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# ADVANCED PHOTONICS

## Theme Issue on
## Quantum Technologies

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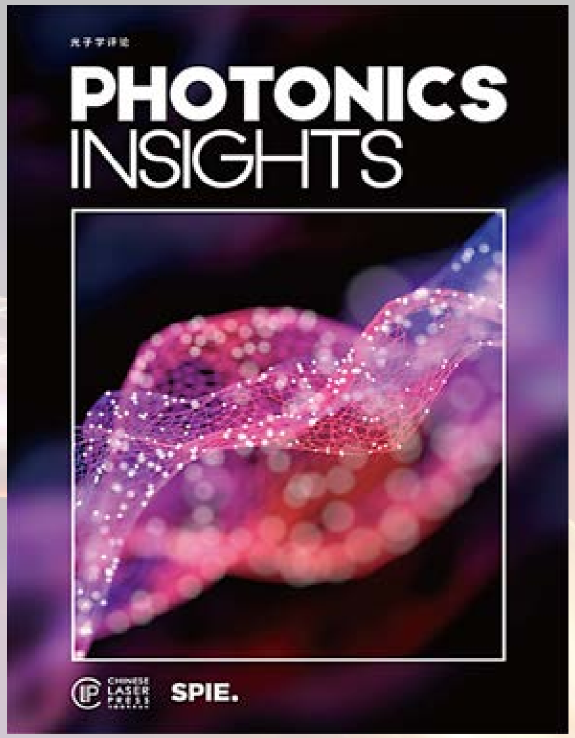

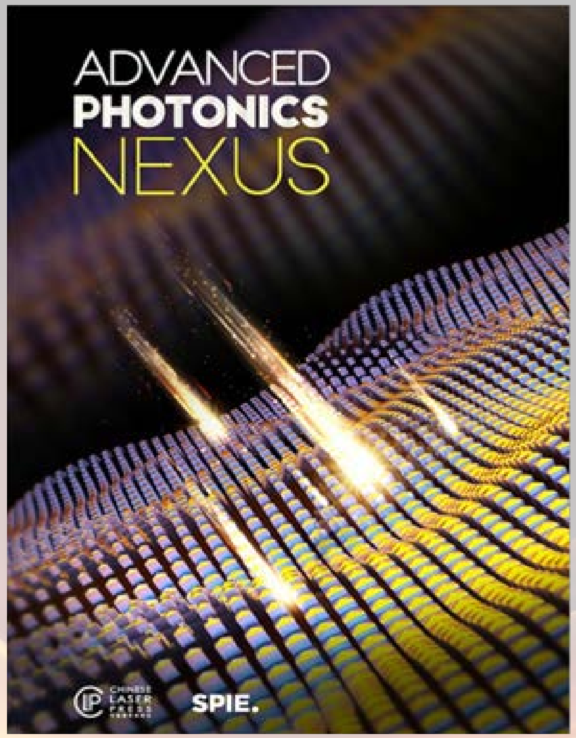

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***Theme Issue*** ***Quantum Technologies***

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# CONTENT

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# Photonics Advances Quantum Science and Technologies

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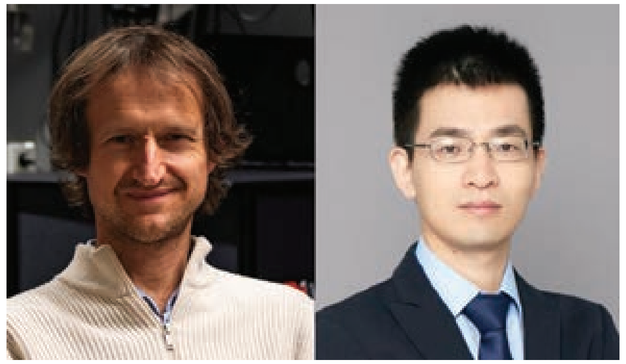

Mario Agio (Univ. of Siegen & CNR-INO; photo credit, S. Nimmrichter) (left); Chao-Yang Lu (USTC) (right).

Quantum science and technology is currently one of the most exciting frontiers in research and innovation. Tremendous effort is being devoted to pushing fundamental science into technology, with support from large, coordinated programs that involve academia, research centers, and industry worldwide. Throughout more than half a century of research, driven by curiosities in fundamental quantum physics, experiments in quantum optics, together with atomic, molecular, and optical physics, have laid the foundation for the development of a second quantum revolution, where fundamental concepts like quantum superposition, entanglement, and indistinguishability are now routinely exploited to realize quantum computing components, secure communications, and quantum-enhanced sensors with unprecedented performances. However, to become practically useful technologies, these ambitious goals still require a great deal of basic research effort, which must be combined with engineering and other disciplines to succeed. This exciting and intriguing perspective can be clearly witnessed in the recent interview of Prof. Xiaosong Ma with Sir Peter Knight in this issue of *Advanced Photonics.*

To spotlight advances in quantum science and technologies, we have invited review articles and original research contributions on this topic, gathered here in a collection. The collection is not intended to be a comprehensive account of photonic advances in quantum, but rather aims at emphasizing the important role of photonics in enabling the development of quantum technologies. We present two review articles and five original contributions from authoritative scientists in the field. S. Castelletto and A. Boretti review the emerging use of color centers in wide-band gap materials for sub-diffraction imaging, pointing out the widening of activities based on solid-state quantum emitters, originally addressed in solid-state quantum optics. Wang et al. discuss the impressive advancements on the implementation of quantum entanglement on a chip, based on progress in different integrated photonics platforms. The original research papers demonstrate how advanced photonics, such as the use of metasurfaces, integrated optics, and quantum dots, represents a unique resource for quantum technologies. They also point out that there is still much room, and need, for improvement in quantum-optical techniques and protocols.

We hope that readers, both established and early career researchers, will find this collection inspiring and, years later, will remember the onset of quantum technologies like Sir Peter Knight did for the onset of quantum optics: "I found it really fascinating!"

For convenience, the collection of articles is listed here:

"From fundamental quantum optics to quantum information technology: the personal journey of Sir Peter Knight" by Xiaosong Ma
DOI: https://doi.org/10.1117/1.AP.3.6.060501

"Color centers in wide-bandgap semiconductors for subdiffraction imaging: a review" by Stefania Castelletto and Alberto Boretti
DOI: https://doi.org/10.1117/1.AP.3.5.054001

"Quantum entanglement on photonic chips: a review" by Xiaojiong Chen, Zhaorong Fu, Qihuang Gong, and Jianwei Wang
DOI: https://doi.org/10.1117/1.AP.3.6.064002

"Heterogeneously integrated, superconducting silicon-photonic platform for measurement-device-independent quantum key distribution" by Xiaodong Zheng, Peiyu Zhang, Renyou Ge, Liangliang Lu, Guanglong He, Qi Chen, Fangchao Qu, Labao Zhang, Xinlun Cai, Yanqing Lu, Shining Zhu, Peiheng Wu, and Xiao-Song Ma
DOI: https://doi.org/10.1117/1.AP.3.5.055002

"Direct characterization of coherence of quantum detectors by sequential measurements" by Liang Xu, Huichao Xu, Jie Xie, Hui Li, Lin Zhou, Feixiang Xu, and Lijian Zhang
DOI: https://doi.org/10.1117/1.AP.3.6.066001

"Enhanced generation of non-degenerate photon-pairs in nonlinear metasurfaces" by Matthew Parry, Andrea Mazzanti, Alexander Poddubny, G. D. Valle, Dragomir Neshev, and Andrey A. Sukhorukov
DOI: https://doi.org/10.1117/1.AP.3.5.055001

"Entanglement-based quantum key distribution with a blinking-free quantum dot operated at a temperature up to 20K" by Christian

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# From fundamental quantum optics to quantum information technology: the personal journey of Sir Peter Knight

**Xiaosong Ma**
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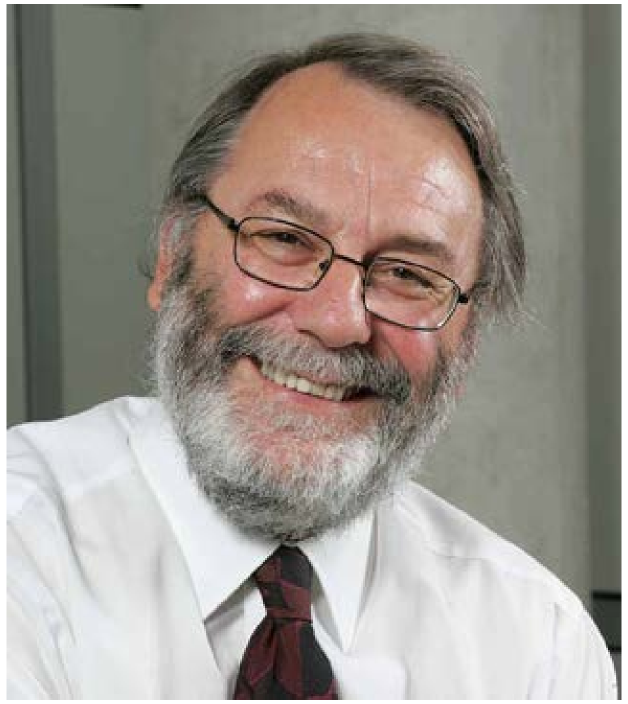
View the full interview ›



Professor Sir Peter Knight, Imperial College London, UK

***Xiaosong Ma:*** What inspired you to choose quantum optics as your major when you were a student, and can you share your experience or research journey in this field?

***Peter Knight:*** Quantum optics, as a discipline, was more or less formed during the time I've been active in the area. I started thinking about things that we would now call quantum optics in the middle of the 1960s when I was a student. As a subject, it was really hardly developed at that point, but looking in particular at the way that the quantum nature of light would manifest itself in regular laser type experiments was then beginning to emerge. The field initially was called "quantum electronics" at that point, and "quantum optics" was a term used by very few people who started to worry about what the quantum nature of light would do.

I started in this area as an undergraduate. Like many students, to demonstrate that you can do something original of your own, I had to do a project. The project I chose was to work on optical pumping: making a cesium cell and looking really carefully at ways in which you could monitor coherent transients in optical pumping. In particular, I was measuring the way that Rabi oscillations could be monitored and looking at decoherence—which sounds like the things we worry about now, but this of course was in the radio frequency regime. This was experimental activity that was done with really simple experiments and simple apparatus. Of course, this is before tunable lasers. This experiment was all done with thermal light sources.

Firstly, I found the field really fascinating. And secondly, I was probably deluded in thinking that I could be an experimentalist, because the apparatus was really simple. So, when I started my PhD, my project was to do a kind of mix of theory and experiment, and it very quickly emerged that I was totally incompetent, really useless as an experimentalist. And I think the people in the lab were really delighted when I said, "I think it would be best if I turned pretty much to theory." So my PhD was in theory. But I've always maintained a really close engagement with experimentalists around me. Rather than being a theorist only in a theoretical environment, I have always enjoyed working with colleagues who were doing experiments so we could feed off each other. So that journey was a kind of accident, but it was fascinating and it's something that I've done ever since, so in all of my roles and positions, I've always had people I could talk with who were doing wonderful experiments. I guess that's kind of unusual in many places in the UK, where theoreticians and experimentalists are often in separate departments.

I did my PhD in that area, and then I went off to the United States as a postdoc, working with Joseph Eberly in the United States. And again, you know, a really powerful theoretician but always working with experimentalists. I had a wonderful three years in Eberly's group as a postdoc, working with really great people and really understanding, for the first time, how we could put together a group, how to plan a long-term career.

I came back to the UK in 1974. Around that time, the number of people interested in quantum optics theory in the UK with proper academic jobs was probably about four or five people, in the whole country. It was an extreme minority interest. But it was something that was becoming really exciting. Coming in at the very beginning of a subject area was always a wonderful experience. When I came back to the UK, one of the leaders in the field was Rodney Loudon at the University of Essex. Of those three or four people other than me working in quantum optics, he was someone who was really influential in my career. And again, Rodney had worked very closely with experimentalists.

I had various fellowships, and that gave me my chance to have my first graduate students of my own. I basically co-supervised graduate students in the US. In particular, some of Eberly's students worked primarily with me. Peter Milonni, for example, worked primarily with me. That already gave me the experience of working with really talented people to hit tough problems. Working in isolation, on your own, you could do something; but working with a group of like-minded people, you could do so much more.

In 1979 I moved to Imperial College, and I've basically been at Imperial College ever since. My group expanded, became almost a subdepartment of the department, always with many experimental colleagues involved. And my experience of working in the US and then coming back to the UK really demonstrated to me that this kind of activity was an international endeavor. I really benefited from collaborating with people from around the world, so my group became extremely

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# Color centers in wide-bandgap semiconductors for subdiffraction imaging: a review

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**Abstract.** Solid-state atomic-sized color centers in wide-band-gap semiconductors, such as diamond, silicon carbide, and hexagonal boron nitride, are important platforms for quantum technologies, specifically for single-photon sources and quantum sensing. One of the emerging applications of these quantum emitters is subdiffraction imaging. This capability is provided by the specific photophysical properties of color centers, such as high dipole moments, photostability, and a variety of spectral ranges of the emitters with associated optical and microwave control of their quantum states. We review applications of color centers in traditional super-resolution microscopy and quantum imaging methods, and compare relative performance. The current state and perspectives of their applications in biomedical, chemistry, and material science imaging are outlined.

Keywords: color centers; quantum optics; single photon emitters; super-resolution imaging; transparent semiconductors.

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## 1 Introduction

The resolution of common fluorescence microscopes (wide-field or confocal microscopes) is limited by the diffraction of light, known as the Abbe limit. The attainable resolution is given by the full-width at half-maximum (FWHM) of the point spread function (PSF) of the beam at the focus of the objective. A high numerical aperture ($\mathrm{NA} = 1.4$) objective with visible light ($\lambda = 532$ nm) can theoretically reach a resolution of $d \approx \lambda/(2\sqrt{2} \times \mathrm{NA}) \sim 134$ nm and $d \approx \lambda/(2 \times \mathrm{NA}) \sim 190$ nm for the confocal and wide field, respectively, whereas the experimental resolution is generally in the range of ~200 to 250 nm due to the sample optical properties and beam imperfections. Super-resolution fluorescence microscopy (SRM) permits us to beat the diffraction limit, and it obtains images with a higher resolution, from 100 nm to as low as 20 nm or, in some cases, even lower, with few nanometer localization in some cases. This is a resolution/localization possible only by electron scanning probe microscopes. SRM's impact in life science, chemical, and physical sciences has been recognized by the Nobel Prize for Chemistry in 2014,[1] and it has revolutionized many areas of cellular microscopy[2] and even virology.[3,4]

Current SRM methods have resolved many problems in imaging using high localization molecules, with the opportunity to reach a very high resolution in principle. In general, they can provide high spatial localization and resolution with, however, limited applicability in tracking real-time biological processes with the required speed. In addition, the application of the currently achieved ultimate resolution in some of the SRM methods to specific biological samples, with associated high localization and the required sensitivity, is a prerequisite that is not yet fully achieved.

The current outstanding limitations in a few SRM approaches are

- the size of the fluorescent probes and their fluorescent properties;
- the use of near-ultraviolet excitation which is responsible for DNA damage and higher imaging background, reducing applicability for extended imaging time and tracking;
- the photobleaching of the fluorescent tags, which limits the duration of observation;

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# Quantum entanglement on photonic chips: a review

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**Abstract.** Entanglement is one of the most vital properties of quantum mechanical systems, and it forms the backbone of quantum information technologies. Taking advantage of nano/microfabrication and particularly complementary metal-oxide-semiconductor manufacturing technologies, photonic integrated circuits (PICs) have emerged as a versatile platform for the generation, manipulation, and measurement of entangled photonic states. We summarize the recent progress of quantum entanglement on PICs, starting from the generation of nonentangled and entangled biphoton states, to the generation of entangled states of multiple photons, multiple dimensions, and multiple degrees of freedom, as well as their applications for quantum information processing.

Keywords: quantum entanglement; integrated optics; photonic chip.

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## 1 Introduction

The famous Einstein–Podolsky–Rosen (EPR) state was originally proposed[1] and later named “entangled state”[2] for the debate of the completeness of the quantum mechanical description of reality. Pioneering experiments of EPR entanglement have allowed the exclusion of the presence of local hidden variables by violating the Bell inequality[3] and allowed significant Bell tests with a closure of detection and distance loopholes.[4–6] Moreover, entanglement has also become the enabling resource for quantum information applications in the fields of quantum communication and networks,[7] quantum metrology and imaging,[8,9] and quantum computation and simulations.[10,11] In all of the above fundamental investigations and technological developments, the photon has been in the core position, owing to its low-noise nature, ease of control, room-temperature operation, and high-speed transmission.[12] For example, the loophole-free Bell tests were implemented in entangled photonic systems.[4–6] The photon is recognized as the inevitable carrier for global-scale quantum key distribution[13] and quantum internet.[14] Recently, Boson sampling with photons was used to demonstrate quantum computational advantages.[15] Universal quantum computing with photons is possible with largely entangled cluster states.[16–18] Integrated quantum photonics provides a compact, reliable, reprogrammable, and scalable platform for the study of fundamental quantum physics and for the implementation of profound quantum applications.[19] Leveraging mature complementary metal-oxide-semiconductor (CMOS) fabrication, integrated photonic quantum technology progressed significantly since its first demonstration in the controlled-NOT logic gate on silica waveguide circuits in 2008.[20] This includes the development of advanced material systems,[20–32] implementations of major quantum communication protocols,[28,32,33] and proof-of-principle demonstrations of quantum computation and quantum simulation algorithms.[34–36] We recommend other reviews of those topics in Refs. 19 and 37.

In this review, we summarize the experimental progress of on-chip generation, manipulation, and measurement of entangled photonic states on integrated silicon-photonic quantum chips. In Sec. 2, we introduce the representation of on-chip quantum states in various degrees of freedom (DoFs) of single photons. In Sec. 3, we introduce integrated parametric photon-pair sources (nonentangled photon-pairs). In Sec. 4, we then focus on various types of photonic entangled states, including entangled biphoton states and entangled states of multiple

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# Heterogeneously integrated, superconducting silicon-photonic platform for measurement-device-independent quantum key distribution

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**Abstract.** Integrated photonics provides a route to both miniaturization of quantum key distribution (QKD) devices and enhancing their performance. A key element for achieving discrete-variable QKD is a single-photon detector. It is highly desirable to integrate detectors onto a photonic chip to enable the realization of practical and scalable quantum networks. We realize a heterogeneously integrated, superconducting silicon-photonic chip. Harnessing the unique high-speed feature of our optical waveguide-integrated superconducting detector, we perform the first optimal Bell-state measurement (BSM) of time-bin encoded qubits generated from two independent lasers. The optimal BSM enables an increased key rate of measurement-device-independent QKD (MDI-QKD), which is immune to all attacks against the detection system and hence provides the basis for a QKD network with untrusted relays. Together with the time-multiplexed technique, we have enhanced the sifted key rate by almost one order of magnitude. With a 125-MHz clock rate, we obtain a secure key rate of 6.166 kbps over 24.0 dB loss, which is comparable to the state-of-the-art MDI-QKD experimental results with a GHz clock rate. Combined with integrated QKD transmitters, a scalable, chip-based, and cost-effective QKD network should become realizable in the near future.

Keywords: quantum key distribution; hybrid photonics; single-photon detector; Bell-state measurement; time-multiplexing.

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## 1 Introduction

Quantum key distribution (QKD) employs the laws of quantum physics to provide information-theoretical security for key exchange.[1–5] Despite the substantial progress in the past 35 years, practical implementations of QKD still deviate from ideal descriptions in security proofs, mainly due to potential side-channel attacks. For instance, a series of loopholes have been identified due to the imperfections of measurement devices.[6–9] Inspired by the time-reversed entanglement-based QKD, measurement-device-independent QKD (MDI-QKD), which removes all detector side attacks, has been proposed.[10,11] Instead of relying on the trusted nodes of traditional QKD protocols, MDI-QKD requires only a central node (Charlie) to perform a Bell-state measurement (BSM). The correlations between the two senders (Alice and Bob) can be obtained from the BSM results. Importantly, even if Charlie is not trusted, one can still guarantee the security of the MDI-QKD as long as Charlie can project his two photons onto Bell states. The outstanding features of MDI-QKD invite global experimental efforts, which

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# Direct characterization of coherence of quantum detectors by sequential measurements

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**Abstract.** The quantum properties of quantum measurements are indispensable resources in quantum information processing and have drawn extensive research interest. The conventional approach to revealing quantum properties relies on the reconstruction of entire measurement operators by quantum detector tomography. However, many specific properties can be determined by a part of the matrix components of the measurement operators, which makes it possible to simplify the characterization process. We propose a general framework to directly obtain individual matrix elements of the measurement operators by sequentially measuring two noncompatible observables. This method allows us to circumvent the complete tomography of the quantum measurement and extract the required information. We experimentally implement this scheme to monitor the coherent evolution of a general quantum measurement by determining the off-diagonal matrix elements. The investigation of the measurement precision indicates the good feasibility of our protocol for arbitrary quantum measurements. Our results pave the way for revealing the quantum properties of quantum measurements by selectively determining the matrix components of the measurement operators.

Keywords: direct tomography; quantum measurement; weak measurement; sequential measurement; coherence.

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## 1 Introduction

The quantum properties of quantum measurements have been widely regarded as an essential resource for the preparation of quantum states,[1–3] achieving the advantages of quantum technologies,[4–7] as well as the study of fundamental quantum theories.[8–15] The time-reversal approach allows for the investigation of the properties of quantum measurements qualitatively from the perspective of quantum states.[16–18] In addition, the quantum resource theories for quantification of quantum properties of quantum measurements have been developed very recently[19–22] and have been applied to investigate coherence of quantum-optical detectors.[23] Thus developing efficient approaches to characterize the quantum properties of quantum measurements is important for both the fundamental investigations and practical applications.

A general quantum measurement and all its properties can be completely determined by the positive operator-valued measure (POVM) $\{\hat{\Pi}_l\}$, in which the element $\hat{\Pi}_l$ denotes the measurement operator corresponding to the outcome $l$. Several approaches have been developed to determine the unknown POVM,[24–27] of which the most representative is quantum detector tomography (QDT).[24] In QDT, a set of probe states $\{\rho^{(m)}\}$ are prepared to input the unknown measurement apparatus, and the probability of obtaining the outcome $l$ is given by $p_l^{(m)} = \mathrm{Tr}(\rho^{(m)}\hat{\Pi}_l)$. Provided that the input states are informationally complete for the tomography, the POVM $\{\hat{\Pi}_l\}$ can be reconstructed by minimizing the gap between the theoretical calculation and the experimental results. To date, QDT has achieved great success in characterizing a variety of quantum detectors, including

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# Enhanced generation of nondegenerate photon pairs in nonlinear metasurfaces

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**Abstract.** We predict theoretically a regime of photon-pair generation driven by the interplay of multiple bound states in the continuum resonances in nonlinear metasurfaces. This nondegenerate photon-pair generation is derived from the hyperbolic topology of the transverse phase matching and can enable orders-of-magnitude enhancement of the photon rate and spectral brightness, as compared to the degenerate regime. We show through comprehensive simulations that the entanglement of the photon pairs can be tuned by varying the pump polarization, which can underpin future advances and applications of ultracompact quantum light sources.

Keywords: optics; photonics; light; metasurface; spontaneous parametric down-conversion; entanglement.

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## 1 Introduction

Metasurfaces (MSs) offer an ultracompact and versatile platform for enhancing nonlinear optical processes, including harmonic generation and frequency mixing.[1,2] To realize such nonlinear interactions in bulk crystals and waveguides, one requires extended propagation distances, but in MSs a strong enhancement of light–matter interactions can be achieved with subwavelength thicknesses through the excitation of high-quality factor optical resonances. Notably, this can be facilitated by designing Bound State in the Continuum (BIC) resonances,[3–7] which support a high confinement of the optical field within the nonlinear material.[8–10]

In addition to classical frequency mixing, nonlinear MSs can also, through Spontaneous Parametric Down-Conversion (SPDC), generate entangled photons with a strong degree of spatial coherence.[11] SPDC in carefully engineered MSs has the potential to drive fundamental advances in the field of ultracompact multi-photon sources[12] that operate at room temperature, which are suitable for integration in end-user devices with applications that include quantum imaging[13] and free-space communications.[14] Traditionally, SPDC is performed in bulk nonlinear crystals with dimensions up to centimeters in length, while integrated waveguides have enabled a reduction of the footprint to millimeter[15] and down to 100 $\mu$m length scales.[16] At the subwavelength scale, generation of photon pairs was reported experimentally from a single AlGaAs nanoresonator[17] and lithium niobate MSs,[18] and studies were also conducted on monolayers of $MoS_2$,[19] carbon nanotubes,[20] and directional emission from nanoresonators.[21]

Importantly, SPDC in ultrathin nonlinear layers[22–24] can give rise to strong spatial correlations and allow quantum state engineering without the constraints of longitudinal phase matching. It has been proposed that a so-called "accidental" BIC at the pump frequency can increase the photon rate at a single nanoresonator,[25] while a photonic crystal slab with a BIC resonance can enhance SPDC in a monolayer of $WS_2$,[26] although the theoretically estimated rate was still much lower than with conventional sources. There is now strong interest in new concepts and

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# Entanglement-based quantum key distribution with a blinking-free quantum dot operated at a temperature up to 20 K

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**Abstract.** Entanglement-based quantum key distribution (QKD) promises enhanced robustness against eavesdropping and compatibility with future quantum networks. Among other sources, semiconductor quantum dots (QDs) can generate polarization-entangled photon pairs with near-unity entanglement fidelity and a multiphoton emission probability close to zero even at maximum brightness. These properties have been demonstrated under resonant two-photon excitation (TPE) and at operation temperatures below 10 K. However, source blinking is often reported under TPE conditions, limiting the maximum achievable photon rate. In addition, operation temperatures reachable with compact cryocoolers could facilitate the widespread deployment of QDs, e.g., in satellite-based quantum communication. We demonstrate blinking-free emission of highly entangled photon pairs from GaAs QDs embedded in a p-i-n diode. High fidelity entanglement persists at temperatures of at least 20 K, which we use to implement fiber-based QKD between two buildings with an average raw key rate of 55 bits/s and a qubit error rate of 8.4%. We are confident that by combining electrical control with already demonstrated photonic and strain engineering, QDs will keep approaching the ideal source of entangled photons for real world applications.

Keywords: quantum optics; quantum dots; nanophotonics; quantum cryptography.

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## 1 Introduction

Quantum key distribution (QKD) relying on single photons is regarded as one of the most mature quantum technologies.[1,2] However, the impossibility of amplifying single photons sets restrictions on the transmission distance. Entanglement-based QKD schemes are able to overcome these range limitations when embedded in quantum networks,[3,4] while also exhibiting a lower vulnerability to eavesdropping attacks.[1,5–8] For both fiber-based[9] and satellite-based[10] quantum cryptography, the most prominent sources of entangled photon pairs to date are based on the spontaneous parametric downconversion (SPDC) process. These sources are commercially available and can be operated in a large temperature range.[11] As a drawback, SPDC sources exhibit approximately Poissonian photon pair emission characteristics,[12] which severely limits their brightness when a high degree of entanglement—and thus a low qubit error rate (QBER)—is demanded. The biexciton–exciton (XX-X) spontaneous decay cascade in epitaxially grown semiconductor quantum dots (QDs) has been demonstrated to be a viable alternative to SPDC sources due to the sub-Poissonian entangled photon pair emission statistics.[13] In particular, GaAs QDs obtained by the Al droplet etching technique[14] are capable of emitting polarization-entangled photon pairs with a fidelity to the $|\phi^+\rangle$ Bell state beyond 0.98,[15,16] owing to an intrinsically low exciton fine structure splitting (FSS),[17] a low exciton lifetime of about 230 ps, and a near-zero multiphoton emission probability even at maximum brightness.[18] This allowed the demonstration of entanglement-based QKD with a QBER as low as 1.9%.[16,19]

Independent of the QD materials used, the best performances in terms of entanglement fidelity and biexciton state-preparation efficiency have been obtained by operating the QD sources at

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# Dynamical learning of a photonics quantum-state engineering process

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**Abstract.** Experimental engineering of high-dimensional quantum states is a crucial task for several quantum information protocols. However, a high degree of precision in the characterization of the noisy experimental apparatus is required to apply existing quantum-state engineering protocols. This is often lacking in practical scenarios, affecting the quality of the engineered states. We implement, experimentally, an automated adaptive optimization protocol to engineer photonic orbital angular momentum (OAM) states. The protocol, given a target output state, performs an online estimation of the quality of the currently produced states, relying on output measurement statistics, and determines how to tune the experimental parameters to optimize the state generation. To achieve this, the algorithm does not need to be imbued with a description of the generation apparatus itself. Rather, it operates in a fully black-box scenario, making the scheme applicable in a wide variety of circumstances. The handles controlled by the algorithm are the rotation angles of a series of waveplates and can be used to probabilistically generate arbitrary four-dimensional OAM states. We showcase our scheme on different target states both in classical and quantum regimes and prove its robustness to external perturbations on the control parameters. This approach represents a powerful tool for automated optimizations of noisy experimental tasks for quantum information protocols and technologies.

Keywords: orbital angular momentum; state engineering; black-box optimization; algorithm; quantum walk.

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## 1 Introduction

Quantum-state engineering of high-dimensional states is a pivotal task in quantum information science.[1–4] However, many existing protocols are platform-dependent and lack universality.[5–10] Conversely, a scheme to engineer arbitrary quantum states, relying on quantum walk (QW) dynamics, was showcased in Ref. 11. QWs are a particularly simple class of quantum dynamics that can be considered to generalize classical random walks.[12] QWs have been implemented in experimental platforms ranging from trapped ions[13,14] and atoms[15] to photonics circuits.[16–23] In particular, engineering of arbitrary qudit states has been experimentally demonstrated with QWs in orbital angular momentum (OAM) and polarization degrees of freedom of light.[11,24,25]

In the paraxial approximation, the angular momentum of light can be decomposed in spin angular momentum, also referred to as polarization in this context, and OAM, which is related to the spatial transverse structure of the electromagnetic field.[26–28] In the classical regime, OAM finds application in particle trapping,[29] microscopy,[30,31] metrology,[32] imaging,[33–35] and communication.[36–40] On the other hand, in the quantum regime, OAM provides a high-dimensional degree of freedom, useful, for example, to encode large amounts of information in single-photon states. Applications include quantum communication,[41–45] computing,[3,4,46] simulation,[47,48] and cryptography.[49,50]

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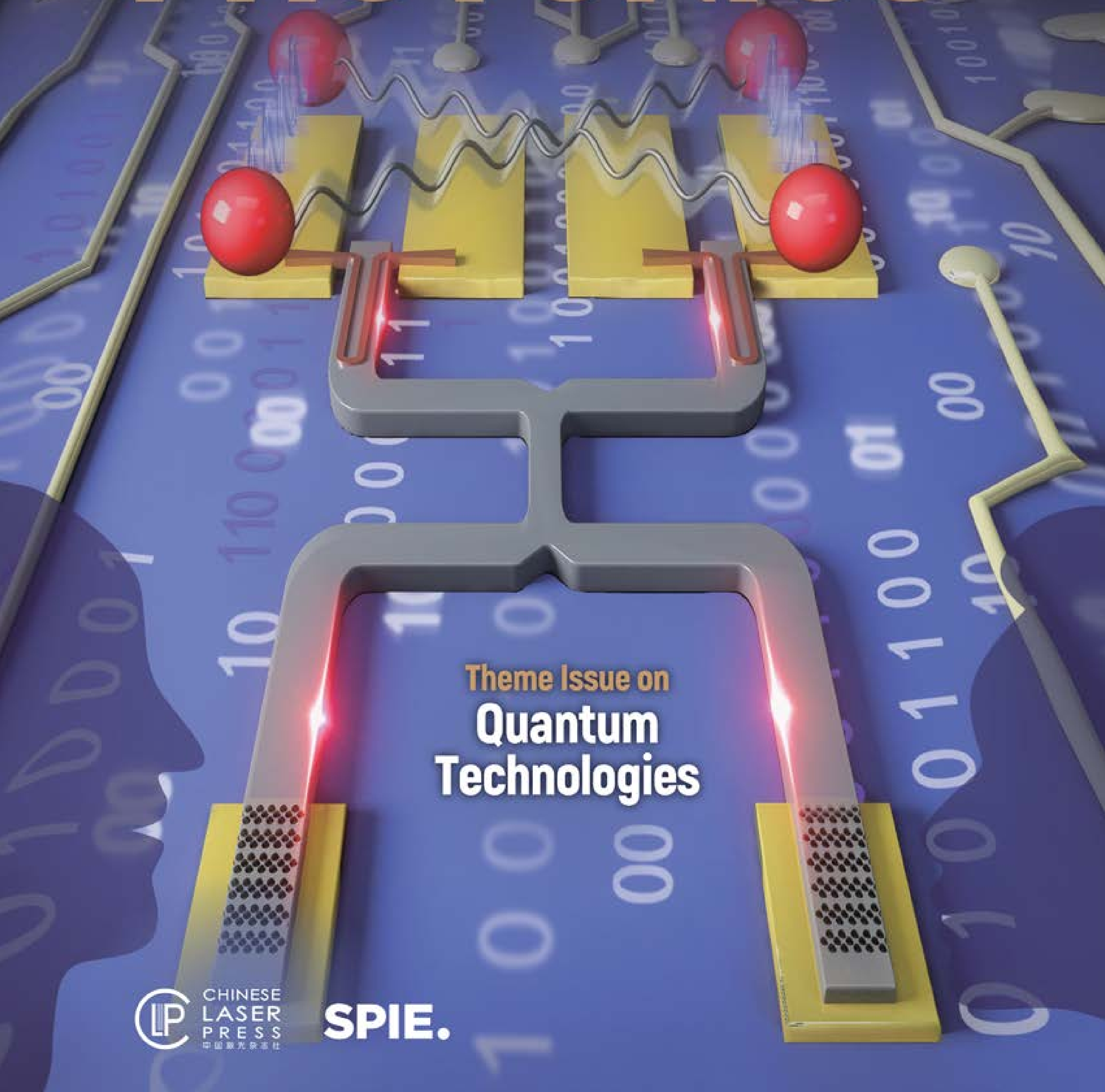

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