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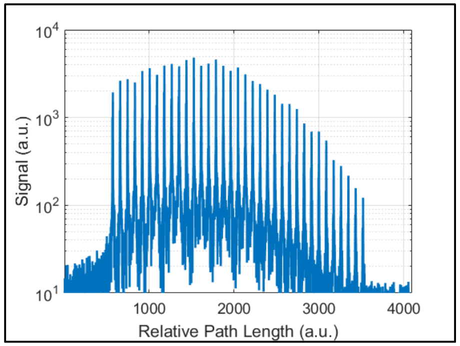

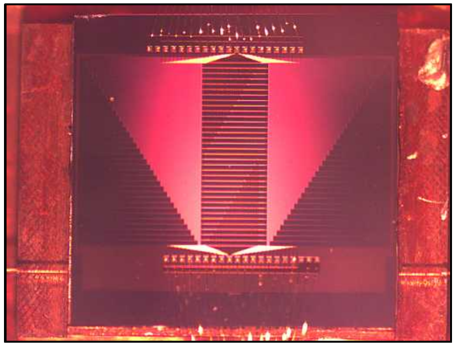

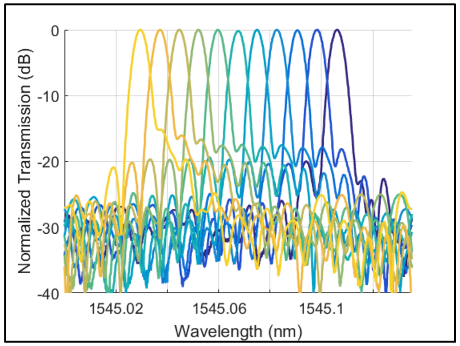

High Resolution Silicon Arrayed Waveguide Gratings for Photonic Signal Processing Applications

Michael Gehl, Doug Trotter, Andrew Starbuck, Andrew Pomerene, Anthony Lentine, Christopher DeRose

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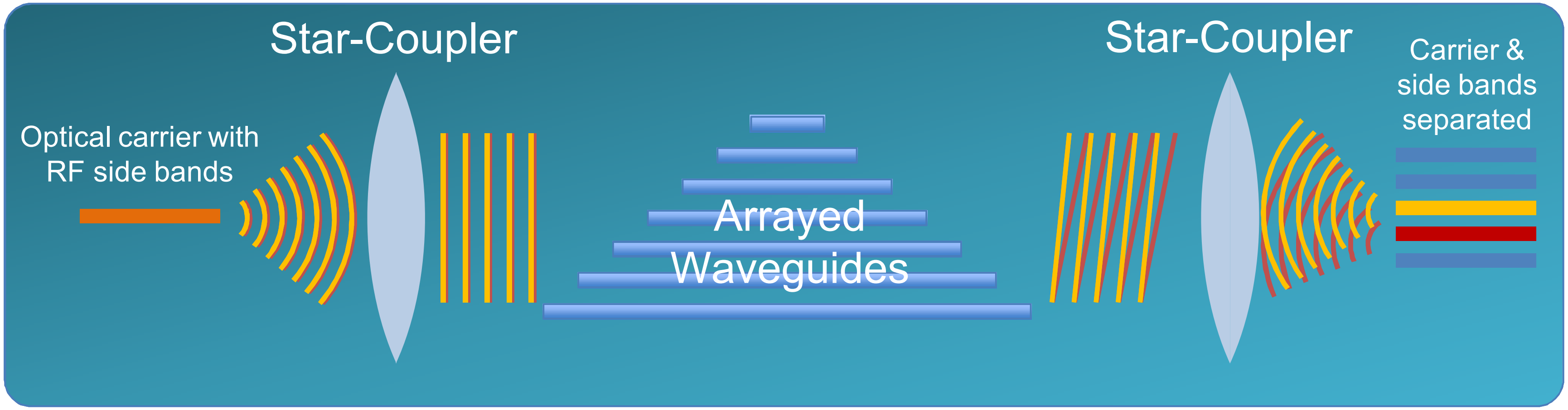
Outline

- Introduction to Arrayed Waveguide Gratings
- Design & Fabrication
- Characterization by Swept Source Interferometry
- Phase Optimization
- Application
- Conclusion

Arrayed Waveguide Grating

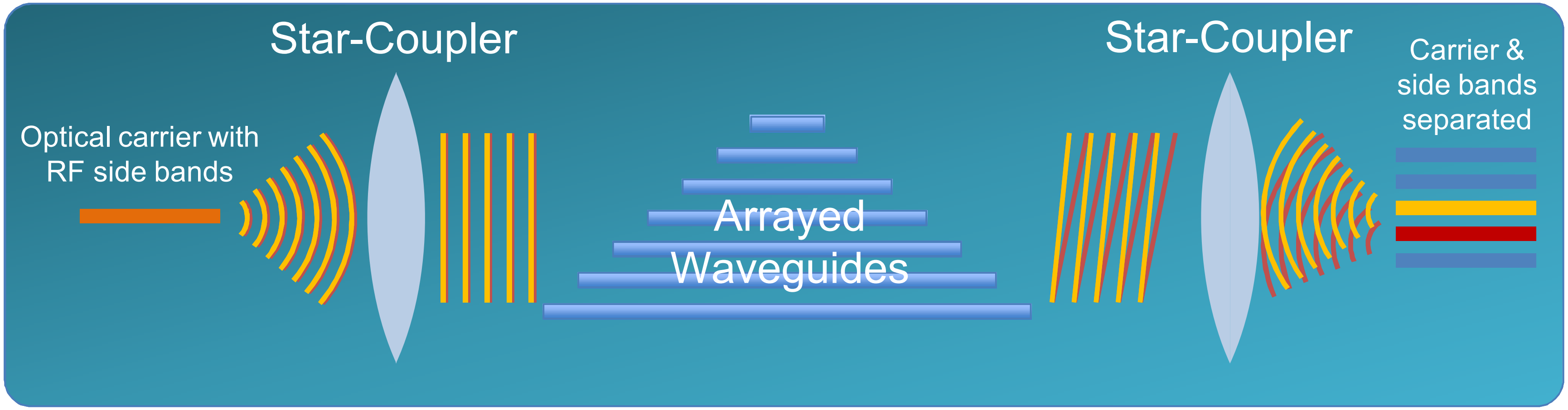
Functionality of an Arrayed Waveguide Grating



- Arrayed waveguide gratings provided integrated spectral filtering
- Bending optical path creates highly compact devices
- Applications
  - RF signal processing
  - Wavelength division multiplexing
  - Spectral and Temporal Pulse Shaping

Arrayed Waveguide Grating

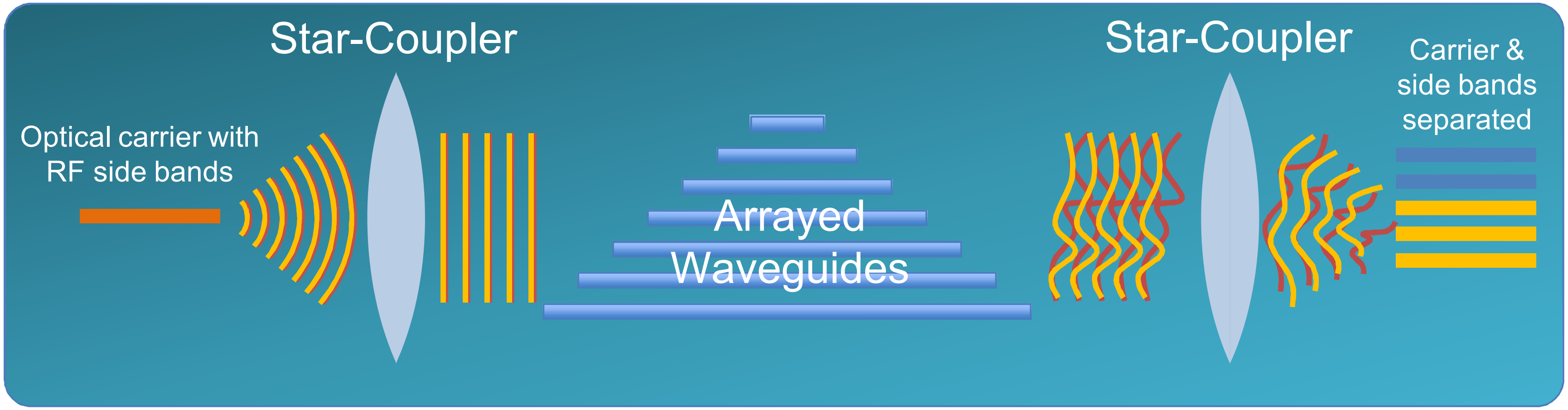
Functionality of an Arrayed Waveguide Grating



- State-of-the-art
  - 1GHz, 16 Channel Silica on Silicon– A ~ 44 cm^2 [K. Takada, et. al. *J. Lightwave Tech.* **20**, 850 (2002)]
  - 25GHz, 512 Channel SOI – A ~ 1.8 cm^2 [S. Cheung, et. al. *J. Sel. Top. Quant. Electronics* **20**, 8202207 (2014)]
  - 10GHz, 100 Channel InP – A ~ 10 cm^2 [F. M. Soares, et. al. *Photonics J.* **3**, 975 (2011)]
  - 25GHz, 400 Channel Silica – A ~ 80cm^2 [Y. Hida, et. al. *Proc. Opt. Fiber Comm. Conf.* **3**, WB2-1 (2001)]
- Cutting-Edge Result (this work):
  - **1GHz, 11 Channel SOI – A ~ 1.1 cm^2** [M. Gehl, et. al. *Opt. Express* **25**, pp. 6320-6334 (2017)]

Optical Phase Errors

Functionality of an Arrayed Waveguide Grating



- Fabrication imperfections create random phase perturbations
  - Perturbations in waveguide width (δw)
  - Perturbations in material index (δn)
- Phase uncertainty increases with waveguide length and index contrast

$$\sigma^2(\delta\phi) = L^2\left(A \cdot \Delta^3 \cdot \sigma^2(\delta w) + B \cdot \sigma^2(\delta n)\right)$$

$$\Delta = \frac{\left(n_{core}^2 - n_{clad}^2\right)}{2n_{core}^2}$$

- Light no longer "focuses" to a single waveguide
  - Increased insertion loss
  - Increased cross-talk

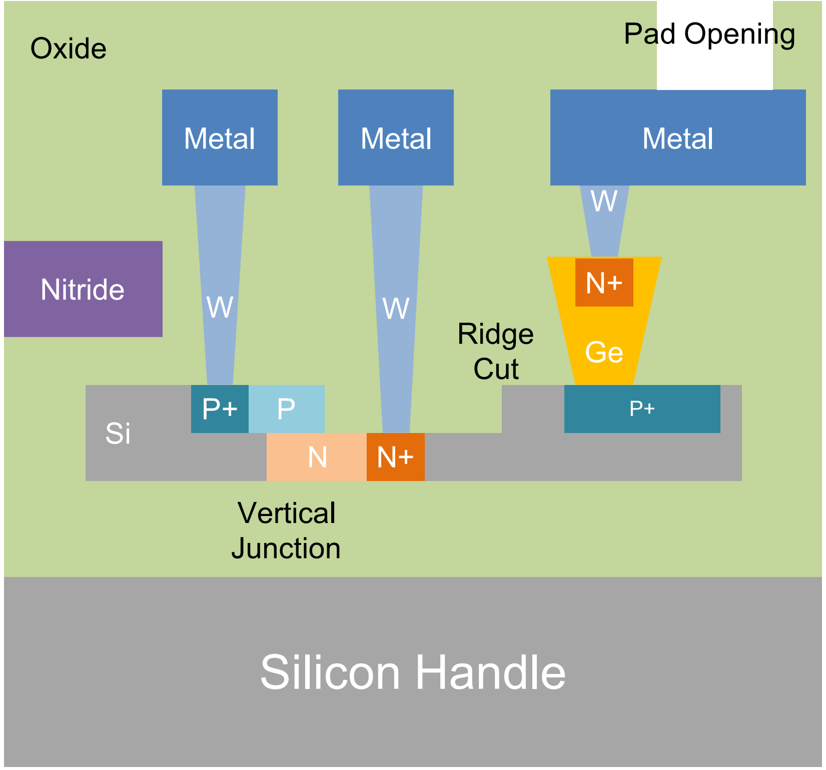
Methods of Phase Correction

- Passive Methods
  - Static Phase Correction
    - Benefit – No power required to maintain correction
    - Disadvantage – Irreversible, Challenging implementation
  - UV Irradiation [K. Takada, et. al. *Electron. Lett.* **36**, 60 (2000)]
  - Photo-Elastic Effect [H. Yamada, et. al. Electron. Lett. **32**, 1581 (1996)]
  - Phase Compensating Plate [H. Yamada, et. al. Electron. Lett. **33**, 1698 (1997)]
- Active Methods
  - Dynamically Applied Phase Correction
    - Benefit – Reversible, Allows active tuning and spectral shaping
    - Disadvantage – Requires constant power
  - Electro-Optic [W. Jiang, et. al. *Laser & Electro-Optics Society*, p. 52 (2008)]
  - Thermo-Optic [H. Yamada, et. al. Electron. Lett. **31**, 360 (1995)], [This Work]

Silicon Photonics Platform

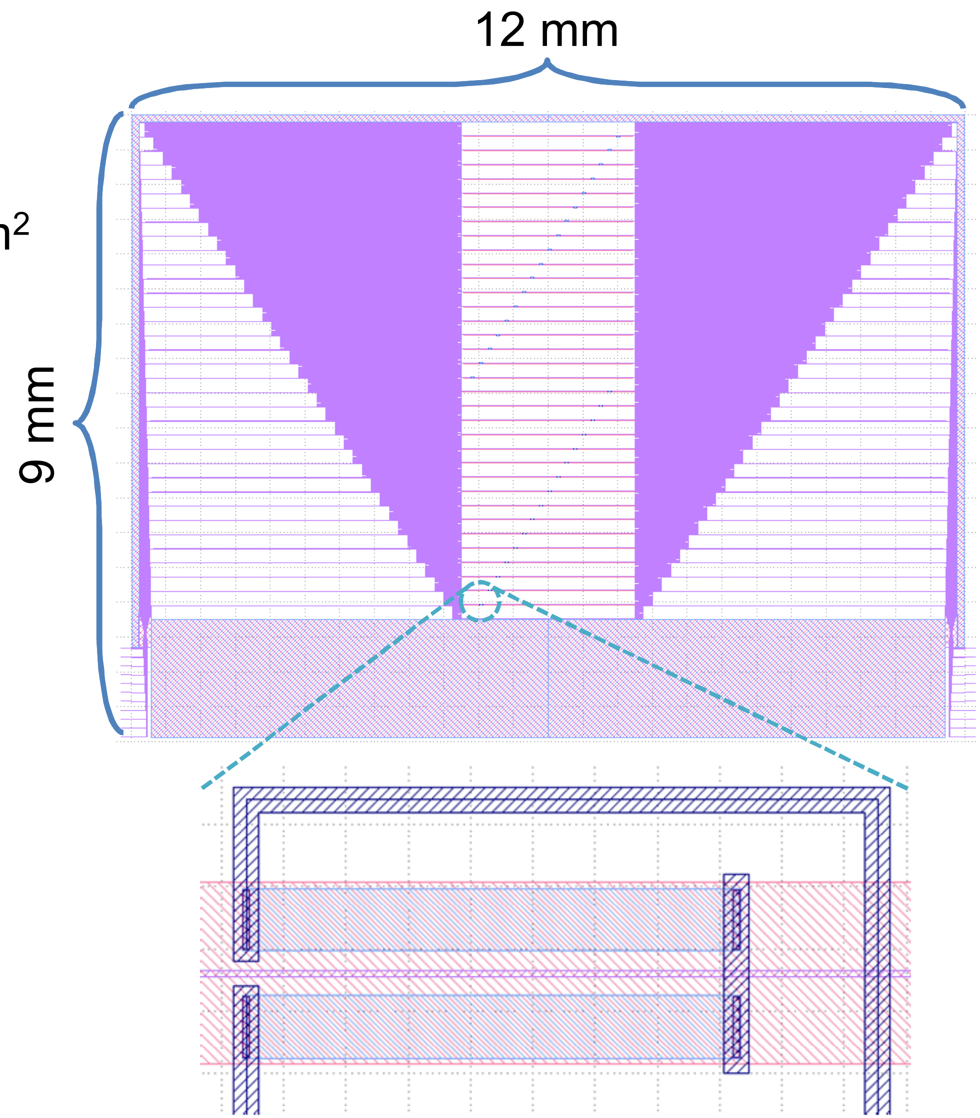
Silicon Photonic Process at the MESA Facility

- 6 in. SOI wafers, 250nm device layer, 3 µm buried oxide layer
- Fully or partially etched silicon for rib or ridge waveguides
- 225nm low loss silicon nitride waveguide layer
- Selective area germanium epitaxy for photodiodes
- 4-6 ion implantation steps
- 1-2 aluminum metal layers

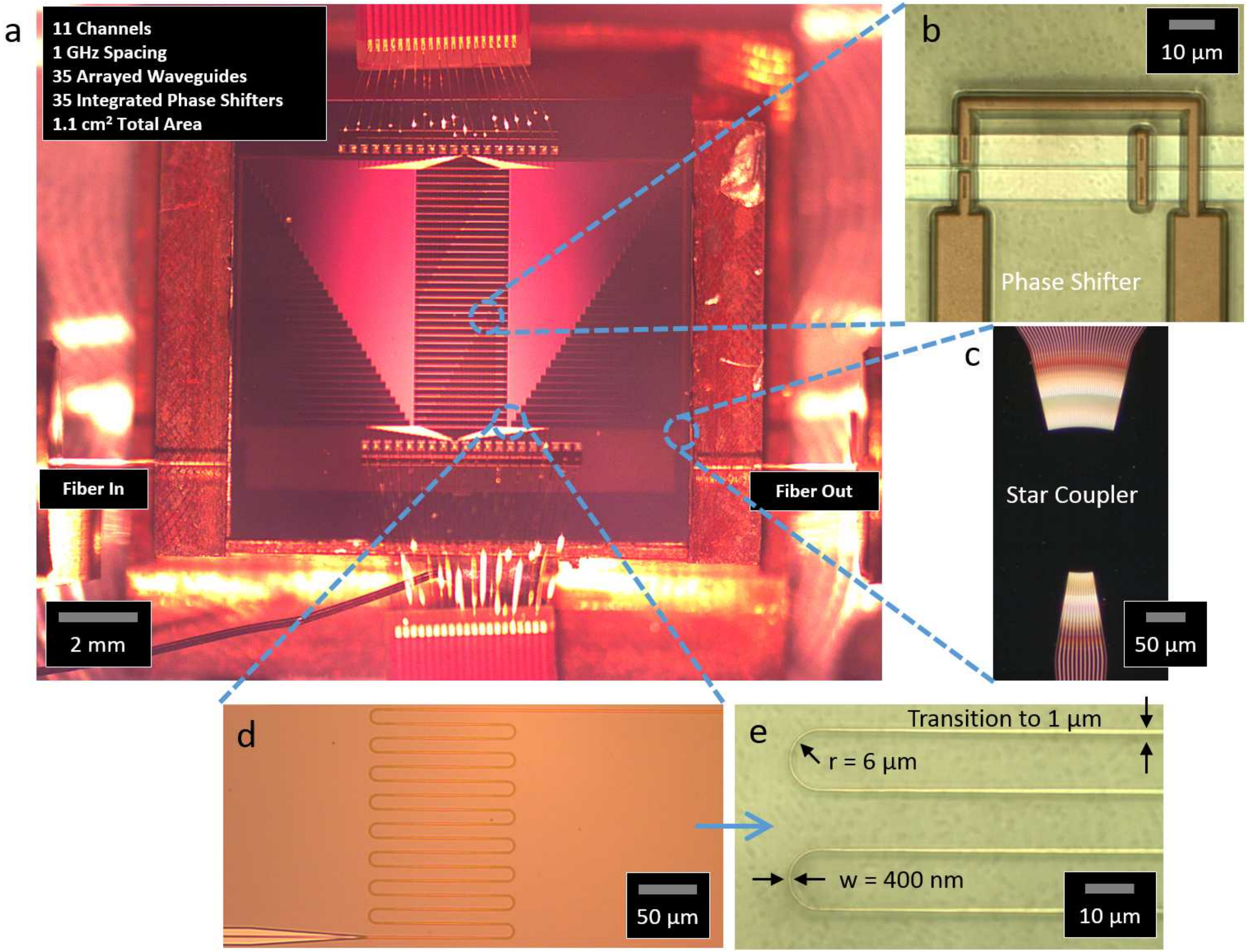


AWG Design

- Serpentine waveguides for compactness
  - Largest – 12 mm x 9 mm = 1.1 cm^2
- 35 Arrayed waveguides
- 1, 10 & 50 GHz channel spacing
- Resistive thermal phase shifter for each waveguide
  - Thermo-optic effect changes effective path length of the waveguide
  - Phase shift approximately proportional to applied power

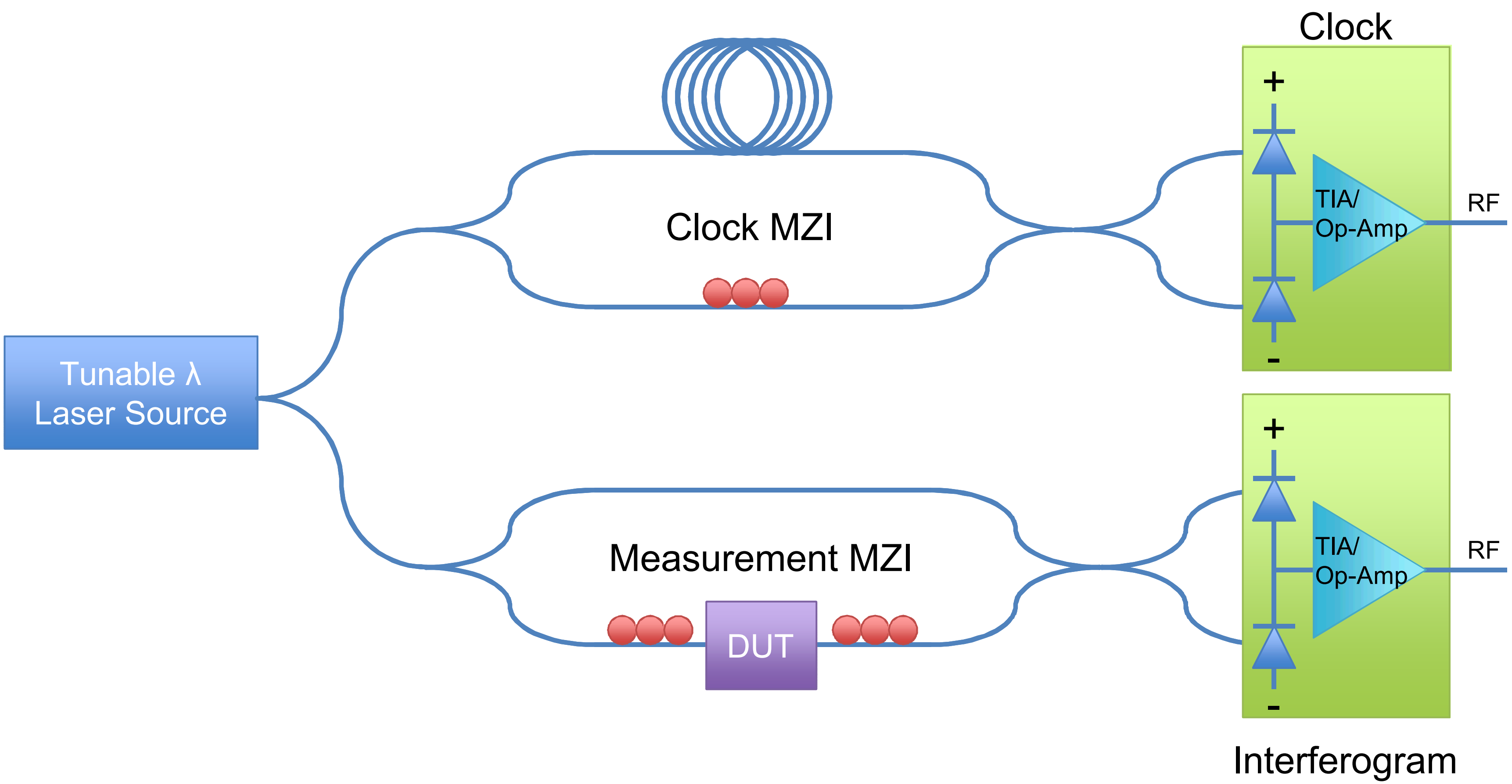


Device Fabrication & Packaging



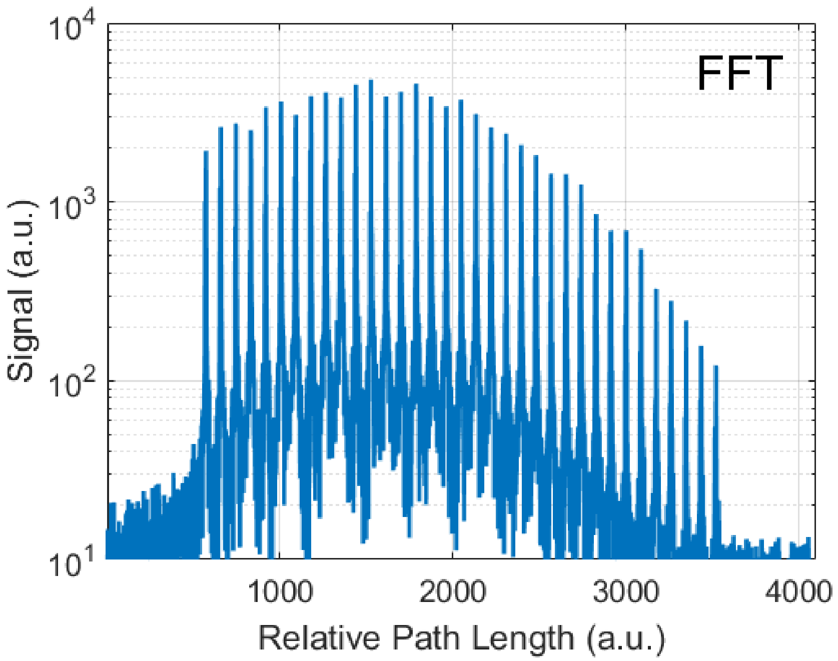
Interferometric Characterization

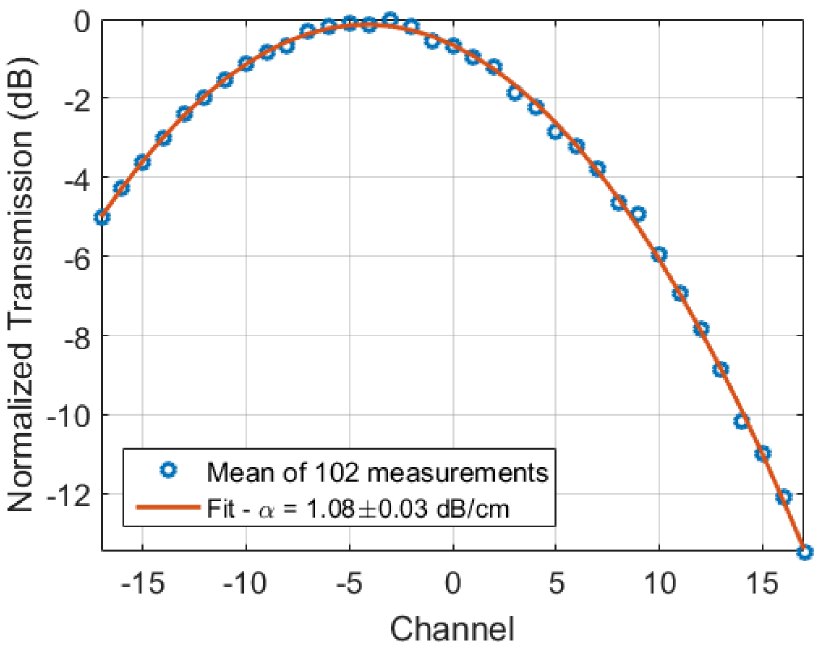
- Swept source interferometer
- Reference MZI to trigger data acquisition
  - $\Delta\lambda \approx 11.278 \text{ fm} \rightarrow \Delta\nu \approx 1.406 \text{ MHz}$



Interferometric Characterization

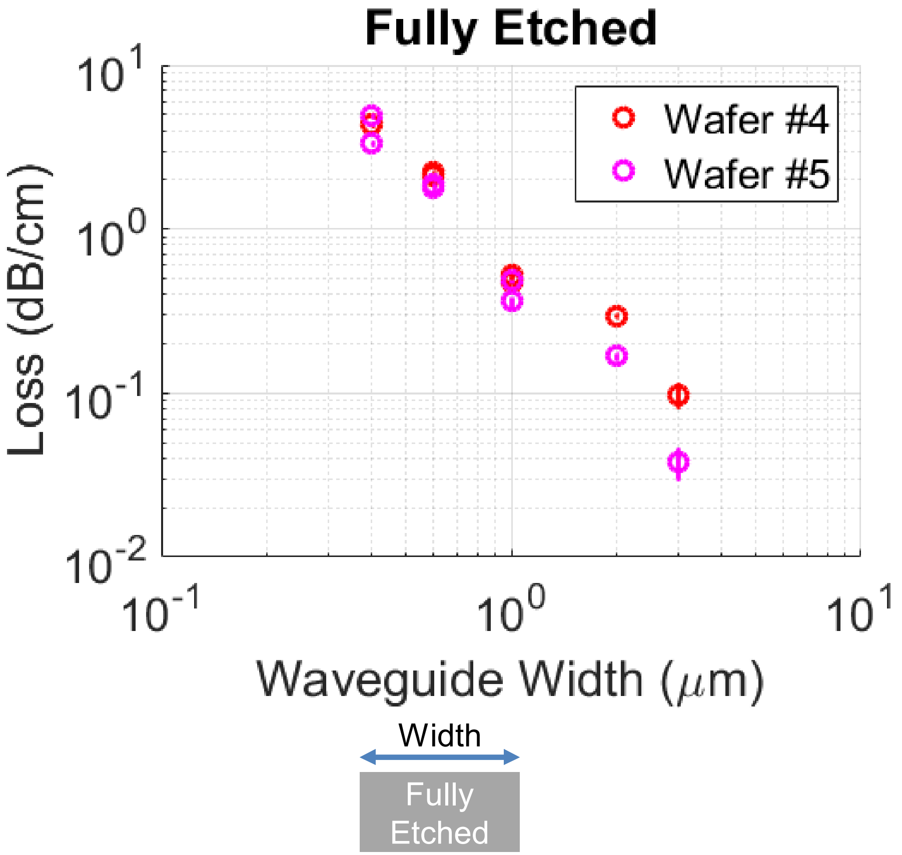
- FFT of interferogram provides phase and amplitude transmission of each optical path through device

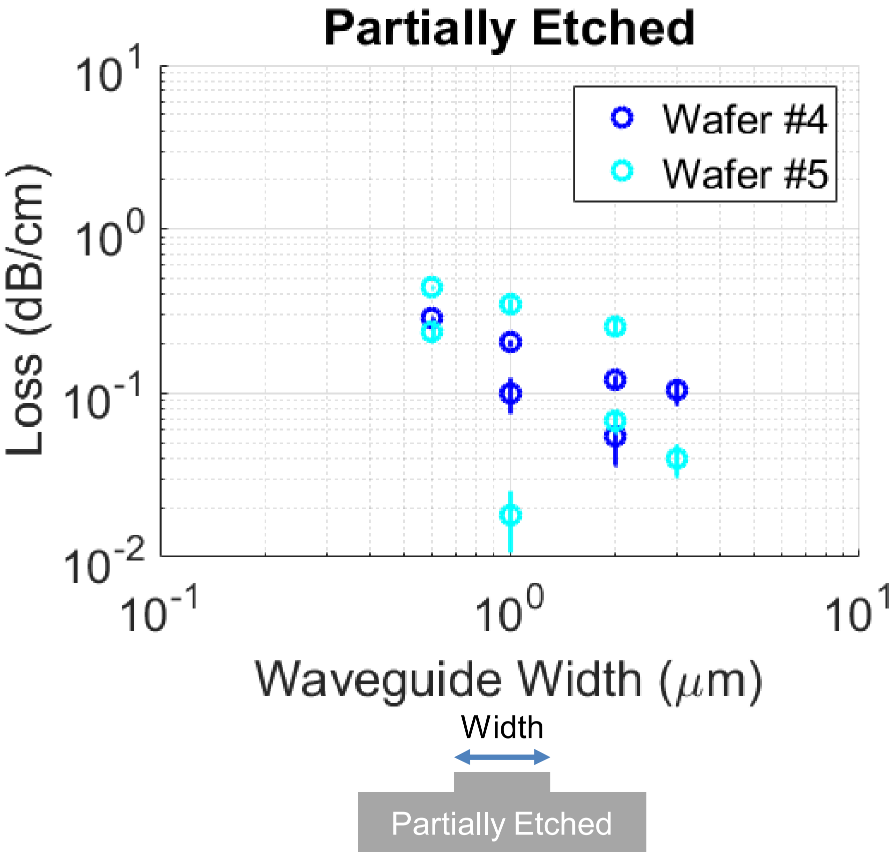




Interferometric Characterization

- From this we can accurately extract waveguide loss and group index





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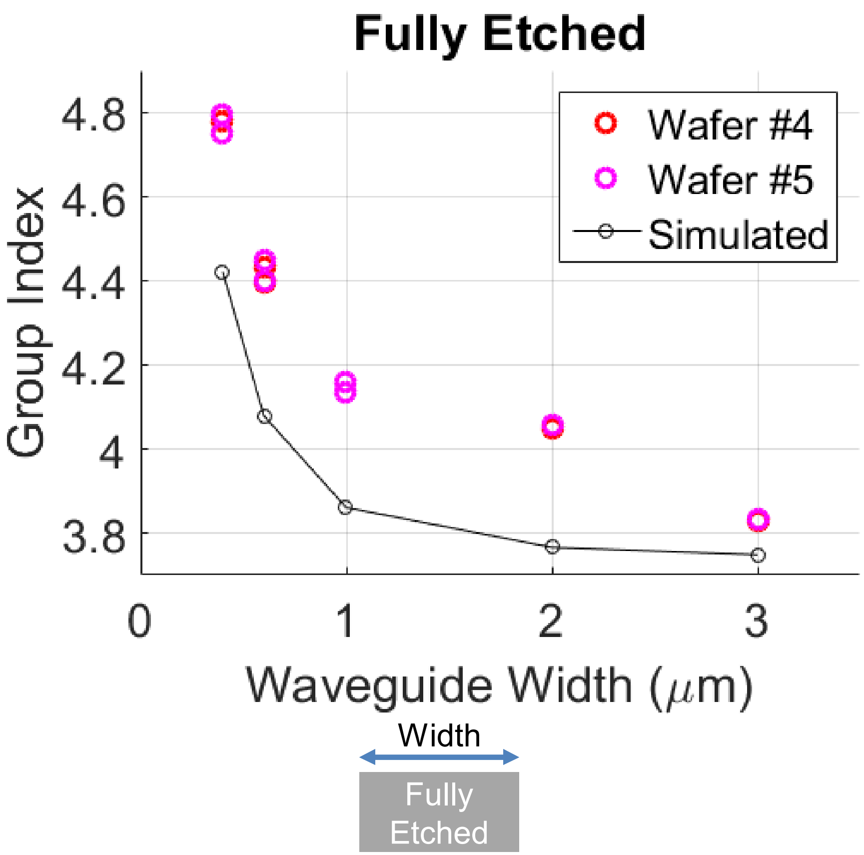
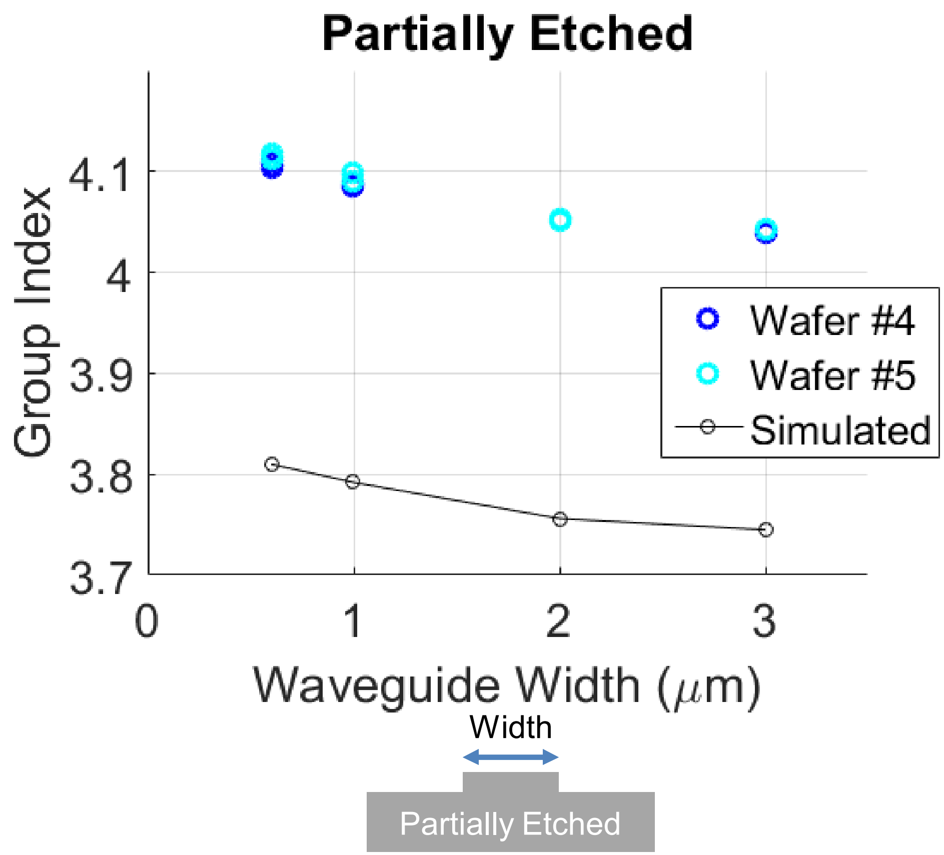
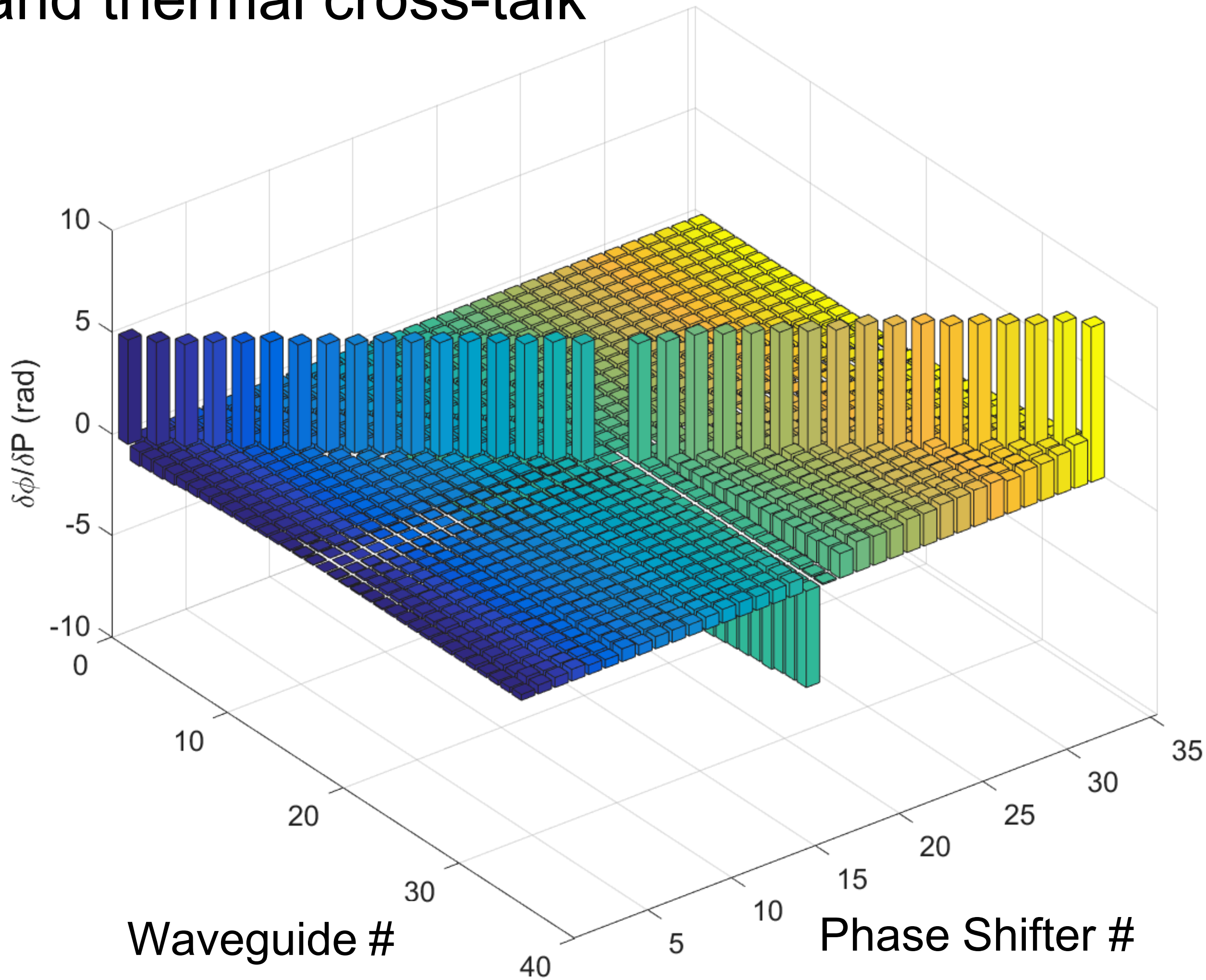




Interferometric Characterization

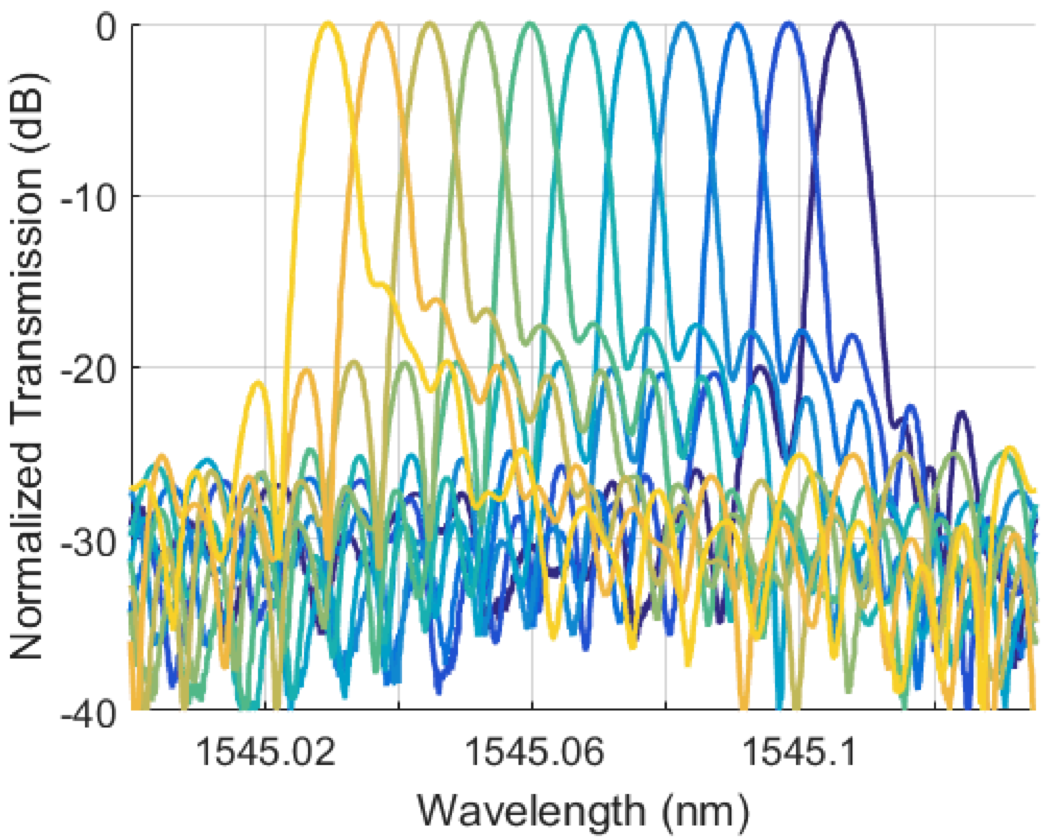
- Phase information provides accurate calibration of phase shifters and thermal cross-talk



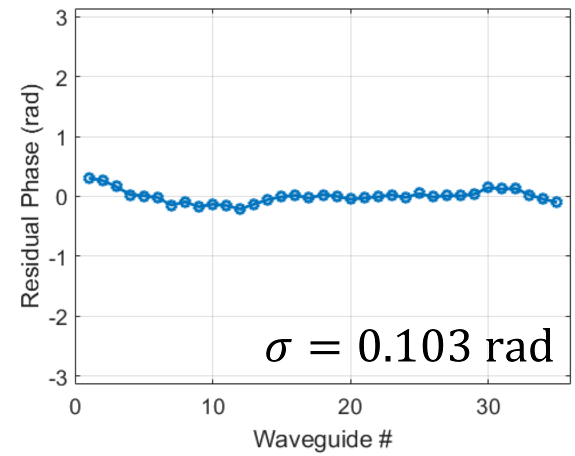
*Phases relative to waveguide #18

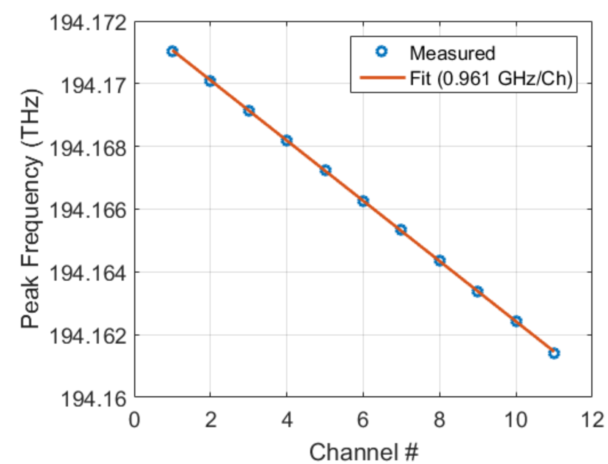
Optimization & Performance

1 GHz Channel Spacing

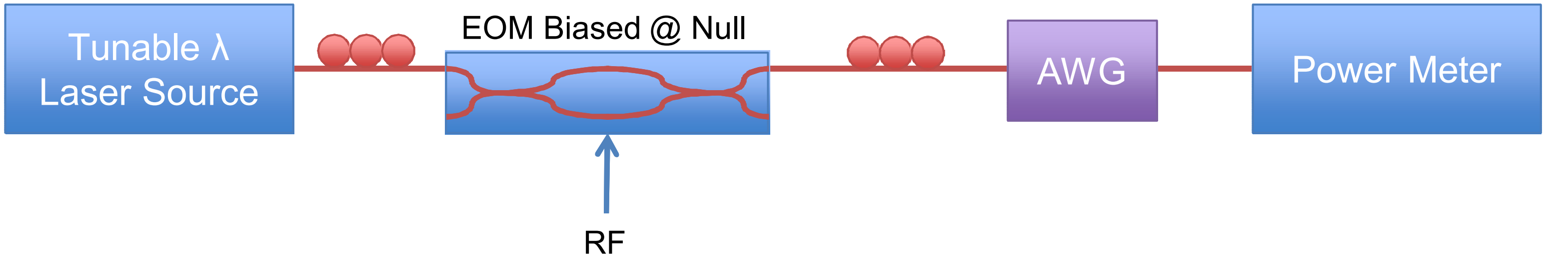


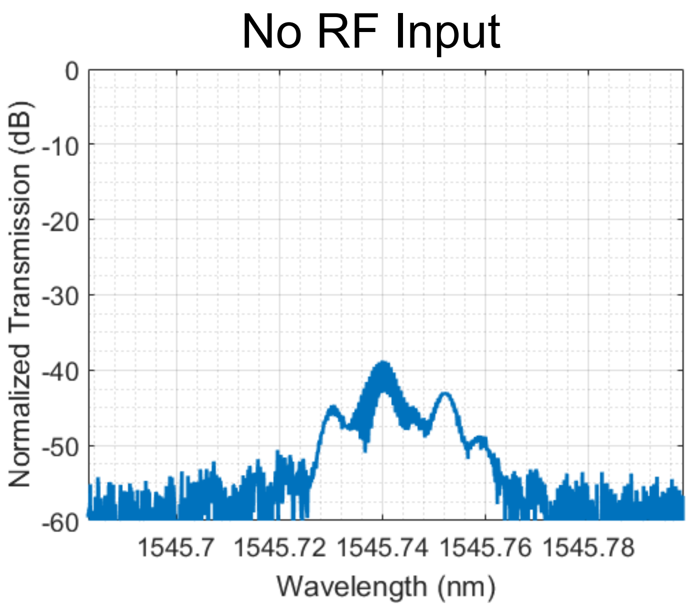
-15→-25dB Adjacent Channel Cross-Talk

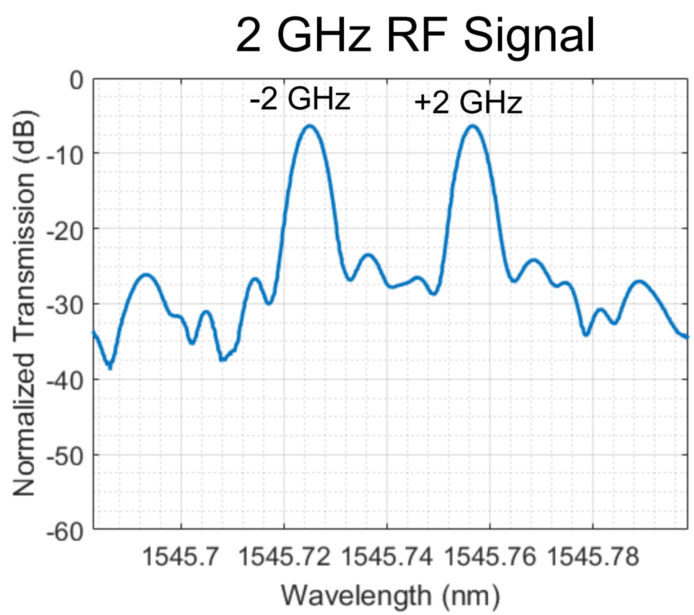




Applications – RF Signal Processing







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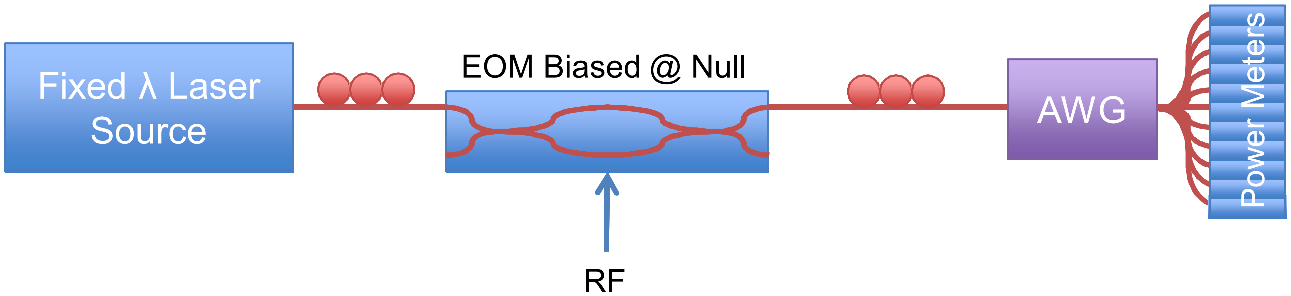
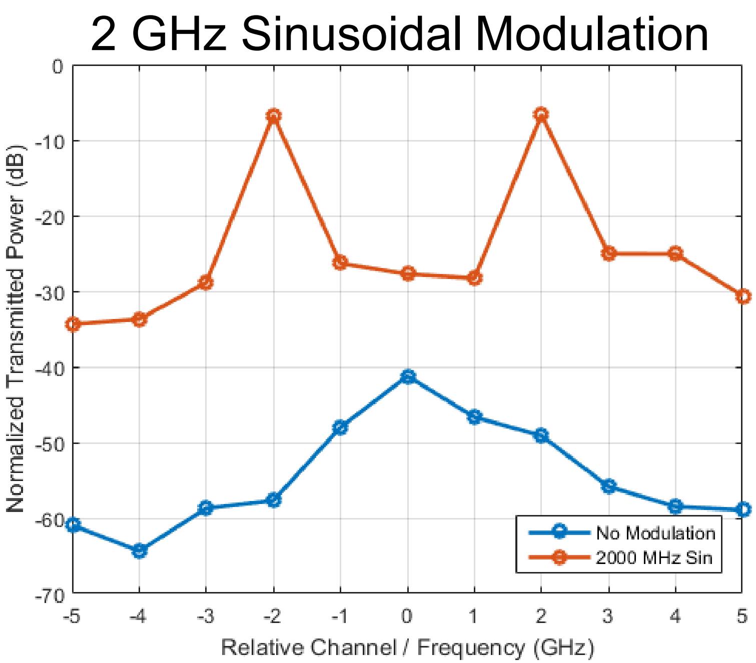
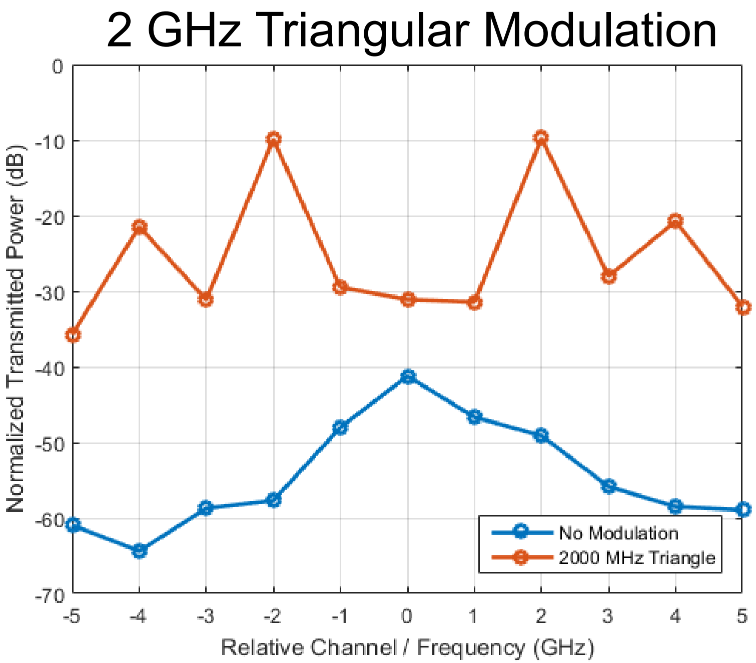
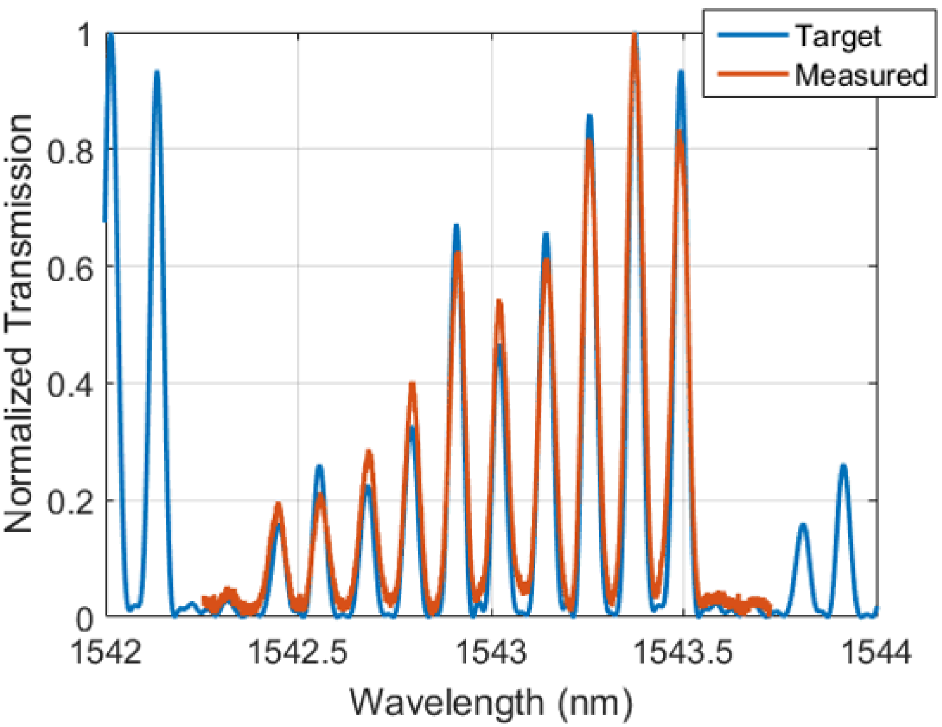


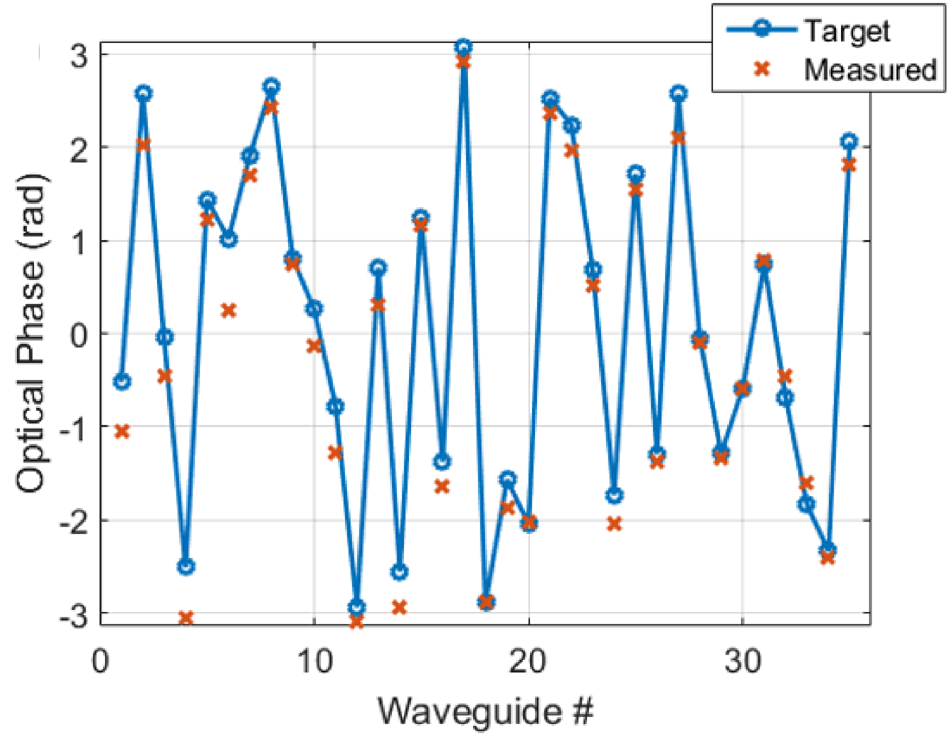




Applications – Spectral Shaping

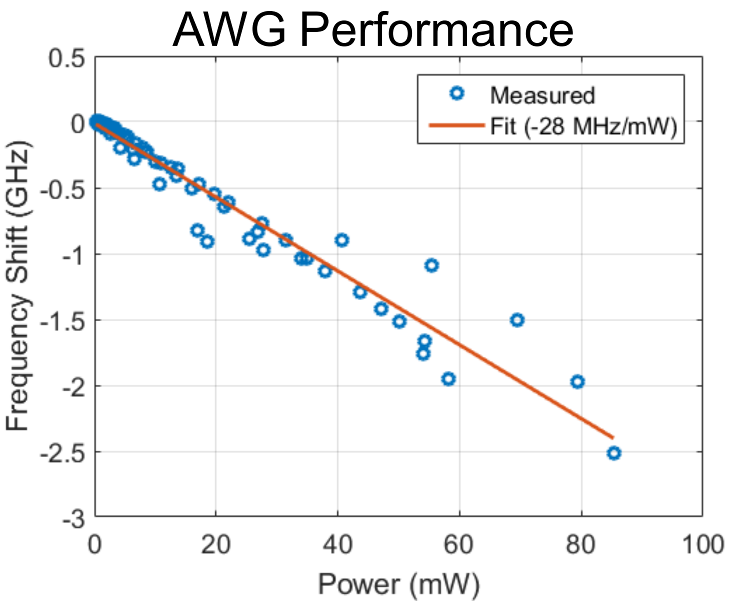
- Gerchberg-Saxton Algorithm can be used to modify spectral transmission
  - Iterative algorithm which provides a target phase offset for each waveguide
  - Possible shapes limited by number of arrayed waveguides

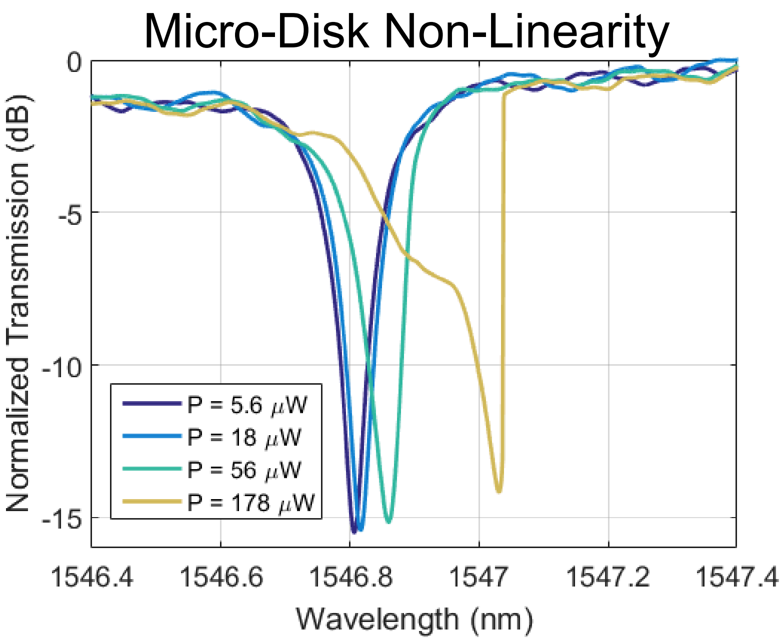




Applications – High Power Handling

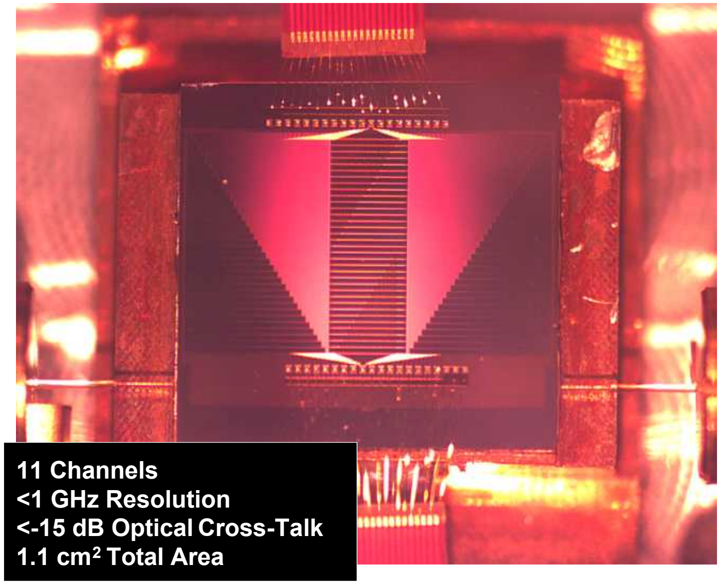
- Resonant structures (i.e. micro-disks) have power limitations due to enhanced non-linearity
- AWG is non-resonant and can handle high powers
  - Observed shift of 28 MHz/mW
  - Could be compensated for by a temperature shift of only $0.003℃/\text{mW}$

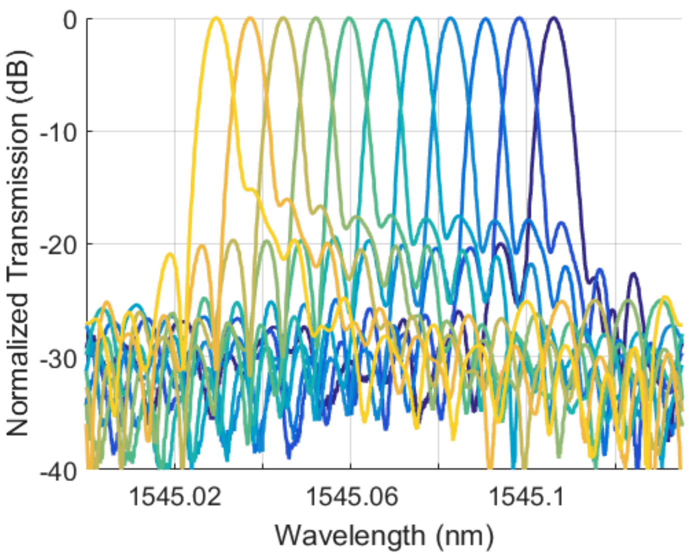




Conclusion

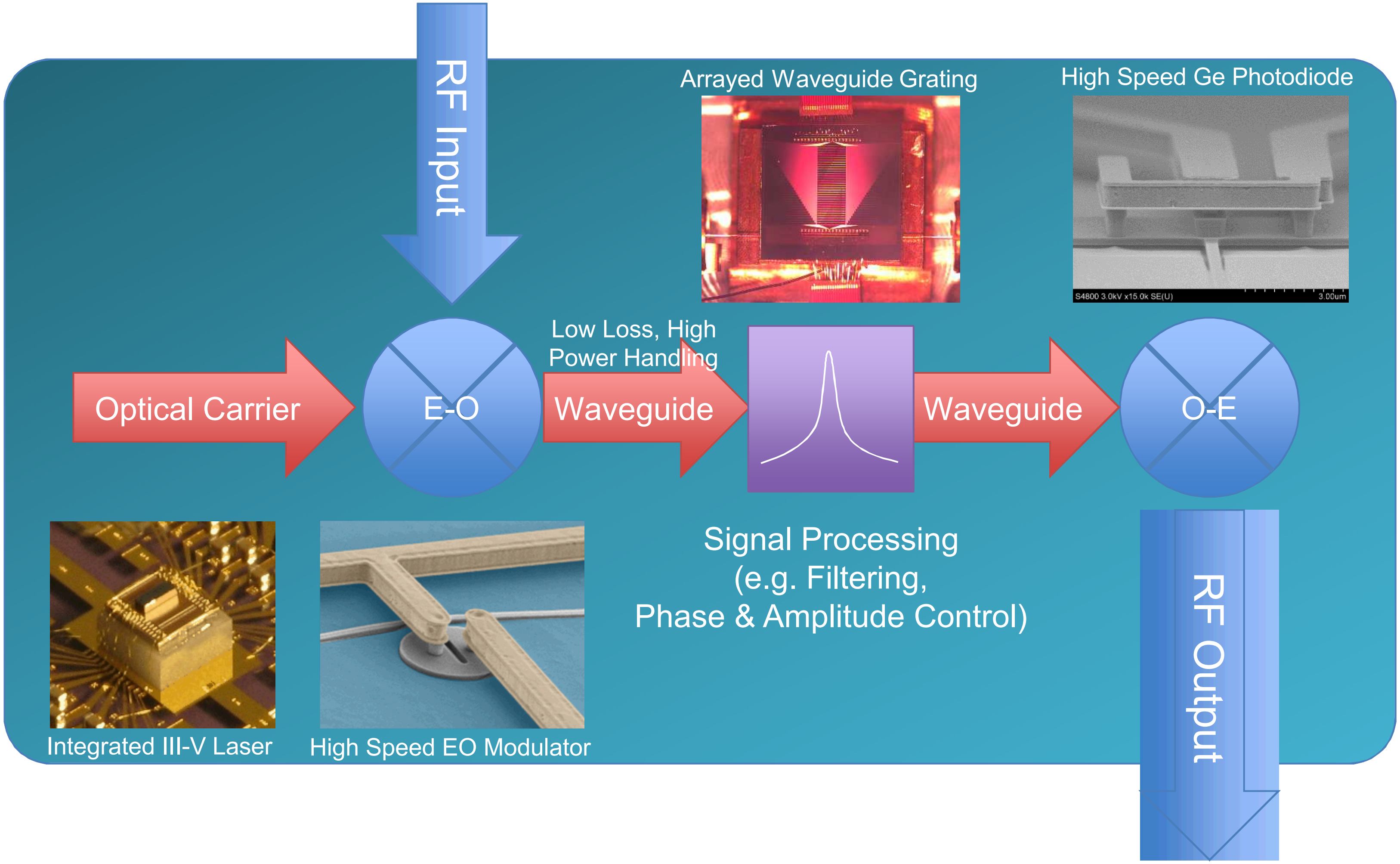
- Silicon photonic arrayed waveguide gratings provide compact and high resolution spectral filtering
- We have demonstrated <1GHz resolution through active thermo-optic phase tuning
- Demonstrated RF Channelization and Spectral Shaping
- Improvement of thermal isolation and phase shifter efficiency will improve performance





Silicon Photonics for RF Processing

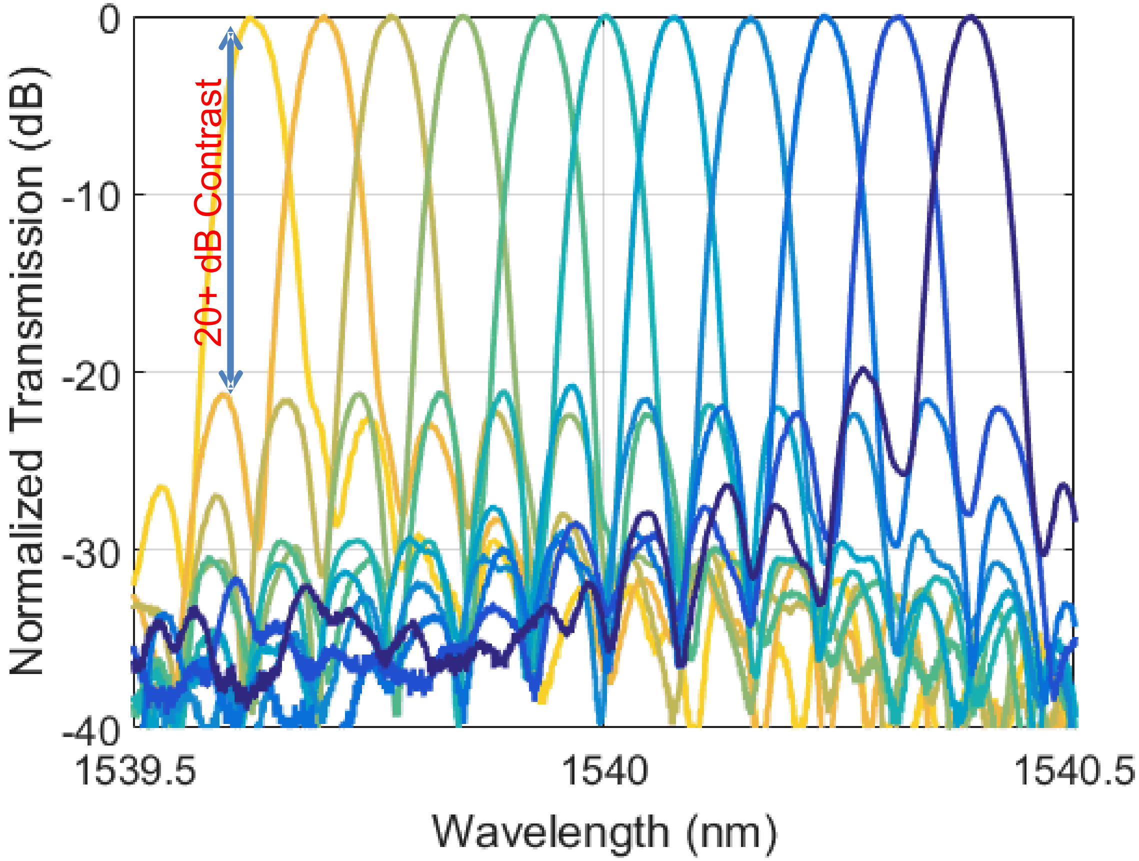
Integrated Photonic Chip for Reduced SWaP-C



Optimization & Performance

- Iterative optimization necessary to account for thermal cross-talk

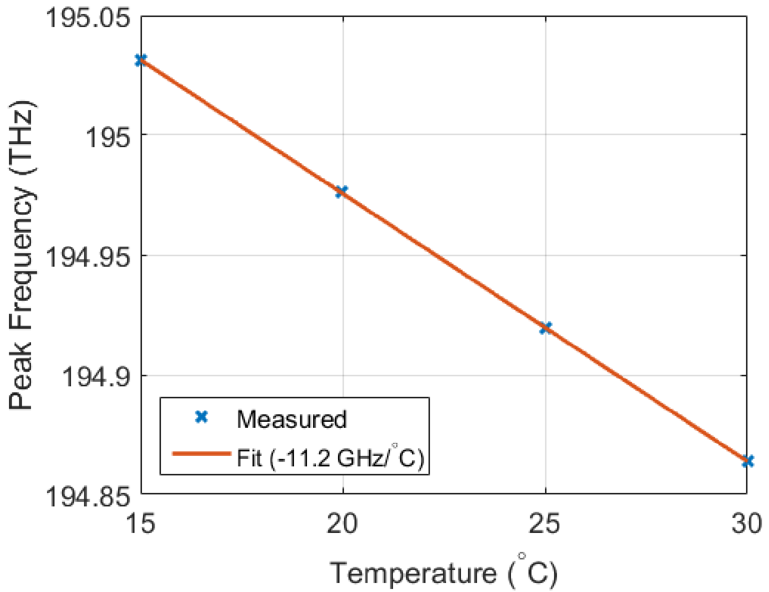
10 GHz Channel Spacing

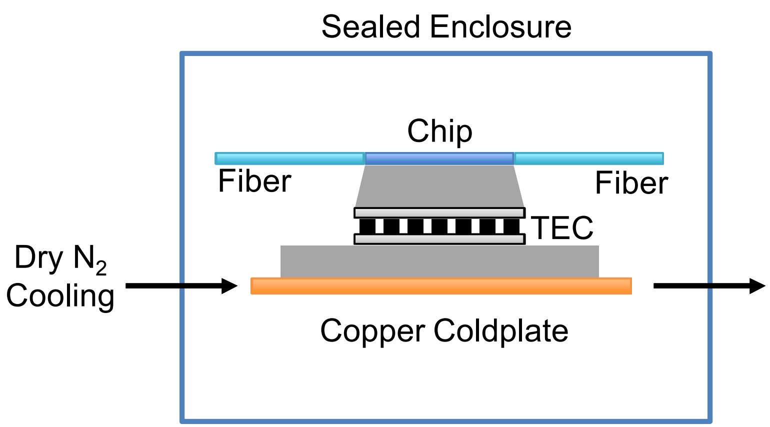


-25.2dB Adjacent Channel Cross-Talk
-19.6dB Total Channel Cross-Talk

Thermal Considerations

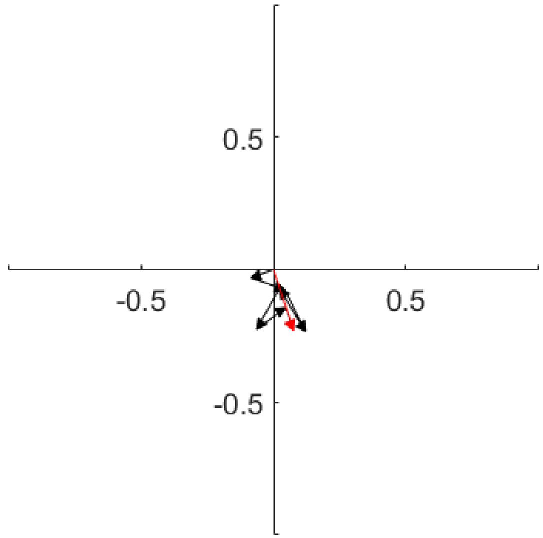
- Temperature change creates a linear phase shift across each waveguide
  - Results in a shift in the peak transmission of $11\ \mathrm{GHz/^\circ C}$
- Initial phase optimization requires demanding stability
  - Can be avoided with more advanced signal processing
- Significant phase shifter heat (>1.5 W) which needs to be removed



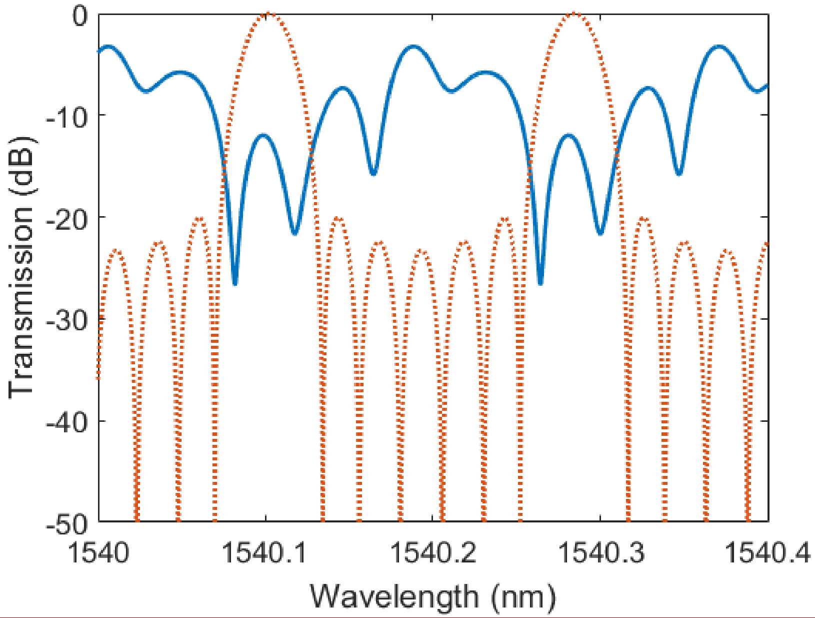


Optimization – Brute Force

- Output intensity at a fixed wavelength can be pictured as phasor addition of each arrayed waveguide
- Phase errors cause random walk in phasor addition
- Rotating a single waveguide phase by 2π causes a sinusoidal variation in the output power
- Choosing the phase which maximizes output power for each waveguide individually will straighten out the random walk



Phases At Peak



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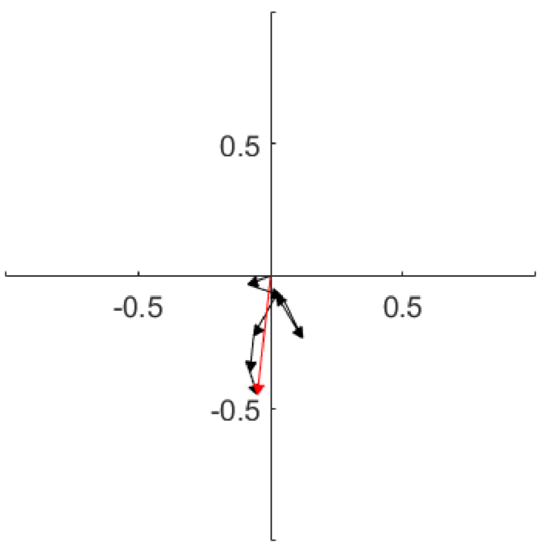

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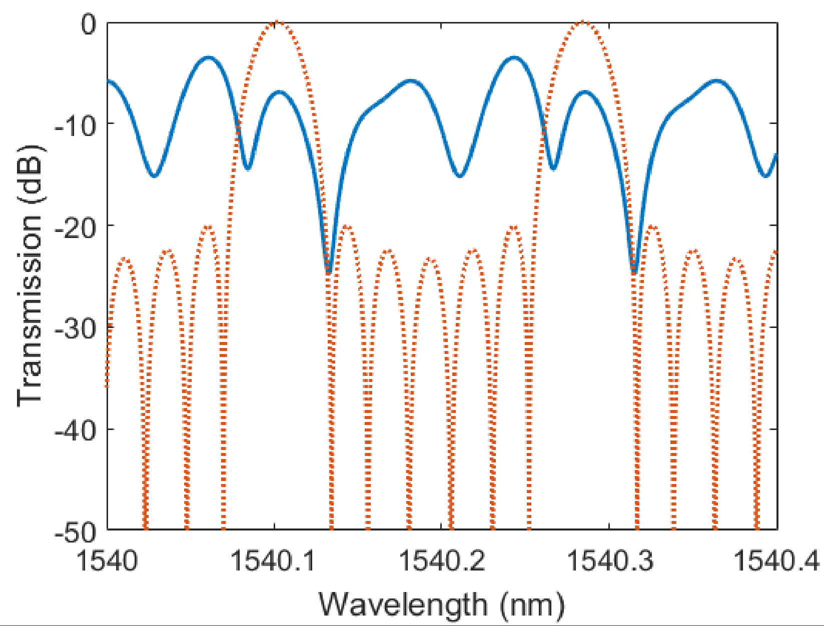

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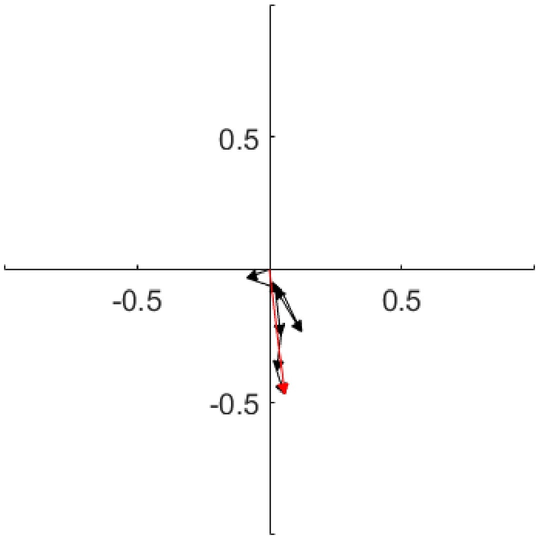

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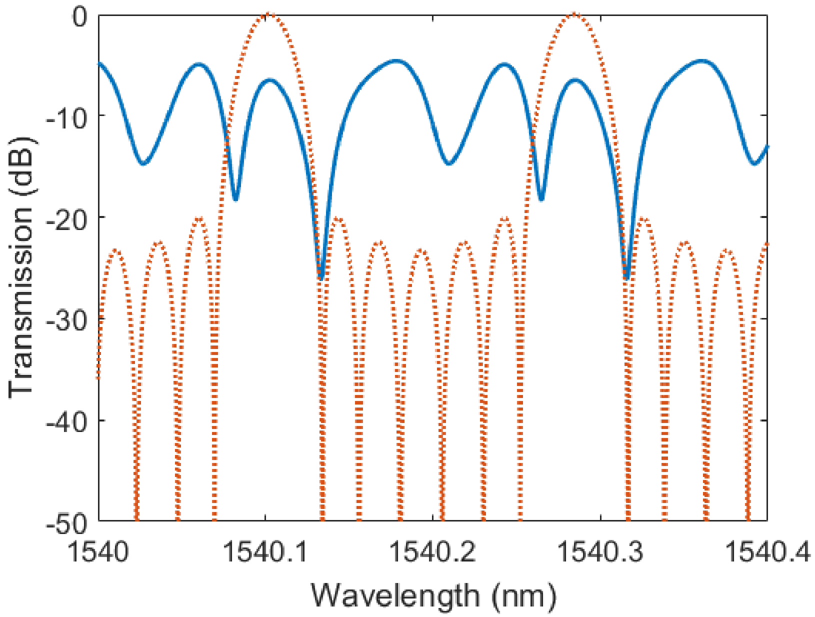

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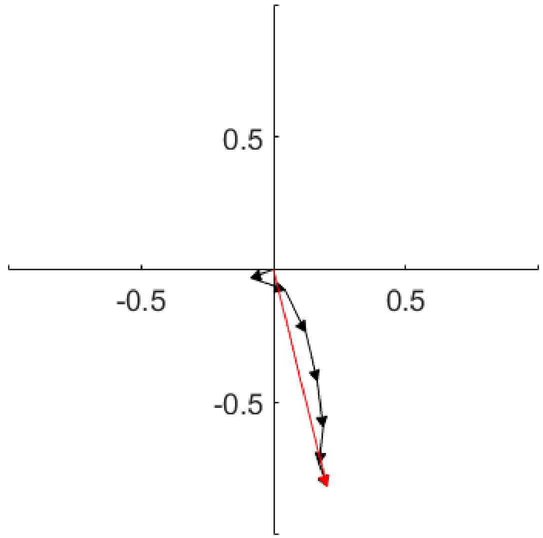

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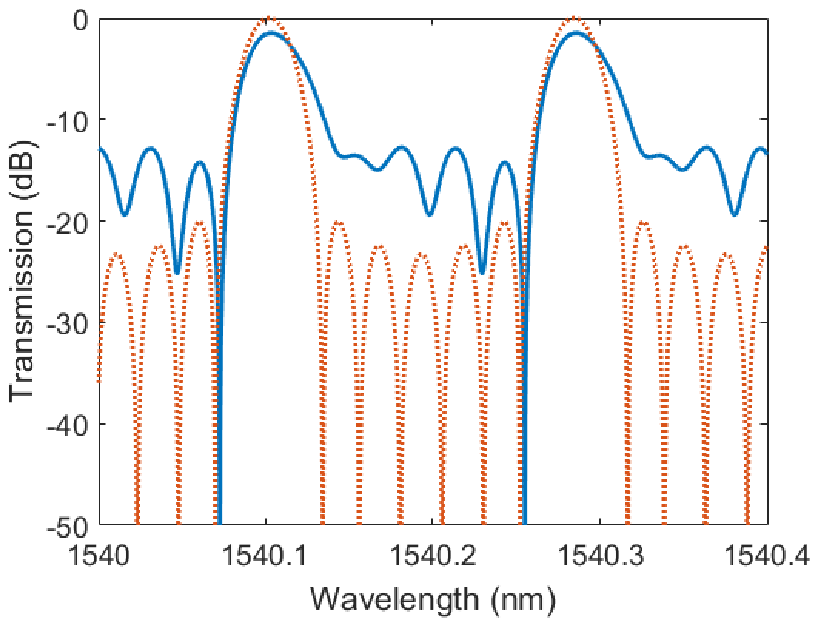

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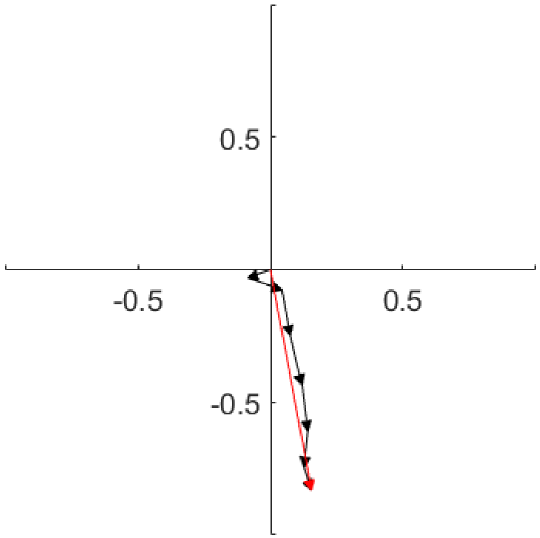

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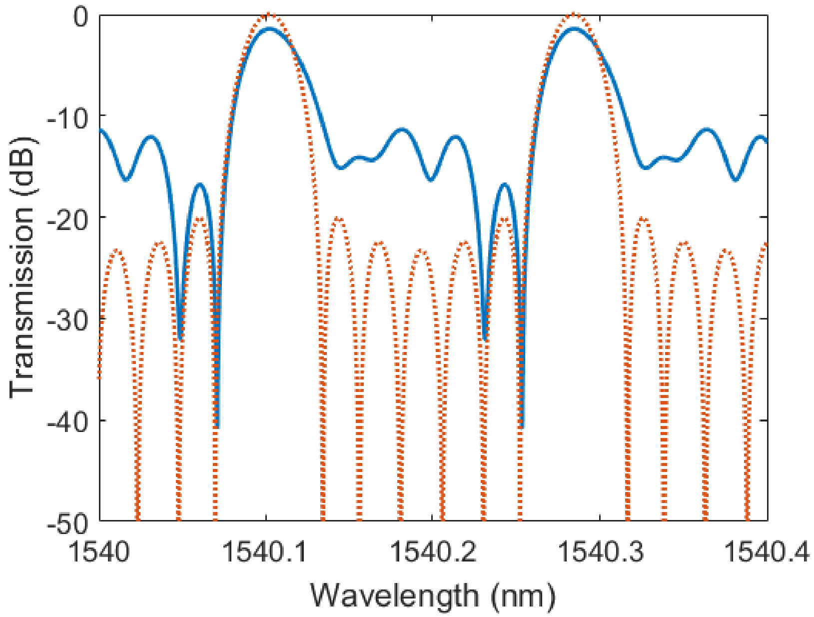

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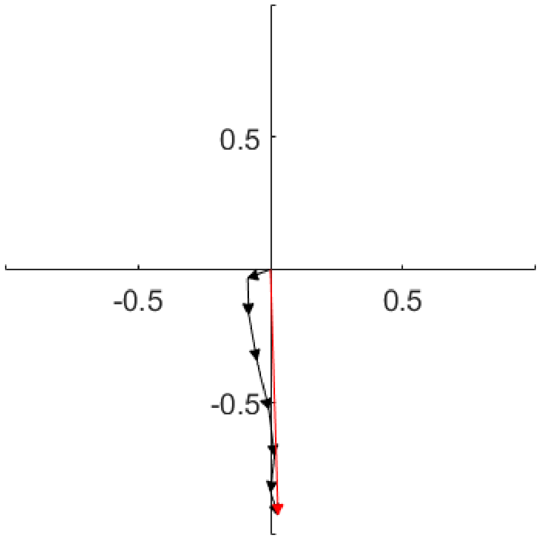

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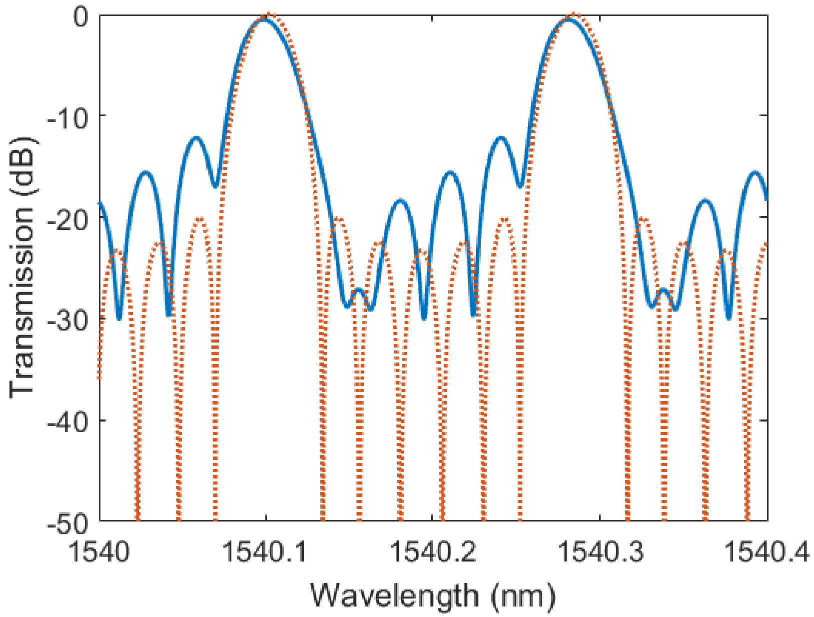

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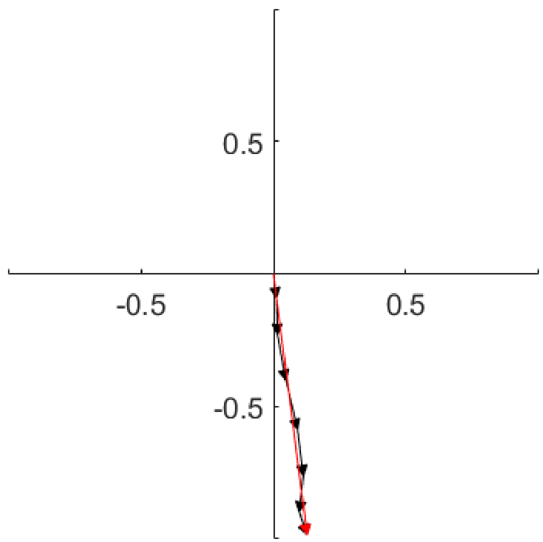
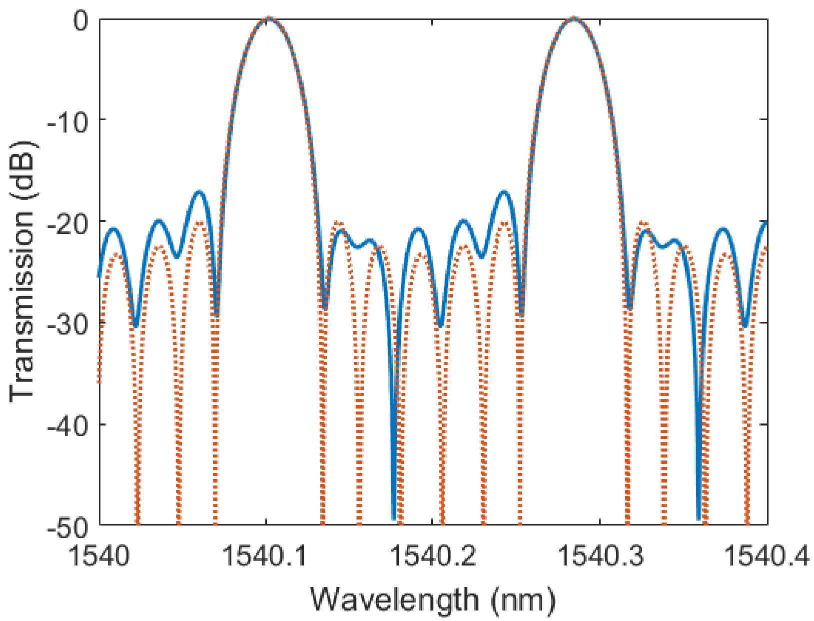


Phases At Peak



Optimization – Brute Force

- Benefits
  - Simple Implementation – Single fixed wavelength laser and power meter
  - High Contrast Ratio
  - Easy to shift peak wavelength
- Challenges
  - Intensity oscillation amplitude is less than 1/(# of channels)
  - Thermal cross-talk complicates simple phasor addition picture

50 GHz Channel Spacing