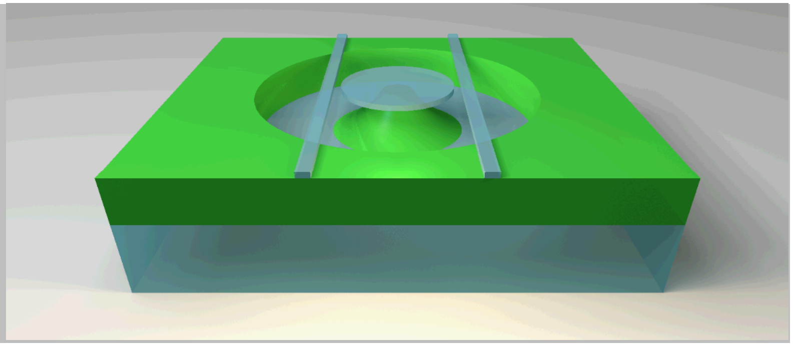
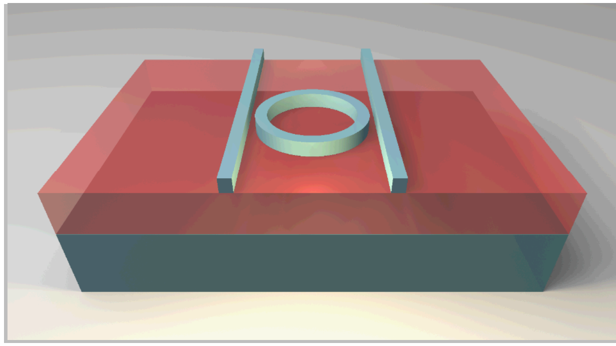
SAND2013-10291P





Micro-systems Enabled QKD

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Ian Frank

Bruce Burkel

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Grating Couplers: vertical incidence

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Properties:

- 0.5 dB per grating maximum reported theoretical efficiency[1]
- 1 dB bandwidth 35 nm[1]
- Directly into device layer
- Vertical incidence allows a greater proportion of the surface to be used.
- 1 dB requires complicated fabrication with sub-surface reflectors.[1]
- TM light is harder: 3.5 dB maximum reported.[2]
- Larger bandwidths can be obtained by "blazing"[3]

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Large arrays will require complex alignment to maintain high efficiency.

1. Taillaert, D., et al. *Optics letters* 29.23 (2004)
2. Halir, R., et al. *Optics letters* 35.19 (2010)
3. Qin, Kun, et al. *J. of Lightwave Tech.* 30.14 (2012)

Butt-coupling: facet-to-facet

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- Efficiencies can approach 100% with proper mode matching.
- TE and TM can both couple efficiently
- Can couple through spot-size converter or directly to device layer with Ultra-High NA fiber or lensed fibers.

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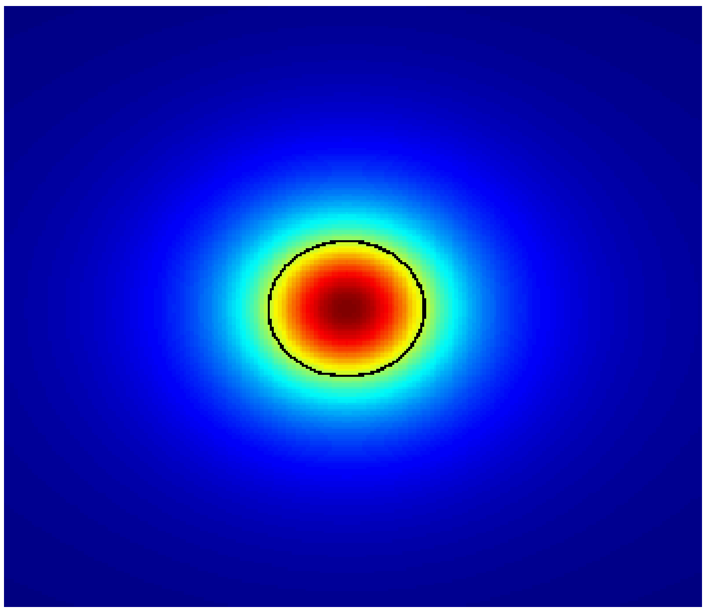
- Fiber cladding limits density of connections along a single facet
- Multiple connections requires precise alignment.

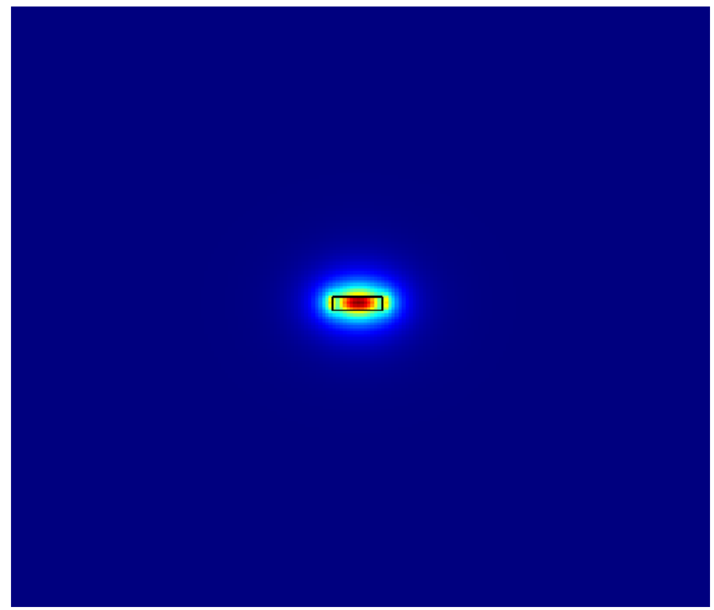
Approaching 0 dB coupling

Ultra-high NA Fiber

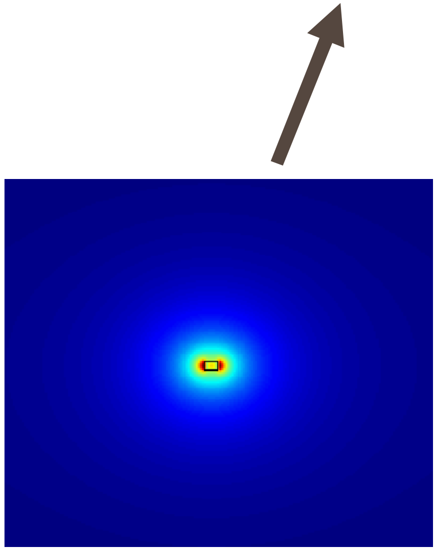


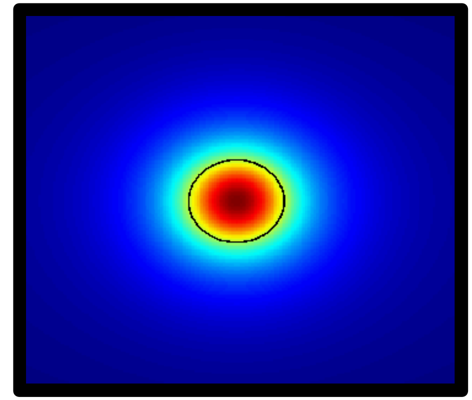
Mode diameter ≈ 4 μm

225 nm x 700 nm Silicon Nitride waveguide

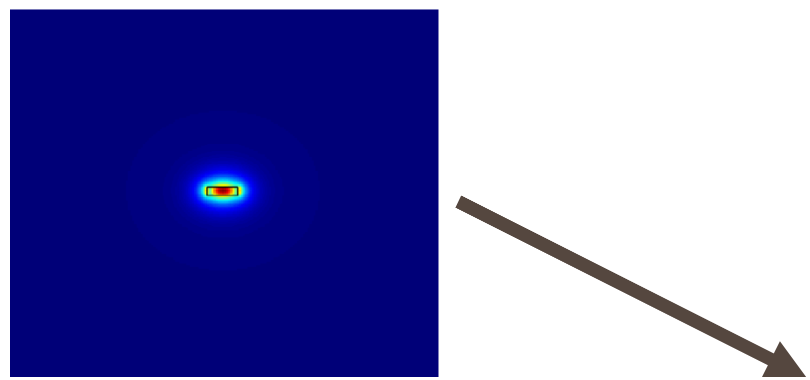


Mode diameter <1 μm





1 dB tolerance:
Angle: 2^0
In-Plane Offset: 1.5 µm



Large arrays: the "array" has to be precise, stability of the platform is essential.

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Sockets can allow stable connections

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Alignment is still precise

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Flared sockets allow for less precision in the array

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Lithographically defined, they can guide fiber for fine adjustments

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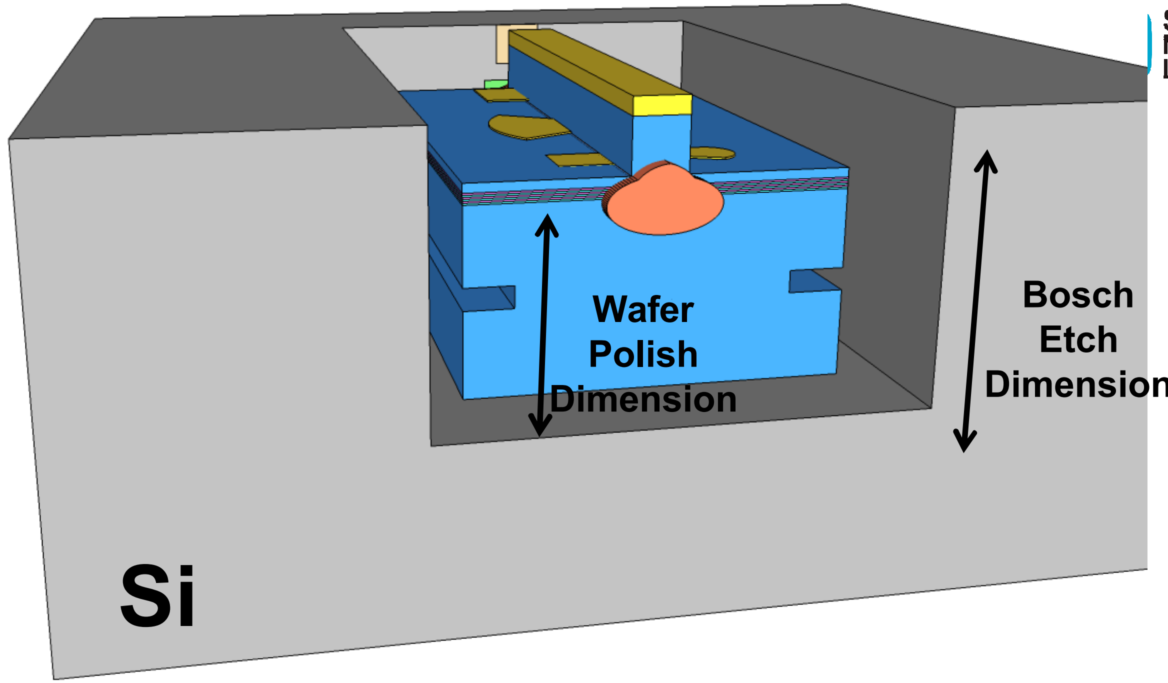
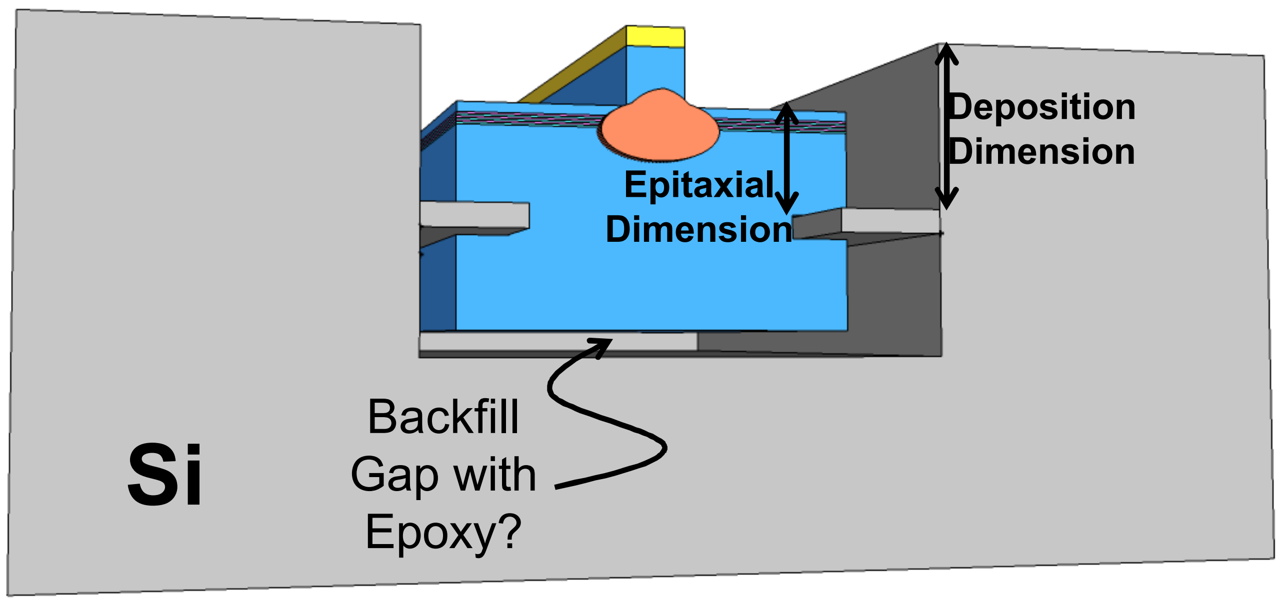
This process is not limited to butt-coupling

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

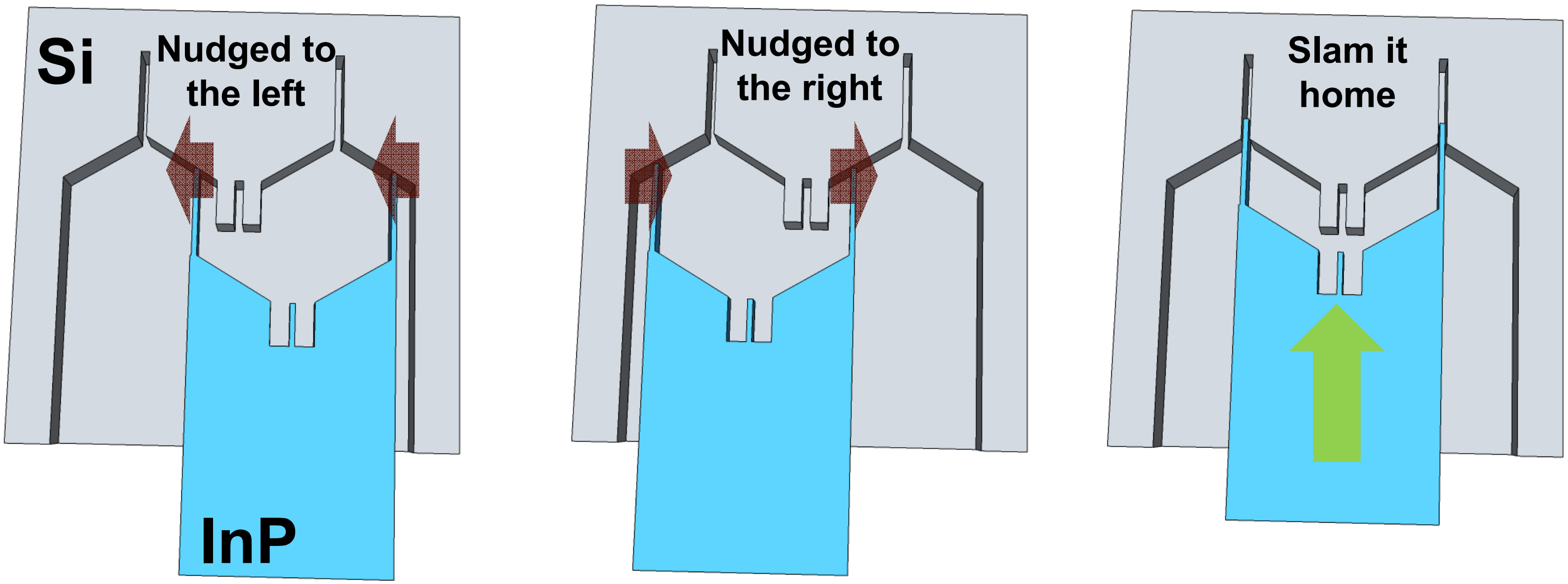
Right Side Up



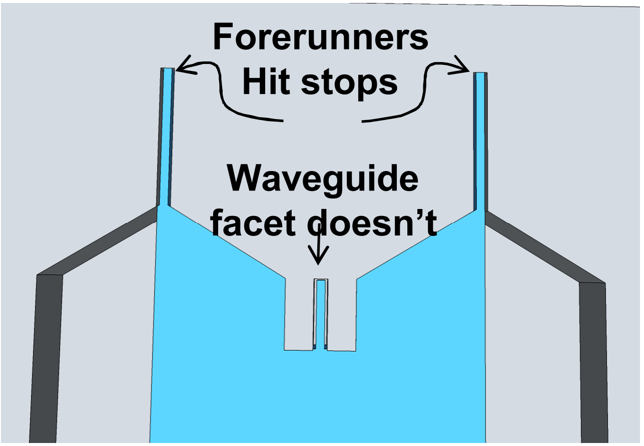
Tongue and Groove



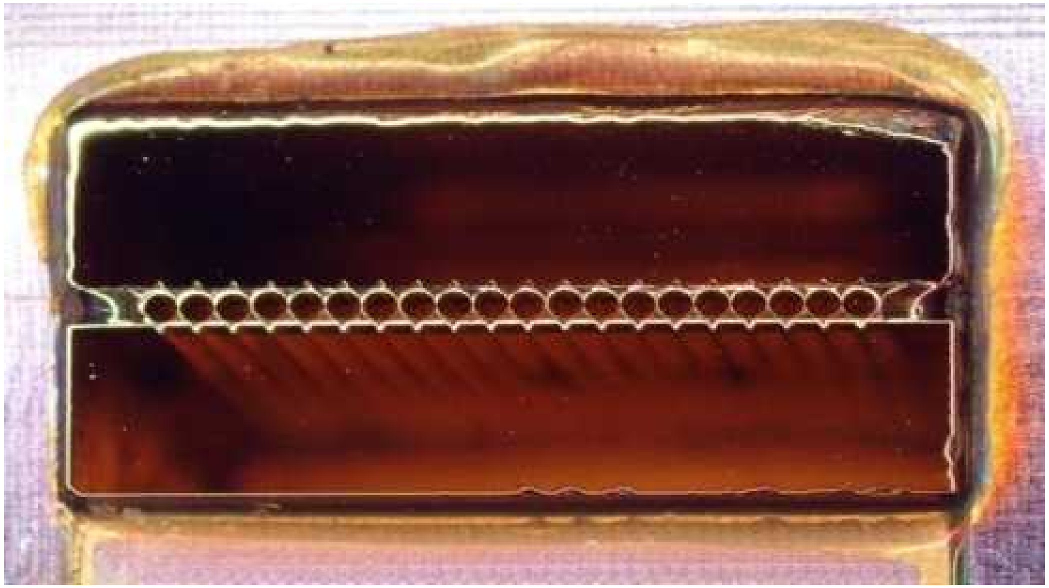
Passive Kinematic Lateral Alignment



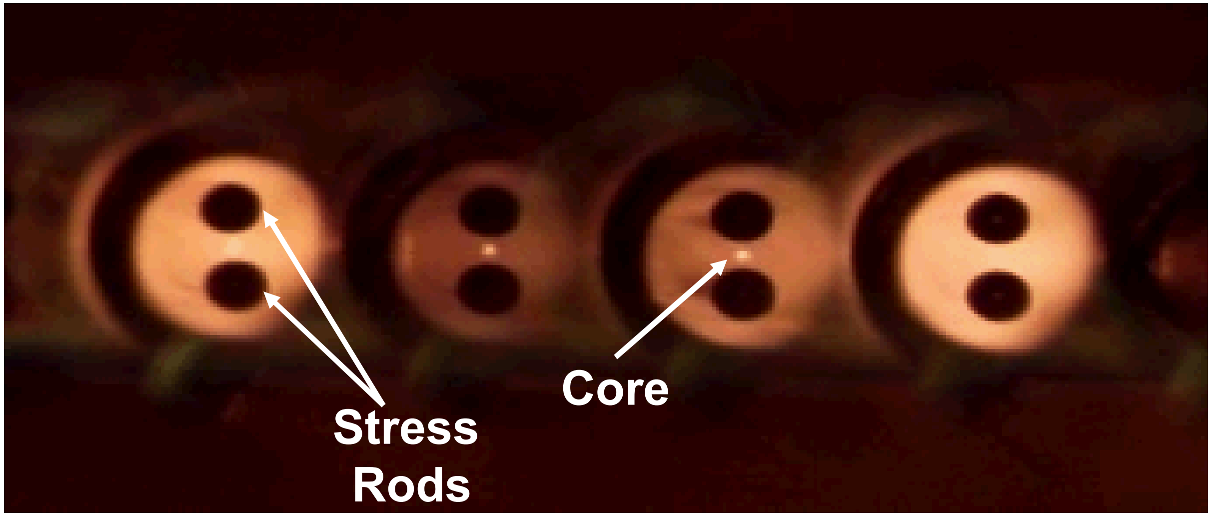
Doesn’t allow for cleaved facets



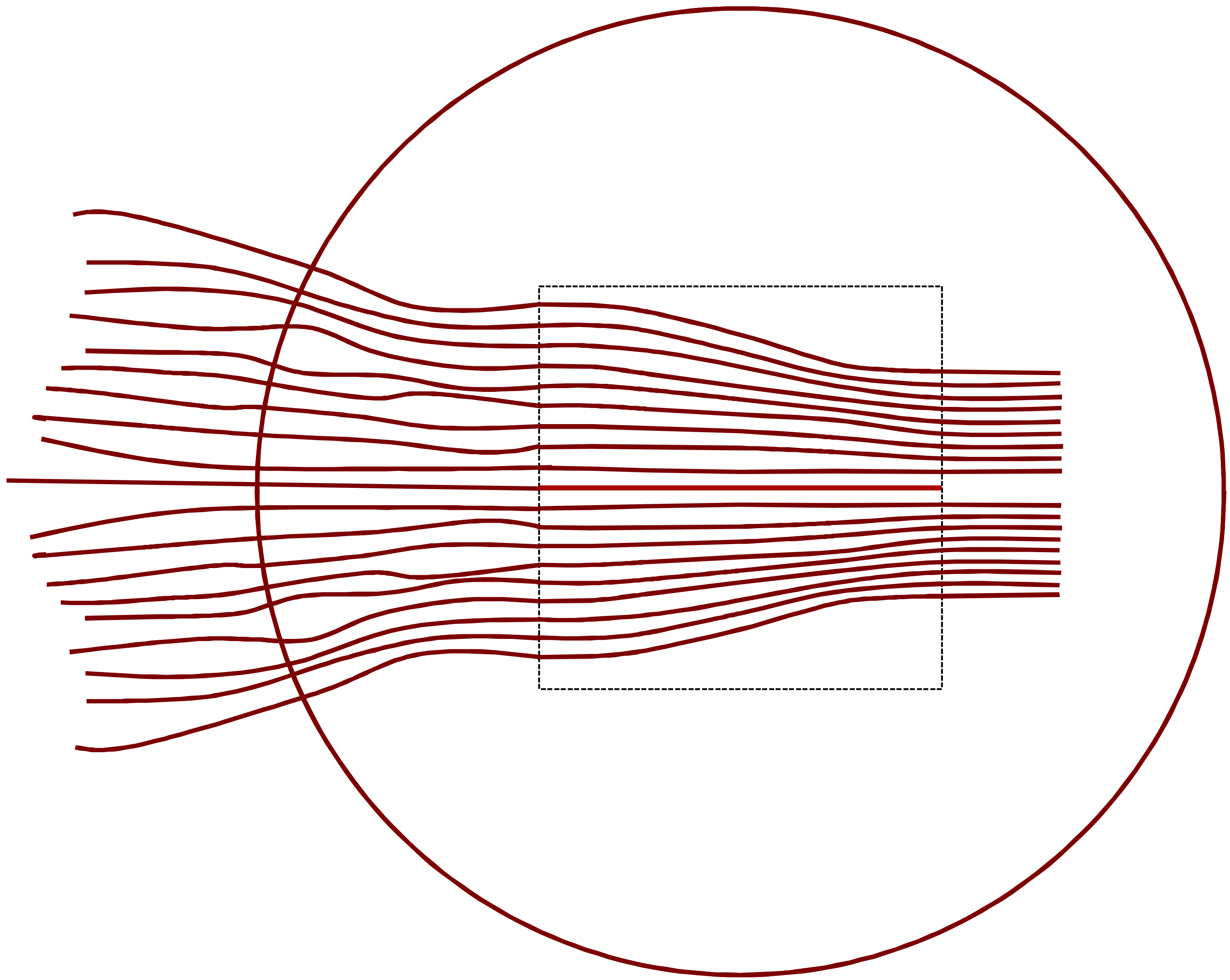
Epoxy Bonded V-groove

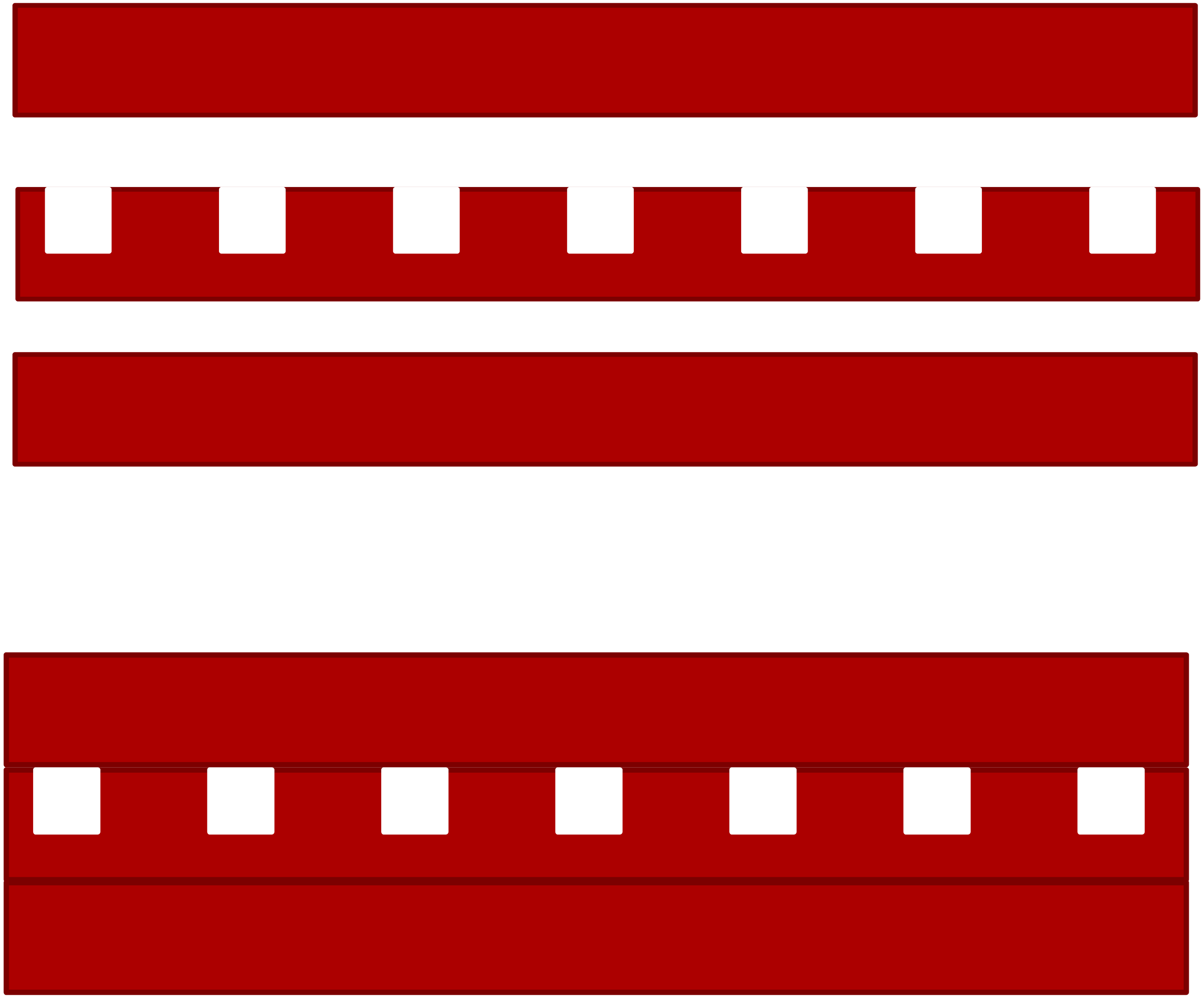


A.

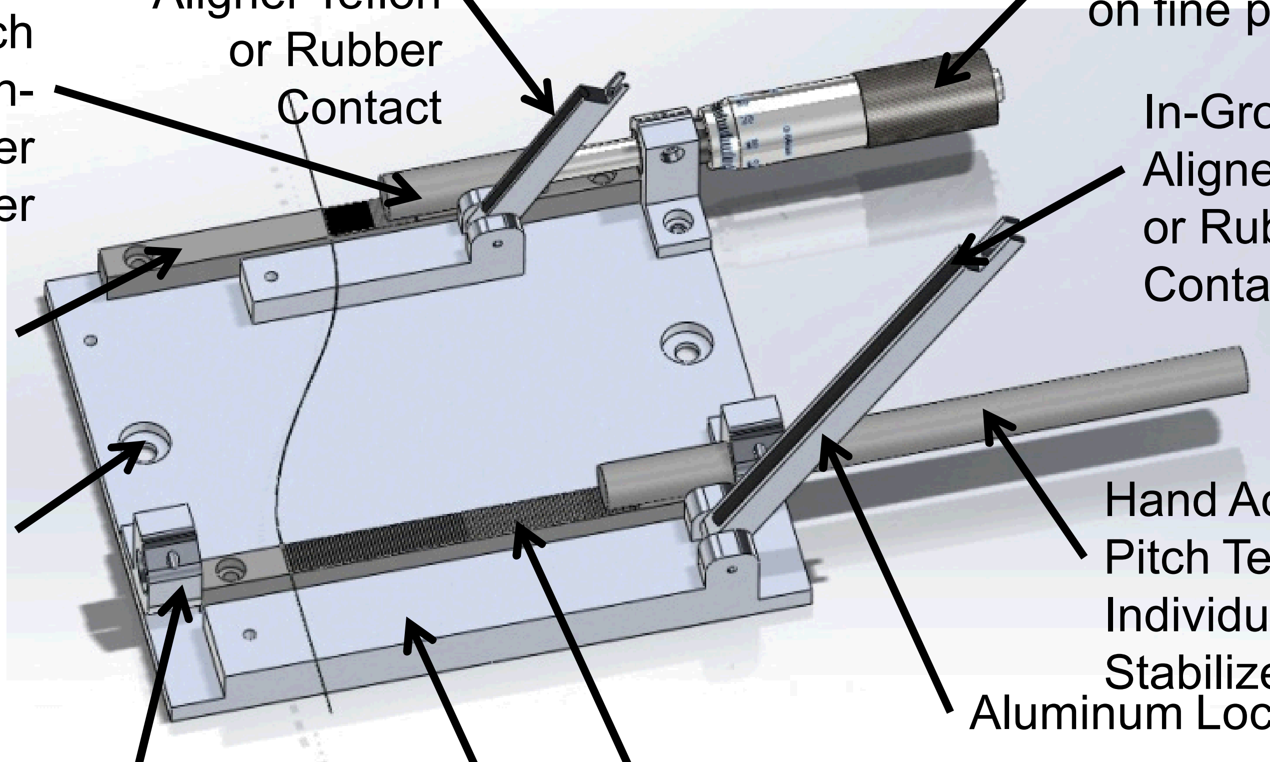


B.



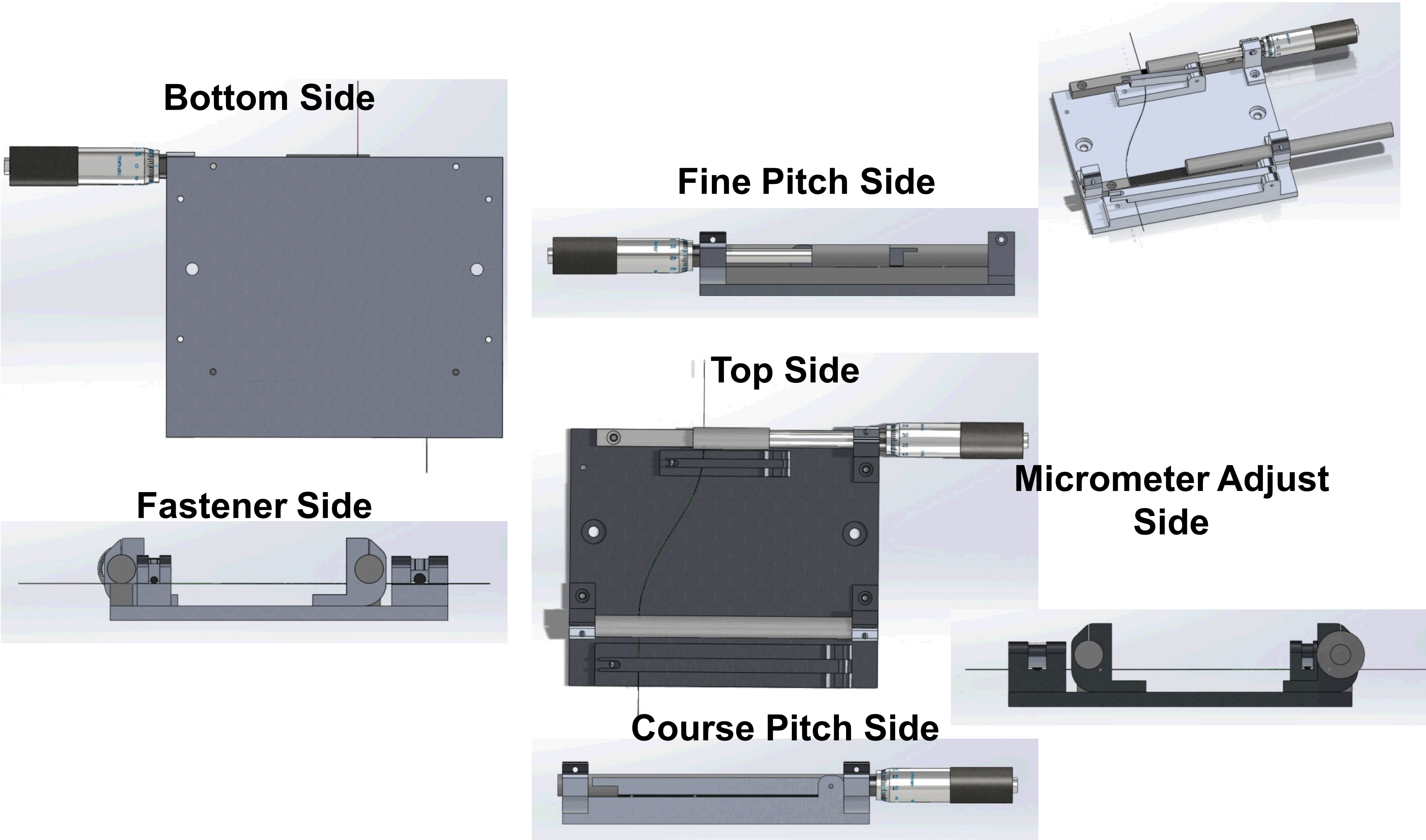


Fiber Aligner Parts



Note: Modular design for fiber number, diameter, and pitch flexibilty.

Fiber Aligner from Mulitple Angles



Fiber Insertion Process Pics

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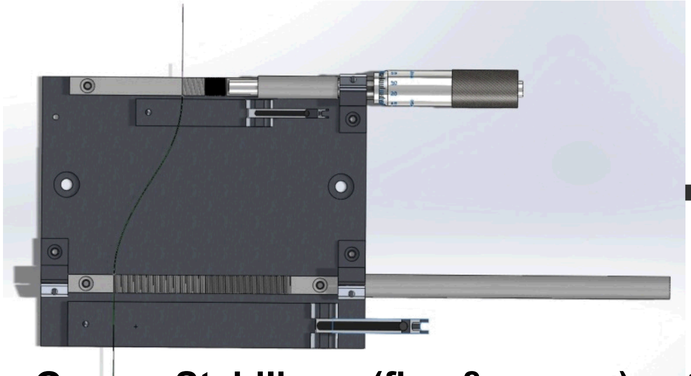
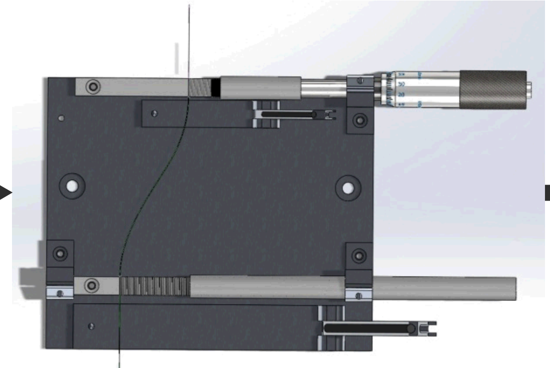


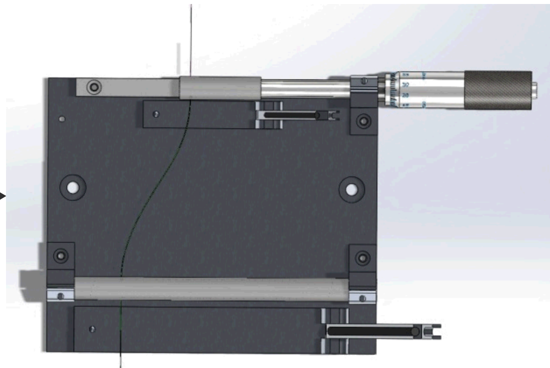
In-Groove Stabilizers (fine & course) out
Locking Stabilizer open

Insert Loose Fiber

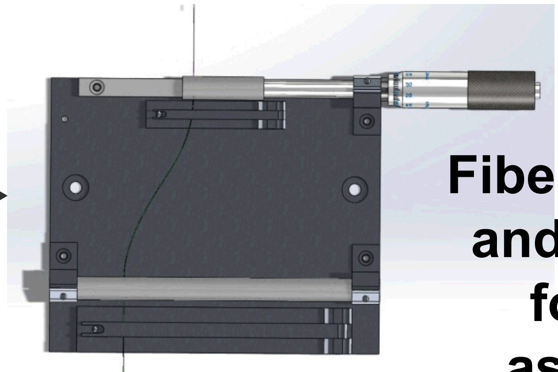


In-Groove Stabilizers cover inserted fiber
Locking Stabilizer open

Insert Additional Loose Fibers – previously inserted fibers are secured with incremental fiber insertion and movement of in-groove stabilizer



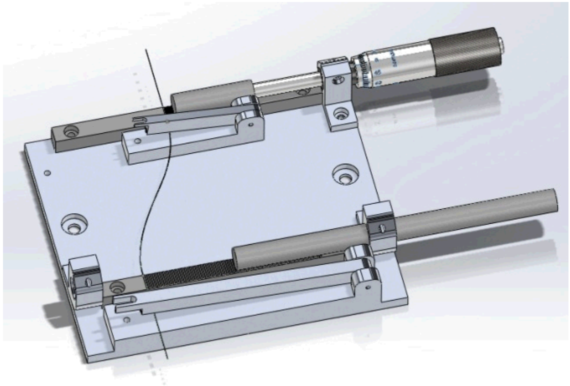
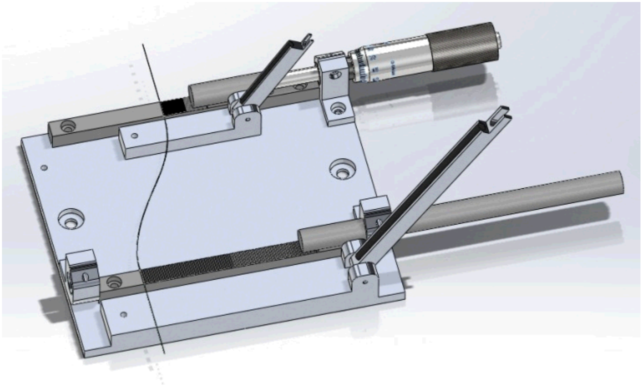
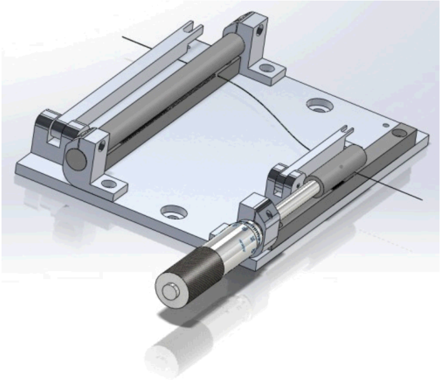
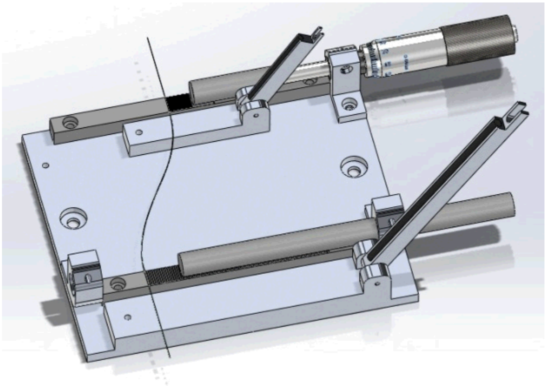
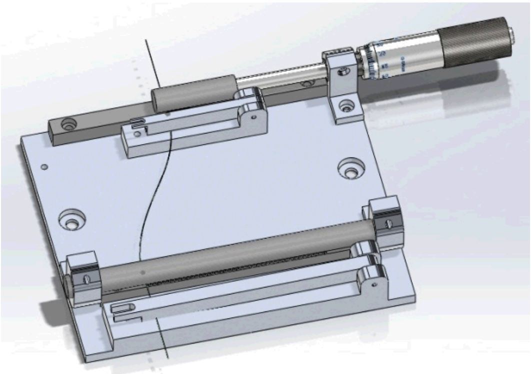
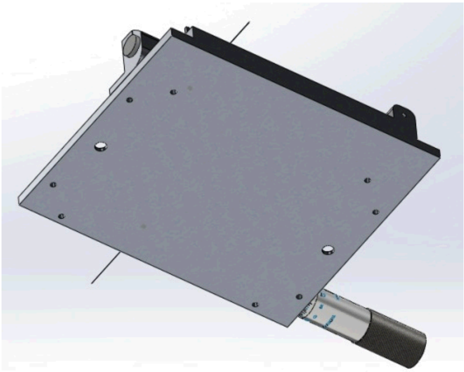
In-Groove Stabilizers fully cover all inserted fibers
Locking Stabilizer open



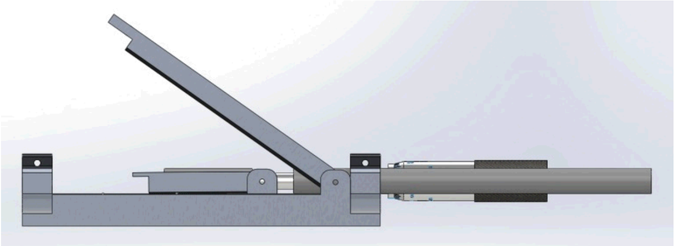
Locking Stabilizer closed

Fibers aligned and secured for next assembly process!

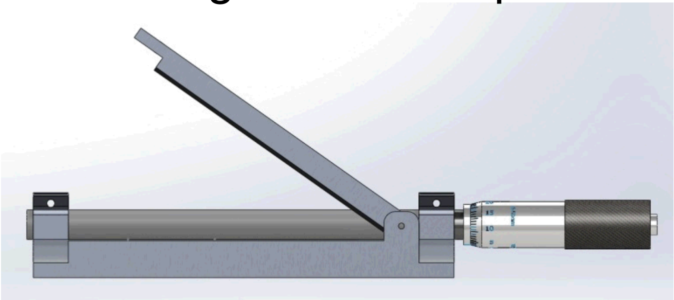
Fiber Aligner Ortho Views

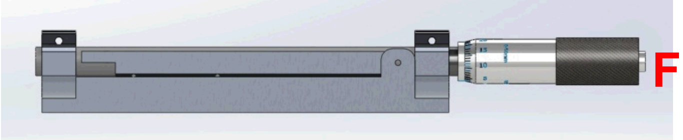
Fiber Aligner On-End Views



In-Groove Stabilizer Out
Locking Stabilizer Open



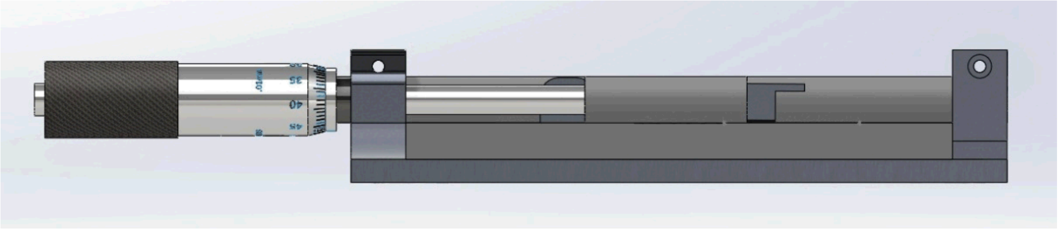
In-Groove Stabilizer In
Locking Stabilizer Open



In-Groove Stabilizer In
Locking Stabilizer Locked

Fiber Aligned & Secured!

Fine Pitch Alignment End of Fixture



With additional engineering our goal is:

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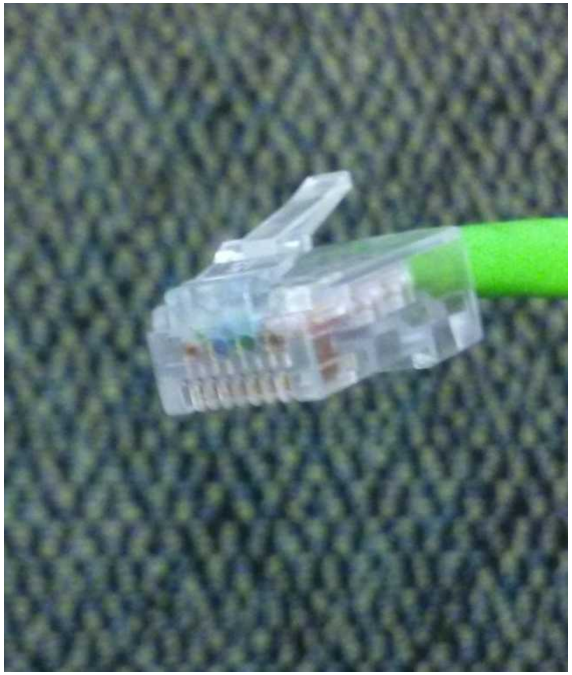
Requirements:

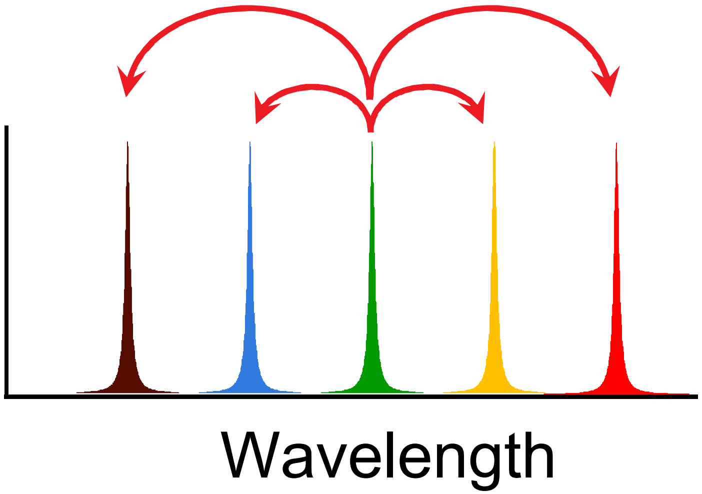
- Micron level alignment of fiber core
  - Pre-sorted fiber
  - Lithographically defined references for X, Y and Z (moving beyond V-grooves).
- Large parallel arrays:
  - 8 or 16 channel
- Interface quantum states to complex silicon photonics platform.

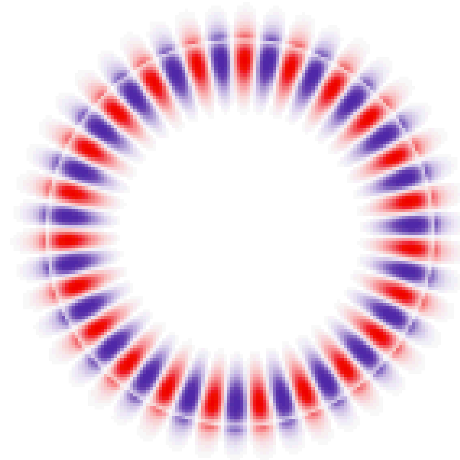
Develop:

- Improved lensed fiber fabrication tolerances.
- Repeatable macro-scale alignment to “clip” into place.

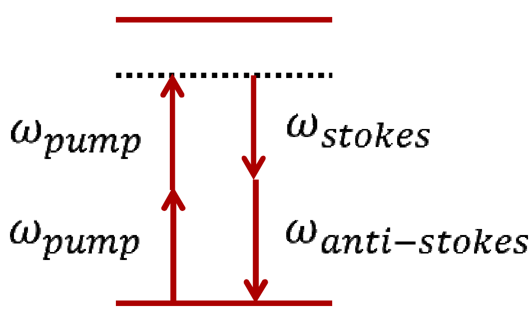


Four-wave Mixing

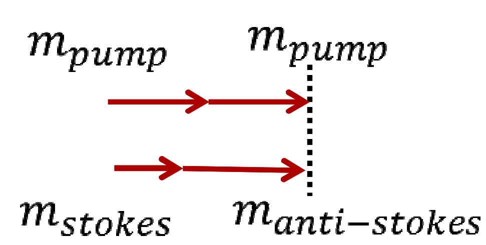




Four-wave mixing must conserve energy and momentum



Energy $(\hbar\omega)$



Angular Momentum $(\hbar m)$

Azimuthally Symmetric Micro-resonators

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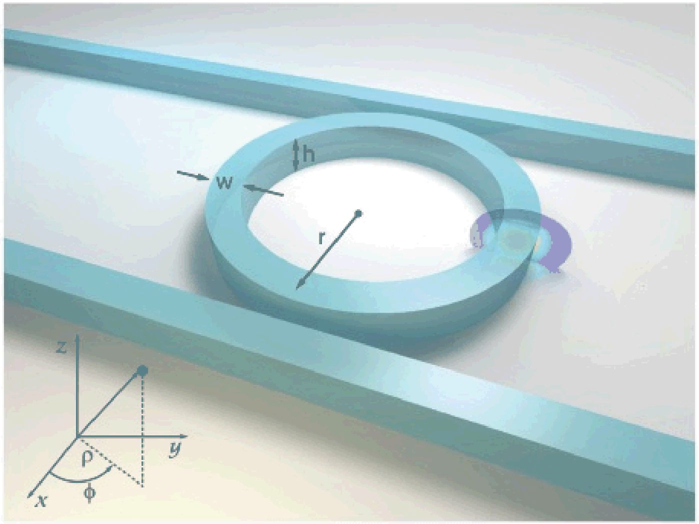
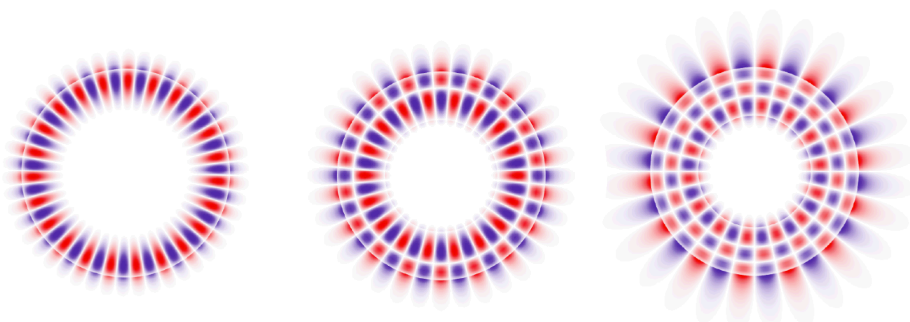
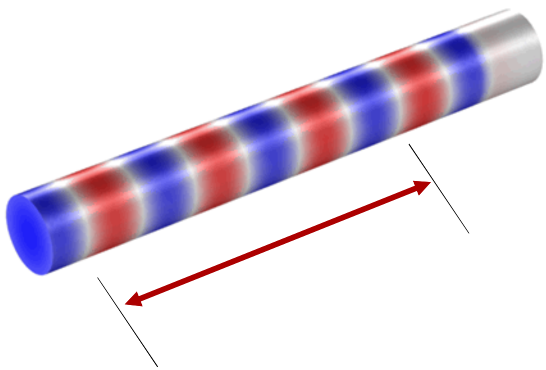


Some Recent Work:
Azzini et al. Optics Express, 20, 23100 (2012)
Engin et al. ArXiv 1204.4922 (2012)
Chen et al., Optics Express 19, 1470 (2011)
Scholz et al., Optics Communications 282, 3518 (2009)
Clemen et al., Optics Express, 17 (2009)



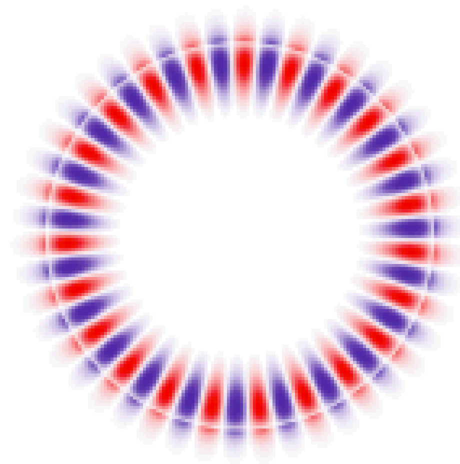
$$\mathbf{E}_m(\mathbf{r},t) = \mathbf{E}_m(\rho,z)e^{-i(\omega_m t + m\phi)}$$

A note on momentum



1. Net linear momentum is zero

?

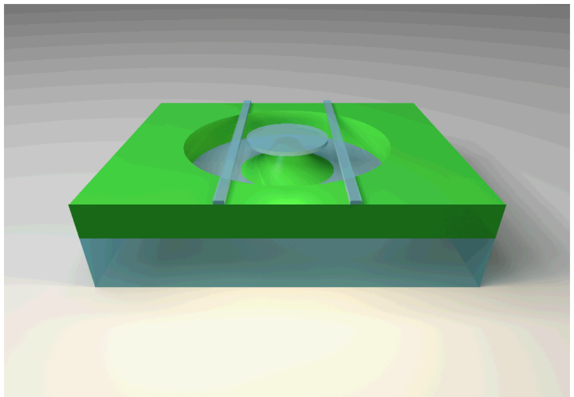


$$k_{photon} = \hbar \frac{\textit{number of waves}}{\textit{distance}}$$

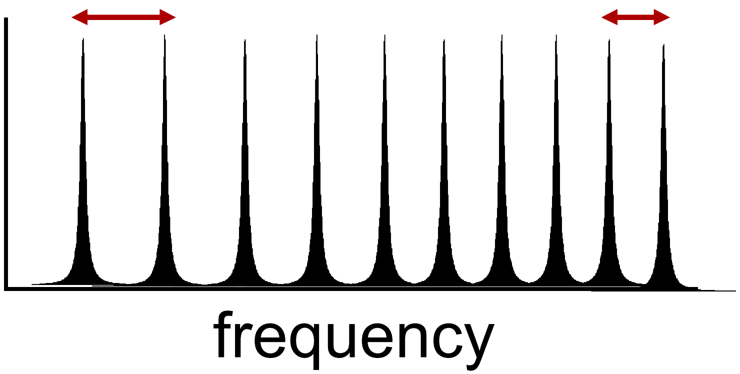
2. No well-defined distance!

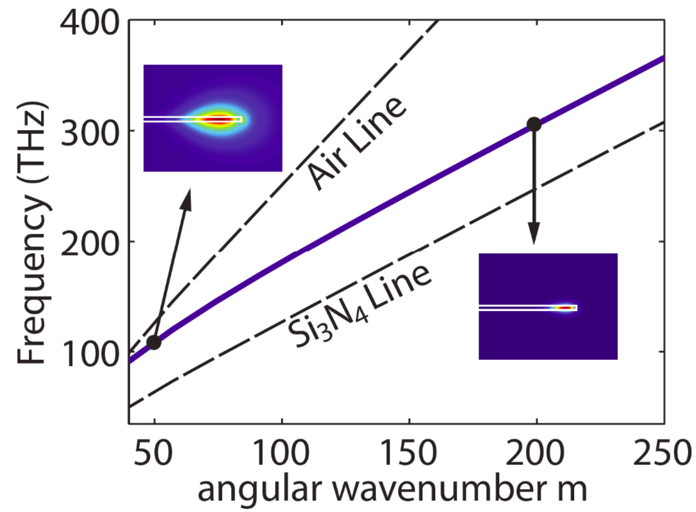
We need to use *angular* momentum to be consistent

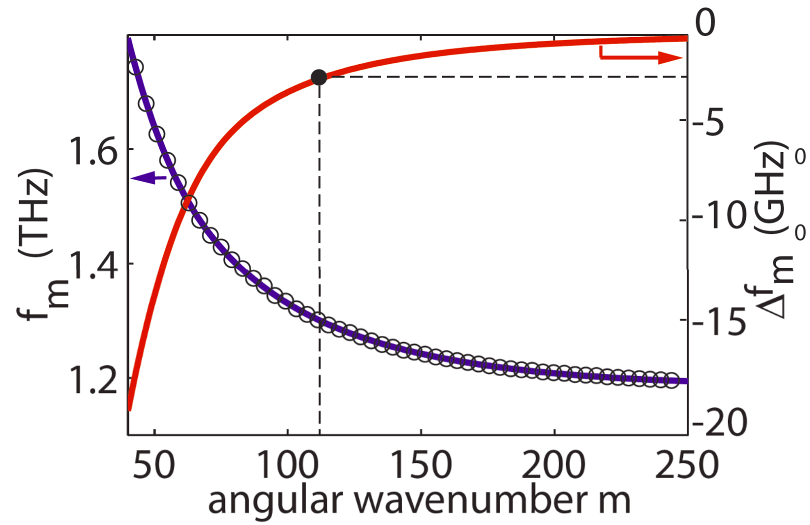
Dispersion in a Silicon Nitride Microdisk



Decreasing free spectral range







Both geometric and material dispersion affect energy conservation

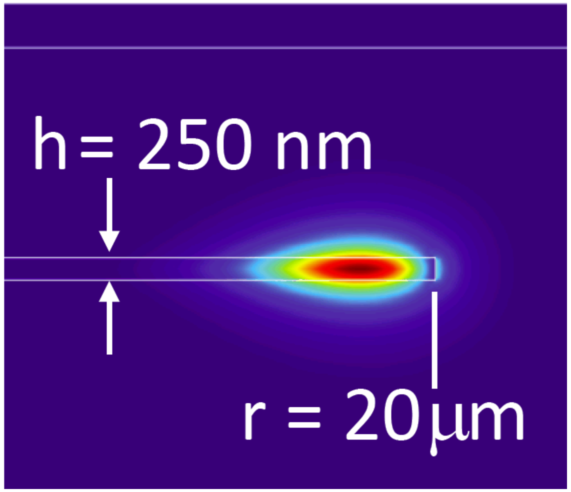
Quantum Wavefunction

$$|\psi\rangle = \frac{1}{i\hbar}\int_{-\infty}^{\infty} \mathrm{d}t H_{int}|0\rangle$$

an energy calculation

$$H_{int} = \varepsilon_0 \int_V \chi^{(3)}(\mathbf{r})\hat{\mathbf{E}}_p^{(+)} \cdot \hat{\mathbf{E}}_p^{(+)} \cdot \hat{\mathbf{E}}_s^{(-)} \cdot \hat{\mathbf{E}}_i^{(-)}$$

To get it right, we need to find the energy in the fields *and* in the dielectric



Quantizing the field

$$U_{vac} = \int_V \varepsilon_0 |\mathbf{E}_m(\mathbf{r})|^2$$

Energy in vacuum

$$U_\varepsilon = \varepsilon U_{vac}$$

Energy in a uniform dielectric

$$U_{\varepsilon(\omega)} = \frac{1}{2}\int_V \varepsilon_0 \frac{\mathrm{d}[\varepsilon(\omega)\omega]}{\mathrm{d}\omega}\Big|_{\omega_m} |\mathbf{E}_m(\mathbf{r})|^2 + \mu_0 \frac{\mathrm{d}[\mu(\omega)\omega]}{\mathrm{d}\omega}\Big|_{\omega_m} |\mathbf{H}_m(\mathbf{r})|^2$$

$$= \varepsilon(\omega)\frac{v_{p_m}}{v_{g_m}} U_{vac}$$

Energy in a uniform *dispersive* dielectric depends on group and phase velocities

This makes physical sense, as the energy propagation velocity is slowed by the ratio of the phase and group velocities, yet the power flow remains the same.

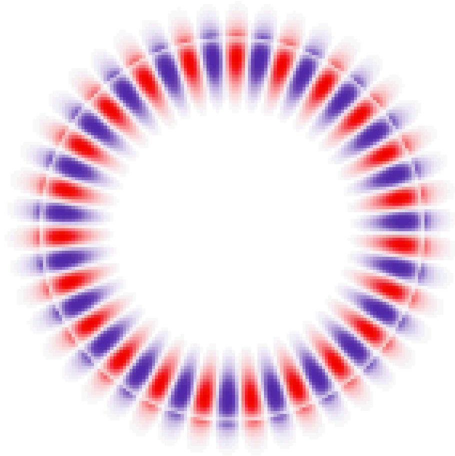
$$\hat{\mathbf{E}}_k(\mathbf{r},t) = i\sqrt{\frac{\hbar\omega_k v_{g_k}}{2\varepsilon_0 v_{p_k}}}\left[\hat{a}_k^\dagger(t) - \hat{a}_k(t)\right]\mathbf{u}_k(\mathbf{r})$$

quantized field

$$\int_V \varepsilon(\mathbf{r})\mathbf{u}_{k_1}(\mathbf{r})\cdot\mathbf{u}_{k_2}(\mathbf{r}) = \delta_{k_1,k_2}$$

orthogonality relation

Group and Phase Velocities



angular phase velocity

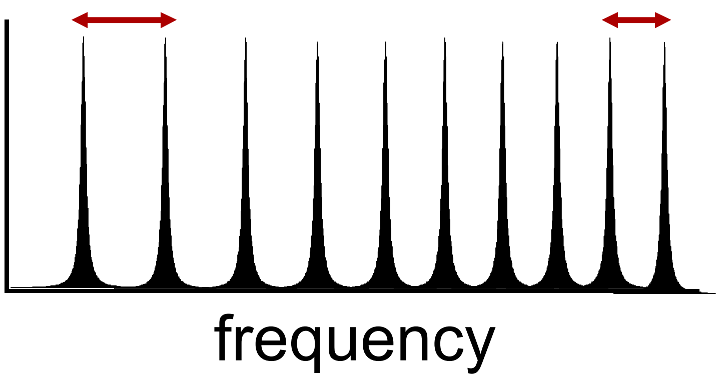
$$v_{p_m} = \frac{\omega_m}{m}$$

angular group velocity

$$v_{g_m} = \frac{\partial \omega_m}{\partial m} \approx \frac{\Delta \omega_m}{\Delta m} = 2\pi f_m$$

field formulation (no derivatives required)

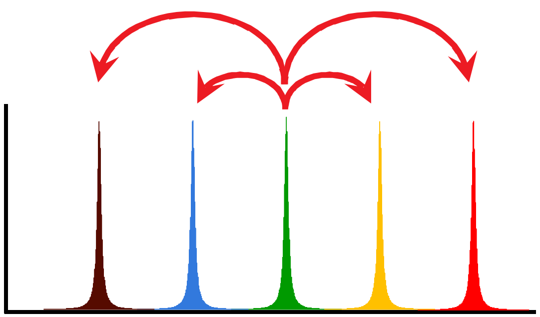
$$v^{\phi}_{g_m} = \frac{\int_S |\hat{\phi} \cdot [\mathbf{E}_m(\mathbf{r}) \times \mathbf{H}^*_m(\mathbf{r})]\,|}{\frac{1}{2}\int_V \varepsilon_0 \frac{d[\varepsilon(\mathbf{r})\omega]}{d\omega}\Big|_{\omega_m} |\mathbf{E}_m(\mathbf{r})|^2 + \mu_0 |\mathbf{H}_m(\mathbf{r})|^2}$$



Two Photon Wavefunction

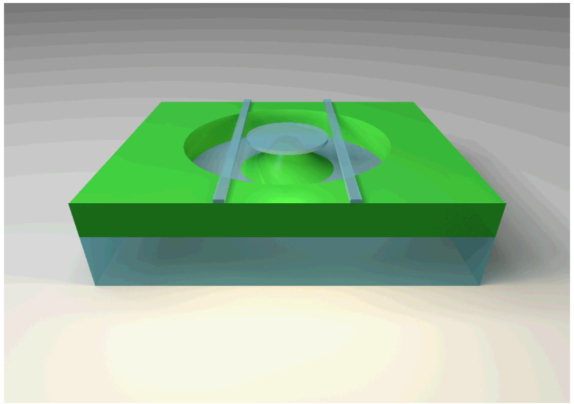
$$\hat{\mathbf{E}}(\mathbf{r},t) = \sum_m i\sqrt{\frac{m\pi\hbar f_m}{\varepsilon_0}}\,(\hat{a}_m^\dagger - \hat{a}_m)\,\mathbf{u}_m(\mathbf{r})$$

$$\langle\psi|\hat{a}^\dagger(\omega_s)\hat{a}(\omega_s)|\psi\rangle = 4\pi^4 \sum_{\Delta m} \frac{4\kappa_1^2 m_+ m_- f_{m_+} f_{m_-}}{|\kappa_{tot} - i(\omega_s - \omega_{m_+})|^2 |\kappa_{tot} + i(\omega_s - \omega_{m_-} - \Delta_0)|^2} \times \left[\int_{\rho,z} \chi^{(3)}(\rho,z)\rho|\mathbf{E}_p(\rho,z)|^2 \mathbf{u}_{m_+}\cdot\mathbf{u}_{m_-}\right]^2$$

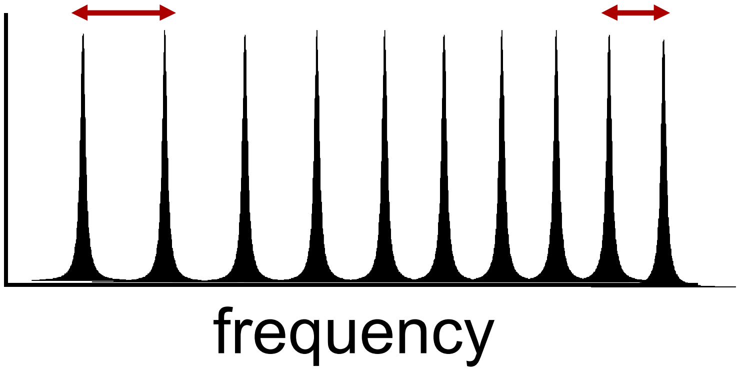


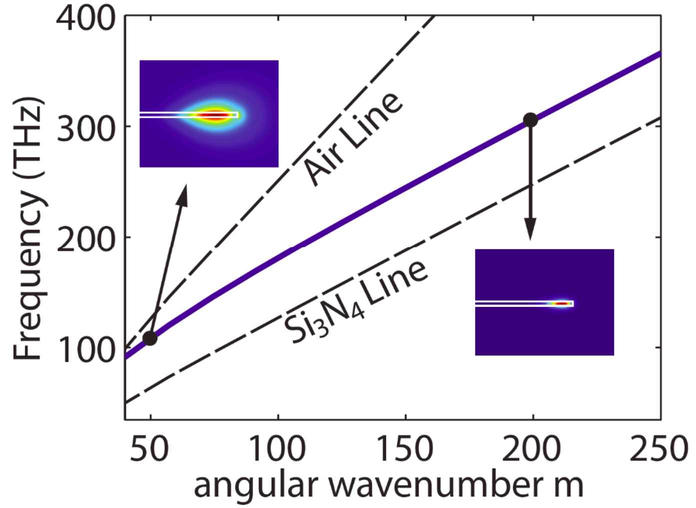
Wavelength

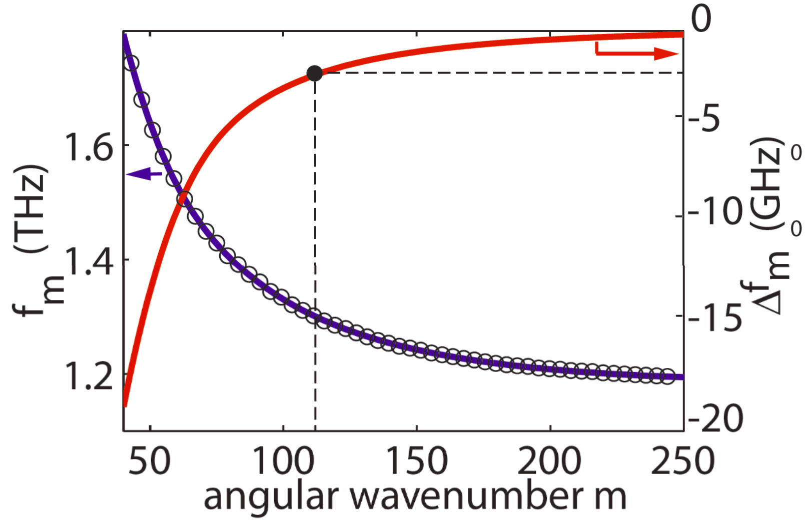
Dispersion in a Silicon Nitride Microdisk



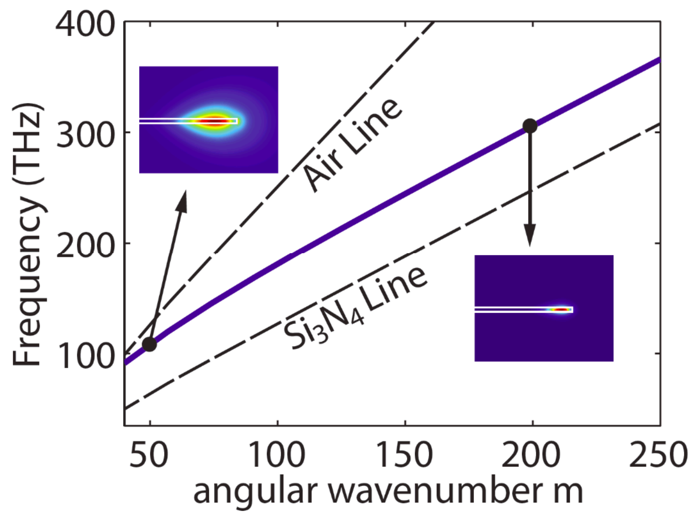
Decreasing free spectral range

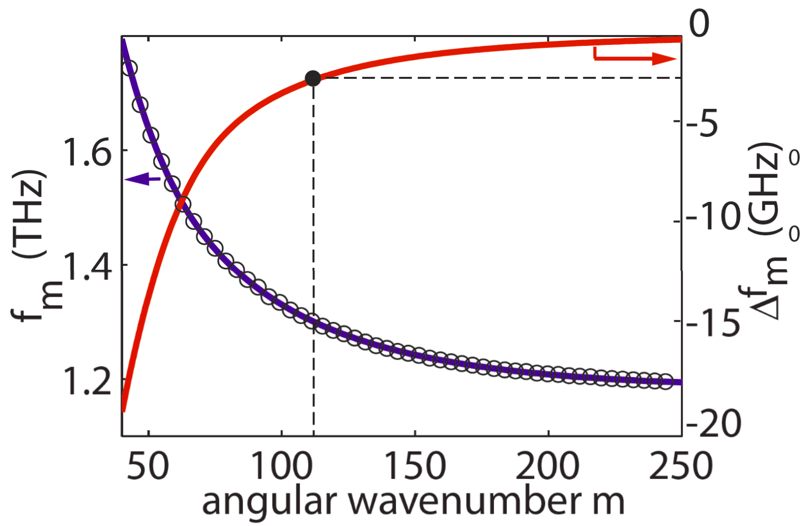




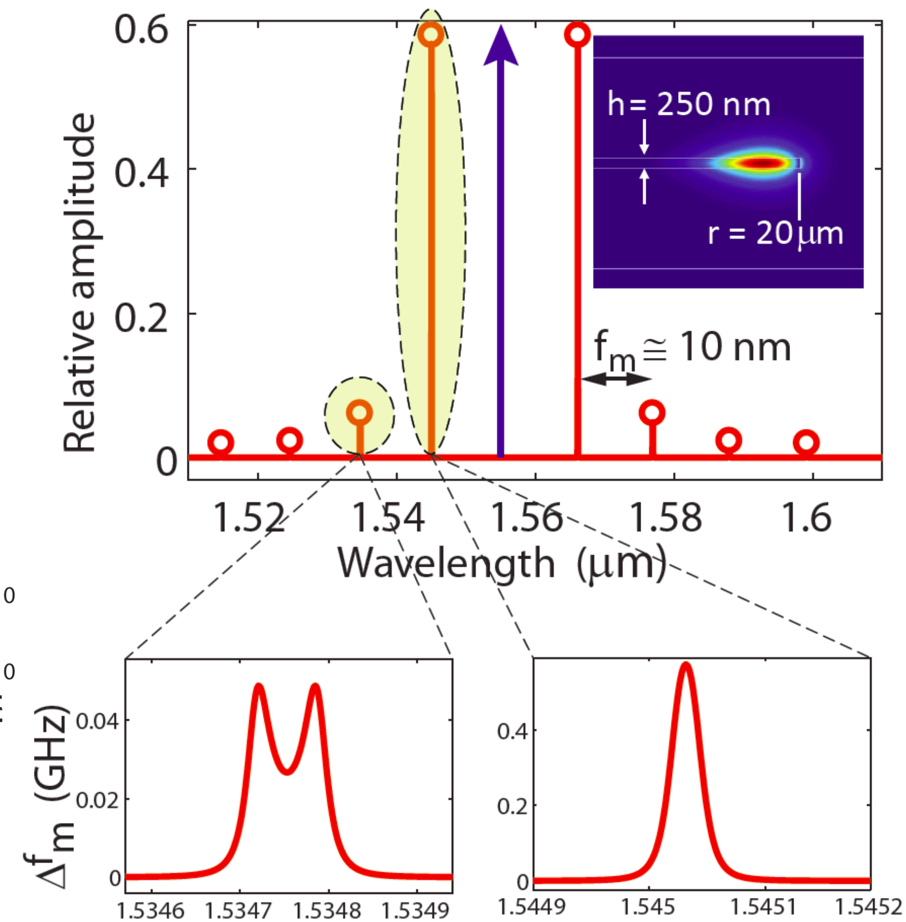


Numerical Example 1: Microdisk

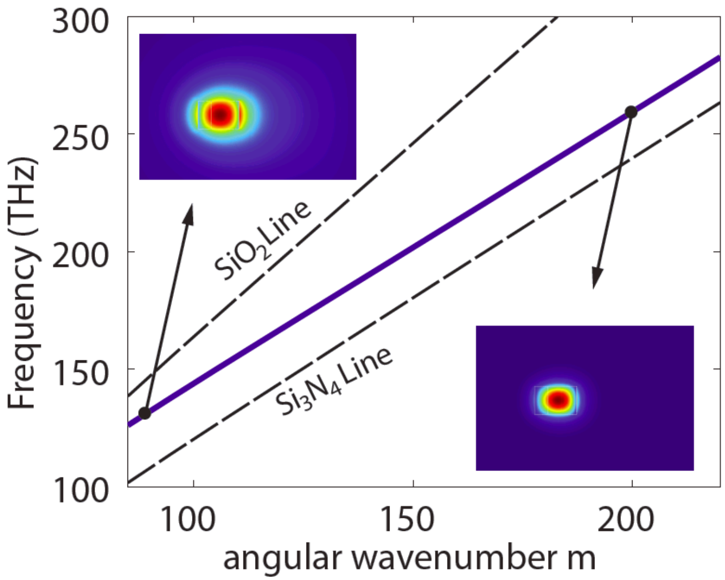


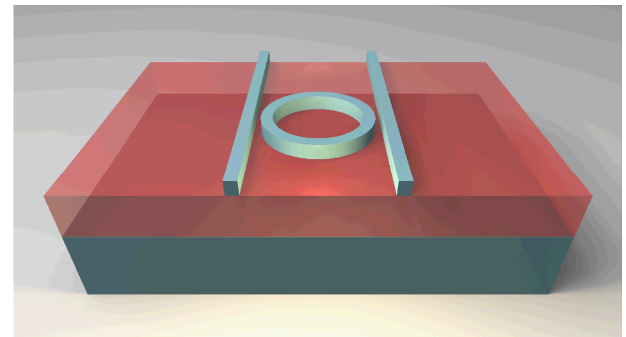


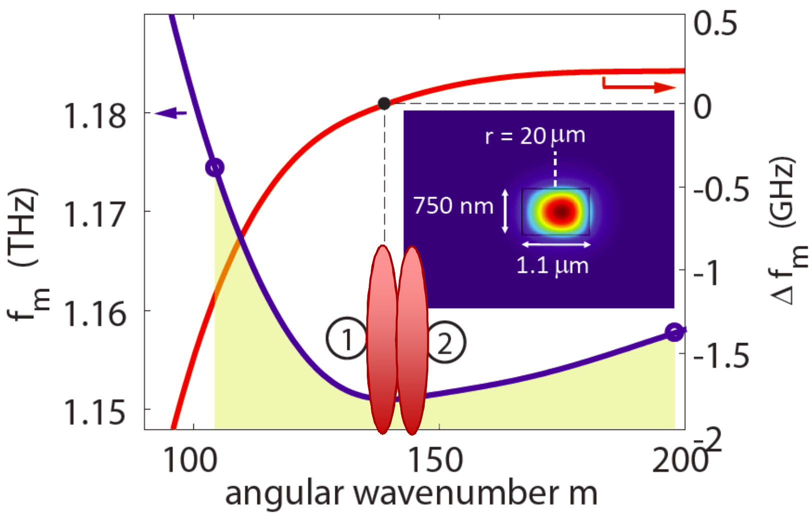
Spectra of entangled photons

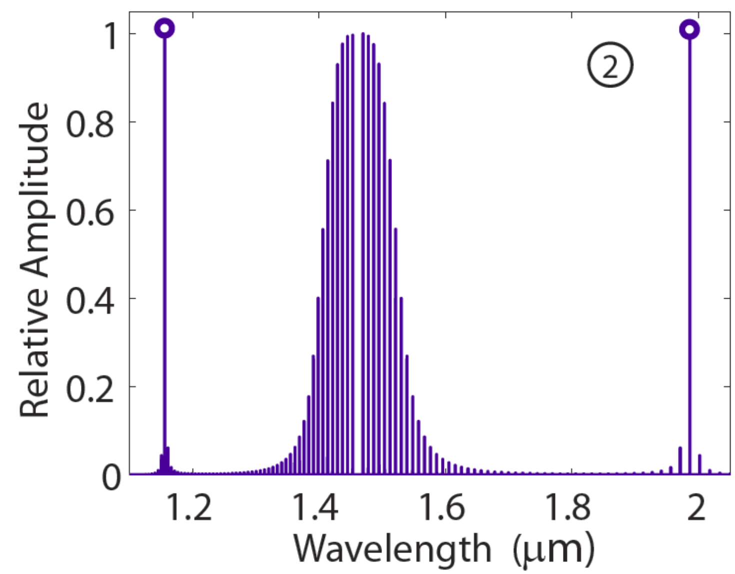


Numerical Example 2: Micro-ring

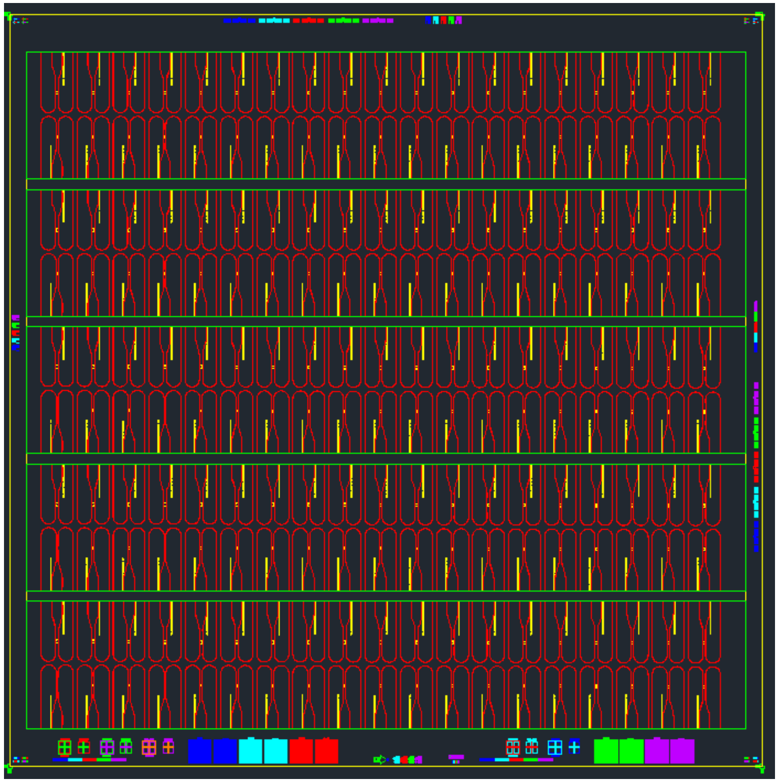


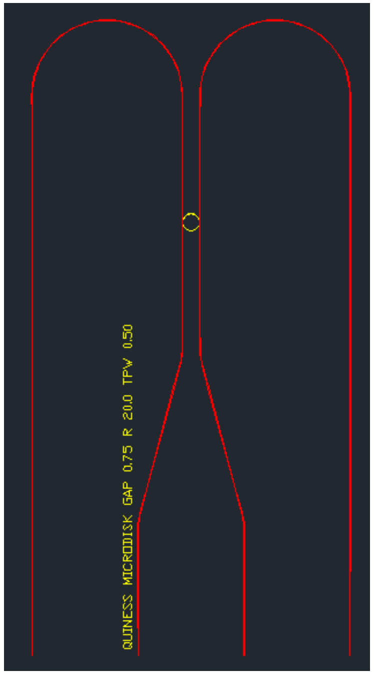






Devices Made for Northwestern Team





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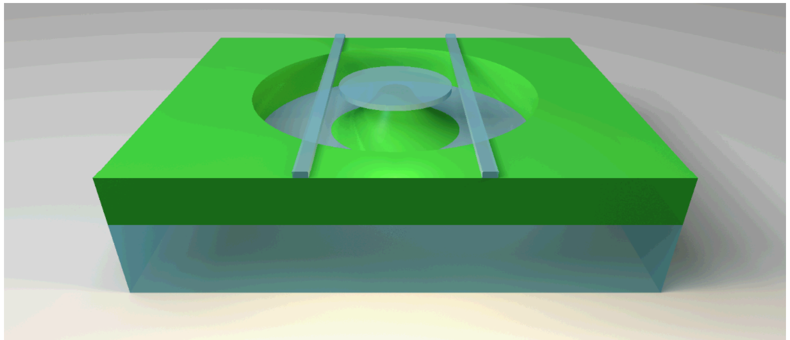
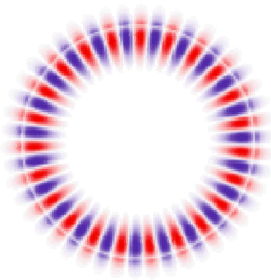
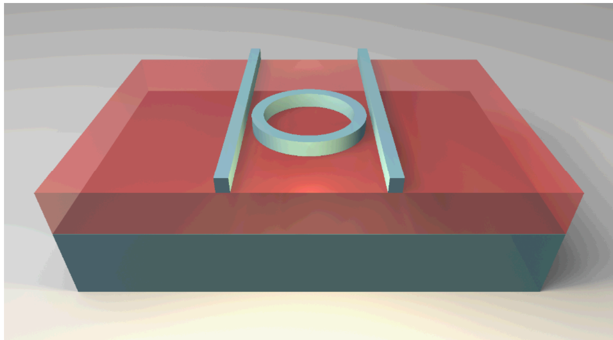
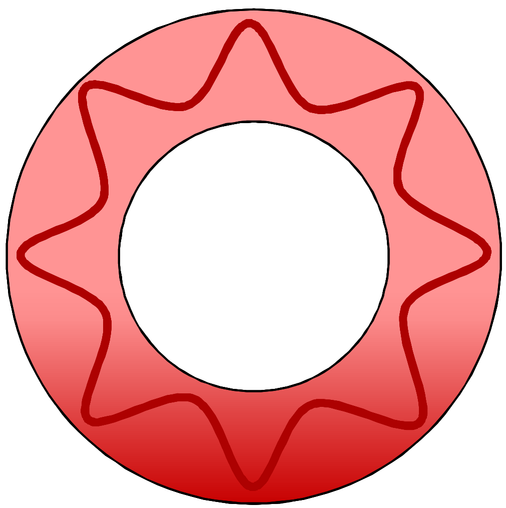
Conclusion

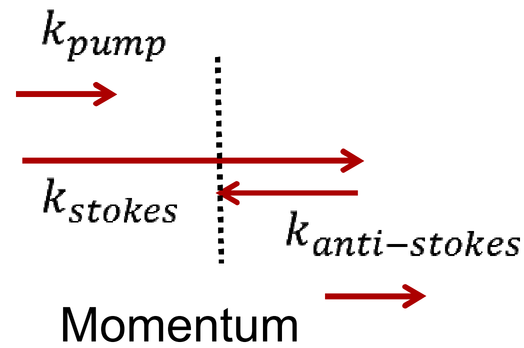
- New formulation of bi-photon wavefunction for azimuthally symmetric system
- Angular group and phase velocities essential
- Existence of "special" modes which conserve energy and momentum via accidental degeneracies
- Thank you for listening

Special Thanks to Peter Milonni, Prem Kumar, and Paul Davids for useful discussions relating to this work.

Extra Slides





$(\hbar k)$

Dispersion in Microresonators