# 南方科技大学

# 优秀硕士学位论文申请材料

作者姓名：陈睿扬

导师姓名：杨胜军/刘骏秋

学科/专业学位类别：量子科学与工程

所在院系：量子科学与工程研究院

# 攻读硕士学位期间代表性成果

SCI 检索源期刊：

1. **Ruiyang Chen**, Yi-Han Luo, Jinbao Long, Baoqi Shi, Chen Shen, and Junqiu Liu. Ultralow-loss integrated photonics enables bright, narrow-band, photon-pair sources, *Physical Review Letters* 2024, 133, 083803.
   （SCI 收录，WOS:001381675200003，DOI:10.1103/PhysRevLett.133.083803, IF=8.1，对应学位论文 3-6 章）
2. **Ruiyang Chen**, Yi-Han Luo, Jinbao Long, and Junqiu Liu. Arbitrary-phase locking of fiber Mach-Zehnder interferometers. *Physical Review Applied* 2024, 22, 054051.
   （SCI 收录，WOS: 001361486400002, DOI:10.1103/PhysRevApplied.22.054051, IF=4.7，对应学位论文第 6 章）
3. Yi-Han Luo, Baoqi Shi, Wei Sun, **Ruiyang Chen**, Sanli Huang, Zhongkai Wang, Jinbao Long, Chen Shen, Zhichao Ye, Hairun Guo, and Junqiu Liu. A wideband, high-resolution vector spectrum analyzer for integrated photonics. *Light: Science & Applications* 2024, 13, 83.
   （SCI 收录，WOS: 001198125300001，DOI:10.1038/s41377-024-01435-z, IF=20.6，对应学位论文第 3.2 节）

专利、获奖：

专利：

“基于不等臂干涉仪的锁相装置及系统”，已授权，专利号：ZL 2024 2 1724551.8

获奖：

1.获得 2024 年国家奖学金。

2.获得 2024 年中国激光杂志社青衿奖（全国唯一获奖的硕士生）。

3.研究工作获评 2024 年世界 30 大光学进展。

**导师对学生参评优秀硕士学位论文代表性成果的审查意见：**

该生攻读硕士期间的代表性成果，数据准确无误、真实可靠，无学术不端和学术失范行为。

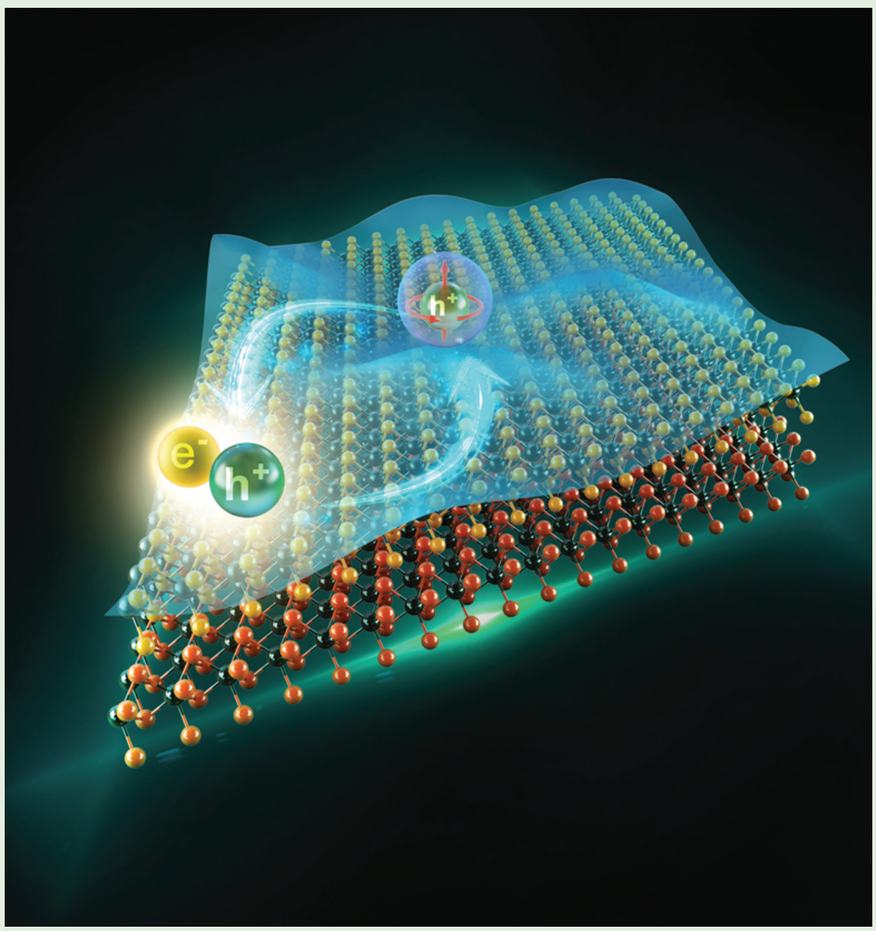
**导师签字：** 杨胜军

**日期：2025 年 5 月 21 日**

133

# PHYSICAL REVIEW LETTERS

Published week ending 23 AUGUST 2024




PRL 133 (8), 080201–088202, 23 August 2024 (252 total pages)

8

Published by
American Physical Society

APS

Volume 133, Number 8

Distinguishing Quantum Phases through Cusps in Full Counting Statistics ..... 083402
Chang-Yan Wang, Tian-Gang Zhou, Yi-Neng Zhou, and Pengfei Zhang
Theory of the Spectral Function of Fermi Polarons at Finite Temperature ..... 083403
Hui Hu, Jia Wang, and Xia-Ji Liu
Collective Dynamical Fermi Suppression of Optically Induced Inelastic Scattering ..... 083404
Camen A. Royse, J. Huang, and J. E. Thomas
Reversible Phasonic Control of a Quantum Phase Transition in a Quasicrystal ..... 083405
Toshihiko Shimasaki, Yifei Bai, H. Esat Kondakci, Peter Dotti, Jared E. Pagett, Anna R. Dardia, Max Prichard, André Eckardt, and David M. Weld
Scalable Spin Squeezing in Two-Dimensional Arrays of Dipolar Large-*S* Spins ..... 083601
Youssef Trifa and Tommaso Roscilde
Realization of a Coherent and Efficient One-Dimensional Atom ..... 083602
Natasha Tomm, Nadia O. Antoniadis, Marcelo Janovitch, Matteo Brunelli, Rüdiger Schott, Sascha R. Valentin, Andreas D. Wieck, Arne Ludwig, Patrick P. Potts, Alisa Javadi, and Richard J. Warburton
Dressed Atom Revisited: Hamiltonian-Independent Treatment of the Radiative Cascade ..... 083603
Francesco V. Pepe and Karolina Słowik
All Optical Zepto-Newton-Meter Nanoscale Silk Sensor ..... 083801
Shivali Sokhi and Kamal P. Singh
Temporal Goos-Hänchen Shift in Synthetic Discrete-Time Heterolattices ..... 083802
Chengzhi Qin, Shulin Wang, Bing Wang, Xinyuan Hu, Chenyu Liu, Yinglan Li, Lange Zhao, Han Ye, Stefano Longhi, and Peixiang Lu
Ultralow-Loss Integrated Photonics Enables Bright, Narrowband, Photon-Pair Sources ..... 083803
Ruiyang Chen, Yi-Han Luo, Jinbao Long, Baoqi Shi, Chen Shen, and Junqiu Liu

**Physics of Fluids, Earth & Planetary Science, and Climate**

Passive Viscous Flow Selection via Fluid-Induced Buckling ..... 084001
Hemanshul Garg, Pier Giuseppe Ledda, Jon Skov Pedersen, and Matteo Pezzulla

**Plasma and Solar Physics, Accelerators and Beams**

Pareto Optimization and Tuning of a Laser Wakefield Accelerator ..... 085001
F. Irshad, C. Eberle, F. M. Foerster, K. v. Grafenstein, F. Haberstroh, E. Travac, N. Weisse, S. Karsch, and A. Döpp

**Condensed Matter and Materials**

Decoding the Drive-Bath Interplay: A Guideline to Enhance Superconductivity ..... 086001
Rui Lin, Aline Ramires, and R. Chitra
Non-Hermitian Fermi-Dirac Distribution in Persistent Current Transport ..... 086301
Pei-Xin Shen, Zhide Lu, Jose L. Lado, and Mircea Trif
Exchange-Correlation Energy from Green's Functions ..... 086401
Steven Crisostomo, E. K. U. Gross, and Kieron Burke
Moiré Exchange Effect in Twisted $WSe_2/WS_2$ Heterobilayer ..... 086501
Jiayi Zhu, Huiyuan Zheng, Xi Wang, Heonjoon Park, Chengxin Xiao, Yinong Zhang, Takashi Taniguchi, Kenji Watanabe, Jiaqiang Yan, Daniel R. Gamelin, Wang Yao, and Xiaodong Xu
Nonlinear Effects on Charge Fractionalization in Critical Chains ..... 086502
Flávia B. Ramos, Rodrigo G. Pereira, Sebastian Eggert, and Imke Schneider
Altermagnetic Anomalous Hall Effect Emerging from Electronic Correlations ..... 086503
Toshihiro Sato, Sonia Haddad, Ion Cosma Fulga, Fakher F. Assaad, and Jeroen van den Brink
Gapped Boundaries of Fermionic Topological Orders and Higher Central Charges ..... 086601
Minyoung You

*(Continued on Preceding Page)*

This paper was highlighted in the APS publication *Physics* (physics.aps.org).
By suggesting a few manuscripts each week, we hope to promote reading across fields. Please see our Announcement Phys. Rev. Lett. 98, 010001 (2007)

# Ultralow-Loss Integrated Photonics Enables Bright, Narrowband, Photon-Pair Sources

Ruiyang Chen,[1,2] Yi-Han Luo,[1,*] Jinbao Long,[1] Baoqi Shi,[1,3] Chen Shen,[1,4] and Junqiu Liu[1,5,†]
[1]International Quantum Academy, Shenzhen 518048, China
[2]Shenzhen Institute for Quantum Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China
[3]Department of Optics and Optical Engineering, University of Science and Technology of China, Hefei, Anhui 230026, China
[4]Qaleido Photonics, Shenzhen 518048, China
[5]Hefei National Laboratory, University of Science and Technology of China, Hefei 230088, China

(Received 28 April 2024; accepted 23 July 2024; published 22 August 2024)

Photon-pair sources are critical building blocks for photonic quantum systems. Leveraging Kerr nonlinearity and cavity-enhanced spontaneous four-wave mixing, chip-scale photon-pair sources can be created using microresonators built on photonic integrated circuit. For practical applications, a high microresonator quality factor $Q$ is mandatory to magnify photon-pair sources' brightness and reduce their linewidth. The former is proportional to $Q^4$, while the latter is inversely proportional to $Q$. Here, we demonstrate an integrated, microresonator-based, narrowband photon-pair source. The integrated microresonator, made of silicon nitride and fabricated using a standard CMOS foundry process, features ultralow loss down to 0.03 dB/cm and intrinsic $Q$ factor exceeding $10^7$. The photon-pair source has brightness of $1.17 \times 10^9$ Hz/mW$^2$/GHz and linewidth of 25.9 MHz, both of which are record values for silicon-photonics-based quantum light source. It further enables a heralded single-photon source with heralded second-order correlation $g_h^{(2)}(0) = 0.0037(5)$, as well as an energy-time entanglement source with a raw visibility of 0.973(9). Our work evidences the global potential of ultralow-loss integrated photonics to create novel quantum light sources and circuits, catalyzing efficient, compact, and robust interfaces to quantum communication and networks.

DOI: 10.1103/PhysRevLett.133.083803

Quantum science and technology have revolutionized our information society by offering a new paradigm to generate, transmit, and process information. Photons offer unrivaled coherence and immunity to perturbation for quantum computation [1–3], and have been ubiquitously used in quantum communication [4–8]. Currently, an emerging trend is to realize quantum information processing using photonic integrated circuit (PIC), which features small size, weight, and power consumption [9–11]. In addition, PIC-based quantum chips can be manufactured with large volume and low cost using established CMOS foundries. Indeed, in the last decade, integrated photonics has enabled increasingly diverse applications on quantum states manipulation [12,13], quantum key distribution [14], quantum networks [15], and quantum frequency conversion [16,17].

For photonic quantum systems, photon-pair sources are key building blocks. Particularly, narrowband photon-pair sources are essential for long-distance quantum communication using quantum repeaters [18,19]. Here, the narrow bandwidth is critical, as it must match the natural linewidth of atomic transition to ensure efficient photon-atom interface. Meanwhile, narrowband sources suffer minimum distortion from chromatic dispersion when transmitting over fibers. Moreover, a narrow band boosts the brightness (i.e., photon flux rate) of photon-pair sources.

To build narrowband photon-pair sources, nonlinear optical microresonators are particularly useful [20,21]. Compared to the methods using cavity-enhanced spontaneous parametric down-conversion with bulky crystals [22,23] or using atomic transition [24,25], optical microresonators are small, compact, and robust. By leveraging the resonant nature for intracavity power enhancement, optical microresonators can offer exaggerated nonlinear effects, and have already been extensively used for optical frequency comb generation [26,27] and wideband frequency translation [28,29].

Previously, using microresonators on silicon PIC, photon-pair sources have achieved brightness of $1.6 \times 10^8$ Hz/mW$^2$/GHz and bandwidth of ~2 GHz [30]. The latter, due to the high optical loss (typically > 1 dB/cm) of silicon waveguides, is overwhelmingly larger than the linewidth of quantum memories based on atoms and ions, e.g., ~6 MHz for rubidium atoms [31] and ~150 MHz for $Er^{3+}$ ions [32,33]. The quest for even lower optical loss in PIC has motivated the rising and quick maturing of silicon nitride ($Si_3N_4$) integrated photonics. Integrated waveguides based on $Si_3N_4$ feature ultralow optical loss down to

*Contact author: luoyh@iqasz.cn
†Contact author: liujq@iqasz.cn

 © 2024 American Physical Society

# Arbitrary-phase locking of fiber unbalanced Mach-Zehnder interferometers

Ruiyang Chen,[1,2] Yi-Han Luo,[1,*] Jinbao Long,[1] and Junqiu Liu[1,3]

[1] *International Quantum Academy, Shenzhen 518048, China*

[2] *Shenzhen Institute for Quantum Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China*

[3] *Hefei National Laboratory, University of Science and Technology of China, Hefei 230088, China*

(Received 24 July 2024; revised 11 October 2024; accepted 22 October 2024; published 19 November 2024)

Optical interferometers are extensively used in fundamental physics studies, gravitational wave detection, quantum metrology, topological photonics, and quantum information processing. Fiber-based interferometers are compact, mechanically robust, and cheap, and thus are ubiquitously deployed. However, the optical phase in fiber interferometers is sensitive to ambient perturbation, resulting in compromised phase-sensing precision. Therefore, phase control, shifting, and stabilization of fiber interferometers are essential. Methods to create stable interference patterns and to lock a fiber interferometer at arbitrary phase have been shown, which however are sophisticated, bulky, and delicate, preventing wider application in harsh environments outside laboratories or in space. Here we demonstrate an innovative method for arbitrary-phase locking of fiber unbalanced Mach-Zehnder interferometers. Compared with existing methods, our method is much simpler. We showcase the preparation and characterization of a narrow-band, energy-time-entangled photon state generated in integrated nonlinear microresonators, where two-photon interference visibility reaches 0.993(6). Our method constitutes a critical building block for photonic quantum networks, and is useful to emerging single-photon interference in curved space-time that facilitates exploration of the interface of quantum mechanics and general relativity.

DOI: 10.1103/PhysRevApplied.22.054051

Optical phase is extensively used for coding information in modern telecommunication systems. As it is sensitive to environmental perturbation, optical phase also provides a route for sensing and measurement, e.g., to precisely characterize temperature, pressure, and vibration along a fiber path. Unlike optical intensity, direct detection of optical phase is challenging. Thus optical interferometers, mediating optical phase and intensity, have been developed and employed. Today optical interferometers are equally essential in emerging applications including fundamental physics studies [1,2], gravitational wave detection [3,4], quantum metrology [5,6], topological photonics [7–9], and quantum information processing [10–16]. In these applications, stable interference is critical. For example, the quantum interference of single photons traveling through curved space-time can be exploited to investigate the interface of quantum mechanics and general relativity [17–19]. To detect a tiny phase difference $\delta\phi$ introduced by gravitational red shift, the interferometer's phase fluctuation must be suppressed orders of magnitude lower than $|\delta\phi|$. In quantum communication, the fidelity of quantum information encoding and decoding critically relies on interferometer stability at the transmitter and receiver ends.

Fiber-based interferometers are compact, mechanically robust, and cheap, and thus are commonly used. However, in contrast to interferometers based on free-space optics, the optical interference in fiber interferometers can be severely corrupted by thermal and mechanical disturbances. Consequently, active feedback control and stabilization of optical phase are critical in these interferometers and their applications. Unbalanced Mach-Zehnder interferometers (UMZIs) are the most widely used fiber interferometers. The phase control and stabilization in a UMZI are illustrated in Fig. 1(a). A laser of frequency $f_0$ enters port 1, while port 2 is idle. The laser is evenly split into two branches by a beam splitter (BS). The fiber length in the upper branch is longer than that in the lower branch by $L$. The two branches recombine on another BS and create optical interference. The phase difference $\Phi$ between the two branches linearly depends on $L$, as $\Phi = 2\pi nLf_0/c = \pi L/L_\pi$, where $n$ is the refractive index of optical fibers, $c$ is the speed of light in vacuum, and $L_\pi = c/(2nf_0)$ is the unit length for $\pi$ phase shift. Neglecting optical loss in optical fibers and BS, we apply $L = L_0 + \Delta L$, where $L_0 = 2NL_\pi$ and the positive integer $N$ is selected such that $|\Delta L| \leq L_\pi$.

*Contact author: luoyh@iqasz.cn

 © 2024 American Physical Society

Official journal of the CIOMP 2047-7538
www.nature.com/lsa

ARTICLE Open Access

# A wideband, high-resolution vector spectrum analyzer for integrated photonics

Yi-Han Luo[1,2], Baoqi Shi[1,3], Wei Sun[1], Ruiyang Chen[1,2], Sanli Huang[1,4], Zhongkai Wang[1], Jinbao Long[1], Chen Shen[1], Zhichao Ye[5], Hairun Guo[6] and Junqiu Liu[1,4]✉

## Abstract

The analysis of optical spectra—emission or absorption—has been arguably the most powerful approach for discovering and understanding matter. The invention and development of many kinds of spectrometers have equipped us with versatile yet ultra-sensitive diagnostic tools for trace gas detection, isotope analysis, and resolving hyperfine structures of atoms and molecules. With proliferating data and information, urgent and demanding requirements have been placed today on spectrum analysis with ever-increasing spectral bandwidth and frequency resolution. These requirements are especially stringent for broadband laser sources that carry massive information and for dispersive devices used in information processing systems. In addition, spectrum analyzers are expected to probe the device's phase response where extra information is encoded. Here we demonstrate a novel vector spectrum analyzer (VSA) that is capable of characterizing passive devices and active laser sources in one setup. Such a dual-mode VSA can measure loss, phase response, and dispersion properties of passive devices. It also can coherently map a broadband laser spectrum into the RF domain. The VSA features a bandwidth of 55.1 THz (1260–1640 nm), a frequency resolution of 471 kHz, and a dynamic range of 56 dB. Meanwhile, our fiber-based VSA is compact and robust. It requires neither high-speed modulators and photodetectors nor any active feedback control. Finally, we employ our VSA for applications including characterization of integrated dispersive waveguides, mapping frequency comb spectra, and coherent light detection and ranging (LiDAR). Our VSA presents an innovative approach for device analysis and laser spectroscopy, and can play a critical role in future photonic systems and applications for sensing, communication, imaging, and quantum information processing.

## Introduction

The analysis of light and its propagation in media is fundamental in our information society. The discovery of light refraction and dispersion in media has resulted in the invention of prisms and gratings that are ubiquitously used in today's optical systems for imaging, sensing, and communication. Key enabling building blocks to these applications are dispersive elements that separate light components of different colors (i.e. frequencies) either spatially or temporally[1], with precisely calibrated chromatic dispersion. With these elements, modern optical spectrum analyzers (OSA) and spectrometers can deliver unrivaled frequency resolution, large dynamic range, and wide spectral bandwidth of hundreds of nanometers. Time-stretched systems[2] can probe ultrafast and rare events in complex nonlinear systems.

For spectrum analysis, precise and broadband frequency-calibration of dispersive elements is pivotal. Due to the ultimate need for spectrometers with reduced size, weight, cost, and power consumption, extensive efforts have been made to create miniaturized spectrometers[3–12] and broadband laser sources[13–30] based on integrated waveguides. For these devices, frequency-calibration is particularly crucial yet challenging since the dispersion of integrated

Correspondence: Junqiu Liu (liujq@iqasz.cn)
[1]International Quantum Academy, 518048 Shenzhen, China
[2]Shenzhen Institute for Quantum Science and Engineering, Southern University of Science and Technology, 518055 Shenzhen, China
Full list of author information is available at the end of the article
These authors contributed equally: Yi-Han Luo, Baoqi Shi.

© The Author(s) 2024
**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 licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

证书号第22783629号

专利公告信息

# 实用新型专利证书

实用新型名称：基于不等臂干涉仪的锁相装置及系统

专 利 权 人：深圳国际量子研究院

地　　址：518045 广东省深圳市福田区福保街道福田保税区槟榔道10号

发 明 人：刘骏秋;罗弋涵;陈睿扬

专　利　号：ZL 2024 2 1724551.8　　授权公告号：CN 222799919 U

专利申请日：2024年07月19日　　授权公告日：2025年04月25日

申请日时申请人：深圳国际量子研究院

申请日时发明人：刘骏秋;罗弋涵;陈睿扬

国家知识产权局依照中华人民共和国专利法进行审查，决定授予专利权，并予以公告。

专利权自授权公告之日起生效。专利权有效性及专利权人变更等法律信息以专利登记簿记载为准。

局长
申长雨

国家知识产权局
2025年04月25日

# 国家奖学金荣誉证书

编号：SSY202469925

陈睿扬同学荣获2024年硕士研究生国家奖学金，特颁此证。

中华人民共和国教育部

2024 年 12 月

青衿奖
2024

# 荣誉证书

陈睿扬

荣获中国激光杂志社第二届“青衿奖”（硕士研究生组），
特发此证，以资鼓励。

中国激光杂志社
CHINESE LASER PRESS

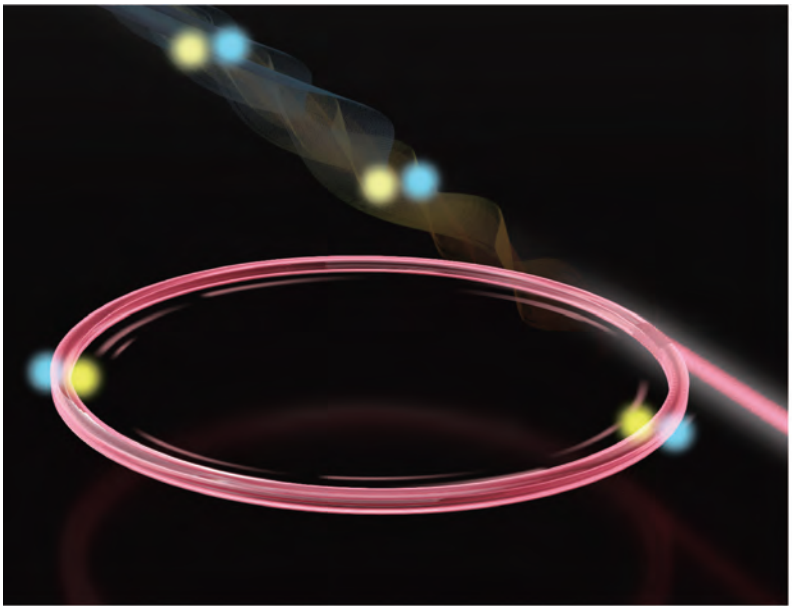
# Bright, Narrowband Photon-Pair Sources via Integrated Photonics

Quantum science and technology offer a new paradigm for generating, transmitting and processing information. Photons are important carriers of quantum information due to their unrivaled coherence and immunity to ambient perturbation. The use of photons has led to significant developments, such as the demonstration of quantum computational advantage[1] and the establishment of metropolitan quantum-communication networks.[2] However, since these advances in photonic quantum computation and communications use optical circuits based on free-space and fiber optics, their scalability and robustness are heavily limited.

Integrated photonics enables the synthesis, processing and detection of optical signals using photonic integrated circuits (PICs). Over the past few decades, its successful transition from laboratory research to foundry development has established integrated photonics as a standard technology deployed in high-data-rate telecommunications and data centers. Recently, silicon nitride ($Si_3N_4$) integrated photonics has gained prominence,[3,4] primarily driven by the low optical loss offered by $Si_3N_4$, which is beyond the reach of silicon and III–V semiconductors. Combined with modest Kerr nonlinearity, tight optical confinement and dispersion engineering, $Si_3N_4$ has become the leading candidate for on-chip photonic quantum information processing.

In recent work, we employed a standard CMOS foundry process to fabricate ultralow-loss $Si_3N_4$waveguides, building bright, narrowband photon-pair sources ,[5] which are essential building blocks for long-distance quantum communication with quantum repeaters and efficient photon–atom interfaces. We achieved a record on-chip generated photon linewidth of 25.9 MHz. Additionally, in our demonstrations, the photon-pair source exhibited a brightness exceeding $1\times10^9$ Hz/mW$^2$/GHz, setting a new record for integrated silicon photonics. This advance also facilitates the creation of a heralded single-photon source, characterized by a heralded second-order correlation $g^{(2)}(0)=0.0037(5)$, as well as an energy–time entanglement source with a raw visibility of 0.973(9).

We believe our work marks a critical step toward using integrated photonics to generate photon pairs whose linewidth can match atomic transitions commonly used for quantum repeaters. It paves the way to constructing efficient photon–atom interfaces in a robust, compact and low-cost manner. We anticipate that our photon-pair sources can naturally mediate a variety of integrated quantum devices. These PIC-based quantum chips can be manufactured at high volume and throughput using established CMOS foundries. Furthermore, we believe that leveraging heterogeneous integration of photon-pair sources and an ultralow-loss linear network with a superconducting nanowire single-photon detector could enable chip-scale quantum communication and internet. OPN



Schematic of the photon-pair source. A pump laser enters the microresonator, then photon pairs are generated from the pump laser through a nonlinear effect.


**RESEARCHERS**

**Ruiyang Chen**, International Quantum Academy, China, and Southern University of Science and Technology, China

**Yi-Han Luo** and **Jinbao Long**, International Quantum Academy, China

**Baoqi Shi**, International Quantum Academy, China, and University of Science and Technology of China

**Chen Shen**, International Quantum Academy, China, and Qaleido Photonics, China

**Junqiu Liu** (liujq@iqasz.cn), International Quantum Academy, China, and Hefei National Laboratory, China


**REFERENCES**


1. H.-S. Zhong et al. Science **370**, 1460 (2020).
2. Y.-A. Chen et al. Nature **589**, 214 (2021).
3. J. Liu et al. Nat. Commun. **12**, 2236 (2021).
4. Z. Ye et al. Photonics Res. **11**, 558 (2023).
5. R. Chen et al. Phys. Rev. Lett. **133**, 083803 (2024).