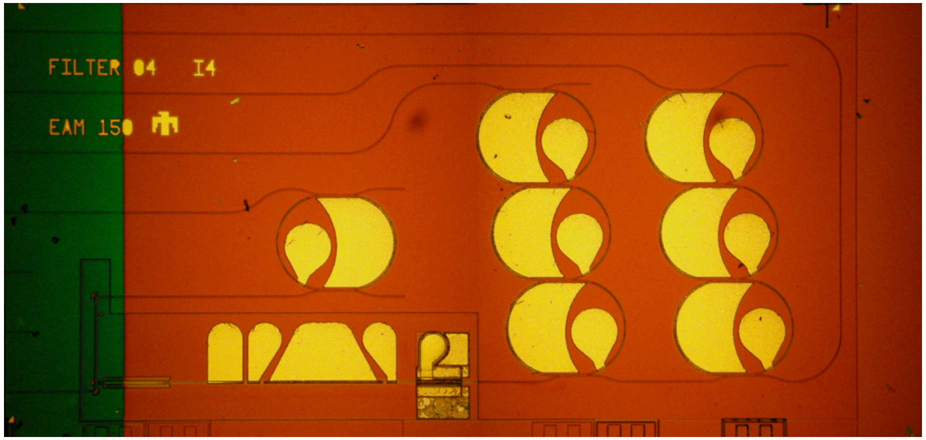
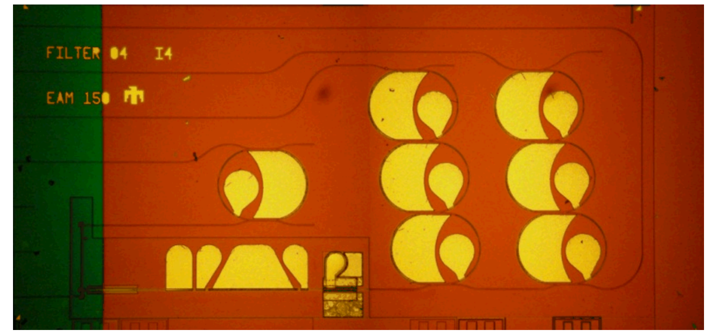
Monolithic RF Channelizing PIC

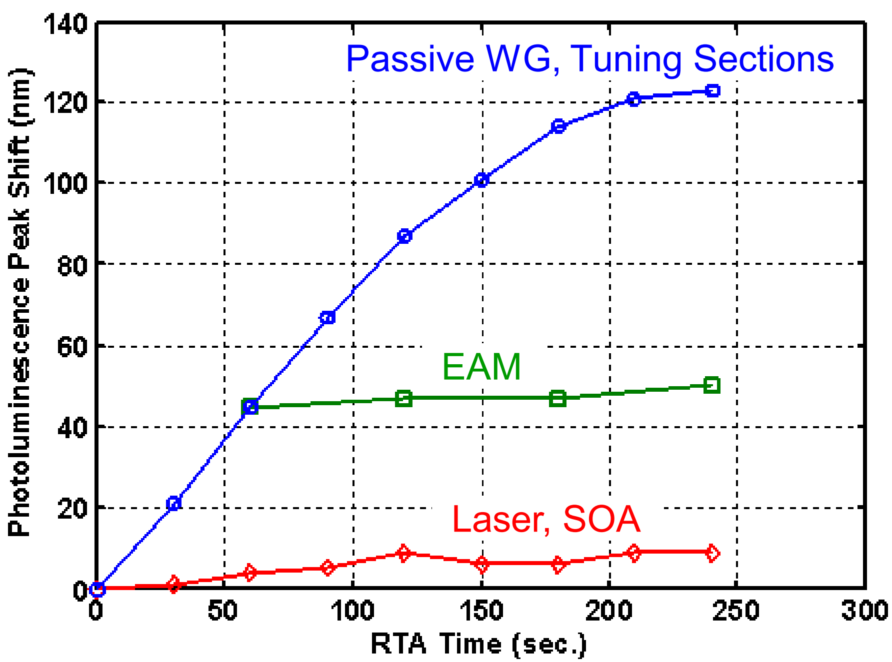
- Important PIC features
  - Cascaded ring resonator filters
    - Tunable over 10's GHz
    - GHz-class pass bands
    - 65 GHz free spectral range
  - Integrated laser-modulator
    - Reduces coupling losses
    - Signal to EAM provides the RF input
  - Integrated extra filter for wavelength monitoring

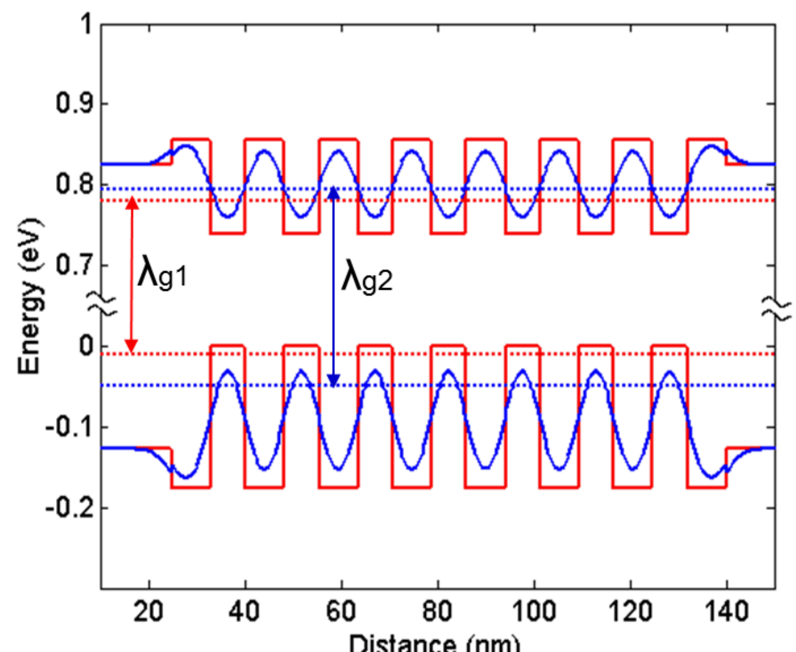


Monolithic Integration Platform

- Quantum well intermixing
  - Metastable interface between well/barrier
  - Add catalyst to enhance interdiffusion
  - Reshaping increases the energy level
    - Reduces the bandgap wavelength
  - Capable >2 bandedges with same epitaxial base







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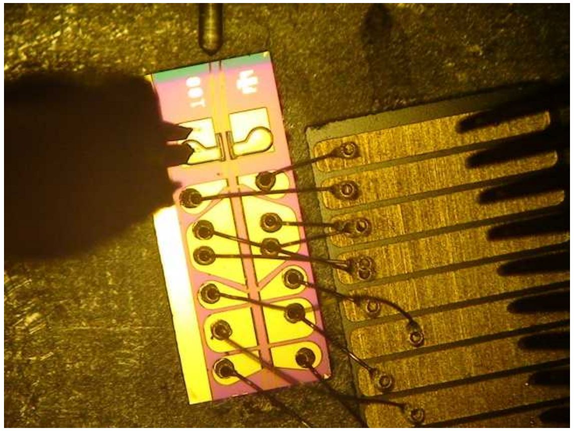
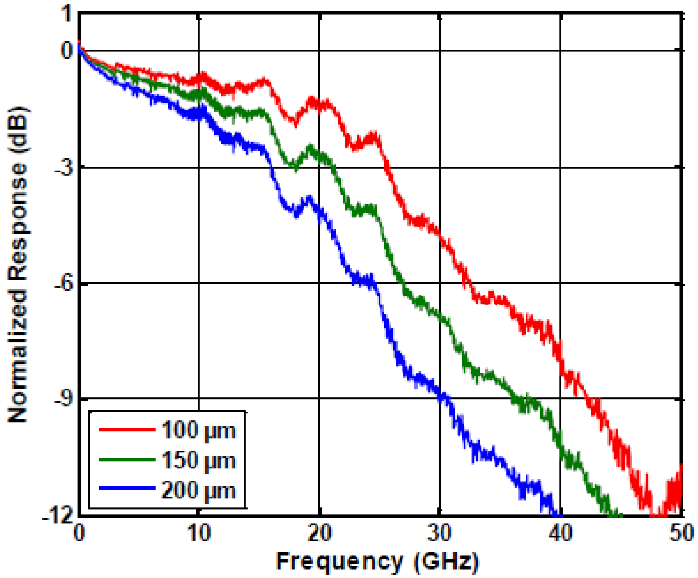
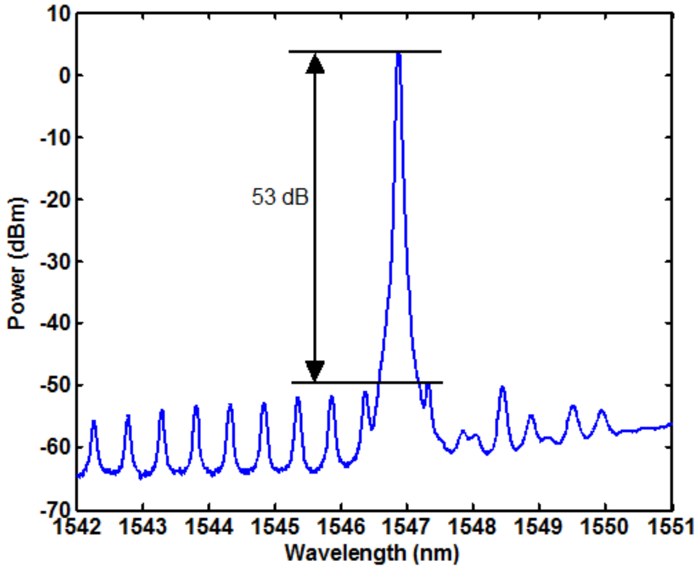
Laser-modulator

- DBR laser
  - >50 dB SMSR
  - Laser tunable over several nm
  - Continuous tuning over 0.3 nm
- Electroabsorption modulator
  - Bandwidth >20 GHz for 150 μm length
- Ridge waveguide design

DBR Laser –EAM







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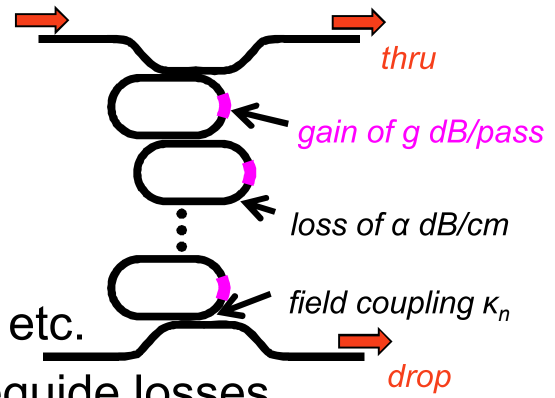
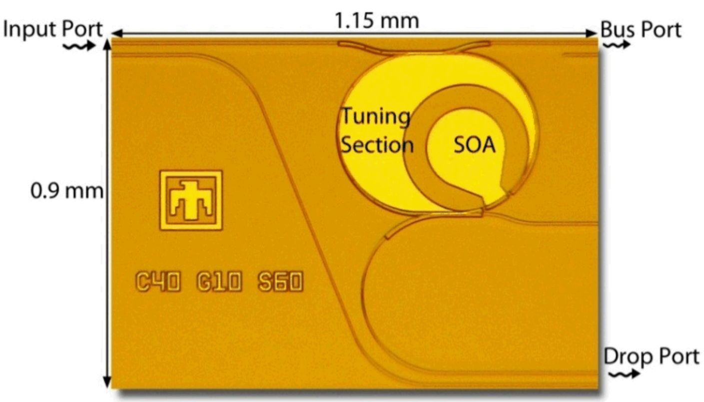
Design of Active Ring Filters



- Active ring resonators offer:
  - Compact size
  - Low, or zero, back reflection
  - Monolithic integration with lasers, modulators, SOA, etc.
  - Gain elements can be used to compensate for waveguide losses
  - Loss, couplers, and optical gain needs to be tightly controlled to achieve designed bandwidth, profile, extinction ratio and low noise
- Our approach
  - Couplers designed for 1-5 GHz linewidth
  - Integrated 60-μm-long SOAs in the ring
    - Manipulate loss through filter
    - Length and total gain designed for low noise
  - Tuning section
    - Current injection



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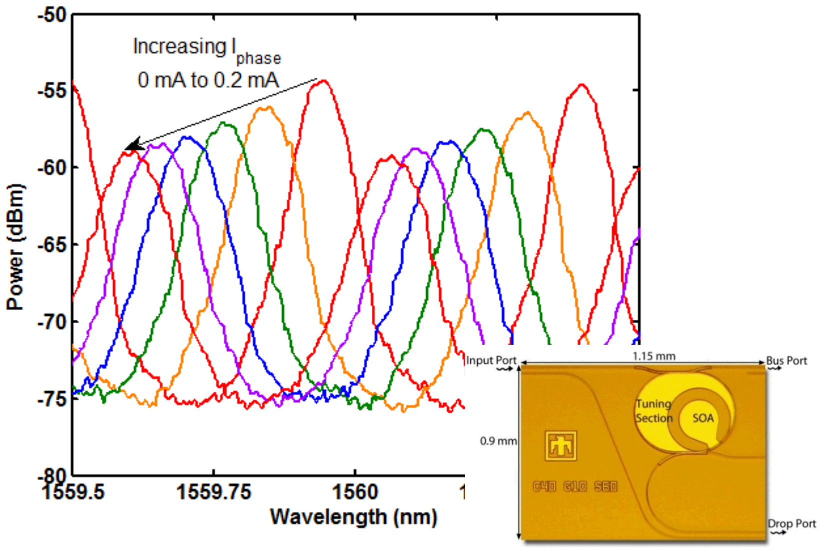
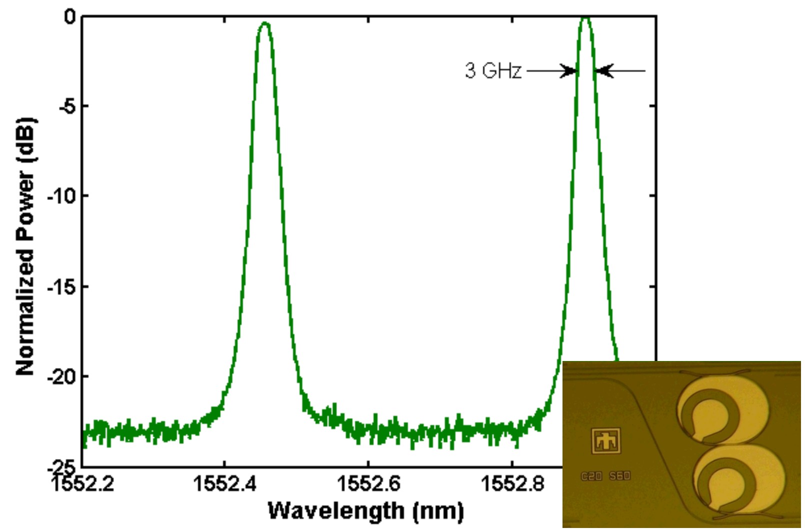
Filters: Previous Work





- Tuning of single ring resonator
  - Tunable over the entire free spectral range
- Developed experimentally verified models for the InP-based resonators

"InP Tunable Ring Resonator Filters", Photonics West 2012

- Cascaded 2-ring resonator
  - 3 GHz 3-dB optical bandwidth
  - >20 dB extinction
  - Quality factor of 65,000

"Cascaded Double Ring Resonator Filter with Integrated SOAs" OFC 2011

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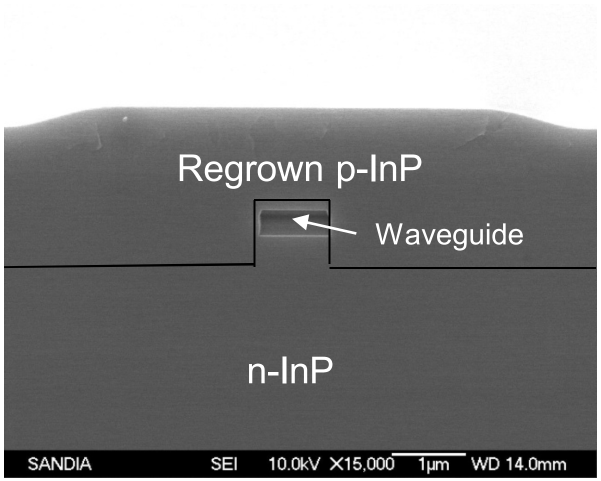
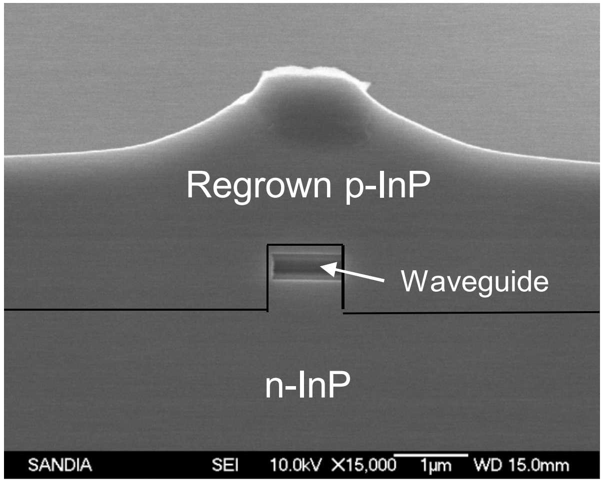
Filters: Waveguides

- Low loss waveguides are necessary for high Q filters
- Couplers need to be tightly controlled to achieve designed bandwidths
- Buried heterostucture advantages
  - Waveguide thickness defined by epitaxial material
  - Semiconductor etch only defines guiding width and coupler gap
  - Devices are essentially not affected by variations in etch depth

Waveguides in [011]



Waveguides in [01$\bar{1}$]



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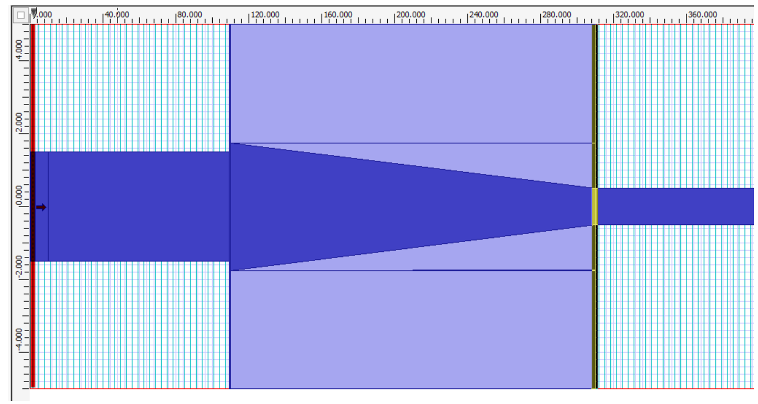
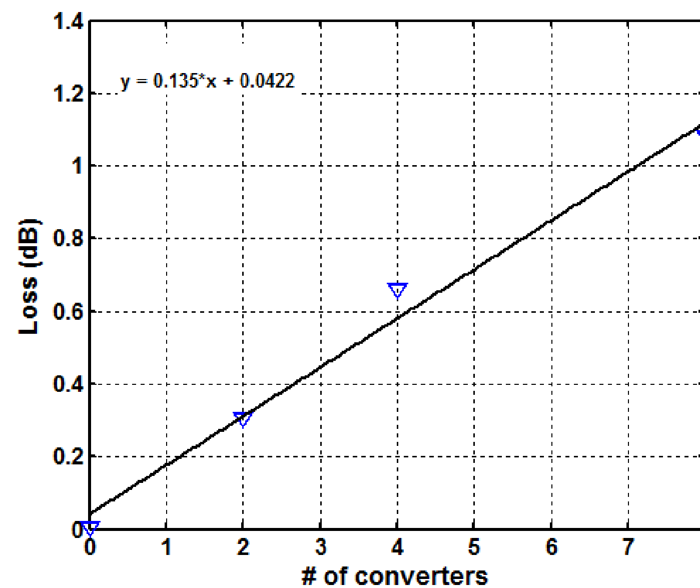
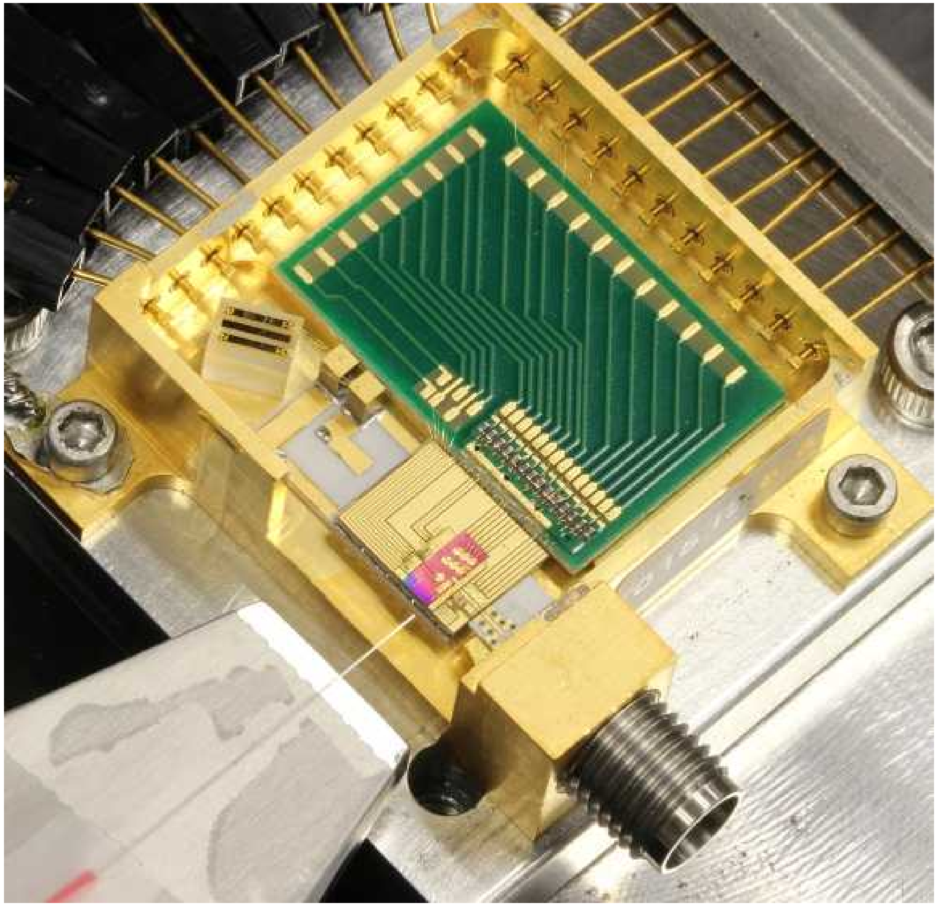
Ridge to Buried Heterostructure Coupler

- Laser and modulator has been optimized for ridge waveguide architecture
- Rings are optimized for buried heterostructure architecture
- Transition between the two waveguide types is done by tapering
- Experimental measurements show excess loss of 0.14 dB/transition
  - Theory predicts 0.11 dB/transition





Characterization of Packaged Devices



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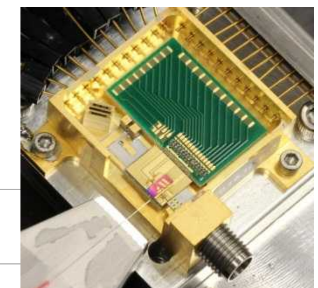
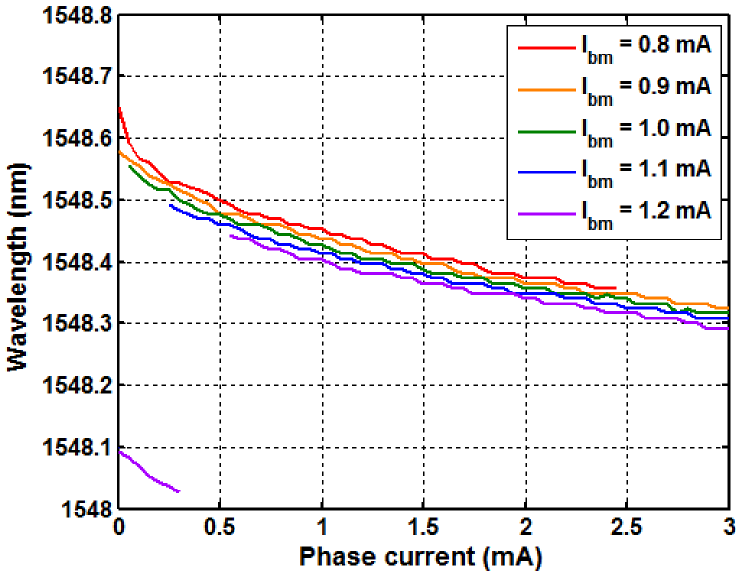
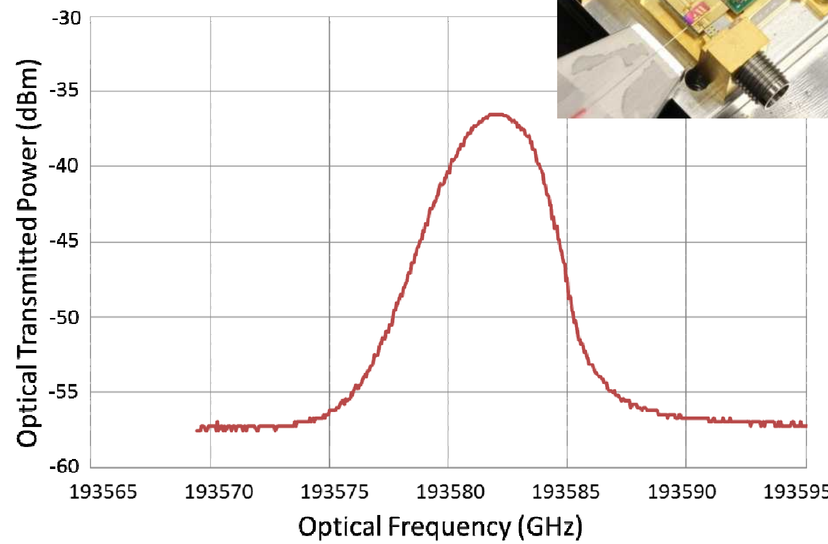
Characterization: Wavelength Scans

- Laser wavelength was scanned by adjusting phase current over a continuous tuning range
- Strong optical power gives the best measurement of filter shape
  - 3-dB optical passbands of 3.8 GHz demonstrated
  - 3-dB electrical passband of 3.36 GHz







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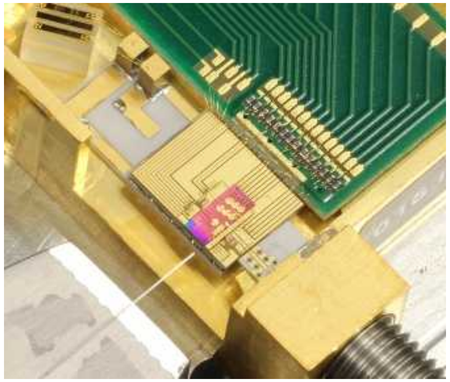
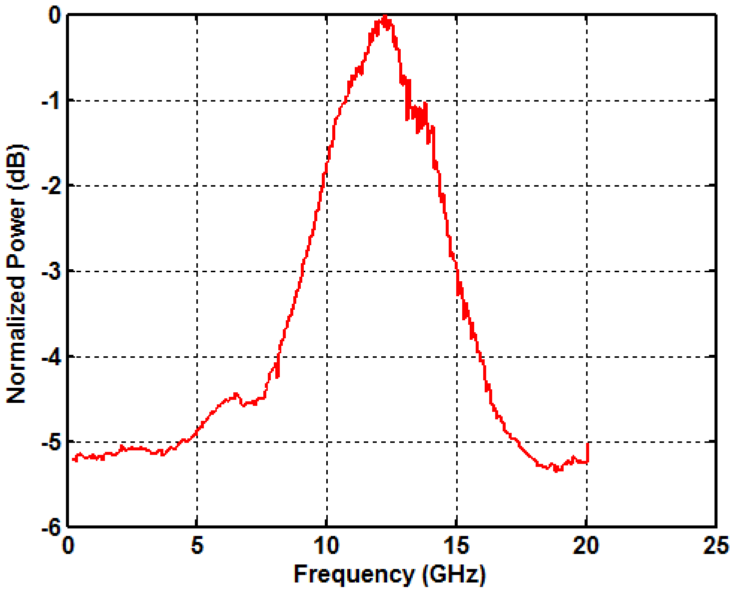
Characterization: RF Scan

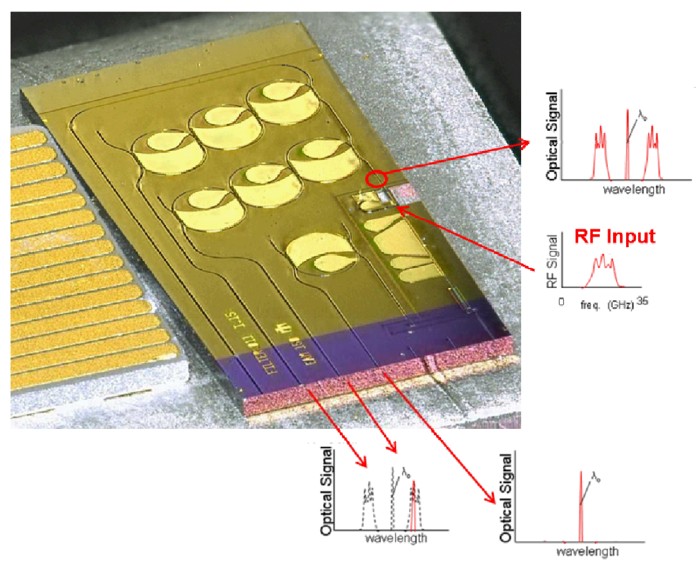
- Sinusoidal signal was applied to modulator to create a sideband
  - The signal frequency was swept to sweep the sideband through the channelizing filter
- The lower signal power from the RF sideband is on the order of this noise
- Lower filter extinction is due to the filter noise floor
  - ASE from SOAs create a noise floor





Summary

- Demonstrated viable approach for optical RF channelizing PIC
  - Active 3-pole ring resonator filters
    - >20 dB of optical extinction
    - State-of-the-art 4 GHz passband matching models
    - Further reduction in passband possible with new designs
    - Lower crosstalk can be achieved with higher pole-filter
  - Demonstrated filtering of RF signal
    - Performance limited by SOA noise and sideband power
    - Improvements in modulator efficiency will improve signal to noise
      - Traveling wave modulators
      - Mach-Zehnder modulators



Backup Slides

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Motivation

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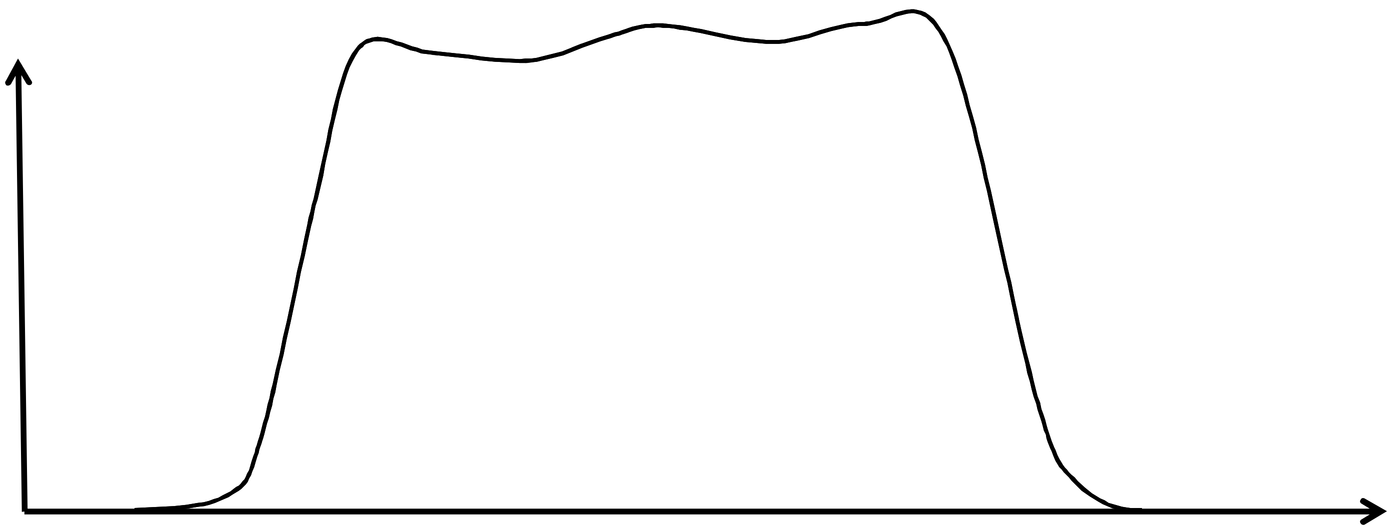

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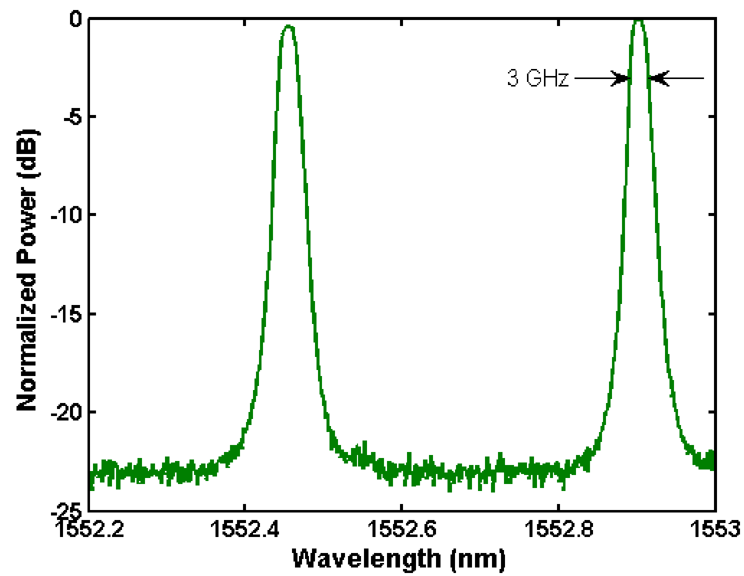
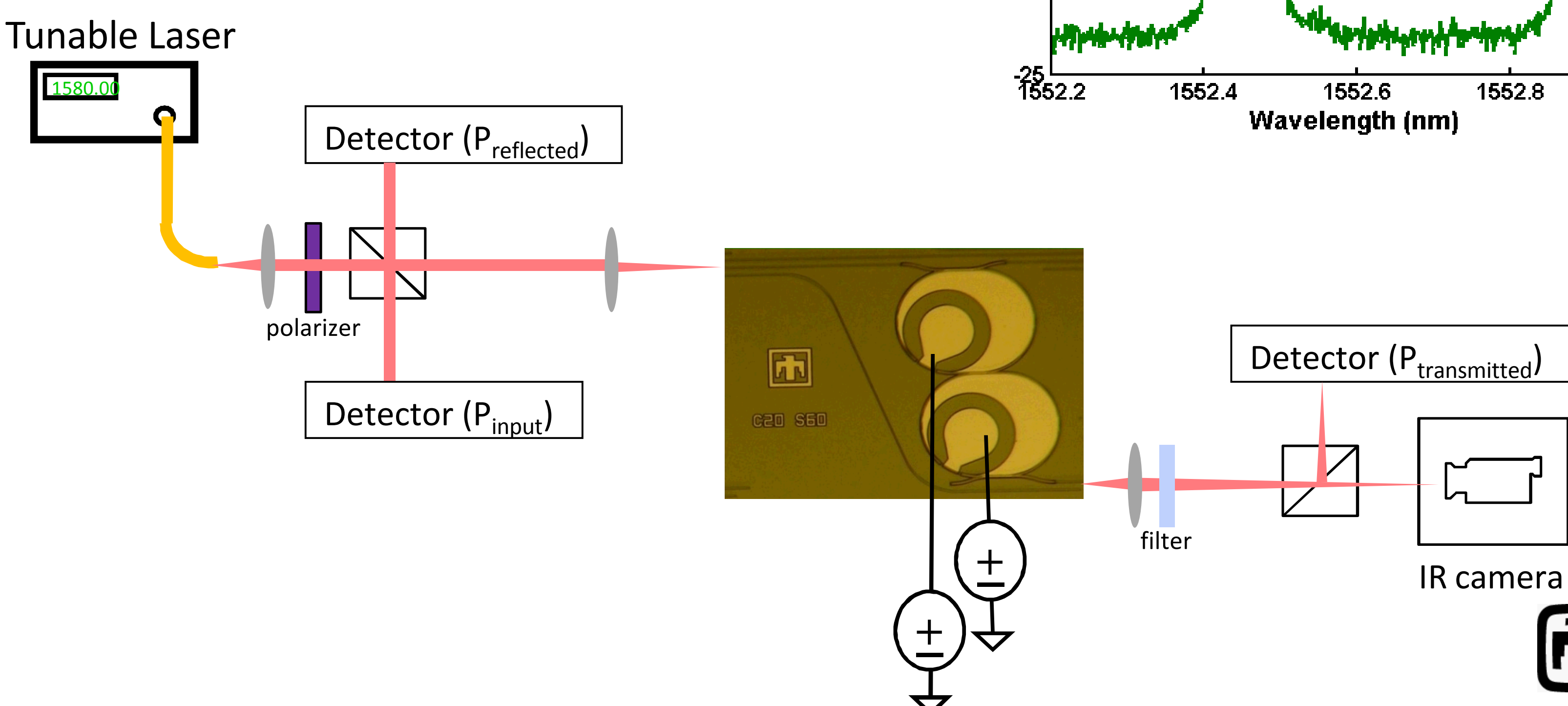
Experimental results

- Scanning source measurement
  - Wavelength swept on a tunable laser source
  - 12 nm filter added to the ring output
    - This filters out much of the ASE from the SOA
  - 3 GHz 3-dB optical bandwidth
  - Quality factor of 65,000





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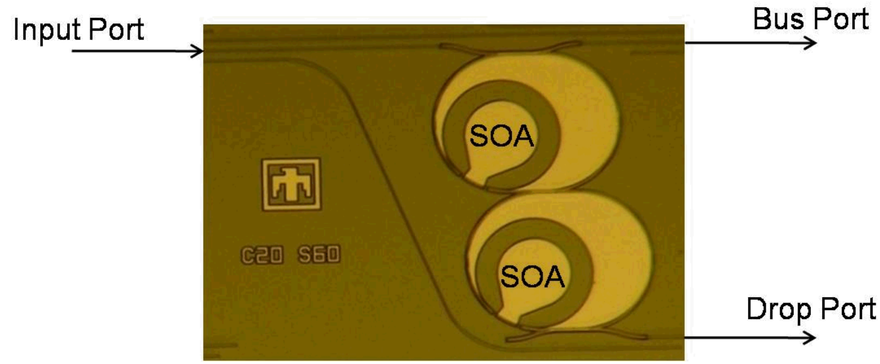
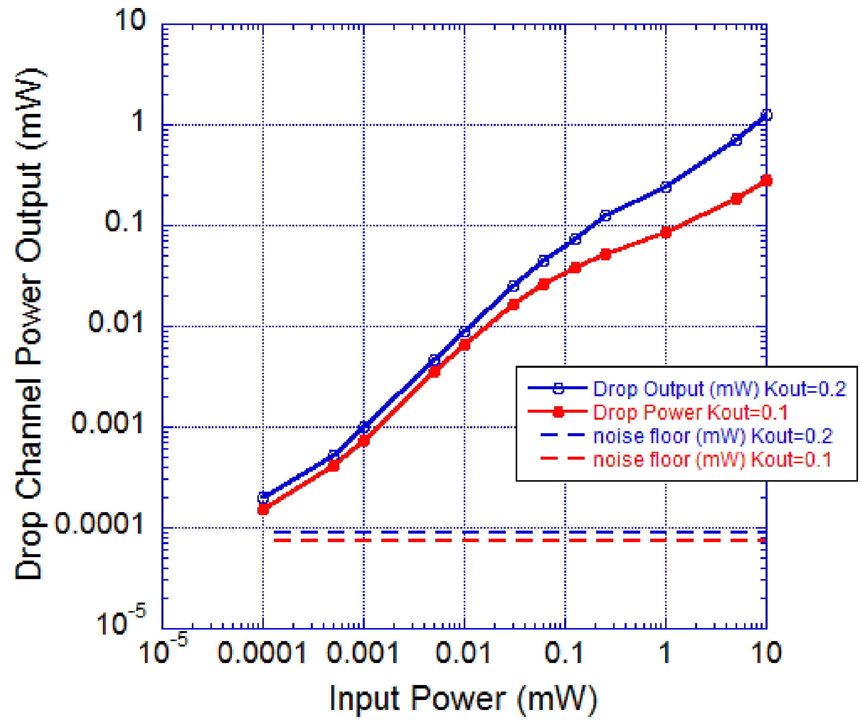
Previous Work

- Dual ring resonators with quality factor of 65,000
  - Linewidth of 3 GHz
- Analysis of dynamic range of active ring resonator filters
  - Active ring resonator filters can offer improved performance over passive filters (SiON) due to no coupling losses
  - Limitations due to amplified spontaneous emission and SOA saturation must be designed in





"Cascaded Double Ring Resonator Filter with Integrated SOAs", OFC 2011
"Wide Dynamic Range of Ring Resonator Channel-Dropping Filters with Integrated SOAs", OFC 2011

Previous Work

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  - Tunable over the entire free spectral range
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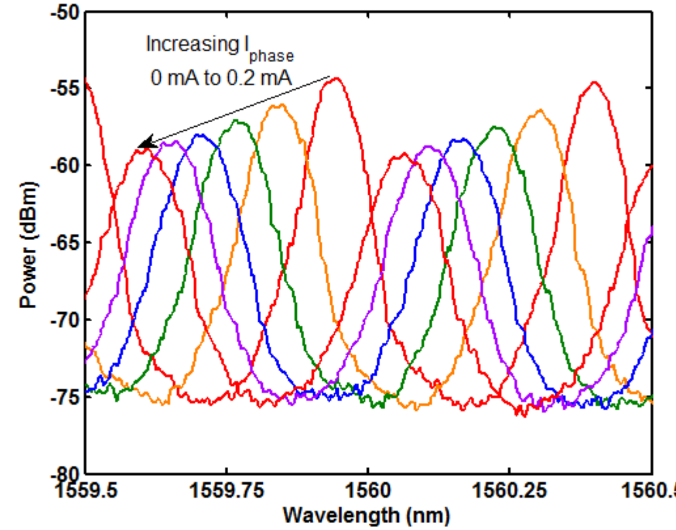
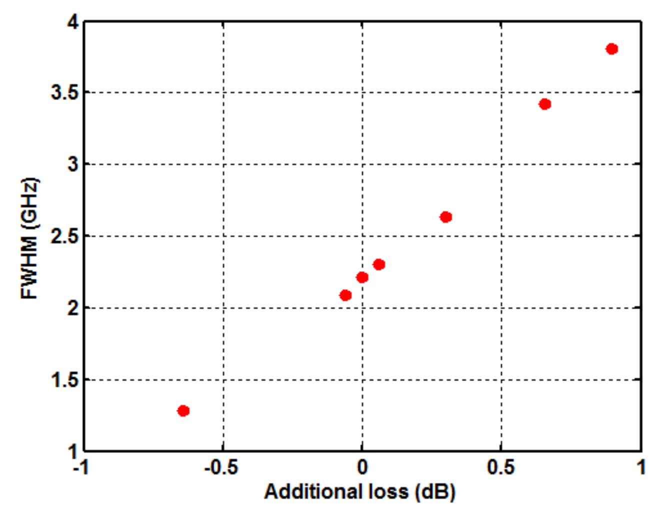
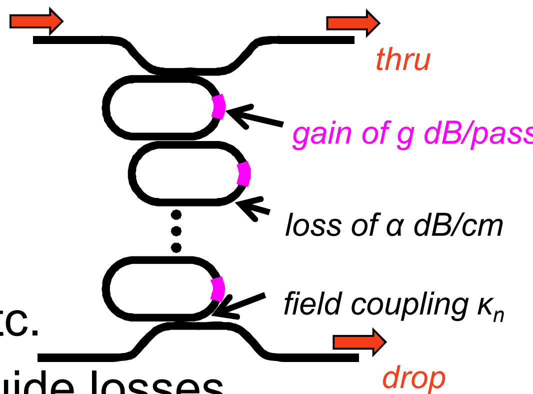




"InP Tunable Ring Resonator Filters", Photonics West 2012

Design of Active Ring Filters



- Active ring resonators offer:
  - Compact size
  - Low, or zero, back reflection
  - Monolithic integration with lasers, modulators, SOA, etc.
  - Gain elements can be used to compensate for waveguide losses
- Design Considerations:
  - Bandwidth determined by:
    - Coupler strength and optical loss
  - Filter profile defined by:
    - Coupler strengths and number of rings and internal net loss
  - Extinction ratio influenced by:
    - Noise from optical amplifiers and optical loss
  - Tunability affected by:
    - Size of tuning section and induced loss

  → Loss, couplers, and optical gain needs to be tightly controlled

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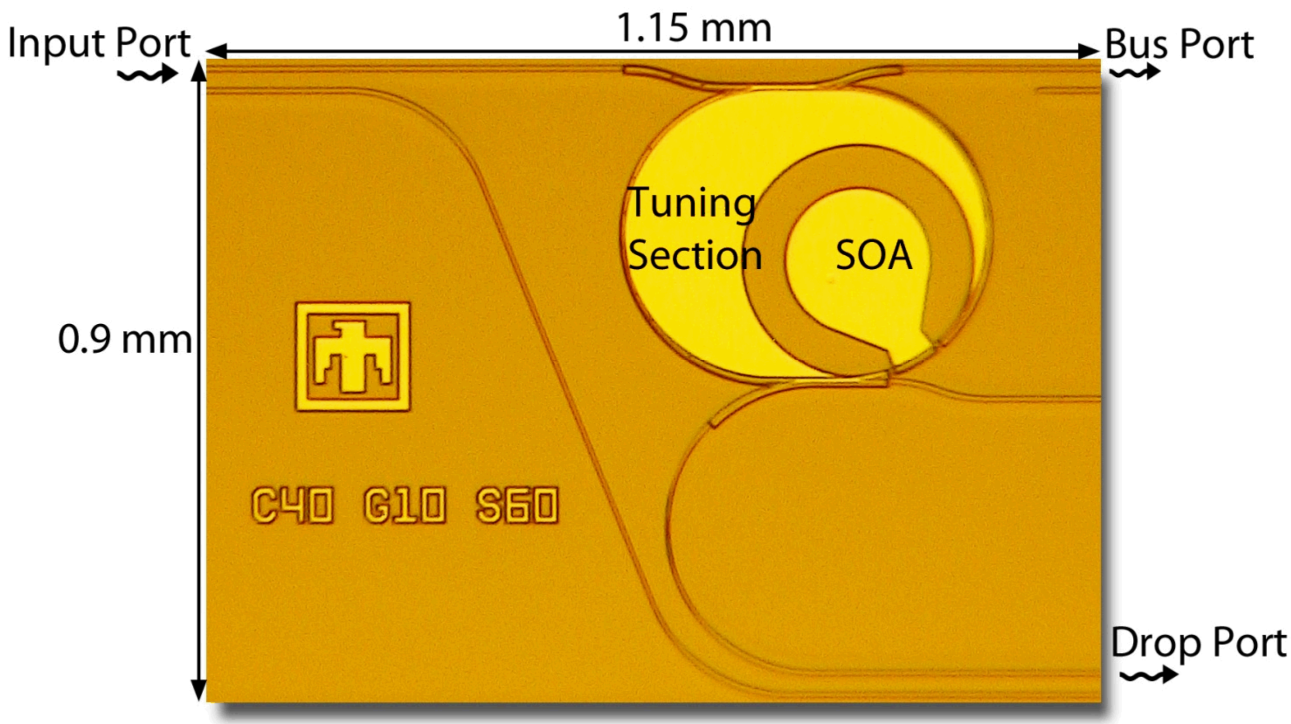
Approach



- Couplers designed for 1-2 GHz linewidth
  - Fractional coupling power of 6% for both couplers
- Integrated 60-µm-long SOAs in the ring
  - Minimize loss through filter
  - Length and total gain designed for low noise
- Tuning section
  - Current injection

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Monolithic Integration Platform

- Quantum well intermixing
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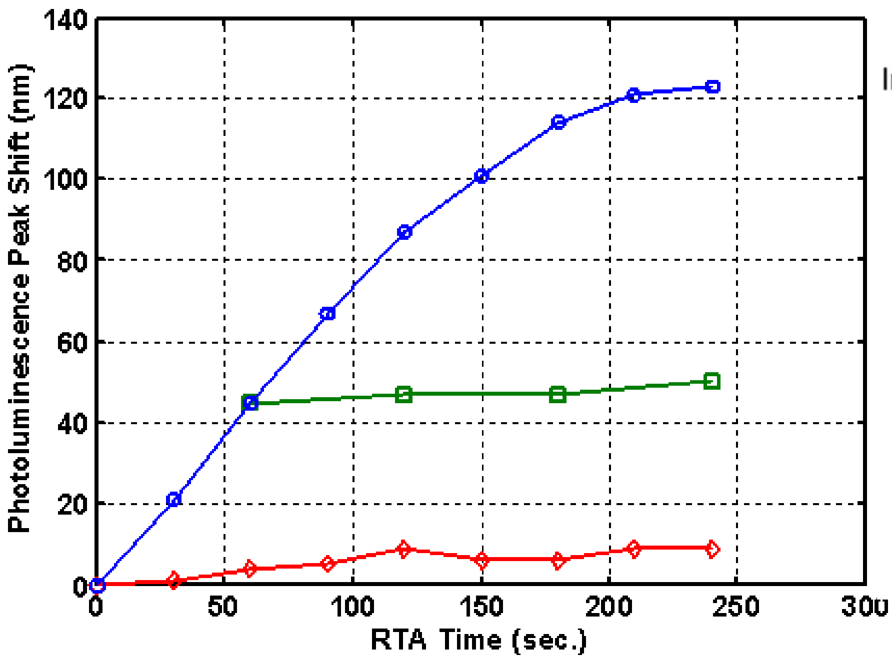

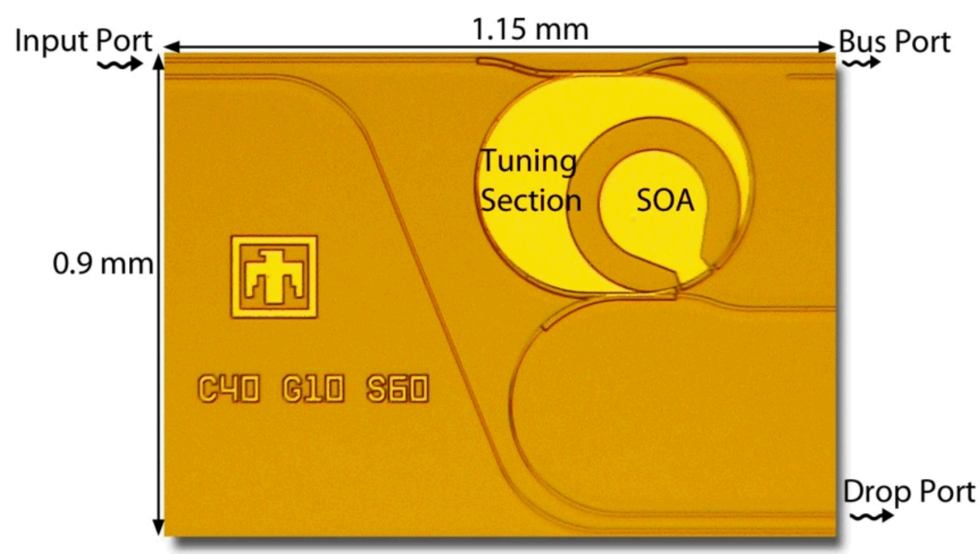

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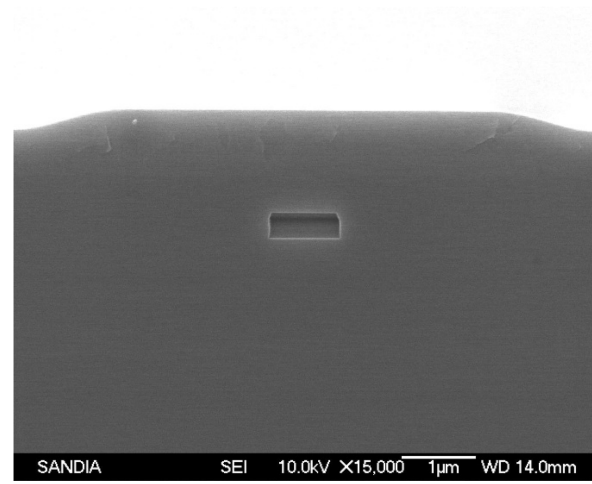
Buried Heterostucture Waveguides

- Waveguide definition process
  - Stepper lithography
    - 0.6 µm resolution
  - Dry etch
  - MOCVD Regrowth
    - InP cladding
    - InGaAs contact layer
- Buried heterostucture advantages
  - Waveguide thickness defined by epitaxial material
  - Semiconductor etch only defines guiding width and coupler gap
  - Devices are essentially not affected by variations in etch depth

Waveguides in [011]



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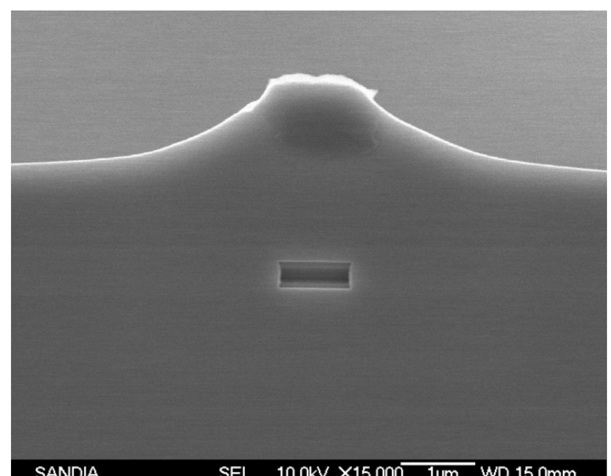

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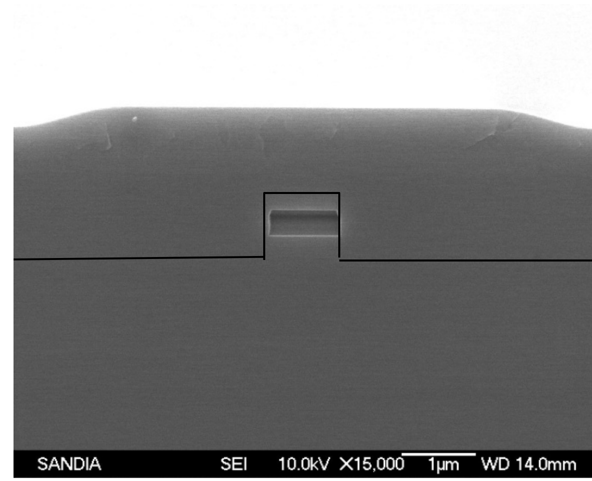

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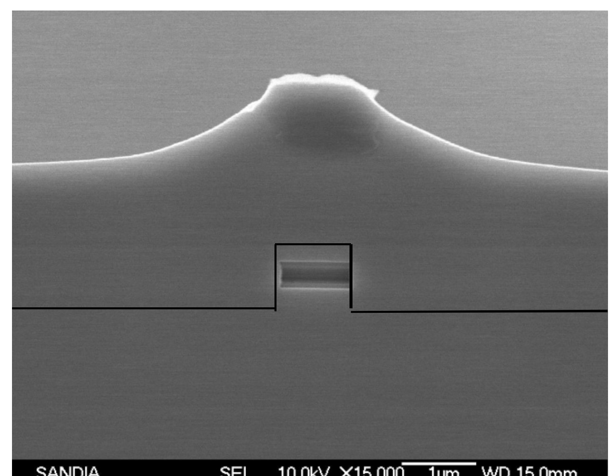

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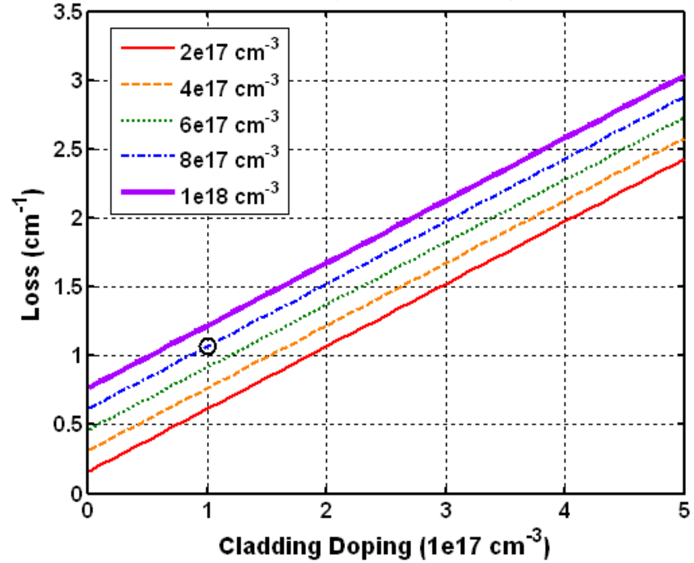
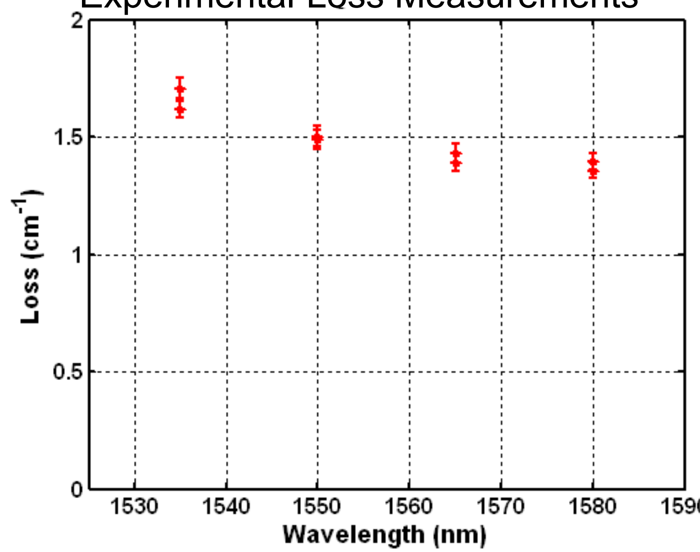
Low Loss Waveguides

- Low loss waveguides
  - Loss and coupling define the bandwidth of the filter
- Scattering and Absorption Loss
  - Modal overlap with InP p-type doping regions is a major source of loss
    - 500 Å doping spike at the regrowth interface
      - Compensates for Si contamination at the regrowth interface
    - Doping of the regrown p-type cladding
  - Waveguide loss was measured using Fabry-Perot cavity measurements
    - 1.5 cm^{-1} at 1550 nm

Simulated p-type Doping Loss

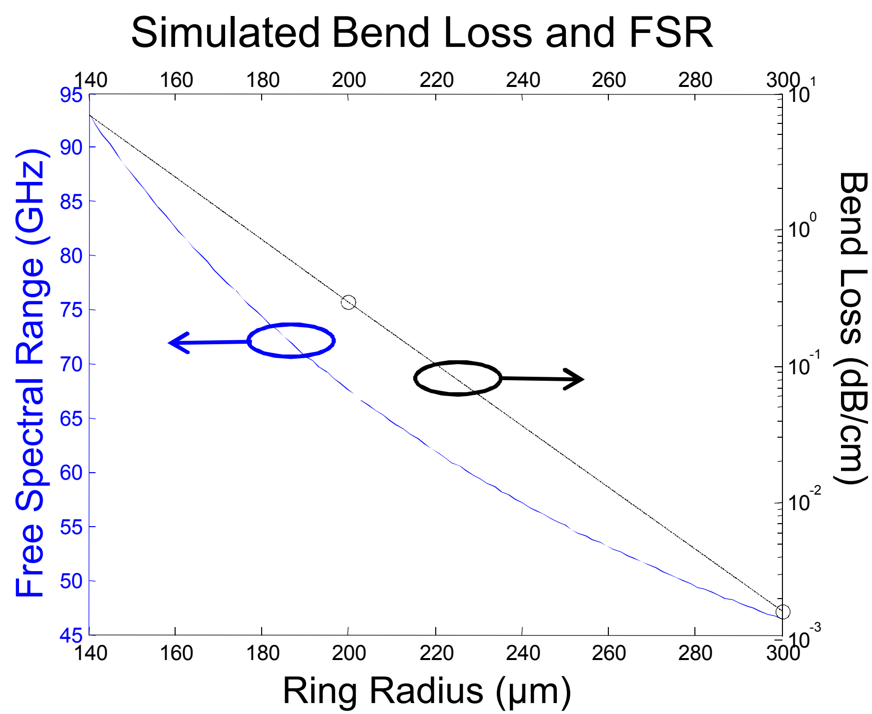


Experimental Loss Measurements



Low Loss Waveguides: Bend Loss

- Low loss waveguides
  - Loss and coupling define the bandwidth of the filter
    - Output coupling and waveguide loss
- Bend loss
  - Tradeoff between loss and FSR
  - 200 μm radius for 1 μm waveguide width



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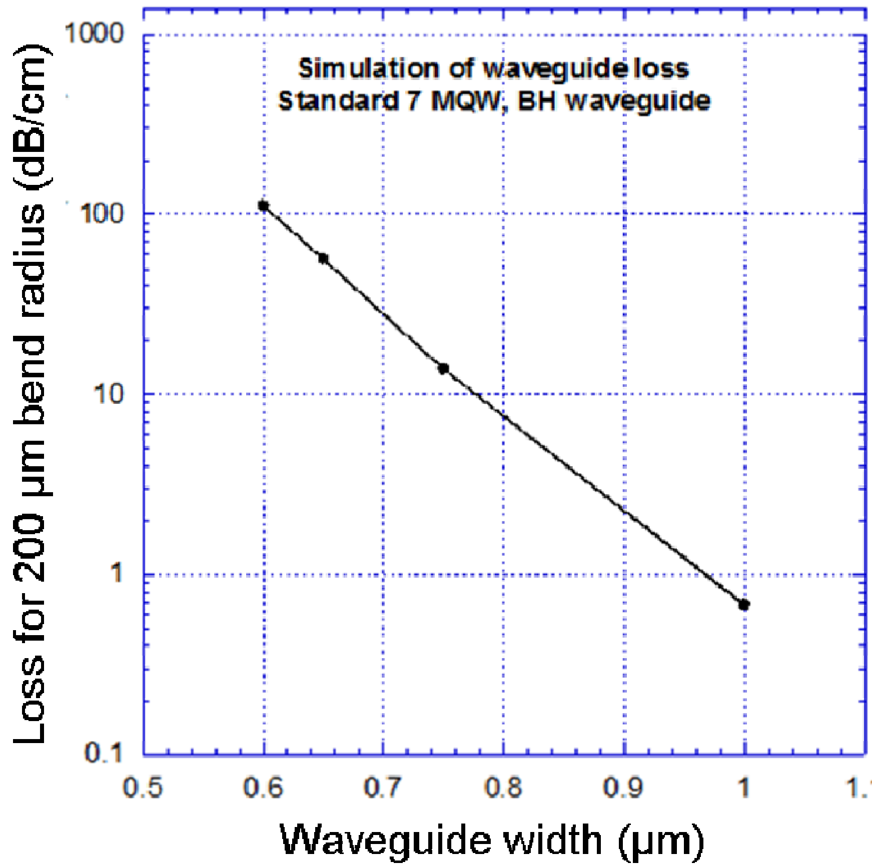
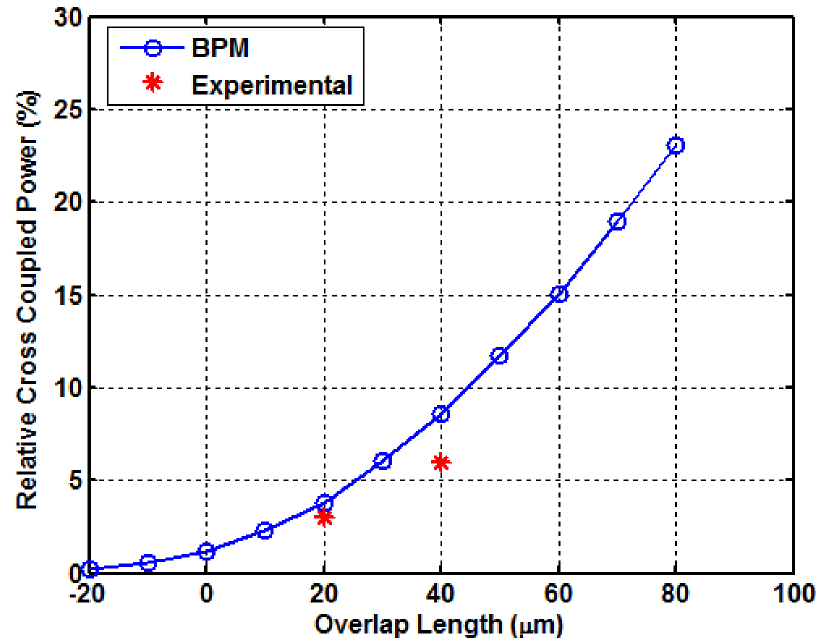
Low Loss Waveguides: Bend Loss

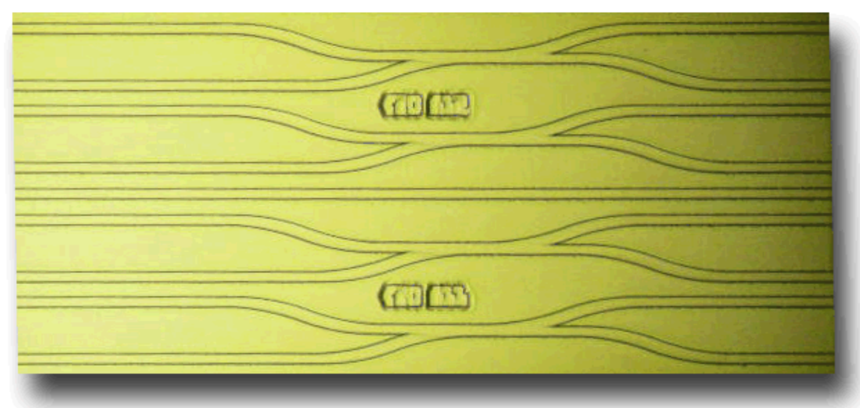
- Waveguide width is very important to bend loss
- Lithographic bias can significantly affect bend losses
  - Projection lithography/stepper used
  - Dimensions verified by CD SEM measurements
    - Monitors bias drift over time
    - Done before waveguide etch allowing for rework.



Couplers

- Coupler design
  - Couplers utilize 1 μm waveguides with 1 μm gap
  - Coupling defined by length overlap region
  - Lithography biases are constant
  - → Consistency in coupler values within and between process runs
- Simulations used to predict coupling
  - BPM simulation
    - Includes waveguide bends
  - Experiment shows lower coupling than predicted by BPM
    - Waveguide widths and gap has a bias due to fabrication





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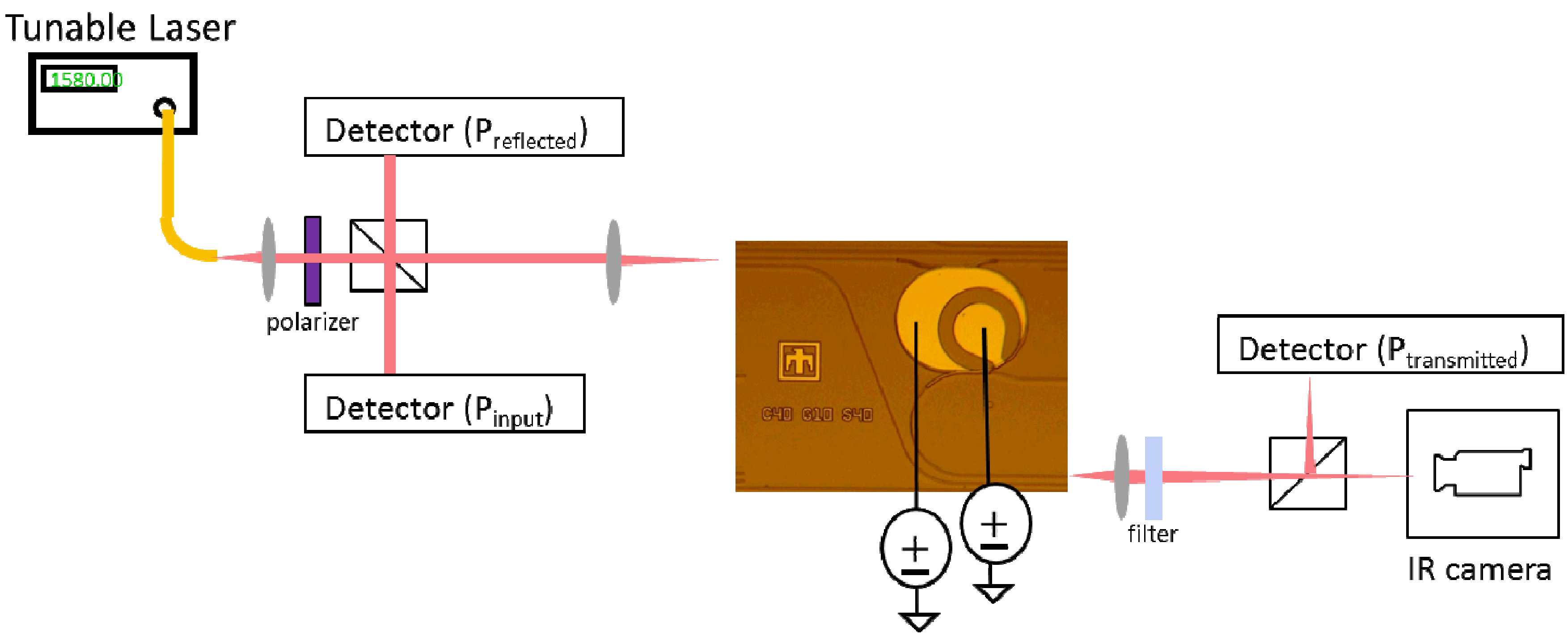
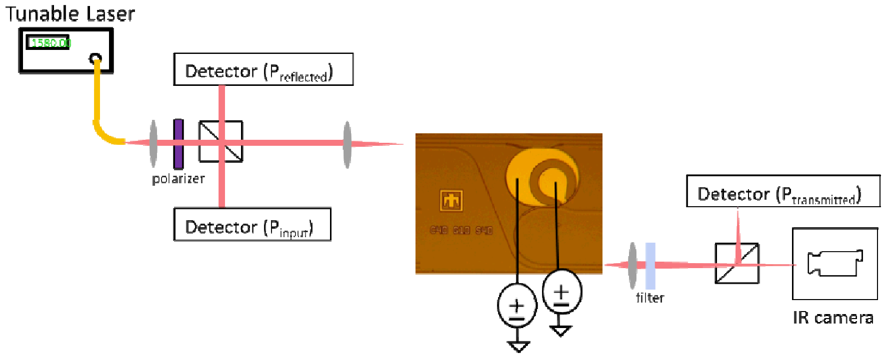
Experimental results

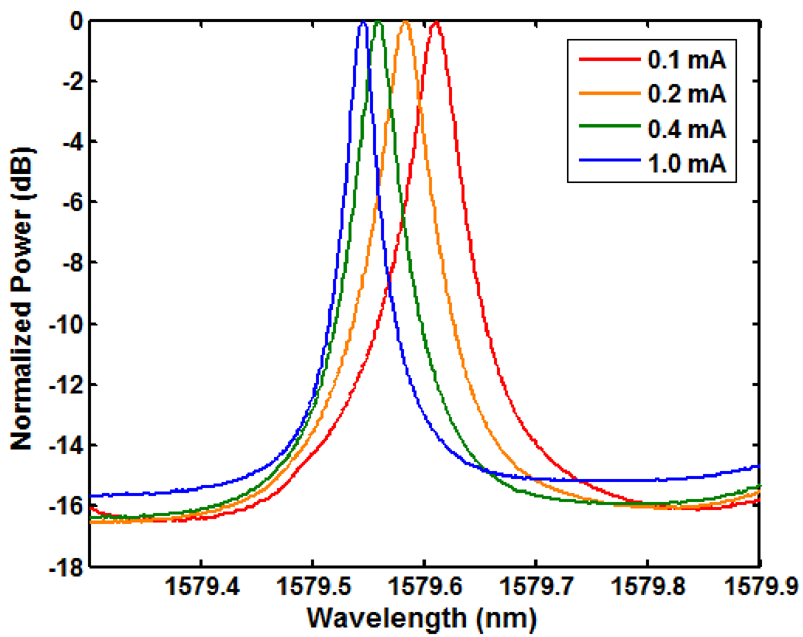
- Scanning source measurement
  - Wavelength swept on a tunable laser source
  - 12 nm filter added to the ring output
    - This filters out much of the amplified spontaneous emission (ASE) from the SOA

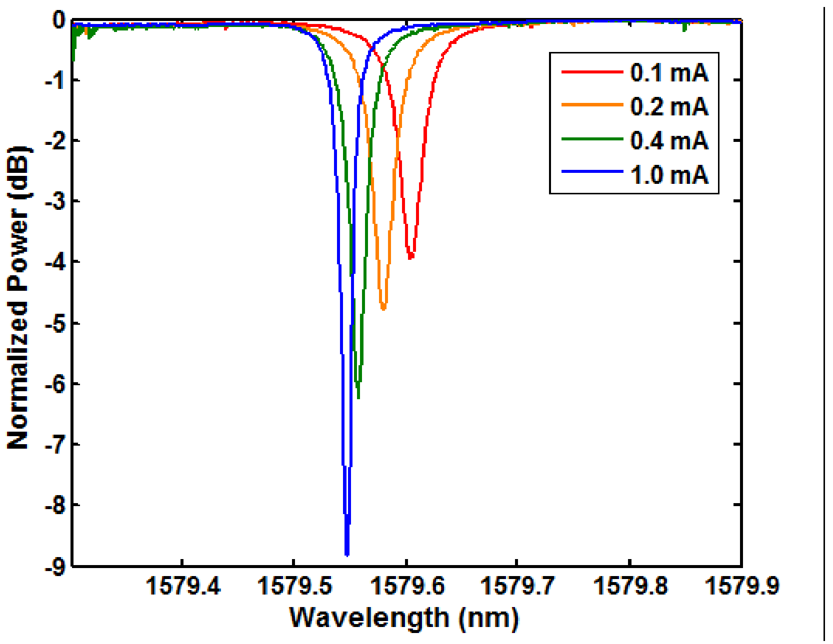


Experimental results

- Scanning source measurement
  - Variation in SOA current from 0.1-1.0 mA
  - >15 dB extinction
  - 3.5 GHz to 2.2 GHz FWHM optical linewidth







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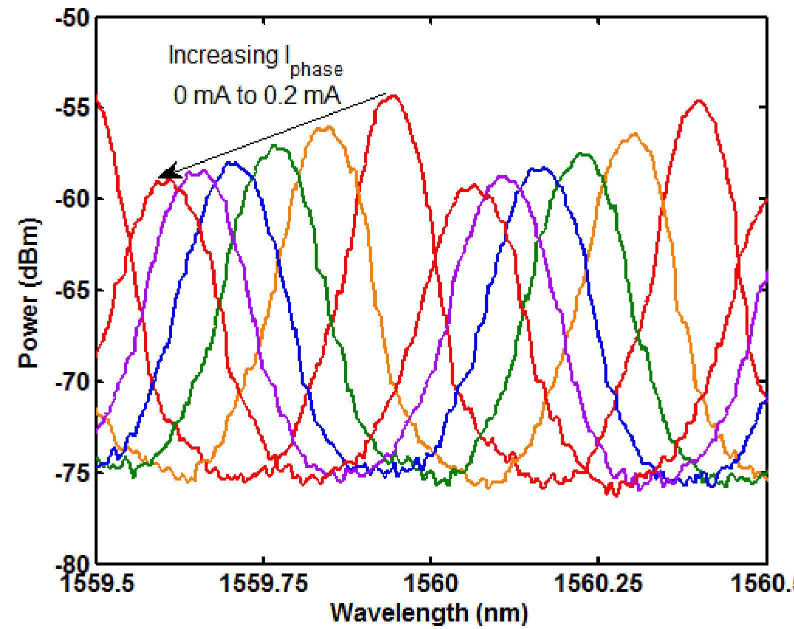
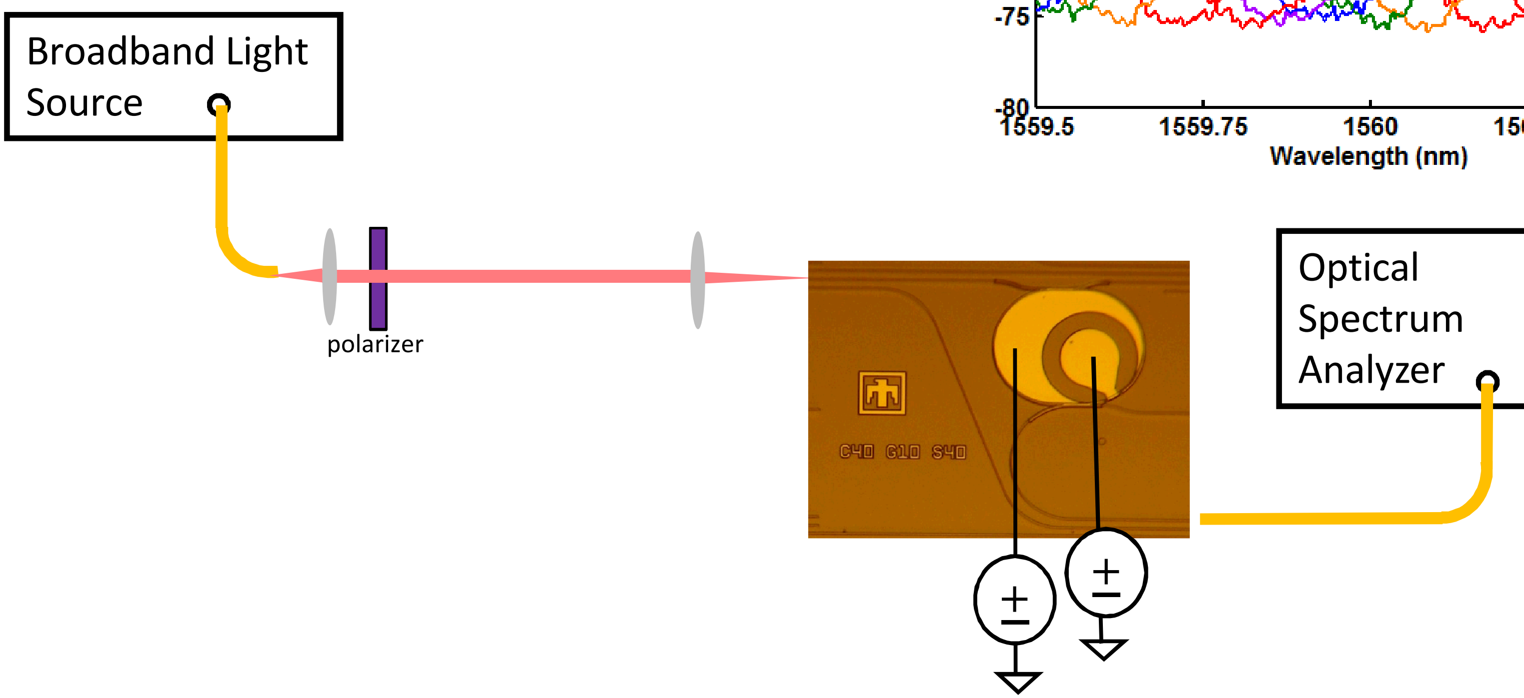
Experimental results

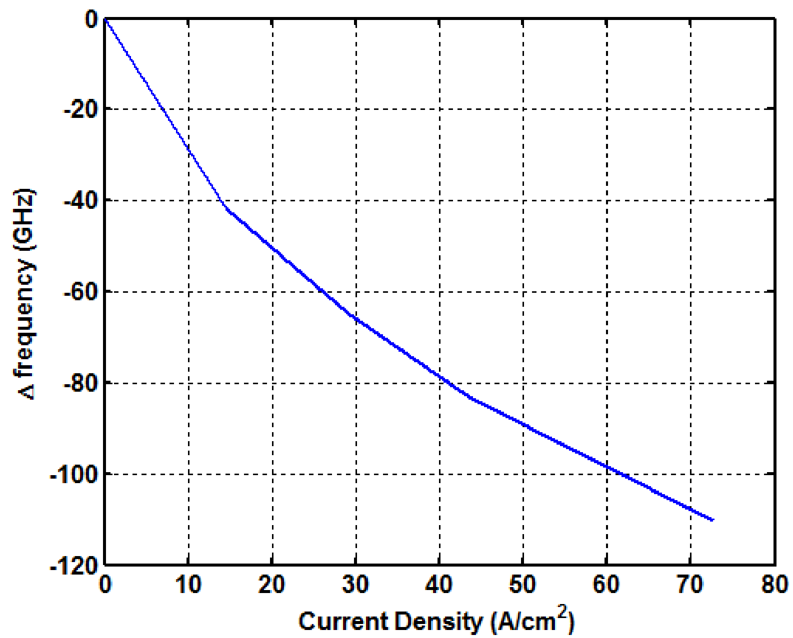
- Optical spectrum analyzer measurement
  - Broadband light source
  - Ring output fiber coupled to OSA
  - Better for larger wavelength scans
  - I_{SOA1} = 2 mA
  - Extinction ratio of >15 dB

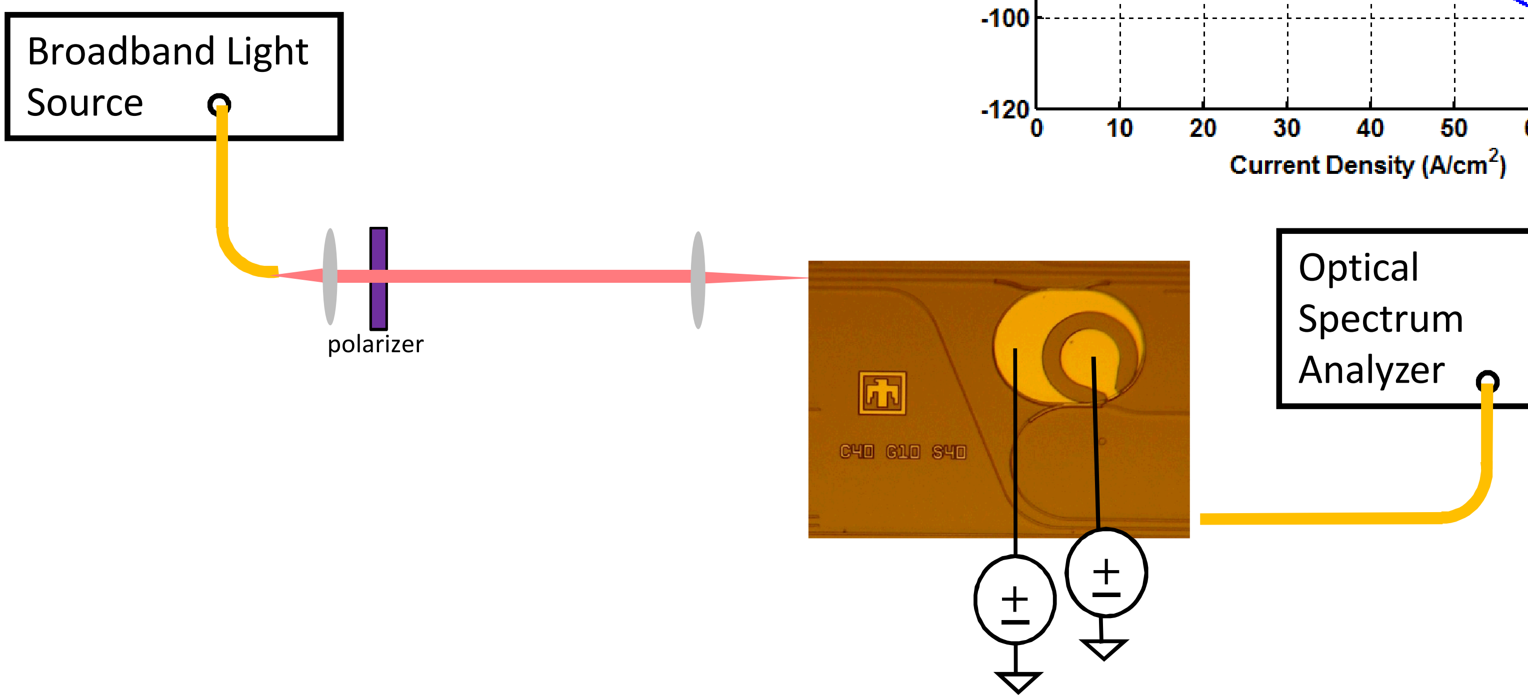




Experimental results

- Optical spectrum analyzer measurement
  - Broadband light source
  - Ring output fiber coupled to OSA
  - I_{SOA1} = 2 mA
  - Extinction ratio of >15 dB
  - 110 GHz with I_{Tune} = 1 mA
    - Nearly twice the free spectral range





Experimental results

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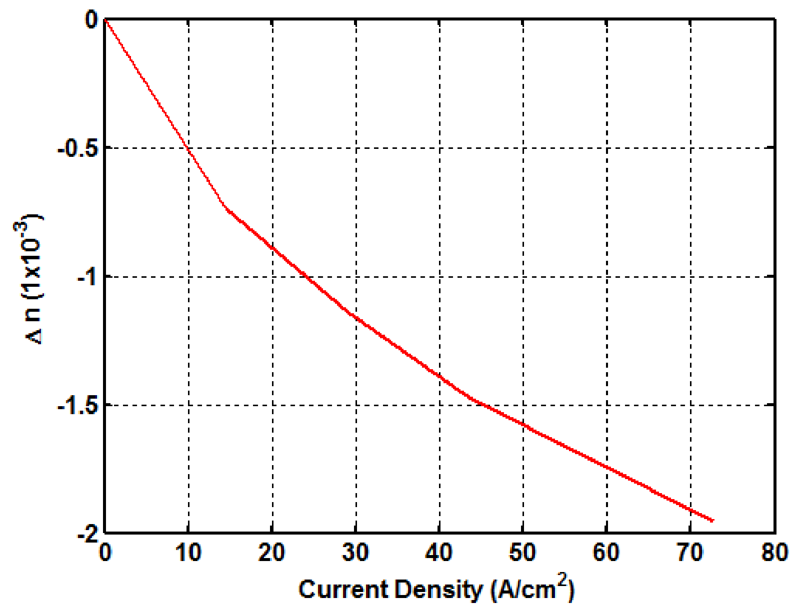
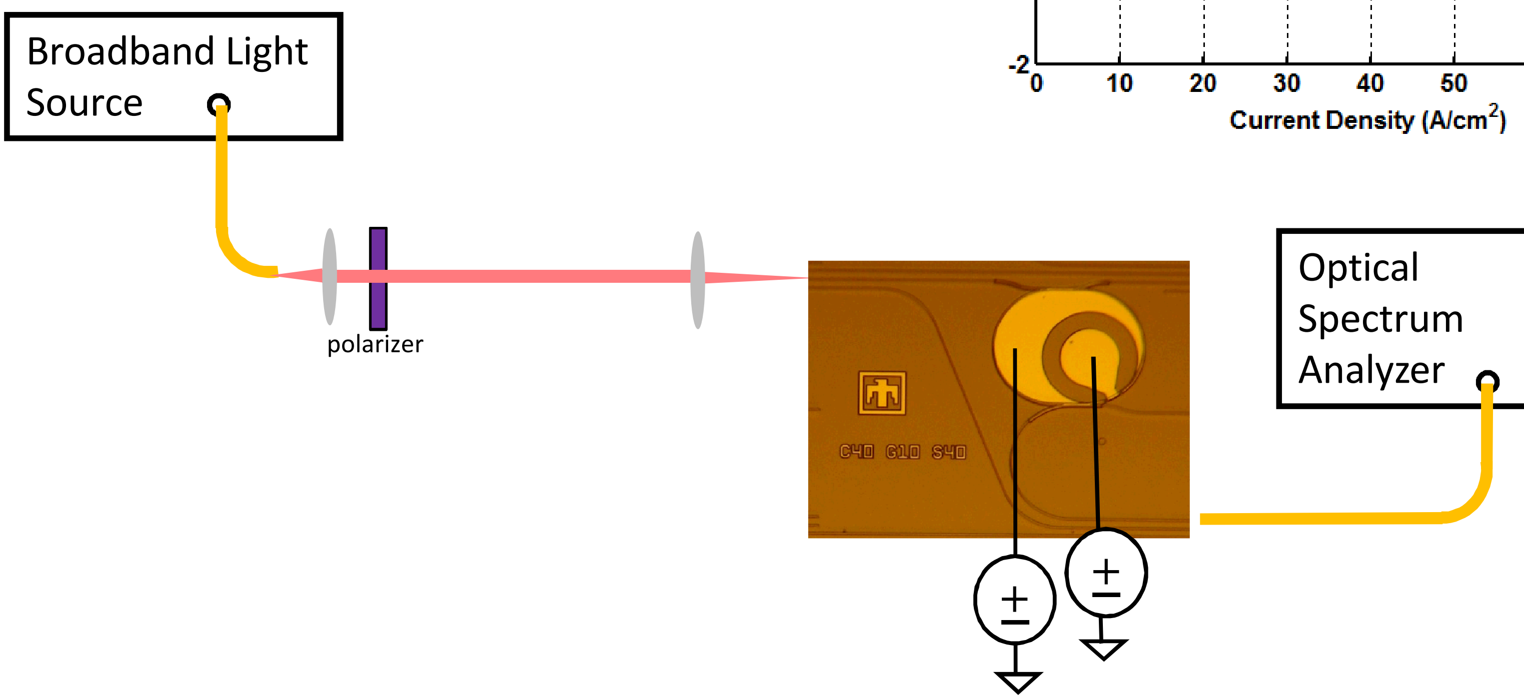
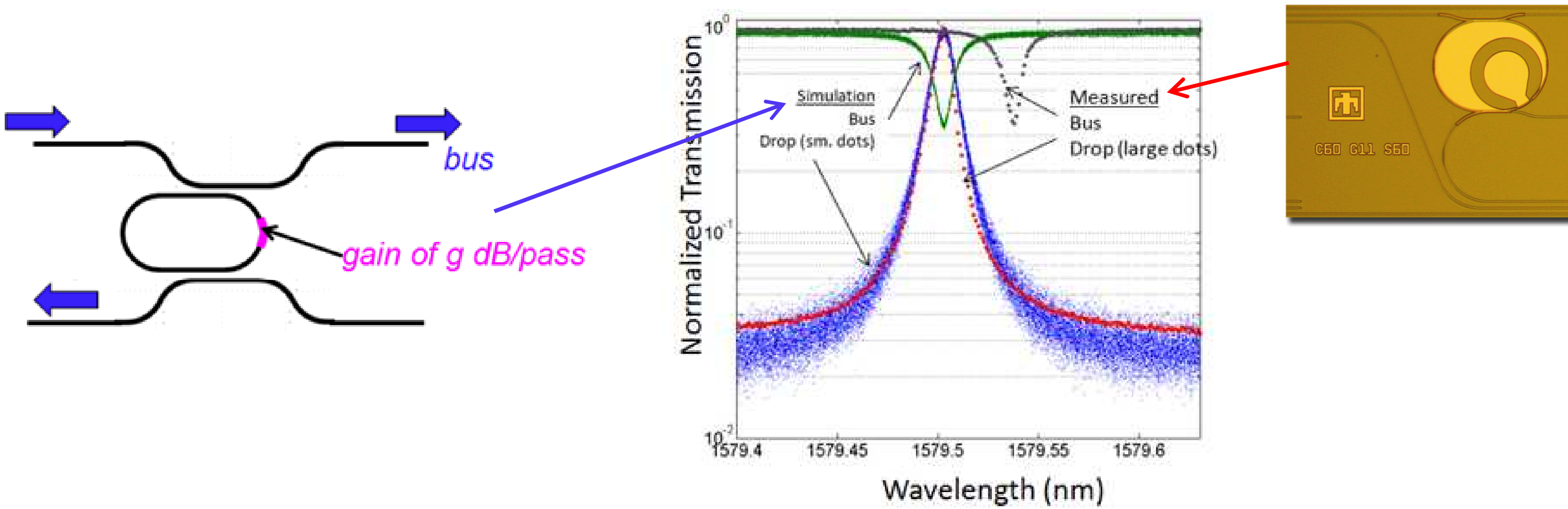




Simulation: Calibration



- Complete simulation of dynamic range and noise of active InGaAsP multi-ring filters
  - Include gain distortions and spontaneous emission noise
- Time dependent rate equation method
  - Gain and spontaneous emission modeled as function of injection current at all wavelengths simultaneously
- Fit experimental bandwidth of drop and extinction of bus to extract net round trip loss and coupling fraction
  - 6% coupler with 1.4 cm^{-1}

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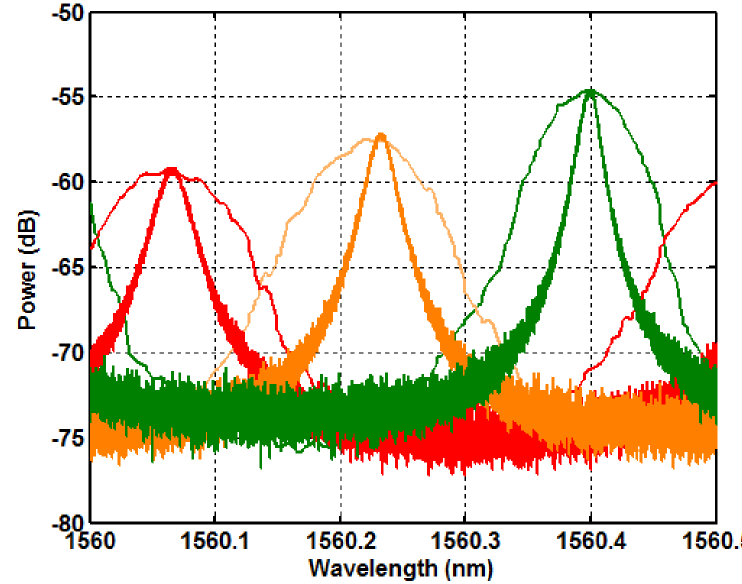
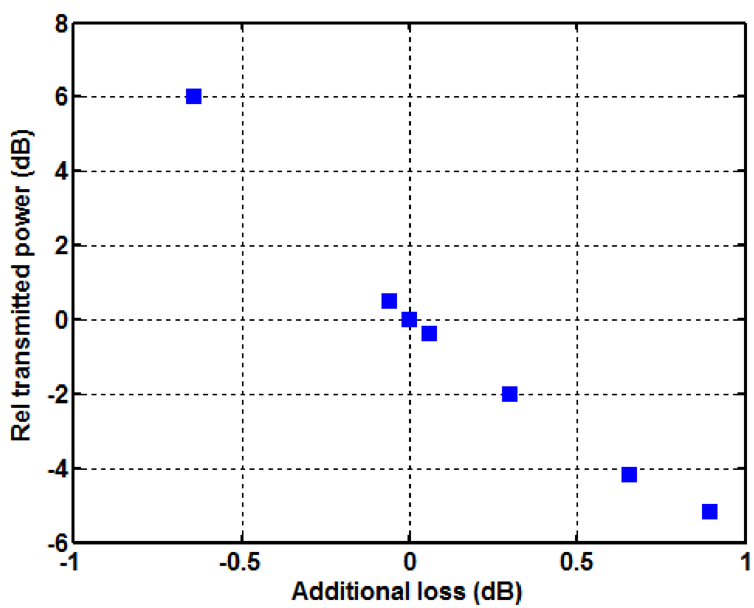
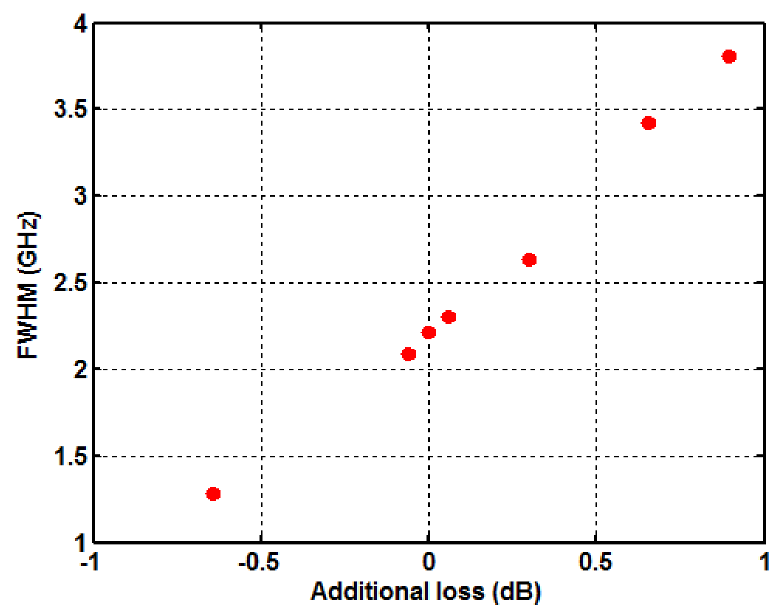
Simulation: Tuning Current Loss

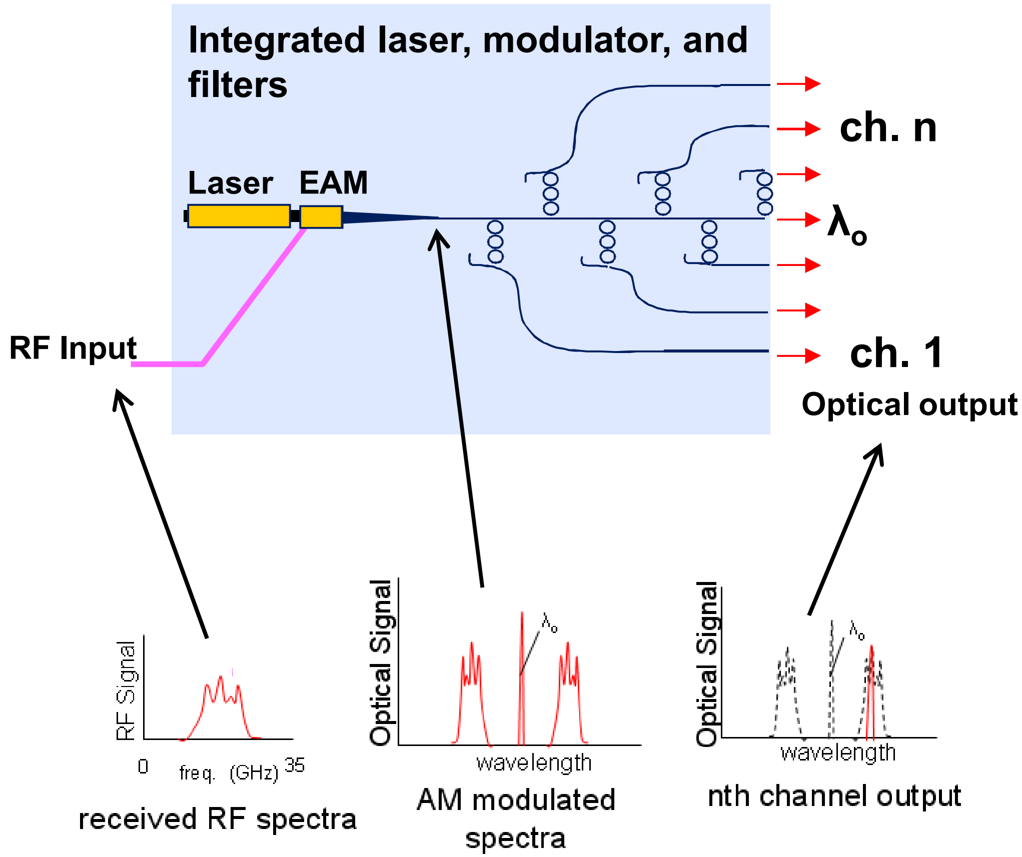
- Tuning and loss from benchmarked from filter tuning data
- Effects of tuning induced loss on FWHM linewidth
- 0.9 dB of additional loss caused by tuning current
  - reduces peak power 5 dB
  - Increase FWHM by 1.6 GHz
- Loss can be compensated by increase in SOA gain





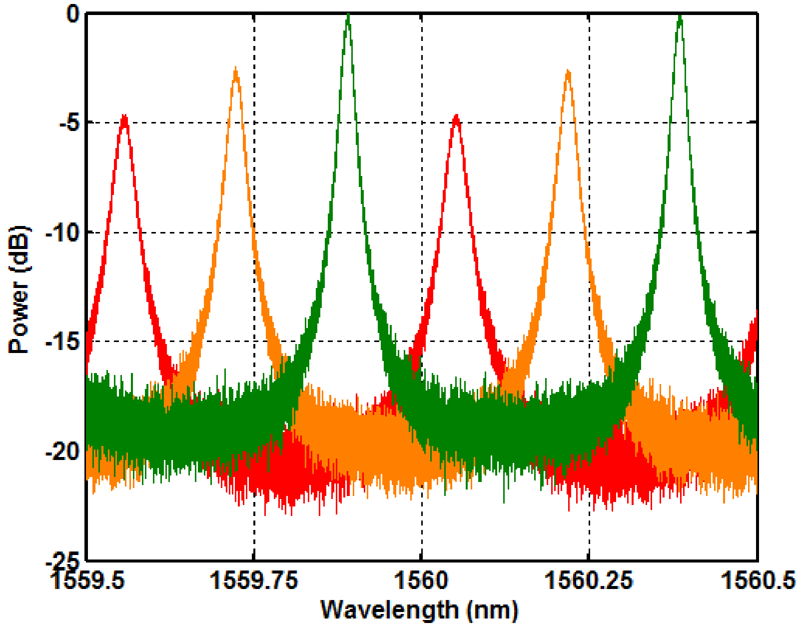


Motivation

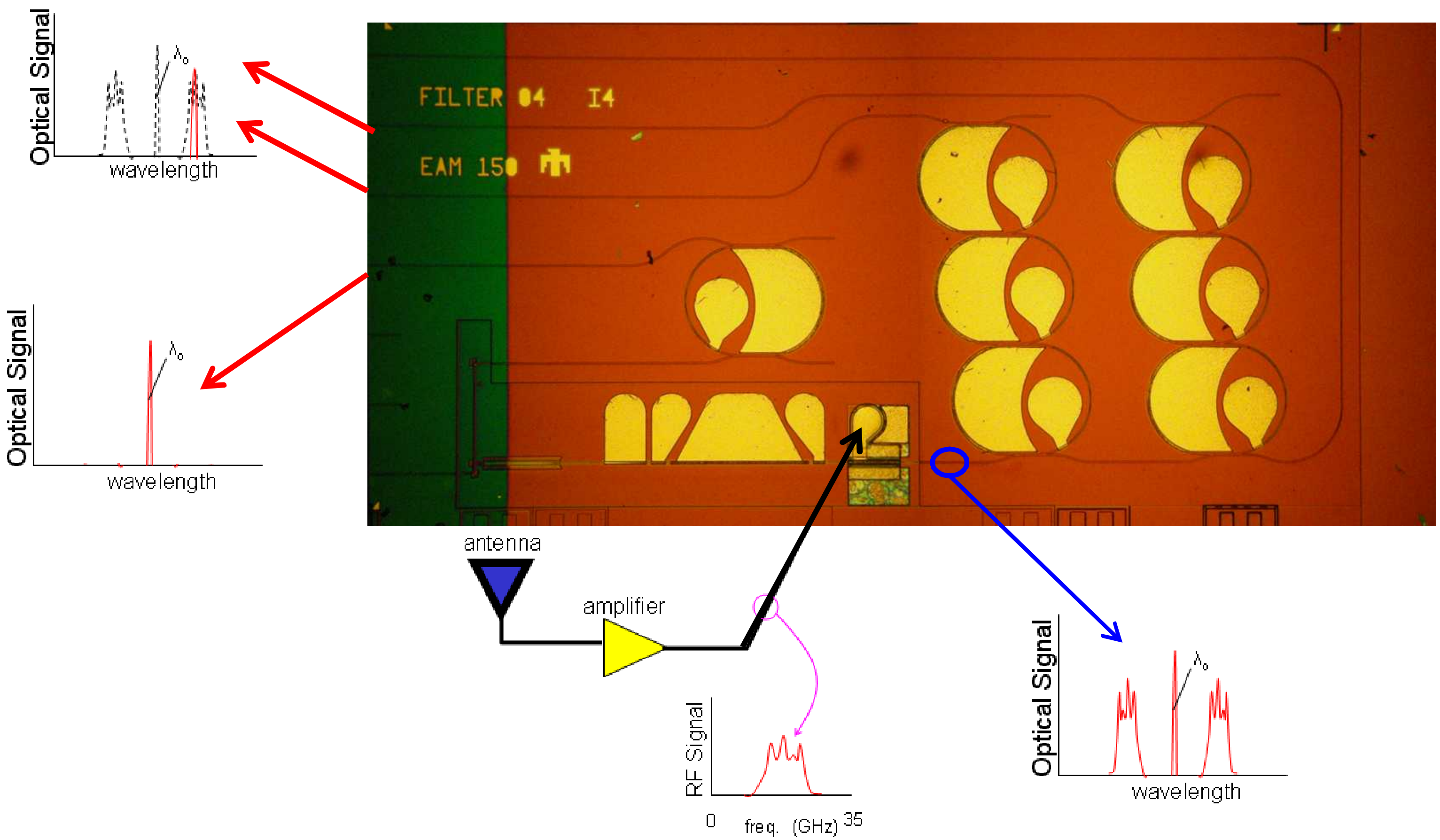


- Analyze an RF signal for frequency content
  - Filter outputs are spectral power density integrated over the filter bandwidth
- Monolithic integration with active components such as lasers and modulators enables compact, highly functional photonic integrated circuits (PICs)

Simulation benchmarking



Monolithic RF Channelizing PIC



- Channelize RF signals for further analysis
- Monolithic integration enables compact, highly functional photonic integrated circuits (PICs)
- Tunable filters enable accurate placement across the frequency band

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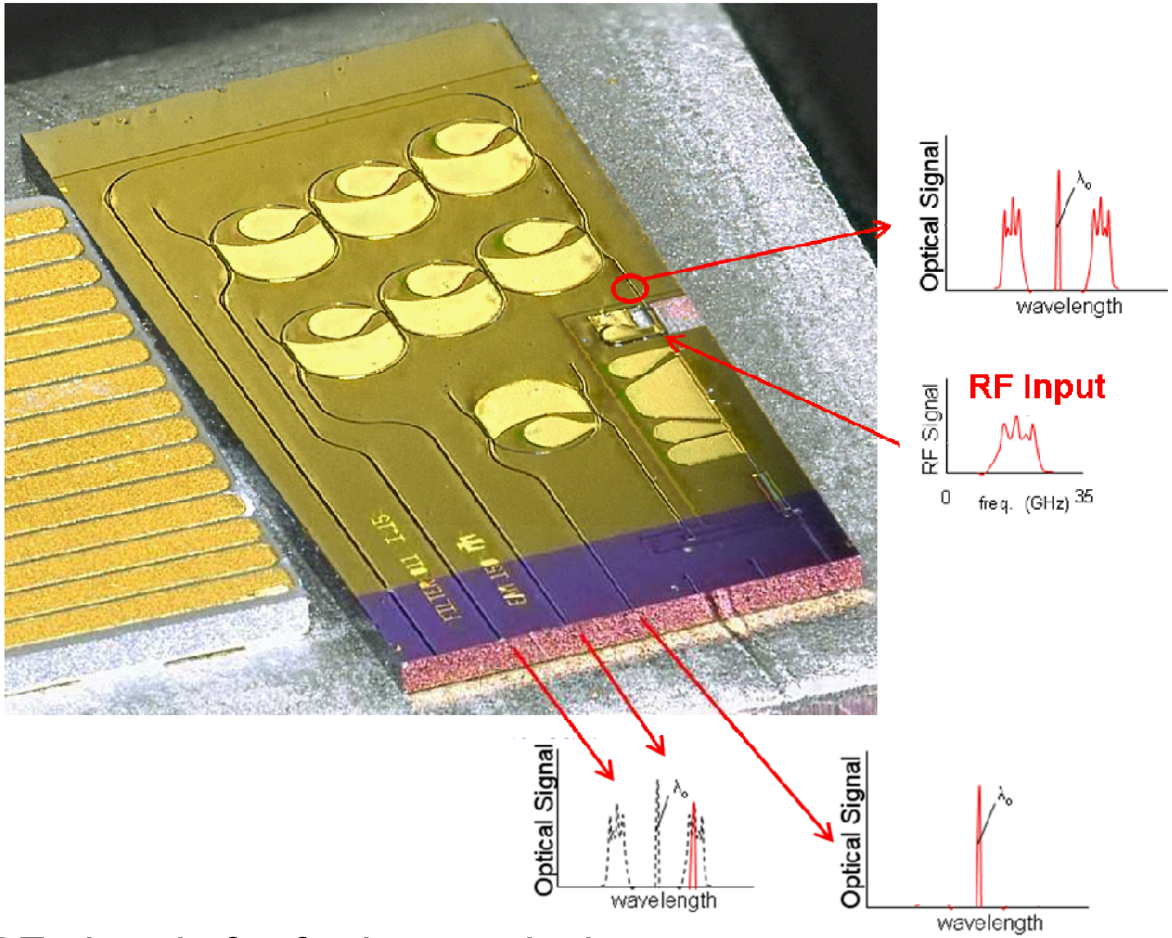
Monolithic RF Channelizing PIC



- Channelize RF signals for further analysis
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- Tunable filters enable accurate placement across the frequency band

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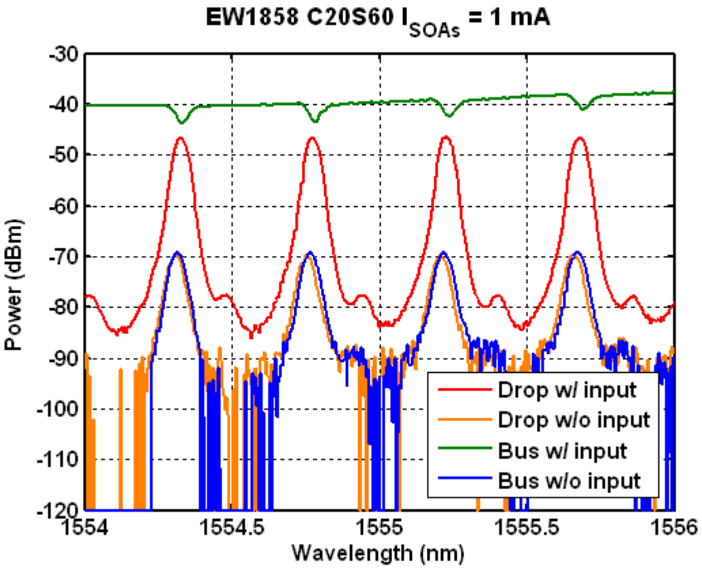
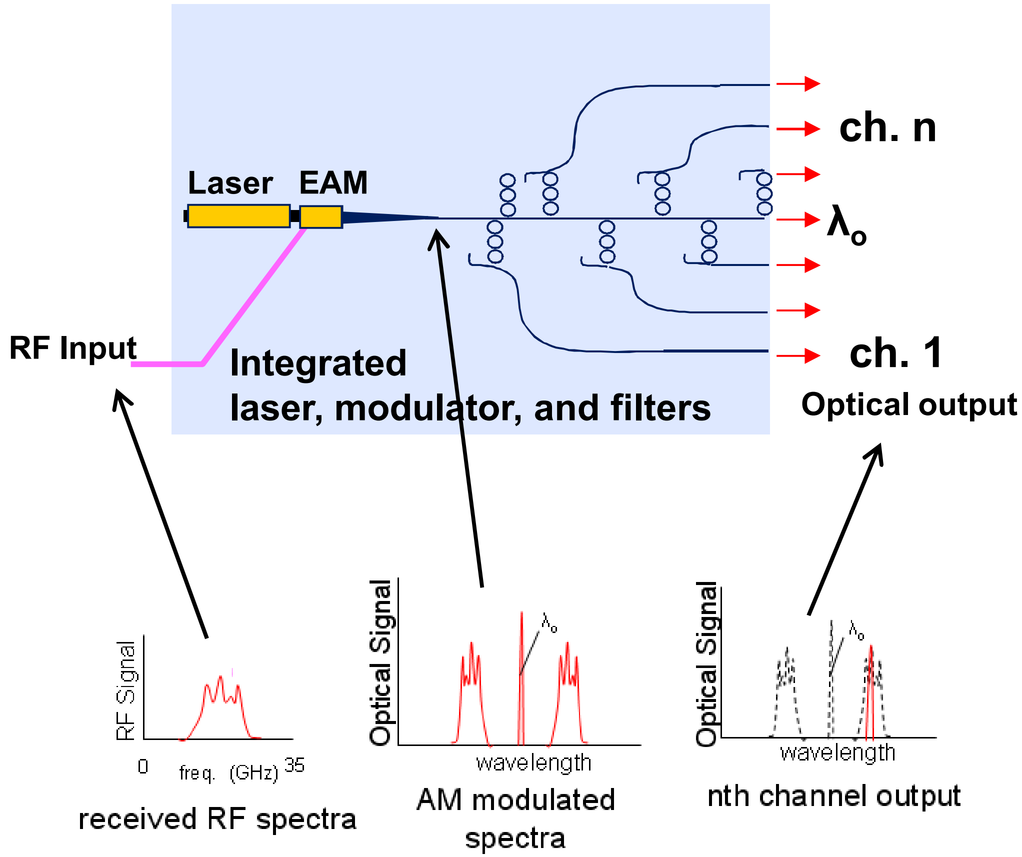
InP Active 2-ring Filter

need bigger font on fig

- ASE source and OSA
  - Higher extinction
    - SOA-ASE goes is correct wavelength 'bin'
- Tunable laser and photodiode
  - Lower extinction
    - off resonance measurement includes SOA-ASE from all wavelengths
  - A filter (~5 nm) will give results similar to OSA
    - This can be external for testing
    - On a monolithic chip we need to add additional filtering



Channel-Dropping Filters



- Analyze an RF signal for frequency content
  - Filter outputs are spectral power density integrated over the filter bandwidth
- Monolithic integration with active components such as lasers and modulators enables compact, highly functional photonic integrated circuits (PICs)

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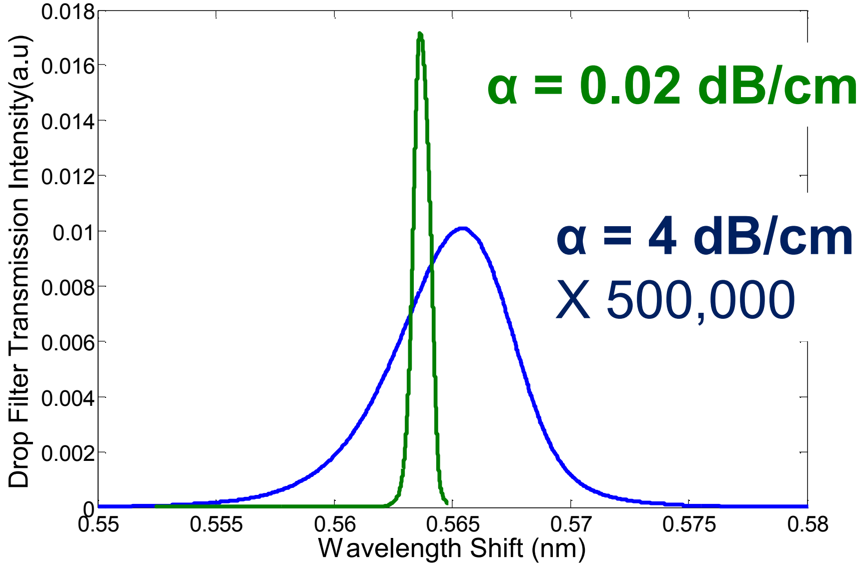
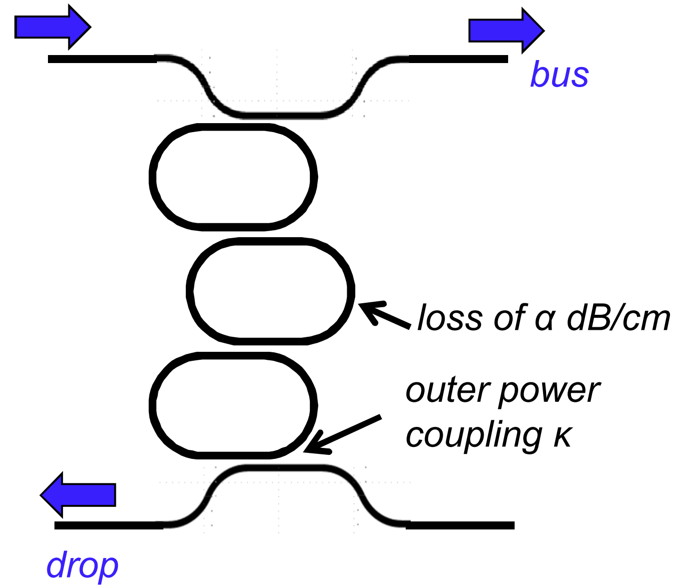
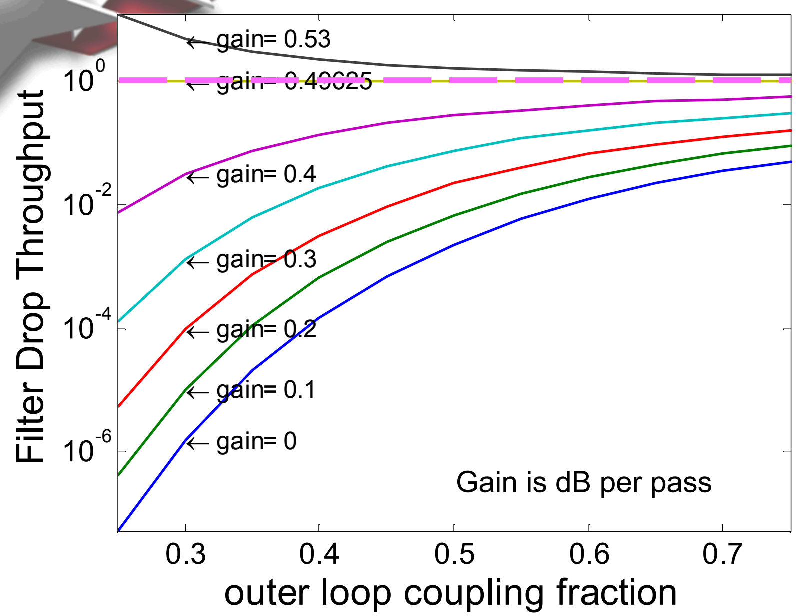
Monolithic Integration and Loss-Limited Filter Response

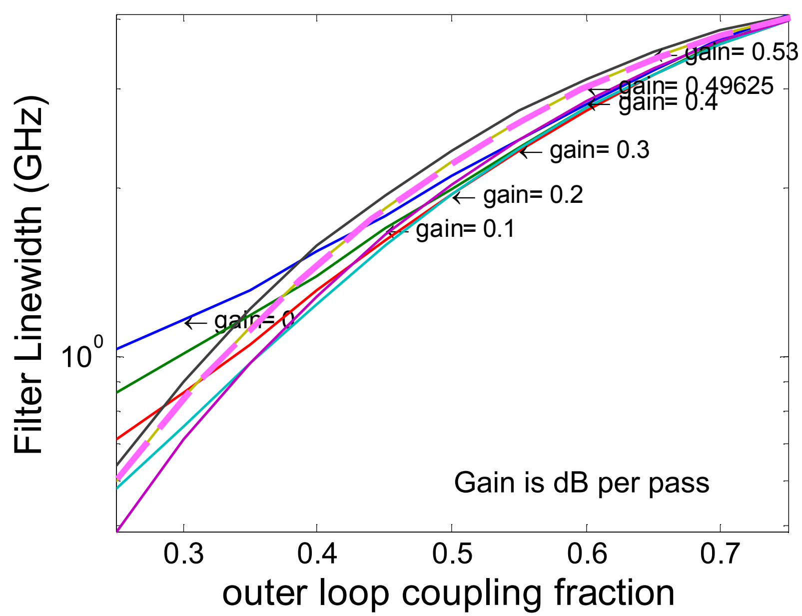


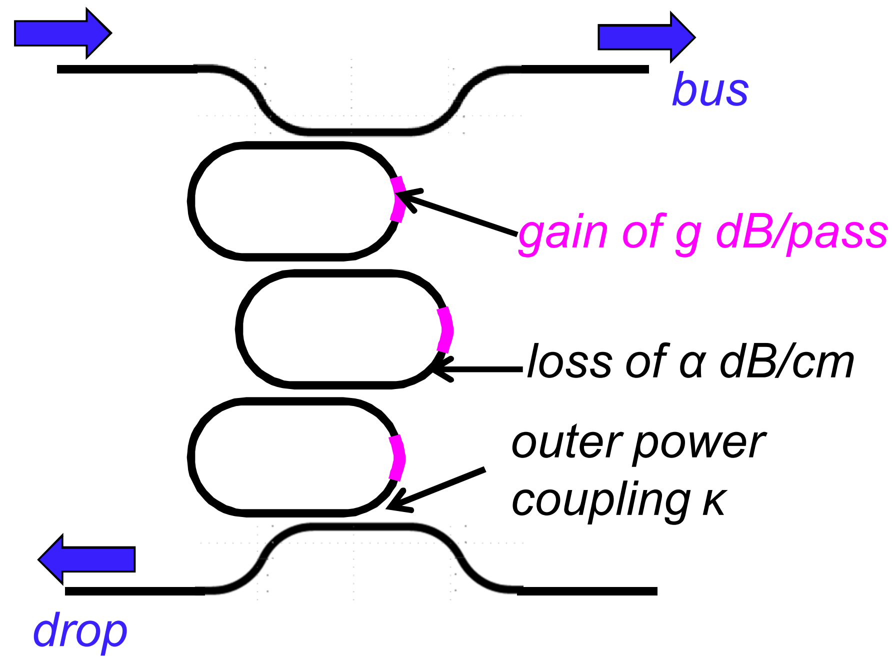


- Optical waveguide losses dominate the filter performance
- Useful passive ring resonant filters are typically made of glasses or undoped semiconductors with very low optical loss.
- Ring Filters with losses commonly seen in doped InGaAsP waveguides for active PICs have too little optical transmission to be useful as GHz-class filters

A Small Amount of Gain Offsets Losses







- SOAs enable monolithic integration
- Introduce an ideal loop gain to each filter
  - No noise in model, yet
- Ring waveguide loss
  - 4 dB/cm
- Loss-less filter achieved
  - 0.5 dB/pass gain element

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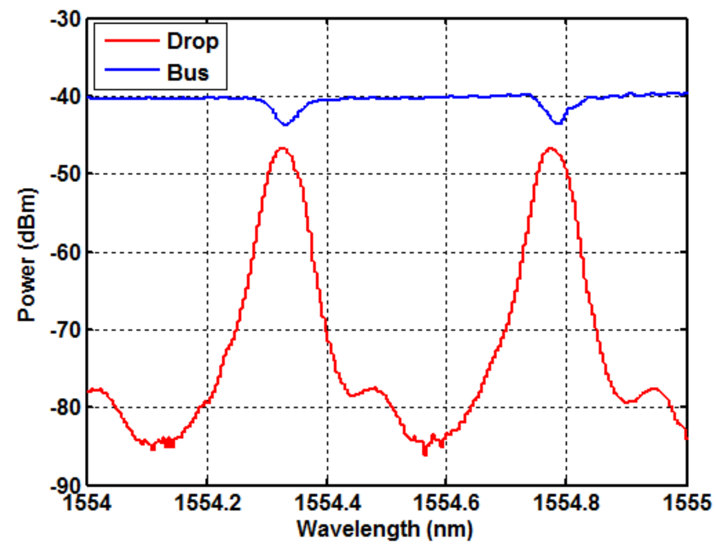
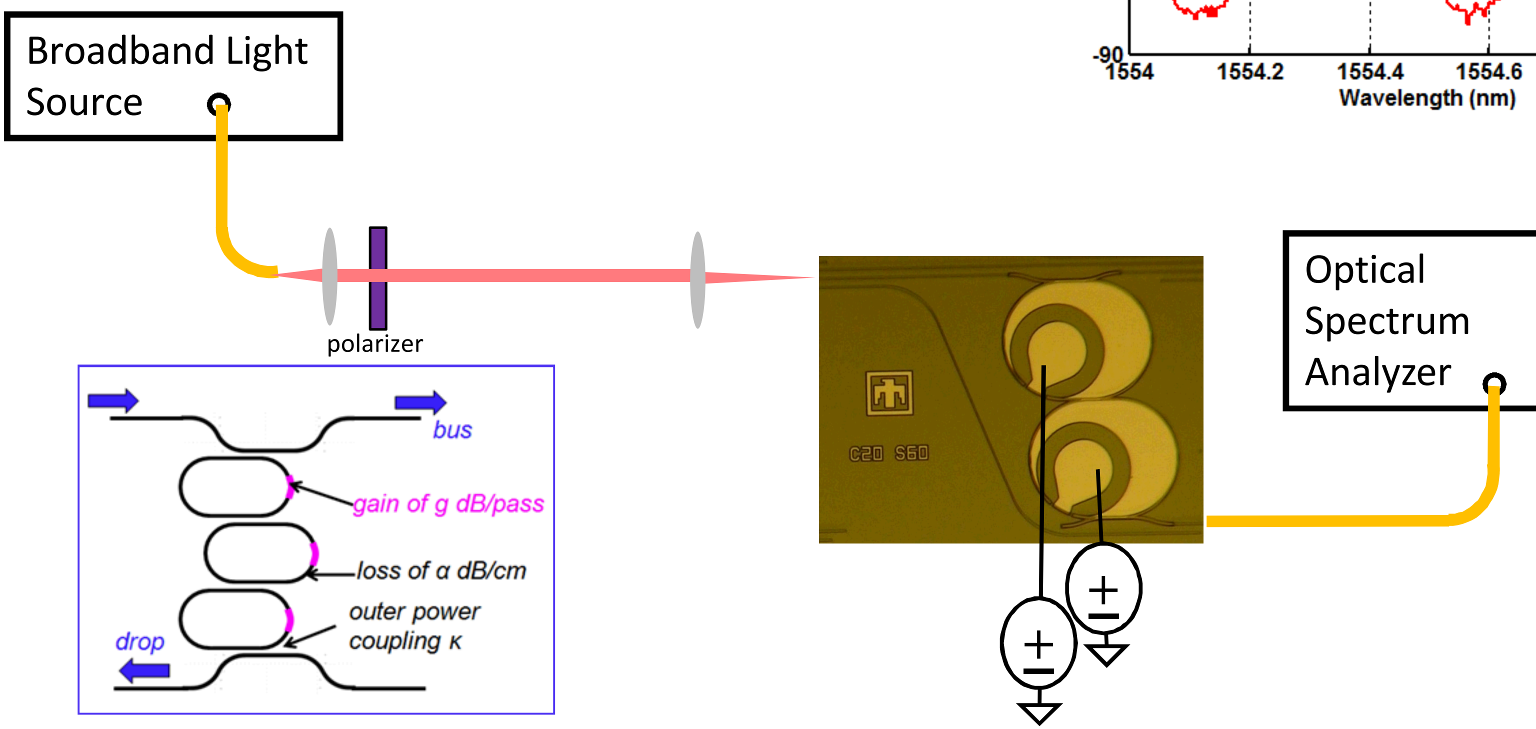
Active Rings : Experimental

See paper OThW2 Thur. @ 4 pm

- Dual-ring filters
  - > 30 dB extinction ratio
  - 2.5 GHz linewidth
  - $I_{SOA1} = I_{SOA2} = 1$ mA
  - Extinction ratio of >30 dB
  - Filter loss of 1.7 dB
    - Loss defined as total power on resonance compare to total power off resonance
- OSA measurement
  - Broadband light source





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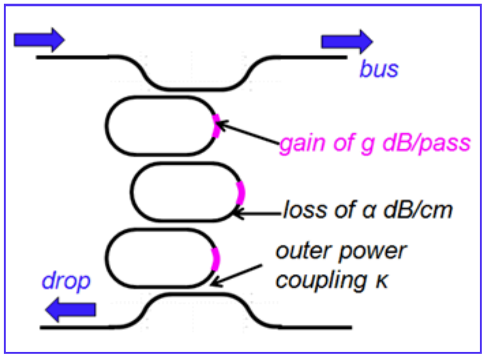
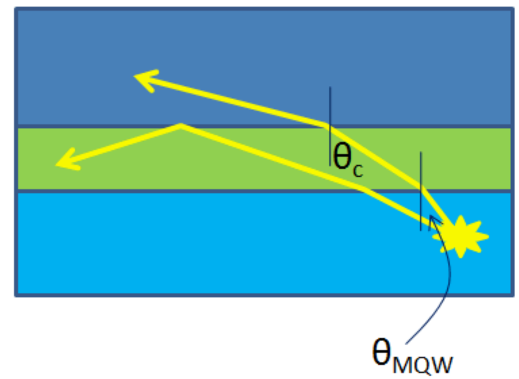
Active filter modeling



- Time domain travelling wave model of single and multi-ring filters
- Semiconductor Optical Amplifier (SOA) embedded in each ring
- Local gain and spontaneous emission modeled as functions of injection current and optical power
  - Time-dependent rate-equation approach
- Complete power spectra computed at each time step

Fraction of SOA spontaneous emission coupled into waveguide mode

- Amplified spontaneous emission (ASE) noise from SOAs creates a noise floor on filter spectra
- ASE noise computation in two steps
  - Spontaneous emission recombination event
  - Coupling of spontaneous emission into guided mode of ring
- The spontaneous emission factor influences the noise floor due to ASE



- Indexes
  - InP , n= 3.168
  - Q13, n = 3.3877
  - MQW, n = 3.427
- Included angle of captured light
  - 44.8 deg
- Area of spherical cap
  - Acap=2πrh
  - H = r(1-cosθ)
- Area of sphere
  - Atotal = $4\pi r^2$
- Fractional area
  - Acap/Atotal = (1-cosθ)/2
  - θ=22.4 deg
  - Fractional area = 0.0378
- Fraction of light capture by guided mode
  - Multiply fractional area by overlap integral with guided mode
  - Γ (fractional area) = 0.06989x0.0378 = 0.00264
- SponBetaNA = 0.00264

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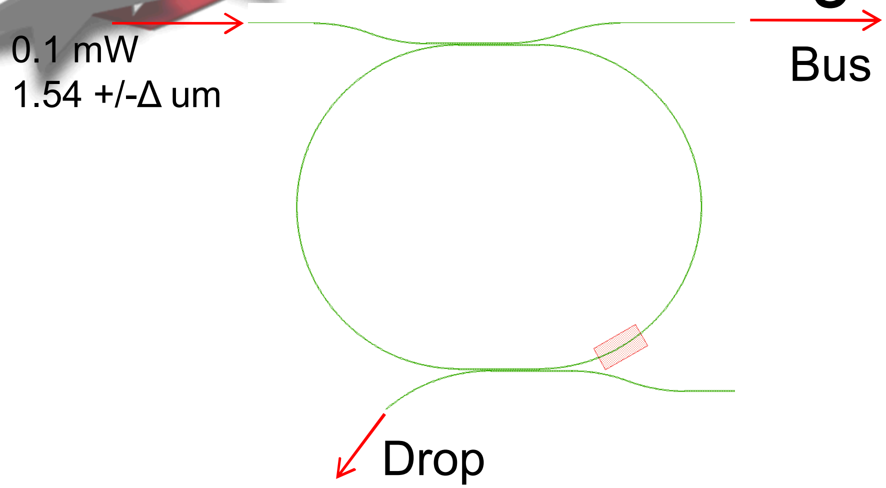
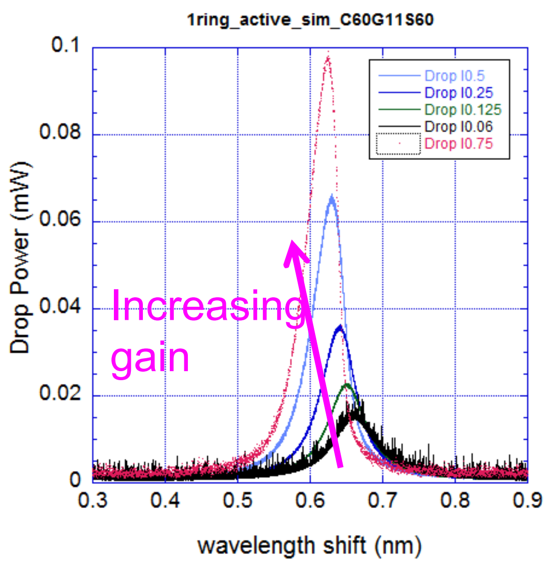
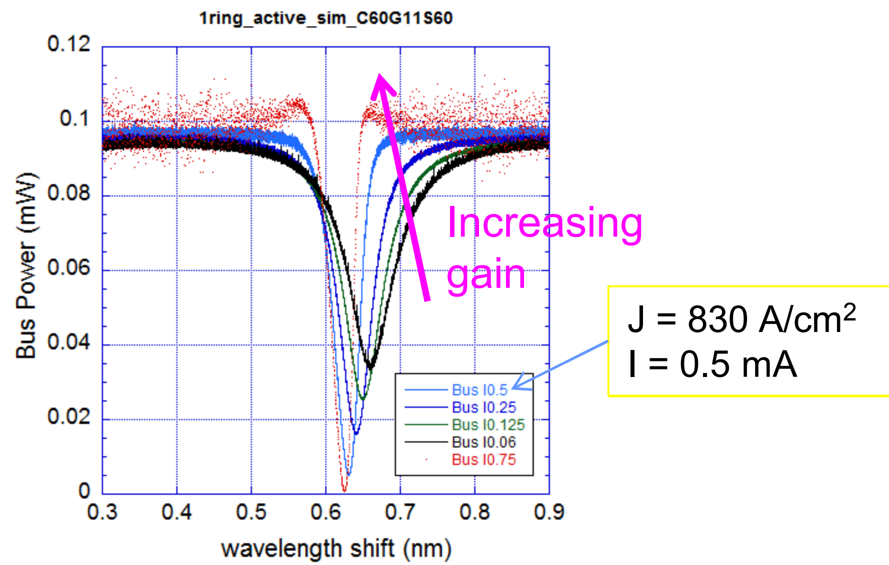
Model of Active Ring



Radius: 200 um
Couplers: 17% power cross-coupling
Passive guides: 3 cm^{-1}
SOA: 60 um long
- 7 QW centered, 25C
- 1 um wide BH
- current flow *only* in the MQW
- Spontaneous Coupling: 0.0037





- Variation of SOA injection current
  - Insertion loss drops and bandwidth narrows as SOA current is increased

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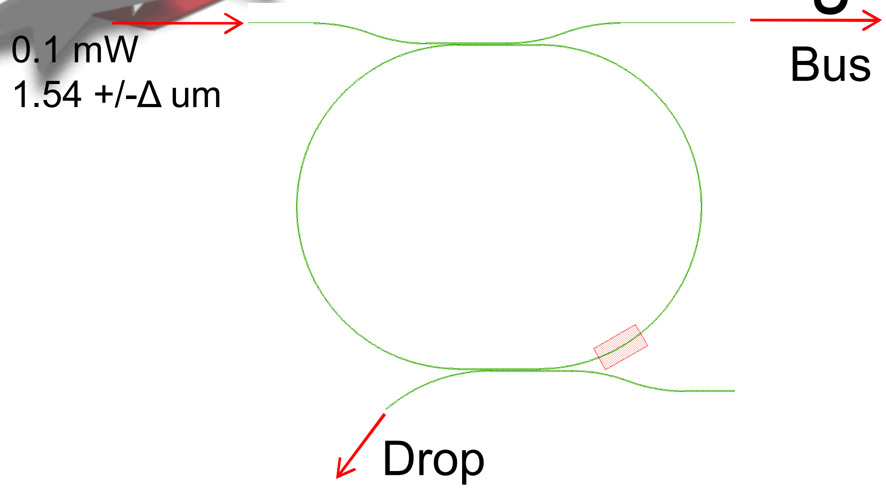
Model of Active Ring



Radius: 200 um
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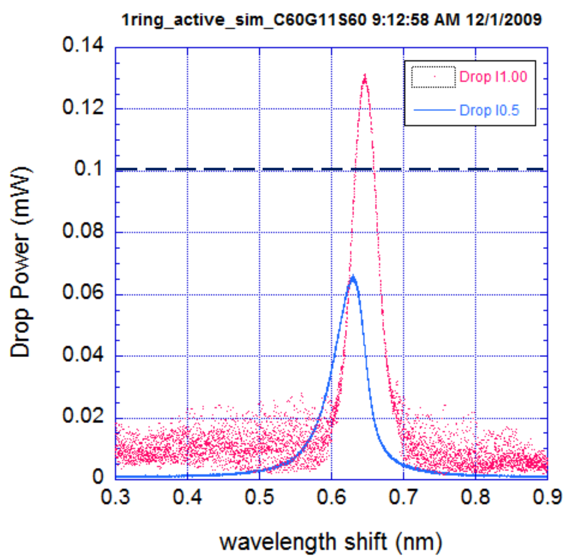

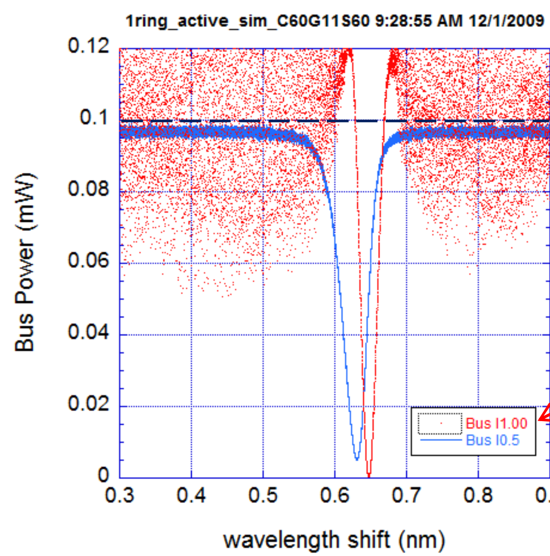

J = 1.67 KA/cm^2
I = 1.0 mA

- Operation at very high gain (SOA injected current)
  - Negative insertion loss achievable, but very noisy

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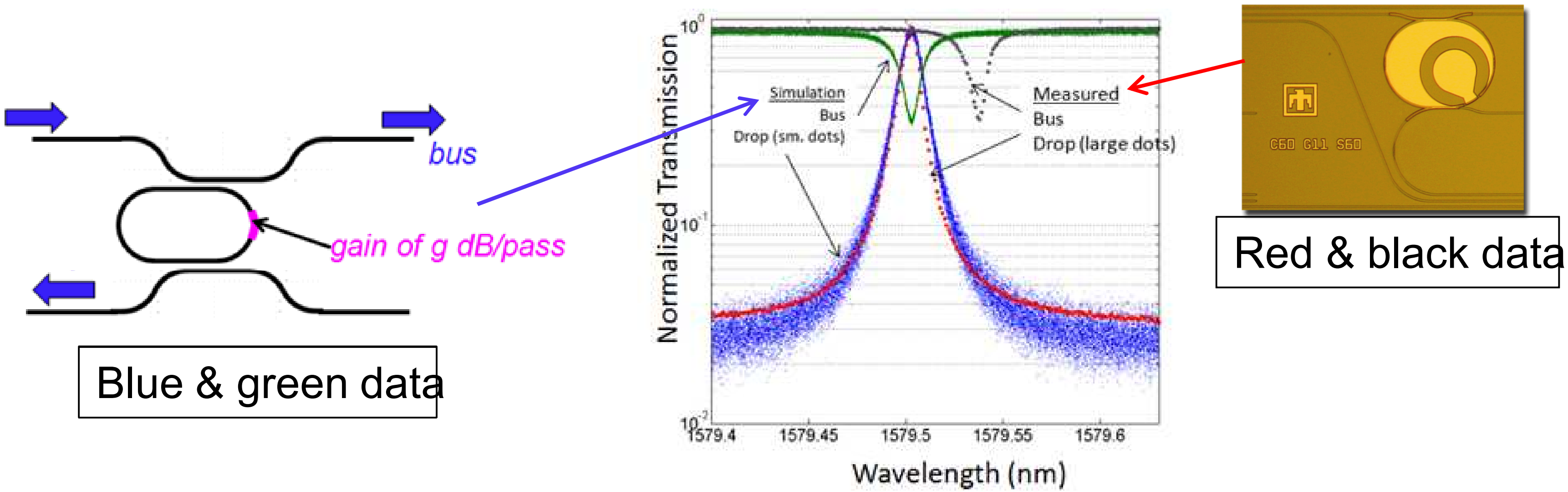
Single Ring Active Filter: Simulation Benchmark to Experiment



- Complete simulation of dynamic range and noise of active InGaAsP multi-ring filters
  - Include gain distortions and spontaneous emission noise
- Time dependent rate equation method
  - Gain and spontaneous emission modeled as function of injection current at all wavelengths simultaneously

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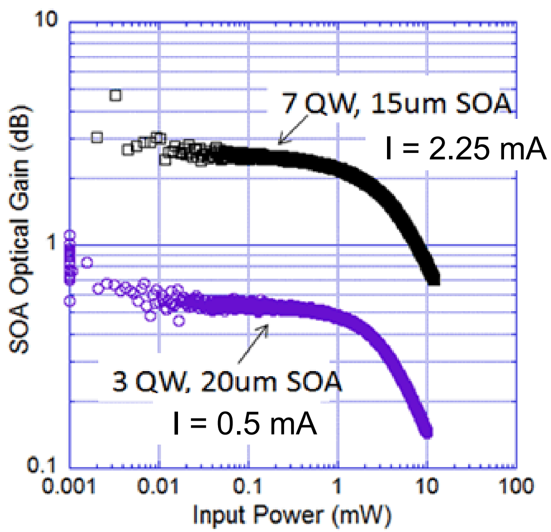
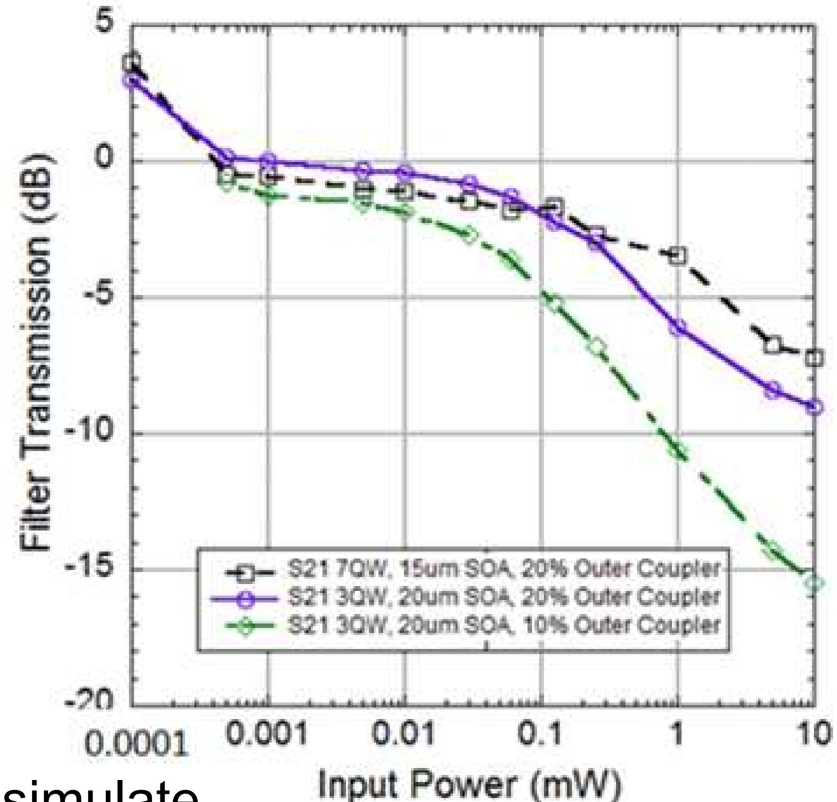
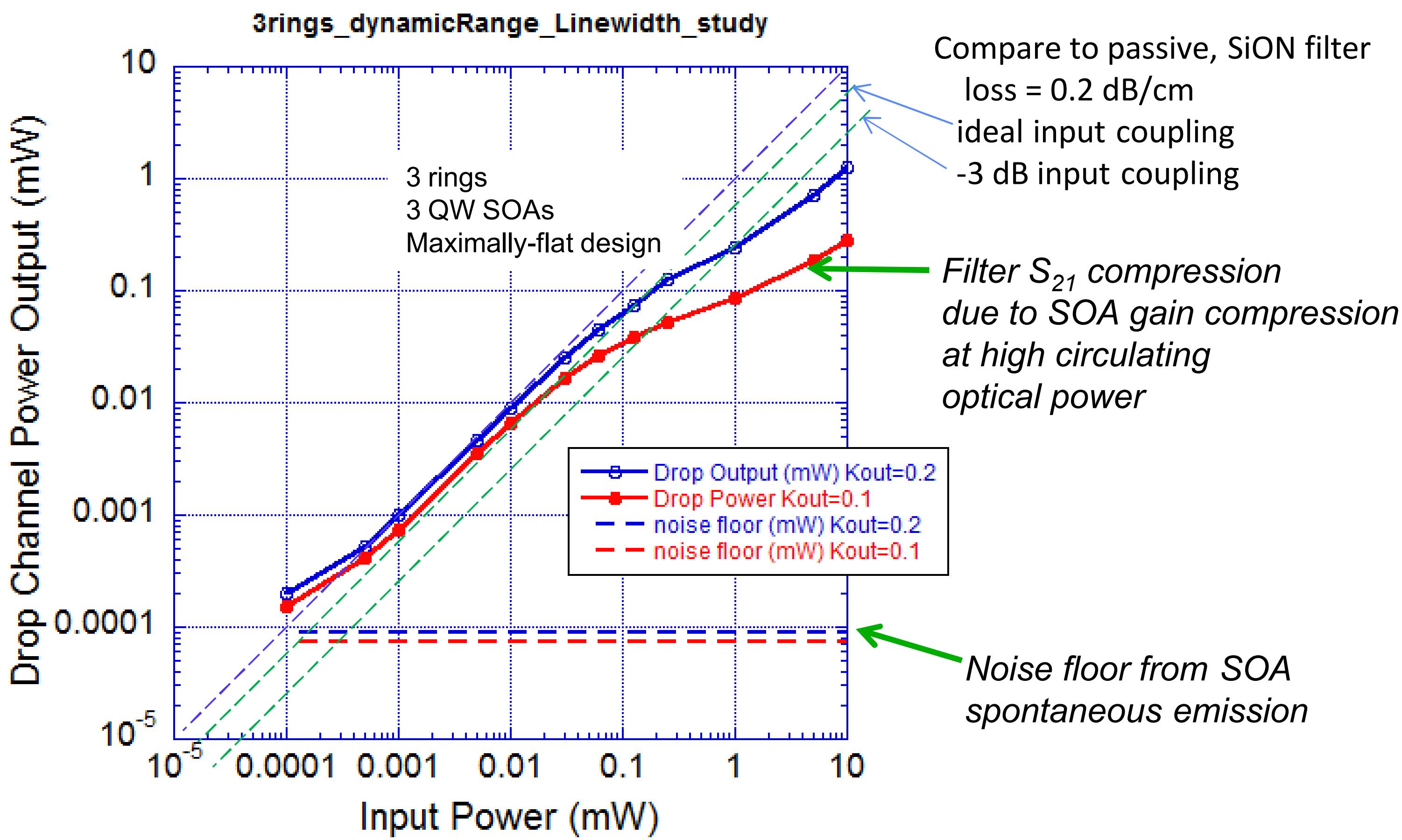
3-ring active filter simulations





- For 3-ring maximally flat filters simulate
  - Linewidth, Insertion loss
  - Dynamic range and Noise floor
- SOA gain and power saturation depend on key factors
  - Number and configuration of QWs and Injected current
  - Simulate case of both 3 and 7 QW SOA

InP Filter Dynamic Range



- Active InGaAsP filter shows improved filter transmission compared to passive SiON design over >30 dB dynamic range
- Spontaneous emission noise in SOAs limits SNR at lowest input optical powers
- SOA saturation causes compression of filter S_{21} at resonance at high end of input power

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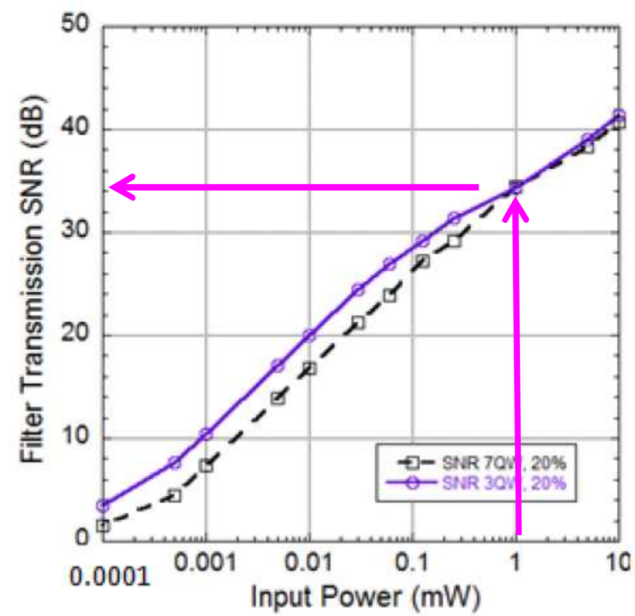
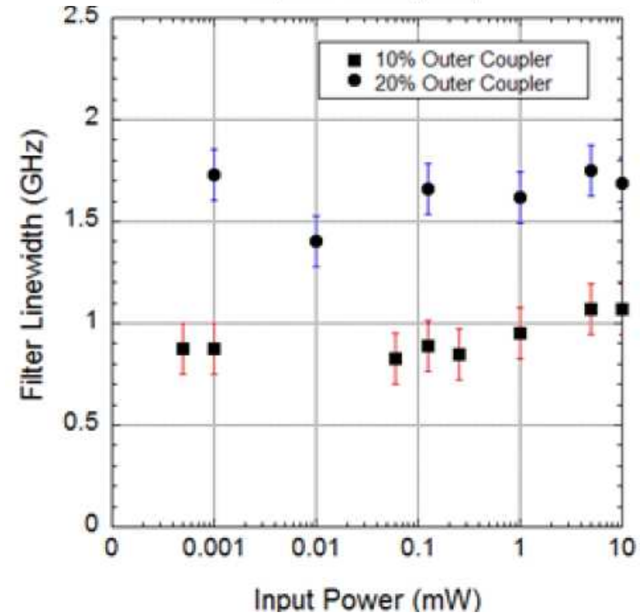
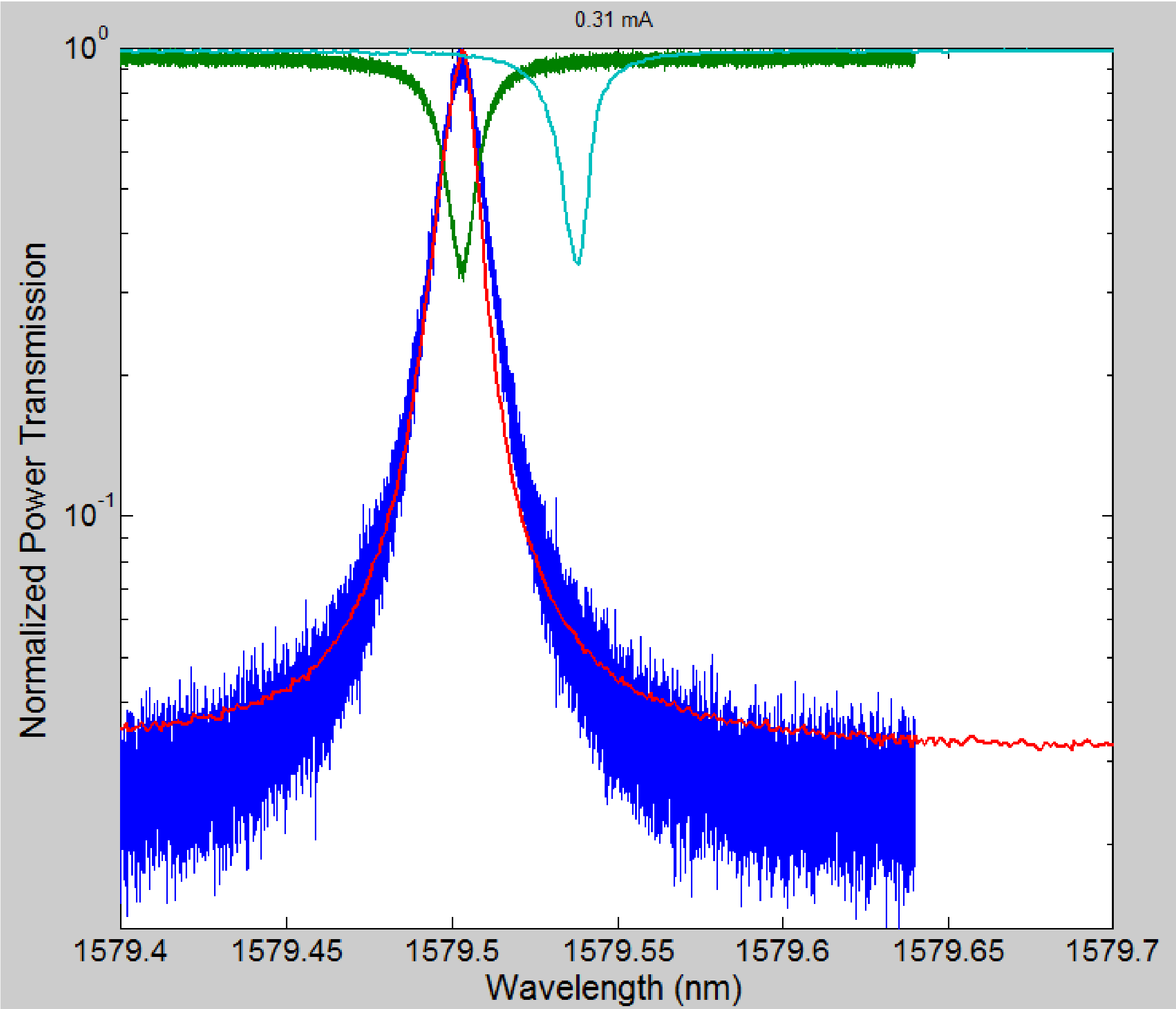
Summary

- Time domain model of active ring with SOAs developed
  - SOA model includes gain saturation and ASE
- 3-ring filter with 3 and 7 quantum well gain sections simulated
  - Optical linewidth
  - Noise floor
  - Linearity and dynamic range of S_{21} versus input power
- InP active filters show promise for frequency-domain signal processing in monolithic integrated photonic integrated circuits
  - 50 dB input dynamic range
    - Output compressed at high power
  - 0 dB loss in mid range accessible for 1 GHz filters
  - Filters with power gain are possible but quickly become limited by noise
  - Possible methods to improve dynamic range
    - Reduce optical confinement factor
      - Balance against lower gain or more complex offset active lasers in remainder of PIC
    - Wider SOAs
    - More pump current





Best Fit to C20G10S100, EW1858



- 8 QW offset
- 100 um SOA
- $K^2 = 0.03$
- Loss = 1.4 cm^{-1}
- P in = 0.005 mW

- I_{SOA} model
  - 0.31 mA
- I_{SOA} exp
  - 1 mA

Simulation data is in SOA100_K03_alpha14_8mqw_offset.xls and .mat

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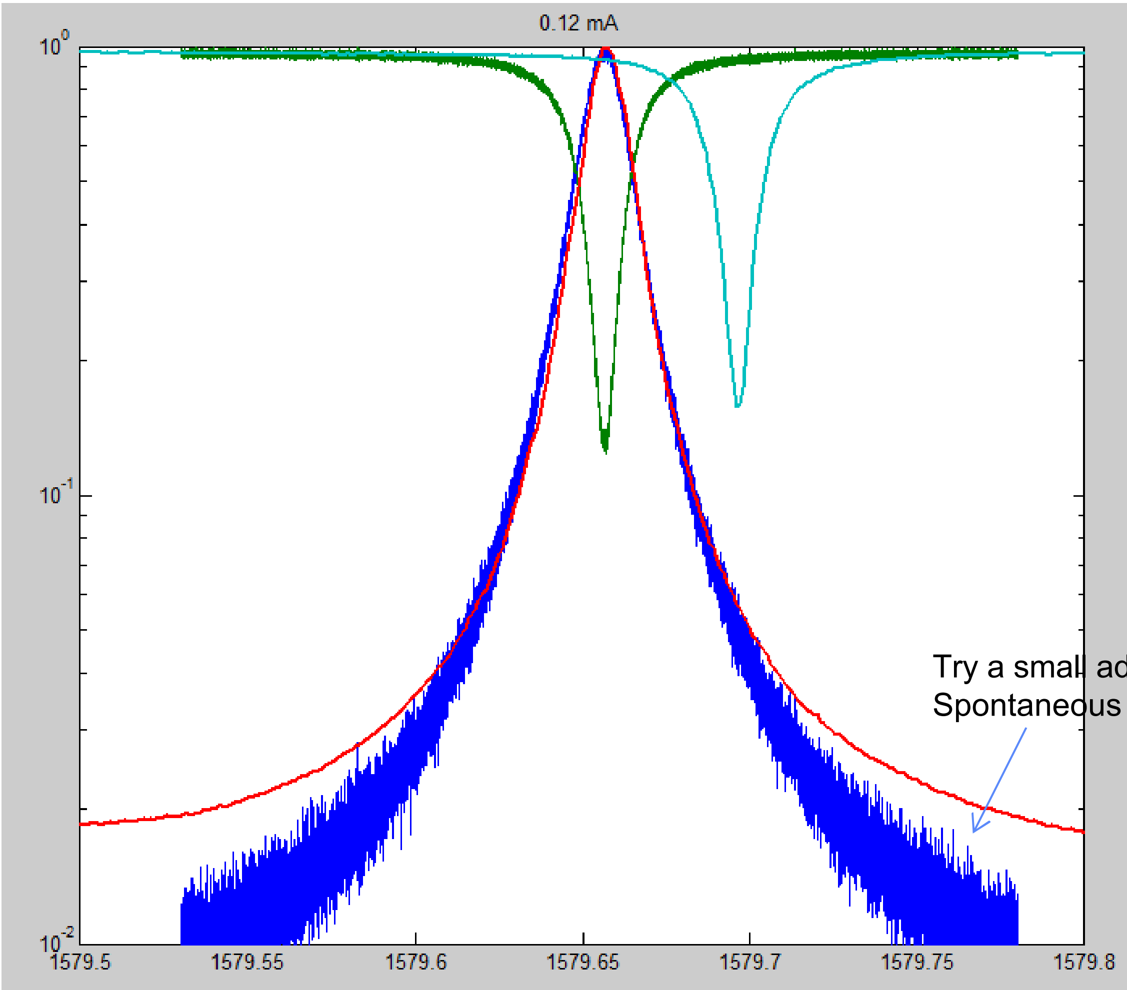
Detail Fit to C40G10S20, EW1858



- 8 QW offset
- 20 um SOA
- $K^2 = 0.06$
- Loss = 1.4 cm^{-1}
- P in = 0.005 mW

- I_{SOA} model
  - 0.12 mA
- I_{SOA} exp
  - 0.2 mA
- Pin exp
  - 0.2 mW

Simulation data is in SOA20_K06_alpha14_8mqw_offset.xls and .mat

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