

Magnetic field imager, compass,
squeezing with Rb vapor.
SHG with whispering gallery mode resonator.

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The College of William & Mary



May 3, 2010

1 Magnetic field imager with Rb

2 Magnetic field compass with Rb

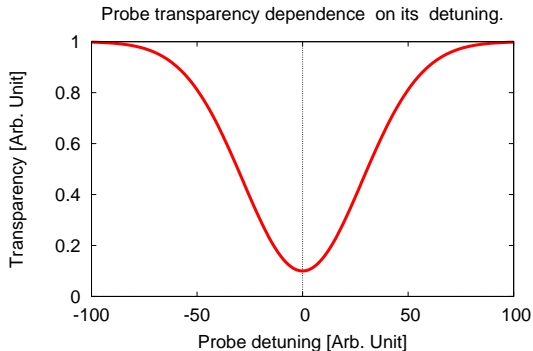
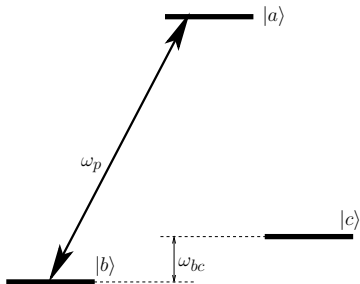
3 Squeezing with Rb

- Summary for crystal squeezing
- Polarization self-rotation squeezing
- Setup
- Low frequency squeezing
- Squeezing region

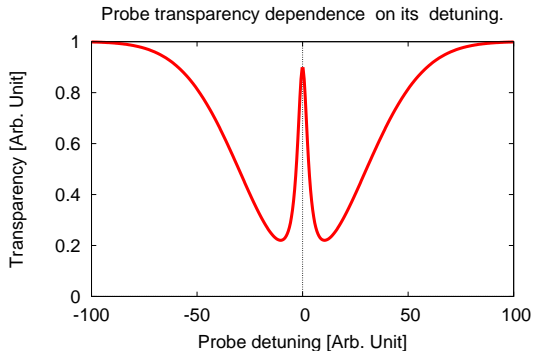
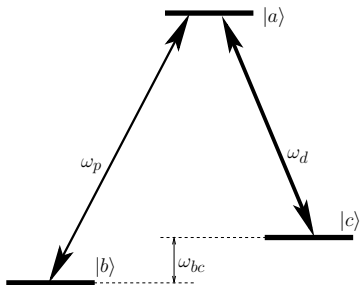
4 SHG with WGM

- Whispering Gallery Mode Resonators (WGMRs)
- SHG in a WGMR

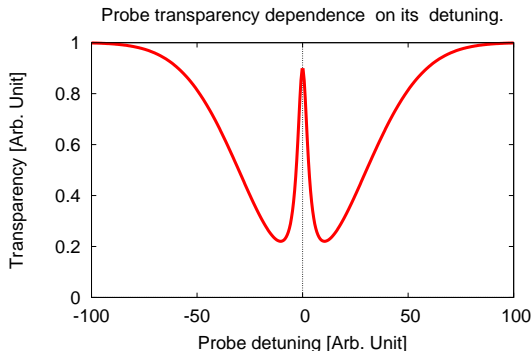
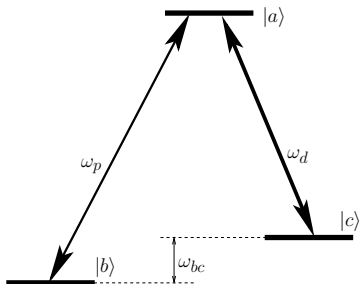
Coherent Population Trapping (CPT)



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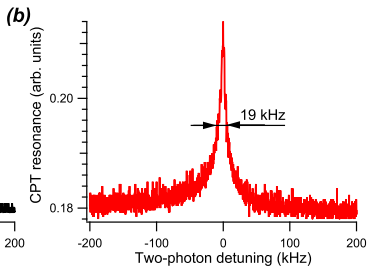
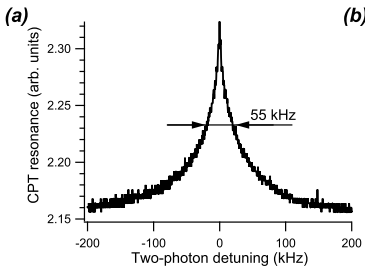
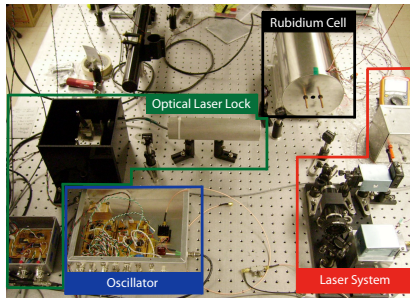
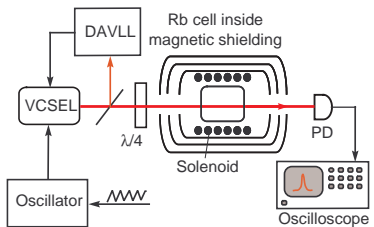
Coherent Population Trapping (CPT)



Coherent Population Trapping

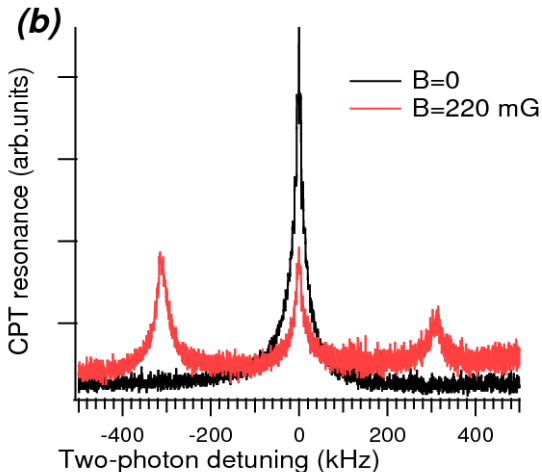
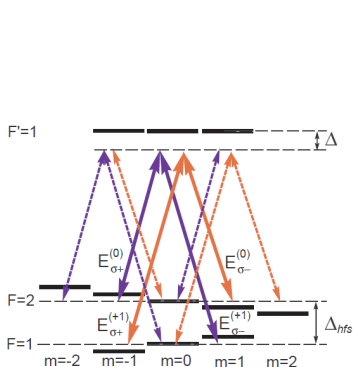
- Dark $|D\rangle = \Omega_d|b\rangle - \Omega_p|c\rangle$ and Bright $|B\rangle = \Omega_d|c\rangle + \Omega_p|b\rangle$ states
- resonance width ($\sim 10\text{kHz}$) much smaller than natural line width

CPT observation

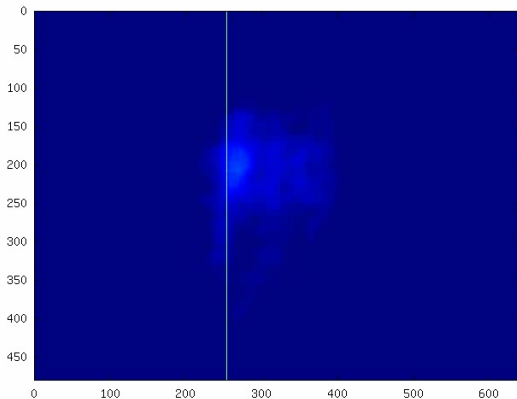


There is no 3-level atom and Rb is not one of them

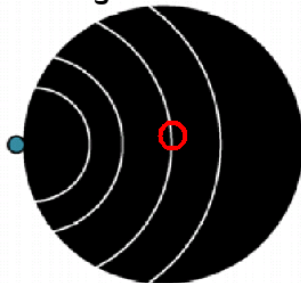
CPT with circularly polarized light



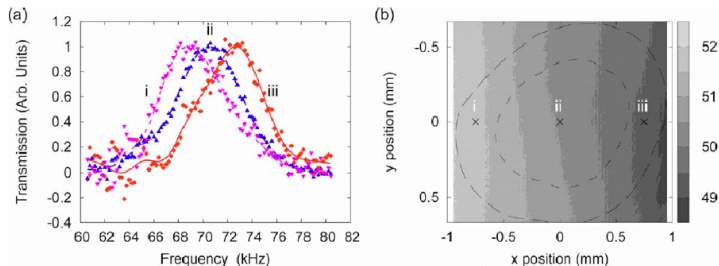
Sample transmission image



**Nonhomogenous
magnetic field**



Magnetic field map

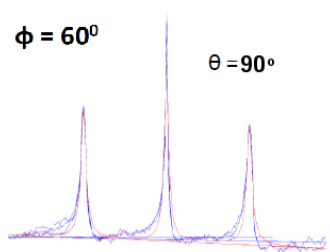
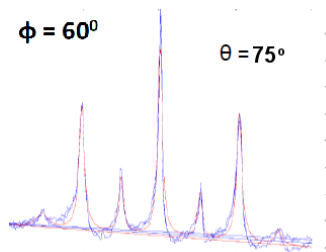
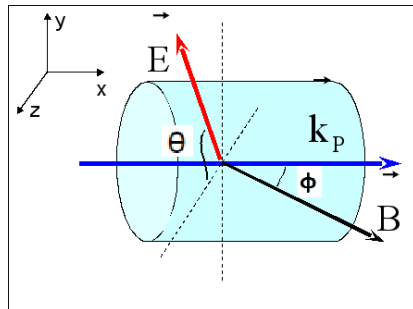
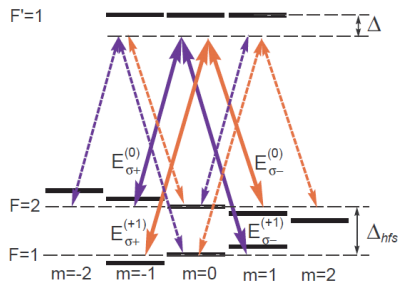


We have demonstrated 2D magnetic field imager with **140 μG per $10\mu\text{m} \times 10\mu\text{m}$** sensitivity

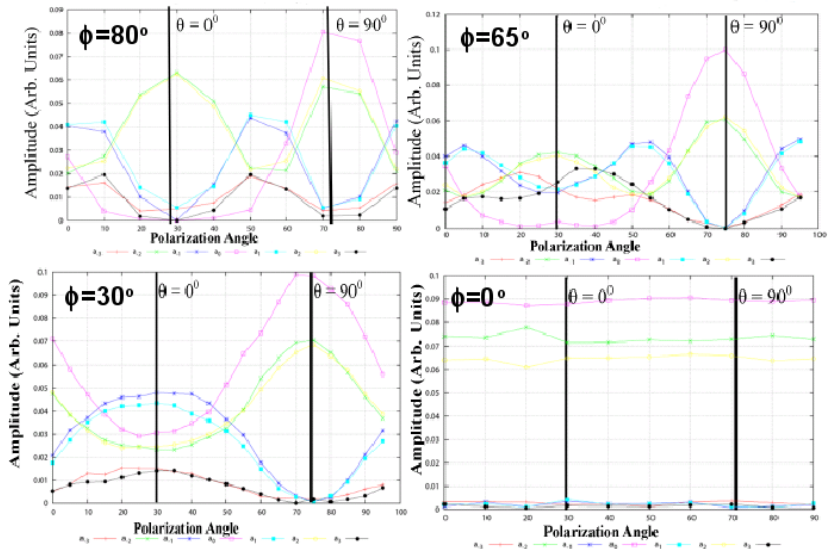
E. E. Mikhailov, I. Novikova, M. D. Havey, and F. A. Narducci, *Optics Letters* **34**, 3529 (2009).

However, this system may be capable of producing 3D maps of magnetic field vector

Magnetic field compass



Zeeman sidebands peak amplitudes



Summary for crystal squeezing

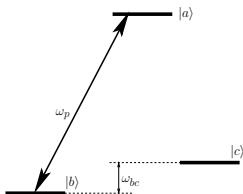
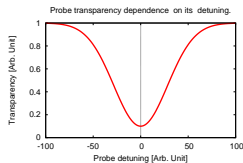
Pros

- mainstream: many different nonlinear crystals available
- so far the best squeezers
 - maximum squeezing value detected **11.5 dB at 1064 nm**
 - Moritz Mehmet, Henning Vahlbruch, Nico Lastzka, Karsten Danzmann, and Roman Schnabel, "Observation of squeezed states with strong photon-number oscillations", Phys. Rev. A **81**, 013814 (2010)
- well understood

Cons

- crystals have limited transparency window
- thus squeezing is hard to generate at visible wavelength
 - at 795 nm only 4-6 dB squeezing is reported
- this limits such squeezer for spectroscopy applications

Quantum memory with atomic ensembles



Storage and retrieval

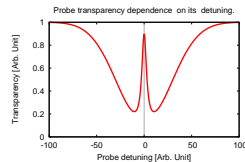
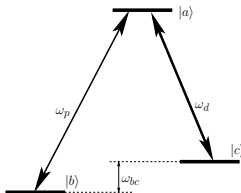
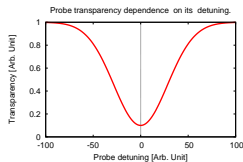
- single photon
- squeezed state (Furusawa and Lvovsky PRL **100** 2008)

Squeezed state requirements

- squeezing carrier at atomic wavelength (780nm, 795nm)
- squeezing within narrow resonance window at frequencies ($< 100\text{kHz}$)

Nonlinear crystal based squeezers are capable of it, but they are **extremely technically challenging** especially at short wave length.

Quantum memory with atomic ensembles



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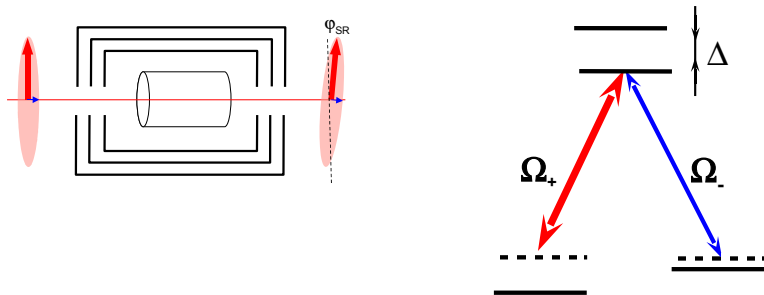
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Self-rotation of elliptical polarization in atomic medium



A.B. Matsko et al., PRA 66, 043815 (2002): theoretical prediction of 4-6 dB noise suppression

$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^\dagger - a_{in}) \quad (1)$$

Will something so simple work?

- **Yes!** J. Ries, B. Brezger, and A. I. Lvovsky, Experimental vacuum squeezing in rubidium vapor via self-rotation, PRA **68**, 025801 (2003).
 - Observed 0.85dB of squeezing at bandwidth 5-10MHz

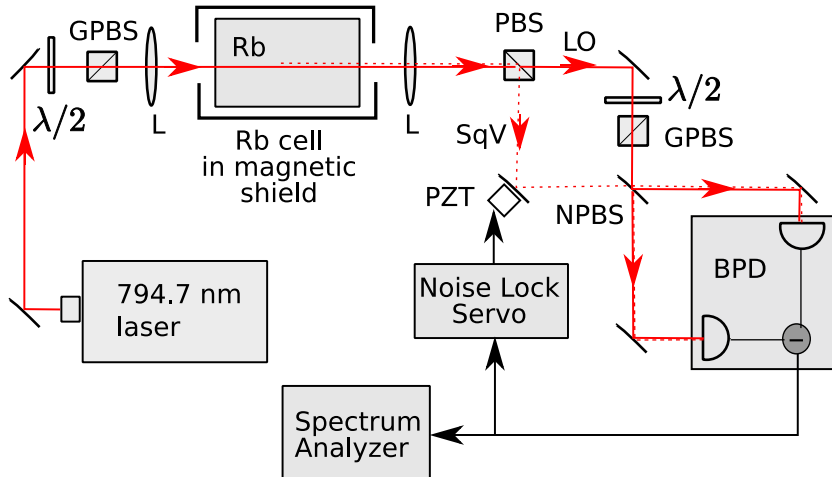
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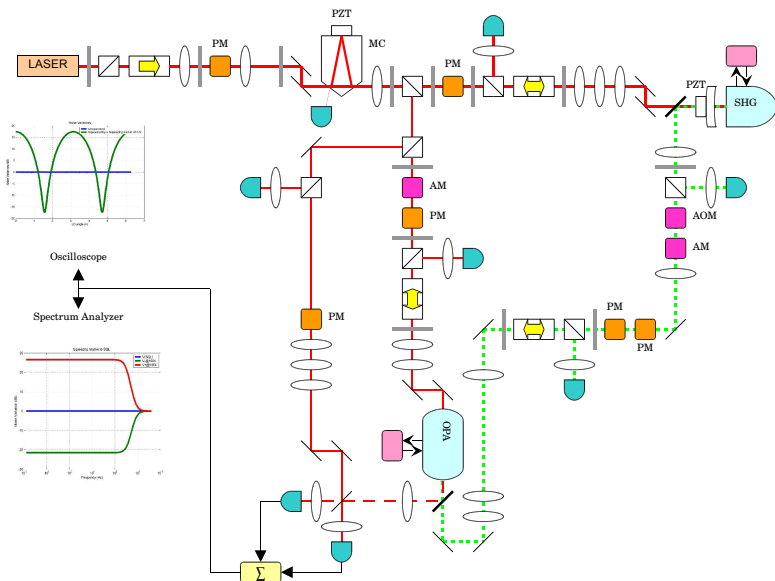
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 - Observed 6dB of excess noise after the cell
- **Possible.** A. Lezama et al., PRA **77**, 013806 (2008).

Setup

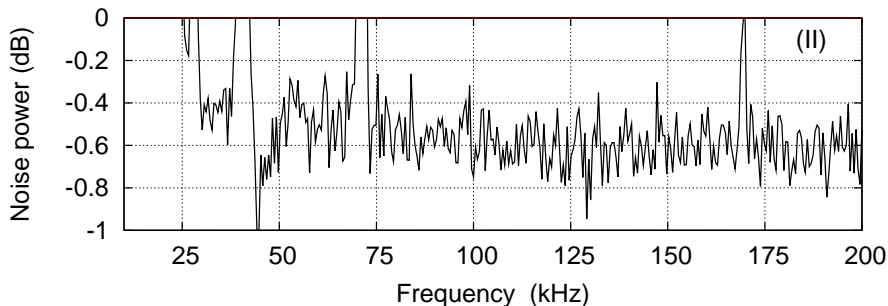


Crystal squeezing setup scheme



Low frequency squeezing vs power in ^{87}Rb at 795 nm

^{87}Rb cell + 2.5Torr Ne, $T=63.3^\circ\text{C}$ $P=1.5$ mW

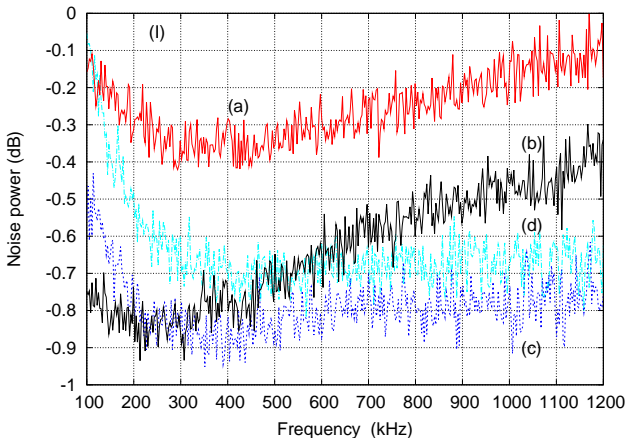


Eugeniy E. Mikhailov, Irina Novikova: Optics Letters, Issue 11, 33, 1213-1215, (2008).

Low frequency squeezing vs detuning in ^{87}Rb at 795 nm

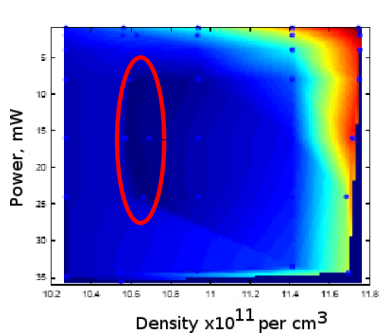
^{87}Rb cell + 2.5Torr Ne, $T=63.3^\circ\text{C}$

(a) $P=1.0$ mW, (b) $P=1.5$ mW, (c) $P=4.2$ mW, (d) $P=6.6$ mW

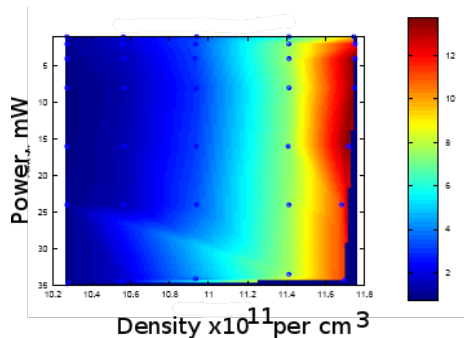


Squeezing region

Squeezing



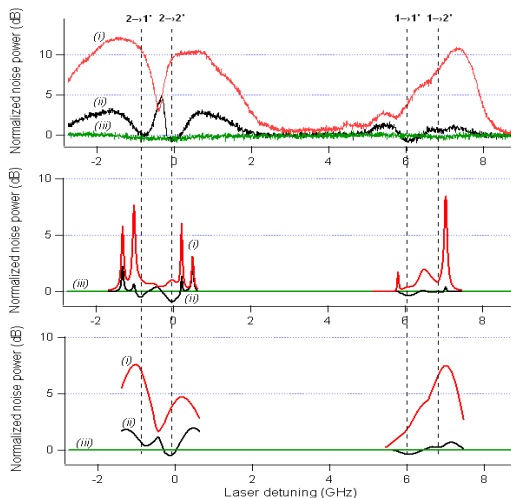
Anti-squeezing



Observation of reduction of quantum noise below the shot noise limit is corrupted by the excess noise due to atomic interaction with atoms.

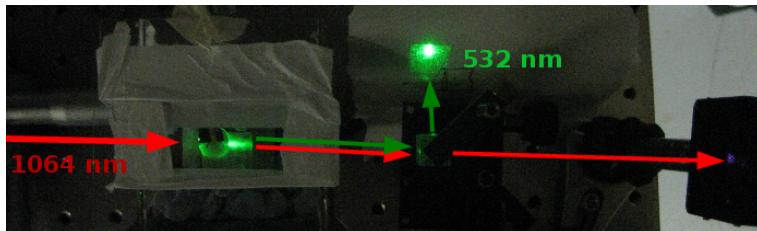
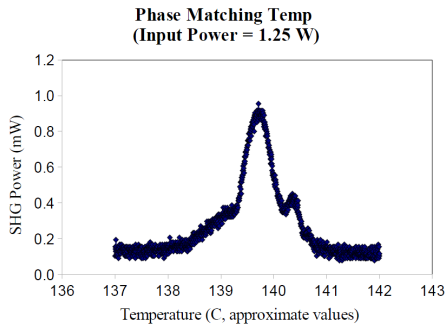
Squeezing theory and experiment

- ^{87}Rb cell
- no buffer gas
- density $2 \cdot 10^{11} \text{ cm}^{-3}$
- laser power 6 mW
- beam size 0.2 mm



E.E. Mikhailov, A. Lezama, T. Noel and I. Novikova,
J. Mod. Opt. **56**, 1985 (2009).

Single-pass SHG



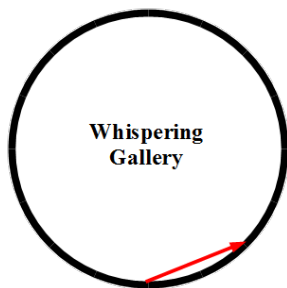
We need a resonator for SHG

- Optical nonlinear effects are small.
- SHG requires high laser power.
- High quality cavity.

Solution: Use whispering gallery mode resonators.

Whispering Galleries

A whispering gallery is a circular cavity

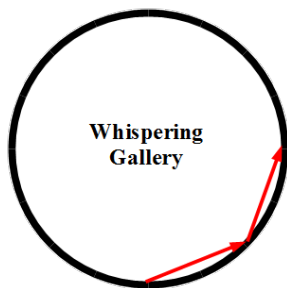


that contains a field through total internal reflection (TIR).

The field contained inside is a *whispering gallery mode* (WGM).

Whispering Galleries

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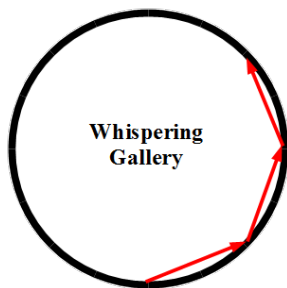


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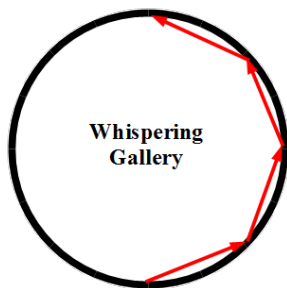


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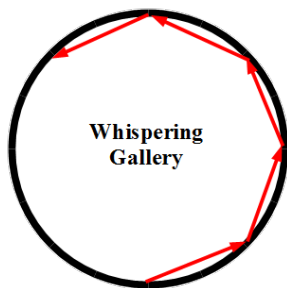


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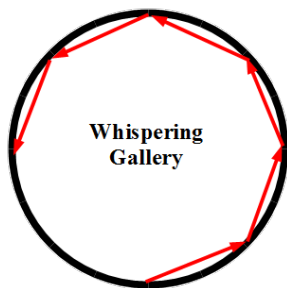


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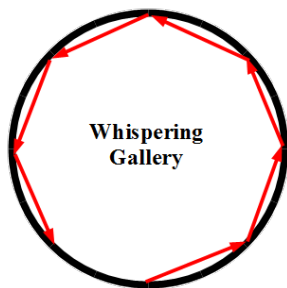


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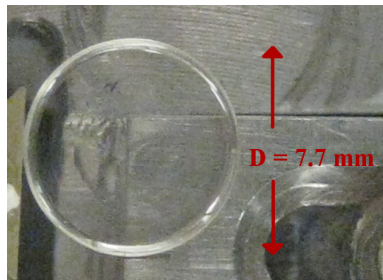
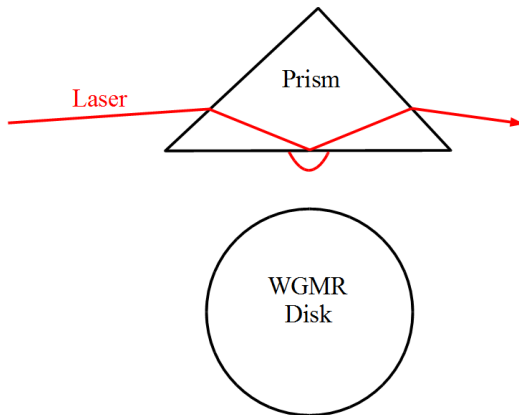


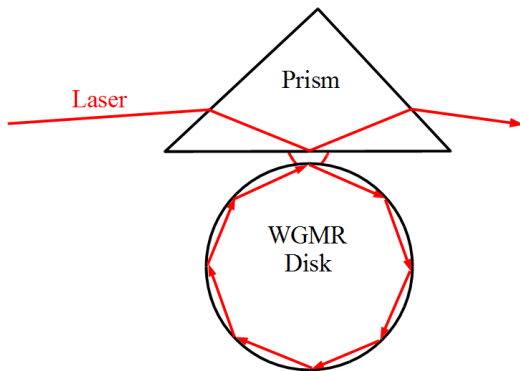
Figure: Lithium niobate resonator.

- Made from lithium niobate ($LiNbO_3$).
- Edge shaped with sandpaper.
- Polished with diamond lapping film.
- Polish quality affects quality factor (Q-factor).

Whispering Gallery Mode Excitation

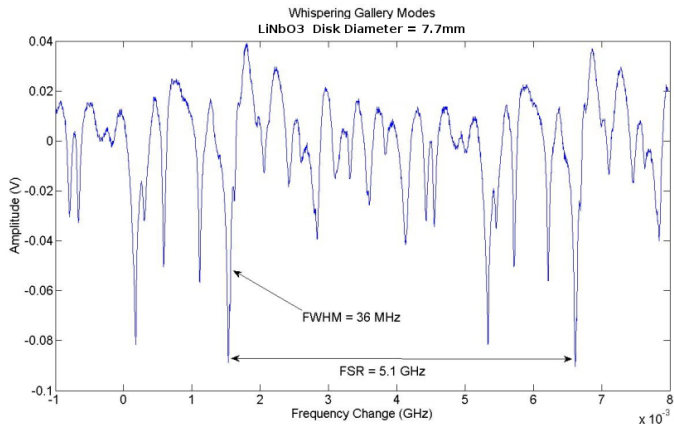


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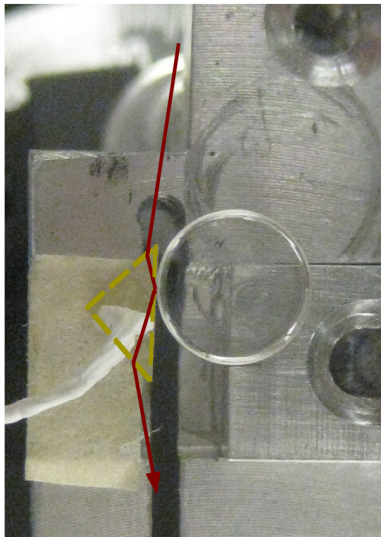
Whispering Gallery Mode Excitation

Frequency scanned output from our LiNbO_3 WGMR disk near 795nm, with a Q-factor of $Q = 10^7$.



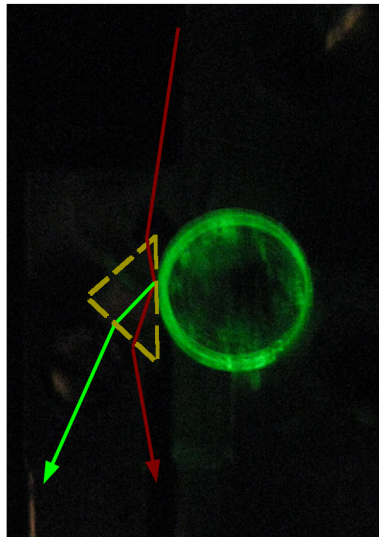
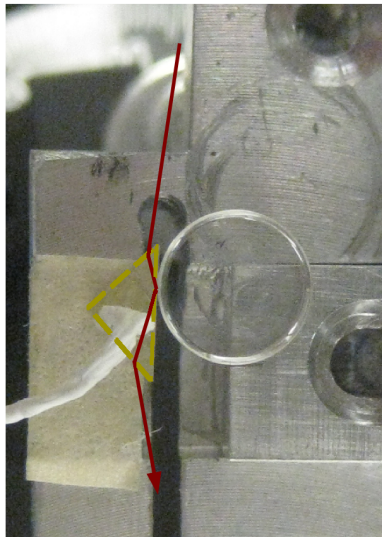
SHG in a WGMR

1064nm to 532nm noncritically phase-matched SHG inside a WGMR.



SHG in a WGMR

1064nm to 532nm noncritically phase-matched SHG inside a WGMR.



Why Whispering Gallery Mode Resonators?

Whispering gallery mode resonators:

- have high quality factors and a small mode volume
- monolithic structures
- reduced power requirements.
 - J. U. Füst et al. “Naturally Phase-Matched Second-Harmonic Generation in a Whispering-Gallery-Mode Resonator” Phys. Rev. Lett. **104**, 153901 (2010).
 - showed SHG at 532 nm at 30 μW



Support from

