Ultralow-threshold thin-film lithium niobate optical parametric oscillator: supplement

JUANJUAN LU, 1 Ayed Al Sayem, 1 Zheng Gong, 1 Joshua B. Surya, 1 Chang-Ling Zou, 2 and Hong X. Tang 1,* 2

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, China
*Corresponding author: hong.tang@yale.edu

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Ultralow-threshold thin-film lithium niobate optical parametric oscillator: supplemental document

This document provides supplementary information to “Ultralow-threshold thin-film lithium niobate optical parametric oscillator”, presenting the design and fabrication details of the devices, and temperature optimization procedure for the optical parametric oscillation (OPO) measurement.

DEVICE DESIGN

The devices have a fixed radius of 70 µm and a width of 1.8 µm. The larger ring width and shallow etched geometry (180 nm thick slab) are chosen to mitigate the scattering losses from the sidewall roughness and thereby achieve high Q factor. A pulley coupling waveguide is designed to realize the efficient coupling at both the near-visible and infrared wavelengths, which has a width of 600 nm and is 400 nm away from the microring. The coupling design is elaborated in our previous work [1].

In order to realize the quasi-phase matching for OPO, a radial poling with an azimuthal number $M$, defined as $M = \frac{2\pi R}{\Lambda}$ with $\Lambda$ being the poling period, is designed to compensate the momentum mismatch between the pump, signal and idler modes. Assuming that all three interacting waves are perfectly resonant, the energy and momentum conservation conditions could be written as:

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}, \quad (S1)$$

$$\frac{2\pi R n_{\text{eff}}(\lambda_p, T)}{\lambda_p} = \frac{2\pi R n_{\text{eff}}(\lambda_s, T)}{\lambda_s} + \frac{2\pi R n_{\text{eff}}(\lambda_i, T)}{\lambda_i} + M, \quad (S2)$$

where $\lambda_{p/s/i}$ denote the respective wavelength of the pump, signal, and idler lights. $n_{\text{eff}}$ is the effective refractive index of the cavity mode as a function of the wavelength and temperature. Considering the degenerate case, where $\lambda_s = \lambda_i$, we derive that $M = \frac{4\pi}{\lambda_s} [n_{\text{eff}}(\frac{\lambda_s}{2}, T) - n_{\text{eff}}(\lambda_s, T)]$. Using a commercial finite-difference-eigenmode solver (Lumerical MODE), the simulated $M$ versus the phased-matched parametric oscillation wavelengths at different temperatures are plotted in Fig. S1. In the simulation, we used the Sellmeier equation for congruent LN in Ref. [2].

![Fig. S1](image_url)

**Fig. S1.** The simulated poling azimuthal number is plotted against the phased-matched wavelengths at different temperatures for the degenerate parametric oscillation. A poling grating number $M$ of 146 is designed to realize the quasi-phase matching between the 1550 nm and 775 nm lights at an elevated temperature around 140 °C. The inset illustrates the cross-sectional view of the microring indicating the key geometric parameters.
and its wavelength-dependent thermo-optic coefficient is also considered [3]. We note that, for a fixed \( M \), the phase-matched wavelength decreases with the increasing temperature. Hence, a \( M \) of 146 is intentionally chosen to realize the quasi-phase matching between 1550 nm and 775 nm lights at an elevated temperature around 140 °C. Moreover, high operating temperature helps mitigate the inherent photorefractive (PR) effect of the lithium niobate [4].

With respect to a general quasi-phase-matched OPO including the non-degenerate case, its parametric signal and idler wavelengths as a function of the pump wavelength and temperature are numerically investigated based on Eqs. S1 and S2. For a poling grating number \( M \) of 146 used in this work, the simulation results are presented in the middle panel of Fig. 3 in the main text.

**FABRICATION METHOD**

The devices are fabricated on a commercial LNOI wafer (supplied by NANOLN) with 610 nm thick Z-cut LN thin film on 1.8 \( \mu \)m silicon dioxide (SiO\(_2\)) on a silicon substrate. The bus waveguide is ultimately tapered to a width of 4 \( \mu \)m 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. The exposed pattern is transferred onto the LN thin film using an optimized inductively couple plasma (ICP) reactive ion etching (RIE) process with Ar\(^{+}\) plasma.

For the subsequent poling process, the concentric nickel electrodes are initially patterned on top of the LN microring via the lift-off process, as shown in Fig. S2(a). The periodic domain inversion is then enabled by keeping the silicon substrate as the electrical ground while applying two 600 V, 250 ms pulses on the electrodes at an elevated temperature of 250 °C. The poling pulse shape is plotted in Fig. S2(b). After removing the nickel electrodes, Fig. S2(c) presents an optical image of the poled lithium niobate microring devices. Finally, 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.

**Fig. S2.** (a) Optical image of the etched microring with the concentric poling electrodes. (b) Poling pulse profile. (c) Optical image of the fabricated PPLNMR devices.

**TEMPERATURE OPTIMIZATION PROCEDURE**

By pumping with telecom light, we firstly identified the frequency matching window via the second-harmonic generation (SHG, the reversal process of degenerate OPO). As indicated in Fig. S3(a), the coarse temperature tuning is secondly implemented to vary the frequency matching window over a wide range. A temperature increase of 120 °C leads to a \( \sim 70 \) nm blue-shift of the phase-matched wavelength, in good agreement with the simulation results [Fig. S1]. Correspondingly, when sweeping a pump laser across a number of near-visible resonances, parametric oscillations were observed from the resonances, whose power threshold is lower than the pump power due to their relatively smaller frequency mismatch [Fig. S3(b)].

The temperature is then precisely controlled at intervals of 0.02 °C to optimize the SHG efficiency for a selected mode. This minimizes the resonance frequency mismatch for the degenerate OPO. The corresponding second-harmonic mode at the near-visible wavelength is finally probed by varying the pump power to detect the lowest OPO threshold. In principle, reversing optimized SHG should automatically satisfy the degenerate OPO phase matching. However, in the experiments, this process only brings us to near degenerate as shown in Fig. 2, due to PR-induced resonance drift arising from a stronger visible pump. By further fine tuning the temperature, the degenerate case could be recovered.
Fig. S3. (a) The frequency matching window is identified via the second harmonic generation and varied by the temperature tuning experimentally. The shaded region corresponds to the attainable pump wavelengths (New Focus TLB-6712, 766-781nm) for the parametric oscillation. (b) Parametric oscillations were observed from different wavelength windows as different temperatures when sweeping a pump laser across a number of near-visible resonances, which are consistent with the SHG measurement (a).

REFERENCES