# Widely tunable optical parametric oscillator in periodically poled congruently grown lithium tantalite whispering gallery mode resonators

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We demonstrate a tunable optical parametric oscillator in a periodically poled congruently grown lithium tantalite whispering gallery mode resonator. The resonator is mechanically polished to millimeter size, and the quality factor is approximately $10^7$ at 1064 nm. Our experiments show that this kind of resonator is capable of reaching a very low threshold and having a wide tuning range. Combined with its narrow resonant linewidth, it is potentially used as a compact, widely tunable, and narrow-linewidth infrared to mid-infrared laser source.

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Whispering gallery mode resonators (WGMRs) with high quality factors have versatile applications in non-linear optics[1–4] owing to their small mode volume, which can provide a dramatic enhancement of the light intensity and make it possible to achieve an unprecedentedly low threshold in nonlinear processes[5,6]. Unlike the traditional WGMR fabricating method, which generally includes a melting procedure[7], crystalline WGMRs can always keep their stoichiometric ratio and high purity, since only a simple mechanical polishing technique is used. With these properties kept, it is easy for crystalline WGMRs to achieve an ultrahigh quality factor[8]. WGMRs made of commercial $CaF_2$ windows with a quality factor over $10^{11}$ were obtained by Savchenkov *et al.* years ago[9].

Nowadays, optical parametric oscillators (OPOs) are irreplaceable in obtaining light with different wavelengths, especially combined with the quasi-phase-matching (QPM) technique[10–13]. Periodically poled WGMRs with a high frequency doubling efficiency were first demonstrated in 2004[14]. Subsequently, efficient frequency down conversion in WGMRs was studied. A highly tunable OPO that generated a signal and idler light around 2 μm was achieved by employing a radially poled WGMR[15]. Obviously, a radially poled structure can offer a strong reciprocal vector, and slight off-centering of the radial structure generates wide tunability. However, compared with a traditional periodically poled structure, this kind of poling pattern is much more difficult to fabricate. The pioneering work shows that a periodically poled $LiNbO_3$ (PPLN) can also achieve efficient frequency doubling[14]. A parametric down conversion process with a low threshold in a PPLN WGMR was also reported recently[6]. Furthermore, it was realized that a periodically poled structure can bring broadband harmonics[16], resulting in a large tuning range in the down conversion process.

In $\chi^{(2)}$ nonlinear optical effects, the QPM technique is based on producing a modulation of the nonlinear susceptibility of the material with a period $\Lambda$, which is determined by $k_p - k_s - k_i = 2\pi/\Lambda$ in bulk crystals, where $k_p$, $k_s$, and $k_i$ are the wave vectors of the pump, signal. and idler, respectively. But in WGMRs, the phase-matching condition is modified in the form of angular momentum conservation, as shown in

$$m_p = m_s + m_i + g_\Lambda, \tag{1}$$

where $g_\Lambda = 2\pi R/\Lambda$. $m_p$, $m_s$, and $m_i$ are the azimuth mode numbers of the pump, signal, and idler, respectively, and can be estimated from

$$\omega = \frac{c}{nR}\left[\ell + \alpha_q\left(\frac{\ell}{2}\right)^{1/3} + p\left(\sqrt{\frac{R}{\rho}} - 1\right) - \frac{\chi \cdot n}{\sqrt{n^2-1}} + \sqrt{\frac{R}{4\rho}} + O(\ell^{-1/3})\right], \tag{2}$$

where $\omega$ is the frequency of resonant light, $n$ is the refractive index and can be estimated from the Sellmeier equation, $p$ is the angular mode number, and $\ell = m + p$ is the polar mode number. $\alpha_q$ is the $q$th root of the Airy function, which is equal to 2.338, 4.008, and 5.521 for radial mode numbers $q = 1, 2, 3$, respectively, and $R$ and ρ are the major and minor radium of the WGMR, respectively[17,18]. According to Eqs. (1) and (2), the poling period at the degeneracy point is smaller in WGMRs than in bulk crystals.

We made several samples to experimentally test the tunability of periodically poled congruently grown $LiTaO_3$ (PPCLT) WGMRs. The poling periods of these crystals are all around 29 μm. They are cut into disks, and the rims of the disks are then mechanically polished into a spheroidal shape with a polycrystalline diamond paste. The major radius of the resonator is designed to be around 1–2 mm, which can be achieved after a series of polishing steps, with polishing paste grit sizing from 15 down to 0.1 μm. The experimental configuration is shown in Fig. 1. The pump source consists of a commercial distributed feedback (DFB) laser with an emitting wavelength of around 1064 nm that is seeding into a $Yb^{3+}$-doped fiber amplifier and is focused onto the back side of a rutile prism after the fiber amplifier. The optical axis of the prism is designed parallel to the symmetry axis of the WGMR to provide a larger refractive index when exciting the TE mode of the resonator. Coupling occurs via frustrated total internal reflection. A piezoelectric ceramic is used to control the gap between the prism and the resonator; hence, the coupling coefficient can be changed. Furthermore, one can also tune the angle of the incident pump to excite a preferable mode. For temperature stabilization and contaminant avoidance, the resonator and coupling prism are mounted in an enclosed package with a temperature stability better than 0.002°C over 24 h. The residual pump and generated light are collimated after coupling out of the prism. The pump light is separated from the parametric light using a dichromatic mirror (transmission for 1.064 μm > 99% and reflection for 1.5–2.4 μm > 99% at 45°) and detected by a photodiode (PD1) for the transmission scanning measurement. The signal light is detected by another photodiode (PD2). A small portion (<1%) of the signal is coupled to an optical

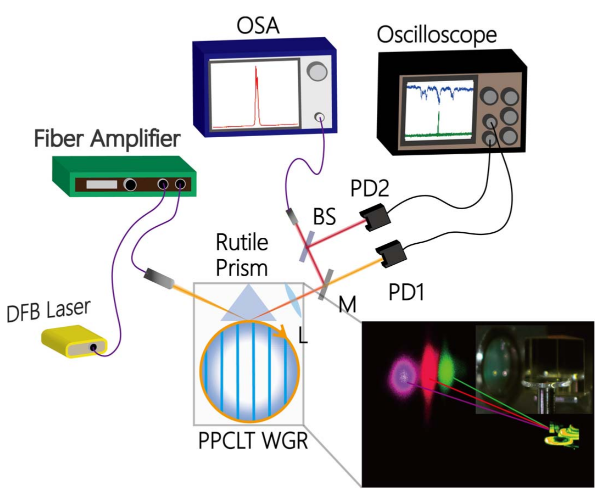


Fig. 1. Schematic configuration of the experimental setup: pump light from a DFB laser is coupled into a WGMR via a rutile prism after being amplified by a $Yb^{3+}$-doped fiber amplifier. The output light is collimated by an aspherical lens L. M is high reflection coated for the signal and anti-reflection coated for the pump and idler. A beam splitter (BS) is used to separate the signal into two beams; hence, the signal can be detected by the OSA and oscilloscope simultaneously. PD1, 2 are used for pump and signal detection, respectively. Inset: the glowing resonator and its outcoupled light recorded by a camera. The pink spot is the residual pump, the red one is the sum frequency of the pump and signal light, and the green is the frequency doubling of the pump.

spectrum analyzer (OSA) for spectrum analysis. The whole linear losses are 2.4 and 1.6 dB for the pump and signal, respectively, which is mainly due to the Fresnel reflection on the uncoated prism and lenses.

The linewidth of the WGMR is measured by scanning the laser frequency, which is fitted to be 37 MHz, and it corresponds to a quality factor $Q_0$ of $7.6 \times 10^6$. The coupling contrast of 50% is achieved under the critically coupled condition.

The OPO process occurs when the pump light exceeds a certain threshold, and at the same time, the PD2 gives an electronic signal. The inset of Fig. 1 gives the glowing resonator and its outcoupled light on a screen. This happens when both $\nu_p + \nu_s$ and $2\nu_p$ both fall into the resonance, where $\nu$ is the frequency of light. Figure 2 reveals which pump mode can satisfy the momentum and energy conservation law for an OPO process in this WGMR in a fixed cavity temperature. It is noted that the WGMR employed in our experiment has dense modes. This feature is normal when WGMRs have large rims, and it is helpful for phase matching. The resonator will be heated by the pump light when a relatively high pump power is coupled into the resonator. This will pull the resonance frequency to a lower frequency and hence broaden the resonance spectrum when the laser frequency sweeps toward the thermal-pulling direction. Even the signal pulse will expand if the pump power significantly exceeds the threshold. We recorded the spectrum of the output light at the same time.

Figure 3 shows the captured spectrum of the signal light at the WGMR temperature of about 23.3°C. The poling period of this sample is chosen to be 29 μm and with a major radius of 1.60 mm, which will offer a stronger harmonic near the degeneracy point. On the other hand, the intrinsic absorption of light near the degeneracy point of 2 μm is weaker. Consequently, a higher optical conversion

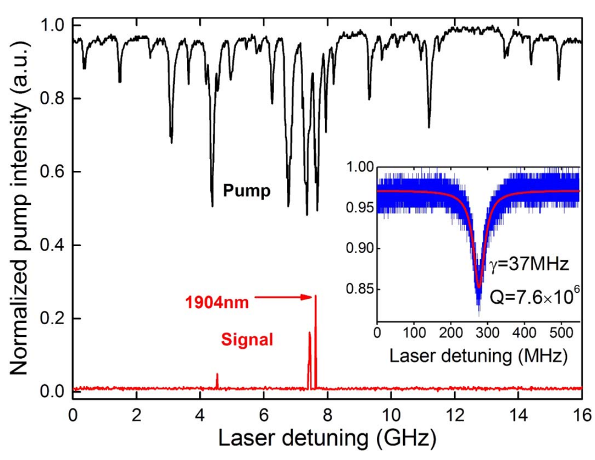


Fig. 2. Transmitted pump and signal from our PPCLT WGMR. Free spectrum range of the WGMR is approximately 13.9 GHZ ($R \approx 1.60$ mm). The fundamental mode is over-coupled for a high-power signal output. The thermal-pulling effect is significant in our experiment because of the high pump power. Inset: the measured quality factor of a PPCLT WGMR under a weak coupling condition.

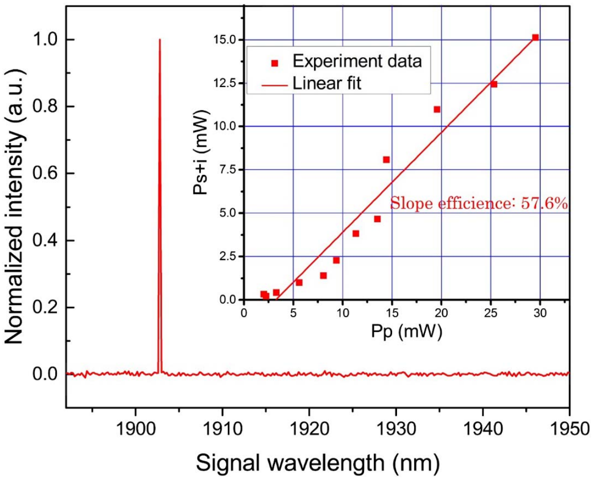


Fig. 3. Spectrum recorded by the OSA. The temperature of the resonator is around 23.3°C. The generated signal is at 1905 nm and the idler at 2410 nm when the pump wavelength is 1063.9 nm. The inset shows obtained the signal and idler power as a function of the coupled pump power. Both the generated light and pump light are corrected for absorption and the Fresnel reflection. The pump is also corrected for coupling efficiency.

efficiency and lower threshold can be obtained. The inset of Fig. 3 is the measured power of the combined signal and idler as a function of the pump and the linear fitting result. From the figure, the threshold is around 3 mW, and the slope efficiency is about 57.6%.

At last, we investigated its tunability by changing the temperature of the cavity. After fixing the cavity temperature, we scanned the pump frequency over one free spectrum range at a relatively high power. As a result, several signal frequencies were obtained. This is caused by two main factors. The first is that the period is chirped when light travels around the periodically poled WGMRs, and the effective periods vary from $\Lambda$ to $1.2\Lambda$[16]. The other one is the so called quasi-resonant condition[19], in which light is not necessarily fully falling into resonance. It allows a detuning value $\delta$ (a larger $\delta$ gives rise to a higher threshold) between the coupled or generated light and the cavity mode, which is caused by the energy conservation law and material dispersion. Therefore, when the pump frequency is swept, the quasi-resonant condition is satisfied occasionally during thermal-pulling process. Another sample with a period of 28.5 μm and $R = 1.75$ mm was used to get a wider tuning range. By recording these signals at different cavity temperatures, we reveal its tunability in Fig. 4. It shows that a periodically poled WGMR can have wide tunability, but it is not always continuously tunable. Light generated at the four equivalent regions of the PPCLT pattern in the WGMR may interfere destructively, leading to an effectively weakening or even vanishing non-linearity at some certain period. A quarter-PPCLT pattern WGMR can be used to further increase the tuning range. However, the threshold will be higher. The reason is that the intensity of the reciprocal vector in that situation is only 1/4 of that of the structure used in our experiment[16].

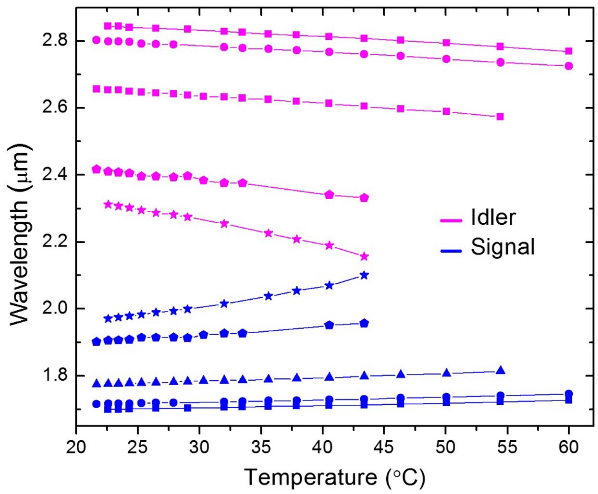


Fig. 4. Tunability of a PPCLT WGMR with a period around 28.5 μm and $R = 1.75$ mm. The poling period is chosen far away from the degeneracy point to offer a wide tuning range.

In conclusion, we successfully make a high-$Q$ PPCLT WGMR for optical parametric down conversion and achieve a very low threshold. We also investigate its tunability. It turns out that even a single PPCLT WGMR can have a wide tuning range. With these characteristics, it has potential to be used as a compact, widely tunable, and narrow-linewidth infrared to mid-infrared laser source. One can further improve its performance by improving the polishing technique for a higher quality factor and coupling efficiency.

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