Cavity-enhanced optical parametric generation in a modal-phase-matched lithium niobate microring

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Abstract: We report cavity-enhanced second-harmonic generation and difference-frequency generation in a high-Q lithium niobate microring resonator with modal phase matching. The second-harmonic generation efficiency is measured to be 1,500% W^{-1}.

OCIS codes: (130.3730) Lithium niobate; (130.3990) Micro-optical devices; (190.4410) Nonlinear optics, parametric processes.

Lithium niobate (LN) has recently attracted remarkable attentions in integrated photonics, due to its wide transparency window and strong quadratic optical nonlinearity. A variety of nanophotonic systems, including waveguides [1–5], microdisks [6–8], microrings [9, 10], and photonic crystal cavities [11, 12], have been studied for optical parametric processes in LN. In particular, cavity-enhanced nonlinear wavelength conversion has been demonstrated in doubly/triply resonant LN microresonators via a variety of phase-matching approaches [6–10]. However, the potential of the LN integrated platform has not yet been fully explored for efficient nonlinear parametric processes, and current devices demonstrate only moderate efficiencies far from what LN can provide. Here, we report optical parametric generation in a high-Q Z-cut LN microring resonator through exact modal phase matching. The device exhibits optical Q's of $\sim 10^5$ for the designed cavity modes in the 1550 and 780 nm bands, and both modes are well coupled to a single bus waveguide, enabling us to conveniently measure a second-harmonic generation (SHG) efficiency of 1,500% W^{-1}. In addition, we are also able to observe difference-frequency generation (DFG) in the telecom band. Our work shows the great promise of modal-phase-matched LN microresonators for efficient optical parametric generation.

To utilize the largest nonlinear term d_{33}, the cross-section of the microring was designed for phase matching between the fundamental quasi-transverse-magnetic mode (TM_{00}) at 1550 nm and a high-order mode TM_{20} at 775 nm, on a Z-cut LN-on-insulator wafer. Figure 1(a) presents the simulated effective indices of optical modes in a straight waveguide, which shows that for a thickness of 600 nm, modal phase matching happens for TM_{00} at 1550 nm and TM_{20} at 775 nm when the waveguide width is about 690 nm. The inset of Fig. 1(b) shows a fabricated microring

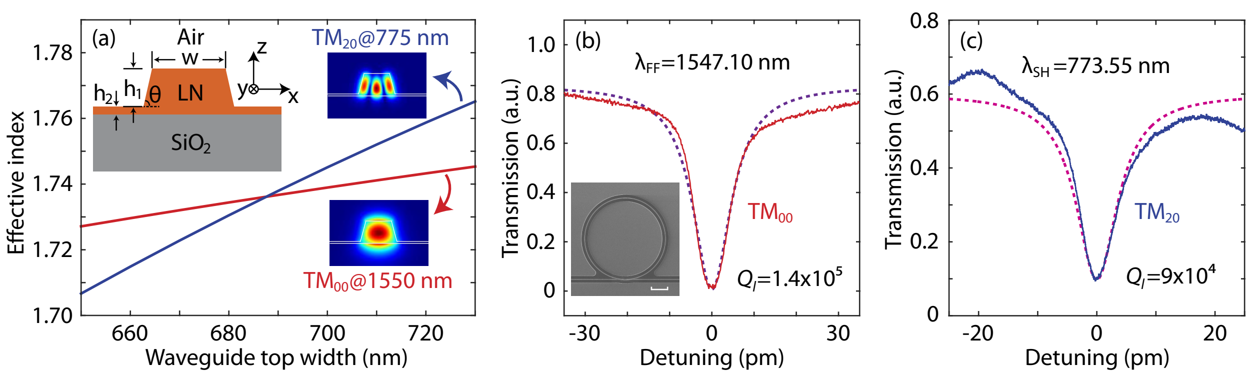

Fig. 1. (a) Numerically simulated effective indices of TM_{00} at 1550 nm and TM_{20} at 775 nm, as functions of the top width w of a straight waveguide. Other waveguide parameters are h_1=550 nm, h_2=50 nm, and θ=75°. (b) and (c) Transmission spectra of the two phase-matched modes. The inset of (b) shows an SEM image of the employed microring, with the scale bar representing 20 μm.

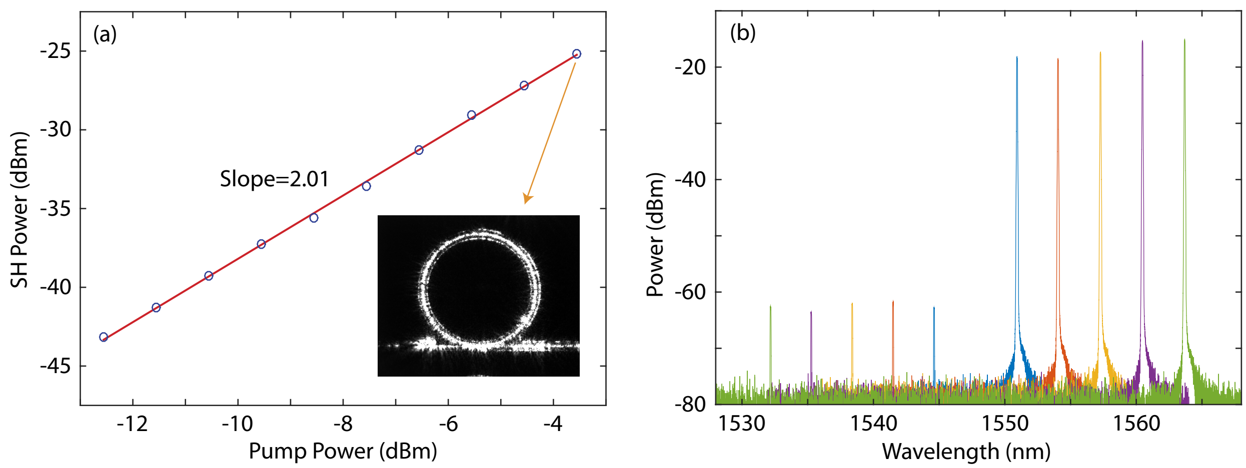

Fig. 2. (a) Power dependence of SHG. The measured conversion efficiency is 1,500% W^{-1}. The inset shows an optical image of generated SH light scattered from the microring, with a pump power of 440 μW at the FF mode. (b) DFG spectra, with a pump power of 6.6 μW at the SH mode.

resonator with a radius of 50 μm, coupled to a pulley waveguide. The top width of the bus waveguide is ∼200 nm, the gap (measured at the top surface of LN) is ∼350 nm, and the coupling length is ∼20 μm. The FF mode at 1547.10 nm is almost critically coupled, with a coupling depth of ∼99% and a loaded optical Q of 1.4×10^5 [see Fig. 1(b)]. The SH mode at 773.55 nm is under-coupled, with a coupling depth of ∼83% and a loaded optical Q of 9×10^4 [see Fig. 1(c)]. The fiber-to-chip coupling losses are about 6.9 and 11.4 dB/facet for the FF and SH modes, respectively.

To study SHG, we launched pump power into the FF mode at 1547.10 nm, and observed strong scattering of generated NIR light from the resonator by an optical microscope, with an example shown in the inset of Fig. 2(a). By varying the pump power, we obtained the power dependence of the SHG, as shown in Fig. 2(a). The experimental data exhibit a quadratic relation between the generated SH power and the FF pump power, with a measured conversion efficiency of 1,500% W^{-1}.

The measured efficient SHG validated phase matching in our microring, and also indicated its capability of other parametric processes. In order to explore this, we launched power in both the SH mode, and one of the modes near the FF mode. Figure 2(b) presents the recorded spectra in the telecom band. With only 6.6 μW of on-chip power at the SH mode, we were able to convert long-wavelength telecom light coherently into shorter wavelengths through DFG. The long-wavelength pump power launched on chip was 105 μW, and the generated power at the difference frequencies was about 480 pW, indicating a conversion rate of about -53 dB.

In conclusion, we have demonstrated cavity-enhanced optical parametric generation in an LN microring with modal phase matching. We have used a single bus waveguide to conveniently couple the FF and SH modes, both showing coupling depths over 80% and exhibiting loaded optical Q's around 10^5, resulting in a measured conversion efficiency of 1,500% W^{-1} for SHG. In addition, we have also observed DFG in the telecom band. Our work represents an important step towards ultra-highly efficient optical parametric generation in LN integrated photonic circuits.

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References

1. R. Geiss *et al.*, Opt. Lett. **40**, 2715 (2015).
2. L. Chang *et al.*, Optica **3**, 531 (2016).
3. C. Wang *et al.*, Opt. Express **25**, 6963 (2017).
4. R. Luo, *et al.*, Optica **5**, 1006 (2018).
5. C. Wang, *et al.*, Optica **5**, 1438 (2018).
6. C. Wang *et al.*, Opt. Express **22**, 30924 (2014).
7. J. Lin *et al.*, Phys. Rev. Appl. **6**, 014002 (2016).
8. R. Luo *et al.*, Opt. Express **25**, 24531 (2017).
9. R. Wolf *et al.*, Optica **5**, 872 (2018).
10. J.-Y. Chen *et al.*, OSA Continuum **1**, 229 (2018).
11. H. Jiang *et al.*, Appl. Phys. Lett. **113**, 021104 (2018).
12. M. Li *et al.*, arXiv:1806.04755 (2018).