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Compound Semiconductor Laboratory

Resonator Stabilized and Tunable Lasers

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Introduction

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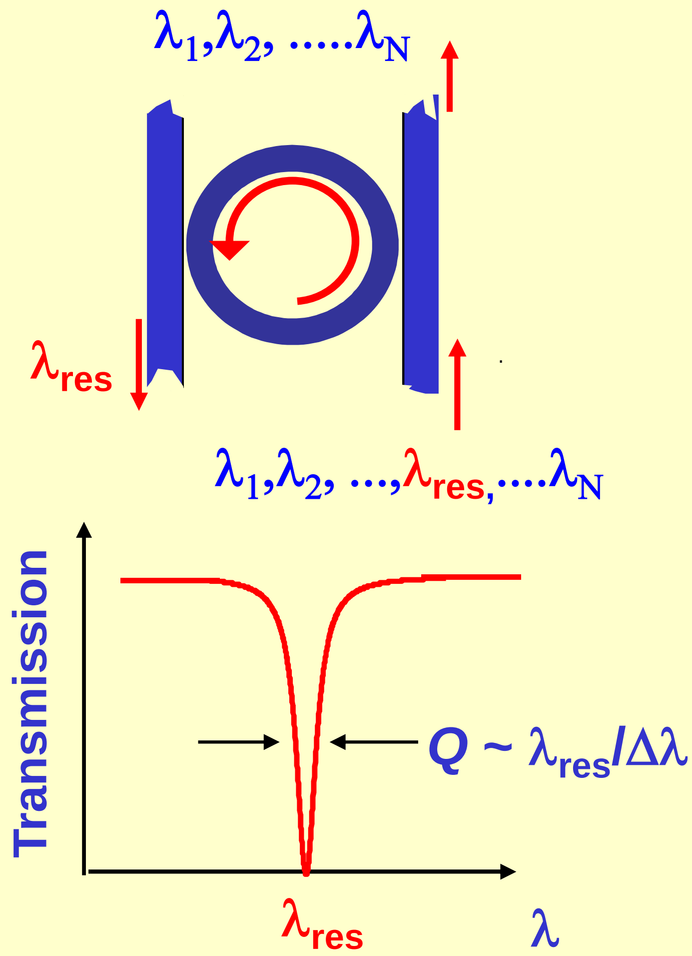
- **Bus-coupled microresonators**
  - **Wavelength selection**
  - ***Q* is the figure of merit**
  - **Versatile functionality: switches, filters, modulators, lasers…**

- **Universal techniques**
  - **A variety of material systems and coupling configurations are available**
  - ***Loss* and *coupling coefficients* are the key parameters to be controlled with care**



Introduction (cont.)

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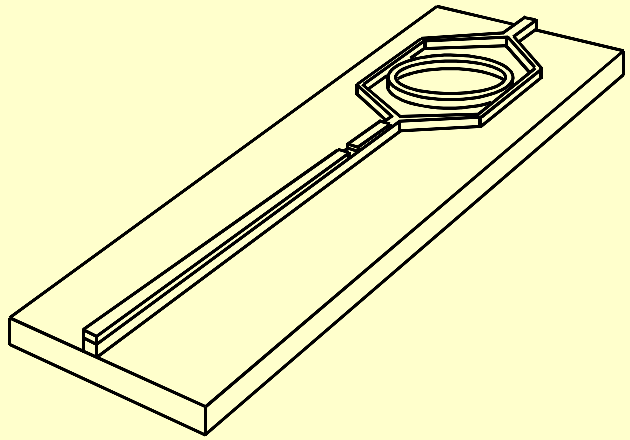

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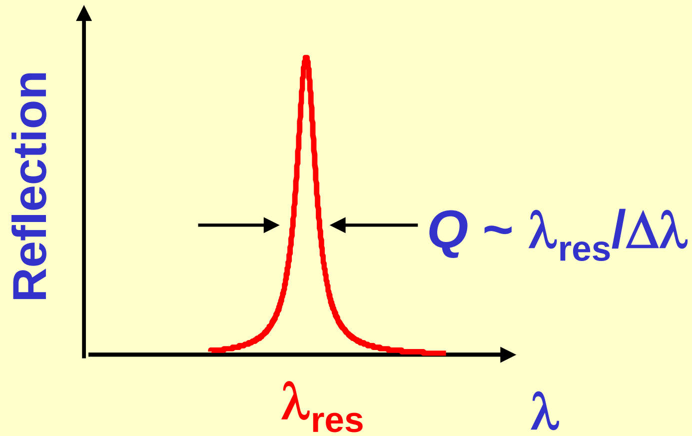

InP Based Resonator Technologies

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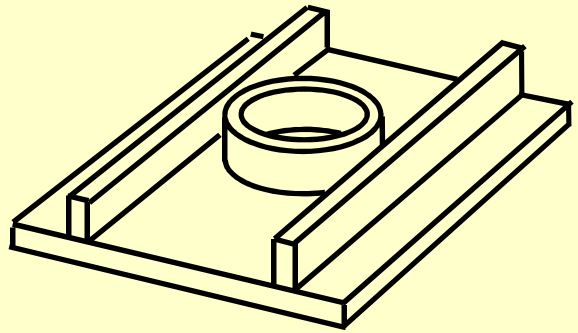
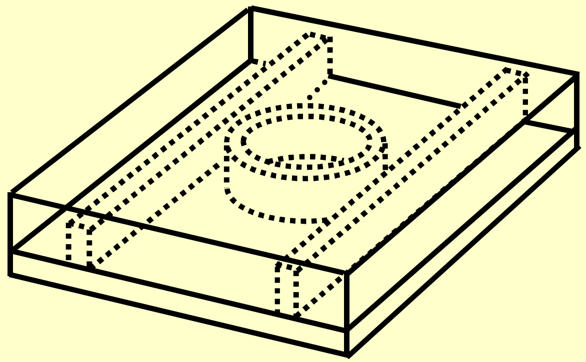
- Conventional air-guided microring
  - Deep-etched, rib-type waveguides
  - Scattering losses (high index contrast)
- BH ring resonator
  - A high Q platform technology for semiconductor resonators
  - Utilizing epitaxial regrowth techniques
  - Low losses (lowered index contrast)
  - Facilitated control of the lateral coupling (high-index coupling medium)



Conventional



Buried Heterostructure (BH)

Microresonator Array Components

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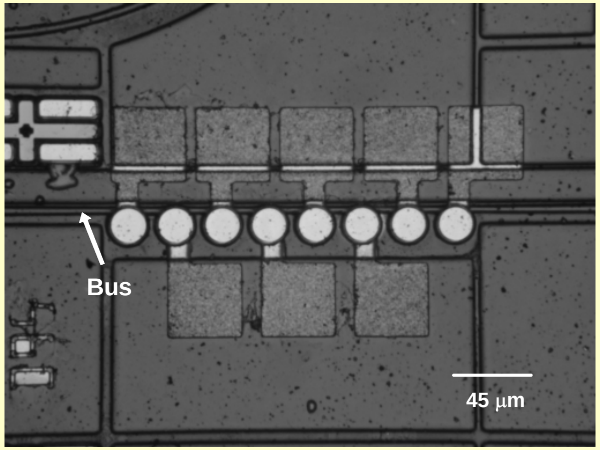
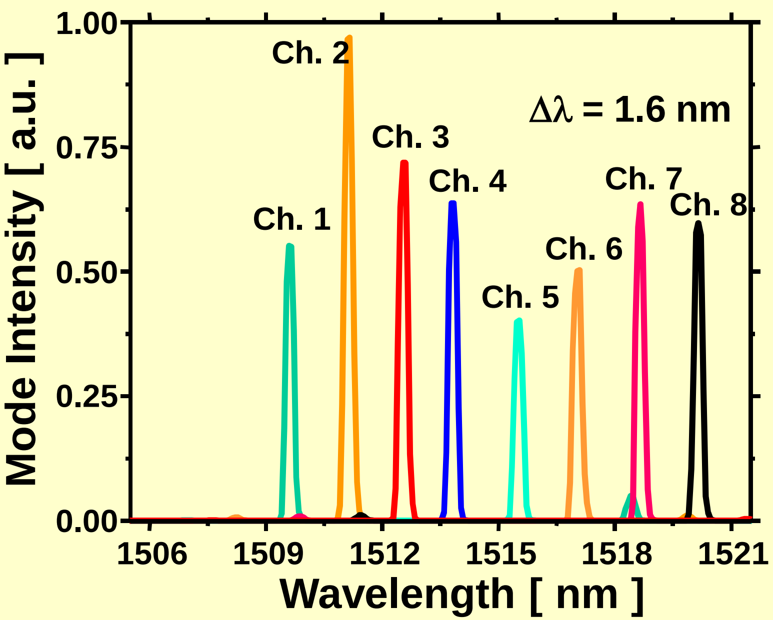
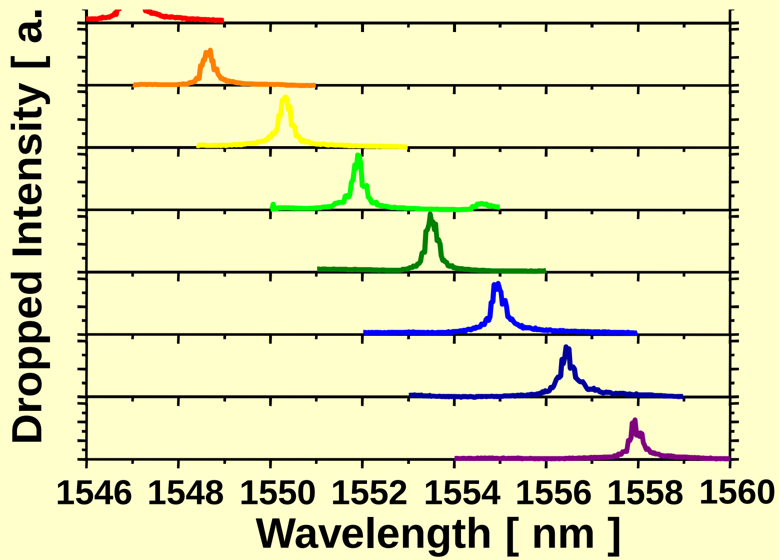
Laser Array



MUX / DEMUX



20 GHz subV Wavelength Selective Modulator Array



Ring Resonators for Lasers

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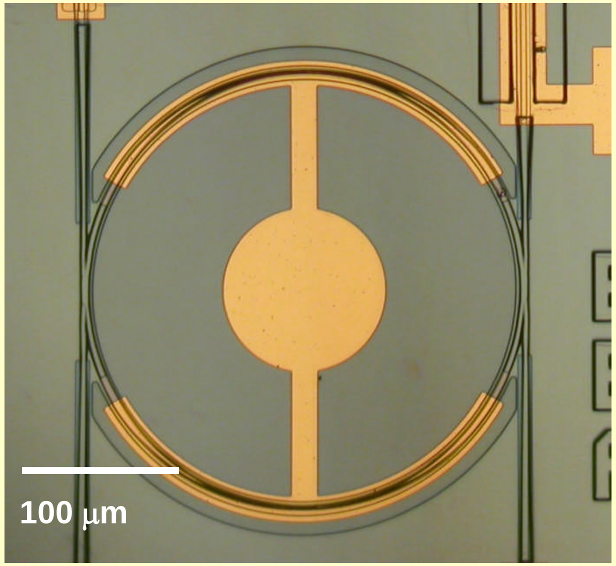
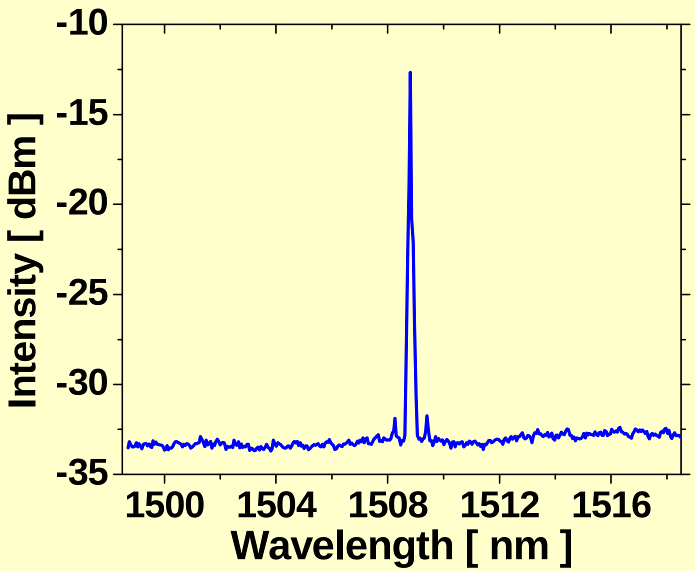
- A bus-coupled BH ring resonator with gain
  - The ring resonator itself serves as a lasing cavity
  - A single-mode, CW laser





Micrograph of a ring laser and the measured CW single-mode laser spectrum

Tunable Second Order Filter Using Vernier Effects

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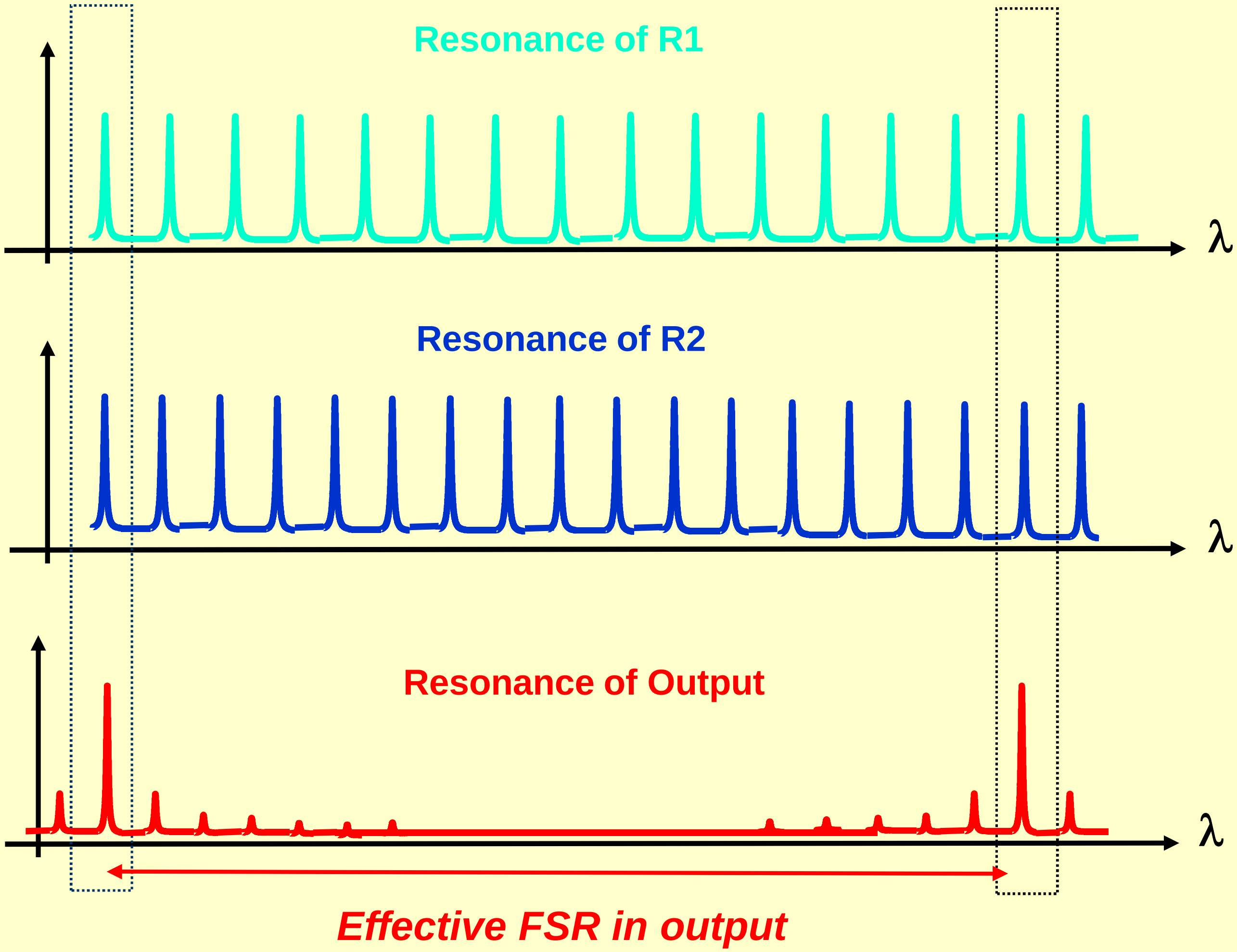

BH Ring Resonators for Lasers

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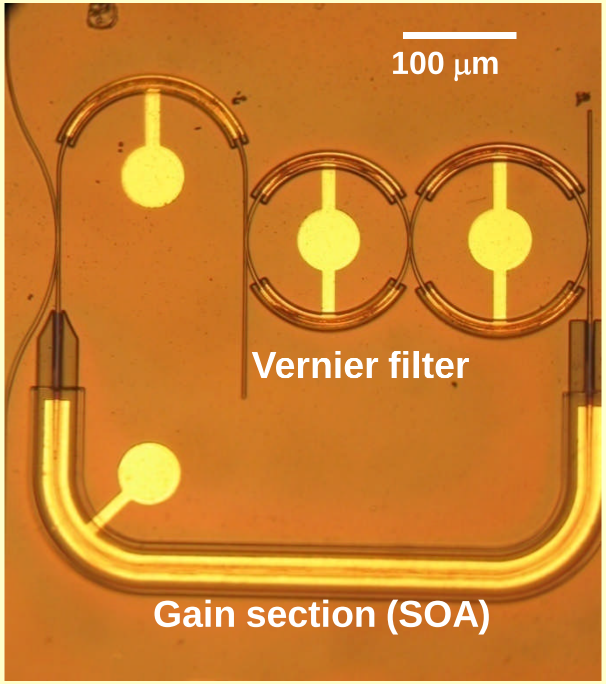
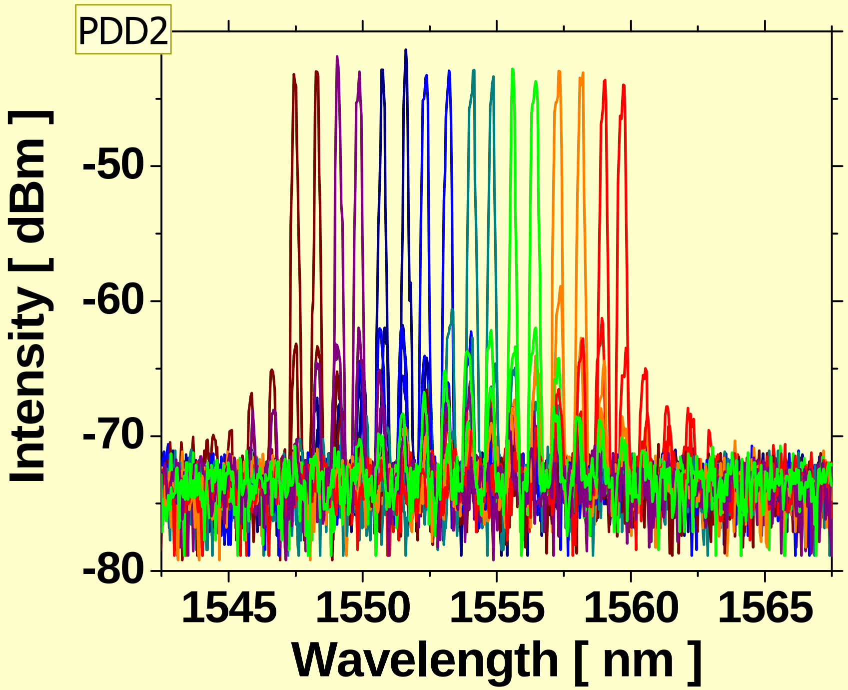
- **BH ring resonators for intra-cavity wavelength selection**
  - **An intra-cavity Vernier filter based on BH rings is integrated with SOA**
  - **Laser wavelength shift is achieved by tuning the Vernier filter**





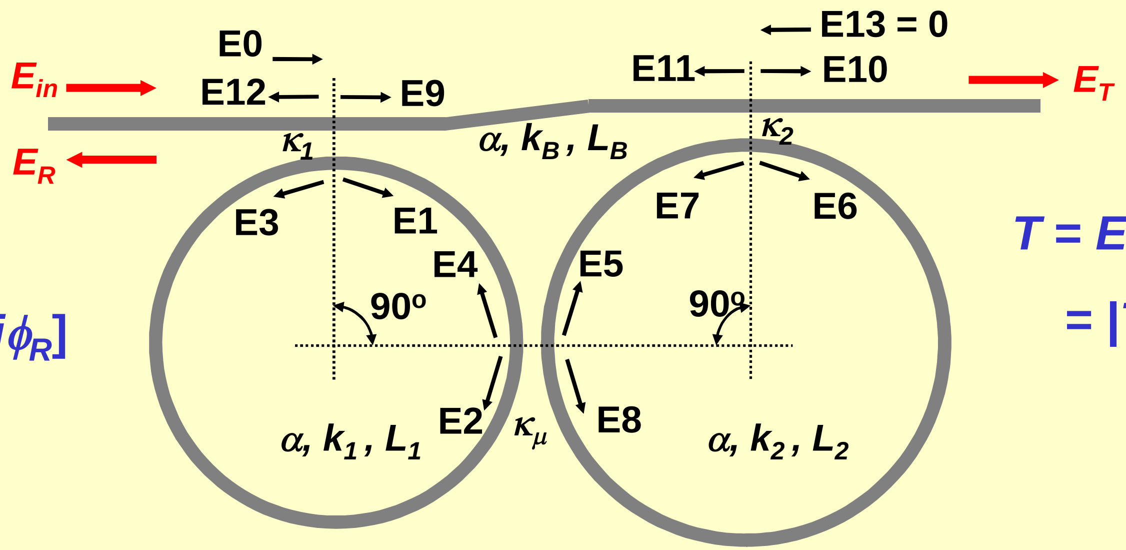
Micrograph of a tunable laser and the measured CW tuning characteristics

Wavelength Selective Reflector (WSR)

- **A novel, in-plane optical feedback element**
  - **An attractive substitute for high-resolution grating systems**
  - **Two ring resonators having slightly different radii are mutually coupled in the Vernier arrangement (wide range of tuning)**
  - **The coupling of modes formalisms are used for the analysis**

$R = E_{in} / E_R$

$= |R| \cdot \exp[j\phi_R]$



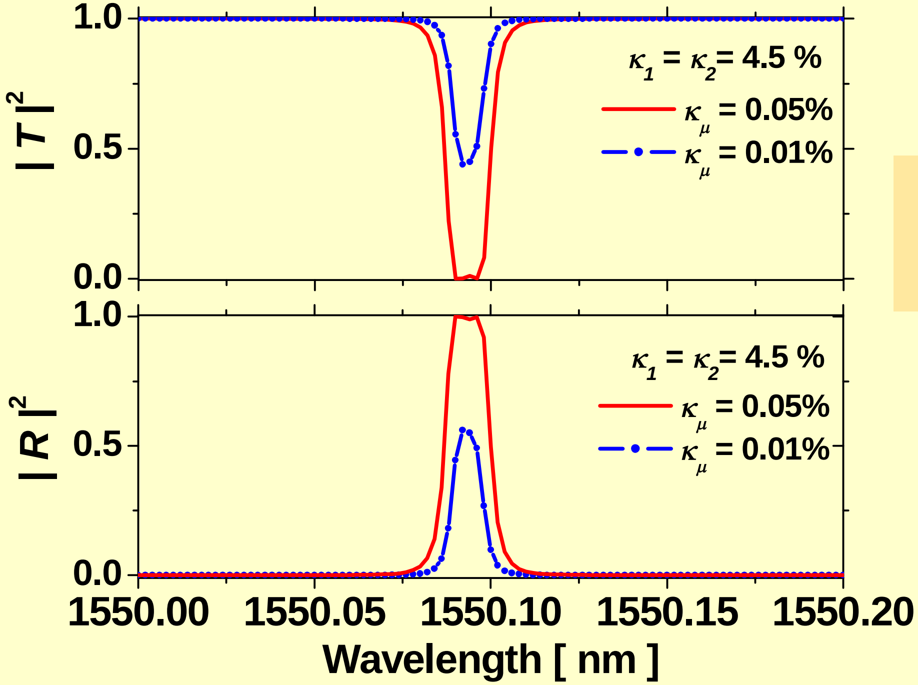
$T = E_{in} / E_T$

$= |T| \cdot \exp[j\phi_T]$

Schematic illustration of the microresoantor-based WSR

Analysis of a WSR

- **Fully scalable reflectivity (*R*) and transmissivity (*T*)**
  - ***R* and *T* are specified by adjusting the coupling ($\kappa_{Ring\text{-}Bus}$ and κ_{mutual})**
  - **$|R|^2 + |T|^2 = 1$ in loss-less waveguides**

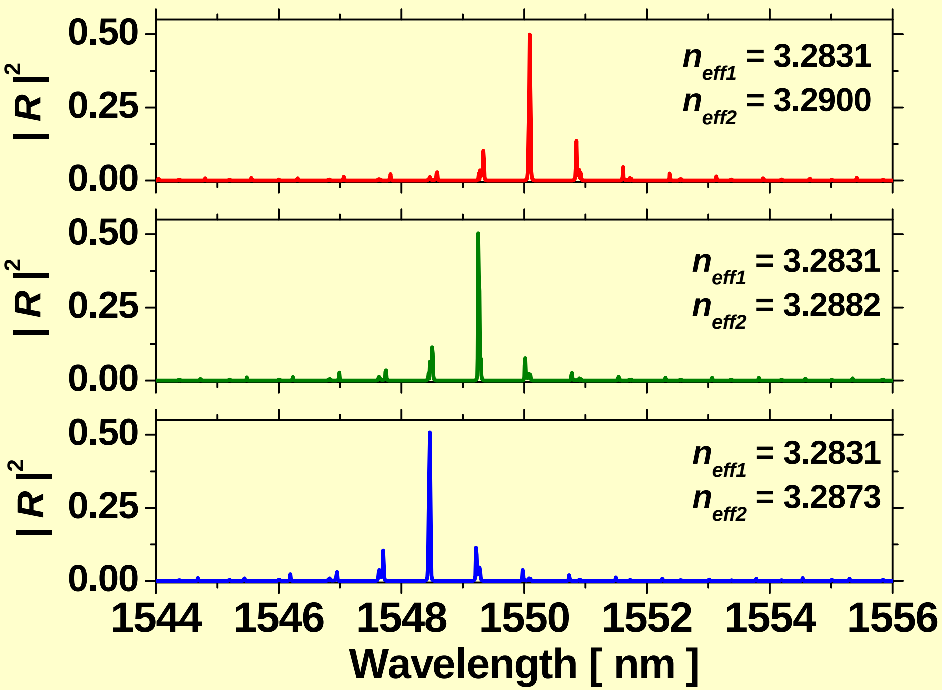


Theoretical $|R|^2$ and $|T|^2$ of a loss-less WSR

- **$\kappa_{Ring\text{-}Bus} \approx \kappa_{mutual} > 0$:**
  Mode splitting
- **$\kappa_{Ring\text{-}Bus} > \kappa_{mutual} > 0$:**
  $|R|^2 = 1$, $|T|^2 = 0$, unity reflector
- **$\kappa_{Ring\text{-}Bus} >> \kappa_{mutual} > 0$:**
  $0 < |R|^2 < 1$, $0 < |T|^2 < 1$
- **$\kappa_{mutual} = 0$:**
  $|R|^2 = 0$, $|T|^2 = 1$, all-pass filter

Design of a Tunable WSR

- A tunable WSR based on low-loss BH ring resonators
  - Free carrier injection (FCI) tuning in the Vernier arrangement
  - $\Delta f_{channel}$ = 100 GHz (= FSR_{R1}) is achieved by tuning $n_{eff,R2}$

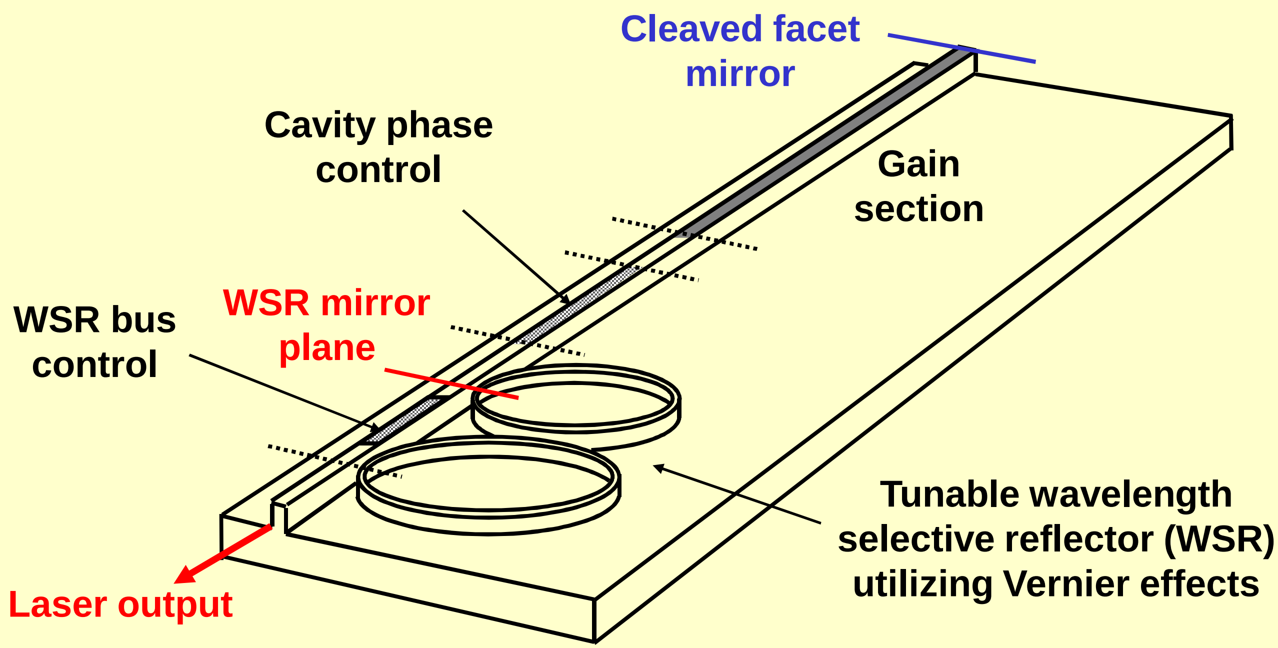


Calculated tuning characteristics of WSR

- Ring radii:
  R_1 / R_2 = 130 / 140 μm
- FSRs:
  FSR_{R1} / FSR_{R2} = 0.8 / 0.75 nm
- Coupling figure:
  $\kappa_{Ring\text{-}Bus}$ = 4.5 % ($d_{R\text{-}B}$ = 0.9 μm)
  κ_{mutual} = 1 % (d_{mutual} = 1.1 μm)
- Mirror characteristics:
  $|R|^2 = 0.5$, $|T|^2 = 0.2$
  (α = 0.5 cm^{-1} is assumed)

Design of a Tunable Laser

- A tunable laser design using a single WSR
  - **Tunable WSR + Cleaved facet mirror to form a resonant cavity**
  - **Lower threshold and improved SMSR are expected, when the cleaved facet mirror is replaced with another WSR**



Schematic illustration of the tunable laser using a single WSR

Tunable Laser Fabrication

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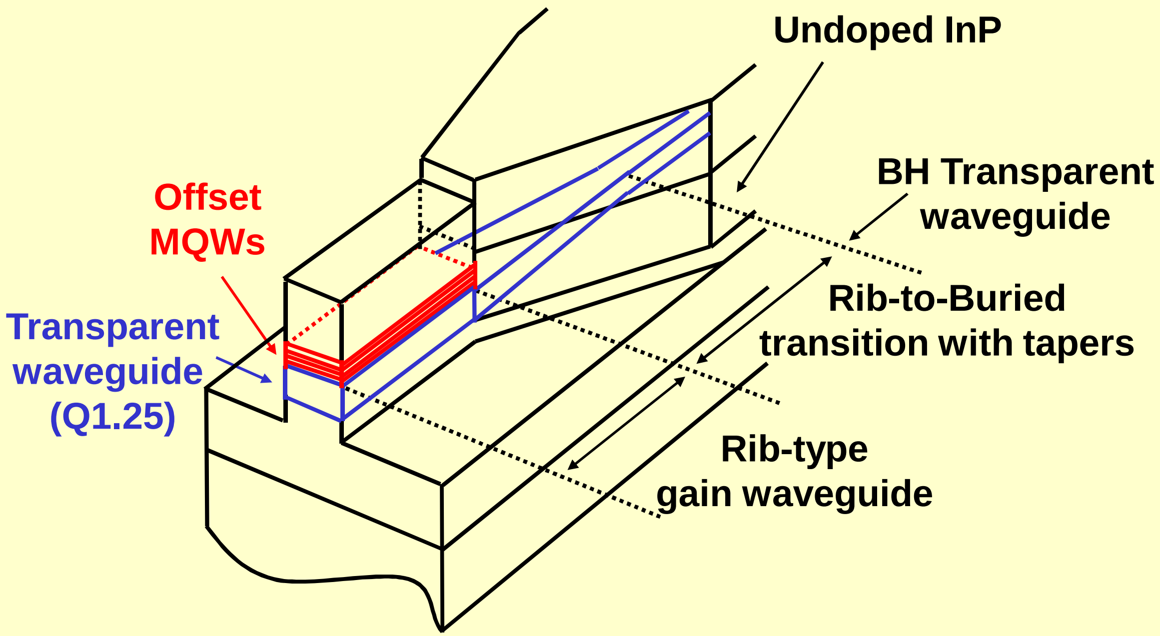
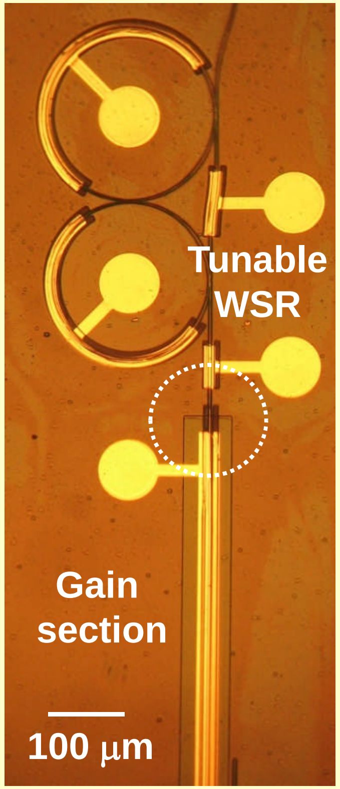
- **Integration of gain and transparent waveguides**
  - **A rib-type waveguide utilizing offset-QWs for the gain section**
  - **BH waveguides for the transparent section**



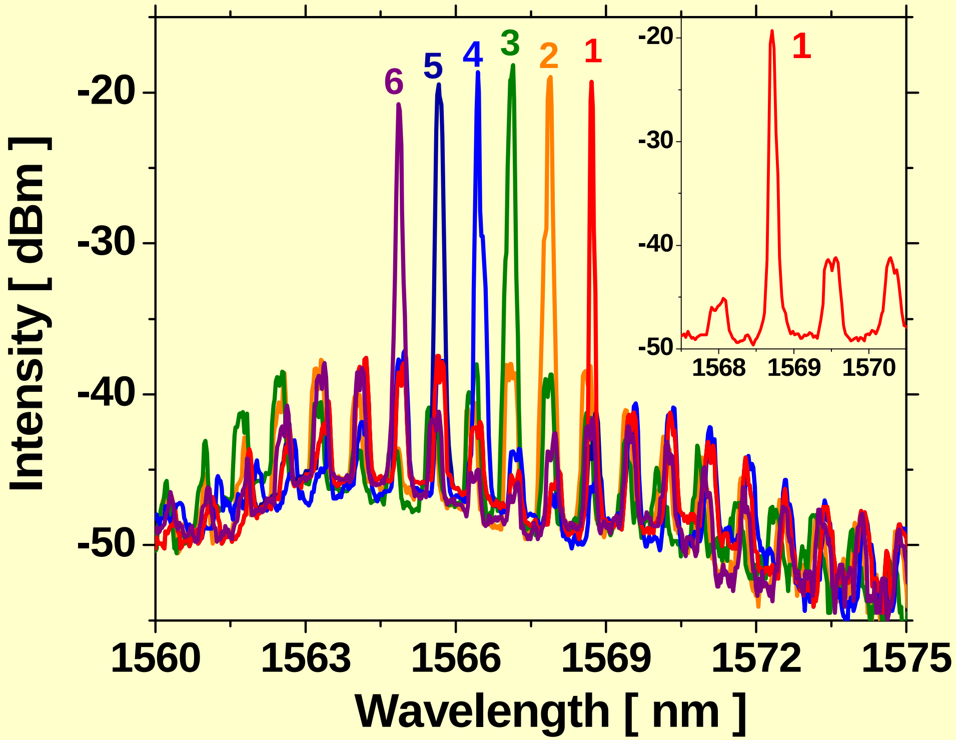
Schematic illustration of the gain and transparent waveguides



Fabricated tunable laser

Measured Tuning Characteristics

- **A 100-GHz-spaced CW tunable laser**
  - **The first demonstration of a microring-based WSR for a tunable laser**



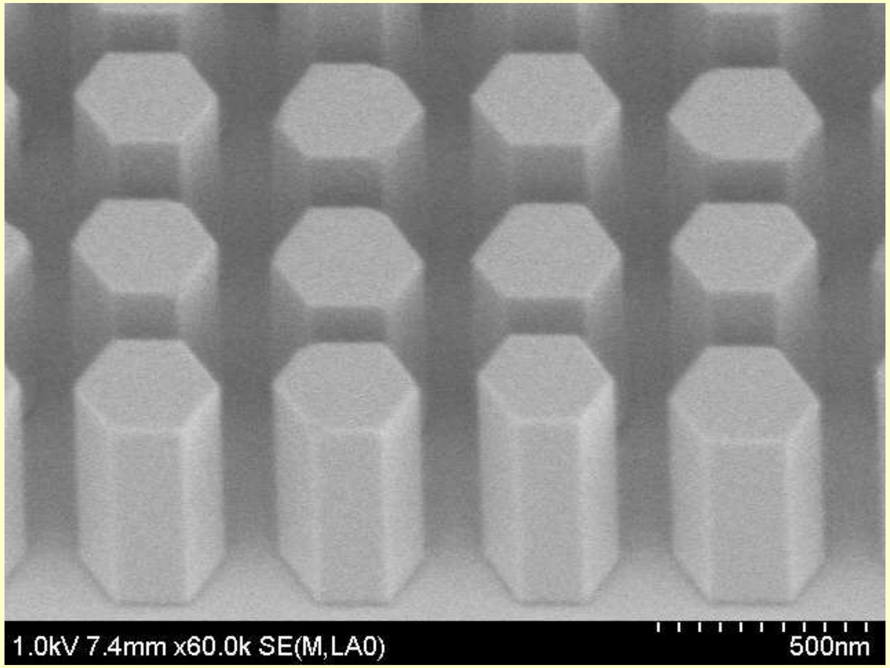
Measured tuning characteristics of 6 CW-laser channels

- **Gain current:**
  I_G = 90 ~ 95 mA (~ 1.2 × I_{TH})
- **Tuning current:**
  I_{R1} = 0 ~ 0.4 mA
  I_{R2} = 0.3 ~ 5.4 mA
- **Phase current:**
  I_B = 0 ~ 4.5 mA
- **SMSR (adjacent channel):**
  20 dB or greater

Tunable Lasers on SOI Photonics Platform – Some Issues

- **Arrays or Tunable Lasers?**
- **Wafer Bonded or Monolithic?**
  - **Scalability of Bonding (18” Si wafers vs 4” InP)**
  - **Thermal Conductivity (SOI has very low thermal conductivity)**
  - **Material Defects (Lattice Constant and Expansion Mismatch)**
  - **Emergence of Nanoscale Selective Area Growth Techniques**
- **III-V or SOI Resonators?**
  - **Process Complexity**
  - **Smaller Electronic Tunability of Si vs InP (~10x less)**
  - **Electrical Tuning vs Thermal Tuning**
- **Low Loss Optical Transitions to SOI**
  - **Intracavity vs Extracavity**
  - **Evanescent, Vertically Tapered or Butt Coupled**

Direct Epitaxy of III-V's on Si?



Summary

- A wavelength selective reflector (WSR)
  - Based on resonators
  - A compact in-plane optical feedback element
  - Scalable reflectivity and transmissivity
  - Tunable (Vernier effects)
- Tunable lasers using WSR feedback elements
  - Ring-based WSR tunable laser
  - BH microresonator platform technology
  - A 100-GHz channel (or continuously) tunable laser