Efficient Frequency Doubling with Active Stabilization on Chip

Jia-Yang Chen,* Chao Tang, Mingwei Jin, Zhan Li, Zhaohui Ma, Heng Fan, Santosh Kumar, Yong Meng Sua, and Yu-Ping Huang*

Thin-film lithium niobate (TFLN) is superior for integrated nanophotonics due to its outstanding properties in nearly all aspects: strong second-order nonlinearity, fast and efficient electro-optic effects, wide transparency window, and little two photon absorption and free carrier scattering. Together, they permit highly integrated nanophotonic circuits capable of complex photonic processing by incorporating disparate elements on the same chip. Yet, there has to be a demonstration that synergizes those superior properties for system advantage. Here, such a chip that capitalizes on TFLN’s favorable ferroelectricity, high second-order nonlinearity, and strong electro-optic effects is demonstrated. It consists of a monolithic circuit integrating a Z-cut, quasi-phase matched microring with high quality factor and a phase modulator used in active feedback control. By Pound–Drever–Hall locking, it realizes stable frequency doubling at about 50% conversion with only milliwatt pump power. This demonstration addresses a long-outstanding challenge facing cavity-based optical processing, including frequency conversion, frequency comb generation, and all-optical switching, whose stable performance is hindered by photorefractive or thermal effects. These results further establish TFLN as an excellent material capable of optical multitasking, as desirable to build multi-functional chip devices.

1. Introduction

The efficiency of photonic integrated circuits can be elevated by orders of magnitude through cavity enhancement, giving rise to ultra-efficient frequency doubling,[1–3] optical parametric oscillation,[4–6] frequency comb generation,[7–9] quantum photon sources,[10,11] and quantum frequency conversion.[12] They promise future chip devices capable of classical and quantum optical processing at large scale and with high modularity. However, any cavity enhancement necessarily comes at the price of aggravated photorefractive (PR) and thermal effects, which challenges, if not preventing, achieving the device’s due performance over time. For example, thin-film lithium niobate (TFLN) microrings can achieve ultrahigh normalized efficiency for second-harmonic generation (SHG), with $\eta_{\text{nor}} = \frac{P_{\text{sh}}}{P_{\text{p}}}$ ($P_{\text{p}}$ being the pump [second-harmonic] power on chip) exceeding 100% mW–1.[1–3,11] There are two performance bottlenecks in previous demonstrations. One is the extraction efficiency, which fundamentally limits the achievable high conversion efficiency.[13,14] The other is the device instability included by thermal and PR effects, which occurs over a fast-time scale from 100 µs to 10 ms. These deficiency and instability must be overcome before cavity-enhanced TFLN devices can be deployed for practical applications.

Here, we demonstrate a scalable and overhead-friendly approach to overcoming low extraction efficiency and the detrimental PR and thermal effects in an over-coupled cavity. The schematic of our device is shown in Figure 1a. Aiming specifically at testing the prospect of creating highly integrated and self-stabilized TFLN devices, we incorporate the cavity with a phase modulator on the same chip. Thanks to TFLN’s exceptional ferroelectric, nonlinear optical, and electro-optic properties, we achieve $(58 \pm 3)$% on-chip SHG efficiency with $(3.4 \pm 0.1)$ mW pump power, presenting new progress among all nanophotonic platforms at such milliwatt level driving power.[1,2,5,11,15–17] Assisted by the on-chip phase modulator, we demonstrate stable SHG with conversion efficiency around 50% for about 30 min by PDH locking. This is an essential step toward practical nonlinear and quantum photonics applications based on lithium niobate microring devices.

2. Device Design and Fabrication

To maximize the conversion efficiency ($\eta_{\text{nor}}$), one will need to improve the extraction efficiency (i.e., the microring to waveguide coupling) for the periodic poled lithium niobate (PPLN) microring. Considering the pump depletion case and assuming...
Figure 1. Integrated TFLN circuits for frequency doubling and stabilization. a) Schematic consisting of an electro-optic phase modulator and a Z-cut, periodically poled microring. High-speed modulation signal (\(\omega \pm \Omega\)) is applied on the electrodes to generate sidebands around the pump’s carrier frequency (\(\omega \pm \Omega\)). The modulated pump then passes through the microring to generate error signal with an off-chip detector and electronic circuits for feedback control. A pulley coupler is designed for efficient coupling both infrared and visible band. In the same microring, the pump could also efficiently generate second-harmonic light at \(2\omega\) via \(\chi^{(2)}\) parametric conversion. b) The microscope image for the electrodes on top of the fabricated structures. c,d) The SEM images of the etched pulley coupler before poling process and the poled microring structure after removing the poling electrodes, respectively.

In the absence of cavity detuning, the maximum conversion efficiency for SHG process is given by [2, 18]:

\[
\eta_{\text{con,max}} \approx \frac{Q_{\text{L,p}} Q_{\text{m,L}}}{Q_{\text{p,c}} Q_{\text{L,c}}} \tag{1}
\]

where \(Q_{m,n}\) is the quality factor, with \(m=p, \text{sh}\) standing for the pump and second-harmonic cavity modes, respectively, and \(n=c,L\) denoting the coupling and loaded \(Q\). The maximum conversion efficiency can be reached at pump power of [2, 18]:

\[
P_p = 16 \frac{\eta_{\text{con,max}}}{\eta_{\text{nor}}} \tag{2}
\]

Thus, high normalized efficiency \(\eta_{\text{nor}}\) (e.g., \(\approx 150\% \text{ mW}^{-1}\)) is important to achieve high efficiency \(\eta_{\text{con}}\) (e.g., \(\approx 60\%\)) with only milliwatt pump power. To that end, we follow the design flow: First, for quasi phase matching, concentric periodic-poling (see Figure 1d; detailed in Section SB, Supporting Information) is applied to the microring resonator to attain the strongest possible interaction between the fundamental quasi-transverse-magnetic (quasi-TM) cavity modes in both infrared (IR) and visible bands, by realizing ideal mode overlapping and utilizing the largest nonlinear tensor \(\alpha_{33}\) in lithium niobate. Second, after determining the width of the ring, we optimize the dimensions of the pulley coupler to satisfy over-coupling condition for both IR and visible cavity modes, as Equation (1) requires. (See Figure 1c; detailed in Section SA, Supporting Information). Third, to stabilize SHG in high pump power region, we integrate an on-chip phase modulator (see Figure 1b; detailed in Section SB, Supporting Information) driven by a gigahertz radio wave, by taking advantage of TFLN’s largest electro-optic tensor \(r_{13}\) to create error signal for feedback control.

3. Experimental Results

3.1. Second-Harmonic Generation in a PPLN Microring Resonator

We first characterize the linear optical properties of the device. As shown in Figure 2b, two polarized tunable lasers (Santec 550, 1500–1630 nm and Newport TLB-6712, 765–781 nm) and tapered fibers (OZ OPTICS) are used to independently characterize fiber-chip-fiber coupling, whose losses are measured to be (17 ± 0.15) dB around 1560 nm and (16 ± 0.2) dB around 780 nm, respectively. Using the same setup, we obtain the loaded (\(Q_L\)), coupling (\(Q_c\)), and intrinsic (\(Q_0\)) quality factors for both bands, where \(Q_L (Q_c, Q_0) \approx 1.5(2.1, 5.0) \times 10^5\) for the IR mode and \(Q_L (Q_c) \approx 0.6(0.67, 5.6) \times 10^5\) for the visible mode, as shown in Figure 3a,b. According to Equation (1), over-coupled condition at both wavelengths are essential to achieve high conversion efficiency. For the current device, the highest possible conversion efficiency is \(\eta_{\text{con,max}} = 64\%\). For near unity efficiency, the cavity needs to be further overcoupled for both the visible and IR modes.

We then characterize the device’s nonlinearity using second-harmonic generation. By sweeping the infrared pump laser and fine tuning the device’s temperature, a quasi-phase matched SHG is achieved for optimal resonance modes at 1561.4 nm and its second-harmonic at 780.7 nm around 75.4 °C. The temperature dependency of the SHG efficiency shows an error tolerance...
of 1.1 °C. To extract the normalized and conversion efficiency, we gradually increase the on-chip pump power from microwatt to milliwatt level, as shown in Figure 3c. In the undepleted region, the normalized SHG efficiency $\eta_{\text{nor}}$ is estimated to be $(137,000 \pm 8100)\%/W$. In the depleted region, on-chip SHG efficiency $\eta_{\text{con}}$ saturates at about $(58 \pm 3)\%$ with about $(3.4 \pm 0.1)\text{ mW}$ on-chip pump power after correcting for the coupling loss. With high conversion efficiency ($\approx 60\%$) achieved at low pump power ($\sim \text{mW}$), our device is outstanding for quantum frequency conversion and beyond, promising ultrahigh efficiency and noise as desirable for system integration.\cite{12,19}

Although the conversion efficiency for the current device can theoretically reach 64%, in practice, the attainable $\eta_{\text{con}}$ is limited by system coupling instability. Besides, the thermal and PR effects\cite{20} could also exert difficulties in accessing those high conversion regime requiring high pump power. When the on-chip pump power is relatively high (e.g., over few hundreds of microwatts in this device), the light-induced static space-charge electric field $E_{\text{sc}}$ will modify both the cavity resonance and quasi-phase matching condition via refractive index change through $\Delta n = -(1/2)n_r^3r_{33}E_{\text{sc}}$.\cite{21} Although new quasi-phase matching condition could be satisfied via fine tuning device’s temperature, the resonance drifting (occurring at a time scale from $100\mu\text{s}$ to $10\text{ms}$) may not be mitigated by self-locking depending on the competition between thermal and photorefractive effect.\cite{8} This calls for an active fast feedback control with bandwidth over $100\text{kHz}$ to stabilize the highly efficient nonlinear conversion process amid the aforementioned effects. To this end, PDH locking is one of the popular methods for optical cavity stabilization.\cite{22}

The primary challenge in implementing PDH stabilization, however, is with the need for high-speed phase modulation, whose bandwidth must be comparable or larger than cavity linewidth (about GHz level). Fortunately, this requirement is well accommodated in thin-film lithium niobate, for its superior nonlinear and electro-optic properties. It allows to integrate the essential optical components, that is, high-speed phase
modulator and efficient frequency conversion microring, on the
same chip. In the next section, we will describe in detail the
feedback control and resulting performance.

3.2. PDH Error Signal Generation with Integrated Phase
Modulator

Different from electric-optic modulation using X-cut TFLN,\(^{[23]}\)
we devise a new electrode configuration for Z-cut orientation
wafer, so as to access its largest electro-optic coefficient \(r_{33}\). As
shown in Figure 4a, we employ a ground-signal-ground (GSG)
scheme rather than the standard ground-signal scheme to en-
hance our modulation by 1.3 times, where the signal pad is placed
on top of the LN waveguide and the two ground pads located
on each side. According to the electrical field simulation using
COMSOL Multiphysics, the voltage-length product \((V_x \times cm)\) is
estimated to be about 10 V\(\times\)cm, which is comparable to com-
mercial products (e.g., Thorlab \(V_x \times cm > 20 V \times cm\)). With
this integrated phase modulator, we reduce the system complexity
and avoid insertion loss that is typically 4 to 5 dB. Mean-
while, high-frequency operation is important for current cavity
linewidth (1.25 GHz for \(Q_c \approx 1.5 \times 10^5\)). To characterize the elec-
trical properties of the RF electrodes, we measure the S21 and S11
parameters using a 3-GHz vector network analyzer (VNA: Agilent
8714ES). As shown in Figure 4b,c, it indicates good impedance
matching of the electrodes through 1 GHz, as limited by our VNA
bandwidth. Then, we use the experiment setup in Figure 2a to ex-
amine the PDH error signal. As shown in Figure 4c, clear PDH
error signal is observed when the telecom laser is swept across
the resonance around 1561.3 nm. The \(+1.5 V\) triangle shape mod-
ulation signal is generated via the Lockbox.\(^1\) (Detailed in Section
SC, Supporting Information.) This indicates our on-chip phase
modulator is functioning properly and ready for the following
locking experiment.

3.3. Stabilization of Efficient Second-Harmonic Generation

The tight mode confinement and high quality factor of the
PPLN microring are the key to achieving 60% conversion ef-
iciency with only milliwatt pump power. However, these two
also enhance the undesirable PR and thermal effects during the
nonlinear process. This is because the intracavity light intensity
is largely boosted to generate strong electrical field, resulting in
detrimental space-charge electric field \(E_{sc}\). To study the PR
effect on SHG, we bidirectionally scan the telecom laser across
the phase matching resonance and monitor the telecom and
visible transmission spectra, as shown in Figure 5. Meanwhile,
to prepare for the locking, we also monitor the PDH error signal.
At the scanning speed 6 nm s\(^{-1}\), we observe the PR effect when
on-chip laser power is above -4.5 dBm (see Figure 5d,e). Accord-
ing to its response under bidirectional scanning, we confirm
that the PR effect dominates the thermal effect\(^{[21]}\) with on-chip
power up to +3.5 dBm. Note that, here the threshold of the PR
effect is over 10 times higher than previous reported results in
X-cut LN microring at a similar scanning speed.\(^{[25]}\) This could
be explained by different orientations of LN wafers are used, a
higher chip temperature (75 °C), or the over-coupling condition
for cavity modes, but a future study is needed.

From the PDH error signal in Figure 5, we find that the dy-
namic range of the PR effect is on the order of millisecond, which
agrees with previous studies.\(^{[21]}\) The induced frequency shift
(~GHz) is within the laser piezo fine-tuning range (~8 GHz), as
indicated in the same figure, even at very high pump power level.
Besides, with faster scanning (GHz \(\mu s\)\(^{-1}\) through the amplitude
modulation port of Santec laser, the PR-induced frequency shift
is suppressed well within laser’s tuning range (~1 GHz). This is
essential as the tuning bandwidth need to be a few times larger
than PR-induced frequency shift. In order to achieve high PDH
locking performance, we use the amplitude modulation port of
the laser whose speed can reach 400 kHz. To stabilize the in-
put pump power (within ±2% variation) over the locking process
(Reference 1 curve in Figure 6b), we flatten the modulated laser
power by using an EDFA with the fixed output, as shown in Fig-
ure 2. We also add the reference laser (1559.8 nm, off resonance)
serving as the monitor for the fiber-chip-fiber coupling. For SHG
locking process, we manually approach the resonance from red to blue
and start the engaging when close to the resonance. If there is no
locking engaged, the SHG process will quickly drift (seconds to
tens of seconds) after reaching to its maximum efficiency. With
active locking, as shown in Figure 6, the conversion efficiency
is stabilized between 54% and 50% for the first 10 min. Later,
because of the coupling instability (drop by 6% in the following
20 min) indicating by Reference 2 curve in Figure 6b, the conver-
sion efficiency starts to gradually drop to about 46% in 30 min. We
Figure 5. The normalized transmission spectra with various on-chip pump power for telecom cavity mode (top black line), the SH light (middle red line), and the PDH error signal (bottom cyan line) at a fix scanning speed of 6 nm s\(^{-1}\).

Figure 6. a) The normalized power of telecom pump (black line), SH light (red line), and the required voltage for the feedback signal (blue line). The locking is engaged after manually tuning the pump close to the cavity resonance. The initial conversion efficiency is 54% with 2.1 mW on-chip pump power. b) The normalized power of input pump laser light (Reference-1 by PM-1) and the reference laser light (Reference-2 by PM-3) after fiber-chip-fiber coupling. c) Allan variance \(\sigma^2(\tau)\) of the generated SH power (unit in \(\mu\)W).

have also shown the Allan variance \(\sigma^2(\tau)\) of the generated SH power (unit in \(\mu\)W) in Figure 6c. To further improve the long term stability of our system, another feedback loop to the EDFA could be implemented to stabilize the on-chip pump power against the drifting of the coupling. Besides, an additional phase modulation component could be added on top of the microring to achieve frequency tuning\(^{[26]}\) to replace current frequency tuning by the external laser.

4. Conclusion

In summary, we have demonstrated highly efficient and actively stabilized frequency doubling, through the optimally integrating a Z-cut phase modulator and a PPLN microring on the same chip, with simultaneous overcoupling for both fundamental and second harmonic modes. This stabilized SHG microring could find immediate applications in quadratic soliton combs generation\(^{[27]}\).
with appropriate dispersion engineering. Although we have only demonstrated the stabilized SHG here, one could slightly modify the device configuration to achieve the stabilized sum-frequency generation or difference frequency generation by either locking the telecom or the visible cavity modes. Overall, enabled by TFLN’s ferroelectricity, strong second-order nonlinearity, and excellent electro-optic property, such monolithically integrated devices will serve for practical quantum frequency conversion, frequency comb generation, and quantum photon sources, where power efficiency, good scalability, and long stability are the key.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
Thanks for Mingming Nie’s suggestions on the PDH locking implementation. The research was supported in part by the National Science Foundation (Award #1641094 and #1842680) and the National Aeronautics and Space Administration (Grant Number 80NSSC19K1618). Device fabrication was performed in Nanofabrication Facility at the Advanced Science Research Center (ASRC), City University of New York (CUNY).

Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
Data available on request from the authors.

Keywords
integrated photonics, lithium niobate, nonlinear optics, Pound–Drever–Hall

[1] J.-Y. Chen, Z.-H. Ma, Y. M. Sua, Z. Li, C. Tang, Y.-P. Huang, Optica 2019, 6, 1244.