Bright squeezed light via second harmonic generation in a whispering-gallery mode resonator

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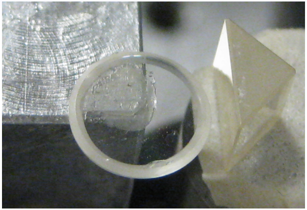
SPIE Photonics West 2013

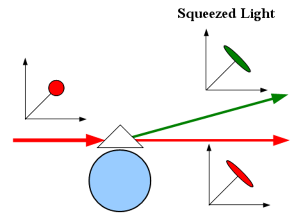
Outline

Whispering-gallery mode resonators

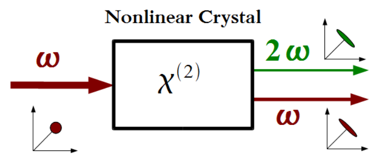
- Low power
- Narrow bandwidth

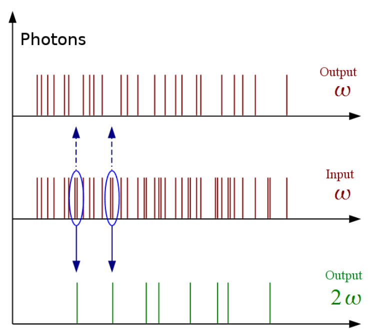


- Nonlinear crystals
- Nonclassical light



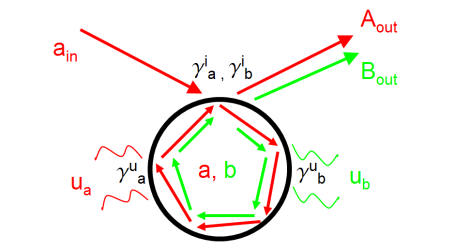
Squeezed light





Outline

Theoretical model



Intracavity Hamiltonian:

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

Theory

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

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

$$\dot{b} = -\imath\omega_b b - \frac{1}{2}\gamma_b^{tot} b - \frac{1}{2}\epsilon aa + \sqrt{\gamma_b^i} b_{in} + \sqrt{\gamma_b^u} u_b \quad (3)$$

Assuming unseeded SHG ($\bar{b}_{in} = 0$), and approximating each field as $x = \langle x \rangle + \delta x$:

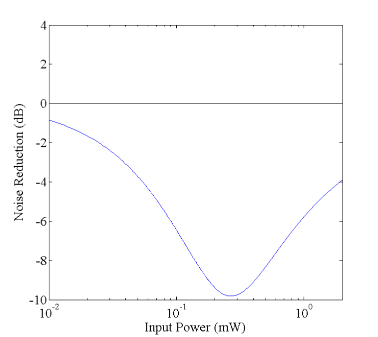
$$\dot{\delta a} = -\frac{1}{2}\gamma_a^{tot}\delta a + \epsilon\bar{a}^*\delta b + \epsilon\bar{b}\delta a^\dagger + \sqrt{\gamma_a^i}\delta a_{in} + \sqrt{\gamma_a^u}\delta u_a \quad (4)$$

$$\dot{\delta b} = -\frac{1}{2}\gamma_b^{tot}\delta b - \epsilon\bar{a}\delta a + \sqrt{\gamma_b^i}\delta b_{in} + \sqrt{\gamma_b^u}\delta u_b \quad (5)$$

$$\delta\tilde{A_1^{out}} = \delta\tilde{A}_{out} + \delta\tilde{A}_{out}^\dagger, \quad \delta\tilde{B_1^{out}} = \delta\tilde{B}_{out} + \delta\tilde{B}_{out}^\dagger \quad (6)$$

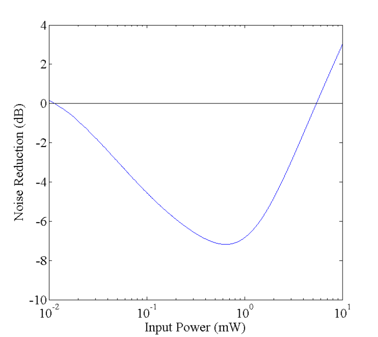
Output variance as a function of input power

Fundamental field $\langle |\delta A_1^{out}|^2 \rangle$



$Q = 10^8$, $\gamma_a^i/\gamma_a^{tot} \sim 0.98$

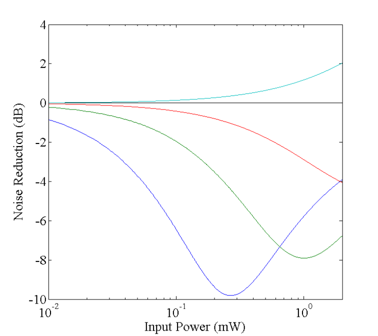
Second harmonic $\langle |\delta B_1^{out}|^2 \rangle$



$Q = 10^8$, $\gamma_a^i/\gamma_a^{tot} \sim 0.83$

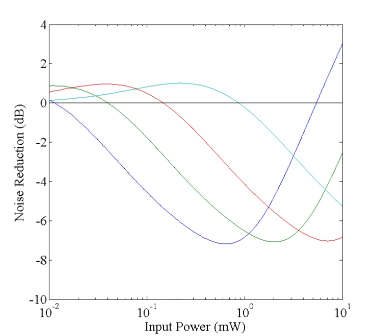
Theory

Fundamental field $\langle|\delta A_1^{out}|^2\rangle$



$Q = 10^8$

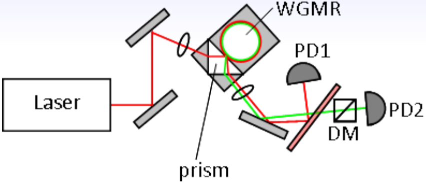
Second harmonic $\langle|\delta B_1^{out}|^2\rangle$



$Q = 10^8$

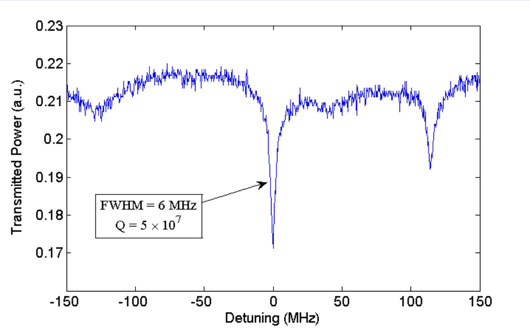
Outline

Experimental setup

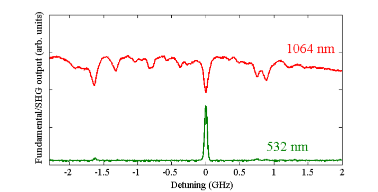


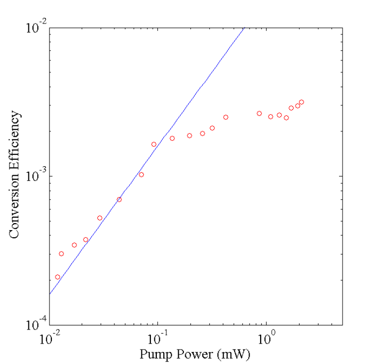
- $MgO{:}LiNbO_3$ disk
- 7mm diameter
- $1064nm \rightarrow 532nm$ at $81°C$

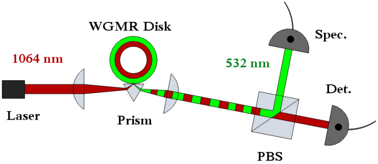
MgO:LiNbO$_3$ Disk



Second harmonic generation





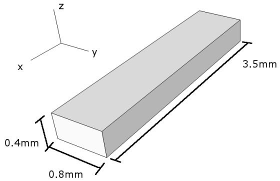


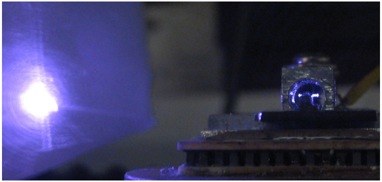
Potassium lithium niobate (KLN)

Second harmonic generation using natural phase matching

802 nm → 401 nm near 24°C

795 nm → 397 nm near 9°C

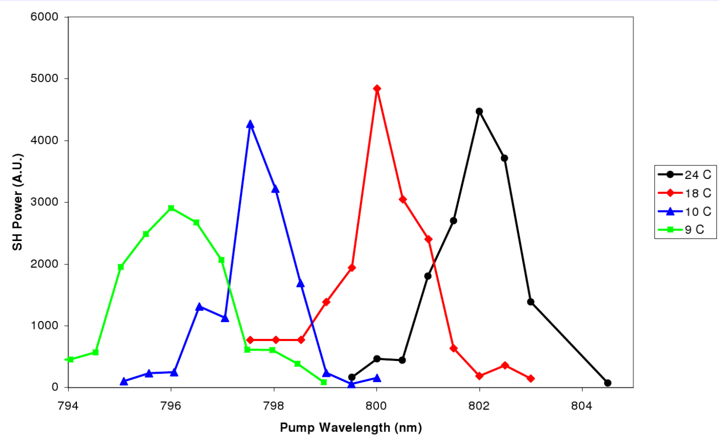




Thank you!

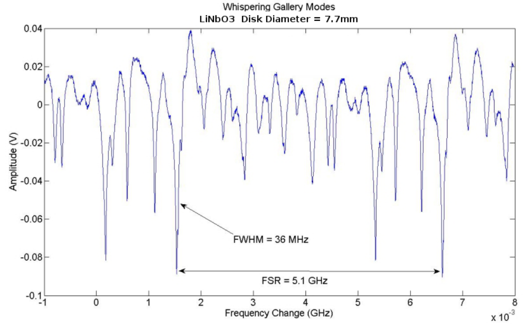
Potassium lithium niobate (KLN)

Second harmonic power vs. pump wavelength



Previously . . .

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



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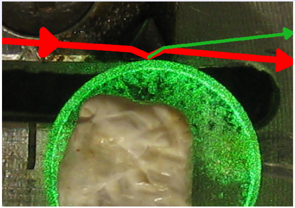

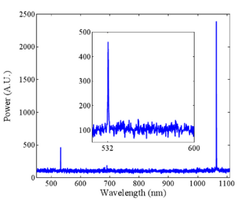

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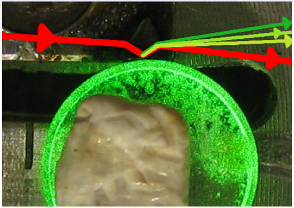
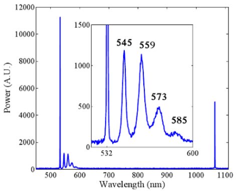
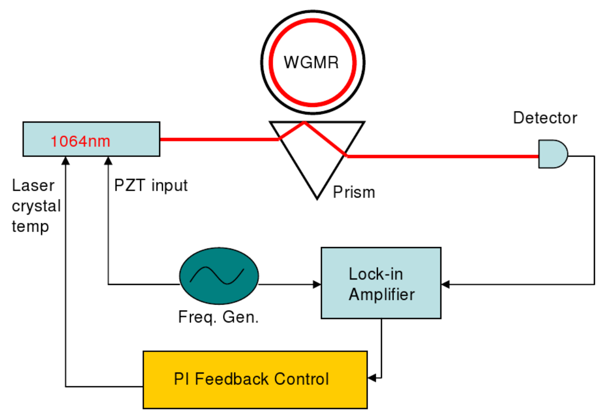


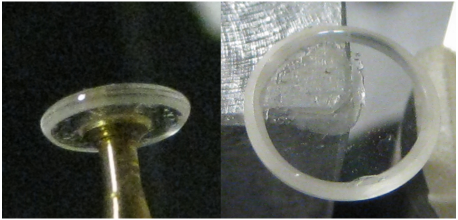


1064nm Tunable laser



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. $Q = 3 \times 10^6 \rightarrow 8 \times 10^6$



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

- WGMR quality factor Q

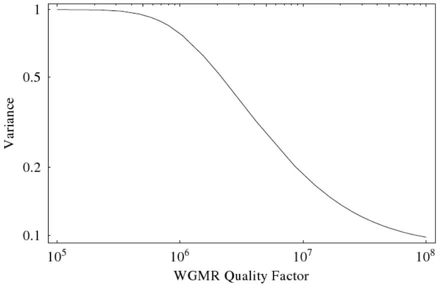


Figure : $f = 10$ MHz, $P_{in} = 500\ \mu$W

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}

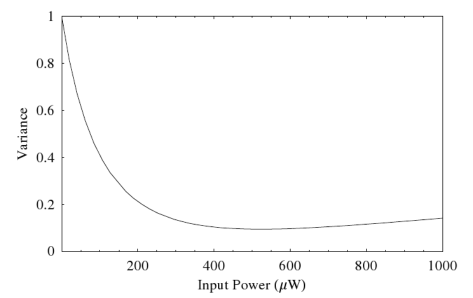


Figure : $Q = 10^8, f = 10$ MHz

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

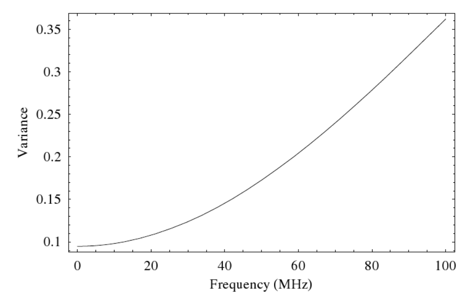
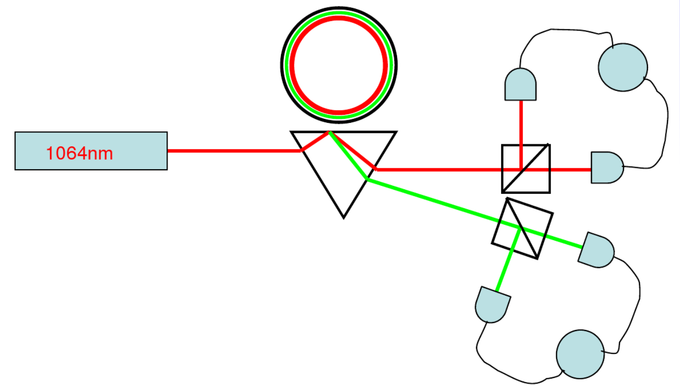


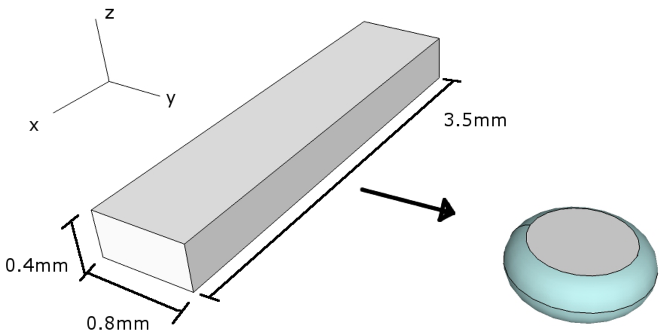
Figure : $Q = 10^8$, $P_{in} = 500\ \mu$W

Second harmonic squeezing



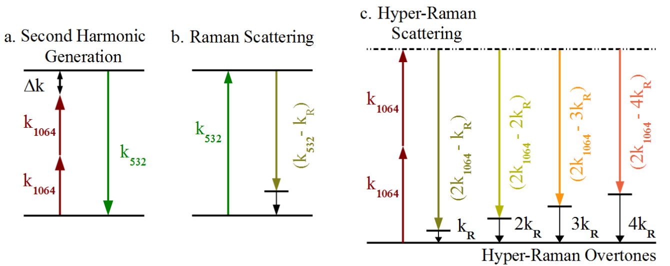
KLN Whispering-gallery disks

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

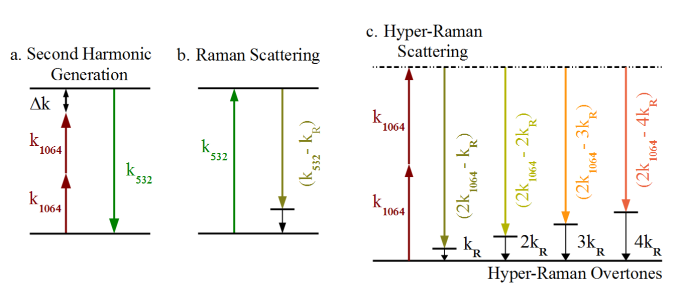


Demonstrate SHG squeezing at 795 nm

Hyper-Raman squeezing

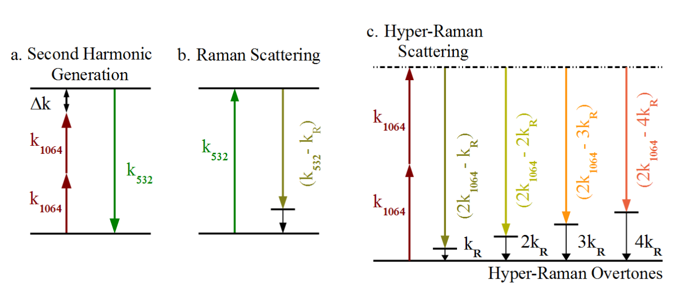


Hyper-Raman squeezing



- "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."

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:

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

Matrices

$$M_c \equiv \begin{pmatrix} -\frac{1}{2}\gamma_a^{tot} & \epsilon\bar{b} & \epsilon\bar{a}^* & 0 \\ \epsilon\bar{b}^* & -\frac{1}{2}\gamma_a^{tot} & 0 & \epsilon\bar{a} \\ -\epsilon\bar{a} & 0 & -\frac{1}{2}\gamma_b^{tot} & 0 \\ 0 & -\epsilon\bar{a}^* & 0 & -\frac{1}{2}\gamma_b^{tot} \end{pmatrix} \tag{11}$$

$$M_{in} \equiv diag\left(\sqrt{\gamma_a^i}, \sqrt{\gamma_a^i}, \sqrt{\gamma_b^i}, \sqrt{\gamma_b^i}\right) \tag{12}$$

$$M_u \equiv diag\left(\sqrt{\gamma_a^u}, \sqrt{\gamma_a^u}, \sqrt{\gamma_b^u}, \sqrt{\gamma_b^u}\right) \tag{13}$$

Theory

$$\tilde{x}_c = (\imath\Omega I - M_c)^{-1} (M_{in}\tilde{x}_{in} + M_u\tilde{x}_u) \tag{14}$$

$$\tilde{x}_o \equiv \begin{pmatrix} \delta A_{out} \\ \delta A_{out}^{\dagger} \\ \delta B_{out} \\ \delta B_{out}^{\dagger} \end{pmatrix} = M_{in}\tilde{x}_c - \tilde{x}_{in} \tag{15}$$

$$\begin{aligned} \tilde{x}_o = [M_{in} (\imath\Omega I - M_c)^{-1} M_{in} - I]\tilde{x}_{in} \\ +M_{in} (\imath\Omega I - M_c)^{-1} M_u\tilde{x}_u \end{aligned} \tag{16}$$

$$\delta A_1^{out} = \delta A_{out} + \delta A_{out}^{\dagger} \tag{17}$$

Variance

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

$$Var\left(A_1^{out}\right) = \langle |A_1^{out} - \langle A_1^{out} \rangle|^2 \rangle \tag{18}$$

$$A_1^{out} = \langle A_1^{out} \rangle + \delta A_1^{out} \tag{19}$$

$$Var\left(A_1^{out}\right) = \langle |\delta A_1^{out}|^2 \rangle \tag{20}$$

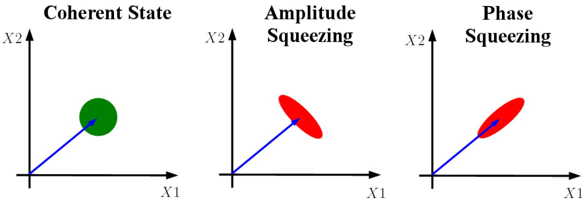
Squeezed light

Particle: position & momentum uncertainty relation:

$$\Delta x \Delta p \geq \frac{\hbar}{2} \tag{21}$$

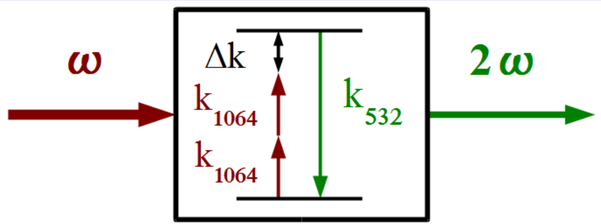
Light: amplitude & phase uncertainty relation:

$$\Delta A \Delta \Phi \geq \frac{1}{2} \tag{22}$$



Second harmonic generation

$$\vec{P} \sim \chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}^2 + \cdots \tag{23}$$



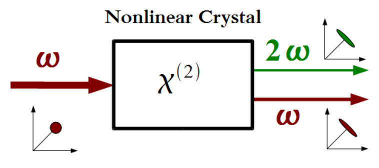
- Energy Conservation

$$\omega + \omega = 2\omega \tag{24}$$

- Momentum conservation

$$\Delta k = k_{2\omega} - 2k_{\omega} = \frac{2\omega}{c}(n(2\omega) - n(\omega)) \tag{25}$$

Squeezed light



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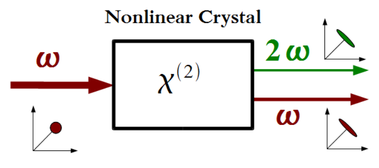
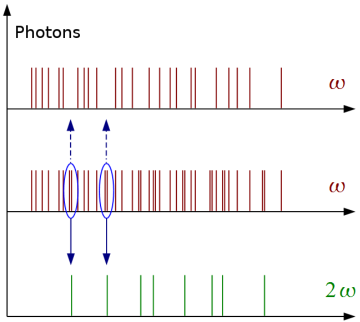


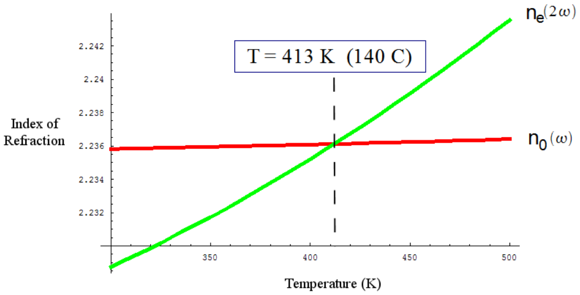


Second harmonic generation

- Momentum conservation

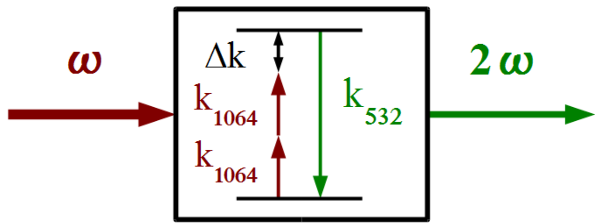
$$\Delta k = k_{2\omega} - 2k_{\omega} = \frac{2\omega}{c}(n(2\omega) - n(\omega))$$

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



Second harmonic generation

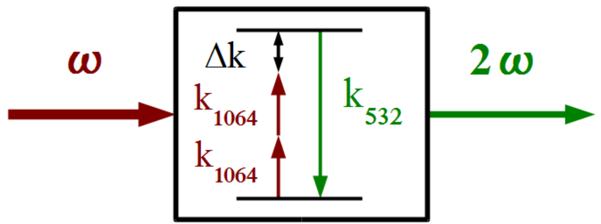
$$\vec{P} \sim \chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}^2 + \cdots$$



Intensity dependent process

Second harmonic generation

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

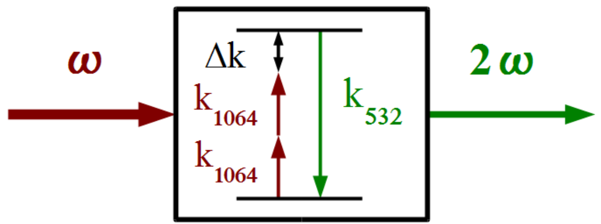


Intensity dependent process

- High-power pump laser

Second harmonic generation

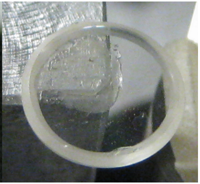
$$\vec{P} \sim \chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}^2 + \cdots$$



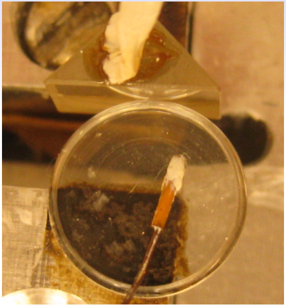
Intensity dependent process

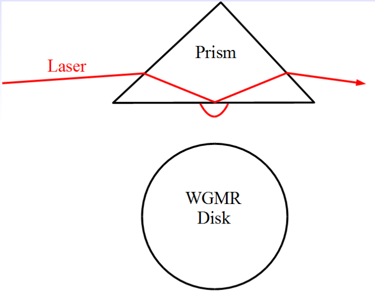
- High-power pump laser
- High-quality cavity

Whispering-gallery mode resonators (WGMRs)



Coupling to whispering-gallery modes





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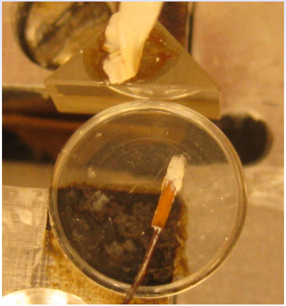
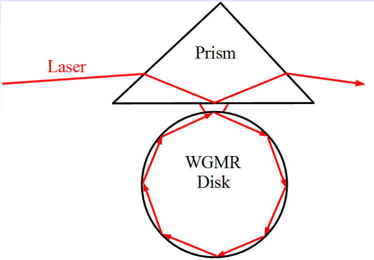
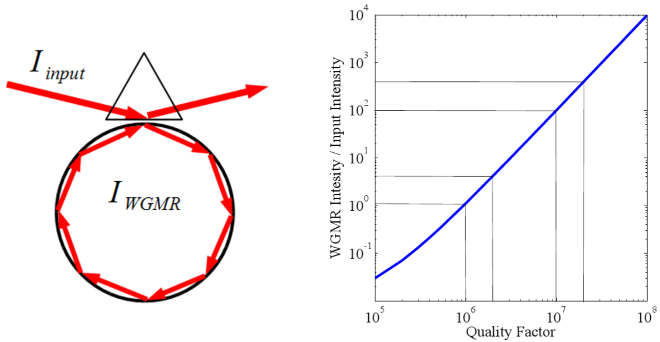




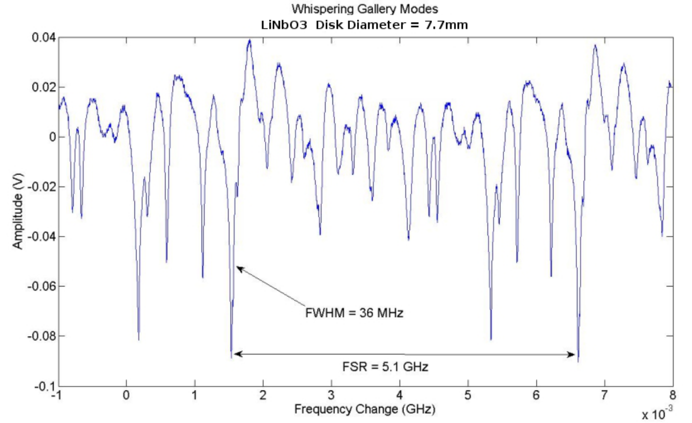
Whispering-gallery mode resonators



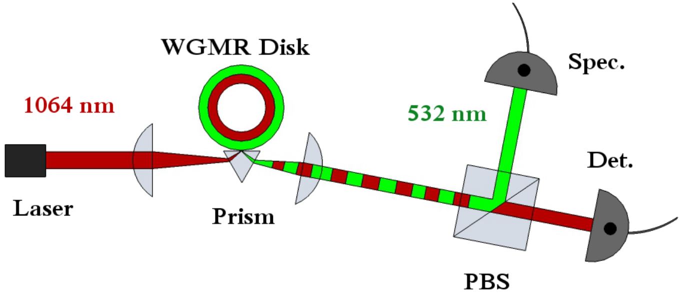
Coupling to whispering-gallery modes

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

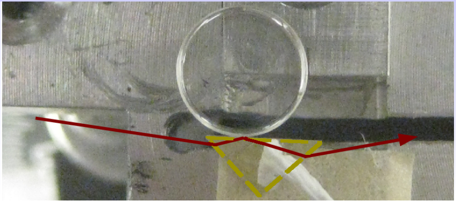
Q-factor of $Q = 10^7$

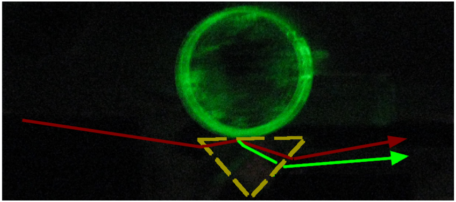


Second harmonic generation



Second harmonic generation

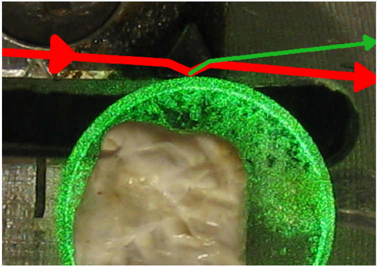


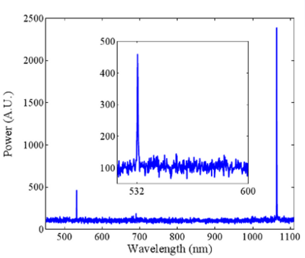


Second harmonic generation

Input 1064 nm Power = 11 mW

T = 26 °C

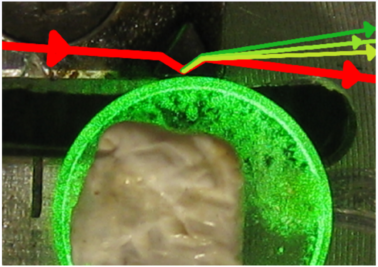


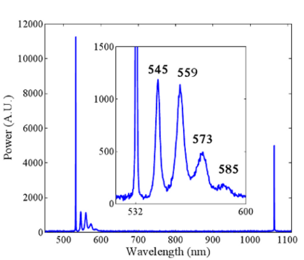


Raman scattering of the second harmonic

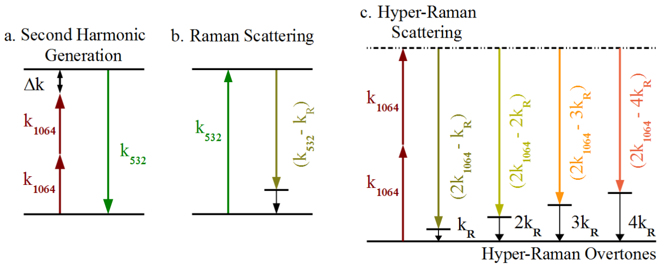
Input 1064 nm Power = 650 mW

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