Annual Review: Whispering-gallery mode resonators, second harmonic generation, and ultrafast lasers

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Outline

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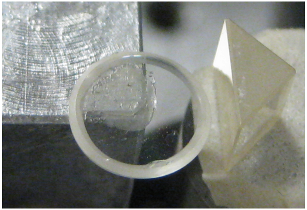
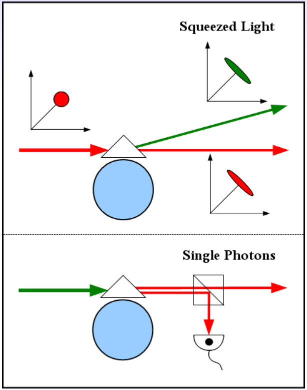
Motivation

Develop a source of nonclassical light based on nonlinear processes using crystalline whispering-gallery mode resonators.

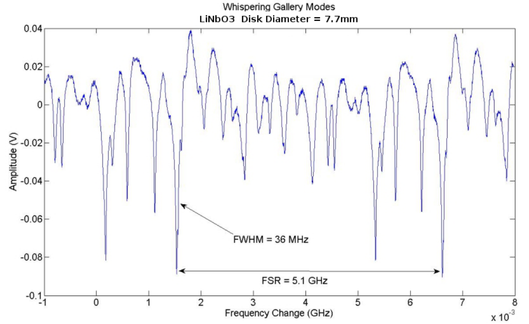
- Source of bright squeezed light
- Heralded single photon source





Previously . . .

- $LiNbO_3$ WGMRs
- Q-factor $> 10^7$
- $1064nm \rightarrow 532nm$
- Hyper-Raman scattering



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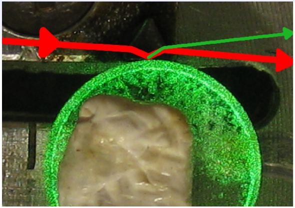

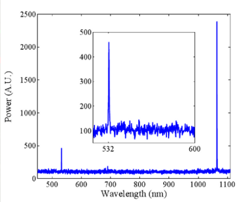

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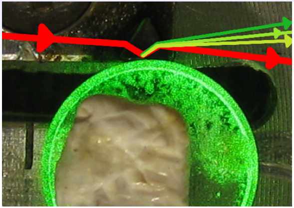

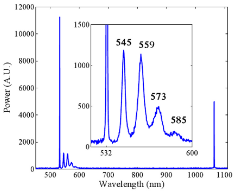

Outline

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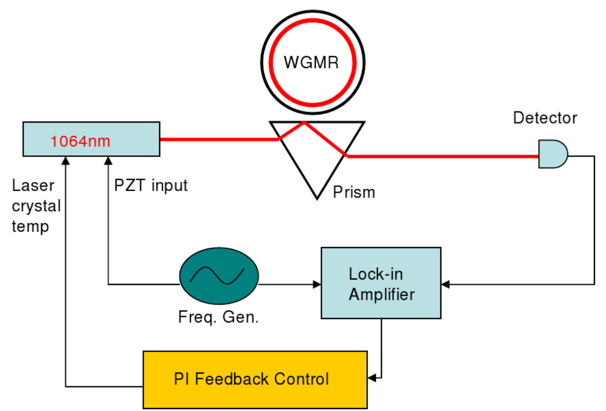
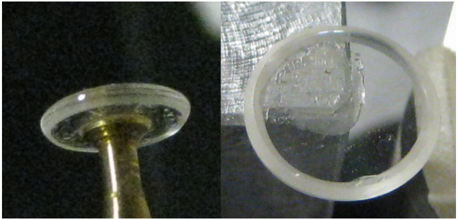
1064nm Tunable laser



Annealing WGMR disk

1. Polish disk with 0.1 μm diamond paper
2. Anneal 600° for 24 hrs.
3. Polish disk with 0.1 μm diamond paper
4. $Q = 3 \times 10^6 \rightarrow 8 \times 10^6$



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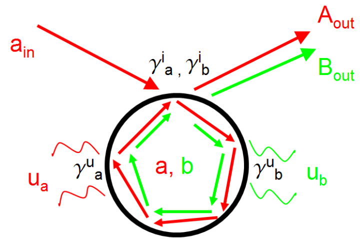
Theoretical model



The Hamiltonian inside the cavity is

$$H_{sys} = \hbar\omega_a a^\dagger a + \hbar\omega_b b^\dagger b + \frac{\imath}{2}\hbar\epsilon(a^\dagger a^\dagger b - aab^\dagger) \qquad (1)$$

Variance

Noise in the amplitude quadrature of the output field ($A_1^{out} = A_{out} + A_{out}^{\dagger}$) is calculated by the variance:

$$Var\left(A_1^{out}\right) = \langle |A_1^{out} - \langle A_1^{out} \rangle|^2 \rangle \tag{2}$$

$$A_1^{out} = \langle A_1^{out} \rangle + \delta A_1^{out} \tag{3}$$

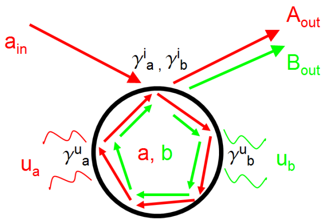
$$Var\left(A_1^{out}\right) = \langle |\delta A_1^{out}|^2 \rangle \tag{4}$$

Theory

With $\dot{x} = -\frac{\imath}{\hbar}[x, H]$ the intracavity fields change in time as:

$$\dot{a} = -\imath\omega_a a - \frac{1}{2}\gamma_a^{tot} a + \epsilon a^\dagger b + \sqrt{\gamma_a^i} a_{in} + \sqrt{\gamma_a^u} u_a \qquad (5)$$

$$\dot{b} = -\imath\omega_b b - \frac{1}{2}\gamma_b^{tot} b - \frac{1}{2}\epsilon a a + \sqrt{\gamma_b^i} b_{in} + \sqrt{\gamma_b^u} u_b \qquad (6)$$



Theory

Assuming unseeded SHG ($\bar{b}_{in} = 0$), and approximating each field as $x = \langle x \rangle + \delta x$, the equations describing the fluctuation of the fields are

$$\dot{\delta a} = -\frac{1}{2}\gamma_a^{tot}\delta a + \epsilon \bar{a}^* \delta b + \epsilon \bar{b} \delta a^\dagger + \sqrt{\gamma_a^i}\delta a_{in} + \sqrt{\gamma_a^u}\delta u_a \quad (7)$$

$$\dot{\delta b} = -\frac{1}{2}\gamma_b^{tot}\delta b - \epsilon \bar{a} \delta a + \sqrt{\gamma_b^i}\delta b_{in} + \sqrt{\gamma_b^u}\delta u_b \quad (8)$$

$$\tilde{x}_c \equiv \begin{pmatrix} \tilde{\delta a} \\ \tilde{\delta a}^\dagger \\ \tilde{\delta b} \\ \tilde{\delta b}^\dagger \end{pmatrix}, \quad \tilde{x}_{in} \equiv \begin{pmatrix} \tilde{\delta a}_{in} \\ \tilde{\delta a}_{in}^\dagger \\ \tilde{\delta b}_{in} \\ \tilde{\delta b}_{in}^\dagger \end{pmatrix}, \quad \tilde{x}_u \equiv \begin{pmatrix} \tilde{\delta u}_a \\ \tilde{\delta u}_a^\dagger \\ \tilde{\delta u}_b \\ \tilde{\delta u}_b^\dagger \end{pmatrix} \quad (9)$$

such that the fluctuation equations can be expressed in matrix form:

$$\imath\Omega\tilde{x}_c = M_c\tilde{x}_c + M_{in}\tilde{x}_{in} + M_u\tilde{x}_u \quad (10)$$

Theory

$$\tilde{x}_c = (\imath\Omega I - M_c)^{-1}(M_{in}\tilde{x}_{in} + M_u\tilde{x}_u) \tag{11}$$

$$\tilde{x}_o \equiv \begin{pmatrix} \delta A_{out} \\ \delta A_{out}^{\dagger} \\ \delta B_{out} \\ \delta B_{out}^{\dagger} \end{pmatrix} = M_{in}\tilde{x}_c - \tilde{x}_{in} \tag{12}$$

$$\begin{aligned} \tilde{x}_o = [M_{in}(\imath\Omega I - M_c)^{-1} M_{in} - I]\tilde{x}_{in} \\ + M_{in}(\imath\Omega I - M_c)^{-1} M_u\tilde{x}_u \end{aligned} \tag{13}$$

$$\delta A_1^{out} = \delta A_{out} + \delta A_{out}^{\dagger} \tag{14}$$

Theory

Solved for $Var\left(A_1^{out}\right) = \langle|\delta A_1^{out}|^2\rangle$ as a function of

- WGMR quality factor Q

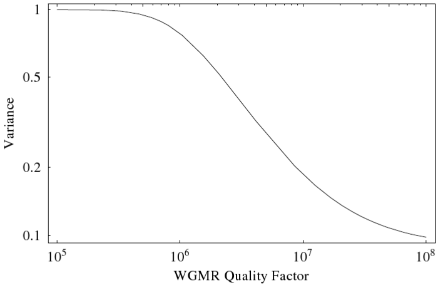


Figure: $f = 10$ MHz, $P_{in} = 500\ \mu$W

Theory

Solved for $Var\left(A_1^{out}\right) = \langle|\delta A_1^{out}|^2\rangle$ as a function of

- WGMR quality factor Q
- Input power P_{in}

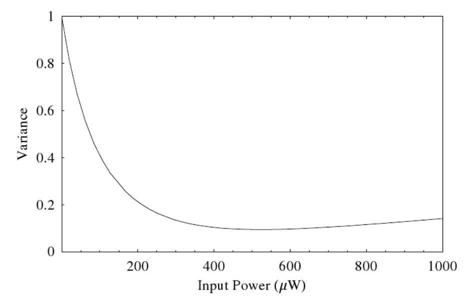


Figure: $Q = 10^8, f = 10$ MHz

Theory

Solved for $Var\left(A_1^{out}\right) = \langle|\delta A_1^{out}|^2\rangle$ as a function of

- WGMR quality factor Q
- Input power P_{in}
- Detection frequency f

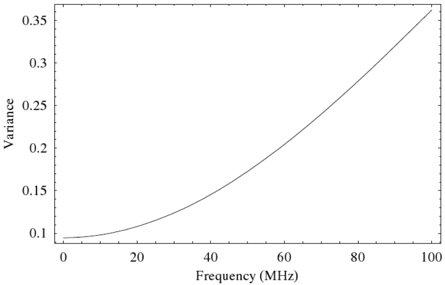
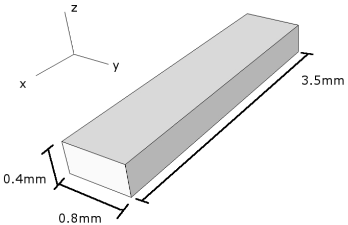


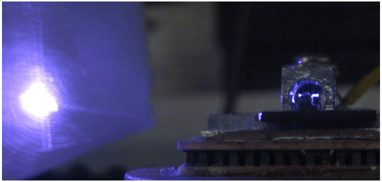
Figure: $Q = 10^8$, $P_{in} = 500\ \mu$W

Outline

Potassium lithium niobate (KLN)

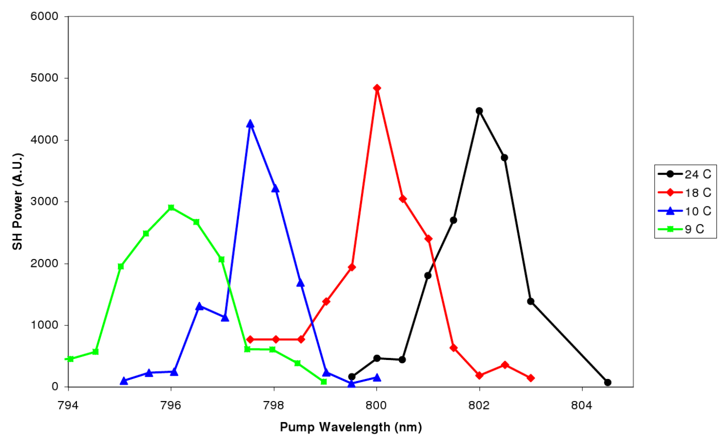
Second harmonic generation 800 nm $\rightarrow$ 400 nm
using natural phase matching





Potassium lithium niobate (KLN)

Second harmonic power vs. pump wavelength
for different KLN crystal temperatures



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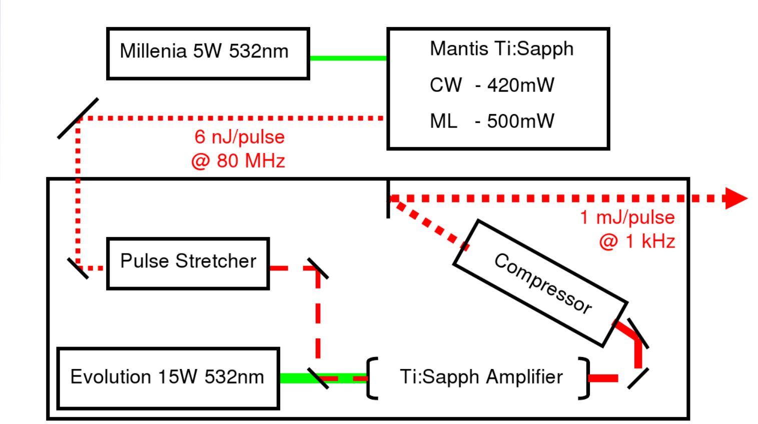
Legend femtosecond laser system

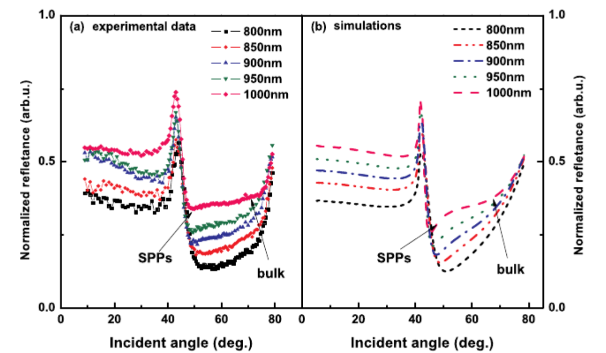


TOPAS

Traveling-wave optical parametric amplifier of super-fluorescence
Tunable from 470 nm to 1600 nm
INSERT GRAPH of WAVELENGTHS

Surface plasmon resonances

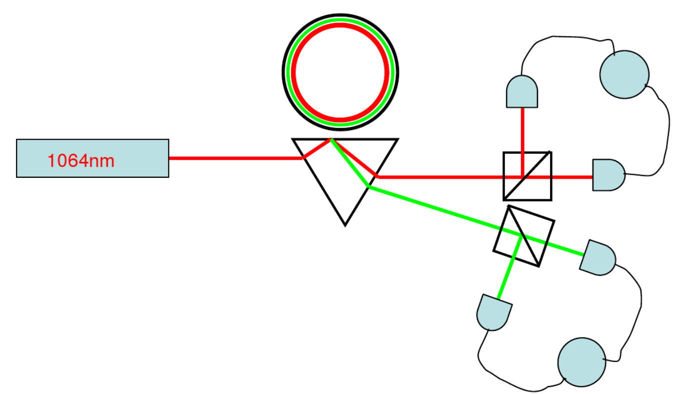
- Measured reflection from RuO_2 thin film
- Using TOPAS $\lambda = 800 \rightarrow 1000$ nm



L. Wang, C. Clavero, K. Yang, E. Radue, M. T. Simons, I. Novikova, and R. A. Lukaszew. *Bulk and surface plasmon polariton excitation in RuO_2 for low-loss plasmonic applications in NIR.* Opt. Express 20, 8618-8628 (2012).

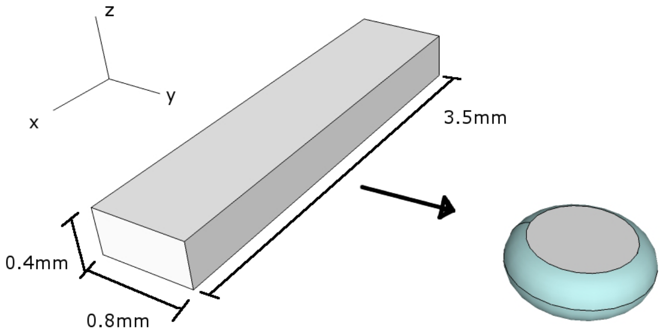
Outline

Second harmonic squeezing



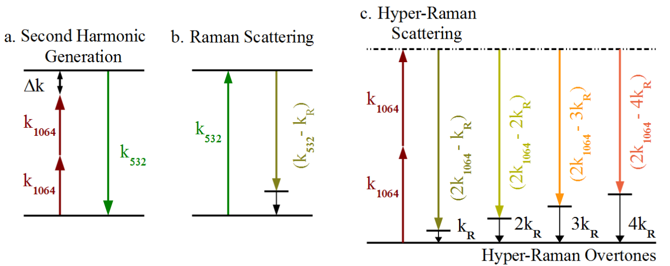
KLN Whispering-gallery disks

Demonstrate naturally-phase matched SHG from 795 $\rightarrow$ 397 nm

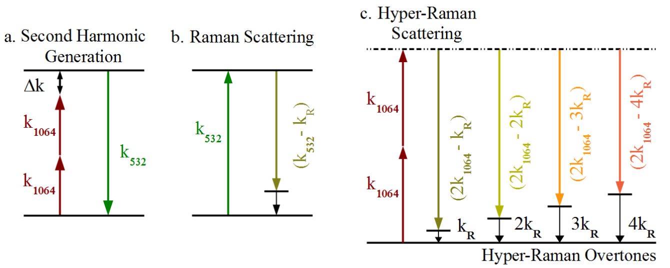


Demonstrate SHG squeezing at 795 nm

Hyper-Raman squeezing

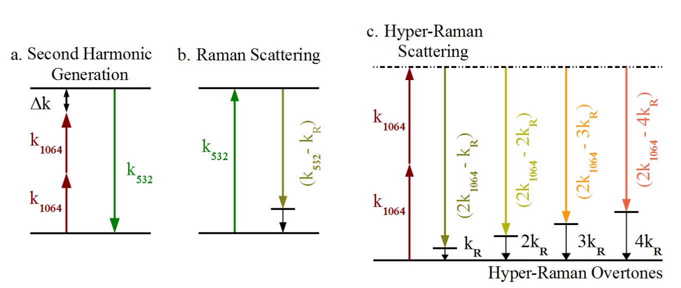


Hyper-Raman squeezing



- "In hyper-Raman scattering squeezing exists . . . in the fundamental pump mode."

Hyper-Raman squeezing



- "In hyper-Raman scattering squeezing exists . . . in the fundamental pump mode."
- "The Stokes mode in hyper-Raman scattering is squeezed when a fundamental mode with amplitude-squared squeezing propagates through a nonlinear medium."

Thank you!

Questions?

Matrices

$$M_c \equiv \begin{pmatrix} -\frac{1}{2}\gamma_a^{tot} & \epsilon\bar{b} & \epsilon\bar{a}^* & 0 \\ \epsilon\bar{b}^* & -\frac{1}{2}\gamma_a^{tot} & 0 & \epsilon\bar{a} \\ -\epsilon\bar{a} & 0 & -\frac{1}{2}\gamma_b^{tot} & 0 \\ 0 & -\epsilon\bar{a}^* & 0 & -\frac{1}{2}\gamma_b^{tot} \end{pmatrix} \tag{15}$$

$$M_{in} \equiv diag\left(\sqrt{\gamma_a^i}, \sqrt{\gamma_a^i}, \sqrt{\gamma_b^i}, \sqrt{\gamma_b^i}\right) \tag{16}$$

$$M_u \equiv diag\left(\sqrt{\gamma_a^u}, \sqrt{\gamma_a^u}, \sqrt{\gamma_b^u}, \sqrt{\gamma_b^u}\right) \tag{17}$$

add

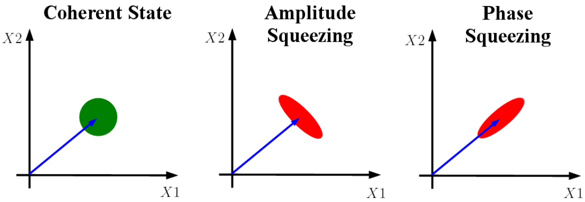
Squeezed light

Particle: position & momentum uncertainty relation:

$$\Delta x \Delta p \geq \frac{\hbar}{2} \tag{18}$$

Light: amplitude & phase uncertainty relation:

$$\Delta A \Delta \Phi \geq \frac{1}{2} \tag{19}$$

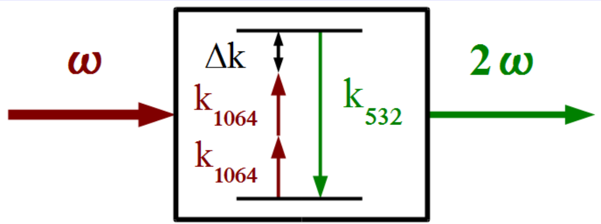


Motivation for squeezed light

- Sensitive measurements (LIGO, etc.)
- Quantum cryptography
- Quantum computing

Second harmonic generation

$$\vec{P} \sim \chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}^2 + \cdots \tag{20}$$



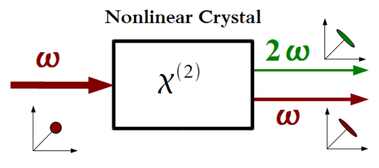
- Energy Conservation

$$\omega + \omega = 2\omega \tag{21}$$

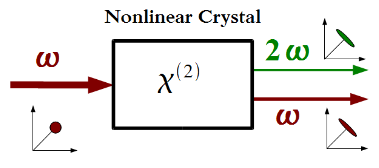
- Momentum conservation

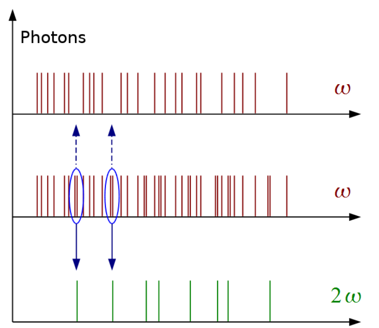
$$\Delta k = k_{2\omega} - 2k_{\omega} = \frac{2\omega}{c}(n(2\omega) - n(\omega)) \tag{22}$$

Squeezed light



Squeezed light



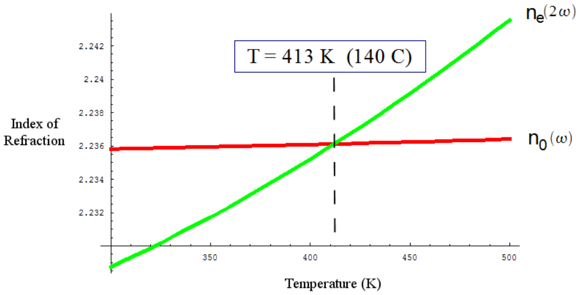


Second harmonic generation

- Momentum conservation

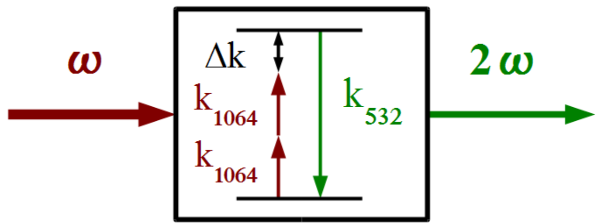
$$\Delta k = k_{2\omega} - 2k_{\omega} = \frac{2\omega}{c}(n(2\omega) - n(\omega))$$

- $\Delta k \to 0$ Phase-matching



Second harmonic generation

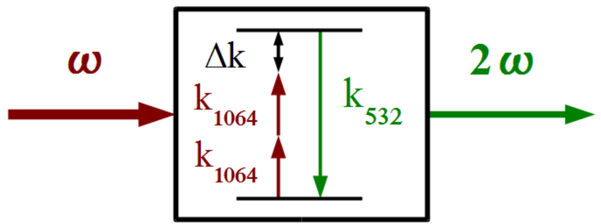
$$\vec{P} \sim \chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}^2 + \cdots$$



Intensity dependent process

Second harmonic generation

$$\vec{P} \sim \chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}^2 + \cdots$$

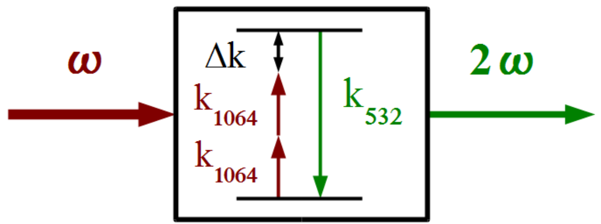


Intensity dependent process

- High-power pump laser

Second harmonic generation

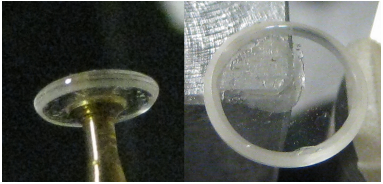
$$\vec{P} \sim \chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}^2 + \cdots$$



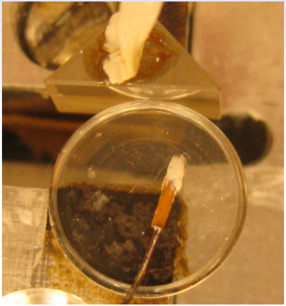
Intensity dependent process

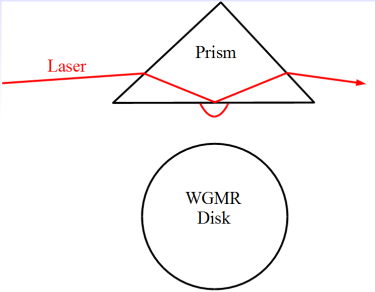
- High-power pump laser
- High-quality cavity

Whispering-gallery mode resonators (WGMRs)

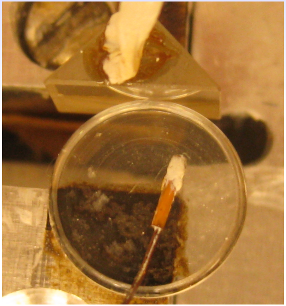


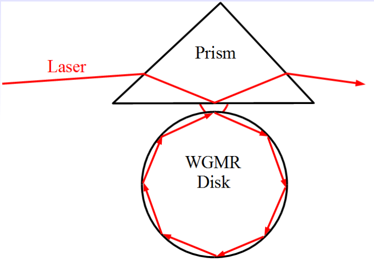
Coupling to whispering-gallery modes



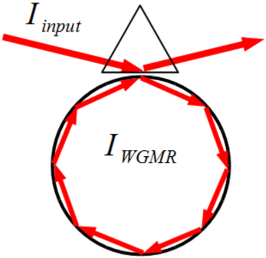


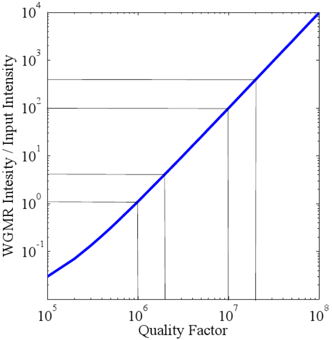
Coupling to whispering-gallery modes





Whispering-gallery mode resonators

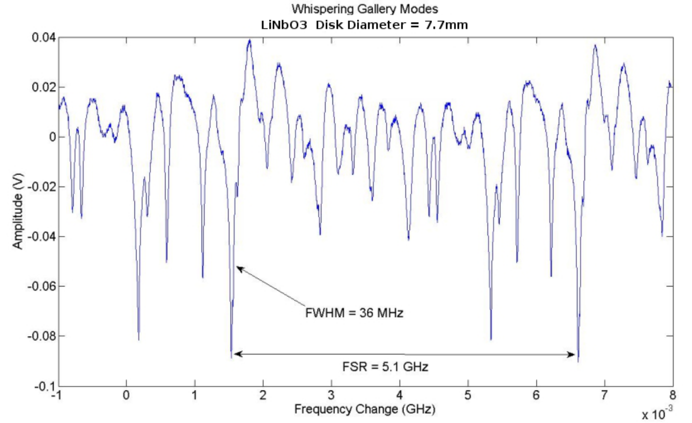




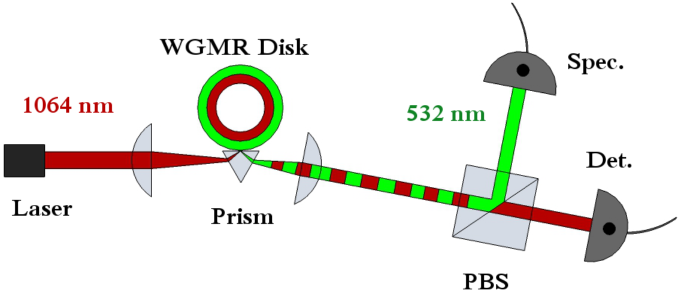
Coupling to whispering-gallery modes

Frequency scanned output from our $LiNbO_3$ WGMR disk near 795nm

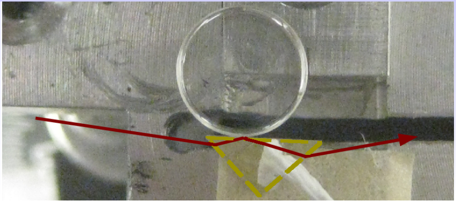
Q-factor of $Q = 10^7$

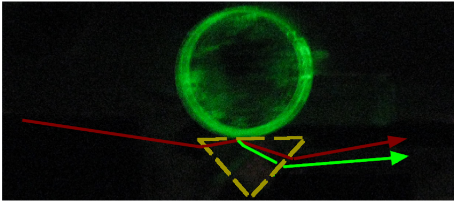


Second harmonic generation



Second harmonic generation

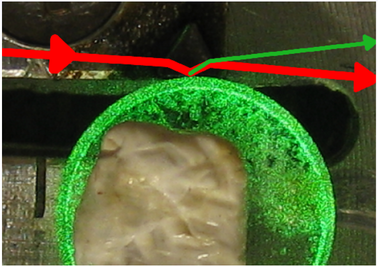


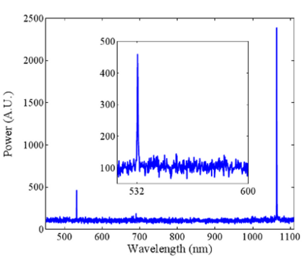


Second harmonic generation

Input 1064 nm Power = 11 mW

T = 26 °C

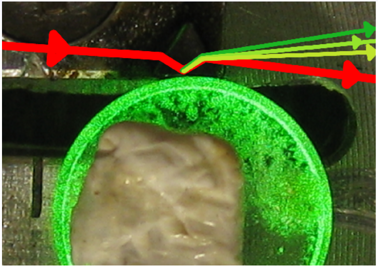


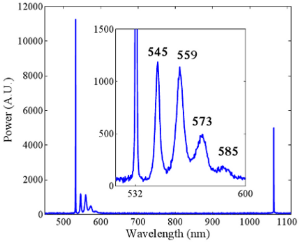


Raman scattering of the second harmonic

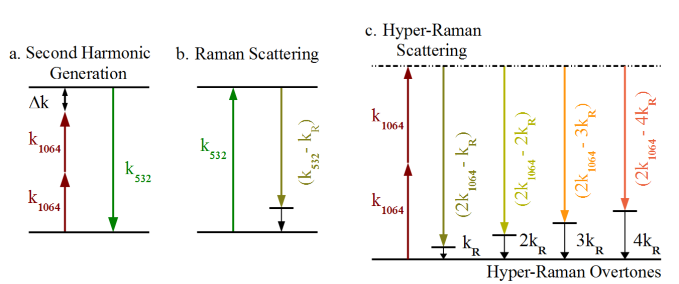
Input 1064 nm Power = 650 mW

T = 26 °C





Hyper-Raman scattering



Summary

- Demonstrated whispering-gallery mode disks
- Observed SHG in WGMR disks
- Predict bright squeezed light
- Observed hyper-Raman scattering

Acknowledgements