Low Voltage Modulators Based on Semiconductor Microresonators

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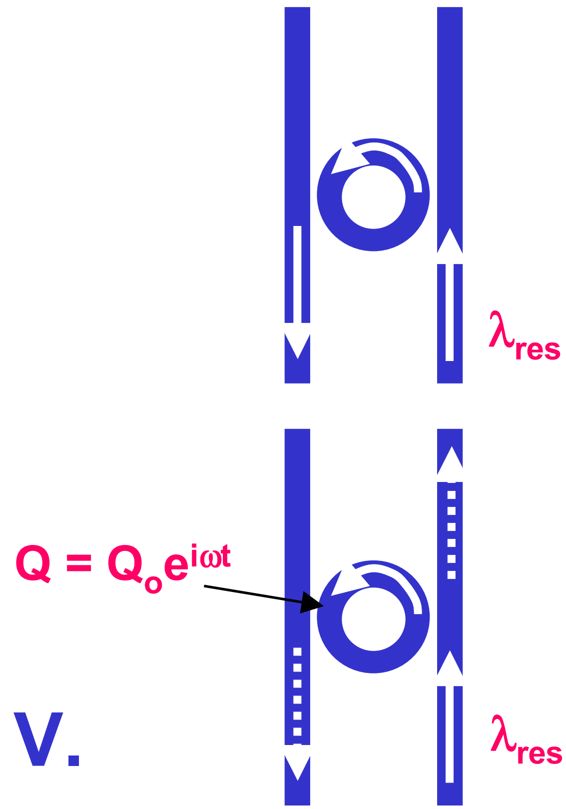
Program Concept

- High Q resonators enhance the coupling between waveguides.
- Low voltage modulation of the resonator Q can modulate the power transfer.
- Develop techniques for fabricating resonators and modulator circuits with $V_p \sim 0.1$ V.



Technology Output

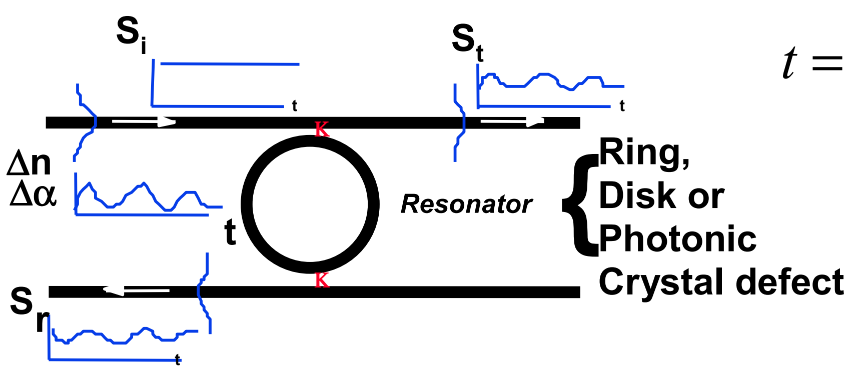
1. Low Voltage Modulators with low insertion loss
2. Vertically coupled WDM component technology.
3. Suite of sophisticated modeling tools.
4. Deliverable modulators for system trials.

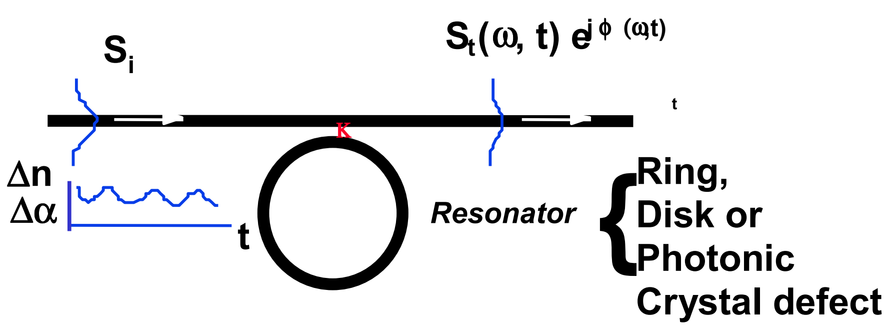
Accomplishments to Date

- Analyzed various modulation mechanisms to assess potential for program goals.
- Modeled vertically coupled resonator to determine device design issues.
- Developed resonator etching to achieve high Q resonators – Q > 7000.
- Demonstrated vertically coupled resonators with > 95% power coupling.

These are the highest performance semiconductor resonant couplers demonstrated to date.

Resonator Response





$$t = \frac{St}{Si} = \frac{j\left(\frac{\Delta\omega}{\omega_0} + \frac{\Delta n}{n_0}\right) + \frac{1}{2}\left(Q_l^{-1} + Q_d^{-1} - Q_c^{-1}\right)}{j\left(\frac{\Delta\omega}{\omega_0} + \frac{\Delta n}{n_0}\right) + \frac{1}{2}\left(Q_l^{-1} + Q_d^{-1} + Q_c^{-1}\right)}$$

At Resonance:

T is 0 when critically coupled

T exhibits a π phase change

T is a minimum unless $Q_l >> Q_c, Q_d$ then T = 1

Modulation Mechanisms

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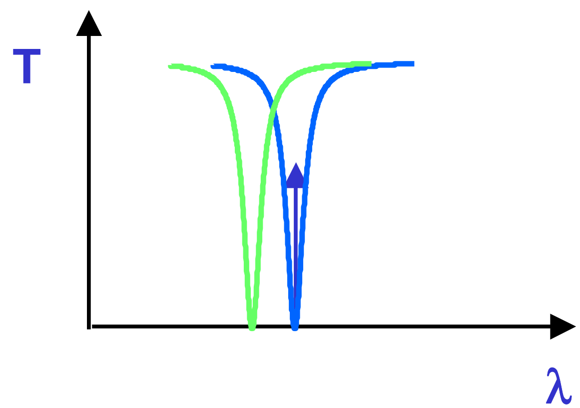
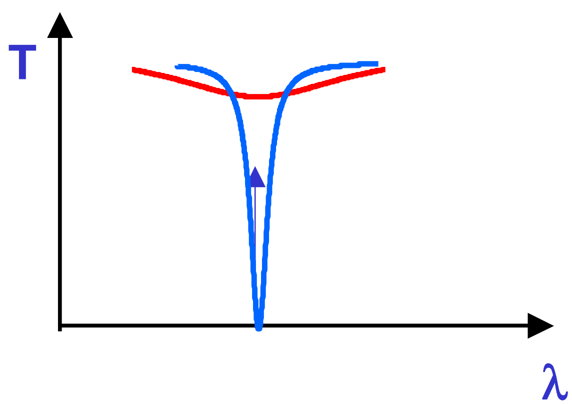


Resonance Tuning, 🖓n

Electro-optic Effect

Electrorefraction Effect

Free Carrier Plasma Effect

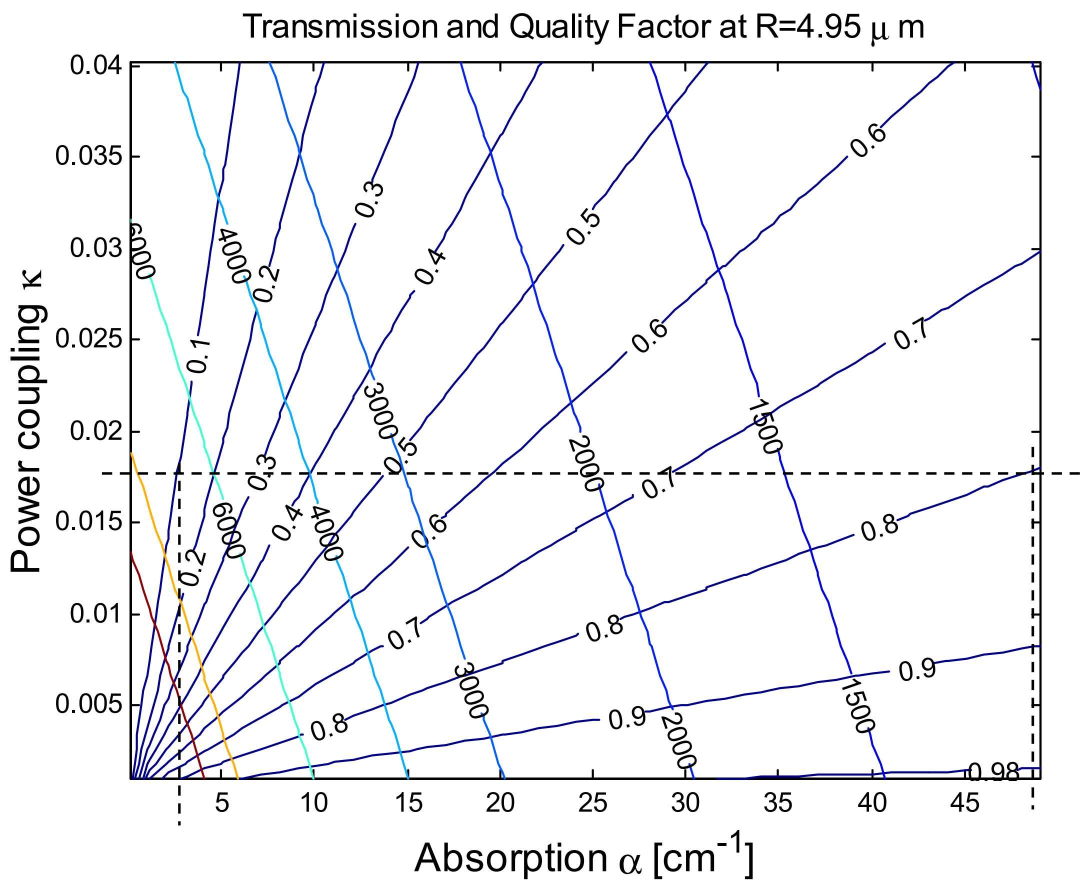


Q Tuning, 🖓♋

Electroabsorption

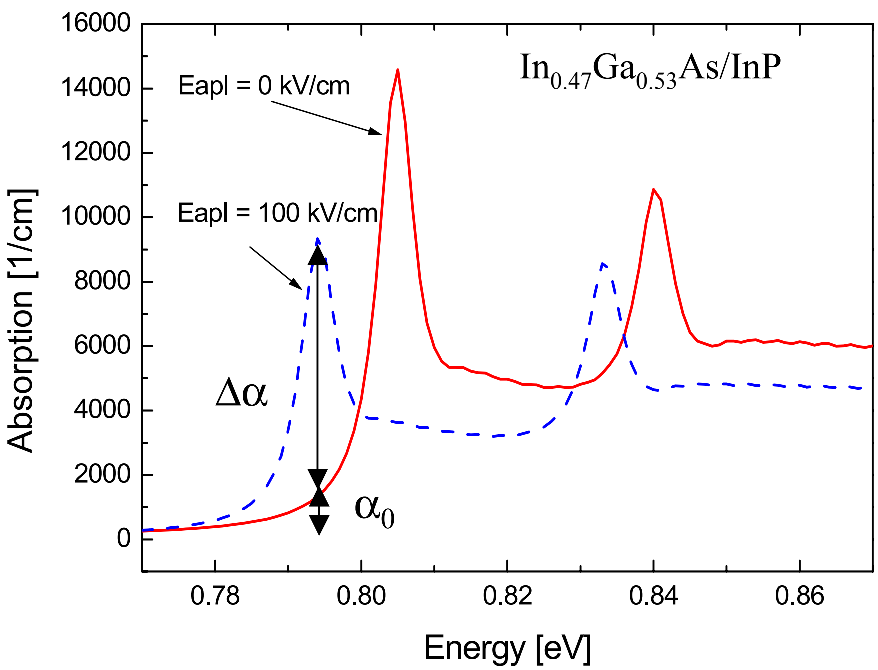
Gain

Loss Modulation



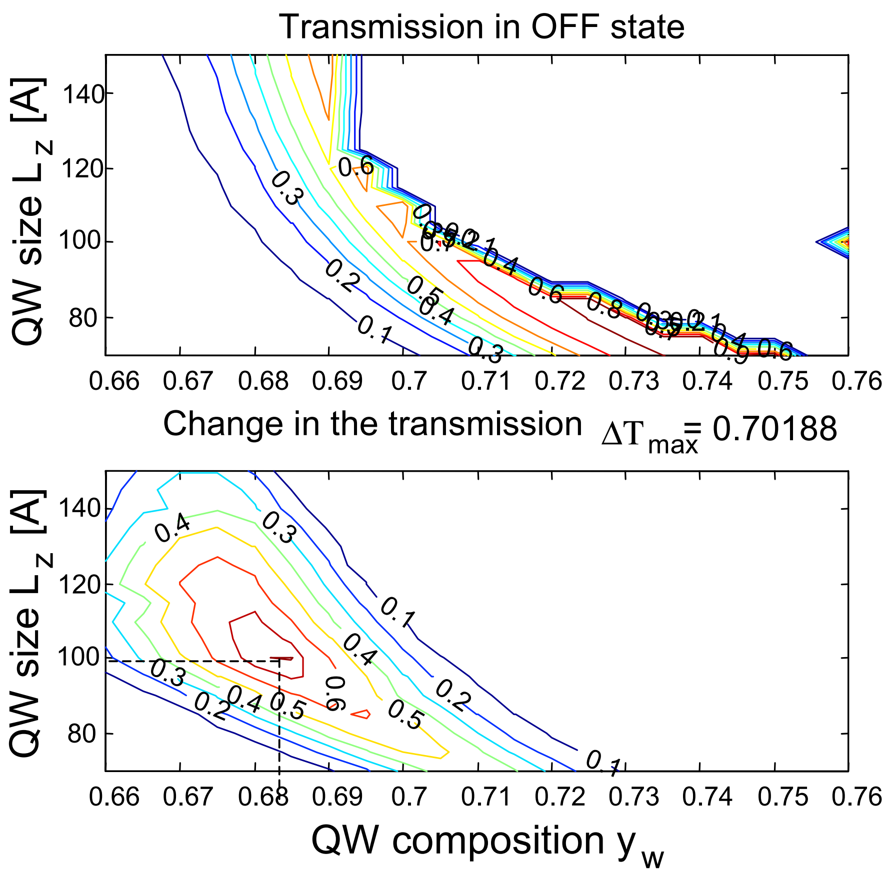
- Plotted T and Q vs. κ and α
- At κ=1.8% and α_{bg}=3cm^{-1} we need $\Delta\alpha$=45cm^{-1} to have CR=10dB
- Higher CR (lower drive voltage) will require lower background losses α_{bg}

Electroabsorption Effect



- QCSE –sensitive to the applied voltage
- The most important issue is the relative position of the mode and the bandgap λ's
- Optimization of $\Delta\alpha/\alpha_0$
- Optimization of the QW (the results depends on the model used)

QCSE/QW optimization



- **Optimal composition:**
  - **L_w=100A, y_w=0.683, λ_w=1.5µm**
- **ΔT_{max}=0.7, T_{off}=0.1, CR=10dB**
- **V_{appl}=2.6V (depends on the lineshape function)**

- **High bandwidth**
- **Precise structure tuning**
- **The losses are detrimental**
- **Confirmation of the model by experiments**

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Gain Active Region

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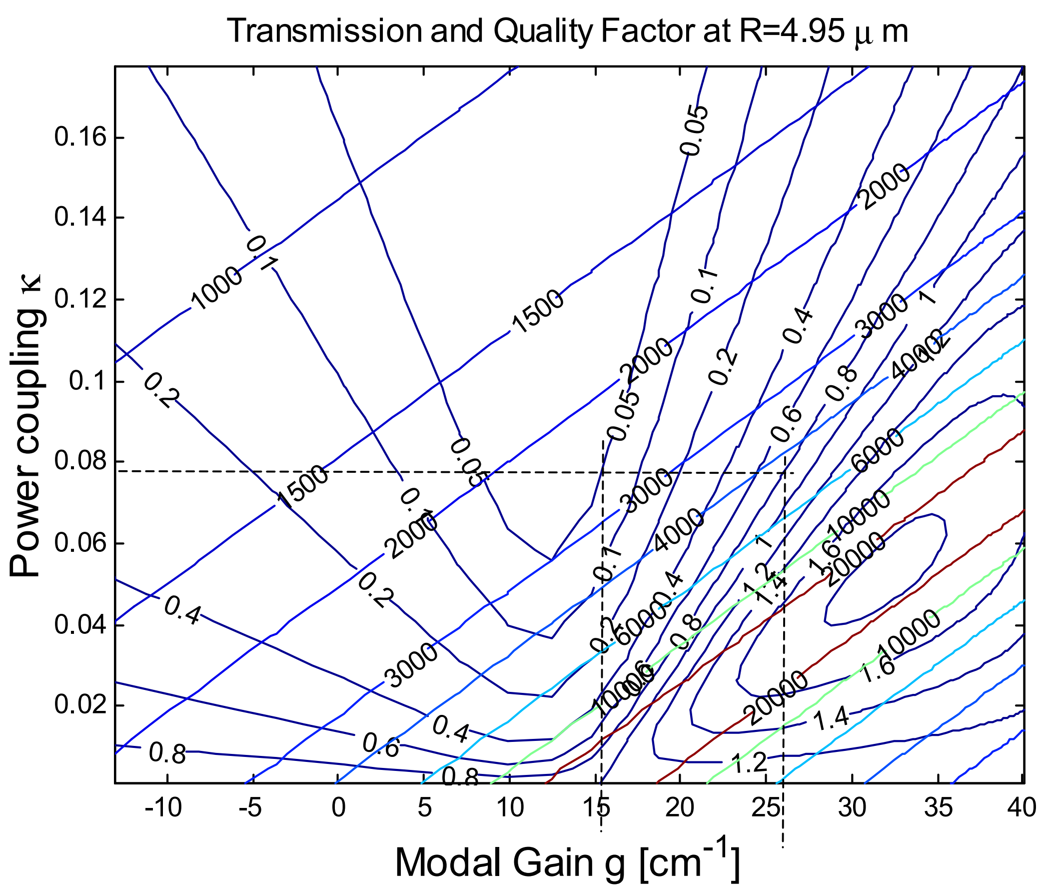

- α_{bg}=15cm^{-1}
- Δn included
- disk laser
- disk modulator
  - for CR=10dB
    - κ=8%
    - Δg=10cm^{-1}

Gain vs. Voltage Relationship

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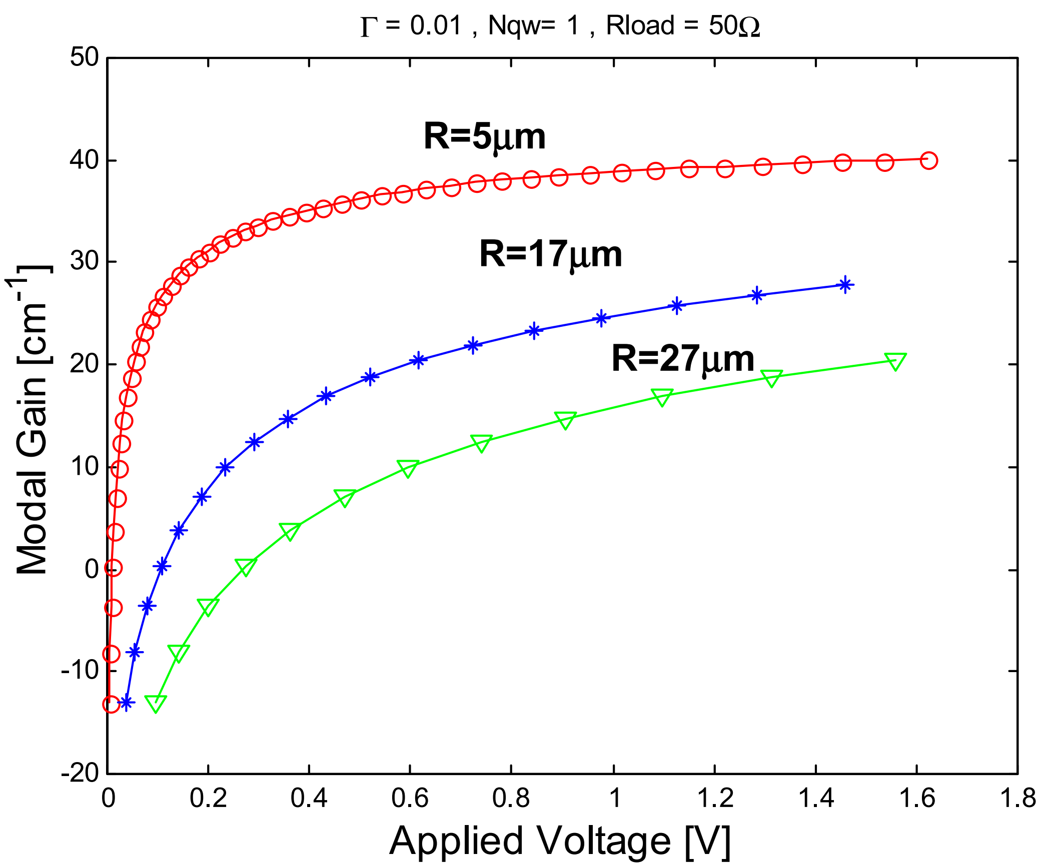
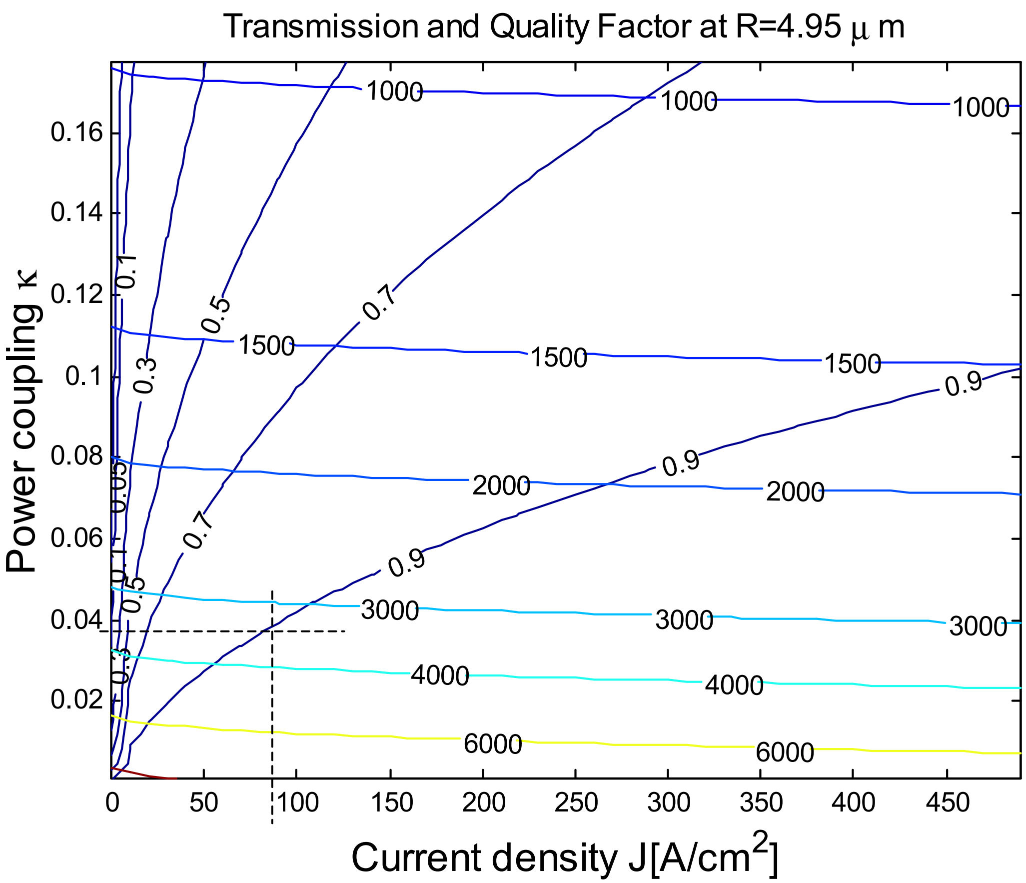
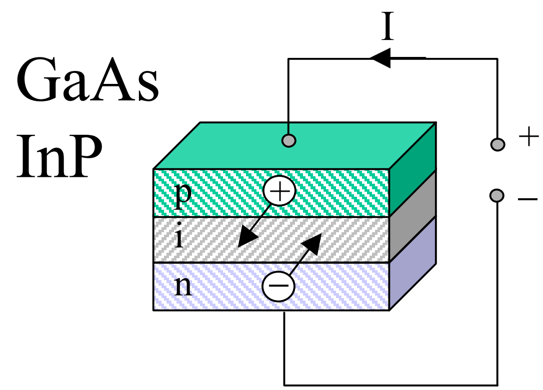


- **$\Delta g = 10 cm^{-1}$ can be achieved with $\Delta V < 0.1V$**

- **Easy to achieve**
- **Bandwidth limited by carrier lifetime**

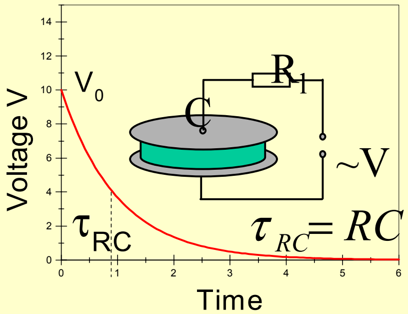
FC injection active region

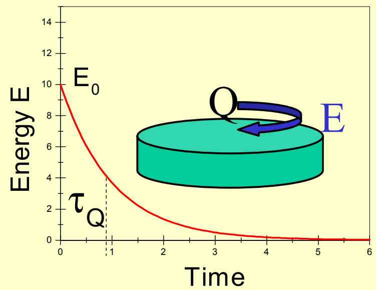




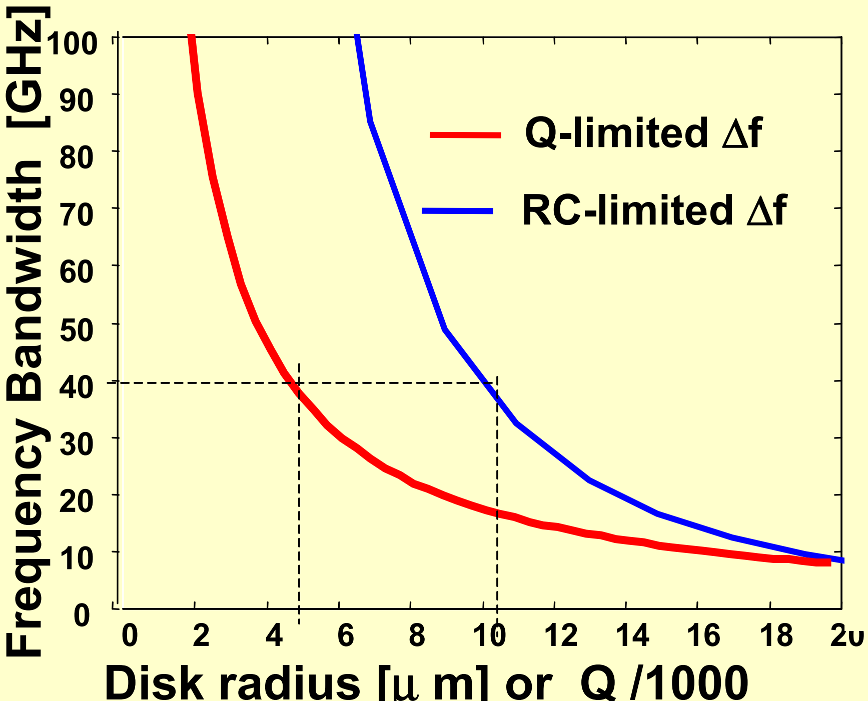
- $\Delta n(I)$, $\Delta\alpha(I)$
- CR=20dB for $\Delta J=80A/cm^2$
- R=5μm, I=200μA

Resonator Time Response





$$\Delta f \approx \frac{1}{\tau} = \frac{1}{\tau_{RC}} + \frac{1}{\tau_Q} + \frac{1}{\tau_N}$$



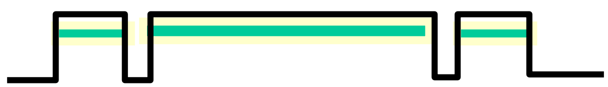
- For Δf 🕔 40GHz
  - Q<5000
  - R<10μm

Structure Design

- Vertical vs. lateral geometry
- Coupling coefficient calculation
  - Finding the modal field distribution
  - Calculation of κ for given structure
- Bus waveguide optimization

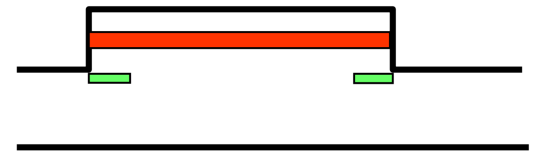
Resonator Designs

Lateral Coupling



- Air coupling and guiding.
- Difficult to integrate active and passive elements
- Submicron control of coupling.
- Submicron waveguide widths.
- Control of waveguide and resonator wall smoothness.

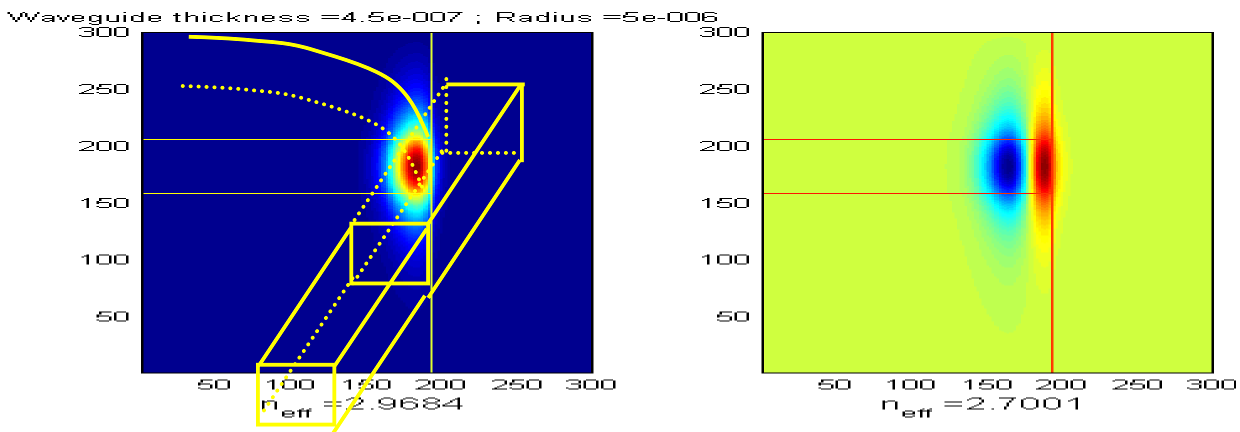
Vertical Coupling



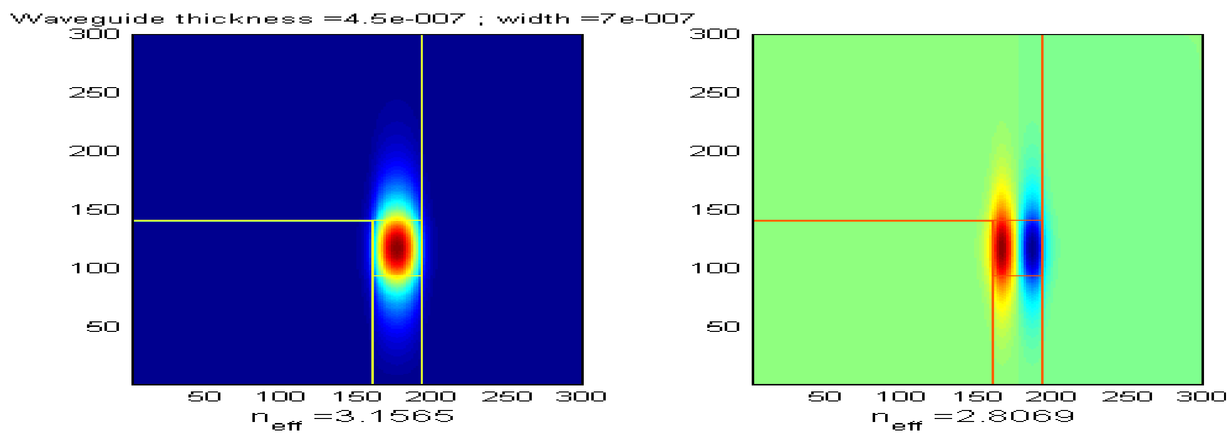
- Epilayer coupling.
- Integration of active and passive structures.
- Control coupling by epilayer thickness.
- Flexible single mode waveguide design.
- Separates resonator and coupler fabrication

Modal fields distribution

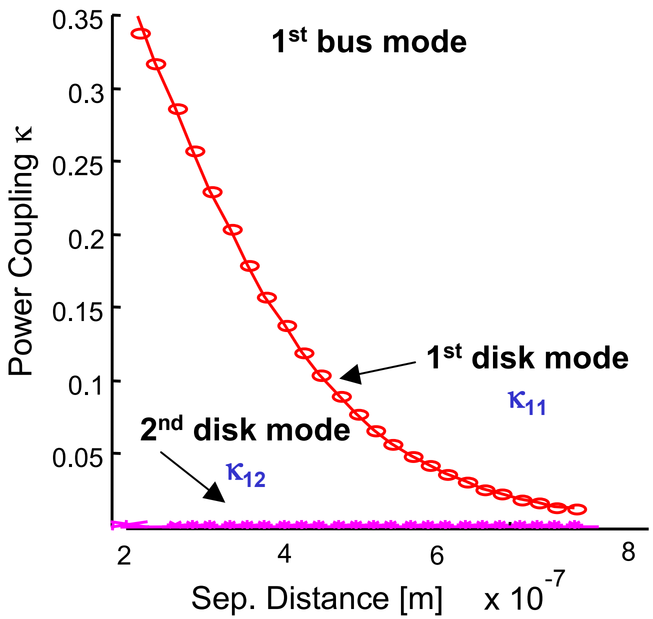
Disk:

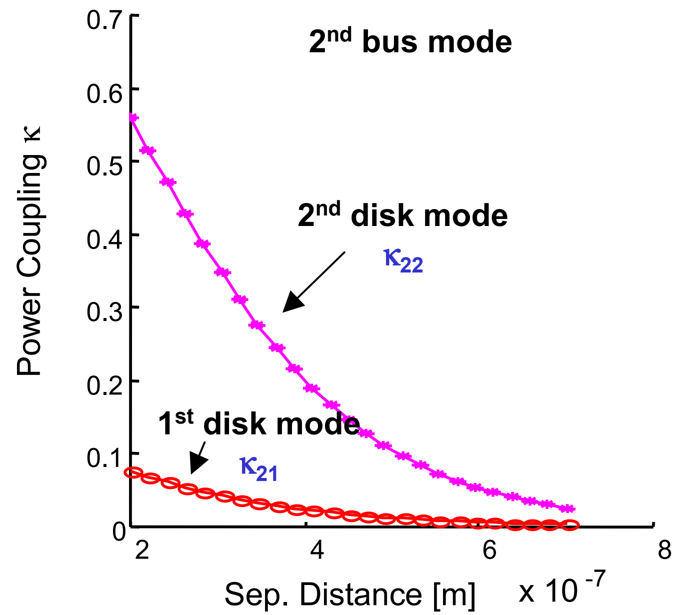


Bus waveguide:



Coupling Coefficient



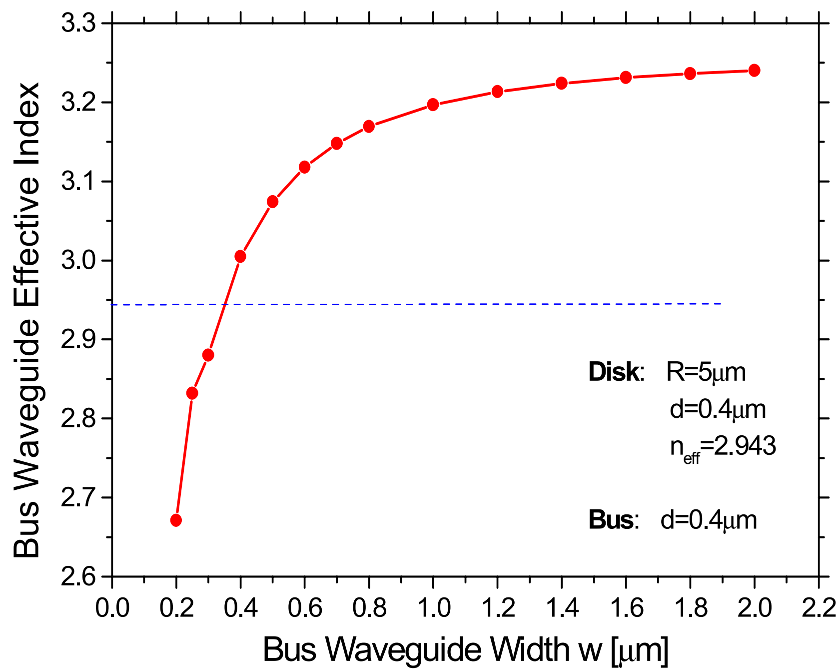


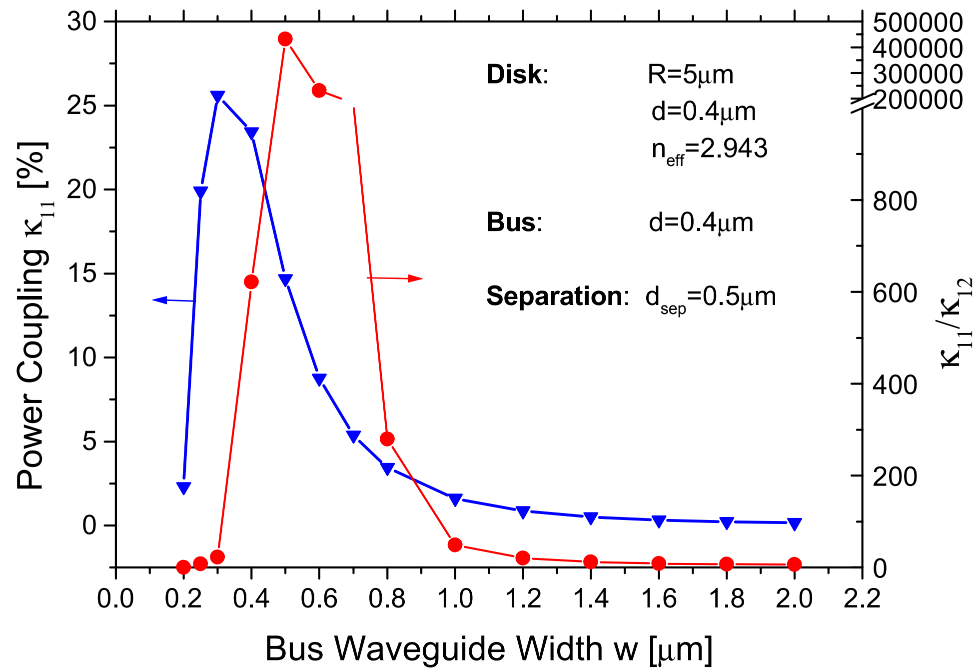
- **Choose the dimensions to suppress the cross-coupling**
- **Single mode waveguides and mode-matching**

Waveguide optimization

- Varying the width of the bus changes the mode index
- Phase matching at ***w*=0.35μm**, for the particular geometry

- Best coupling at phase-matched conditions
- The best suppression of cross-coupling is at ***w*=0.6μm**, for this geometry





Technology Objectives

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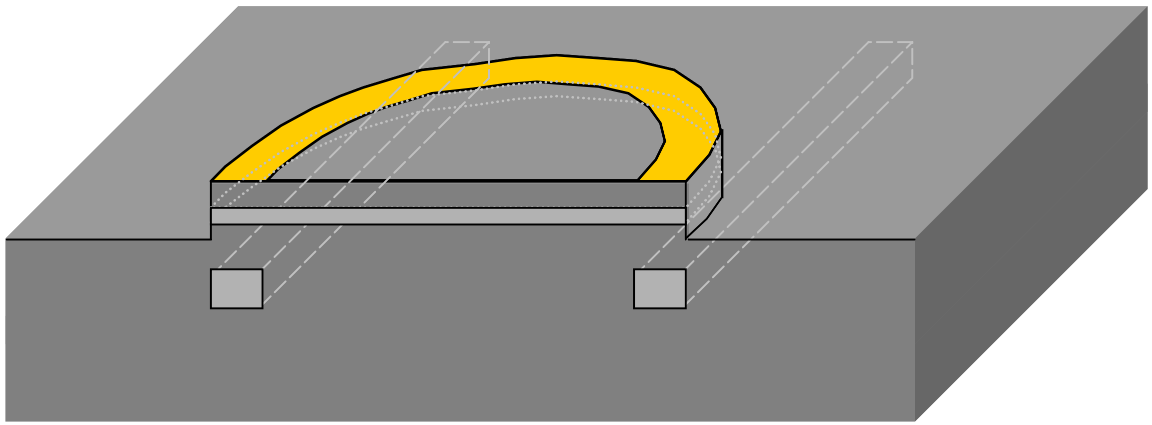


Uniform resonator potential / current flow

Single mode waveguides

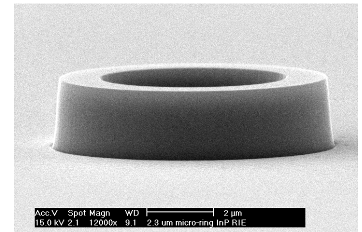
Coupling to single resonator mode

Low loss couplers to fiber

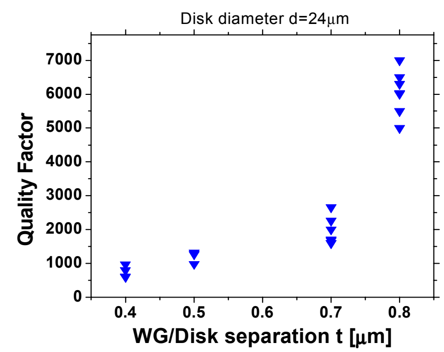
Loss and Q Control

- **Assess residual absorption in resonator**

✓**Minimize scattering at edges**
- **High Q resonators have been developed by careful optimization of the dry etching.**

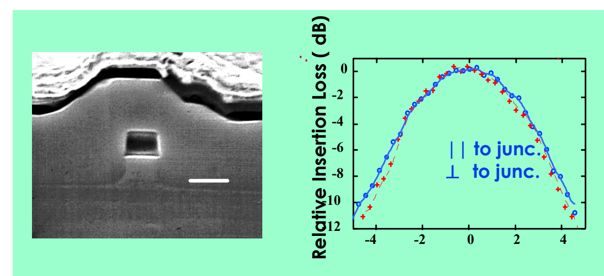


✓**Design controlled coupling**
- **Coupling controlled Q's have been achieved with vertically coupled structures.**



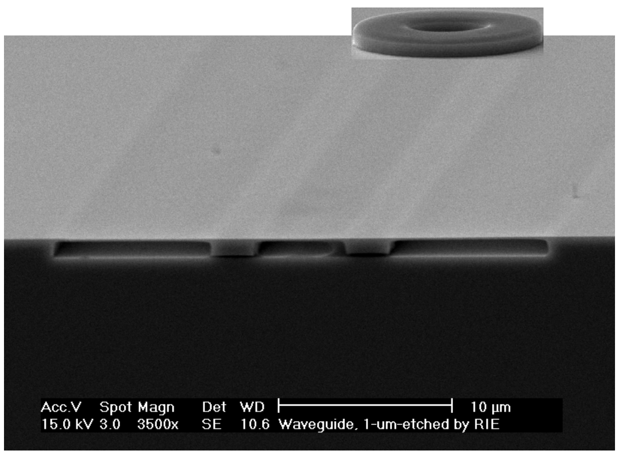
- **Minimize insertion loss**
- **Optimize mode matching**

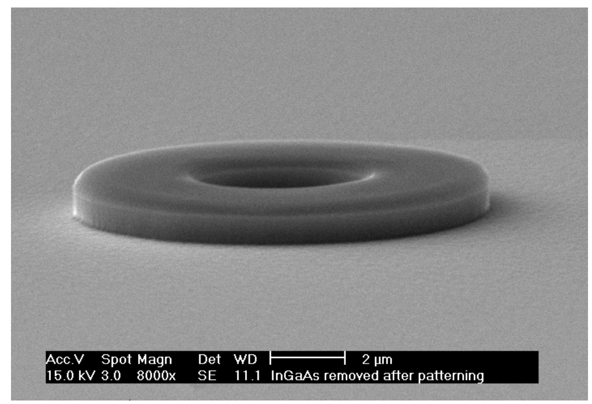
Mode couplers in design



Process Flow

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





High Q Resonators

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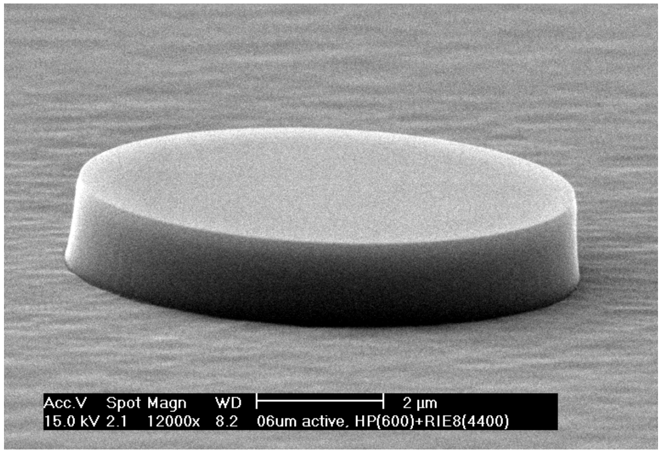

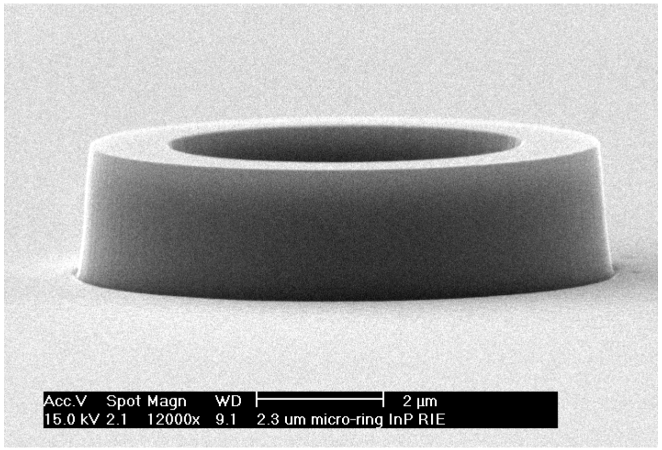

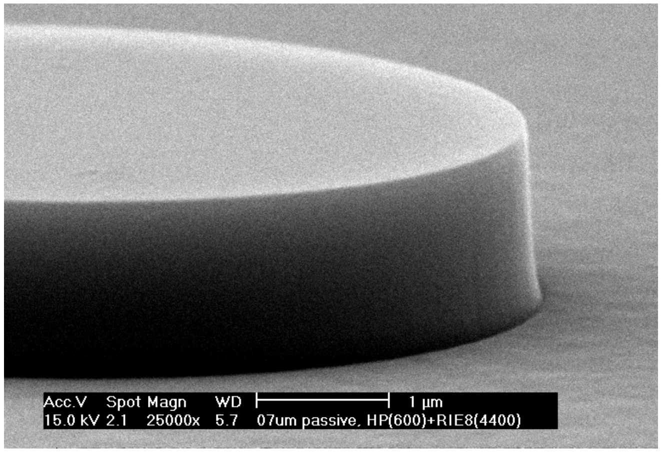

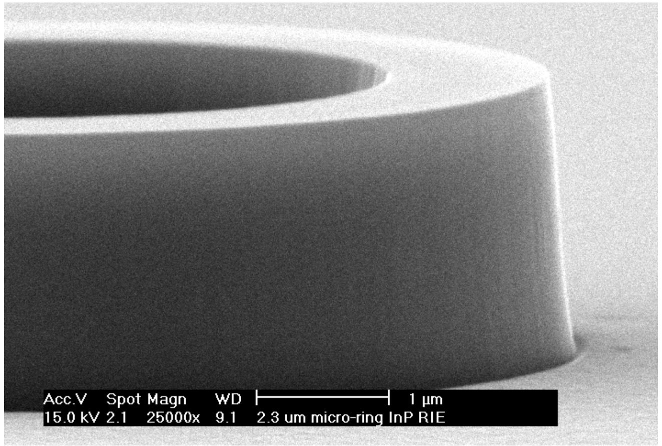

Coupling Limited Q's

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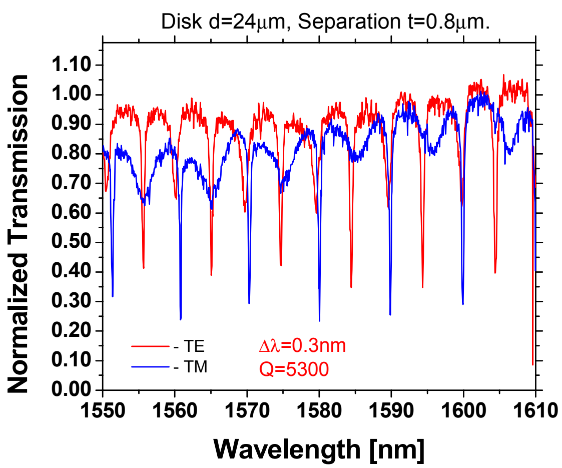
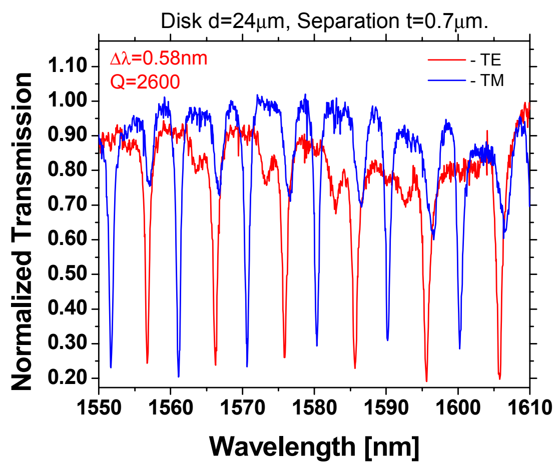
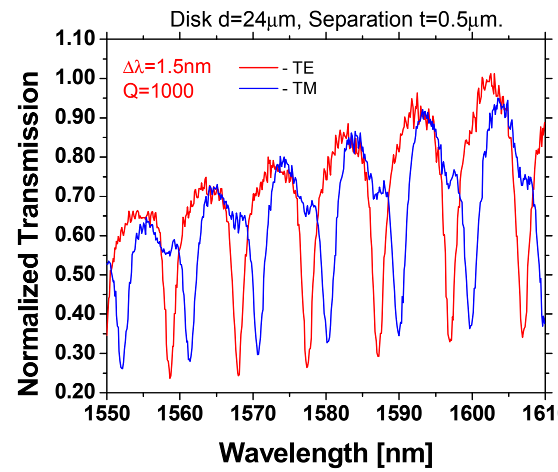
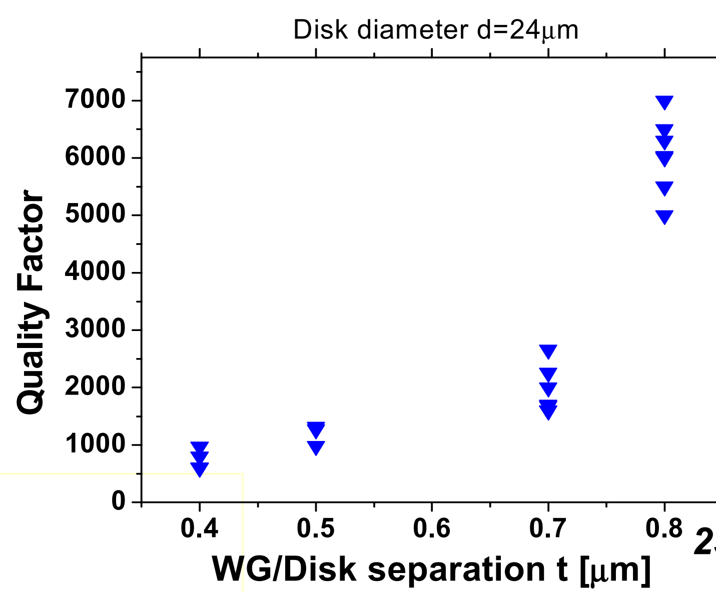






- Q is strongly dependent on vertical separation.
  - ➢ Critically coupled structures
- Resonance depth varies from sample to sample.
  - ➢ Lateral alignment is variable



July 30, 2001

Most Significant Accomplishment
0.22 nm Linewidth Resonator

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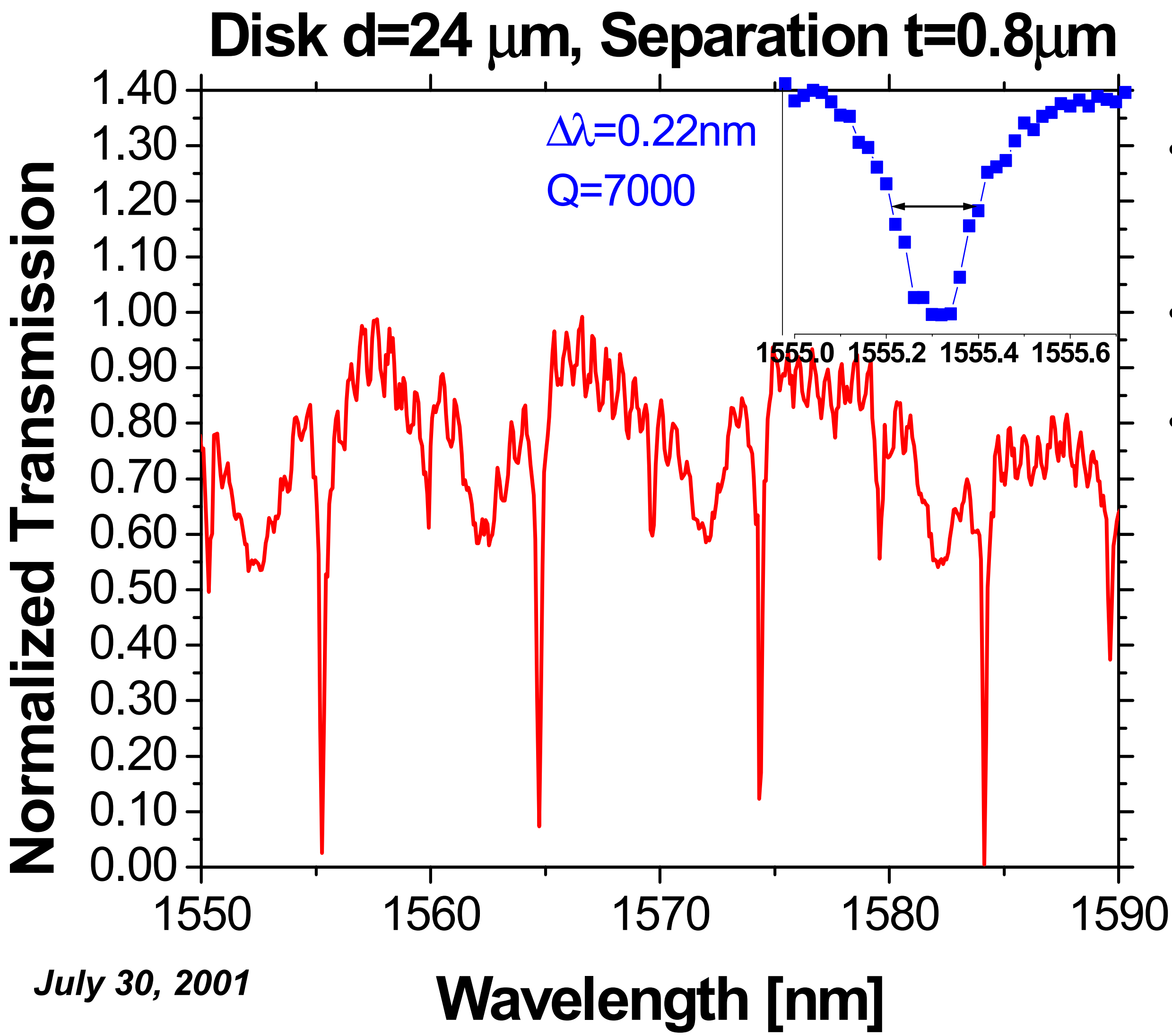

- Highest Q InP Resonator Demonstrated.
- > 90% power transfer.
- Critically coupled system.

Previously Demonstrated μ Disk Resonant Components

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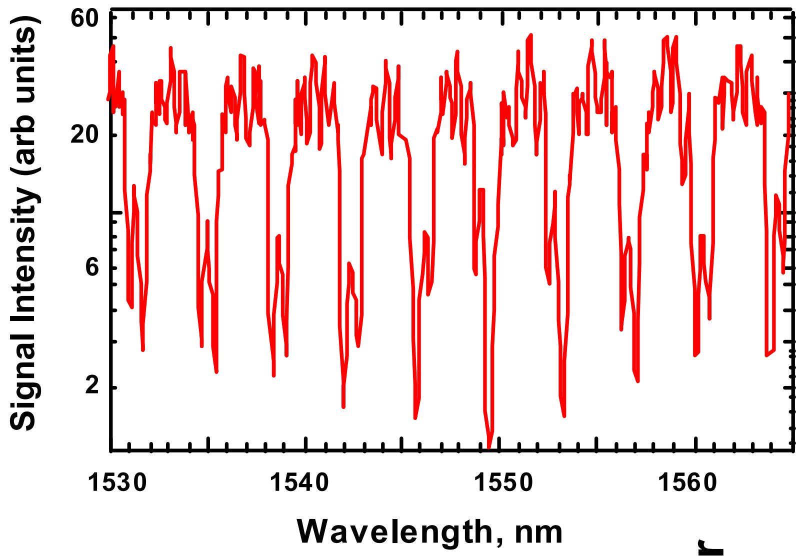
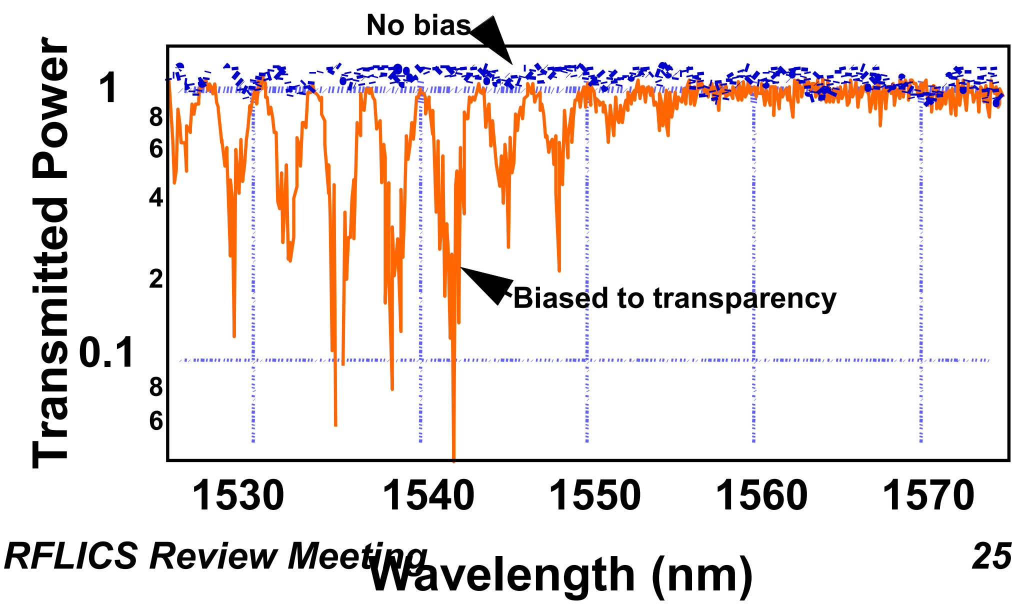


Passive μ disk coupler

Active μ disk tunable filter / switch



Deficiencies of Previous Designs

- Disk resonator and waveguides are multimode. This leads to closely spaced and degenerate resonances.
  Resolved in this program
- Resonators are suspended. This leads to poor uniformity of applied potential or current and poor heat sinking. Resolved in this program
- Resonator Q's are too low to support low voltage modulators. Resolved in this program
- Chip edge feedback is too large and must be reduced.
  Resolved in this program

Program Roadmap

- Task 1 Modeling of Modulator Design and Characteristics
  - Preliminary designs of EA and ER modulators. 3Q
  - Theoretically optimized coupling design. 8Q
- Task 2 Modulator Fabrication Technology Advancement
  - Resonator fabrication approach chosen. 4Q
  - Fabrication process optimized. 8Q
  - Vertical Integration approach choice. 10Q
- Task 3 Modulator Optimization
  - Residual loss near E_G characterized vs λ. 3Q
  - EA vs. ER choice made. 8Q
  - Ring vs Disk scattering loss measurement. 4Q
  - Measurement of Q-limited modulation limit. 10Q
  - Low resistance contact demonstrated. 4Q
  - Air bridge technology demonstration. 10Q
- Task 4 Modulator Demonstration, Characterization and Delivery
  - DC characterization setup complete. 4Q
  - High frequency modulation characterization setup complete. 6Q
  - Eight (8) low $V\pi$ modulators delivered in years 1-3 according to selected integrator. 12Q