Electromagnetically Induced Transparency with Hybrid Silicon-Plasmonic Travelling-Wave Resonators

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Presentation Outline

- **Introduction**
  - Plasmonic waveguides
  - Conductor-Gap-Silicon (CGS) waveguide
  - CGS-based passive components

- **CGS-based travelling-wave resonator filters**
  - Microring resonator filters
  - Comparison with coupled mode theory
  - Microdisk resonator filters

- **Electromagnetically Induced Transparency**
  - Two-microring-resonator structure
  - Comparison with coupled mode theory
  - Two-microdisk-resonator structure
  - Tunability / Switching Capabilities

- **Conclusion**
Introduction – Plasmonic Waveguides

Surface Plasmon Polaritons (SPP):  
Transverse magnetic (TM)-polarized optical surface waves

2D Plasmonic Waveguides:
✓ SPP mode is confined in the plane transverse to the direction of propagation
✓ Trade-off between mode confinement and propagation losses

Trade-off overview

Berini & De Leon, Nat. Phot., 2012
Introduction – Hybrid Plasmonic Waveguides

- **Key idea:** low-index dielectric “gap” **sandwiched** between a high-index medium and a conductor.
- Electric field $\rightarrow$ highly confined in the low-index **sub-wavelength** layer
- High-index ($\sim 3.5$) $\rightarrow$ Merging with **silicon platform**

Oulton et al., 2008, Nature Photonics.

Wu et al., 2010, Optics Express
CGS: “Conductor-Gap-Silicon”

- Planar version
- Efficient coupling with underlying SOI-waveguide

Concept: Dielectric cylindrical nano-wire separated by a metallic half-space with a dielectric “gap”
Introduction – CGS waveguide - Modal characteristics

Modal characteristics of the quasi-TM fundamental mode:

- $E_y$ dominant component
- Confinement in the SiO$_2$ gap
- Small effective mode area: $A_{\text{eff}} = 0.0217 \, \mu$m$^2$
- Effective refractive index: $n_{\text{eff}} @ 1550\text{nm} : 2.034-0.002i$
- Low propagation losses ($L_{\text{prop}} \approx 60 \, \mu$m)
- Axial component in Si region

**Strong optical field confinement and limited propagation losses**
Introduction – CGS-based components

Passive CGS-based components:

- Taper Couplers
- Waveguide Bends
- Splitters

Wu et al., Opt. Express 18, 2010

Wavelength-selective components

- Ring/Disk resonators
- Add-drop filters

Song et al., J. Opt., 2011
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Microring Resonator – Eigenvalue Analysis

✓ Sub-micron resonator footprint
  Outer ring radius: 930 nm

✓ Relatively high intrinsic Q
  At 1556 nm ➔ Q=355

Eigenvalue analysis results

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>1418</th>
<th>1556</th>
<th>1743</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuthal mode number (m)</td>
<td>8</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Q</td>
<td>675</td>
<td>355</td>
<td>175</td>
</tr>
</tbody>
</table>

Re(\(E_y\)) on a mid-plane of SiO₂ gap

Modes tightly confined – Candidate for filtering applications
Microring Resonator – Lightwave filtering (1/2)

- Radius = 0.93 μm
- gap = 120 nm ➔ Critical coupling achieved
- High loaded quality factors: Q > 120
- Free Spectral Range: $\Delta \lambda_{FSR} \approx 140$ nm
- Minimal insertion loss (IL < 0.2 dB)

Efficient lightwave filtering
Microring Resonator – Lightwave filtering (2/2)

Comparison between propagation and eigenvalue analysis

<table>
<thead>
<tr>
<th>Azimuthal mode number $m = 7$</th>
<th>Azimuthal mode number $m = 8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue Analysis (unloaded)</td>
<td>Eigenvalue Analysis (loaded)</td>
</tr>
<tr>
<td>$\lambda_{res}$ (nm)</td>
<td>1556</td>
</tr>
<tr>
<td>Quality Factor</td>
<td>355</td>
</tr>
</tbody>
</table>

- In the presence of the bus waveguide the resonance wavelength is slightly reduced (Coupling-Induced resonance Frequency Shift-CIFS) whereas the quality factor decreases due to coupling.

- Resonance wavelengths and quality factors for the loaded eigenvalue problem and the propagation analysis are in very good agreement.

Excellent agreement between eigenvalue and propagation results
Coupled Mode Theory in time

\[ \frac{da(t)}{dt} = j\omega_L a(t) - \frac{1}{\tau} a(t) - j|\kappa|s_i \]

- \( s_i, s_t \): Waveguide mode amplitudes
- \( |a(t)|^2 \): Energy stored in the cavity
- \( |\kappa| \): Coupling Coefficient
- \( \omega_L \): Loaded cavity resonant frequency
- \( 1/\tau \): Decay rate for the loaded resonator

Comparison between FEM and CMT

- CMT fed with intrinsic and loaded quality factors
- Good agreement between CMT and FEM response
- CMT: Useful prediction tool
CMT needs only two FEM eigenvalue analyses for each resonance

- Eigenvalue analysis of **uncoupled** ring resonator
- Eigenvalue analysis of ring **coupled** to waveguide

\[
\begin{align*}
Q_{\text{intrinsic}} & \quad \left| \kappa \right| \\
Q_{\text{loaded}} & \quad 1/\tau \\
\omega_L & \\
Q_{\text{waveguide}}
\end{align*}
\]

- CMT fed with eigenvalue FEM simulation results
- Clear indication of the transmission spectrum before the time consuming FEM simulation
- Beneficial for more complex structures
Microdisk Resonator – Eigenvalue Analysis (1/2)

✓ An alternative to the ring resonator
✓ Lower radiation losses (absence of inner boundary)
✓ Busy spectrum due to possible excitation of higher radial order modes

- High quality factor
  - At 1550 nm \( \Rightarrow Q \approx 1000 \)
- Higher radial order modes

### Eigenvalue analysis results

<table>
<thead>
<tr>
<th>( \lambda ) (nm)</th>
<th>1421.2</th>
<th>1447.8</th>
<th>1464.2</th>
<th>1563.9</th>
<th>1599.4</th>
<th>1614.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuthal mode number (m)</td>
<td>8</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Radial mode number (n)</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>( Q )</td>
<td>1700</td>
<td>186</td>
<td>1650</td>
<td>920</td>
<td>615</td>
<td>105</td>
</tr>
</tbody>
</table>

Submicron footprint
Disk radius: 850 nm

Re(\( E_y \)) on xz-planes

1. \( m=8 \) \( n=1 \)
2. \( m=5 \) \( n=2 \)
3. \( m=7 \) \( n=1 \)
4. \( m=7 \) \( n=1 \)
5. \( m=6 \) \( n=1 \)
6. \( m=4 \) \( n=2 \)
Microdisk Resonator – Eigenvalue Analysis (2/2)

$|E|^2$ on a vertical $xy$-plane

- First-radial order modes: 1, 4
- Second-radial order modes: 2, 6
- Photonic modes located in Si layer: 3, 5

The transmission spectrum of a filtering structure using disk resonators is expected to be more complex.
Microdisk Resonator – Lightwave filtering

- Radius=0.85μm – Footprint < 1μm²
- gap=120nm

- High quality factors: Q>160
- Minimal insertion loss (IL < 0.5 dB)

Can second-radial-order modes located in the SiO₂ gap be eliminated using a “donut” shape?

1 & 4 : First-radial-order SiO₂ gap modes
2 & 6 : Second-radial-order SiO₂ gap modes
3 & 5 : First-radial-order Si modes
Donut Resonator – Lightwave filtering

✓ Radius=0.85µm – Submicron footprint
✓ gap=120nm

☐ High quality factors: Q>160
☐ Minimal insertion loss (IL < 0.5 dB)

Second-radial-order modes located in the SiO₂ gap be eliminated using a “donut” resonator

1 & 4: First-radial-order SiO₂ gap modes
2 & 6: Second-radial-order SiO₂ gap modes
3 & 5: First-radial-order Si modes
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Electromagnetically Induced Transparency - EIT

Photonic analogs of Electromagnetically Induced Transparency

Standing-wave resonator structures

- Lu et al., Optics Letters, 2011

Travelling-wave resonators

- Silicon photonics
- Control the EIT resonance based on the adjustment of the spacing between detuned rings

EIT-Response with hybrid silicon plasmonic travelling-wave resonators
Slightly detuned resonators ($R_0 = 1.3 \ \mu m$)

$\delta r = 5nm / \delta \lambda_{res} = 9nm$

Phase accumulating between the detuned resonators

$\varphi = \omega n_{eff} s / c$

For distances $s = m\lambda_g = m\lambda_0 / n_{eff}$

Symmetric EIT-like response

FEM analysis for three detuning scenarios

<table>
<thead>
<tr>
<th>$\delta \lambda_{res} (nm)$</th>
<th>9</th>
<th>18.5</th>
<th>21.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{peak}$</td>
<td>345</td>
<td>165</td>
<td>100</td>
</tr>
<tr>
<td>Extinction Ratio (dB)</td>
<td>6.6</td>
<td>11.5</td>
<td>13</td>
</tr>
</tbody>
</table>
EIT-like Response – Parametric Analysis

Varying gap size

- Higher $Q_{peak}$ values for longer gaps but lower extinction
- Transmission minima change (critical coupling)

Mismatched interelement spacing

- EIT peak moves to different directions for ±50nm mismatch.
- Sharper peaks suffer more from mismatched distances.
EIT-like Response – Comparison with Coupled Mode Theory

**Coupled Mode Theory in time**

\[
\frac{da_1(t)}{dt} = j\omega a_1(t) - \frac{1}{\tau_1} a_1(t) - j|k_1|s_{1i} - j|k_1|s_{2r}
\]

\[
\frac{da_2(t)}{dt} = j\omega a_2(t) - \frac{1}{\tau_2} a_2(t) - j|k_2|s_{2i}
\]

**CMT fed with intrinsic and loaded quality factors**

- 4(+1) eigenvalue problems solved
  - Unloaded and loaded eigenvalue analysis for each resonator
  - + Waveguide eigenvalue problem

**Comparison between FEM and CMT**

- Good agreement between CMT and FEM response

\[\delta r = 5\text{nm}\]
Detuned disk resonators ($R_0 = 0.85 \, \mu m$)

$\delta r = 5 \, nm$ / $\delta \lambda_{res} = 15.5 \, nm$

- **EIT-like response**
  - Higher values of $Q_{peak}$ than ring resonator configuration
  - Observable transparency peak for even $\pm 3 \, nm$ radius detuning

<table>
<thead>
<tr>
<th>$\delta \lambda_{res} (nm)$</th>
<th>9.4</th>
<th>15.5</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{peak}$</td>
<td>390</td>
<td>195</td>
<td>125</td>
</tr>
<tr>
<td>Extinction Ratio (dB)</td>
<td>9.4</td>
<td>11.8</td>
<td>12.9</td>
</tr>
</tbody>
</table>
Tunability / Switching Capabilities

Thermo-optic effect

**Si**: Thermo-optic coefficient (TOC) $\sim 1.8 \times 10^{-4}$

- $\Delta \lambda_{res} \sim 4$ nm shift for $\Delta T = 60$ K
- 1560nm: Extinction ratio $\sim 8$ dB
- EIT peak is replaced by a minimum transmission region

**Heating**:

- Current passing through Si region
  - $E$ axial component located in the Si layer
- Heating stages
  - Ag layer can be used
Conclusions

- Advantageous characteristics of disk resonators for filtering applications
  - Donut structure for a cleaner transmission spectrum
- EIT-like spectrum responses using hybrid plasmonic travelling-wave resonators
  - Disk resonators offer higher $Q_{peak}$ values
- Simulation responses ‘predicted’ using a CMT-based analysis fed by FEM eigenvalue simulation results
- Tunability through thermo-optic effect - Switching capabilities

Thank you!