Ultralow-threshold thin-film lithium niobate optical parametric oscillator

Juanjuan Lu, Ayed Al Sayem, Zheng Gong, Joshua B. Surya, Chang-Ling Zou, and Hong X. Tang

1 Department of Electrical Engineering, Yale University, New Haven, Connecticut 06511, USA
2 Department of Optics, University of Science and Technology of China, Hefei 230026, P. R. China.
(Dated: January 30, 2022)

Materials with strong $\chi^{(2)}$ optical nonlinearity, especially lithium niobate, play a critical role in building optical parametric oscillators (OPOs). However, chip-scale integration of low-loss $\chi^{(2)}$ materials remains challenging and limits the threshold power of on-chip $\chi^{(2)}$ OPO. Here we report the first on-chip lithium niobate optical parametric oscillator at the telecom wavelengths using a quasi-phase matched, high-quality microring resonator, whose threshold power ($\sim$30 $\mu$W) is 400 times lower than that in previous $\chi^{(2)}$ integrated photonics platforms. An on-chip power conversion efficiency of 11% is obtained at a pump power of 93 $\mu$W. The OPO wavelength tuning is achieved by varying the pump frequency and chip temperature. With the lowest power threshold among all on-chip OPOs demonstrated so far, as well as advantages including high conversion efficiency, flexibility in quasi-phase matching and device scalability, the thin-film lithium niobate OPO opens new opportunities for chip-based tunable classical and quantum light sources and provides a potential platform for realizing photonic neural networks.

Optical parametric oscillators (OPOs) are critical sources of coherent radiation over a wide spectral range and have been workhorses for spectroscopy in the near-and mid-infrared regime [1-3]. They are also widely used as non-classic light sources for applications in quantum information processing, including quantum random number generation, quantum key distribution, and recently demonstrated Ising machines [4-7]. Microcavity-based OPO has been particularly attractive due to its miniaturization and power-efficiency. With ultra-high optical quality (Q) factor of $10^7$–$10^8$ afforded by the whispering gallery resonator (WGR) system, low-threshold OPOs have been achieved in various bulk WGRs [8-14], especially the highly polished lithium niobate (LN) WGRs with $\chi^{(2)}$ nonlinearity.

Over the past decade, the demand for scalability in photonic components has stimulated efforts to produce on-chip OPOs via either $\chi^{(2)}$ or $\chi^{(3)}$ nonlinearity [15-20]. Among these, $\chi^{(2)}$ OPO has only been demonstrated with an aluminum nitride (AlN) microring resonator while its threshold power is tens of milliwatts [20], which is orders of magnitude larger than state-of-the-art value of lithium niobate WGR. Hence, low threshold and scalable $\chi^{(2)}$ OPO remains challenging. Recently, thin film LN has emerged as a compelling integrated nonlinear and quantum photonics platform, whose favorable performances including but not limited to electro-optic modulation [21-23], frequency comb generation [24-26], frequency conversion [27-30], and entangled photon pair generation [31, 32], have by now been well demonstrated.

In this Letter, we present an ultralow-threshold, chip-integrated OPO using a periodically poled lithium niobate microring resonator (PPLNMR). With high optical confinement and strong spatial mode overlap via the quasi-phase matching, a threshold power as low as 30 $\mu$W is demonstrated for the parametric oscillation at the infrared band, which is a state-of-the-art value reported among all current integrated photonics platforms. Meanwhile, an absolute power conversion efficiency of 11% is obtained at a pump power of 93 $\mu$W. A tuning bandwidth of 180 nm (23 THz) could be addressed through a small change of 5 nm (2.5 THz) in pump wavelength (frequency). Alternatively, the temperature tuning is investigated to fine control the signal and idler wavelengths and a degenerate OPO is achieved at an optimal temperature. Overall, low-threshold, wide-tunability, as well as flexibility in phase-matching by domain poling make thin-film LN OPO the ideal candidate for compact, versatile light sources for various on-chip optical applications, such as sensing, frequency comb spectroscopy, and quantum squeezers.

Figure 1(a) illustrates the principle of our lithium niobate microring OPO device, in which $\chi^{(2)}$-based parametric down-conversion process allows the generation of the infrared signal and idler lights with a near-visible pump. $\omega_p$/ω$_s$/ω$_i$ represent the pump/signal/idler mode frequencies with their energy conservation (ω$_p$ = ω$_s$ + ω$_i$) shown in the inset. When the phase-matching and triply-resonant conditions are satisfied for these three optical modes, the parametric process would be enhanced by the high-Q resonator. The theoretical pump power threshold $P_{th}$ for parametric oscillation could be obtained when the optical loss and parametric gain are balanced [20]:

$$P_{th} = \frac{\hbar \omega_p}{8g^2} \frac{\kappa_x \kappa_y \kappa_z}{\kappa_{p,1}} = \frac{\hbar \omega_s \omega_i}{64g^2} \frac{Q_{p,1}}{Q_s Q_i Q_p^2},$$

where $g$ is the vacuum coupling strength between the three interacting modes, $Q(\kappa)_s$/$\omega_p$ is their respective loaded Q factor (total dissipation rate), and $Q(\kappa)p,1$ is the coupling Q factor (external dissipation rate) of the pump mode. Therefore, a large $g$ and high Q factors are always demanding to reduce the OPO threshold power.

In the microring resonator, the coupling rate $g$ is de-
FIG. 1. Design and fabrication of a quasi-phase-matched optical parametric oscillator. (a) Illustration of the parametric oscillation using a $\chi^{(2)}$ PPLNMR. Signal and idler lights are generated by a near-visible pump. $\omega_p$, $\omega_s$ and $\omega_i$ represent frequencies for pump, signal and idler light, respectively. (b) Cross-sectional view of the microring indicating the key geometric parameters. (c) Optical image of the fabricated PPLNMR devices. (d) Schematics of the mode frequencies and their respective transmission spectrum with the extracted Q values shown in the inset. The subscripts 0, 1 represent the intrinsic and coupling Q factors, respectively.

In practice, due to the resonance frequency mismatch ($\delta = \omega_s - \omega_i - \omega_p$) induced during the fabrication process, the OPO threshold rises to \( P_{th} \cdot (1 + \delta^2/\kappa_s) \). By controlling the chip temperature to adjust $\delta$ and varying the pump power, the parametric oscillation with the lowest threshold is observed when the device is pumped at the resonance near 774.1 nm at an optimal temperature of 125°C, as indicated in Fig. 2(a). The measured on-chip OPO power (blue circles) is plotted against the on-chip pump power, where a threshold power of 120 $\mu$W is identified and corresponds to an intra-cavity pump photon number of $\sim 5.4 \times 10^4$. The parametric oscillation spectrum at a pump power of 120 $\mu$W is captured using an optical spectrum analyzer (Yokogawa AQ6374, 350–1750 nm), where distinct signal and idler waves are resolved at 1529.7 and 1568.4 nm respectively, as shown in the inset.
applications. For example, a coupling condition could be adapted by varying the gap between the bus waveguide and microring for various applications. Different coupling conditions could be adapted by varying the gap between the bus waveguide and microring for various applications. For example, a \( \eta_{\text{max}} \) of 0.25 is derived with the assumption that all three interacting modes are critically coupled whilst strong over-coupling condition provides a \( \eta_{\text{max}} \) approaching unity. In our case, the under-coupling condition provides an ultralow threshold of 30 \( \mu \)W though limits our current \( \eta_{\text{max}} \) to 11%.

We further demonstrate the feasibility of our ultralow-threshold OPO in wavelength tuning over a large spectrum range, which promises flexible coherent optical sources for future on-chip applications. It is well-known that, in the microring resonators, the phase-matching condition could be satisfied simultaneously by many signal-idler mode pairs, with their wavelength difference increasing at intervals of 2 times of free spectral range (FSR) for a given pump mode and temperature. However, due to the inherent dispersion, the frequency mismatch \( \Delta \) varies for different mode pairs, and only one pair of modes oscillates with the lowest threshold. Therefore, we investigate the tuning of signal and idler wavelengths by varying the resonator temperature as well as the pump mode number.

As indicated by the solid color lines in the middle panel of Fig. 3, the theory predicts that the quasi-phase-matched signal and idler wavelengths could be continuously tuned as a function of the pump wavelength and the chip temperature (see Methods for simulation details). However, due to the constrain of resonance condition, we can only experimentally access discrete points on the lines, as marked by the blue dots. On one hand, for a given temperature, the spectral separation between the signal and idler increases with the decreasing pump wavelengths. For example, by fixing the operation temperature at 125°C, the OPO wavelength could be tuned from 1450 to 1650 nm, with the pump wavelength change of only 5 nm. The detailed spectra are plotted on the right panel, whose signal and idler wavelengths (blue circles) are mapped to the left panel and show good agreement with the theoretical prediction. On the other hand, for a given pump mode, the temperature tuning allows for the fine-control of the OPO wavelengths. As indicated on the left panel, for a fixed pump mode around \( \sim 770.5 \) nm (red shaded region), the signal-idler separation is observed to narrow as the temperature increases and an degenerate OPO is experimentally demonstrated at an optimal temperature of 140°C, which match well with the prediction. Hence, our OPO device has shown good potential to realize the relatively precise control of oscillation wavelengths by combining pump wavelength and temperature tunings. Noting that the demonstrated wavelength tuning is broad but inherently discrete, continuous tuning (mode-hop free) is always demanding and remains to be investigated via several promising strategies: One approach is the material refractive index change via either thermo-optic or electro-optic effect, which allows tens of GHz tuning range \([36] [37]\). Another is cascading multiple microrings with varying geometry parameters on each individual bus waveguide \([35] [36]\), so that the tuning range of multiple resonators could possibly overlap and cover one single FSR.
Finally, we compare the performances of various integrated platforms, including both $\chi^{(3)}$ and $\chi^{(2)}$ mechanisms, for their respective state-of-the-art cavity-enhanced OPOs in terms of the material, refractive index $n_0$, nonlinear coefficients, device structure, operating wavelengths, Q factor, and threshold power, as presented in Tab. I. Theoretically, $P_{th} \propto 1/Q^2$ for the $\chi^{(3)}$ OPO. However, in the case of $\chi^{(2)}$ process, $P_{th} \propto 1/Q^3$ [Eq. (1)]. Therefore, to reach the same threshold, $\chi^{(2)}$ OPO has a less stringent requirement on its Q factor. Despite the fact that silicon photonics, including Si, Si$_3$N$_4$ and SiO$_2$, have much higher Q factors due to their mature fabrication techniques, the demonstration in this work, to the best of our knowledge, delivers the lowest threshold power among all on-chip OPOs so far. Moreover, due to the three-wave mixing nature, $\chi^{(2)}$ OPO offers broader spectral-separation between the pump and signal/idler fields intrinsically, which promises for sufficient on-chip filtering. We note that piezoelectric III–V materials, such as Al(Ga)N, (Al)GaAs and GaP, feature both significant $\chi^{(2)}$ and $\chi^{(3)}$ nonlinear coefficients, while relying on challenging waveguide geometrical engineering to achieve modal phase matching between fundamental and high-order modes which limits their OPO performance as well as operation wavelengths. Overall, the periodically poled thin-film lithium niobate microresonator proved to be an efficient OPO with the lowest power threshold. In addition, due to its flexibility in ferroelectric domain control for quasi-phase matching and greatly enhanced light-matter interaction afforded by its high effective $\chi^{(2)}$ nonlinearity and Q factor, our device on a integrated photonic chip opens new possibilities for various applications and alternative device designs could be envisioned based on target applications. Firstly, PPLNMR device promises chip-based tunable classical and quantum light sources. For example, the poling grating number $M$ could be tailored to realize parametric oscillation at the mid-infrared wavelengths for the molecule spectroscopy [42]. Over-coupling the degenerate signal modes could lead to efficient on-chip squeezers, which play a crucial role in continuous variable quantum information processing [43]. Secondly, due to the multiple modes and nonlinear optical processes present in the same device, the OPO dynamics could be an indicator for novel physics of light-matter interactions in the microresonator [44]. For example, inspired by the recent demonstration on AlN [45], ultra-efficient pockels soliton microcomb could be foreseen in the same device with the efforts of coordinating its Kerr, quadratic, and photorefractive effects [46]. Lastly, by coupling several PPLNMRs, significant nonlinear interplay between the OPOs offers an platform for realizing the photonic neural networks and Ising models, which find applications in artificial machine learning [47, 48].

In conclusion, we demonstrate $\chi^{(2)}$ optical parametric oscillation in lithium niobate nanophotonics. Leveraging the high optical confinement, as well as optimized quasi-phase matching condition, an ultra-low power threshold (30 µW) of optical parametric oscillation is obtained and an on-chip conversion efficiency of 11% is measured with an on-chip pump power of 93 µW. The tunability of the OPO wavelengths is also investigated via the pump-wavelength and temperature tuning, and the experimental results indicate a wide tuning range. By further pushing the Q factor to that of bulk LN WGRs, approaching $10^8$, a pump threshold down to several picowatts could be attainable in PPLNMR devices, allowing the study of OPO at a few-photon level and is critical for the scala-
Table I. Performances of various nonlinear integrated platforms for microcavity-enhanced parametric oscillation.

| Materials | \( n_0 \) | \( \chi^{(3)} \times 10^{-18} \text{m}^2/\text{W} \) | \( \chi^{(2)} \text{pm/V} \) | Structure | Process | \( \lambda_p - \lambda_i \), \( \lambda_i \) (nm) | \( Q \times 10^6 \) | \( P_{th} \) (mW) | Ref. |
|-----------|---------|----------------|----------------|---------|---------|----------------|----------------|---------------|-----|
| LN        | 2.2     | 0.18           | 40             | microring | \( \chi^{(2)} \) | 775–1550       | 0.6            | 0.030         |      |
|           |         |                |                |          | \( \chi^{(3)} \) | 1560–1540     | 1.1            | 80            |      |
| AlN       | 2.1     | 0.23           | 6              | microring | \( \chi^{(2)} \) | 780–1560       | 1.0            | 12            |      |
|           |         |                |                |          | \( \chi^{(3)} \) | 1560–1530     | 1.6            | 25            |      |
| Si_3N_4   | 2       | 0.25           | —              | microring | \( \chi^{(3)} \) | 1560–1540     | 37             | 0.33          |      |
|           |         |                |                |          |           | 900–700        | 2.5            | 0.90          |      |
| AlGaAs    | 3.4     | 26             | 120            | microring | \( \chi^{(3)} \) | 1540–1520     | 1.5            | 0.036         |      |
| GaP       | 3.1     | 11             | 82             | microring | \( \chi^{(3)} \) | 1560–1540     | 0.2            | 3.0           |      |
| SiC       | 2.7     | 1              | 12             | microring | \( \chi^{(3)} \) | 1560–1530     | 1.1            | 8.5           |      |
| Si        | 3.5     | 10             | —              | microring | \( \chi^{(3)} \) | 2600–2500     | 0.6            | 3.1           |      |
| SiO_2     | 1.4     | 0.022          | —              | microtoroid | \( \chi^{(3)} \) | 1550–1500     | 100            | 0.050         |      |
|           |         |                |                | microdisk  |               | 1550–1549     | 1100           | 0.95          |      |

ability of photonic quantum systems. In light of the most recent works on near-octave comb generation, efficient SHG, and bright photon pair generation, PPLNMR devices hold promise for the chip-based tunable coherent light sources as well as the monolithic realization of nonlinear and quantum photonics.

**METHODS**

**Nanofabrication.** The devices are fabricated on a commercial LNOI wafer (supplied by NANOLN) with 610 nm thick Z-cut LN thin film on 1.8 µm silicon dioxide (SiO_2) on a silicon substrate. The bus waveguide is ultimately tapered to a width of 4 µm at both facets to improve the fiber-to-chip coupling efficiency. The pattern is defined by a 100 kV electron beam lithography system (Raith EBPG 5000+) with a negative FOX-16 resist, which is then developed in 25% TMAH solution to ensure a high contrast. The exposed pattern is transferred onto the LN thin film using an optimized inductively coupled plasma (ICP) reactive ion etching (RIE) process with Ar+ plasma. For the subsequent poling process, the radial nickel electrodes are initially patterned on top of the LN microring via the lift-off process. The periodic domain inversion is then enabled by keeping the silicon substrate as the electrical ground while applying several 600 V, 250 ms pulses on the electrodes at an elevated temperature of 250°C. After removing the nickel electrodes, the chip is cleaved to expose the waveguide facets for fiber-to-chip coupling. The insertion losses are calibrated to be 8.4 and 11.1 dB/facet for the infrared and near-visible lights, respectively.

**Numerical simulation.** The parametric signal and idler wavelengths as a function of the pump wavelength and temperature are numerically investigated using a commercial finite-difference-eigenmode solver (Lumerical MODE) based on the equations:

\[
\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}, \tag{3}
\]

\[
n_p(T) = n_s(T) \frac{\lambda_s}{\lambda_p} + n_i(T) \frac{\lambda_i}{\lambda_p} + \frac{M}{2\pi R}. \tag{4}
\]

where \( \lambda_{p/s/i} \) and \( n_{p/s/i} \) denote the wavelengths and refractive indices for the pump, signal, and idler lights, respectively. In the simulation, we used the Sellmeier equation for congruent LN in Ref. [49] and its wavelength-dependent thermo-optic coefficient is also considered [50].

**REFERENCES**

[1] M. H. Dunn and M. Ebrahimzadeh, “Parametric generation of tunable light from continuous-wave to femtosecond pulses,” Science 286, 1513 (1999).

[2] D. D. Arslanov, M. Spunei, J. Mandon, S. M. Cristescu, S. T. Persijn, and F. J. M. Harren, “Continuous-wave optical parametric oscillator based infrared spectroscopy for sensitive molecular gas sensing,” Laser & Photonics Reviews 7, 188 (2013).

[3] L. Maidment, P. G. Schunemann, and D. T. Reid, “Molecular fingerprint-region spectroscopy from 5 to 12 µm using an orientation-patterned gallium phosphide optical parametric oscillator,” Opt. Lett. 41, 4261 (2016).

[4] U. L. Andersen, T. Gehring, C. Marquardt, and G. Leuchs, “30 years of squeezed light generation,” Physica Scripta 91, 053001 (2016).

[5] L. S. Madsen, V. C. Usenko, M. Lassen, R. Filip, and U. L. Andersen, “Continuous variable quantum key distribution with modulated entangled states,” Nat. Commun. 3, 1 (2012).

[6] T. Inagaki, K. Inaba, R. Hamerly, K. Inoue, Y. Yamamoto, and H. Takesue, “Large-scale Ising spin network based on degenerate optical parametric oscillators,” Nat. Photonics 10, 415 (2016).

[7] Y. Yamamoto, K. Aihara, T. Leleu, K.-i. Kawarabayashi, S. Kako, M. Fejer, K. Inoue, and H. Takesue, “Coherent Ising machines—optical neural networks operating at the quantum limit,” npj Quantum Information 3, 49 (2017).
[8] S. J. Herr, C. S. Werner, K. Buse, and I. Breunig, “Quasi-phase-matched self-pumped optical parametric oscillation in a micro-resonator,” Opt. Express 26, 10813 (2018).

[9] N. L. B. Sayson, T. Bi, V. Ng, H. Pham, L. S. Trainor, H. G. Schwefel, S. Coen, M. Ekinatalo, and S. G. Murdock, “Continuous-wave optical parametric oscillation tunable up to an 8 µm wavelength,” Optica 4, 189 (2017).

[10] X. Lu, G. Moille, A. Singh, Q. Li, D. A. Westly, A. Rao, S.-P. Yu, T. C. Bries, S. B. Papp, and K. Srinivasan, “Milliwatt-threshold visible–telecom optical parametric oscillation using silicon nanophotonics,” Optica 6, 1535 (2019).

[11] X. Lu, G. Moille, A. Rao, D. A. Westly, and K. Srinivasan, “On-chip optical parametric oscillation into the visible: generating red, orange, yellow, and green from a near-infrared pump,” Optica 7, 1417 (2020).

[12] M. A. Guidry, K. Y. Yang, D. M. Lukin, A. Markosyan, X. Lu, G. Moille, A. Singh, Q. Li, D. A. Westly, A. Rao, S.-P. Yu, T. C. Bries, S. B. Papp, and K. Srinivasan, “Milliwatt-threshold visible–telecom optical parametric oscillation using silicon nanophotonics,” Optica 6, 1535 (2019).

[13] Z. Hao, H. Li, Y. Luo, J. Yan, T. Wei, Y. Zhang, and Y.-P. Huang, “Ultra-bright quantum photon sources on chip,” (2020), arXiv:2012.05293 [physics.optics].
P. Seidler, “Integrated gallium phosphide nonlinear photonics,” Nat. Photonics 14, 57 (2020).
[39] A. G. Griffith, R. K. Lau, J. Cardenas, Y. Okawachi, A. Mohanty, R. Fain, Y. H. D. Lee, M. Yu, C. T. Phare, C. B. Poitras, A. L. Gaeta, and M. Lipson, “Silicon-chip mid-infrared frequency comb generation,” Nat. Commun. 6, 1 (2015).
[40] P. Del’Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, and T. J. Kippenberg, “Optical frequency comb generation from a monolithic microresonator,” Nature 450, 1214 (2007).
[41] L. Wu, H. Wang, Q. Yang, Q.-X. Ji, B. Shen, C. Bao, M. Gao, and K. Vahala, “Greater than one billion Q factor for on-chip microresonators,” Optics Lett. 45, 5129 (2020).
[42] F. K. Tittel, D. Richter, and A. Fried, “Mid-infrared laser applications in spectroscopy,” in Solid-state mid-infrared laser sources (Springer, 2003) pp. 458–529.
[43] Y. Zhao, Y. Okawachi, J. K. Jang, X. Ji, M. Lipson, and A. L. Gaeta, “Near-degenerate quadrature-squeezed vacuum generation on a silicon-nitride chip,” Phys. Rev. Lett. 124, 193601 (2020).
[44] M. Li, C.-L. Zou, C.-H. Dong, X.-F. Ren, and D.-X. Dai, “Enhancement of second-harmonic generation based on the cascaded second- and third-order nonlinear processes in a multimode optical microcavity,” Phys. Rev. A 98, 013854 (2018).
[45] A. W. Bruch, X. Liu, Z. Gong, J. B. Surya, M. Li, C.-L. Zou, and H. X. Tang, “Pockels soliton microcomb,” Nat. Photonics (2020), 10.1038/s41566-020-00704-8
[46] Y. He, Q.-F. Yang, J. Ling, R. Luo, H. Liang, M. Li, B. Shen, H. Wang, K. Vahala, and Q. Lin, “Self-starting bi-chromatic LiNbO3 soliton microcomb,” Optica 6, 1138 (2019).
[47] J. Feldmann, N. Youngblood, C. D. Wright, H. Bhaskaran, and W. H. P. Pernice, “All-optical spiking neuromorphic networks with self-learning capabilities,” Nature 569, 208 (2019).
[48] Y. Yamamoto, T. Leleu, S. Ganguli, and H. Mabuchi, “Coherent ising machines—quantum optics and neural network perspectives,” Applied Physics Letters 117, 160501 (2020) [https://doi.org/10.1063/5.0016140].
[49] D. E. Zelmon, D. L. Small, and D. Jundt, “Infrared corrected sellmeier coefficients for congruently grown lithium niobate and 5 mol.% magnesium oxide–doped lithium niobate,” J. Opt. Soc. Am. B 14, 3319 (1997).
[50] L. Moretti, M. Iodice, F. G. Della Corte, and I. Rendina, “Temperature dependence of the thermo-optic coefficient of lithium niobate, from 300 to 515 K in the visible and infrared regions,” J. Appl. Phys. 98, 036101 (2005).

Acknowledgements. This work is supported by Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Grant DE-SC0019406. The authors thank Michael Rooks, Yong Sun, Sean Rinehart, and Kelly Woods for assistance in device fabrication.

Competing interests. The authors declare no competing interests.