

Nearly vertically emitted nonlinear light sources with high efficiencies enabled by high-Q nearly-degenerate polygon modes

Chuntao Li, Yingnuo Qiu, Renhong Gao, Lingling Qiao, Jielei Ni*, Min Wang, Jintian Lin* and Ya Cheng*

Citation: Li CT, Qiu YN, Gao RH et al. Nearly vertically emitted nonlinear light sources with high efficiencies enabled by high-Q nearly-degenerate polygon modes. *Opto-Electron Technol* **2**, 260011 (2026).

<https://doi.org/10.29026/oet.2026.260011>

Received: 31 March 2026; Accepted: 29 June 2026; Published online: 2 September 2026

Related articles

High fiber-to-fiber net gain in erbium-doped thin film lithium niobate waveguide amplifier as an external gain chip

Jinli Han, Mengqi Li, Rongbo Wu, et al

Opto-Electronic Science 2025, **4**(9): 250004 doi: [10.29026/oes.2025.250004](https://doi.org/10.29026/oes.2025.250004)

Narrow beam and low-sidelobe electro-optic beam steering on thin-film lithium niobate optical phased array

Yang Li, Shiyao Deng, Xiao Ma, et al

Opto-Electronic Science 2026, **5**(2): 260002 doi: [10.29026/oes.2026.260002](https://doi.org/10.29026/oes.2026.260002)

Ferroelectric domain engineering of Lithium niobate

Jackson J. Chakkoria, Aditya Dubey, Arnan Mitchell, et al

Opto-Electronic Advances 2025, **8**(2): 240139 doi: [10.29026/oea.2025.240139](https://doi.org/10.29026/oea.2025.240139)

Strong-confinement low-index-rib-loaded waveguide structure for etchless thin-film integrated photonics

Yifan Qi, Gongcheng Yue, Ting Hao, et al

Opto-Electronic Advances 2025, **8**(9): 250056 doi: [10.29026/oea.2025.250056](https://doi.org/10.29026/oea.2025.250056)

More related articles in Opto-Electronic Journals Group website



Nearly vertically emitted nonlinear light sources with high efficiencies enabled by high-Q nearly-degenerate polygon modes

Chuntao Li^{1,2}, Yingnuo Qiu^{3,4}, Renhong Gao², Lingling Qiao³, Jielei Ni^{5*}, Min Wang², Jintian Lin^{3,4*} and Ya Cheng^{1,2*}

Abstract: Vertically emitted integrated light sources, typically constrained to a narrow bandwidth, play a pivotal role in optical displays, telecommunications, integrated quantum information processing, and terahertz photonics. Achieving transversely emitted nonlinear light sources with high efficiency is essential for extending the integrated coherent emission wavelength and facilitating the interface between free space optics and photonic integrated circuits. However, this remains challenging due to the difficulty in transverse phase matching. In this work, nearly vertically emitted light signal is observed in a thin-film lithium niobate (TFLN) microresonator by exciting high-Q nearly-degenerate square modes. Such modes are formed in the TFLN microresonator by introducing weak perturbation by a tapered fiber, significantly enhancing Rayleigh backscattering of the forward pump light, and simultaneously facilitating nonlinear interactions with high mode field overlap factors. Under pumping the high-Q square mode with a unidirectionally injected continuous-wave laser at 1555 nm, bi-directionally propagating stimulated Raman scattering (SRS) signals are generated at 1721 nm, achieving threshold powers as low as 0.43 mW and high conversion efficiencies up to 32%. Furthermore, a nearly vertically emitted nonlinear light source at 817 nm is demonstrated via transverse-phase matched sum-frequency generation between the pump and SRS signals in the counter-propagating configuration, attaining a conversion efficiency of 0.272%/mW. This transverse-phase matching nonlinear interaction in counterpropagating configuration not only effectively extends the spectral coverage of vertically emitted integrated light sources, but also advances the development of the integrated classical and quantum light sources.

Keywords: thin-film lithium niobate; stimulated Raman scattering; sum-frequency generation; phase matching; optical microresonator

DOI: [10.29026/oet.2026.260011](https://doi.org/10.29026/oet.2026.260011) | CSTR: [32419.14.oet.2026.260011](https://cstr.cn/32419.14.oet.2026.260011)

Citation: Li CT, Qiu YN, Gao RH et al. Nearly vertically emitted nonlinear light sources with high efficiencies enabled by high-Q nearly-degenerate polygon modes. *Opto-Electron Technol* **2**, 260011 (2026).

1 Introduction

Vertically emitted integrated light sources, such as vertical-cavity surface-emitting lasers¹, offer high brightness and have been recognized as essential components in optical displays, telecommunications, integrated quantum light sources, photonic integrated circuits, and terahertz photonics²⁻⁶.

Their emission wavelengths, however, are typically constrained by the limited gain bandwidth of the semiconductor materials, resulting in a narrow operating range. In particular, vertically emitted integrated light sources operating around 810 nm which is a wavelength highly sought after for precision atomic, molecular and optical (AMO) physics, related quantum technologies, and laser surgery,

Received: 31 March 2026

Accepted: 29 June 2026

Published online: 2 September 2026

¹State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200062, China; ²The Extreme Optoelectromechanics Laboratory (XXL), School of Physics, East China Normal University, Shanghai 200241, China; ³State Key Laboratory of Ultra-Intense Laser Science and Technology, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China; ⁴University of Chinese Academy of Sciences, Beijing 100049, China; ⁵Nanophotonics Research Center, Institute of Microscale Optoelectronics & State Key Laboratory of Radio Frequency Heterogeneous Integration, Shenzhen University, Shenzhen 518060, China.

*Correspondence: JL Ni, E-mail: nijielei@szu.edu.cn; JT Lin, E-mail: jintianlin@siom.ac.cn; Y Cheng, E-mail: ya.cheng@siom.ac.cn

remain scarce^{7–9}.

Nonlinear optical frequency convertors have been extensively used to extend the emission wavelength in both the benchtop and integrated optical systems^{10–14}, and could in principle enhance the emission bandwidth of the vertically emitted light sources. Yet the incorporation of such convertors with vertically emitted integrated light sources on a single chip remains exceptionally challenging, primarily due to the difficulties in heterogeneous integration of semiconductor materials and optical crystalline materials.

To address this issue, recent efforts have utilized high-*Q* whispering gallery microresonators to generate octave-spanning nearly vertically emitted nonlinear light sources on thin-film lithium niobate (TFLN) platforms¹⁵, leveraging stimulated Raman scattering (SRS) and second-order nonlinear processes in TFLN microresonators through a transverse phase matching configuration assisted by self-organized photorefractive gratings (SPGs). It is worth noting that the outstanding material properties featuring large second-order nonlinearity ($d_{33} \sim 27$ pm/V), strong Pockels effect, large band gap, wide transparency window (0.35–5 μm), and tight optical confinement have endowed TFLN as one of the most important photonic platforms, which lay the foundation for extending spectral coverage of the integrated vertical-cavity surface emitting light sources enabled by nonlinear frequency conversion and electro-optic tuning. Despite this progress, nonlinear interaction between the pump laser and the generated SRS in a counter-propagating configuration has not yet been demonstrated. In addition, light emission around 810 nm remains unattainable, and the accessible spectral coverage of vertical nonlinear light emission was sparse. Moreover, the heavy dependence on cascaded SRS processes considerably increases experimental complexity, thereby restricting the practical applicability of this approach.

In this work, a transverse-phase matching nonlinear interaction in a counterpropagating configuration is employed to overcome this issue^{16,17}. High-*Q* nearly-degenerate square modes are coherently induced in an X-cut TFLN microdisk resonator through weak perturbation introduced by coupling with a tapered fiber^{18,19}, which significantly enhances Rayleigh backscattering of unidirectionally injected pump light and facilitates nonlinear interaction with high mode field overlap factors (>80%)^{19,20}. Under pumping of the square mode at 1555 nm, counter-propagating pump signals are observed, which further trigger SRS process in the microresonator. Forward and backward SRS signals are observed at 1721 nm with a low threshold of 0.43 mW. Furthermore, a nearly vertically emitted light source at 817 nm is realized via transverse-phase matched sum-frequency generation between the pump and the SRS signals in counterpropagating configuration, achieving a conversion efficiency of 0.272%/mW. This result will facilitate the construction of highly efficient nonlinear optical light sources with extended spectral coverage and broadened photonic applications.

2 Demonstration of nearly vertically emitted integrated nonlinear light sources around 810 nm

2.1 Experimental setup

2.1.1 Fabrication of high-*Q* X-cut thin-film lithium niobate microdisk resonators

Commercially available X-cut lithium niobate on insulator (LNOI) wafers with an 800-nm-thick TFLN layer were used to fabricate the suspended microdisk resonators. The dispersion engineered microresonators with a diameter of approximately 65.9 μm and a thickness of approximately 750 nm, were fabricated using femtosecond laser photolithography assisted chemo-mechanical etching (PLACE) technique. Detailed fabrication procedures can be found in ref.^{20–22}.

2.1.2 Experimental setup for the generation of nonlinear processes and the *Q*-factors measurement

Figure 1 illustrates the experimental setup for generating the vertically emitted nonlinear light from the dispersion engineered TFLN microdisk. A tunable continuous-wave (CW) laser (TLB-6728, New Focus Inc.) operating in the telecom band served as the pump source, and its output power was amplified by an erbium-doped fiber amplifier (EDFA). The pump power was precisely controlled using a variable optical attenuator (VOA), and the polarization state was optimized by an inline polarization controller (PC) to efficiently excite the transverse-electric (TE) modes in the microdisk. The pump light was routed through an in-fiber optical circulator (OC) and coupled into the suspended microdisk via a tapered fiber with a waist diameter of 2 μm . The tapered fiber was placed in contact with the top surface at the periphery of the microdisk to introduce weak perturbation, enabling coherent formation of the nearly perturbed high-*Q* cavity square modes. The generated nonlinear light signals were coupled out of the microdisk through the same tapered fiber, and directed to an optical spectrum analyzer (OSA, model: AQ6375B and AQ6370D, Yokogawa Inc.) for spectral analysis. In addition to the forward-propagating nonlinear light signals, backward-propagating pump light and the nonlinear light signals (e.g., backward SRS) were also generated by the Rayleigh backscattering process and backward nonlinear processes, respectively. These backward signals were coupled out of the microdisk by the same tapered fiber, extracted via the OC, and analyzed by the OSA. Meanwhile, nonlinear optical radiation emitted nearly normal to the microdisk plane from the top surface was collected using an objective lens combined with wavelength-selective optical filters, and recorded by a charge-coupled device (CCD) camera or a power meter. To measure the *Q* factors of the cavity square modes, the transmitted signal from the tapered fiber was detected by a photodetector (PD) connected to an oscilloscope by finely scanning the pump laser frequency across the cavity resonances using an

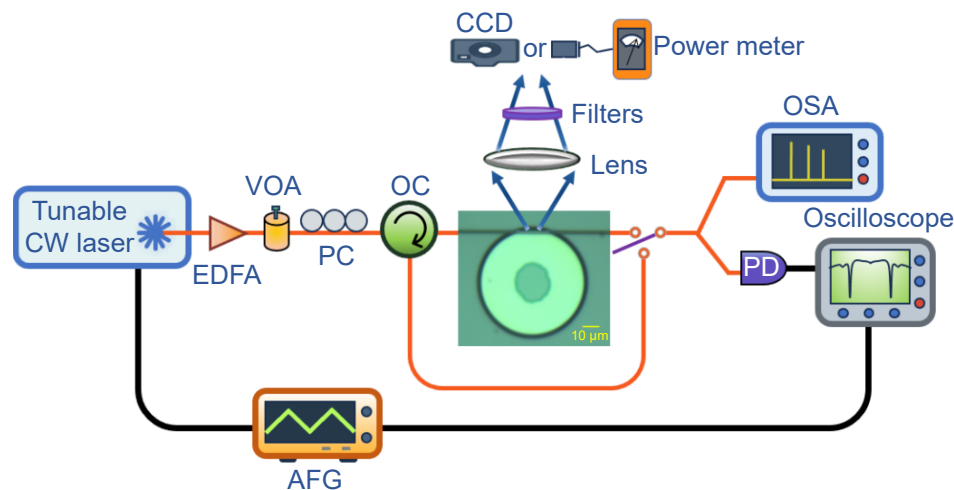


Fig. 1 | Experimental setup for the generation of the nearly vertically emitted integrated nonlinear light sources in the TFLN microdisk. Inset: Optical micrograph of the microdisk coupled with the tapered fiber.

arbitrary function generator (AFG). And to avoid exciting the nonlinear optical processes and thermo-optic effect in the microdisk, the pump power was reduced to 5 μ W for the Q factor measurement.

2.2 Characterization of the nonlinear light sources

When the pump wavelength was tuned to 1555.42 nm and the pump power exceeded the SRS threshold, pronounced stimulated Raman lasing (SRL) signals centered at 1721.26 nm were observed in both the forward and backward propagation directions, as shown in Fig. 2(a) and 2(b). The emission pattern of these SRL signals and the pump light from the microdisk was recorded, as shown in the inset of Fig. 2(a), clearly revealing a square-patterned intensity distribution. This polygon mode was formed through the mechanism of mode trimming and clustering in weakly perturbed whispering gallery mode (WGM) microresonators²³, where the tapered fiber can act as a localized dielectric perturbation source. This dielectric perturbation breaks the rotational symmetry of the circular resonator, and causes coherent recombination of the quasi-degenerate inherently spatial WGM sequence of the circular microdisk. Under the current pump wavelength and fiber coupling position, a fourfold-symmetric quasi-degenerate WGM sequence is selectively excited, thereby forming a high-Q square mode. The output powers of these two SRL signals dependent on the pump power are depicted in Fig. 2(c). Both SRL signals grow linearly with pump power above certain thresholds, consistent with typical lasing behavior. Distinct threshold behaviors are observed, with thresholds of 0.439 mW and 0.427 mW for the forward and backward directions, respectively. Above threshold, the output powers increase linearly with the on-chip pump power, yielding slope efficiencies of 32.3% and 21.1% from linear fits,

respectively. It is worth noting that counter-propagating SRL signals and pump signals coexist within the microdisk (Fig. 2(a) and 2(b)), which can participate in the subsequent cascaded nonlinear processes in both the propagating directions. When the on-chip pump power exceeds approximately 3 mW, a roll-off of the backward-propagating SRL output power can be observed. This phenomenon can be attributed to energy competition among coexisting nonlinear processes and intracavity thermally induced resonance detuning. As the pump power increases, cascaded SRS and second-order nonlinear processes in the microresonator gradually become stronger, consuming part of the intracavity pump energy and the generated SRL energy, thereby reducing the backward SRL power. In addition, high power pumping may induce thermo-optic effects, leading to local refractive-index changes and resonance detuning of the cavity modes, thereby weakening the multi-resonance enhancement in the high-Q microresonator. These factors together lead to the roll-off of the backward SRL output power at high pump power.

To elucidate the mechanism underlying the low-threshold SRL, the temporal confinement of the optical fields in the microdisk resonator must be evaluated. The measured transmission spectrum of the pump mode fitted with a Lorentzian function, is plotted in Fig. 2(d). A mode splitting with a wavelength spacing of 0.001 nm is observed. The loaded Q factors of these two nearly-degenerated square modes were measured to be as high as 4.48×10^6 and 4.39×10^6 , respectively, enabling significant field enhancement that boosts nonlinear interactions with high conversion efficiencies. Notably, this mode splitting arises from the material inhomogeneity of the X-cut microdisk with an anisotropic property, which significantly enhances the Rayleigh backscattering of both the pump light and the generated SRL signals, laying the foundation for the nearly

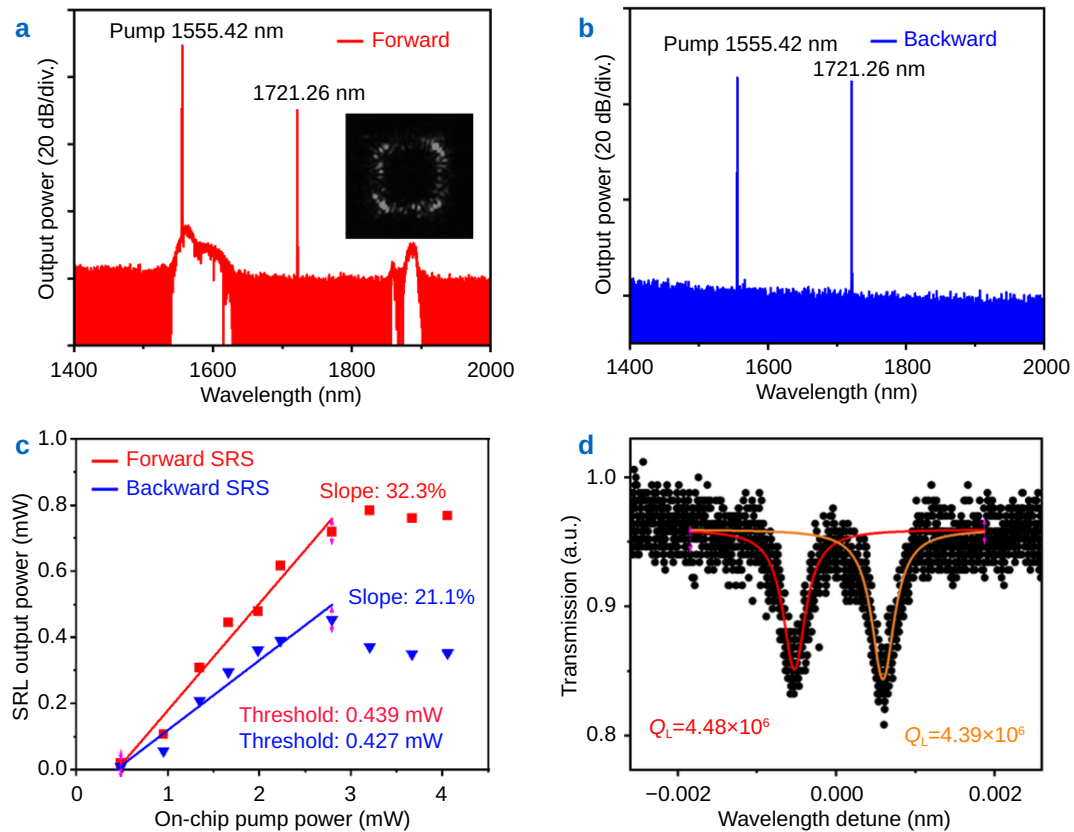


Fig. 2 | Optical spectra of (a) forward and (b) backward propagating optical signals, showing the pump light at 1555.42 nm and SRL at 1721.26 nm. Inset in (a): Optical micrograph of the infrared light emission. (c) SRL output power as a function of the on-chip pump power for the forward and backward directions, with linear fitting above threshold. (d) Transmission spectrum of the pump mode with Lorentzian fitting, showing loaded Q factors of 4.48×10^6 and 4.39×10^6 .

vertically emitted nonlinear light sources.

With efficient bidirectional SRL established, when the pump power was raised to above 0.48 mW, short-wavelength nonlinear signals below 1000 nm emerged in the microdisk resonator. Figure 3(a) presents the measured optical spectrum in the visible and near-infrared wavelength ranges in the forward propagating direction. Several distinct spectral peaks were observed at 777.71 nm, 817.06 nm, and 860.61 nm. Based on the energy conservation principle, the signal at 817.06 nm was identified as arising from sum-frequency generation (SFG) between the pump and SRL waves, while the signals at 777.71 nm and 860.61 nm were attributed to second harmonic generation (SHG) of pump light and the SRL signal, respectively. Notably, the output power of the SFG signal was significantly higher than those of the simultaneously observed SHG signals, indicating a more favorable phase matching condition between the pump and SRL waves.

To quantitatively characterize the SFG process, the output power of the vertically emitted SFG signal from the top surface of the microdisk was measured as a function of the square of the on-chip pump power, as shown in Fig. 3(b). A clear linear dependence above certain pump level is

observed, yielding a total conversion efficiency of 0.272%/mW. In addition, the scattering optical field distributions of the microdisk were characterized using the visible-light CCD camera, as shown in Fig. 3(c–e). With an 800-nm short-pass filter, the image was dominated by the SHG of the pump light showing a square patterned distribution, whereas an 800-nm long-pass filter primarily revealed scattering from the SFG of the pump and SRL lights. Notably, fine glow fringe-like microstructures with a period Λ' of approximately 3.51 μm are periodically distributed along the square-patterned light path, as visible in Fig. 3(e).

3 Phase matching and mode overlap analysis

Because this glow fringe arises from the interference between two SFG light fields propagating with different wavevectors $\mathbf{k}$, the period Λ' satisfies $\Lambda' = \lambda_{\text{SFG}} / (2 \times \sin \theta)^{15}$. Here, λ_{SFG} is the wavelength of the SFG signal in vacuum, and θ is the angle between either SFG wavevector $\mathbf{k}$ and the vertical direction (normal) of the microdisk plane. Thus, θ is calculated to be 6.684°. And the generated nonlinear lasers at 817 nm are emitted nearly

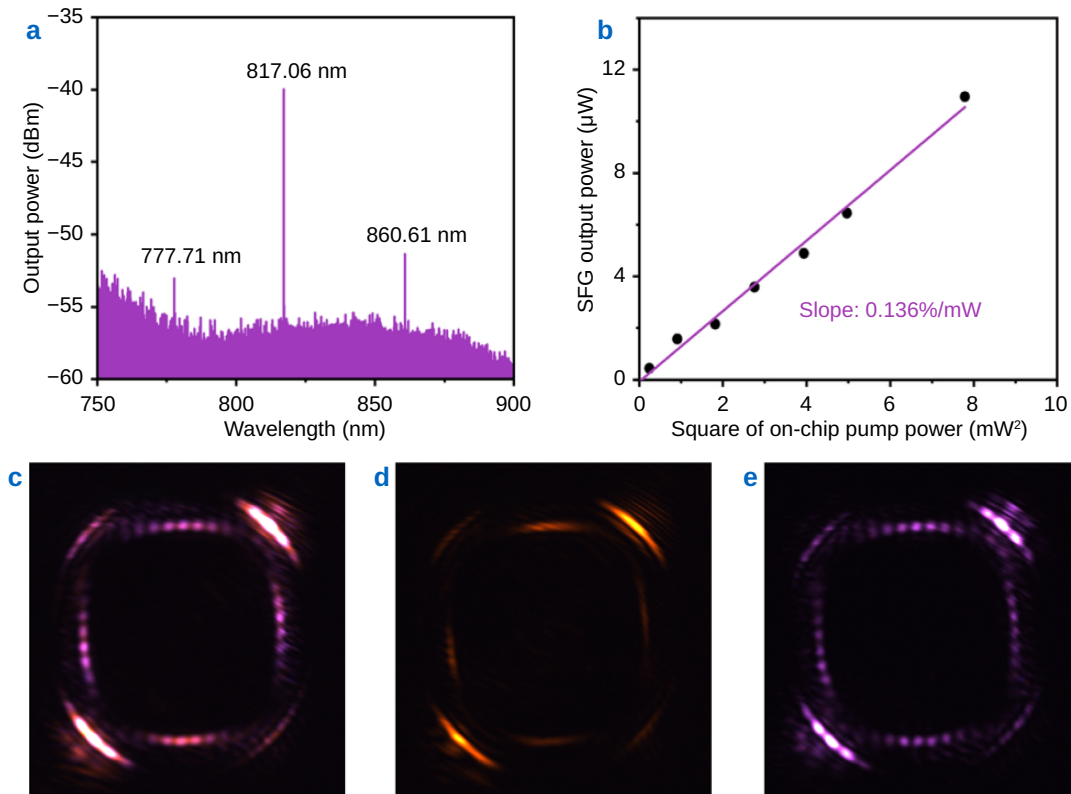


Fig. 3 | (a) Optical spectrum measured in the short-wavelength range. (b) Vertically collected SFG output power as a function of the square of the on-chip pump power. Top-view optical microscope images of the microdisk collected (c) without optical filtering, (d) with an 800-nm short-pass filter, and (e) with an 800-nm long-pass filter, respectively.

perpendicular to the microdisk plane, with the wavevectors tilted by only $\pm 6.684^\circ$ relative to the normal direction of the microdisk. Consequently, the in-plane wavevector components of the SFG signals are $\Delta\beta = k_{\text{SFG}} \cdot \sin \theta = 0.895/\mu\text{m}$, where k_{SFG} represents the wavevector magnitude of the SFG signal in vacuum. For laser signals coupled into thin-waveguides or thin-microresonators in a counterpropagating configuration, transverse second-order nonlinearity signal is generated in the directions perpendicular to the waveguide or resonator, as required by phase matching^{16,17}. The phase matching condition for the nearly vertically emitted nonlinear laser source at 817 nm can be expressed as

$$\Delta\beta = \beta_{\text{pump}} - \beta_{\text{SRL}}, \quad (1)$$

where β_{pump} and β_{SRL} are the propagation constants of the pump and the SRL signals, respectively, as illustrated in Fig. 4. Using the experimental parameters, β_{pump} and β_{SRL} were calculated to be $8.214/\mu\text{m}$ and $7.321/\mu\text{m}$, respectively. Substituting these values into Eq. (1), giving the right-hand side as $0.893/\mu\text{m}$, which agrees well with the measure $\Delta\beta = 0.893/\mu\text{m}$. Therefore, phase matching was successfully achieved with the nonlinear interaction between the pump light and the SRL signal in the counter-propagating configuration in the nearly degenerate square modes.

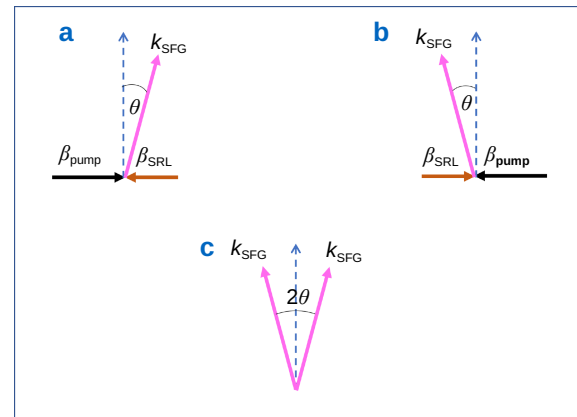


Fig. 4 | Transverse-phase matching diagram of transverse phase-matching condition. (a) Forward direction. (b) Backward direction. (c) Emitting angles of the forward and the backward SFG signals.

4 Discussion and conclusions

The X-cut microresonator with its crystal axis lied in the plane of the microresonator is important for forming the nearly-degenerate square modes and enabling efficient transverse phase matching. In the X-cut TFLN microdisk, the anisotropic refractive-index profile of the transverse-electric modes breaks the rotational symmetry of the

resonator, enhances the Rayleigh backscattering and the mode splitting, and thereby boosts the formation of counter-propagating optical fields under unidirectional pumping. Together with the weak perturbation introduced by the tapered fiber, this anisotropy facilitates the formation of high-Q square modes with favorable spatial overlap between the pump and SRL fields^{19,20}, thereby enhancing efficient nearly vertically emitted SFG.

Notably, the emission angle θ of the SFG light depending on the transverse phase-matching condition can be varied. According to the transverse phase-matching condition $k_{\text{SFG}} \cdot \sin\theta = \beta_{\text{pump}} - \beta_{\text{SRL}}$, reducing the difference between β_{pump} and β_{SRL} can bring the emission direction closer to the surface normal. In principle, in the case of polygon modes, this angle can be engineered by changing the geometry dispersion (including thickness and diameter) of the TFLN microdisk, which modifies the effective refractive indices and the propagation constants of the involved square modes. In addition, considering that lithium niobate is highly Raman-active medium, by exciting different Raman phonon modes with other Raman shifts, this phase-matching condition can be tuned. While in the case of WGMs, for example, vertically emitted SFG can be achieved through the excitation of a high-order spatial WGM and a fundamental WGM as the pump and Stokes SRS modes, respectively, which share the same effective indices. Therefore, the observed $\pm 6.684^\circ$ emission angle originates from the specific microdisk dispersion, pump wavelength, and the excited Raman phonons in the present device, rather than being an inherent and unchangeable feature of the SPG-assisted transverse phase-matching scheme.

In summary, by introducing transverse-phase matched nonlinear interaction between optical waves in the counter-propagating configuration through the unidirectional excitation of high-Q nearly-degenerate polygon modes under single laser pumping, nearly vertically emitted nonlinear coherent light sources were demonstrated with a high efficiency of 0.272%/mW. Once combined with the outstanding properties of the tightly confined TFLN photonic structures^{24–32}, featuring high second-order nonlinearity, strong Pockels effects, and low loss propagation, vertically emitted light sources with narrow linewidth operation, high speed modulation and multi-wavelength outputs can even be achieved on the TFLN platform. This approach provides new additional optical momentum to facilitate transverse phase matching for integrated classical and quantum light sources, and significantly extends the spectral bandwidth for promoting associated photonic applications, such as laser display, precision metrology, coherent communication, and quantum information processing.

References

1. Liu AJ, Wolf P, Lott JA et al. Vertical-cavity surface-emitting lasers for data communication and sensing. *Photonics Res* 7, 121–136 (2019).
2. Wang H, He YM, Chung TH et al. Towards optimal single-photon sources from polarized microcavities. *Nat Photonics* 13, 770–775 (2019).
3. Larsson A. Advances in VCSELs for communication and sensing. *IEEE J Select Top Quantum Electron* 17, 1552–1567 (2011).
4. Yang YH, Xu XB, Wang JQ et al. Nonlinear optical radiation of a lithium niobate microcavity. *Phys Rev Appl* 19, 034087 (2023).
5. Williams BS. Terahertz quantum-cascade lasers. *Nat Photonics* 1, 517–525 (2007).
6. Mahler L, Tredicucci A, Beltram F et al. Vertically emitting microdisk lasers. *Nat Photonics* 3, 46–49 (2009).
7. Young AW, Eckner WJ, Milner WR et al. Half-minute-scale atomic coherence and high relative stability in a tweezer clock. *Nature* 588, 408–413 (2020).
8. Ludlow AD, Boyd MM, Ye J et al. Optical atomic clocks. *Rev Mod Phys* 87, 637–701 (2015).
9. Isichenko A, Hunter AS, Bose D et al. Sub-Hz fundamental, sub-kHz integral linewidth self-injection locked 780 nm hybrid integrated laser. *Sci Rep* 14, 27015 (2024).
10. Luo Q, Bo F, Kong YF et al. Advances in lithium niobate thin-film lasers and amplifiers: a review. *Adv Photonics* 5, 034002 (2023).
11. Lin JT, Bo F, Cheng Y et al. Advances in on-chip photonic devices based on lithium niobate on insulator. *Photonics Res* 8, 1910–1936 (2020).
12. Zheng YL, Chen XF. Nonlinear wave mixing in lithium niobate thin film. *Adv Phys X* 6, 1889402 (2021).
13. Xie ZD, Bo F, Lin JT et al. Recent development in integrated Lithium niobate photonics. *Adv Phys X* 9, 2322739 (2024).
14. Breunig I. Three-wave mixing in whispering gallery resonators. *Laser Photonics Rev* 10, 569–587 (2016).
15. Li CT, Yao N, Yu HK et al. Efficient transverse multiwave interactions up to six-wave mixing in a high-Q lithium niobate microresonator. *Phys Rev Lett* 134, 213801 (2025).
16. Ding YJ, Lee SJ, Khurgin JB. Transversely pumped counterpropagating optical parametric oscillation and amplification. *Phys Rev Lett* 75, 429–432 (1995).
17. Yu HK, Lun YP, Lin JT et al. Frequency-resolved optical gating in transverse geometry for on-chip optical pulse diagnostics. *Laser Photonics Rev* 17, 2201017 (2023).
18. Gao RH, Fu BT, Yao N et al. Electro-optically tunable low phase-noise microwave synthesizer in an active lithium niobate microdisk. *Laser Photonics Rev* 17, 2200903 (2023).
19. Fu BT, Gao RH, Yao N et al. Soliton microcomb generation by cavity polygon modes. *Opto-Electron Adv* 7, 240061 (2024).
20. Lin JT, Farajollahi S, Fang ZW et al. Electro-optic tuning of a single-frequency ultranarrow linewidth microdisk laser. *Adv Photonics* 4, 036001 (2022).
21. Wu RB, Zhang JH, Yao N et al. Lithium niobate micro-disk resonators of quality factors above 10^7 . *Opt Lett* 43, 4116–4119 (2018).
22. Wang Z, Fang ZW, Liu ZX et al. On-chip tunable microdisk laser fabricated on Er^{3+} -doped lithium niobate on insulator. *Opt Lett* 46, 380–383 (2021).
23. Fu BT, Gao RH, Lin JT et al. Modes trimming and clustering in a weakly perturbed high-Q whispering gallery microresonator. *Laser Photonics Rev* 17, 2300116 (2023).
24. Jia YC, Wang L, Chen F. Ion-cut lithium niobate on insulator technology: recent advances and perspectives. *Appl Phys Rev* 8, 011307 (2021).
25. Chakkoria JJ, Dubey A, Mitchell A et al. Ferroelectric domain engineering of Lithium niobate. *Opto-Electron Adv* 8, 240139 (2025).
26. Zhu YR, Fu BT, Fang ZW et al. A hybrid integrated high-precision tunable semiconductor laser. *Opto-Electron Adv* 9, 250274 (2026).
27. Li MX, Chang L, Wu L et al. Integrated Pockels laser. *Nat Commun* 13, 5344 (2022).

28. Feng HK, Ge T, Guo XQ et al. Integrated lithium niobate microwave photonic processing engine. *Nature* **627**, 80–87 (2024).
29. Li Y, Deng SY, Ma X et al. Narrow beam and low-sidelobe electro-optic beam steering on thin-film lithium niobate optical phased array. *Opto-Electron Sci* **5**, 260002 (2026).
30. Sun XL, Jia YC, Chen F. Thin-film lithium niobate-based detector: recent advances and perspectives. *Opto-Electron Sci* **4**, 250028 (2025).
31. Han JL, Li MQ, Wu RB et al. High fiber-to-fiber net gain in erbium-doped thin film lithium niobate waveguide amplifier as an external gain chip. *Opto-Electron Sci* **4**, 250004 (2025).
32. Sun XL, Sheng Y, Gao X et al. Self-powered lithium niobate thin-film photodetectors. *Small* **18**, 2203532 (2022).

Acknowledgements

We are grateful for financial supports from National Key R&D Program of China (Nos. 2025YFA1411803, 2022YFA1205100, 2024YFB2808100); National Natural Science Foundation of China (Nos. 62335019, 62475269, 12192251, 12334014, 12474378, 92480001); Quantum Science and Technology-National Science and Technology Major Project (No. 2021ZD0301403); Science and Technology Commission of Shanghai Municipality (No. 23ZR1481800); Shanghai Municipal Science and Technology Major Project (No. 2019SHZDZX01);

Fundamental Research Funds for the Central Universities; National Postdoctoral Program for Innovative Talents (No. GZC20240481).

Author contributions

J. L., Y. C., and J. N. proposed the original idea. C. L., Y. Q., and R. G. fabricated the samples and performed the measurements. C. L., J. L., J. N., and Y. C. participated in experimental data analysis. J. L. performed the analysis of phase matching. C. L. and J. L. wrote the initial draft of the manuscript, and J. L. and Y. C. revised the manuscript. Y.C., M.W., and J. L. supervised the project. All authors contributed extensively to the work presented in this paper.

Competing interests

The authors declare no competing financial interests.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>

©The Author(s) 2026.

Published by Editorial Office of *Opto-Electronic Technology*, Institute of Optics and Electronics, Chinese Academy of Sciences.

