

Research Article

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Efficient high-quality photon pair generation in modal phase-matched thin-film lithium niobate micro-ring resonators

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Abstract: Efficient generation of high-quality photon pairs is essential for modern quantum technologies. Micro-ring resonator is an ideal platform for studying on-chip photon sources due to strong nonlinear effect, resonant-enhanced optical fields, and high integration. Thin-film lithium niobate (TFLN) micro-ring resonators with periodically poled quasi-phase matching have shown high-quality photon pair generation. However, periodic poling technology remains expensive and requires complex fabrication hindering its scalability and capability for practical application in nonlinear photonic devices. To address this, we propose a scalable approach using TFLN micro-ring resonators based on modal phase matching to achieve cost-effective, efficient high-quality photon pair generation, significantly simplifying fabrication. We achieved pair generation rates up to 40.2 MHz/mW through spontaneous parametric down-conversion, with coincidence-to-accidental ratios exceeding 1,200. By combining micro-ring resonance enhancement

with modal phase matching, our approach reduces device size and fabrication cost while maintaining high nonlinear efficiency. These results advance the development of compact, efficient on-chip photon sources for next-generation nonlinear and quantum photonic applications.

Keywords: thin-film lithium niobate; micro-ring resonator; modal phase-matching; spontaneous parametric down-conversion; photon pairs

1 Introduction

Modern quantum information technologies exploit the utility of single photons for quantum computation, quantum communication, and metrology, demonstrating superior advantages over classical approaches [1]–[3]. Quantum-encoded encryption keys, for example, can fundamentally enhance communication security, utilizing quantum photon properties to achieve unprecedented measurement precision [4]. Quantum protocols to realize these processes rely on an efficient and stable photon source as a vital component, and as a result, extensive research has been conducted on single photon sources, including spontaneous parametric down-conversion (SPDC) in bulk crystals, optical waveguides, metasurfaces, and two-dimensional materials [5]–[9], spontaneous four-wave mixing (SFWM) in optical fibers and silicon materials [10], [11], and quantum dot exciton processes in semiconductor materials [12]. Quantum dots have been shown to generate single photons or photon pairs through exciton cascade recombination, enabling deterministic single-photon generation, but require low-temperature and resonant pumping [13]. Both SPDC and SFWM, however, use nonlinear optical processes to generate correlated photon pairs, offering inherent advantages. Particularly, as discussed in [14], these inherent advantages include room-temperature operation, simple signal filtering, coherent emission characteristics, multi-degree-of-freedom entanglement capabilities, and inherent compatibility with photonic

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integration platforms. Notably, with a higher nonlinear coefficient, SPDC process requires lower pump light power compared to the SFWM process, making it a primary method for generating photon pairs.

LN is a multifunctional crystal with excellent optical properties such as wide transparent window, low optical loss, large second-order nonlinear coefficient, and long-term stability, making it an ideal material system for integrated optics and nonlinear optics [15]. Various nonlinear and quantum photonic devices have been realized based on LN material, such as efficient frequency conversion using second-harmonic generation (SHG), sum-frequency generation (SFG), difference-frequency generation (DFG) [16]–[20], supercontinuum generation [21], [22], optical frequency combs [23]–[25], etc. Nevertheless, second-order nonlinear effects in LN and subsequent periodic poling can serve as a platform for efficient photon sources [26]. LN processing is still undergoing optimization with recent developments in micro-fabrication technology. In particular, the tightly confined thin-film lithium niobate (TFLN) ridge waveguide platform shows significant progress with respect to its early counterparts regarding weakly confined proton exchange/titanium diffusion waveguides. These technological advances not only improve the yield of photon pairs but also greatly promote quantum optical integrated chip development [27]–[30].

As one of the important devices in the field of integrated optics, micro-ring resonators (MRRs) have wide applications in filtering [31], modulation [32], all-optical switches [33], lasers [34], and other fields. Compared to straight waveguides, MRRs are advantageous due to their small size and resonant enhancement, which can induce strong nonlinear optical processes, thereby reducing the requirements for a long waveguide length and larger pump intensity. TFLN MRRs made of TFLN materials based on periodic poling have shown efficient SPDC and generation of high-quality photon pairs [35]–[38]. However, the preparation technology of quasi-phased matching based on periodic poling is complex and costly, which hinders the large-scale development and application of nonlinear devices. In contrast, modal phase matching does not comprise complex fabrication processes and is easy to integrate on-chip. Moreover, resonant enhancement from MRRs reduces the requirement for the system's intrinsic nonlinear strength and circumvents the need for complex and costly periodic poling technology. The research on modal phase matching in TFLN MRRs, however, remains relatively unexplored, especially in the context of photon pair generation.

In this work, we design and fabricate TFLN MRRs based on modal phase matching to achieve efficient high-quality

photon pair source on chip. We also design and implement an asymmetric coupler as a mode converter to help meet phase-matching conditions for the pump light mode. Our fabricated chips achieved Q-factors exceeding 10^5 and met triple-resonance conditions through precision temperature stabilization and wavelength selection. As a result, we experimentally observed an overall pair generation rate (PGR) as high as 40.2 MHz/mW, with a coincidence-to-accidental ratio (CAR) higher than 1,200. Overall, the TFLN MRR modal phase-matched platform shows promise for an overall smaller footprint, easier photonic integration, and simplified fabrication processes, proving beneficial to future development advancements in nonlinear and quantum optical technologies.

2 Structural design and numerical calculation

A schematic of the designed TFLN MRR structure on chip is shown in Figure 1(a), consisting of two main parts: the MRR and the mode converter. The mode converter converts 775 nm light from the TM00 mode to the TM20 mode. The mode converter is then paired with the corresponding MRR that satisfies phase-matching conditions of two light waves near 775 nm and 1,550 nm. As a result, efficient high-quality photon pair generation can be achieved through SPDC in the telecommunications frequency band, as shown in Figure 1(b).

2.1 Photon pair generations based on modal phase matching

We employ Z-cut TFLN to ensure efficient nonlinear conversion, where light propagates along the circumference of the MRR and the crystal's optical axis is oriented perpendicular to the light propagation direction. This alignment ensures the preservation of Type I collinear phase matching. In contrast, using X-cut TFLN – with a horizontal optical axis – introduces a continuously changing angle between the propagation direction and the optical axis, thereby hindering efficient nonlinear processes [39].

To achieve efficient nonlinear processes in the MRR, both phase matching and resonance conditions must be simultaneously met. The required phase matching condition must satisfy $\Delta k = k_p - k_s - k_i = 0$, where k_p , k_s , and k_i are the propagation constants of the pump, signal, and idler light, respectively. Here, we choose the TM20 mode for the pump light and TE00 mode for the signal and idler light to achieve modal phase matching. Simultaneously, we

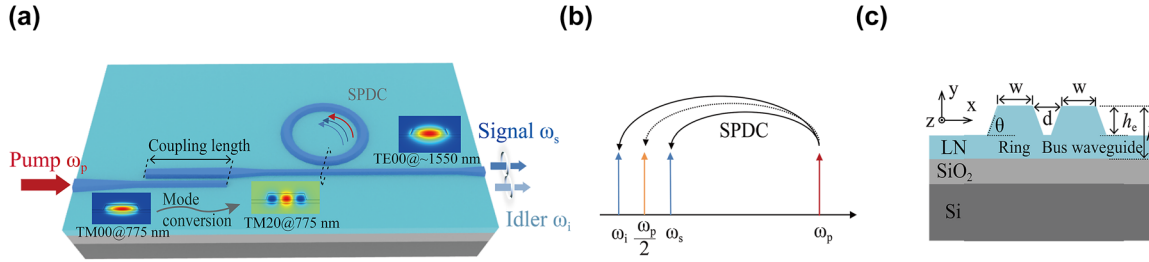


Figure 1: On-chip TFLN MRR chip for photon pair generation. (a) Schematic diagram of the device, where the pump is sent into a straight waveguide, coupled and converted in mode converter, and then into the MRR, where SPDC takes place. Then the output signal and idler are coupled out and measured. (b) Schematic depiction of SPDC process, showing degenerate parametric down conversion (dashed line) and nondegenerate parametric down conversion (solid lines). ω_p , ω_i , and ω_s are the pump, signal, and idler light of the SPDC process, respectively. (c) Schematic diagram of MRR waveguide cross section (corresponding to the black dashed box in (a)). The TFLN layer thickness (h), the etching depth of the waveguide (h_e), and the sidewall angle (θ) are 300 nm, 200 nm, and 70°, respectively. d is the coupling gap between the bus waveguide and the micro-ring waveguide. The width of the bus waveguide (w_{bus}) is equal to the width of the micro-ring waveguide (w).

require that the MRR free spectral range (FSR) is not too large to ensure all interacting beams can resonate. Therefore, we choose a minimal micro-ring radius of 150 μm , corresponding to an FSR of 1.1 nm. Under these conditions, along with temperature control and precise wavelength selection, the pump, signal, and idler can simultaneously

achieve resonance with ease. To ensure properly control, we calculate the waveguide mode dispersion of the MRR.

Figure 1(c) shows the MRR waveguide cross section. We choose a TFLN layer thickness of 300 nm, etching depth of 200 nm, and the waveguide sidewall inclination angle of 70°. Here, we consider the change in the effective refractive

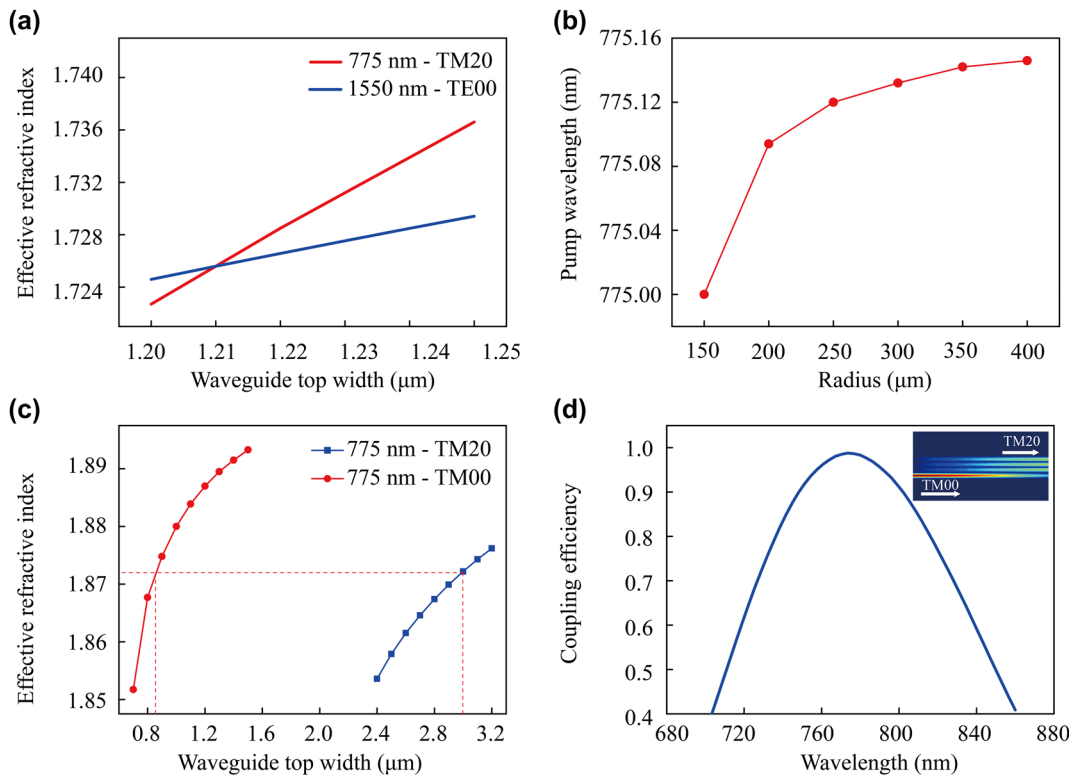


Figure 2: Numerical calculations for modal phase-matching conditions and mode conversion. (a) The effective refractive index of 775 nm TM20 and 1550 nm TE00 as a function of waveguide top width at $R = 150 \mu\text{m}$. (b) Pump wavelength required for phase matching as a function of different MRR radii for a waveguide top width of $w = 1.21 \mu\text{m}$. (c) Effective refractive index of two modes at 775 nm with varying waveguide top width of the mode converter. (d) The coupling efficiency versus input pump wavelength. The inset in (d) shows the modal field distribution of the mode converter at 775 nm.

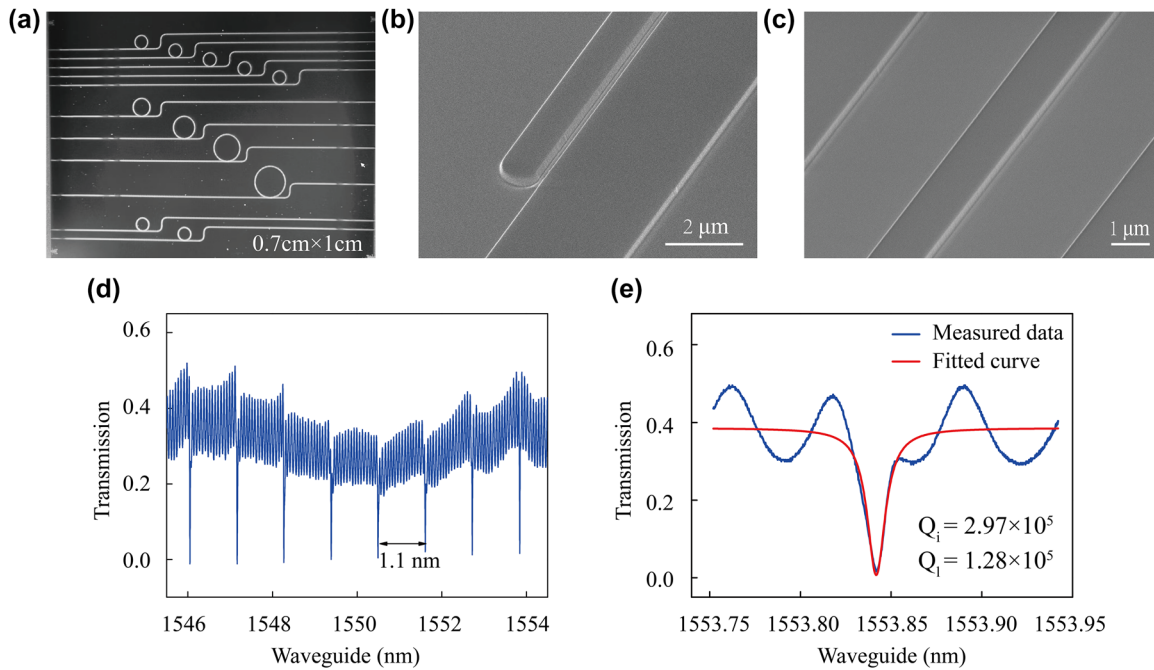


Figure 3: Sample characterization. (a) Microscopic image of the MRRs. (b) SEM image of the mode converter. (c) SEM image of the waveguide. (d) Transmission spectrum of TFLN MRR for a radius of 150 μm and coupling gap of 0.45 μm, showing FSR of 1.1 nm for the MRR. (e) Transmittance spectrum around the resonant wavelength of the MRR in blue and the corresponding fitted curve in red indicating the intrinsic versus measured Q-factor.

index caused by waveguide bending. The variation of the effective refractive index of TM₂₀ mode at 775 nm and TE₀₀ mode at 1,550 nm are shown in Figure 2(a). Here, we vary the top width of the 150-μm-radius MRR waveguide. From Figure 2(a), it can be seen that the TM₂₀ mode at 775 nm and the TE₀₀ mode at 1,550 nm satisfy modal phase matching when the top width is 1.21 μm. Figure 2(b) shows that for a top width of 1.21 μm, the pump wavelength satisfying phase matching also increases with increase of the MRR radius. However, only a 0.1 nm change in the required pump wavelength for phase matching is observed when varying the radius from 150 μm to 400 μm.

2.2 Mode converter design

We designed and integrated a mode converter at the front end of the micro-ring structure to achieve modal phase matching in the MRR system, such that the pump light operates in the TM₂₀ mode and the input straight waveguide supports the fundamental mode, TM₀₀ (see Figure 1(a)). As shown in Figure 2(c), the effective refractive indices of the TM₀₀ and TM₂₀ modes of 775 nm pump light were calculated under different waveguide widths. Effective energy exchange can be achieved between these two modes when their effective refractive indices in each waveguide are equal. As a result, we chose top widths of 0.84 μm and

3 μm, for the mode converter input and output waveguide, respectively, as depicted by the red lines of Figure 2(c). The coupling gap between these waveguides was set to be 0.2 μm, making an overall compact structure. To achieve complete mode conversion, a coupling length of 600 μm is required. Using a coupling length of 600 μm, we calculated the coupling efficiency of different pump wavelengths using FDTD, plotted in Figure 2(d), resulting in a maximum coupling efficiency of 98 % within the range of 700–850 nm. The field distribution at optimal energy transfer is shown in the insert in Figure 2(d).

3 Experimental results

3.1 Sample preparation and characterization

The fabricated sample consists of commercial Z-cut silicon-based TFLN (NANOLN Inc.), with a 525-μm-thick silicon bottom layer, a 2.025-μm-thick silicon dioxide middle layer, and a 300-nm-thick TFLN layer on top. The sample fabrication process primarily involves electron beam lithography and ion beam etching, thereby avoiding the complexity associated with periodically poled waveguides. From here, MRRs with different coupling gaps and radii were prepared. One sample set varied the coupling gap from 0.3 μm to 0.5 μm

in $0.05 \mu\text{m}$ increments while holding a constant radius of $150 \mu\text{m}$. The other sample set held a constant coupling gap of $0.3 \mu\text{m}$ while varying the radius from $150 \mu\text{m}$ to $300 \mu\text{m}$ with $50 \mu\text{m}$ increments. After etching, a polish of $150 \mu\text{m}$ was applied to both ends of the chip to reduce end face roughness. Figure 3 shows the detailed analysis of the fabricated samples.

The MRR microscopy image is shown in Figure 3(a), and SEM images of the coupler and waveguide are shown in Figure 3(b) and (c). The measured transmission spectrum of the sample without a mode converter with $150 \mu\text{m}$ radius and $0.45 \mu\text{m}$ coupling gap is shown in Figure 3(d). Under these conditions, we observed critical coupling and measured the FSR to be 1.1 nm , consistent with our theoretical calculation. We found that the propagation loss is

approximately 1.36 dB/cm at $1,550 \text{ nm}$. The intrinsic quality factor can reach 2.97×10^5 and the measured loaded quality factor to be 1.28×10^5 , as shown in Figure 3(e).

3.2 Second-harmonic generation

The experimental setup for SHG is shown in Figure 4(a). A continuously tunable laser (Santec TSL-570) is amplified by an erbium-doped fiber amplifier, directed through a polarization controller, and coupled into a waveguide using a fiber with a diameter of $3.2 \mu\text{m}$. The output power and spectrum of the SHG signal is captured by a power meter and spectrometer. Note that the fundamental light is coupled directly, while the SHG signal is coupled with the mode converter for output, as depicted in Figure 4(a).

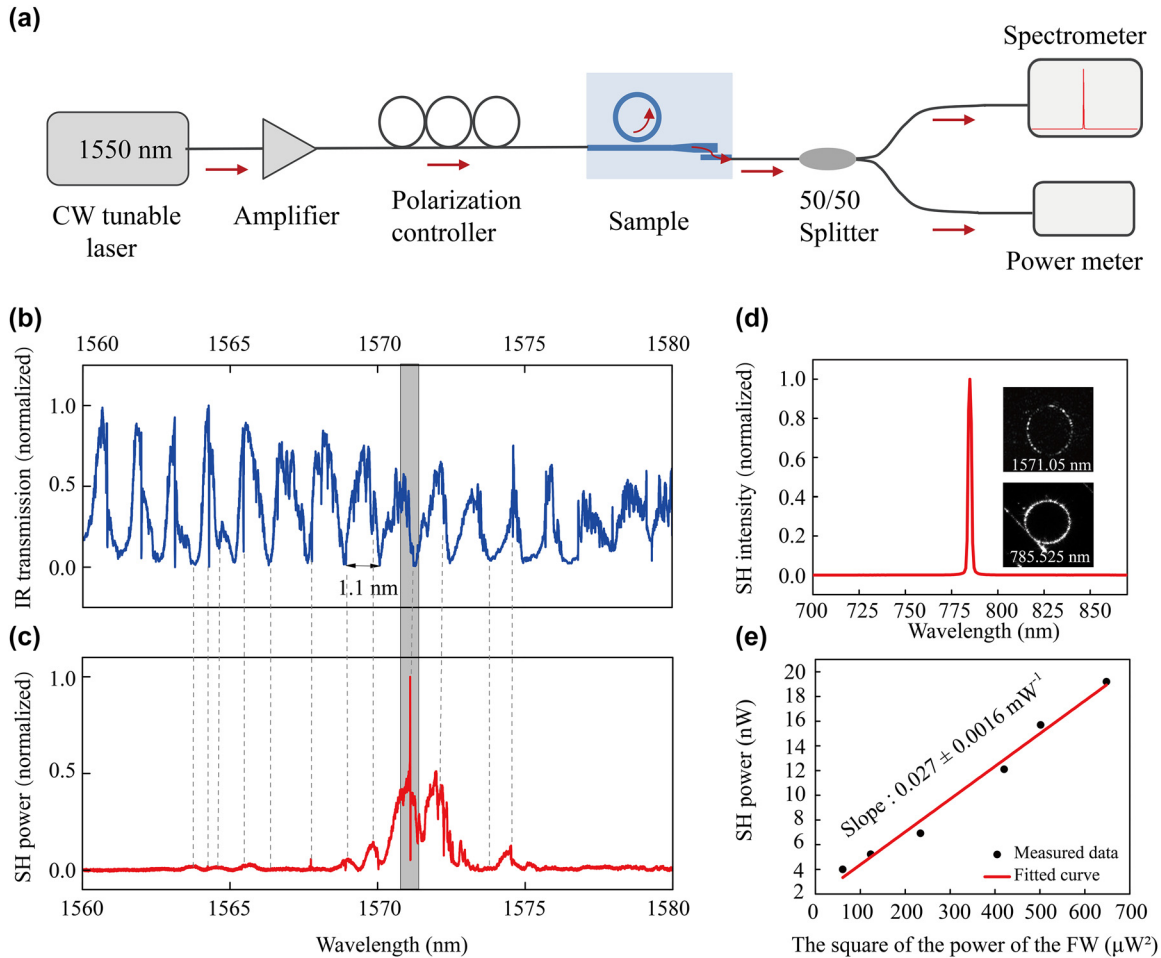


Figure 4: Measurement results of SHG for the MRR ($R = 150 \mu\text{m}$, $d = 0.45 \mu\text{m}$) with a mode converter. (a) Schematic diagram of experimental setup for SHG. A tunable CW laser centered at $1,550 \text{ nm}$ is sent through an amplifier and polarization controller. The input fundamental light is coupled in the sample, and the output SHG light is sent through a 50/50 beam splitter to measure both the transmission spectrum and the output power. (b) Measured transmission spectrum of the fundamental light signal through the sample, and (c) the corresponding SHG signal. (d) The SHG signal intensity for a fundamental wavelength of $1,571.05 \text{ nm}$, corresponding to the fundamental and SHG signal's resonance and phase-matched conditions. The insets in (d) show the fundamental and SHG signal in the MRR captured by CCD cameras. (e) The SHG power as a function of the square of the fundamental light power, confirming the quadratic dependence (slope = $0.027 \pm 0.0016 \text{ mW}^{-1}$).

Figure 4(b) shows the transmission spectrum of the fundamental light from 1,560 to 1,580 nm for the critically coupled MRR, with a radius and coupling gap of 150 μm and 0.45 μm , respectively. The discrepancy between the transmission spectra presented here and those measured previously arises from the mode converter. The fundamental wavelength that satisfies the resonance condition of the MRR corresponds to the valley position on the transmission spectrum. Figure 4(c) shows the SHG signal measured in the range of 1,560–1,580 nm. It can be seen that in Figure 4(b) and (c), the SHG signal remains weak regardless of the resonant fundamental signal, as depicted by dashed lines outside the shaded regions. Only when fundamental signal and SHG signal are resonant and phase matched, we achieve efficient SHG, as depicted by the shaded area in Figure 4(b) and (c). Careful tuning of the temperature allows for precise control of the optimal conditions. Figure 4(d) shows the second harmonic spectrum, with a maximum signal at $\lambda_{\text{SHG}} = 785.525$ nm, corresponding to a fundamental wavelength of $\lambda_{\text{FF}} = 1,571.05$ nm. The SHG and fundamental signals are measured using CCD cameras, as shown by the two inserts in Figure 4(d), indicating that both signals are resonant. Moreover, the CCD measurement shows that SHG is indeed generated in the MRR, rather than the straight waveguide. Finally, the power dependence of the SHG signal is measured by varying the input power of the fundamental

plotted in Figure 4(e), following the expected quadratic dependence of the input fundamental power.

3.3 Photon pair generation

The schematic diagram of the experimental setup for photon pair generation and detection is shown in Figure 5(a). A near-visible wavelength tunable laser (SL-N-780-L-CW semiconductor laser) is passed through a polarization controller and then coupled through a 775 nm lens fiber into the tapered waveguide. The light is converted to a TM₂₀ mode by the mode converter and then coupled into an MRR through the straight waveguide. Photon pairs are then generated from the MRR and coupled through a tapered waveguide to an output fiber with a diameter of 3.2 μm . After filtering the input pump light, the generated photon pairs are sent down two paths via a 50:50 beam splitter. The polarization of the light in each path is first controlled and then subsequently detected on a superconducting nanowire single photon detector (SNSPD, detection efficiency $\sim 60\%$). The coincidence counts between the photon pairs are measured using a time-dependent single photon counter (TCSPC) (PicoQuant PicoHarp 300). The chip-to-fiber coupling losses are 10.7 dB around 780 nm and 6.2 dB around 1,570 nm. The losses in each path from the output fiber to the detector are 7.47 dB and 6.68 dB at 1,570 nm, respectively.

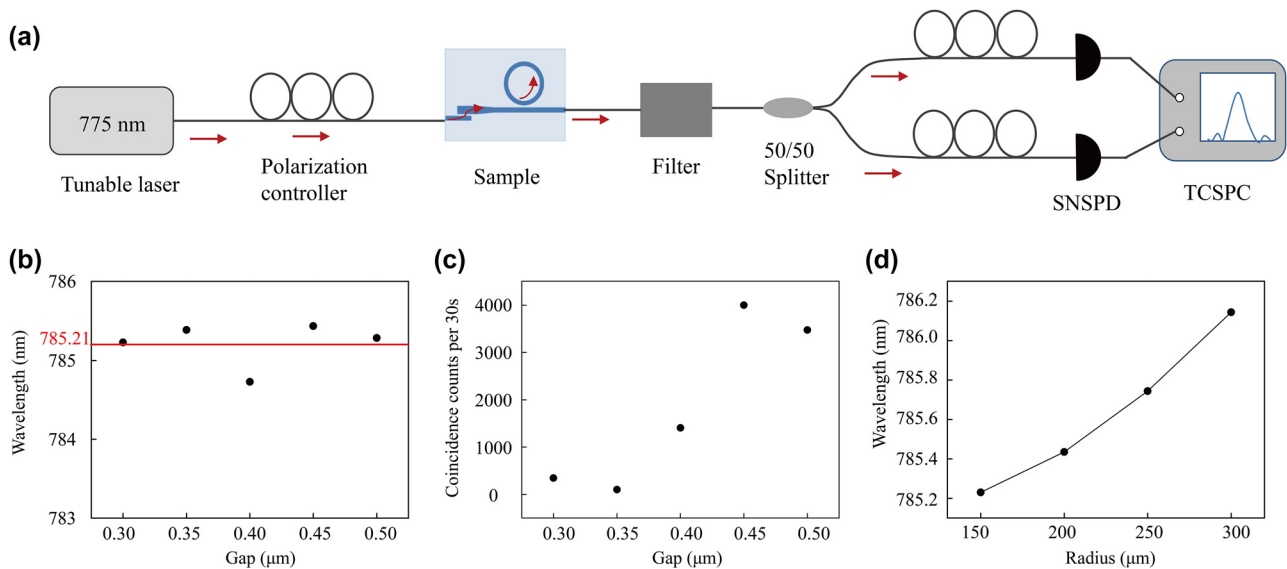


Figure 5: Photon pair generation, detection, and measurement. (a) Schematic diagram of experimental setup for measuring photon pairs. A tunable pump laser at 775 nm is sent through a polarization controller and then coupled into the sample. The fundamental light is then filtered at the output such that only the generated signal is detected. The generated photon pairs are sent through a 50/50 beam splitter, subsequently sent through polarization controllers. Finally, single photon counts and coincidence counts are measured using a time-dependent single-photon counter. (b) The pump wavelength for max coincidence count at different coupling gaps. The red line at $\lambda = 785.21$ nm corresponds to near-degenerate photons generated by SPDC. (c) Coincidence counts for different coupling gaps for a 150 μm radius MRR. (d) Resonant pump wavelength for an MRR with a coupling gap of 0.3 μm for different radii.

The photon pair generation was analyzed for various MRRs with different coupling gaps and radii. Firstly, the coupling gap directly affects the pump light coupling efficiency into the MRR and the output signal coupling efficiency, thereby affecting the overall nonlinear conversion efficiency. As previously stated, optimal SHG efficiency occurs at a radius of $150\ \mu\text{m}$ with a coupling gap of $0.45\ \mu\text{m}$. Therefore, one can expect similar peak in efficiency for photon pair generation under these conditions. Consequently, the average measured pump light wavelength for near-degenerate SPDC occurs at $785.21\ \text{nm}$, as shown in Figure 5(b). Note that, the change of gap width does not affect the phase-matching condition, but as the coupling gap gradually increases, the coincidence count increases up to a maximum at a gap of $0.45\ \mu\text{m}$, and hereby after decreases, as shown in Figure 5(c). Figure 5(d) shows monotonic increase of the measured pump light wavelength for near-degenerate SPDC with respect to the MRR radius. The experimentally measured results are consistent with theory. Slight only differences can be attributed to minor fabrication errors affecting the resonance characteristics of the MRR.

Figure 6 shows a more detailed analysis of the photon pair generation. The spectral dependence of the pump light on pair generation is plotted in Figure 6(a) for an MRR with a $150\ \mu\text{m}$ radius and a $0.45\ \mu\text{m}$ coupling gap. Maximum coincidence counts were found to be at a pump wavelength of $785.44\ \text{nm}$. Note that the pump wavelength of the SPDC process only differs by approximately $0.1\ \text{nm}$ from that of the SHG process. This discrepancy arises primarily from the inherent measurement uncertainty associated with the

wavelength meter employed in the SPDC experiment. These results reveal a wavelength consistency between the two processes.

Figure 6(b) details about the measured rates and overall statistics of the source. Single photon and coincidence counts are measured as a function of input pump power and used to determine the on-chip photon pair generation rate (PGR) per unit of time, defined as:

$$\text{PGR} = \frac{N_1 N_2}{2N_{12}} \quad (1)$$

where $N_{1(2)}$ is the single-photon detection count rate in each path and N_{12} is the two-photon coincidence count rate. The brightness of a photon source quantified by its PGR serves as a metric for evaluating performance as a quantum light source. Hence, the PGR at different pump powers is plotted in red, with the corresponding fit shown in black in Figure 6(b). When the pump light power is $12.3\ \mu\text{W}$, the coincidence count rate is found to be $167\ \text{Hz}$, and singles are found to exceed $14\ \text{KHz}$, the dark count is $1.5\ \text{KHz}$, resulting in a PGR up to $0.49\ \text{MHz}$. The slope of the fitting indicates the two-photon source brightness of $40.2\ \text{MHz/mW}$.

The coincidence-to-accidental ratio (CAR) plotted in blue in Figure 6(b) provides relevant information about the quality and is defined as:

$$\text{CAR} = \frac{N_{\text{CC}} - N_{\text{AC}}}{N_{\text{AC}}} \quad (2)$$

where N_{CC} is the number of total coincidence counts and N_{AC} is the number of accidental coincidence counts. The maximum CAR was found to be 1786 at an input pump power of $6.14\ \mu\text{W}$. The CAR shows monotonic decrease with

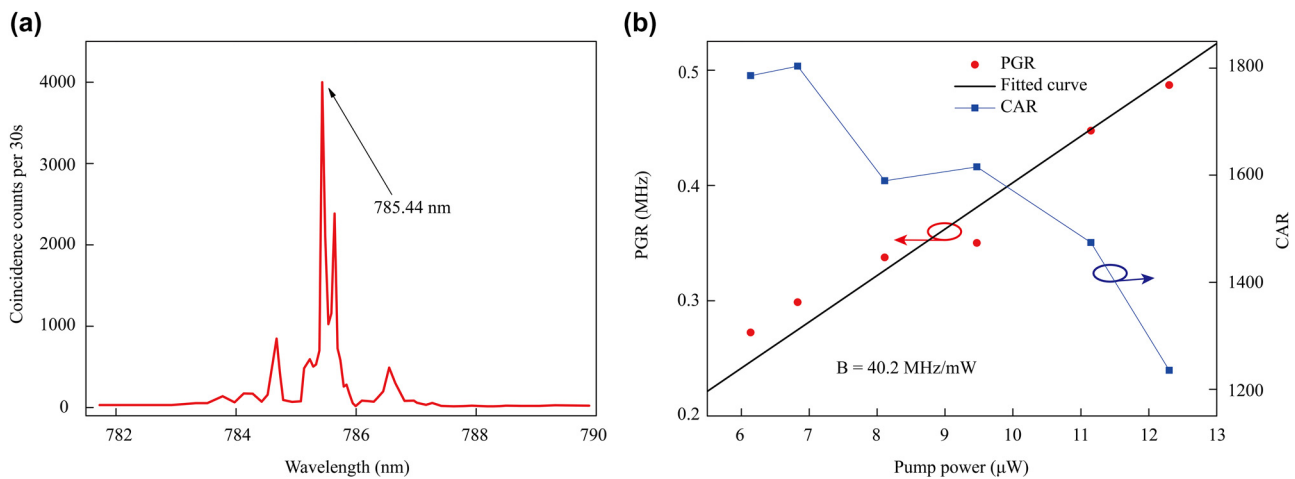


Figure 6: Characterization of the quality of the generated photon pairs for an MRR of $150\ \mu\text{m}$ radius and a $0.45\ \mu\text{m}$ coupling gap. (a) Measured coincidence counts highlight the SPDC spectrum as a function of pump wavelength, indicating maximum coincidence for an input pump wavelength of $785.44\ \text{nm}$, consistent with the conditions for SHG. (b) Measured PGR in red, with corresponding fit curve in black, and CAR in blue for different input pump powers. The brightness, B , is found to be $B = 40.2\ \text{MHz/mW}$.

Table 1: Performance comparison of photon-pair sources based on continuous-wave pumped micro-ring resonators with modal phase matching.

Platform	Radius (μm)	Type	Pump power	PGR (MHz)	Brightness @1 μW	CAR	Ref.
SOI	73	SFWM	19 μW	0.8	2.2 KHz	600	[40]
SOI	10	SFWM	59 μW	0.52	149 Hz	532	[41]
AlN	30	SPDC	1.9 mW	11	5.8 KHz	–	[42]
Si_3N_4	25	SFWM	46 μW	10	4.8 KHz	2,200	[43]
InP	24	SFWM	22 μW	0.07	145 Hz	277	[44]
AlGaAsOI	13.91	SFWM	$\sim 20 \mu\text{W}$	~ 8	20 KHz	353	[45]
SiC	43	SFWM	0.17 mW	0.009	0.31 Hz	600	[11]
TFLN	150	SPDC	12.3 μW	0.49	40.2 KHz	1,235	This work

input pump power but remains above 1,200 over a relatively wider range of input powers up to 12.3 μW . These results demonstrate the high quality of the generated photons from our source. Furthermore, we present a comparative assessment of MRRs fabricated from different materials for photon-pair generation using modal phase matching and continuous-wave pumping as shown in Table 1. Table 1 clearly indicates that the TFLN MRR developed in this work achieves exceptional brightness and CAR metrics, establishing their advantages as high-performance photon pair sources. Future improvements targeting the mode converter efficiency and quality of the chip facet coupling are expected to further elevate photon pair spectral brightness within the TFLN MRR.

4 Conclusions

We have demonstrated an on-chip integrated photon-pair source using a TFLN MRR based on modal phase matching. The MRR's structural parameters were engineered to achieve modal phase matching between telecommunication and near-visible wavelengths. Additionally, through optimization of the mode converter, the pump laser was configured to operate in higher-order mode under phase-matching condition during SPDC. The PGR was measured to be as high as 40.2 MHz/mW, with a CAR exceeding 1,200 at input pump powers of 12.3 μW . These results confirm the efficiency and high-quality photon pair generation enabled by modal phase-matched TFLN MRRs. Despite lower nonlinear efficiency compared to quasi-phase matching, modal phase matching may be more suitable for the integration of dense on-chip nonlinear quantum devices, such as state generation, manipulation, and detection. Advancements in fabrication technology, especially the development of ultra-high-Q TFLN MRRs, may enable the modal phase-matched approach to achieve results comparable to periodically poled TFLN MRRs. This would thereby simplify fabrication, optimize performance, and facilitate easier integration

into modern nonlinear and quantum photonic devices, expanding the potential applications of on-chip photon sources.

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Author contribution: TC and FX contributed equally to this work. TC contributed to the device proposal and design, numerical simulations, experimental measurements, data processing and analysis, and manuscript writing. FX contributed to device design, experimental measurements, data analysis, and the writing of the paper. RH contributed to the writing of the paper and discussion of the results. XM contributed to numerical simulations. JZ and YZ contributed to experimental measurements. YX contributed to the writing of the paper. ZY contributed to the fabrication of the sample. CS, QW, and SZ contributed to the analysis and discussion of the results. HL supervised various parts of the project and contributed to the device proposal, the analysis and discussion of the results, and the writing of the paper. All authors have accepted responsibility for the entire content of this manuscript and consented to its submission to the journal, reviewed all the results, and approved the final version of the manuscript.

Conflict of interest: Authors state no conflict of interest.

Data availability: The data that support the findings of this study are available from the authors on reasonable request.

References

- [1] E. Knill, R. Laflamme, and G. J. Milburn, "A scheme for efficient quantum computation with linear optics," *Nature*, vol. 409, pp. 46–52, 2001.

- [2] X. Lu, *et al.*, “Chip-integrated visible-telecom entangled photon pair source for quantum communication,” *Nat. Phys.*, vol. 15, no. 4, pp. 373–381, 2019.
- [3] V. Giovannetti, S. Lloyd, and L. Maccone, “Quantum-enhanced measurements: beating the standard quantum limit,” *Science*, vol. 306, no. 5700, pp. 1330–1336, 2004.
- [4] A. Orieux, M. A. M. Versteegh, K. D. Jons, and S. Ducci, “Semiconductor devices for entangled photon pair generation: a review,” *Rep. Prog. Phys.*, vol. 80, no. 7, p. 076001, 2017.
- [5] S. Tanzilli, *et al.*, “PPLN waveguide for quantum communication,” *Eur. Phys. J. D*, vol. 18, no. 2, pp. 155–160, 2002.
- [6] J. Zhao, C. Ma, M. Rusing, and S. Mookherjee, “High quality entangled photon pair generation in periodically poled thin-film lithium niobate waveguides,” *Phys. Rev. Lett.*, vol. 124, no. 16, p. 163603, 2020.
- [7] B. Jin, D. Mishra, and C. Argyropoulos, “Efficient single-photon pair generation by spontaneous parametric down-conversion in nonlinear plasmonic metasurfaces,” *Nanoscale*, vol. 13, no. 47, pp. 19903–19914, 2021.
- [8] Q. Guo, *et al.*, “Ultrathin quantum light source with van der Waals NbOCl₂ crystal,” *Nature*, vol. 613, pp. 53–59, 2023.
- [9] F. Xuan, M. Lai, Y. Wu, and S. Y. Quek, “Exciton-enhanced spontaneous parametric down-conversion in two-dimensional crystals,” *Phys. Rev. Lett.*, vol. 132, no. 24, 2024. <https://doi.org/10.1103/PhysRevLett.132.246902>.
- [10] Q. Lin, F. Yaman, and G. P. Agrawal, “Photon-pair generation by four-wave mixing in optical fibers,” *Opt. Lett.*, vol. 31, no. 9, pp. 1286–1288, 2006.
- [11] A. Rahmouni, *et al.*, “Entangled photon pair generation in an integrated SiC platform,” *Light: Sci. Appl.*, vol. 13, no. 1, p. 110, 2024.
- [12] Y. M. He, *et al.*, “On-demand semiconductor single-photon source with near-unity indistinguishability,” *Nat. Nanotechnol.*, vol. 8, no. 3, pp. 213–217, 2013.
- [13] P. Senellart, G. Solomon, and A. White, “High-performance semiconductor quantum-dot single-photon sources,” *Nat. Nanotechnol.*, vol. 12, no. 11, pp. 1026–1039, 2017.
- [14] T. Liu, *et al.*, “Efficient photon-pair generation empowered by dual quasibound states in the continuum,” *Phys. Rev. B*, vol. 109, no. 15, p. 155424, 2024.
- [15] A. Boes, *et al.*, “Lithium niobate photonics: unlocking the electromagnetic spectrum,” *Science*, vol. 379, no. 6627, p. eabj4396, 2023.
- [16] C. Wang, *et al.*, “Metasurface-assisted phase-matching-free second harmonic generation in lithium niobate waveguides,” *Nat. Commun.*, vol. 8, no. 1, p. 2098, 2017.
- [17] R. Luo, Y. He, H. Liang, M. Li, and Q. Lin, “Highly tunable efficient second-harmonic generation in a lithium niobate nanophotonic waveguide,” *Optica*, vol. 5, no. 8, pp. 1006–1011, 2018.
- [18] C. Wang, *et al.*, “Ultrahigh-efficiency second-harmonic generation in nanophotonic PPLN waveguides,” *Optica*, vol. 5, no. 11, pp. 1438–1441, 2018.
- [19] A. Rao, K. Abdelsalam, T. Sjaardema, A. Honardoost, G. F. Camacho-Gonzalez, and S. Fathpour, “Actively-monitored periodic-poling in thin-film lithium niobate photonic waveguides with ultrahigh nonlinear conversion efficiency of 4600% $W^{-1}cm^{-2}$,” *Opt. Express*, vol. 27, no. 18, pp. 25920–25930, 2019.
- [20] R. Luo, Y. He, H. Liang, M. Li, J. Ling, and Q. Lin, “Optical parametric generation in a lithium niobate microring with modal phase matching,” *Phys. Rev. Appl.*, vol. 11, no. 3, p. 034026, 2019.
- [21] M. Yu, B. Desiatov, Y. Okawachi, A. L. Gaeta, and M. Loncar, “Coherent two-octave-spanning supercontinuum generation in lithium-niobate waveguides,” *Opt. Lett.*, vol. 44, no. 5, pp. 1222–1225, 2019.
- [22] J. Lu, Y. Xu, J. Surya, X. Liu, Y. Xu, and H. X. Tang, “Octave-spanning supercontinuum generation in nanoscale lithium niobate waveguides,” *Opt. Lett.*, vol. 44, no. 6, pp. 1492–1495, 2019.
- [23] C. Wang, M. Zhang, M. Yu, R. Zhu, H. Hu, and M. Loncar, “Monolithic lithium niobate photonic circuits for Kerr frequency comb generation and modulation,” *Nat. Commun.*, vol. 10, p. 978, 2019.
- [24] Y. Hu, *et al.*, “High-efficiency and broadband on-chip electro-optic frequency comb generators,” *Nat. Photonics*, vol. 16, pp. 679–685, 2022.
- [25] Z. Gong, M. Shen, J. Lu, J. B. Surya, and H. X. Tang, “Monolithic Kerr and electro-optic hybrid microcombs,” *Optica*, vol. 9, no. 9, pp. 1060–1065, 2022.
- [26] S. Tanzilli, *et al.*, “Highly efficient photon-pair source using periodically poled lithium niobate waveguide,” *Electron. Lett.*, vol. 37, no. 1, 2001. <https://doi.org/10.1049/el:20010009>.
- [27] H. Jin, *et al.*, “On-chip generation and manipulation of entangled photons based on reconfigurable lithium–niobate waveguide circuits,” *Phys. Rev. Lett.*, vol. 113, no. 10, p. 103601, 2014.
- [28] U. A. Javid, J. Ling, J. Staffa, M. Li, Y. He, and Q. Lin, “Ultrabroadband entangled photons on a nanophotonic chip,” *Phys. Rev. Lett.*, vol. 127, no. 18, p. 183601, 2021.
- [29] K. Kwon, *et al.*, “Photon-pair generation using inverse-designed thin-film lithium niobate mode converters,” *APL Photonics*, vol. 9, no. 5, p. 056108, 2024.
- [30] X. Shi, *et al.*, “Efficient photon-pair generation in layer-poled lithium niobate nanophotonic waveguides,” *Light: Sci. Appl.*, vol. 13, no. 1, p. 282, 2024.
- [31] H. Qiu, *et al.*, “A continuously tunable sub-gigahertz microwave photonic bandpass filter based on an ultra-high-Q silicon microring resonator,” *J. Lightwave Technol.*, vol. 36, no. 19, pp. 4312–4318, 2018.
- [32] Q. Lin, *et al.*, “Versatile tuning of compact microring waveguide resonator based on lithium niobate thin films,” *Photonics*, vol. 10, no. 4, p. 424, 2023.
- [33] V. R. Almeida, C. A. Barrios, R. R. Panepucci, and M. Lipson, “All-optical control of light on a silicon chip,” *Nature*, vol. 431, pp. 1081–1084, 2004.
- [34] C. Sun, *et al.*, “High-efficiency single-mode erbium-doped lithium niobate microring laser with milliwatt output power,” *Opt. Lett.*, vol. 49, no. 24, pp. 6996–6999, 2024.
- [35] Z. Ma, *et al.*, “Ultrabright quantum photon sources on chip,” *Phys. Rev. Lett.*, vol. 125, no. 26, p. 263602, 2020.
- [36] T. P. McKenna, *et al.*, “Ultra-low-power second-order nonlinear optics on a chip,” *Nat. Commun.*, vol. 13, p. 4532, 2022.
- [37] U. A. Javid, R. L. Rois, J. Ling, A. Graf, J. Staff, and Q. Lin, “Chip-scale simulations in a quantum-correlated synthetic space,” *Nat. Photonics*, vol. 17, pp. 883–890, 2023.
- [38] H. Hwang, *et al.*, “Spontaneous parametric downconversion photon pair generation in small footprint X-cut periodically poled lithium niobate micro-resonator,” *Opt. Lett.*, vol. 49, no. 19, pp. 5379–5382, 2024.
- [39] R. R. Xie, G. Q. Li, F. Chen, and G. Long, “Microresonators in lithium niobate thin films,” *Adv. Opt. Mater.*, vol. 9, no. 19, p. 2100539, 2021.

- [40] E. Engin, *et al.*, “Photon pair generation in a silicon micro-ring resonator with reverse bias enhancement,” *Opt. Express*, vol. 21, no. 23, pp. 27826–27834, 2013.
- [41] C. Ma, X. Wang, V. Anant, A. D. Beyer, M. D. Shaw, and S. Mookherjea, “Silicon photonic entangled photon-pair and heralded single photon generation with $CAR > 12,000$ and $g(2)(0) < 0.006$,” *Opt. Express*, vol. 25, no. 26, pp. 32995–33006, 2017.
- [42] X. Guo, C. Zou, C. Schuck, H. Jung, R. Cheng, and H. X. Tang, “Parametric down-conversion photon-pair source on a nanophotonic chip,” *Light: Sci. Appl.*, vol. 6, no. 5, p. e16249, 2017.
- [43] X. Lu, *et al.*, “Chip-integrated visible–telecom entangled photon pair source for quantum communication,” *Nat. Phys.*, vol. 15, pp. 373–381, 2019.
- [44] R. R. Kumar, M. Raevskaia, V. Pogoretskii, Y. Jiao, and H. K. Tsang, “Entangled photon pair generation from an InP membrane micro-ring resonator,” *Appl. Phys. Lett.*, vol. 114, no. 2, p. 021104, 2019.
- [45] T. Steiner, *et al.*, “Ultrabright entangled-photon-pair generation from an AlGaAs-On-Insulator microring resonator,” *PRX Quantum*, vol. 2, p. 010337, 2021.