OPTICAL SECOND HARMONIC GENERATION IN A WHISPERING GALLERY MODE RESONATOR

Matt T. Simons
College of William & Mary

Abstract

We are developing high quality factor whispering gallery mode resonator (WGMR) disks for use in quantum information experiments. Our polished lithium niobate disks achieved a quality factor on the order of $10^7$. We report the use of Type-I non-critical phase matching in a lithium niobate whispering gallery mode resonator disk to produce optical second harmonic generation at $\lambda = 532\text{nm}$. This process can be used to create both squeezed light and a single photon source, which are important steps toward quantum memory scheme.

Introduction

Many quantum information applications require a method for storing quantum information. Reversible mapping of quantum states of photons into long-lived spin states of atoms based on electromagnetically-induced transparency (EIT) is a promising scheme for realizing quantum memory\(^1\). While the possibility of light storage has been already demonstrated by many research groups, any practical application depends on development of a reliable source of on-demand single photons at the frequencies of atomic transitions and with a narrow bandwidth matching the spectral width of the EIT resonance. Alternatively, a continuous light field with non-classical statistics (such as squeezed light or squeezed vacuum) can be used to transmit quantum information. Squeezing reduces the uncertainty in one quantum variable of a light field below the fundamental quantum limit at the expense of the the conjugated one. In addition to quantum information, squeezed light can be used to improve sensitivity of an interferometer, a necessary component of many modern technologies including advanced atomic clocks.

Frequency conversion in nonlinear optical crystals can be used for both single photon production and the generation of squeezed light. Second harmonic generation (SHG) converts two photons of a strong continuous pump into a new photon at twice the frequency. If the pump is operated near the SHG threshold, then at random times two pump photons combine in the nonlinear medium to produce one single second harmonic (SH) photon. However, it is impossible to predict at what time this photon is emitted. In the reciprocal process - parametric down conversion (PDC) - one pump photon generates a pair of correlated photons. Detection of one of these photons signals (heralds) the presence of the other. This scheme is known as heralded single photon generation\(^2\). These two processes are often used together to produce heralded single photons - a strong laser field at the fundamental frequency is up-converted in SHG to produce a pump-field for a down-converter that generates photon pairs at the fundamental frequency again. SHG can also produce squeezed light\(^3,4\): as the fundamental field is converted to the second harmonic field as it propagates through a nonlinear medium the fluctuations in both fields are attenuated. After propagation through the medium, both light fields are squeezed. These nonlinear interactions are well-known and often used in quantum optics; however, they require high laser power and very high quality cavities, which make these experiments expensive and rather involved.

Whispering gallery mode resonators (WMGRs) made from nonlinear crystals provide a nice alternative to traditional designs. The crystalline material of the resonator serves as a nonlinear medium, and high quality factors (Q-factors) attainable in WMGRs reduces the input power required for SHG. Their monolithic design has advantages over external mirrored cavities in terms of stability. Our research has produced high Q-factor disks of nonlinear crystals, coupled light fields into whispering gallery modes inside these
disks, and generated a second harmonic field inside the whispering gallery mode resonator.

WGMR Production

Our whispering gallery mode resonators are disks cut from a birefringent uniaxial crystal, lithium niobate (LiNbO$_3$) (shown in Figure 1.) The disks are 1mm thick with diameters of 7mm – 10mm. We turn the disks on a lathe for shaping and polishing by hand. Sandpaper (600 - 1200 grit) is used to create curvature along the edge of the disk, and a progression of diamond sanding sheets (grain sizes from 30µm to 0.1µm) is used to achieve an optical quality polish.

The quality of polish and curvature of the disk control the quality factor (Q-factor) of the WGMR disk. The Q-factor is an important characteristic of a cavity as it is directly related to the lifetime of a photon in the cavity. A WGMR with a higher Q-factor has a longer lifetime, allowing for greater power build-up and thus has a lower input power threshold for nonlinear effects. Though we have achieved scratch/dig polish qualities of 25 = 15 and high Q-factors of 10$^7$, we remain focused on improving our techniques for sanding and polishing.

Excitation of WGMs

Excitation of a whispering gallery mode is similar to coupling light into a waveguide. A prism of a higher index of refraction than the WGMR disk is used to satisfy the coupling condition through frustrated total internal reflection (frustrated TIR). By bringing the disk within the skin depth, the light entering the disk is directed parallel to the edge of the disk, and undergoes total internal reflection as it travels around the circumference. It also scatters off of imperfections on the surface (left by polishing the edge). Currently the polish quality is the limiting factor for the Q-factors of our disks.

The light in the disk is out-coupled through the same prism. The transmission of the out-coupled and reflected beam is detected as the frequency of the laser is scanned. Whispering gallery modes are seen where there is missing transmission in the detected beam. This is the light that remains in (or is scattered out from) the WGMR disk. We designed and constructed a mount that controls the separation between the prism and disk (Figure 2). The coupling efficiency is dependent on the prism-disk separation - the disk must be within the skin depth, but if it is too close the cavity will be over-coupled and not receive the maximum input power. The skin depth is defined as

$$\delta = \frac{\lambda \cos[\theta_{\text{incident}}]}{\sqrt{(4\pi^2n^2 \sin^2[\theta_{\text{incident}}] - 1)}} \quad (1)$$

and is typically on the order of tens of nanometers. For our parameters ($\lambda = 795\text{nm}$, rutile prism $n_{\text{rutile}} = 2.52$) the skin depth is $\delta = 30\text{nm}$.

We coupled a $\lambda = 795\text{nm}$ ($\nu = 3.77 \times 10^{14}\text{Hz}$) diode laser scanned over a 10GHz range into a lithium niobate disk of diameter $d = 7.7\text{mm}$. For lithium niobate we use a rutile prism (which has an index of refraction of $n_{\text{rutile}} = 2.52$) The free spectral range (FSR) of a cavity, defined as

$$\text{FSR} = \frac{c}{n\pi d} \quad (2)$$

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Figure 3: Frequency scanned output from our LiNbO$_3$ WGMR disk near 795nm, showing a Q-factor of $Q = 10^7$.

characterizes the physical specifications of the disk. This is measured as the distance in frequency between adjacent modes. The full-width half max (FWHM) of the mode peaks measures the Q-factor of the disk

$$Q = \frac{\nu}{FWHM}$$

where $\nu$ is frequency of the laser. Figure 3 shows the output from our best WGMR disk, with a $Q$ of $10^7$. This result is on par with previous results.

**Second Harmonic Generation**

Generation of second harmonics requires that energy and momentum be conserved. The exchange of two fundamental photons for one SH photon $\omega + \omega = 2\omega$ satisfies the first condition. Momentum conservation requires a medium with an appropriate birefringence to satisfy

$$k_{2\omega} - 2k_\omega = \frac{2\omega}{c} (n(2\omega) - n(\omega)) = 0$$

which is the phase matching condition. For a particular fundamental frequency a crystal must have a birefringence that can compensate for the dispersion. There are several ways to tune the birefringence: angle phase matching (critical phase matching), quasi-phase matching, and temperature phase matching (noncritical phase matching). The circular geometry of the WGMR prohibits the use of critical phase matching. Quasi-phase matching has been used in other WGMR experiments, where periodically-poled lithium niobate disk was polished and then used to produce frequency doubling at fundamental wavelengths of $\lambda = 1.55\mu m$ and $1.319\mu m^{7}$. We have chosen to use the third method, which does not require a crystal to be periodically-poled. Since most nonlinear crystals’ birefringence depends on temperature on the order of $10^{-5}$ per $^\circ C$, there is only a small range of fundamental wavelengths that can support second harmonic generation. The birefringence (and thus the wavelength range) is heavily dependent on a crystal’s melt stoichiometry$^{8}$. For lithium niobate, a negative uniaxial crystal, at $\lambda = 1.064\mu m$ a congruent sample (ratio of lithium to niobium 0.95) can achieve non-critical phase matching at $T_{PM} = -6^\circ C$, while a stoichiometric sample (Li/Nb = 1) has a phase matching temperature of $T_{PM} = 140^\circ C$. In these cases the fundamental is polarized along the ordinary axis, and the second harmonic polarized along the extraordinary axis (also known as Type-I phase matching).
SHG in a Whispering Gallery Mode Resonator

We mounted a polished stoichiometric LiNbO$_3$ disk and brought it to the prism. With an infrared $\lambda_f = 1.064\mu m$ fiber laser aligned to couple into a whispering gallery mode of the disk, we covered and heated the system to 140°C. The input power of the laser was $P_0 = 250mW$. Near $T = 140°C$, the phase matching condition was met inside the WGMR, and a green SH field was generated at $\lambda_s = 532nm$ (see Figure 4).

Our future work will be to measure the SHG output from our WGMRs, and optimize the coupling conditions to maximize this output. The coupling efficiency of the disk used was 10%. The input power into the disk was then about 25$mW$. The scattered green SH light observed from the WGMR disk was significantly brighter than the single pass SH light from an input power of 25$mW$. Further measurements will compare the transmitted SHG power from the WGMR with single pass SHG power for similar input pump powers. With an improved coupling efficiency, our WGMR SHG scheme will significantly reduce the input power required for frequency doubling.

Conclusions

Whispering gallery mode resonators offer potential for advancing the field of quantum information storage. We have shown that our WGMRs can achieve high quality factors ($Q = 10^7$), and can support optical second harmonic generation (Figure 4). We used Type-I noncritical phase matching in a stoichiometric LiNbO$_3$ WGMR to produce SHG from $\lambda = 1064nm$ to $\lambda = 532nm$.

In subsequent work we will optimize the degree of squeezing we can obtain from our WGMR SHG for use in quantum information experiments. For implementation into an EIT-based light storage system we will reproduce this process in a crystal with appropriate properties for up-conversion from $\lambda = 795nm$ ($^{87}$Rb D$_1$ transition) to $\lambda = 397.5nm$, and explore producing the reciprocal process (down-conversion) to achieve heralded single photon generation.

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References


