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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Gaurav Bahl
					19b. TELEPHONE NUMBER
					217-333-8175

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RPPR Final Report
as of 14-May-2019

Agency Code:

Proposal Number: 68064PH

Agreement Number: W911NF-15-1-0588

INVESTIGATOR(S):

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Country: USA

DUNS Number: 041544081

EIN: 376000511

Report Date: 06-Dec-2018

Date Received: 11-Feb-2019

Final Report for Period Beginning 07-Sep-2015 and Ending 06-Sep-2018

Title: Engineered photonic crystals for spontaneous Raman laser cooling in silicon

Begin Performance Period: 07-Sep-2015

End Performance Period: 06-Sep-2018

Report Term: 0-Other

Submitted By: Gaurav Bahl

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 3

STEM Participants: 3

Major Goals: We proposed that Raman scattering, a fundamental inelastic phonon-photon scattering process that is available in all materials, can be used to cool any transparent solid. This can be achieved through a specific engineering of the photonic density of states (DoS) of the system. Our theoretical analysis revealed the possibility of Raman cooling of various materials using telecom wavelength pump light. Our overall research goal was to demonstrate that the engineering of photonic DoS for anti-Stokes enhancement and Stokes suppression is practical in the case of Raman scattering.

Specific goals were --

1. Fabricate on-chip photonic microdevices for Raman cooling: We used aluminum nitride as a host material for these devices (e.g. resonators, photonic crystals) since we have a lot of experience with e-beam lithography and etching in the material, it can achieve very good optical transparency, and it has distinct LO and TO phonon modes that are Raman-active.

2. Demonstrate suppression of Stokes Raman scattering, and enhancement of anti-Stokes Raman scattering in a microfabricated sample.

3. Demonstrate cooling of a phonon mode: Once the above tasks are successfully achieved, we aimed to demonstrate cooling of a single optical phonon mode in aluminum nitride. The cooling will be quantified through the Raman sideband spectrum -- reduction of the integrated sideband amplitude and spectral broadening of the scattered light are both independent indications of cooling of the phonon modes.

Accomplishments: Our theoretical and experimental work in this period focused on laser cooling through inelastic light scattering processes -- both with Brillouin and Raman scattering.

1. Study of laser cooling using Brillouin light scattering in waveguides --
We developed an analytical model for opto-acoustic cooling of phonons in linear waveguides through the Brillouin scattering interaction. We elucidated the regimes of phonon lifetime and group velocity where appreciable cooling may be possible, and the spectral characteristics of the phonon population. We published a journal paper in the New Journal of Physics. http://iopscience.iop.org/article/10.1088/1367- 2630/18/11/115004

2. Study of Raman laser cooling with anisotropic density of states --
We performed a theoretical study, showing for the first time how Raman scattering is modified by anisotropic

density of states. Using this tool, we performed full 3D anisotropic calculation of Raman scattering patterns and the corresponding Raman cooling efficiency. This work enables optimization studies on photonic design and material crystal orientation, to would maximize total Raman cooling efficiency. Results were published in Phys Rev A - https://journals.aps.org/pra/abstract/10.1103/PhysRevA.97.043835

3. Experimental study on modification of Brillouin cooling by photonic density of states --
We performed an experimental study on how the photonic density of states in both energy and momentum space affects Brillouin cooling. This confirms that Raman scattering could be engineered by a similar approach. The results were published in Optics Express. https://www.osapublishing.org/oe/abstract.cfm?uri=oe-25-2-776

4. Experimental effort on Raman cooling --
We fabricated nanophotonic devices (waveguide-resonator coupled systems) in which the anti-Stokes optical density of states is engineered for maximum Raman cooling efficiency. We produced several generations of these devices but are yet to see the intended results as per the goals of this project. This work is experimentally challenging and still ongoing.

Training Opportunities: Nothing to Report

Results Dissemination: Raman Cooling of Solids through Photonic Density of States Engineering
Optica, 2(10), pp.893-899, 2015.
Y.-C. Chen, G. Bahl

Brillouin Cooling in a Linear Waveguide
New Journal of Physics, 18, 115004, 2016.
Y.-C. Chen, S. Kim, G. Bahl

Role of optical density of states in two-mode optomechanical cooling
Optics Express, 25(2), pp.776-784, 2017.
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Optimization of anisotropic photonic density of states for Raman cooling
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Raman Cooling of Solids through Density of States Engineering
at Frontiers in Optics, San Jose, CA, Oct 2015.
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Raman cooling in silicon photonic crystals
at SPIE Photonics West (Optical and Electronic Cooling of Solids), San Francisco CA, Feb 2016.
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Brillouin and Raman cooling in resonant and non-resonant systems (invited paper)
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at SPIE Photonics West, San Francisco, Feb 2017.
Y.-C. Chen, I. Ghosh, G. Bahl

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Gaurav Bahl
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Yin-Chung Chen
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Seunghwi Kim
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Indronil Ghosh
Person Months Worked: 8.00 **Funding Support:**
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National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
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Date Submitted: 2/11/19 12:00AM Date Published: 4/1/18 12:00AM
Publication Location:
Article Title: Optimization of anisotropic photonic density of states for Raman cooling of solids
Authors: Yin-Chung Chen, Indronil Ghosh, André Schleife, P. Scott Carney, Gaurav Bahl
Keywords: Raman cooling
Abstract: Optical refrigeration of solids holds tremendous promise for applications in thermal management. It can be achieved through multiple mechanisms including inelastic anti-Stokes Brillouin and Raman scattering. However, engineering of these mechanisms remains relatively unexplored. The major challenge lies in the natural unfavorable imbalance in transition rates for Stokes and anti-Stokes scattering. We consider the influence of anisotropic photonic density of states on Raman scattering and derive expressions for cooling in such photonically anisotropic systems. We demonstrate optimization of the Raman cooling figure of merit considering all possible orientations for the material crystal and two example photonic crystals. We find that the anisotropic description of the photonic density of states and the optimization process is necessary to obtain the best Raman cooling efficiency for systems having lower symmetry. This general result applies to a wide array of other laser cooling methods
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Volume: 25 Issue: 2 First Page #: 776
Date Submitted: 2/11/19 12:00AM Date Published: 1/1/17 6:00AM
Publication Location:
Article Title: Role of optical density of states in Brillouin optomechanical cooling
Authors: Seunghwi Kim, Gaurav Bahl
Keywords: Brillouin cooling, Optomechanics, Laser cooling
Abstract: Dynamical back-action cooling of phonons in optomechanical systems having one optical mode is well studied. Systems with two optical modes have the potential to reach significantly higher cooling rate through resonant enhancement of both pump and scattered light. Here we experimentally investigate the role of dual optical densities of states on Brillouin optomechanical cooling, and the deviation from theory caused by thermal locking to the pump laser. Using this, we demonstrate a room temperature system operating very close to the strong coupling regime, where saturation of cooling is anticipated.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
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Volume: 18 Issue: 11 First Page #: 115004
Date Submitted: 2/11/19 12:00AM Date Published: 11/1/16 10:00AM
Publication Location:
Article Title: Brillouin cooling in a linear waveguide
Authors: Yin-Chung Chen, Seunghwi Kim, Gaurav Bahl
Keywords: Brillouin cooling
Abstract: Brillouin scattering is not usually considered as a mechanism that can cause cooling of a material due to the thermodynamic dominance of Stokes scattering in most practical systems. However, it has been shown in experiments on resonators that net phonon annihilation through anti-Stokes Brillouin scattering can be enabled by means of a suitable set of optical and acoustic states. The cooling of traveling phonons in a linear waveguide, on the other hand, could lead to the exciting future prospect of manipulating unidirectional phonon fluxes and even the nonreciprocal transport of quantum information via phonons. In this work, we present an analysis of the conditions under which Brillouin cooling of phonons of both low and high group velocities may be achieved in a linear waveguide. We analyze the three-wave mixing interaction between the optical and traveling acoustic modes that participate in forward Brillouin scattering, and reveal the key regimes of operation for the process. Our calc
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DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: University of Illinois at Urbana-Champaign
Date Received: 11-Feb-2019 Completion Date: 12/30/18 10:24PM
Title: Laser Cooling of Solids Through Inelastic Light Scattering
Authors: Yinchung Chen
Acknowledged Federal Support: **N**

Final Report
W911NF-15-1-0588

PI: Dr. Gaurav Bahl

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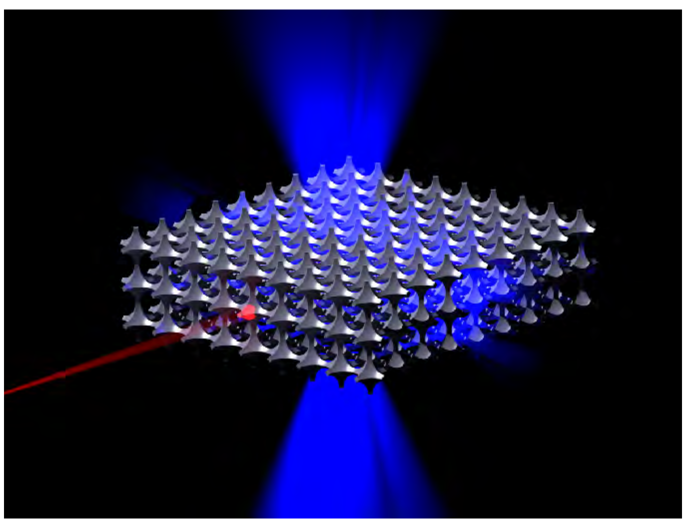

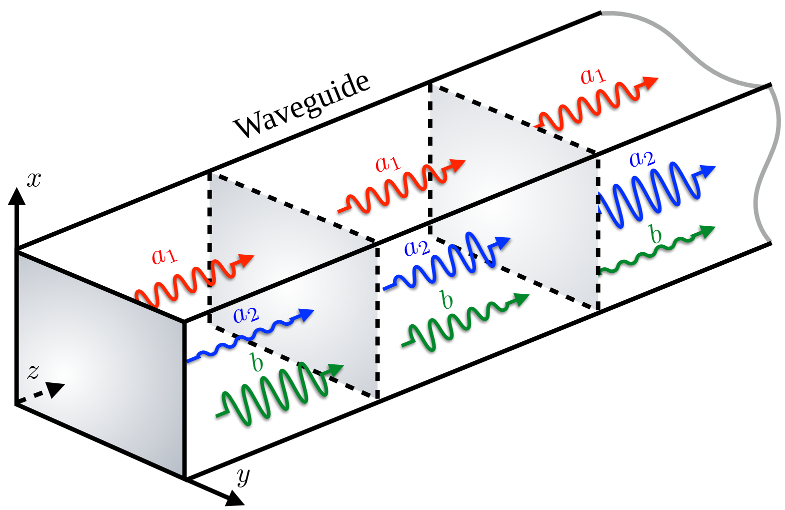

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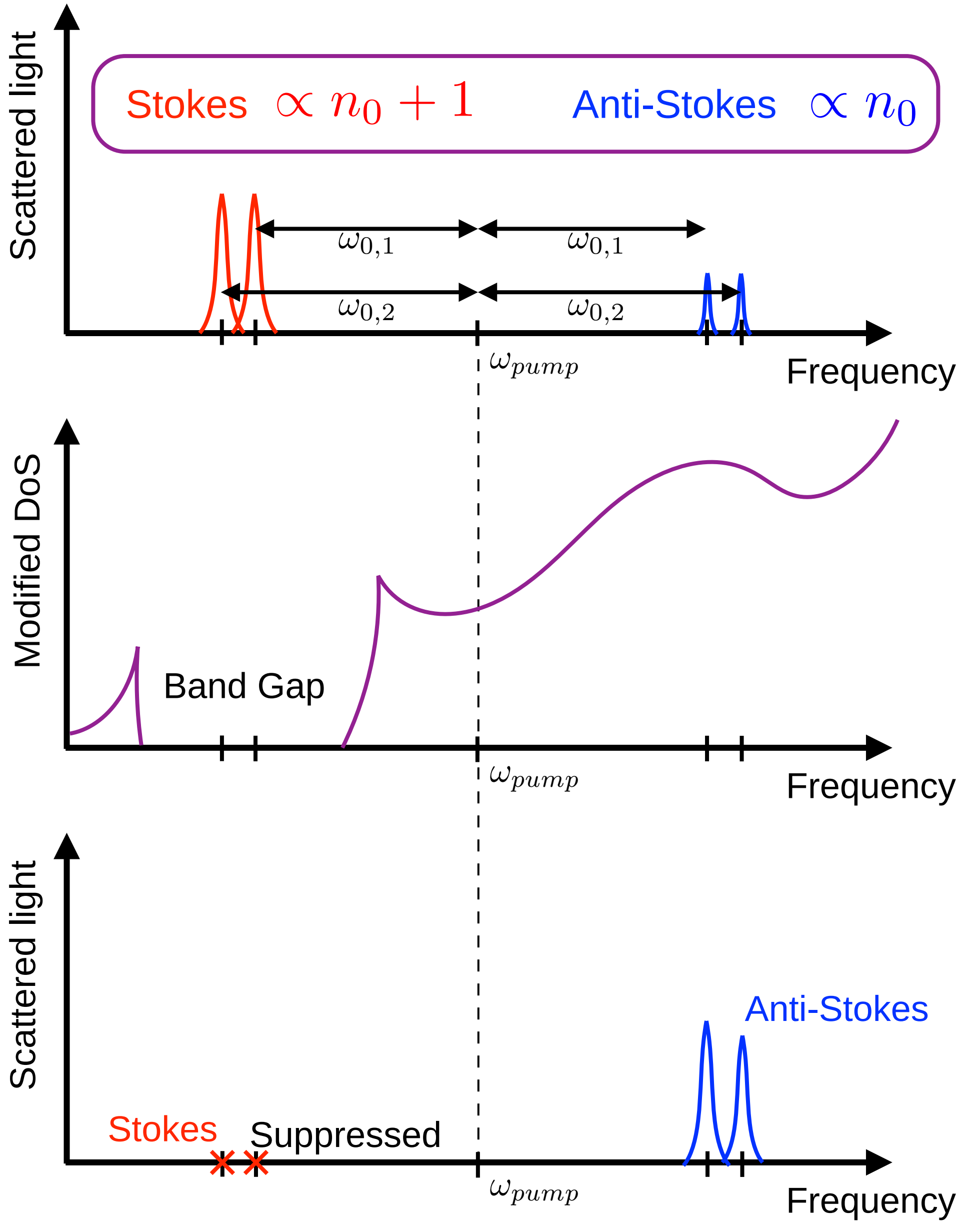
Goal: Engineer photonic DoS to enable Raman cooling in solids



- **Challenge:** Ratio of anti-Stokes intensity to Stokes intensity is always less than one. For silicon at room temperature this ratio is about 0.1.

$$n_0 = \frac{1}{exp(\frac{\hbar\omega_0}{k_B T}) - 1} \qquad \frac{n_0}{n_0 + 1} \approx 0.1$$

- **Solution:** If we have a photonic density of states (DoS) that is engineered such that there is no available modes at the Stokes frequency, we can suppress the Stokes scattering.

Multiple Stokes modes can potentially be suppressed simultaneously by the photonic DoS

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Journal papers and Conference presentations

Journal Publications

Raman Cooling of Solids through Photonic Density of States Engineering
Optica, 2(10), pp.893-899, 2015.
Y.-C. Chen, G. Bahl

Original proposal on achieving Raman cooling with photonic DoS engineering.

Brillouin Cooling in a Linear Waveguide
New Journal of Physics, 18, 115004, 2016.
Y.-C. Chen, S. Kim, G. Bahl

Theoretical study on the possibility of DoS engineering in linear waveguides

Role of optical density of states in two-mode optomechanical cooling
Optics Express, 25(2), pp.776-784, 2017.
S. Kim, G. Bahl

Experimental study on the role of photonic DoS in Brillouin optomechanical cooling

Optimization of anisotropic photonic density of states for Raman cooling
Phys. Rev. A 97, 043835, 2018.
Y.-C. Chen, I. Ghosh, A. Schleife, P.S. Carney, G. Bahl

Study on the use of anisotropic photonic DoS for controlling Raman cooling.

Conferences

Raman Cooling of Solids through Density of States Engineering
at Frontiers in Optics, San Jose, CA, Oct 2015.
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Raman cooling in silicon photonic crystals
at SPIE Photonics West (Optical and Electronic Cooling of Solids), San Francisco CA, Feb 2016.
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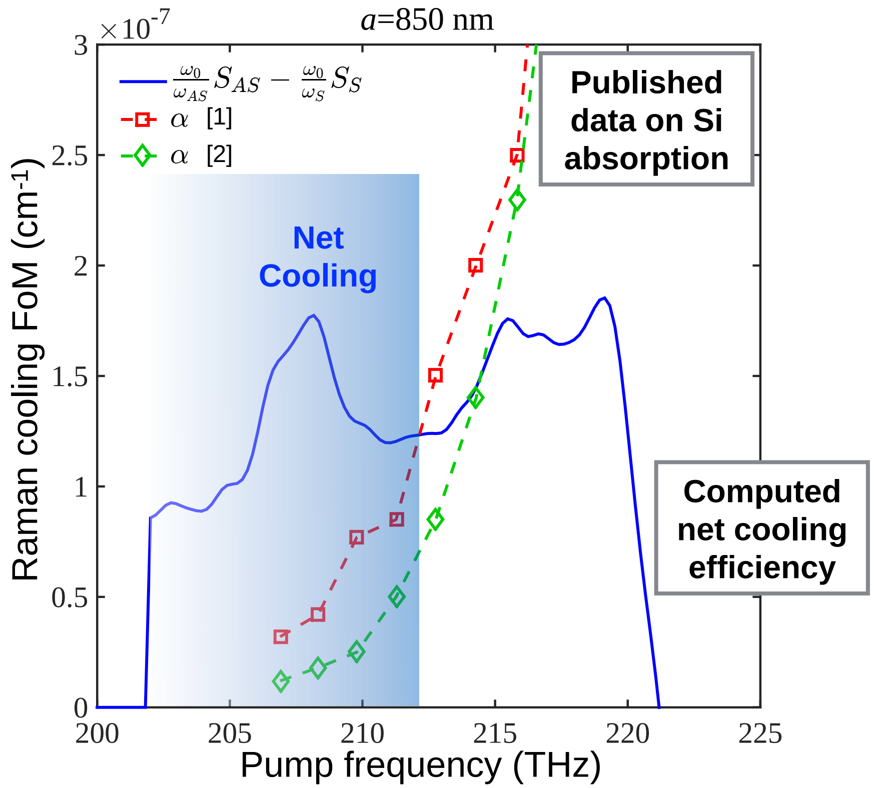
Summary:
Raman cooling of solids through photonic density of states engineering

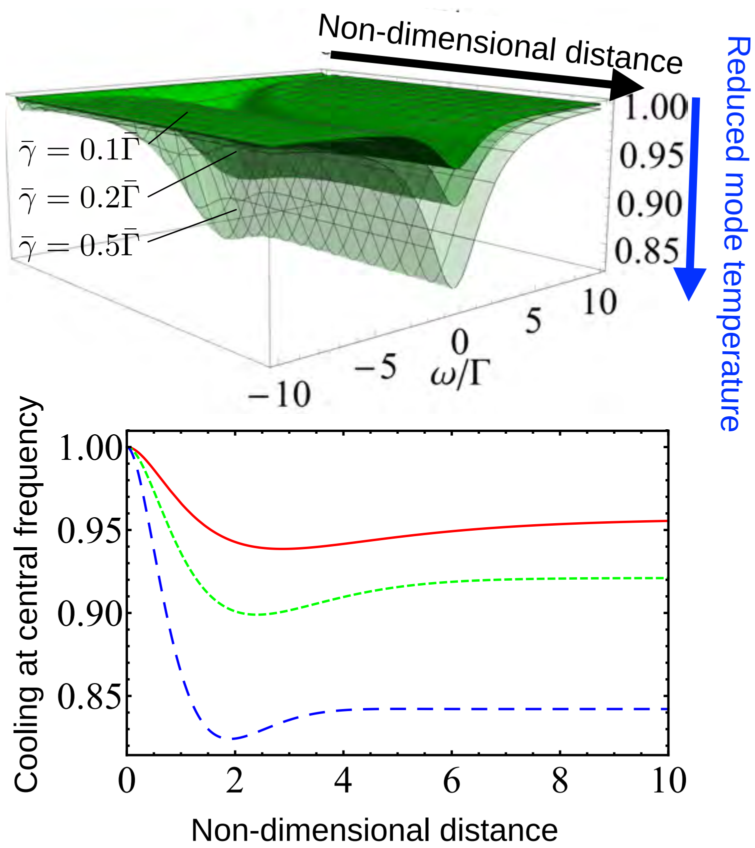


[Raman Cooling of Solids through Photonic Density of States Engineering]
Optica, 2(10), pp.893-899, 2015.
Y.-C. Chen, G. Bahl

We showed analytically that photonic density of states (DoS) engineering can address the two fundamental requirements for achieving spontaneous Raman cooling: suppressing the dominance of Stokes (heating) transitions and the enhancement of anti-Stokes (cooling) efficiency beyond the natural optical absorption of the material.

We developed a general model for the DoS modification to spontaneous Raman scattering probabilities, and elucidated the necessary and minimum condition required for achieving net Raman cooling. With a suitably engineered DoS, we established the enticing possibility of the refrigeration of intrinsic silicon by annihilating phonons from all its Raman active modes simultaneously, through a single telecom wavelength pump. This result points to a highly flexible approach for the laser cooling of any transparent semiconductor, including indirect band gap semiconductors, far away from significant optical absorption, band-edge states, excitons, or atomic resonances.

Summary:
Brillouin Cooling in a Linear Waveguide

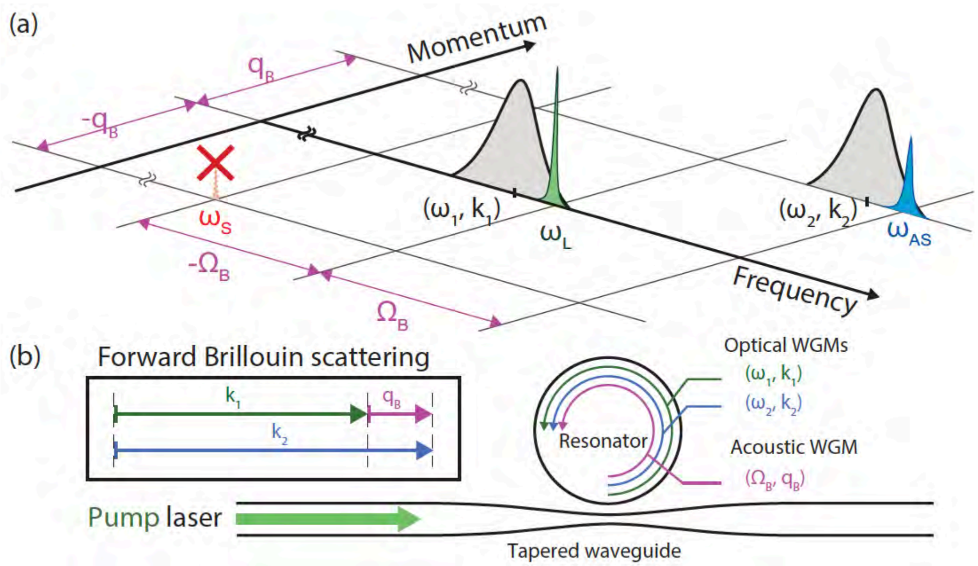


Brillouin Cooling in a Linear Waveguide
New Journal of Physics, 18, 115004, 2016.
Y.-C. Chen, S. Kim, G. Bahl

In this work, we presented an analysis of the conditions under which Brillouin cooling of phonons of both low and high group velocities may be achieved in a linear waveguide.

We analyzed the three-wave mixing interaction between the optical and traveling acoustic modes that participate in forward Brillouin scattering, and revealed the key regimes of operation for the process. Our calculations indicated that measurable cooling may occur in a system having phonons with spatial loss rate that is of the same order as the spatial optical loss rate. If the Brillouin gain in such a waveguide reaches the order of 10^5 $m^{-1}W^{-1}$, appreciable cooling of phonon modes may be observed with modest pump power of a few mW.

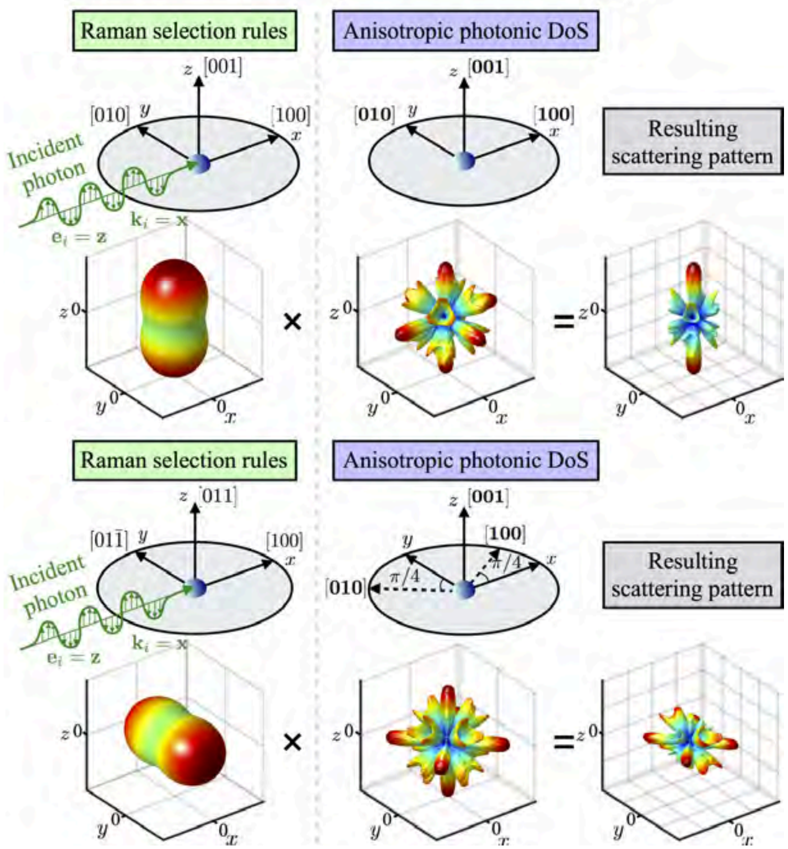
Summary:
Role of optical density of states in two-mode optomechanical cooling



[Role of optical density of states in two-mode optomechanical cooling]()
Optics Express, 25(2), pp.776-784, 2017.
S. Kim, G. Bahl

Dynamical back-action cooling of phonons in optomechanical systems having one optical mode is well studied. Systems with two optical modes have the potential to reach significantly higher cooling rate through resonant enhancement of both pump and scattered light. Here we experimentally investigated the role of dual optical densities of states on Brillouin optomechanical cooling, and the deviation from theory caused by thermal locking to the pump laser. Using this, we demonstrated a room temperature system operating very close to the strong coupling regime, where saturation of cooling is anticipated.

Summary: Optimization of anisotropic photonic density of states for Raman cooling



[Optimization of anisotropic photonic density of states for Raman cooling]()
Phys. Rev. A 97, 043835, 2018.
Y.-C. Chen, I. Ghosh, A. Schleife, P.S. Carney, G. Bahl

We considered the influence of anisotropic photonic density of states on Raman scattering and derived expressions for cooling in photonically anisotropic systems.

We demonstrated optimization of the Raman cooling figure of merit considering all possible orientations for the material crystal and two example photonic crystals. We found that the anisotropic description of the photonic density of states and the optimization process is necessary to obtain the best Raman cooling efficiency for systems having lower symmetry. This general result applies to a wide array of other laser cooling methods in the presence of anisotropy.

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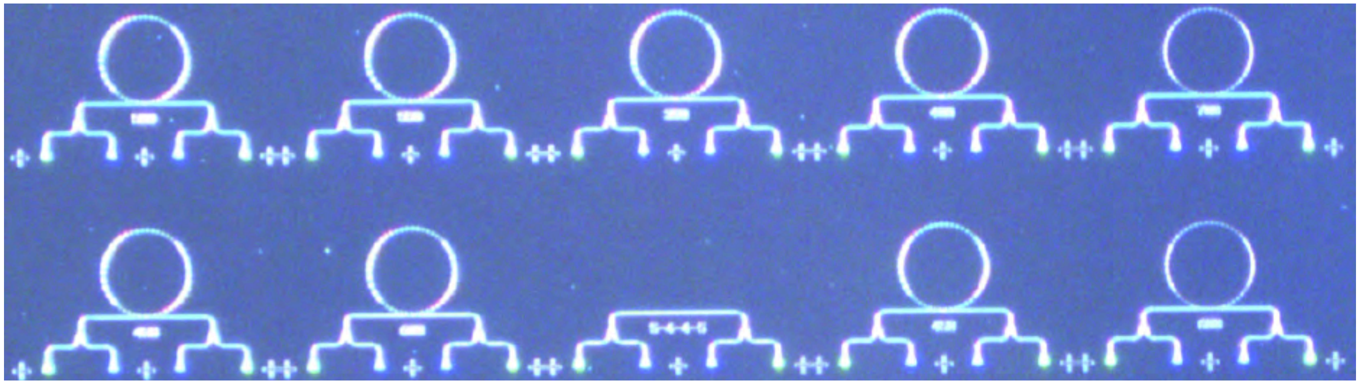
Experimental results



Practical considerations for Raman cooling experiment

General design considerations

- Raman scattering efficiency is low
  - Need long interaction length
  - Need large pump power
- Issues with photonic crystal approach
  - Difficult to fabricate at large scale
  - Require high finesse optical, which is not easy to achieve
- Benefits of ring resonators
  - Provide large interaction distance
  - Easy to fabricate with a single litho step

Material considerations

- Material choice: AlN
  - Very wide bandgap -> High transparency
  - Relatively easy to fabricate wavguides and high-Q resonators
- Targeted phonon modes: (TE to TE scattering)
  - Backward scattering: A_1 (TO)
  - Forward scattering: A_1 (LO)
- Raman wavelengths (1550 pump, backscattering)
  - Stokes: ~1710 nm
  - Anti-Stokes: ~1410 nm
- Typical Raman linewidth ~ 20 cm^{-1}
  - FSR between modes required < 5 nm

Raman scattering in ring resonators *--> Large interaction length in small structures*

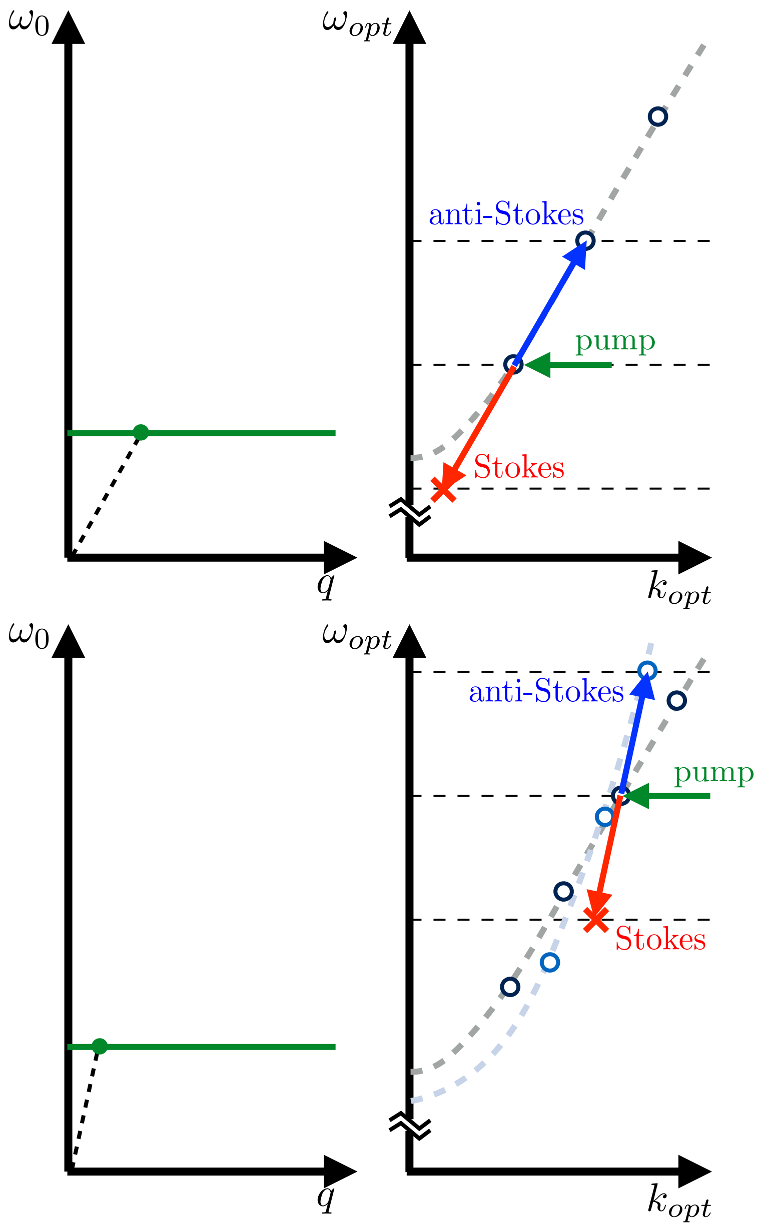
finesse $$\mathcal{F} = \frac{\Delta\lambda_{FSR}}{\lambda} Q$$

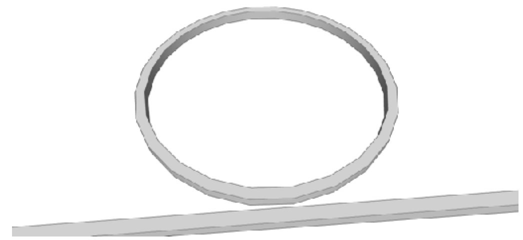
free spectral range $$\Delta\lambda_{FSR} = \frac{\lambda^2}{2\pi r n_g}$$

interaction length $$l \approx \mathcal{F} \times 2\pi r = \frac{\lambda}{n_g} Q$$

$$Q \sim 100,000 \quad \lambda \sim 1,550 \text{ nm} \quad \boxed{l \sim 0.1 \text{ m}}$$

Achieving Stokes suppression with ring resonators

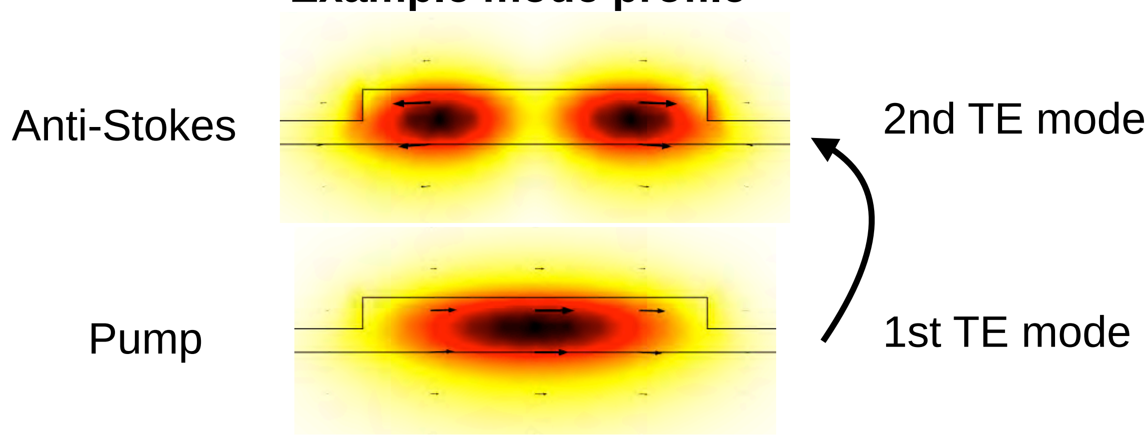




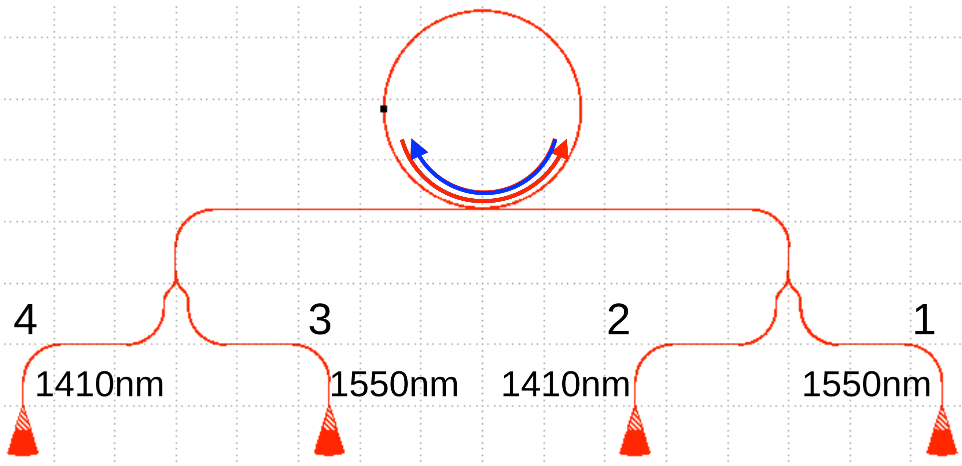
Method 1: cutoff frequency of the ring resonator

Method 2: multi-mode ring resonator with different transverse orders

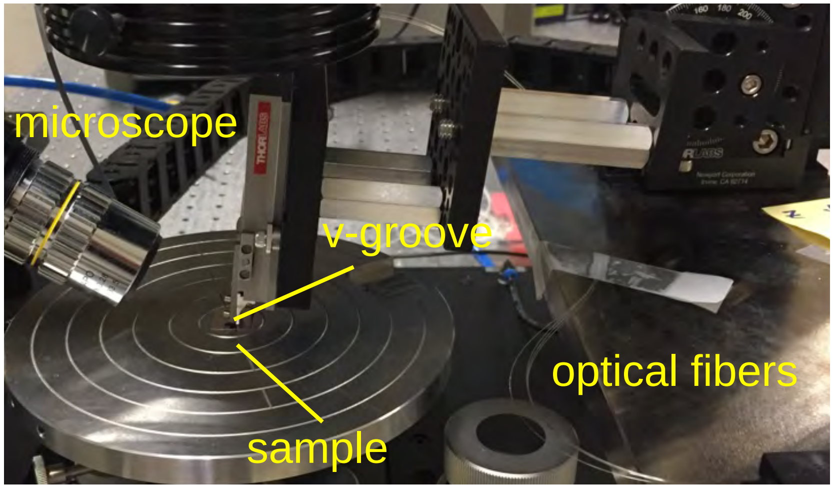
Example mode profile

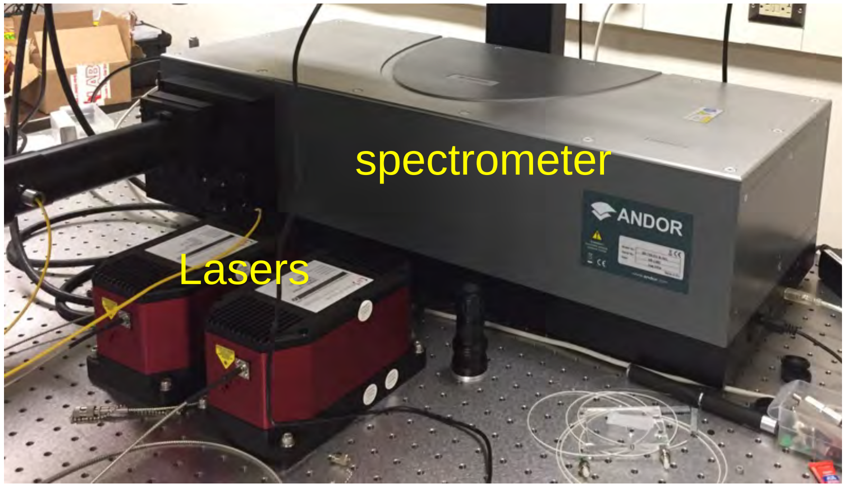


Design and experimental setup



1. Identify available modes around both 1410 nm and 1550 nm
2. Couple pump into modes in the 1410 nm range, observe scattered Stokes modes around 1550nm
3. Reverse the experiment, couple pump into one of the observed Stokes modes in the 1550 nm range, observe anti-Stokes scattering in the original 1410 nm mode





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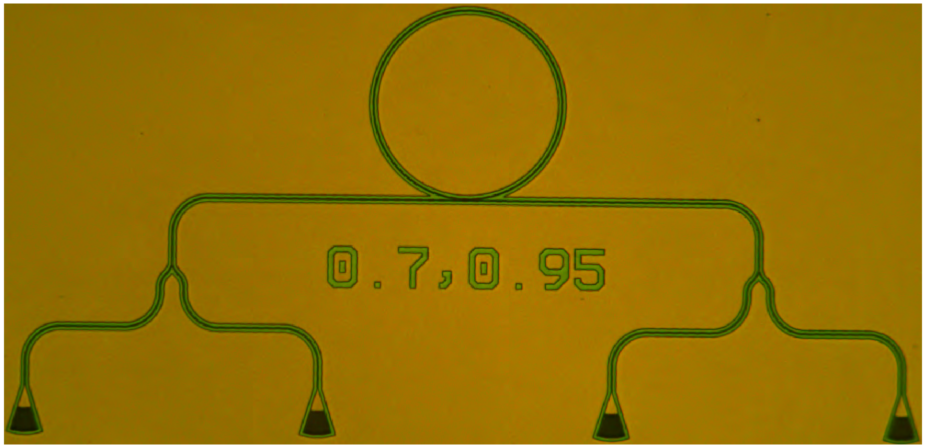
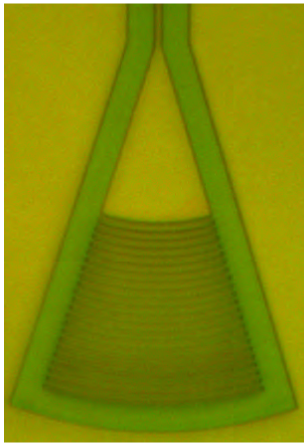
Fabricated device components

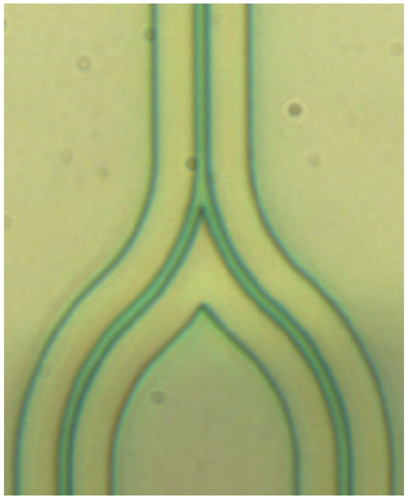
Microscope image



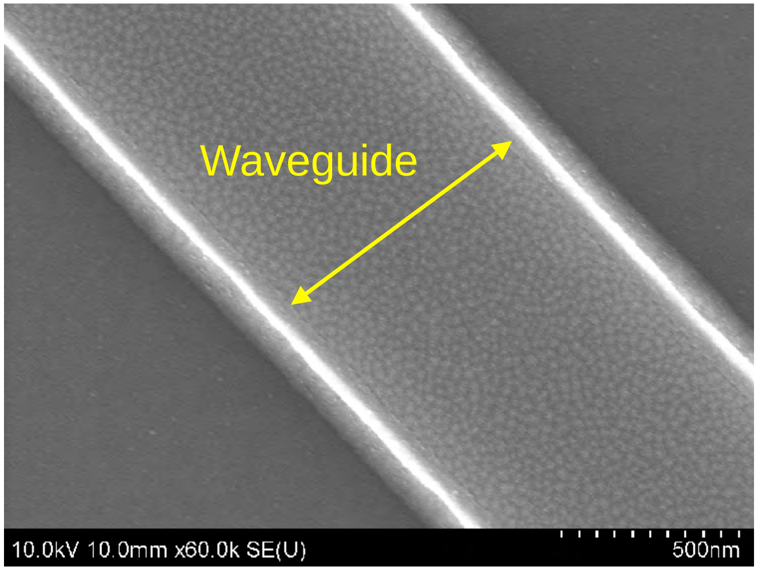
Grating coupler



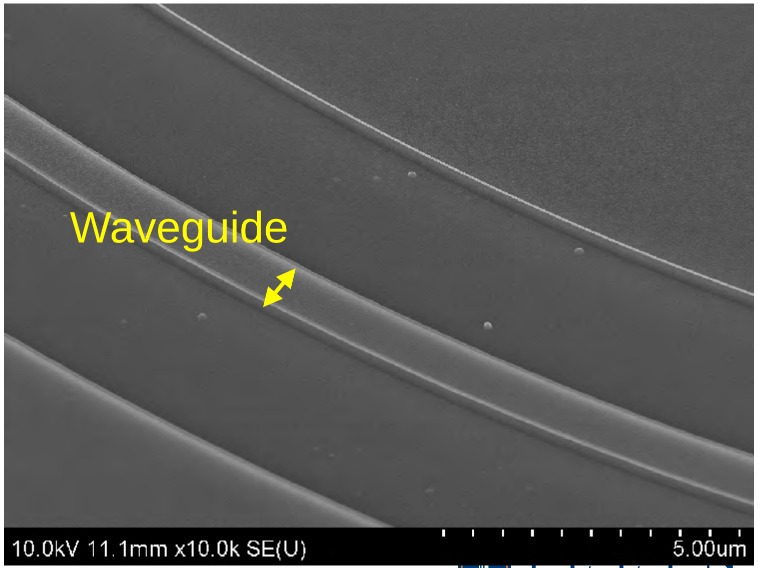
Y-Branch



SEM image of the ridge waveguide



SEM image of the ridge waveguide



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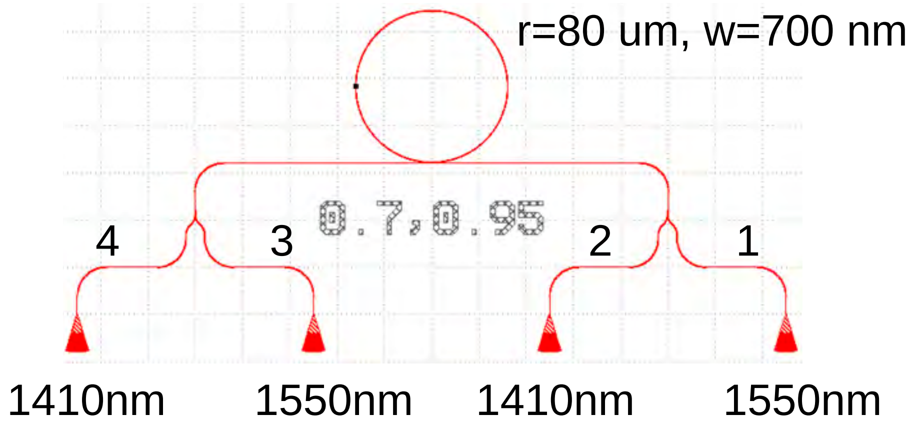
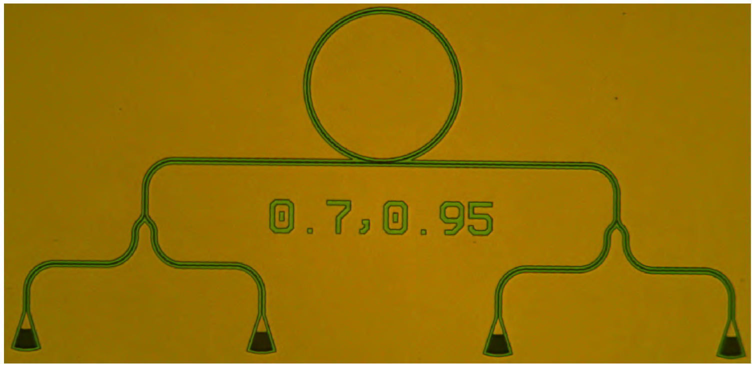
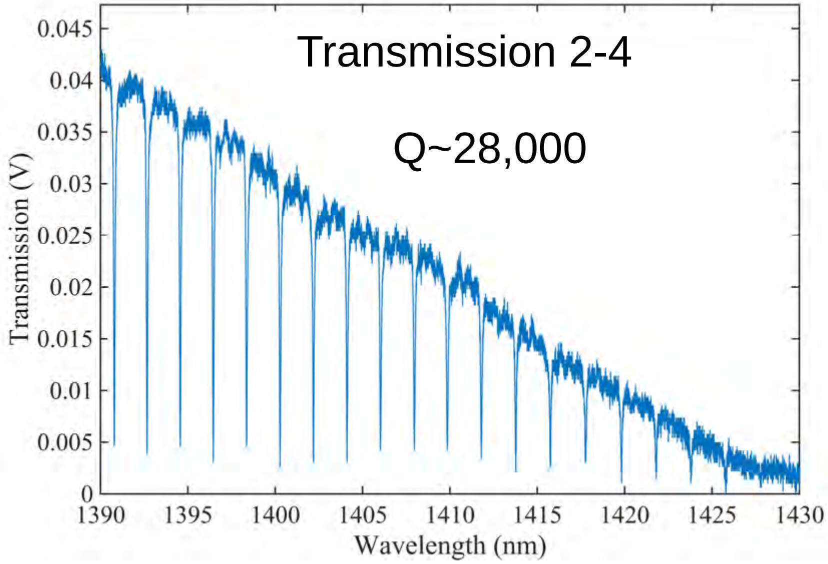
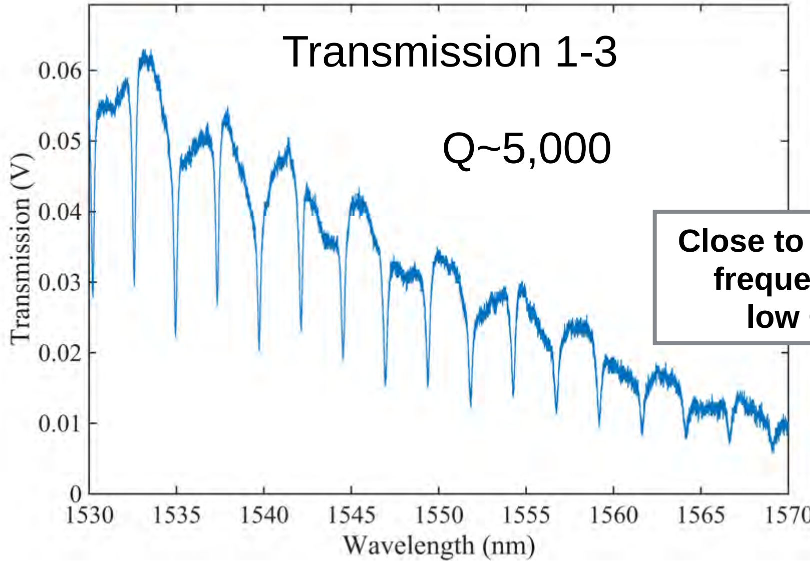
Preliminary results: single mode resonators









Close to cutoff frequency low Q

Not able to detect Stokes Raman when pumped at 1410 nm

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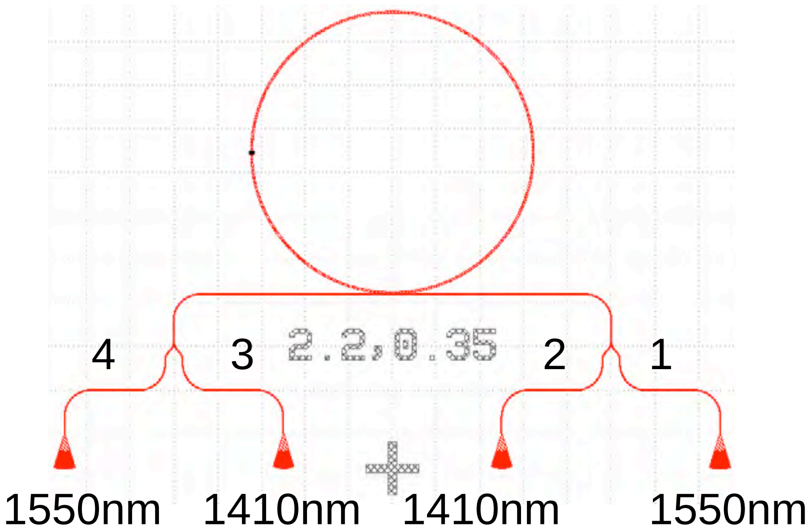
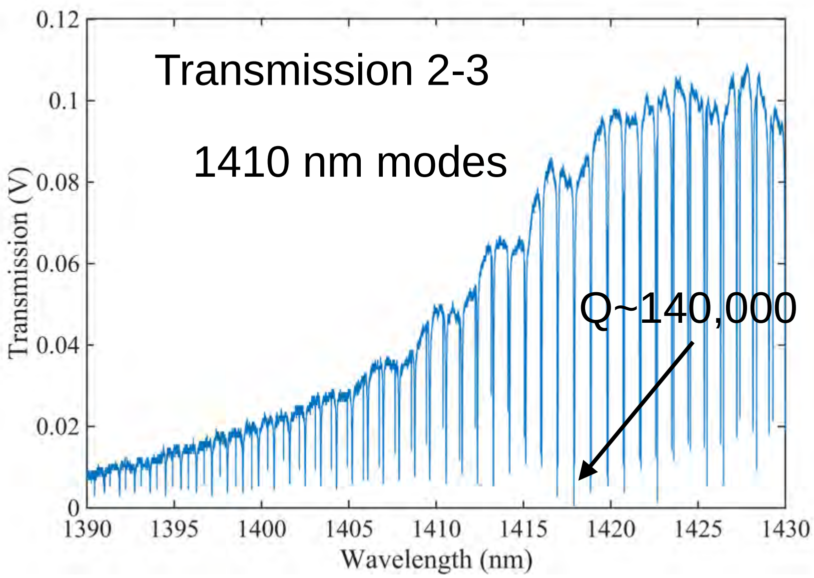
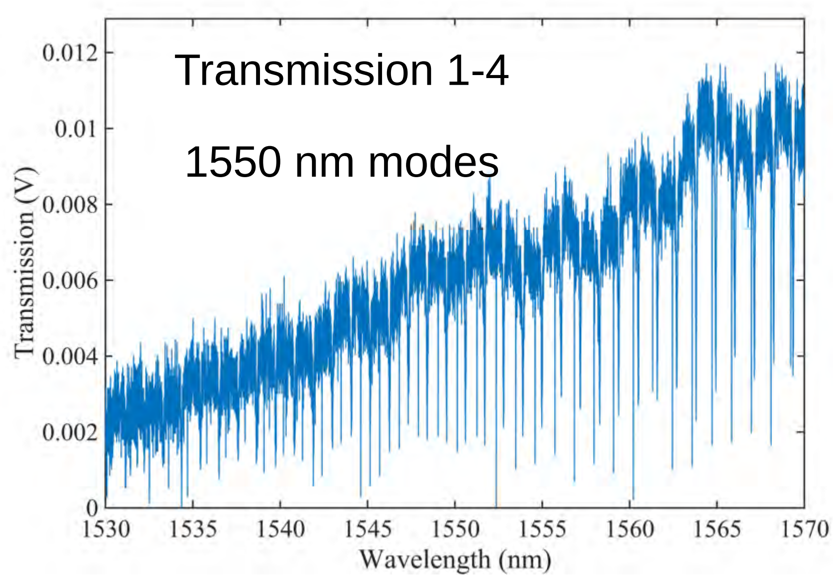
Improved design: two-mode ring resonators



Goal: Improve chance of phase-matching

- 160 um radius, reduced free spectral range
- 2.2 um guide width, two transverse order modes
- Achieved higher Q modes, Q > 140,000
- Technical issue: Transmission between port 1-4 was poor
- Not able to obtain Raman signal





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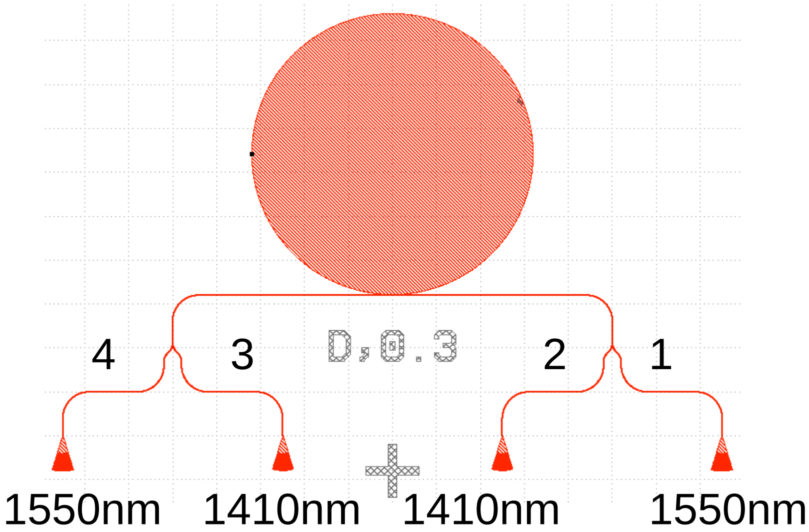
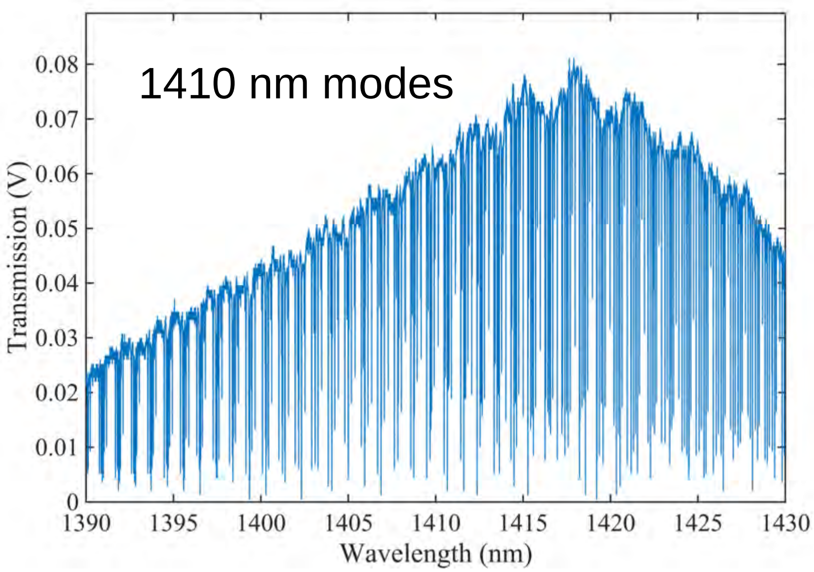
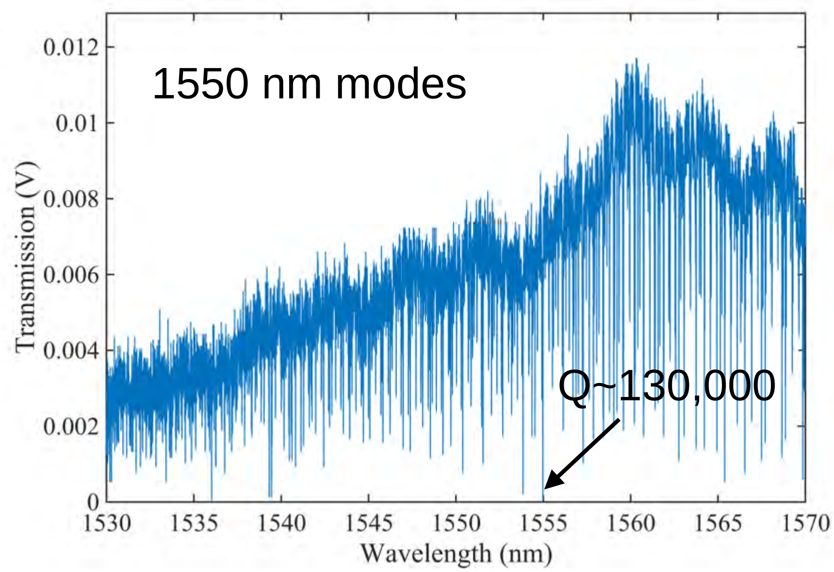
Improved design: disk resonators



Goal: Brute-force observation of Raman scattering

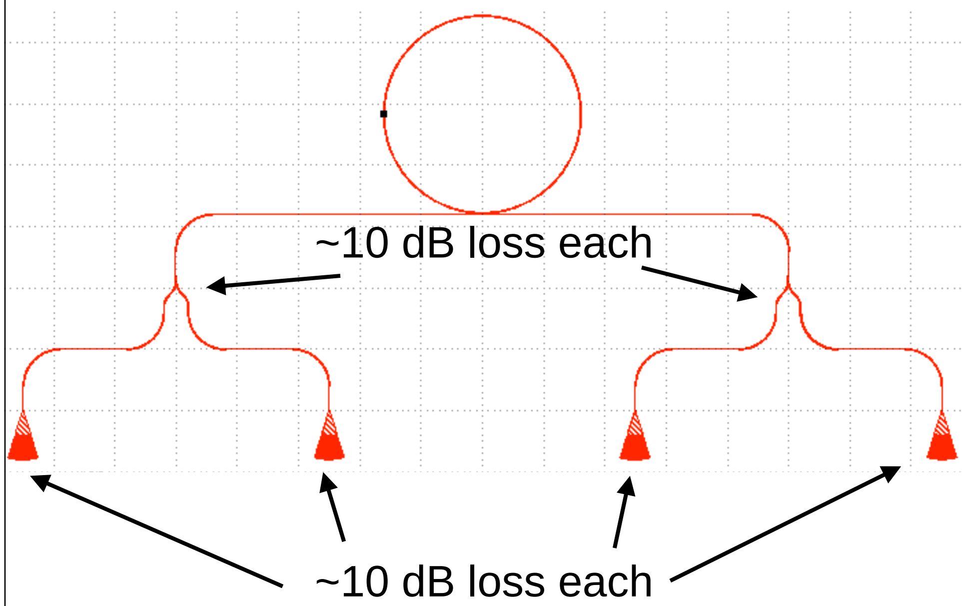
- 160 um radius, reduced free spectral range
- Multiple transverse orders
- Stokes and anti-Stokes cannot be suppressed
- Higher Q modes, Q > 130,000
- Lower transmission between port 1-4
- Not able to obtain Raman signal



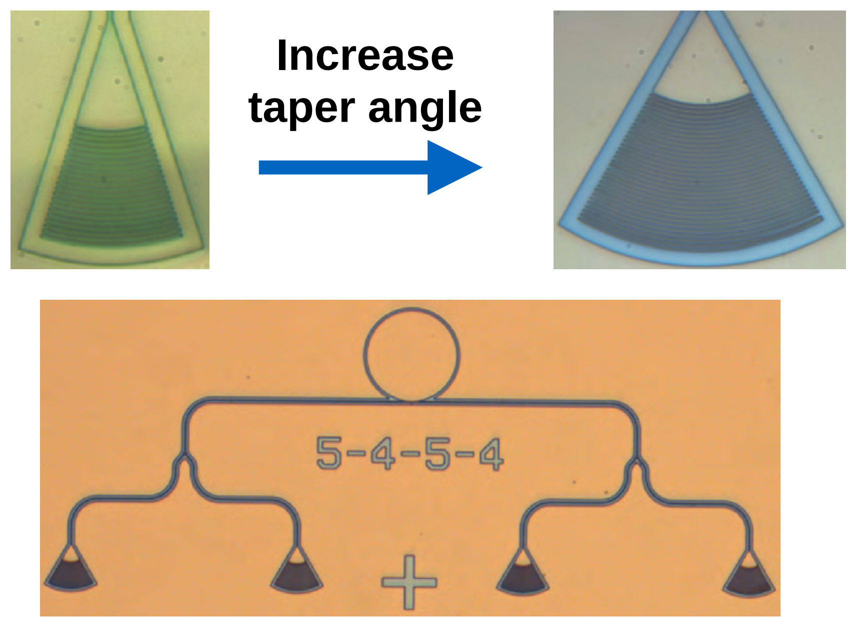


Potential reason for not observing Stokes Raman scattering

- Each component (grating couplers, Y-branches) introduces ~10 dB loss
- Improved grating couplers (larger taper angle) only provide ~ 20% more in transmission
- With EDFA the pump power in the coupling region is about ~100 uW
- Not enough pump power at the coupling region to generate observable Stokes scattering

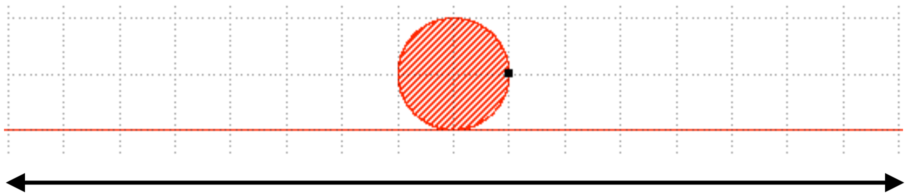


Improved design



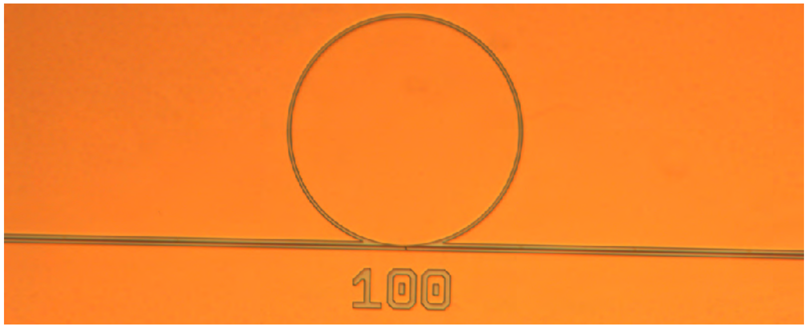
Edge coupled devices *to mitigate grating coupler loss

CAD design

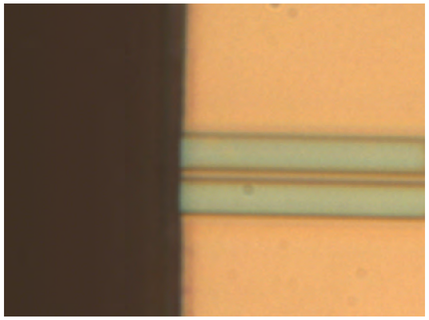


> 5 mm

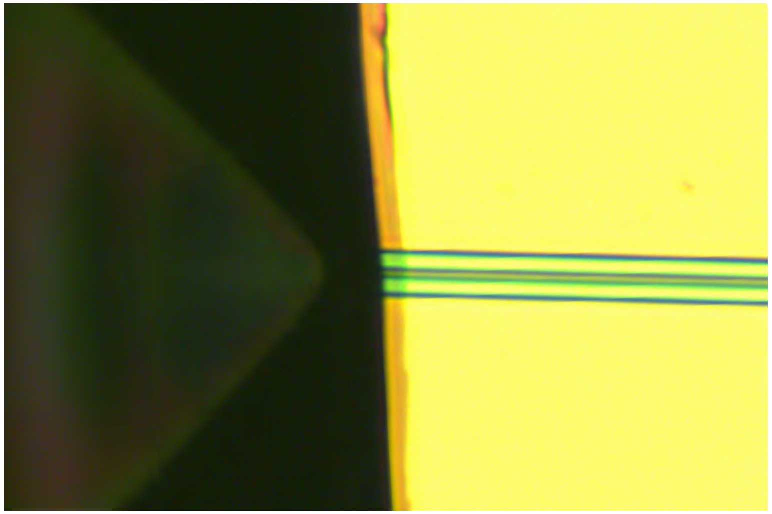
Fabricated device



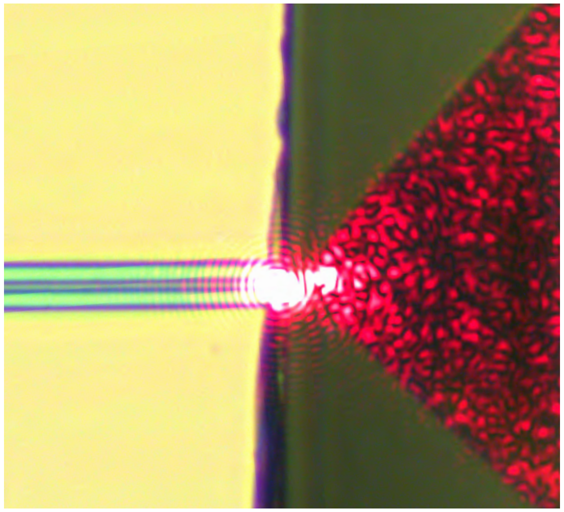
Waveguide edge



Fiber-waveguide coupling at 1550 nm

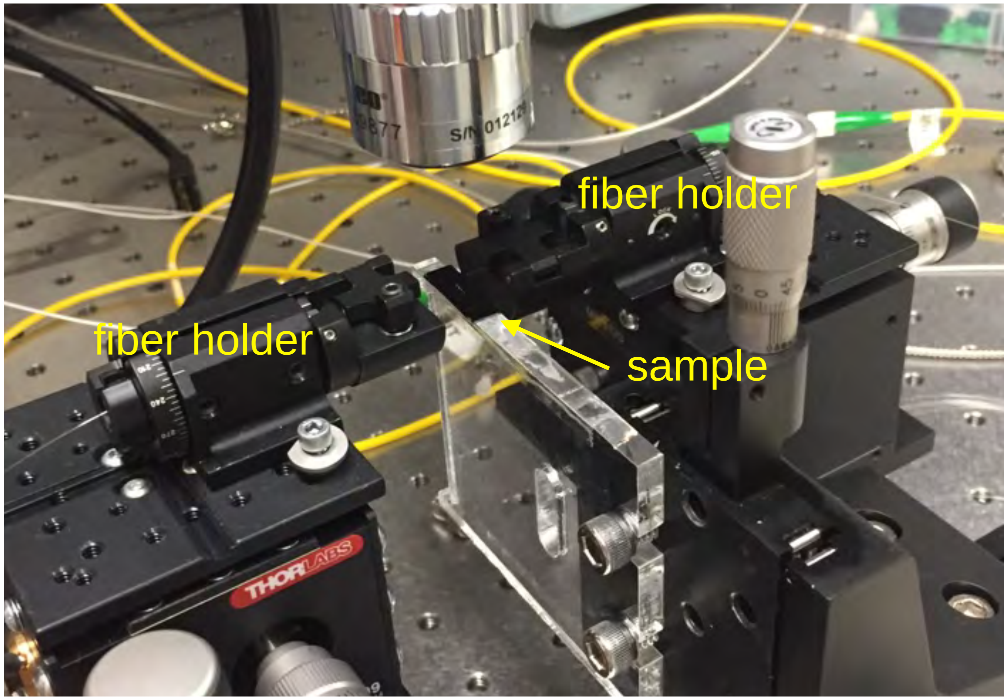


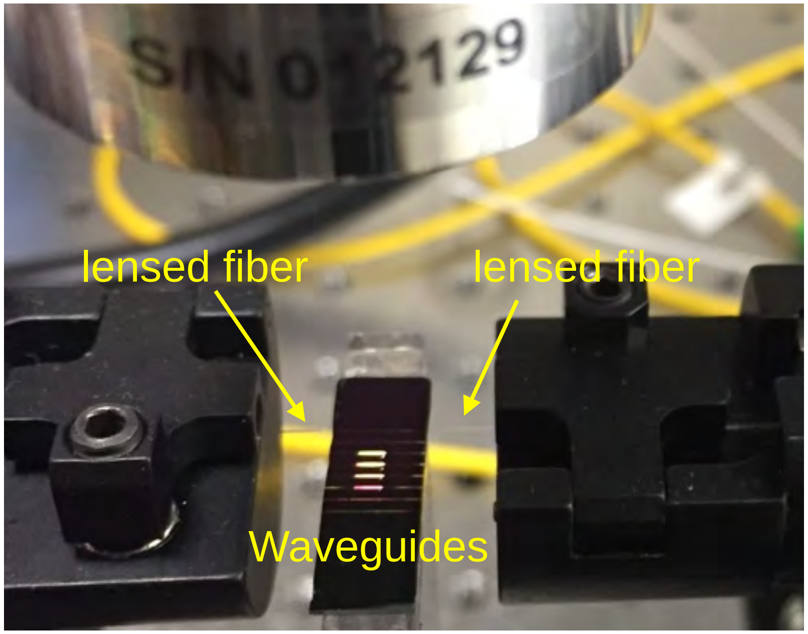
Alignment with HeNe laser



Setup for edge coupling

- Edge coupling allows 100x more pump power in the waveguide than the grating-coupler devices
- With EDFA pump power at the waveguide-resonator coupling region can be > 10 mW
- Free spectral range of all the resonators < 5 nm, no Raman suppression should occur
- Not able to observe Stokes Raman scattering despite the increased power





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Proposal for future effort -- Conversion to 780 nm

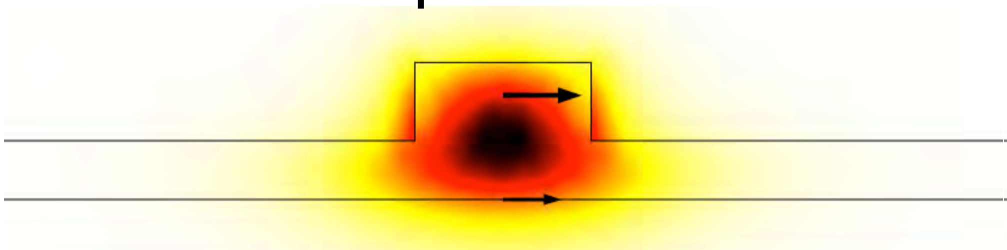
Potential reasons for still not observing Stokes Raman scattering

- The thickness of the AlN region in all our designs is 350 nm, which limits the wavelength of the allowed Raman-active phonons to 350 nm
- This may cause a change in Raman selection rules
- Pump power in the edge-coupler devices may still not be enough

Advantages of using a 780 nm pump

- 780 nm pump laser will give at least 16 times greater Raman efficiency (2^4)
- Both TE and TM modes are supported at 780 nm, allowing more Raman-active modes to be observed: A1(LO), A1(TO), E1(LO), E1(TO)
- Since TE <-> TM scattering is allowed the change in selection rules in the waveguide should have less effect

TE mode profile at 780 nm



TM mode profile at 780 nm