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Integrated Photon-Pair Sources with Nonlinear Optics

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Assisted by the rapid development of photonic integrated circuits, scalable and versatile chip-based quantum light sources with nonlinear optics are increasingly tangible for real-world applications. In this review, we introduce the basic concepts behind parametric photon pair sources and discuss the current state-of-the-art photon pair generation in detail but also highlight future perspectives in hybrid integration, novel waveguide structures and on-chip multiplexing. The advances in near-deterministic integrated photon pair sources are deemed to pave the way for the realization of large-scale quantum photonic integrated circuits for applications including quantum telecommunication, quantum sensing, quantum metrology and photonic quantum computing.

I. INTRODUCTION

Integrated quantum photonics arises from the encounter of two fields that have revolutionized our understanding of the nature and are starting to reshape our future: quantum technology and integrated photonics.1–3 Quantum technology, which enables us to generate, manipulate and detect quantum states in a complex system, has attracted increasing attention in recent years4. Its applications including metrology5, computing6,7, sensing8,9 and communication10 are deemed to change the way in which we measure, process, and transmit and store information. Many proof-of-principle experiments of quantum information science employing single-photons have been demonstrated with free-space optics. The integration and miniaturization of such systems independent of laboratory environment will be crucial for large-scale implementations and real-world applications11–13.

Integrated photonics, and in particular silicon photonics, has been considered one of the most suitable platforms for next-generation data processing and telecommunication applications14,15. Being compatible with the current mature electronic integrated circuit manufacturing infrastructure, it is inherently cost- and power-efficient. In recent years, quantum photonic integrated circuits (QPICs) were experimentally demonstrated on the silicon photonic platform16. Other material platforms such as silicon nitride (SiN), lithium niobate (LN), III–V semiconductors and fiber devices are also being actively investigated for QPIC applications12,17.

To implement a quantum photonic integrated circuit (QPIC) with practical functionalities, fundamental building blocks for the generation, manipulation and detection of quantum states of light are in immediate need of development2. Tremendous efforts have been devoted to the study of efficient generation of single-photons and correlated photon pairs18. For their simplicity of implementation with integrated photonic devices, the photon pair source exploiting nonlinear frequency conversion processes is a promising alternative to the atom-like single-photon emitter. By optimizing nonlinear light-matter interaction with quasi phase-matching techniques or passive enhancement of electric field in resonant structures, high-brightness photon pair sources have been developed providing heralded single-photons with high degrees of indistinguishability. Various techniques have been employed to directly generate two-photons and multi-photons entangled states on integrated photonic chips via nonlinear processes that can be directly applied for on-chip quantum information processing or computing19,20.

In this article, we review recent advances of integrated photon pair sources with nonlinear optics. In Section II we describe the basic concepts of photon pair generation via nonlinear parametric processes, the main parameters for photon pair source characterization and the most promising integration material platforms. The current state-of-the-art high-efficiency generation of both heralded single-photons and entangled states is discussed in Section III. Future perspectives of integrated photon-pair sources are discussed in Section IV. A short conclusion is given in Section V.

II. FUNDAMENTALS OF PHOTON PAIR GENERATION WITH NONLINEAR OPTICS

Nonlinear optics has been intensely studied and now deeply involved in many photonic applications, in particular, the generation of coherent electromagnetic waves through nonlinear parametric processes21, such as second harmonic generation (SHG), four-wave mixing, and difference frequency generation. The generation of quantum-correlated pairs of photons is based on spontaneous parametric processes such as spontaneous parametric down-conversion (SPDC) and spontaneous four-wave mixing (SFWM) arising from $\chi^{(2)}$ or $\chi^{(3)}$ nonlinearities of materials, respectively22. In SPDC and SFWM processes, pump photons generate pairs of signal and idler photons probabilistically. The detection of one photon of the pair could herald the presence of the other since they are inherently correlated in time and energy.

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The second- and third-order polarization can be written as:

\[ \mathbf{P} = \mathbf{P}^{(1)} + \mathbf{P}^{(2)} + \mathbf{P}^{(3)} \ldots \]
\[ = \varepsilon_0 (\chi^{(1)} \mathbf{E} + \chi^{(2)} \mathbf{E}^2 + \chi^{(3)} \mathbf{E}^3 + \ldots), \]

where \( \varepsilon_0 \) is the vacuum electric permittivity; \( \mathbf{P}^{(i)} \) and \( \chi^{(i)} \) are the \( i \)-th order polarization and susceptibility, respectively. This vectorial expression can be written in a scalar form using a Cartesian basis and expressing susceptibilities as tensors. The second- and third-order polarization can be written as:

\[ P^{(2)} = \varepsilon_0 \sum_{jk} \chi^{(2)}_{jk} E_j E_k \]
\[ P^{(3)} = \varepsilon_0 \sum_{jkl} \chi^{(3)}_{jkl} E_j E_k E_l, \]

where the indices \( i, j, k \) and \( l \) are the corresponding x, y and z components of the interacting electric field.

Conventionally, the second-order nonlinearity of an optical material is often characterized by its contracted second-order susceptibility tensor \( d_{ij} \) of the full tensor \( d_{ijk} = \chi^{(2)}_{ijk}/2 \), when the condition of Kleinmann symmetry is satisfied. Instead, the third-order nonlinearity of an optical material is often characterized by the nonlinear refractive index \( n_2 \):

\[ n_2 = \frac{3}{4n_0^2 c \varepsilon_0} \chi^{(3)}, \]

Traditionally, in free-space propagation the nonlinear interaction is optimized by a proper orientation of a birefringent nonlinear crystal for achieving the phase-matching condition between the interacting wave components, due to the limitation that most commonly used nonlinear material exhibit normal dispersion in visible to near-infrared wavelength range. However, with the possibility of dispersion engineering, optical waveguides can permit the phase-matching condition to be satisfied with a broader bandwidth, e.g. the full width at half maximum gain bandwidth of four-wave mixing exceeding 300 nm at telecom wavelength.

With the involvement of multiple wave components at different frequencies, many processes such as sum frequency generation, difference frequency generation and frequency doubling could take place if their relative conditions were satisfied. The second-order SPDC and the third-order SFWM processes generally used for photon-pair generation are discussed in detail as follows.

1. **Spontaneous parametric down-conversion**

If a crystalline material is non-centrosymmetric, its electronic potential function is asymmetric. This leads to non-zero even order susceptibilities, including the second-order term \( \chi^{(2)} \). In such a nonlinear material, various second-order nonlinear optical frequency mixing processes involving three wave components can take place when both energy and momentum conservation conditions are satisfied, such as SHG and SPDC.

The SPDC process is typically illustrated as an electron being excited by a pump photon to a virtual level corresponding to \( \hbar \omega_p \) and then decays by spontaneously emitting two photons referred to as the signal and the idler (here we simply define the wave component with lower frequency as ‘idler’ and the other as ‘signal’; they do not share the traditional denotation as in a parametric amplification process where the amplified wave is referred to as the signal), whose sum in frequency equals to that of the pump \( \omega_s + \omega_i = \omega_p \), as shown in Fig.1(b). Here we consider the most commonly used degenerate case in which the signal and idler are both at half of the pump’s frequency \( \omega_{s,i} = 1/2 \omega_p \). The energy and momentum conservation laws during this process require that:
the pump power, \( \Delta k = k_s + k_i - 2k_p \approx 0 \), \( \Delta k \) represents the phase mismatch in the nonlinear process, \( \hbar \) is the Plank constant and \( k_{p,s,i} \) are magnitudes of the wave vectors of the pump, signal and idler waves. 

The SPDC process could be considered as an inverse sum-frequency generation (non-degenerate) or an inverse SHG process (degenerate). With a detailed quantum treatment of the SPDC process, it can be shown that the process is probabilistic in which an arbitrary quantity \( n \) of photon pairs can be generated \( (n = 0, 1, 2, \ldots) \) each with an associated probability. The pair generation rate (PGR), which indicates the number of photon pairs generated per second (with a unit of \( s^{-1} \) or \( Hz \)), can be shown to have the following dependence \(^{24-26} \):

\[
r_{\text{SPDC}} \propto \frac{4d_{\text{eff}}^2 P_p L^2}{9\epsilon_0^2 c^2 A_{\text{eff}}} \frac{\sin^2 \left( \frac{\Delta k L}{2} \right)}{A_{\text{eff}}}.
\]

where \( r_{\text{SPDC}} \) is the PGR for the SPDC process, \( P_p \) is the pump power, \( A_{\text{eff}} \) is the mode interaction overlap area and in a waveguide this can be approximated by the effective area of the smaller mode among the wave components, \( L \) is the waveguide length and \( d_{\text{eff}} \) is the effective value of the second-order nonlinearity tensor. The sinc term takes into account the non-perfect phase-matching among the wave components, limiting the useful waveguide length to around the coherence length \( L_c = \left( \frac{2}{\Delta k} \right) \). From this expression, we can conclude that increasing the light confinement contributes inverse-linearly to the PGR. An increasing pump power instead contributes only linearly to the PGR in the SPDC process\(^{24} \). At the same time, if the phase mismatch is small enough, increasing the length of the waveguide would also quadratically increase the rate of pair generation.

### 2. Spontaneous four-wave mixing

The SFWM is a third order nonlinear process and involves four wave components. In a degenerate pumping scheme, two pump photons at \( \omega_p \) generates a pair of photons at \( \omega_s \) and \( \omega_i \) around \( \omega_p \). It can be typically illustrated as shown in Fig.1(c), in which an electron is excited by two pump photons to a virtual level corresponding to \( 2\hbar\omega_p \) and then decays by emitting two photons with energy \( \hbar \omega_s \) and \( \hbar \omega_i \). The energy and momentum conservation laws during this process require:

\[
2\hbar \omega_p = \hbar \omega_s + \hbar \omega_i,
\]

\[
\Delta k = k_s + k_i - 2k_p \approx 0,
\]

Under more detailed treatments of the FWM process, the phase-matching condition will also include an additional phase term accounting for the nonlinear phase accumulation related to the Kerr effect, the free carrier effect and the Raman scattering\(^{23,27} \). As in many cases the four interacting wave components have very small differences in frequency, the phase matching condition can be easily satisfied with a proper dispersion engineering of the integrated waveguide structure.

An associated photon-pair generation rate can be written also for the SFWM process, assuming a near-perfect phase matching\(^{28,29} \):

\[
r_{\text{SFWM}} \propto \sqrt{ \frac{3\omega_p \chi^{(3)} P_p L}{2\hbar \epsilon_0^2 c^2 A_{\text{eff}}} } \approx \frac{2\omega_p n_2 P_p L}{c A_{\text{eff}}},
\]

where \( A_{\text{eff}} \) is the mode interaction overlap area, \( \omega_p \) is the pump wavelength, \( n_2 \) is the nonlinear refractive index of the pump wavelength. This expression shows that, under the assumption of a near-perfect phase matching, the generation efficiency of photon pairs via SFWM depends quadratically on the material nonlinearity, the pump power and the inverse of the mode size. Similar to the SPDC process, the PGR depends again quadratically on the waveguide length \( L \) in the SFWM process.

Considering the guided-wave nature of PICs, the effective third order nonlinearity of a waveguide structure can be described by the nonlinear coefficient \( \gamma [m^{-1}W^{-1}] \) defined as\(^{15} \):

\[
\gamma = \frac{\omega_p n_2}{c A_{\text{eff}}}.
\]

The nonlinear coefficient \( \gamma \) takes into account both the material nonlinearity and the mode confinement of the waveguide.

### 3. Differences between SPDC and SFWM

SFWM and SPDC can both be employed for photon pair generation and they share some common grounds in the optimization of the pair generation rate. For example, in waveguide-based nonlinear devices, for materials with higher refractive index such as silicon and gallium arsenide, the mode confinement could be stronger when the cladding has a much lower index (e.g. silicon oxide or air) hence increasing light intensity and enhancing the nonlinear conversion efficiency.

There are some significant differences that limit their compatibility with different material platforms. First of all, SPDC requires that the nonlinear medium shows second-order nonlinearity, either naturally in non-centrosymmetric crystals or induced by strain\(^{30} \) and photo-galvanic effect\(^{31} \) or by tuning the structure orientation of 2D crystals\(^{32} \). As a result, SFWM is more widely applicable, since all materials exhibit odd order nonlinearities. Secondly, the phase matching condition for SPDC is more restrictive as the pump and the generated pair are separated in wavelength by a factor of two. The SPDC
therefore requires special strategies to be typically used such as exploiting quasi-phase-matching in periodic structures or Bragg reflection waveguides.

B. Material platforms for nonlinear integrated photonics

Several material platforms used for integrated nonlinear optics are being considered for QPIC implementations. The essential requirements of a potential material platform for the generation of photon pairs via nonlinear parametric processes typically include high $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities, low linear and nonlinear losses (e.g., due to two-photon absorption and free-carrier absorption) losses within desired wavelength ranges, availability of appropriate integrated pump sources and the availability of mature manufacturing processes. As an example, for quantum communication, the compatibility with current telecom infrastructure is of great importance. Therefore, one of the focuses of the photon pair source development is to achieve high performance at around 1.55 µm. Mature manufacturing processes and low losses are also crucial as complex structures are needed for integration of quantum light sources for practical applications which typically require multiple active and passive components. As an example, the preparation of entangled bi-photon states makes use of multiple directional couplers and phase shifters for on-chip path, time-bin/energy-time or polarization entanglement schemes. Key optical properties of major materials for QPIC implementation are listed in Table I.

1. Silicon

Silicon-based platforms, in particular silicon-on-insulator (SOI), are among the most mature for PIC realization. Since the beginning of its development from 1985, SOI technology has been behind many recent breakthroughs in integrated photonics. Following the successful demonstration of critical integrated components such as modulators, directional couplers, wavelength multiplexers and photodetectors, silicon PICs have been widely used for telecommunication and datacenter interconnects.

Silicon is transparent from ~1.1 µm up to 9 µm. However in the context of SOI PIC structures, the cladding material, silicon dioxide, typically limits the transmission up to around 2 µm. At the telecom wavelength around 1.55 µm, silicon-based devices have a low linear loss but a high nonlinear loss for its high TPA coefficient which limits its nonlinear figure-of-merit to less than 0.5. Crystalline silicon has a centrosymmetric diamond cubic lattice. Therefore, silicon crystal lacks intrinsic $\chi^{(2)}$ nonlinearity which makes it unsuited for the SPDC process. In recent years, strained silicon was demonstrated to manifest electro-optic effect and can be used for second harmonic generation. Therefore, in principle the strain or other approaches including photogalvanic effect can be used for symmetry-breaking to enable pair generation via SPDC. On the other hand, silicon has strong $\chi^{(3)}$ nonlinearity ($n_2 = 4.5 \times 10^{-18}$ m²/W at 1.55 µm). Combined with the possibility of tight mode confinement allowed by the large refractive index contrast with respect to the most common cladding material silicon dioxide ($\Delta n \approx 2$ at 1.55 µm), silicon waveguides could provide an extremely high nonlinear coefficient $\gamma$ greater than 300 W⁻¹m⁻¹ at 1550 nm, making it a promising candidate for integrated SFWM photon pair sources.

2. Silicon nitride

Silicon nitride (typically $\text{Si}_3\text{N}_4$, SiN) has been routinely used in fabrication processes and final device structures for electronic integrated circuits. Following investigations of SiN waveguide structures in the 1980s, technologies for plasma-enhanced chemical vapor deposition (PECVD) and low-pressure chemical vapor deposition (LPCVD) of high-quality SiN layers have been extensively studied. Recent progress on advanced SiN fabrication processes has enabled ultra-low propagation losses in waveguide structures that leads to microresonators with quality factors (Q-factor) over $10^{4}$. With a larger energy bandgap, SiN also shows negligible TPA in the telecom bands. A complete toolbox of high-performance PIC components including directional couplers, modulators, and photodetectors are also available for complex system integration, which are beneficial for fully integrated quantum photonics.

CVD SiN in the CMOS process is amorphous therefore centro-symmetric and does not exhibit $\chi^{(2)}$ nonlinearity. As a result, pristine SiN is not suited for photon-pair generation via SPDC, leaving SFWM to be the main solution for photon pair generation. Although SiN lacks second-order nonlinearity for electro-optic effects, the Kerr effect could be exploited for optical modulation. On the other hand, SiN shows $\chi^{(3)}$ nonlinearity with a Kerr coefficient of $n_2 \approx 2.6 \times 10^{-19}$ m²/W⁻¹ at ~1.55 µm, more than an order of magnitude lower than that of silicon. LPCVD SiN has a refractive index of ~1.55 µm (~1.83 for PECVD SiN), which implies a lower index contrast compared to silicon waveguides, leading to weaker mode confinement and lower effective nonlinear coefficient. However, for its lower linear loss and the absence of two-photon absorption (TPA), SiN nonlinear waveguides can be operated at much higher power levels, in particular in the visible and telecom windows. With a combination of great linear and nonlinear optical properties, SiN is a potential alternative material platform to SOI for QPIC implementation.

3. III-V semiconductors

Among the several common semiconductor materials formed between group III elements (B, Al, Ga, In) and group V elements (N, P, As, Sb), GaAs is among the most extensively investigated and developed for nonlinear optics. GaAs is transparent from 1 to 10 µm. Waveguides in GaAs with lower than 1 dB/cm propagation loss have been demonstrated. With a high refractive index of 3.4 at 1.5
μm, strong mode confinement can be realized. Bragg-grating reflector waveguides, phase shifters, modulators, directional couplers are readily available on GaAs platform thanks to many years of active research in the field\textsuperscript{3,64}.

GaAs has a non-centrosymmetric crystalline structure which leads its non-zero $\chi^{(2)}$ nonlinearity. Furthermore, GaAs possess one of the highest second-order nonlinearity ($d_{36}=170$ pm/V at 1 μm\textsuperscript{54}) and a very strong Kerr coefficient $n_{2} = 1.6 \times 10^{-17} \text{m}^{2}\text{W}^{-1}$ at 1.5 μm\textsuperscript{52}. Therefore, both SPDC\textsuperscript{65} and SFWM\textsuperscript{66} processes could be used to generate photon-pairs in GaAs/AlGaAs waveguides, making it a very versatile platform. The mature laser diode technology on III-V semiconductor platform could also be exploited to build monolithic electrically injected photon-pair sources\textsuperscript{67}.

In recent years, alternative III-V semiconductors including AlN, GaN, GaP and InP were also investigated for integrated photonic devices. AlN shows optical properties similar to SiN (refractive index, transparency and $n_{2}$) but possesses second-order nonlinearity, for which it has been used for the development of ring resonators for photon pair generation via SPDC\textsuperscript{68,69}. The III-V materials are also widely used for the development of quantum dots as single-photon and photon-pair emitters\textsuperscript{69}.

4. Lithium niobate

Lithium niobate (LN) is one of the most widely used materials for nonlinear frequency conversion\textsuperscript{30}. LN is transparent in a wide wavelength range from 0.5 to 4 μm. Assisted by the advance in femtosecond laser micromachining technique\textsuperscript{71}, ion in-diffusion\textsuperscript{72} or proton exchange techniques\textsuperscript{73}, ultra-low-loss waveguides (0.6 dB/cm) have been realized in LN\textsuperscript{60}. With intrinsic birefringence and ferroelectricity, LN can be periodically poled (PPLN) with alternate domains of inverted electric dipole orientation to meet quasi phase-matching conditions for efficient parametric generation\textsuperscript{21}.

For its non-centrosymmetric structure, LN shows both $\chi^{(2)}$ and $\chi^{(3)}$ optical nonlinear responses. Therefore, both SPDC and SFWM processes can be exploited for photon-pair generation in LN. With the capability to achieve high efficiency via QPM in a periodically poled structure, its high electrooptic coefficient ($d_{13} = 25$ pm/V) and Kerr coefficient $n_{2} = 9.1 \times 10^{-20} \text{m}^{2}\text{W}^{-1}$\textsuperscript{54}, PPLN has been one of the most prominent materials for high efficiency nonlinear frequency conversion. In recent years, LN-on-insulator (LNOI) wafer fabrication process has been rapidly advanced, integrated photonic components, including superconducting single-photon detectors\textsuperscript{74,75}, have been further developed\textsuperscript{76,77}. LNOI is foreseen to become a potential platform for fully integrated quantum photonics combining sources and detectors.

5. Glasses

The optical fiber based on fused silica glass is one of the most important platforms for guided-wave optics. For its excellent properties including extremely low losses between ~0.2 to 2 μm, low dispersion and low nonlinearity, it has been the backbone of the contemporary telecom infrastructure. Due to the low Kerr coefficient of $\approx 2.0 \times 10^{-20} \text{m}^{2}\text{W}^{-1}$\textsuperscript{61}, standard step-index fused silica fiber is not the most suitable for nonlinear optics. By engineering the fiber geometries, photonic crystal fibers (PCFs) can have greatly enhanced effective nonlinearity due to the strong field confinement and unique dispersion engineering capability. Fused silica is in an amorphous glass state therefore it is centrosymmetric and lacks second-order nonlinearity. However, poling can be applied to silica fibers to enable second-order nonlinear processes including SPDC for photon pair generation. On the other hand, SFWM could be used in standard silica fibers.

High-index glass (Hydex\textsuperscript{TM}) is a special type of doped fused silica glass with refractive index in the range from 1.5 to 1.9. It has been used as an alternative material for CMOS compatible low-loss optical waveguides. It has a relatively low Kerr nonlinearity of $\sim 1.15 \times 10^{-19} \text{m}^{2}\text{W}^{-1}$, between fused silica and silicon nitride. The low nonlinearities could be mitigated by the possible high quality-factor (Q-factor) of micro-ring resonators beyond 10\textsuperscript{6} to provide an attractive level of performance for photon pair generation\textsuperscript{62}.

Chalcogenide glasses including As$_{2}$S$_{3}$ and As$_{2}$Se$_{3}$ have also attracted considerable attention for their high nonlinearities ($n_{2} \approx 3 \times 10^{-18} \text{m}^{2}\text{W}^{-1}$ for As$_{2}$S$_{3}$\textsuperscript{78}). They have excellent transparency in the mid-IR region where conventional silica glass shows strong absorptions\textsuperscript{79}. Chalcogenide step-index\textsuperscript{80} and microstructured fibers\textsuperscript{81} have been widely used for supercontinuum generation in the mid-IR region for frequency comb synthesis. Therefore, they are suited for photon pair

<table>
<thead>
<tr>
<th>Material</th>
<th>$n$</th>
<th>$d_{\text{max}}$ [pm/V]</th>
<th>$n_{2}$ [m$^{2}$W$^{-1}$]</th>
<th>Transparency [μm]</th>
<th>Propagation loss [dB/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>3.8</td>
<td>15 ($\chi^{(2)}$ of strained-Si)\textsuperscript{30}</td>
<td>$4.5 \times 10^{-18}$</td>
<td>1.1 - 9</td>
<td>0.026,\textsuperscript{33}</td>
</tr>
<tr>
<td>Si$<em>{3}$N$</em>{4}$</td>
<td>2</td>
<td>-</td>
<td>$2.6 \times 10^{-19}$</td>
<td>0.4 - 4</td>
<td>0.01,\textsuperscript{47}</td>
</tr>
<tr>
<td>GaAs</td>
<td>3.4</td>
<td>170 ($d_{36}$ at 1 μm)\textsuperscript{54}</td>
<td>$1.6 \times 10^{-17}$</td>
<td>1.0 - 10</td>
<td>$&lt;1.55$</td>
</tr>
<tr>
<td>AlN</td>
<td>2.1</td>
<td>23.2 ($d_{33}$ at 1 μm)\textsuperscript{56}</td>
<td>$2.3 \times 10^{-19}$</td>
<td>0.2 - 5</td>
<td>0.6,\textsuperscript{58}</td>
</tr>
<tr>
<td>LiNbO$_{3}$</td>
<td>2.21</td>
<td>25.2 ($d_{31}$ at 1 μm)\textsuperscript{54}</td>
<td>$9.1 \times 10^{-20}$</td>
<td>0.5 - 4</td>
<td>0.6,\textsuperscript{60}</td>
</tr>
<tr>
<td>Silica</td>
<td>1.44</td>
<td>-</td>
<td>$2.7 \times 10^{-20}$</td>
<td>0.2 - 2</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>Hydex</td>
<td>1.5 - 1.9</td>
<td>-</td>
<td>$1.15 \times 10^{-19}$</td>
<td>0.2 - 2</td>
<td>0.06,\textsuperscript{62}</td>
</tr>
</tbody>
</table>

TABLE I. Related properties of common materials for integrated photon pair sources. Values are at 1.55 μm if not specified. The nonlinear susceptibilities, $d_{\text{max}}$, are the largest reported values for the corresponding orientation. The waveguide losses are the lowest values reported in the literature.
generation via SFWM especially in the mid-IR region.

C. Fundamentals of photon pair sources

Being a quantum light source, photon pair sources are usually characterized in ways radically different from those commonly used for traditional coherent light sources such as laser sources. In this Section, we introduce very concisely the general parameters and terminologies used for the quantitative characterization of the photon pair sources.

![Diagram](image)

**FIG. 2. Typical photon pair source characterization setups for:**
(a) inter-beam coincidence counting, (b) intra-beam heralded coincidence counting with an HBT interferometer, (c) TPI for indistinguishable photons in a HOM interferometer and (d) TPI for entangled photons with a Franson interferometer. HSPS, heralded single photon source. Filter, e.g. WDM to separate the signal and the idler and reject the residual pump. SPD, single photon detector. BS, 50:50 beam splitter. \( I_{1,2} \), interferometers (e.g. Michelson or Mach-Zehnder interferometers) with variable delays. Note that for the degenerate SPDC process the signal and the idler are at the same frequency and could be separated with polarization optics when they are cross-polarized.

1. Characterization of photon pair sources

The performance of a photon pair source could be characterized by a few commonly used parameters\textsuperscript{19,82,83} including:

- Pair generation rate (PGR, \( r \)), which is the rate of on-chip pair generation events. The pair generation rate usually refers to the inferred numbers of pairs generated per second inside the waveguide from the measured coincidence rate \( C \) divided by the efficiencies of signal collection (\( \eta_{s} \)) and single-photon detectors (\( \eta_{d} \)):

\[
r = \frac{C}{\eta_{s} \eta_{d} r};
\]

- Brightness (\( B \)) of the pair source, which is a normalized PGR per unit pump power \( P_{p} \) and unit spectral bandwidth \( \Delta \lambda \), with a unit of Hz/mW/nm (or Hz/mW\(^2\)/nm to emphasize the quadratic dependence on pump power):

\[
B = \frac{r}{P_{p} \Delta \lambda};
\]

- Coincidence (\( C \)) and accidental (\( A \)) count rates, which are the measured rates at which coincidences of signal and idler photons, can be measured in a standard measurement configuration shown in Fig. 2(a).

\[
C_{\text{raw}} = (\eta_{c,s} \eta_{d,s})(\eta_{c,i} \eta_{d,i}) r + A = \eta_{s} \eta_{i} r + A = C_{\text{net}} + A,
\]

where \( \eta_{c,s}, \eta_{d,s} \) and \( \eta_{c,i}, \eta_{d,i} \) are collection, detection and total efficiencies of signal and idler photon counting measurements, respectively. The net coincidence rate is the measured raw coincidence rate minus the accidental coincidence rate which includes the detector dark count rate and accidental counts due to noises in the generation processes:

- Coincidence-to-accidental ratio (CAR), which is a measure of the signal-to-noise ratio of the source and equals to the ratio between the net coincidence count rate and the accidental count rate. Consider that at the signal and idler detection branches, uncorrelated photons due to noises in the waveguides (e.g. due to spontaneous Raman scattering) and in the detectors will be counted towards the total signal. The unconditioned photon count rates of the signal and idler detectors \( N_{s} \) and \( N_{i} \) can be written as:

\[
N_{s,i} = \eta_{s,i} (r + n_{s,i}) + d,
\]

where \( n_{s,i} \) are the uncorrelated noise photon generation rates for signal and idler branches and \( d \) is the dark count rate of the single photon detectors. The net CAR can be written as\textsuperscript{84}:

\[
\text{CAR} = \frac{C_{\text{net}}}{A} = \frac{\eta_{s} \eta_{i} r}{N_{s} N_{i}} = \frac{\eta_{s} \eta_{i} r}{[\eta_{s} (r + n_{s}) + d][\eta_{i} (r + n_{i}) + d]}.
\]

To understand the general behavior of CAR, here we assume that \( \eta_{s} \approx \eta_{i} \) and \( r \gg n \). At low pump powers, \( \eta r \ll d \), the accidental coincidence is dominated by the dark count rates of the detectors, CAR can be expressed as \( \text{CAR} \approx \eta^{2} r/d^{2} \). At high pump power, the accidental rate is dominated by the pair generation rate itself (\( \eta r \gg d \)), giving an expression as \( \text{CAR} \approx 1/r \) (this is due to the probability of generating multiple pairs, please see Refs.\textsuperscript{84,85}). As a result, CAR increases linearly with pump power at low power levels until a maximum is reached when the detected count rate is...
close to the dark count rate of the detector, afterwards it decreases inversely with further increasing pump power due to the higher chance of generating multiple pairs.

The parameters generally used to quantitatively evaluate the quality of the quantum states of light include:

- Second-order correlation function $g^{(2)}(\tau)$, which characterizes the degree of photon anti-bunching, can be retrieved using the Hanbury Brown-Twiss (HBT) experiment by means of a heralding gate shown in Fig.2(b). $g^{(2)}(\tau)$ can be expressed as following:

$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle\langle I(t+\tau)\rangle}.$$  

(22)

where $I$ is the intensity of the light being characterized and $I(t) = c\epsilon_0E(t)^2/2$, the angle brackets denote the time average by integrating over a long time period. When the photons are in discrete photon number states (Fock states), the intensities $I(t)$ in the second-order correlation function can be substituted by the number of photon counts registered on the detectors at the given time $N(t)$. Theoretically, following a quantum treatment of the HBT experiment\(^82\), the second-order correlation function at zero delay can be written as:

$$g^{(2)}(0) = 1 - \frac{1}{n}.$$  

(23)

where $n$ is the eigenvalue of an anti-bunched photon number state $|n\rangle$. For a ideal heralded single photon source ($n = 1$), its $g^{(2)}(0)$ approaches zero;

- Two-photon interference (TPI) effects are often used for the characterization of photon indistinguishability. With a Hong-Ou-Mandel (HOM) interferometer\(^86\) as shown in Fig.2(c) realized with additional heralding gates, one can retrieve HOM dip visibility $V_{\text{HOM}}$ as a measure for the indistinguishability and purity of generated photons.

- Entangled two-photon states can be characterized, for polarization entangled photon-pair sources, with a simple coincidence setup (similar to Fig.2(a)) by adding waveplates for the polarization control and polarizers as filters on each of the beam paths; and for time-bin/energy-time entangled photon-pair sources, with a Franson interferometer\(^87\) as shown in Fig.2(d). The quality of entangled two-photon states from a photon-pair source could be tested by evaluating the violation of CHSH (Clauser-Horne-Shimony-Holt) inequality\(^88\) as a generalization of the Bell’s test. However the Franson interferometer is known to have constraints on the range of interferometer delays and loopholes in its geometry for a proper Bell-CHSH inequality test\(^10,89\). By changing the relative delay or the polarization orientation between the beam paths in the two detection arms (for time-bin/energy-time entangled states or polarization entangled states, respectively), relevant coincidence measurements can be performed. In the case of polarization entanglement, the inequality condition $|S| \leq 2$ can be tested. For time-bin/energy-time entanglement, a two-photon interference visibility $V_{\text{TPI}}$ defined as the following ratio can be retrieved:

$$V_{\text{TPI}} = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}}}.$$  

(24)

where $C_{\text{max}}$ is the maximum coincidence rate and $C_{\text{min}}$ is the minimum coincidence rate while varying the relative delay. This visibility can be used to test for the violation of CHSH inequality ($V_{\text{TPI}} \geq 96\%$\(^90\)).

- Joint spectral distribution (JSD), more specifically the joint spectral amplitudes (JSA) and intensities (JSI) between the signal and idler photons in the SPDC and SFWM processes, are of great importance for quantum information processing and quantum communication applications\(^90,91\), where interference between two or more independent photon sources are necessary. The JSA $f(\omega_s, \omega_i)$ between the signal and the idler photons can be written as:

$$f(\omega_s, \omega_i) = \alpha(\omega_s, \omega_i)\phi(\omega_s, \omega_i).$$  

(25)

where $\alpha(\omega_s, \omega_i)$ denotes the pump envelope function which takes into account the energy conservation and $\phi(\omega_s, \omega_i)$ is the phase-matching function which describes the momentum conservation. The JSA could be expanded according to Schmidt decomposition into a series based on temporal eigenmodes with their corresponding coefficient (with a characteristic Schmidt number)\(^96\).

The JSD of a pair source could be characterized by a variety of techniques, including the scanning monochromator technique and the diagonal Fourier transform spectroscopy technique. For more details on this topic please see Ref.\(^90\). As a result, the purity of the single-photon state can be characterized using the joint spectral measurements through the retrieval of the Schmidt number. The JSD of SPDC and SFWM sources is closely related to the property of pump pulses and the phase matching condition. With the versatility of dispersion engineering by designing the geometry of the waveguide structure, the engineering of the JSD has been demonstrated for the preparation of decorrelated photon pairs with high single-photon state purity\(^92,93\).

2. The ideal integrated photon pair source

In recent years, parametric photon pair generation has been demonstrated with integrated photonic devices on different material platforms with various waveguide geometries. The common goals shared among researchers for further developments include increasing the conversion efficiency and the brightness (B) of the photon pair sources while at the same time reducing the noise in the generation process thus increasing the CAR. Ideally, generated photon pairs should have a high degree of quantum correlation ($g^{(2)}(0)$ approaching zero) and should be indistinguishable ($V_{\text{HOM}}$ approaching 100%). Considerable efforts have been devoted to on-chip direct generation of entangled two-photon and high-dimensional entangled states with high purity ($V_{\text{TPI}}$ approaching 100%).

Ideally, when pumped with a pulsed laser source, it is desired that a single photon pair is generated per pump pulse.
for practical applications. However, due to the probabilistic nature of the parametric nonlinear process, there is always a non-zero chance to generate multiple pairs\(^94,95\). The photon statistics of the pair generation process as two-mode squeezed vacuum follow a thermal distribution, assuming pairs to be generated in a single spatial-temporal mode\(^82,96\). The probability of \(n\) pairs of photons being generated in the parametric process can be expressed as:

\[
\rho_{\text{th}}(n) = \frac{n!}{(\pi + 1)^{n+1}}, \quad (26)
\]

where \(\pi\) is the mean number of pairs generated in a unit time interval (e.g. during the duration of a pump pulse). For \(\pi = 1\) and \(n = 1\), this probability is 25\%, which is the maximum value achievable.

Therefore, the photon per pulse generation rate is generally kept low enough to reduce the generation efficiency hence reducing \(\pi\), to avoid the generation of multiple pairs. Such an approach would limit the scaling of brightness by increasing the pump power. The probabilistic nature is the main drawback of the parametric photon pair sources when compared to atom-like single-photon emitters\(^97\) whose generation process is deterministic. Tremendous efforts have been devoted to circumventing this problem with active multiplexing\(^98,99\), which will be discussed in more detail in Section V. Ideally, with 17 independent pair sources, a near-deterministic heralded single-photon source could be realized\(^100\).

### III. CURRENT STATE-OF-THE-ART

Since the first experimental confirmation\(^101\) of the proposed correlated twin photon concept\(^102\), the SPDC process has been the most frequently used technique to generate correlated photon-pairs and prepare quantum states of light in bulk nonlinear crystals\(^24\). In this Section we review the current state-of-the-art heralded photon-pair sources on integrated photonic platforms. The major results of photon pair sources are summarized in Table II according to their material platforms and device geometries with details discussed as follows.

#### A. Fiber photon pair sources

Here we include also the results in fiber devices as they can be easily integrated with waveguide-based photonic systems. Being in an amorphous state, glasses used to fabricate optical fibers such as fused silica are centrosymmetric and lack even-order nonlinear responses. For this reason, SFWM has been the most investigated mechanism for photon-pair generation in conventional optical fibers.

##### 1. Dispersion-shifted fibers

Dispersion-shifted fibers (DSF) are special optical fibers designed to shift the zero-dispersion wavelength of fused silicate from 1300 nm to 1550 nm where the fiber losses are minimal. The generation of squeezed state in a 300-meter-long DSF was demonstrated in 2001 with a Sagnac loop interferometer\(^109\). In the same year, fiber-based SFWM correlated photon-pair source was demonstrated in 20-meter-long double-clad and quadruple-clad optical fibers with a near-zero dispersion parameter at 1.53 \(\mu\)m\(^105\). By pumping close to the fiber zero-dispersion wavelength, quantum noise correlation measurements showed a quantum noise squeezing of 1.1 dB below the shot-noise. Soon the same group demonstrated photon-pair coincidence measurements observing a PGR of 10\(^7\) pairs/s\(^103\) with a CAR higher than 10\(^6\). The role of Random scattering in the SFWM processes was also studied as a major contribution to the accidental coincidence signal\(^104,106\). By cooling the fiber to cryogenic temperatures, noises related to spontaneous Raman scattering (SpRS) were suppressed, resulting in reduced accidental coincidences, hence increasing CAR to 30\(^107\), and later to >100 (at a brightness of 500 kHz/mW/nm)\(^108\).

Entangled two-photon states were soon demonstrated with DSF-based systems. The generation of polarization-entangled two-photon state via SFWM was demonstrated in a Sagnac loop interferometer setup providing a V\(_{\text{TPI}}\) larger than 90\%\(^110\) and in combination with polarization maintaining (PM) fibers with V\(_{\text{TPI}}\) greater than 95\%\(^113\) (as shown in Fig.3(a)). Time-bin entangled photon pairs were demonstrated via SFWM in a 2.5-km-long DSF, with a V\(_{\text{TPI}}\) larger than 99.3\%\(^112\). Following these pioneering researches in fiber-based photon-pair sources, theoretical models were also developed to describe the SFWM process in fiber waveguide structures\(^105,212\).

##### 2. Photonic crystal fibers

PCFs have been an innovation that broadened the boundaries of fiber technologies by trapping light inside a central core (either hollow or solid) with photonic bandgap materials. It has already been widely used for high-power ultrafast pulse delivery, extreme nonlinear optics and many other applications\(^213\).

Following the early demonstrations of photon-pair generation in DSFs, interests in PCFs for photon-pair generation arose because of their high effective nonlinear coefficients due to tight field confinement and their versatile dispersion engineering capabilities for the multiple degrees of freedom in PCF design. Correlated photon-pair generation pumped in anomalous dispersion regime was demonstrated using a 5.8-meter-long microstructured fiber in a Sagnac loop interferometer setup and analyzed in detail the role of fiber group-delay dispersion in the SFWM process\(^115\). Furthermore, by pumping in normal dispersion regime, far-detuned photon-pairs were generated in single-mode PCF with a high coincidence rate of 4.5 kHz in a simple single-pass setup with only 3 meters of PCF (8 kHz coincidence rate for a 6-meter-long PCF), with a maximum PGR of 6.7 \(\times\) 10\(^6\) pairs/s and CAR around 5\(^116\). In a later work, by shifting from ns-pulse pumping to ps-pulse pumping thus mitigating influence of noises due to the SpRS, with a 2-m-long PCF, PGR was increased...

<table>
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<tr>
<th>Material</th>
<th>Waveguide geometry</th>
<th>Pair wavelength</th>
<th>Brightness [MHz/mW]</th>
<th>CAR</th>
<th>(V_{\text{TPI}})</th>
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<td>12206</td>
<td>- polarization205, high-dimension205, 93%204</td>
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up to \(10^7\) pairs/s and the coincidence rate was improved to 3.2 \(\times\) \(10^5\) counts/s (or a brightness of 200 kHz/mW/nm) with a CAR of 8 (as shown in Fig.3(b))\(^{117}\). With a similar setup, pumping 1.8-m-long PCF in normal dispersion regime with ps pulses, a coincidence rate of \(3.8 \times 10^4\) (50 kHz/mW/nm) counts/s was demonstrated at a CAR of 8 with a narrower intrinsic bandwidth of 0.7 nm\(^{118}\).

In later works, a more detailed theoretical model was developed\(^{85}\) and path-entangled states were demonstrated with two PCFs generating indistinguishable photon-pairs showing four-fold coincidence with \(V_{\text{HOM}}\) up to 95%\(^{119}\) and polarization-entangled Bell states with a fidelity of 89%\(^{122}\). With a narrow-band pumping scheme, external filtering could be avoided and \(V_{\text{HOM}}\) of 77% was demonstrated\(^{114,120}\). Using PM microstructured fibers, polarization-entangled photon-pairs were also generated at a brightness of 26 kHz/mW/nm showing \(V_{\text{TPI}}\) up to 97%\(^{121}\).

### 3. Other fibers

SFWM in PM step-index optical fibers has also been investigated. In few-mode PM fibers, intermodal SFWM was employed and correlated photon pair generation has been demonstrated\(^{214,215}\). Nondegenerate dual-pump SFWM was also investigated in PM fibers for photon pair generation\(^{216,217}\).

The periodic poling treatment by applying strong electric field to the optical fiber was shown to enable second-order nonlinearity in fused silica glass\(^{218}\). Correlated photon-pair generation via SPDC process was observed in periodically-poled silica fiber\(^{123,124}\). Further experiments with poled fibers have demonstrated the generation of polarization-entangled two-photon states with \(V_{\text{TPI}}\) as high as 97%\(^{125,126}\) (see Fig.3(c)).

Highly nonlinear fibers are a special type of optical fiber of-
ten incorporating air-holed micro-structure claddings to maximize the mode confinement hence greatly increasing its effective nonlinear coefficient. Correlated photon-pair generation and polarization-entangled two-photon states via SFWM have also been demonstrated in short sections of highly nonlinear fibers, with $V_{\text{TPP}} > 98\%$ at a CAR of 29 and an efficiency of 0.1 pair/pulse.

**B. On-chip waveguide photon pair sources**

Various waveguide structures exploiting the optical nonlinearity of the guiding materials have also been extensively studied for photon-pair generation. The scalable integration of quantum light sources is vital for the miniaturization of quantum communication systems, photonic quantum computing systems, and other applications. In this Section, recent advances in on-chip heralded single photon and entangled-state generation are reviewed according to different geometries.

1. **Channel waveguides**

Channel waveguides have the simplest structures among commonly used on-chip photon pair waveguide sources. They can have rib, ridge, or buried cross-section geometries and can be arranged either in simple strips or into spirals to significantly increase the waveguide length.

In 2001, the first PPLN waveguide-based photon pair source was demonstrated. With the QPM capability of PPLN and the strong mode confinement in waveguide structures, a conversion efficiency of $2 \times 10^{-6}$ was demonstrated (4 orders of magnitude higher than in typical bulk nonlinear crystals) giving a very high brightness of 250 MHz/mW/nm (measured coincidence rate of 1550 Hz) at a CAR of $7\%$. Employing nondegenerate SPDC schemes, correlated photon pairs were also demonstrated and further extending the wavelength of pairs into the mid-infrared (MIR) range beyond 3 μm. Soon, energy-time and time-bin entangled states were demonstrated with $V_{\text{TPP}}$ reaching 97% and 99%, and $V_{\text{TPP}}$ was also demonstrated with $V_{\text{TPP}}$ reaching 97%. Polarization entanglement, path entanglement, and high-dimensional entanglement were also demonstrated in integrated PPLN waveguides. With the rapid advance in fabrication techniques (such as proton exchange and laser inscription), entangled sources with passive and active components were integrated on-chip further showcasing the potential of the PPLN QPIC platform. Using a dielectric coating on the waveguide endfaces, resonant cavities could be realized. Singly- and doubly-resonant optical parametric oscillator (OPO)-based SPDC photon pair sources have been demonstrated showing 25-fold enhancement of conversion rate reaching a pair brightness of 2.2 MHz/mW/nm. Time-bin entanglement has been demonstrated with doubly-resonant Ti-infused PPLN waveguides. With recent advances in the fabrication of high-quality PPLN waveguides, a high brightness of 56 MHz/mW/nm (at a CAR over 600) with a maximum CAR of 67000 has been achieved.

Silicon waveguides, with their larger Kerr coefficient (200 times higher than fused silica) and tighter mode confinement (see Table I), have effective nonlinear coefficients $\gamma$ five orders of magnitude higher than that of standard optical fibers. Not long after photon pair generation had been demonstrated in fibers and LN waveguides, correlated photon pair generation in silicon waveguides via SFWM was proposed and experimentally demonstrated in a buried silicon rectangular waveguide. Thanks to the strong nonlinearity coefficient in silicon, using a waveguide only 9.11 mm in length, with pulsed pumping, a pair production rate of ~0.05 pair/pulse and a CAR as high as 25 were achieved. By further suppressing the SpRS and improving input and output coupling, a maximum CAR of 673 and a brightness of 0.19 MHz/mW/nm were demonstrated. The high CAR at room temperature is an evidence that the limitation due to SpRS induced noises is less prominent in the crystalline silicon as compared to the silica glass. Soon after the demonstrations of correlated photon pairs, various types of entangled two-photon states in integrated silicon waveguides were demonstrated. Time-bin entangled, path-entangled, polarization-entangled and recently high-dimensional polarization-entangled states were prepared on-chip (a simple waveguide design is shown in Fig. 4(a)), showing $V_{\text{TPP}}$ higher than 99% (as shown in Fig. 4(b)) and very high entangled Bell state fidelity of 98.9%.

Compared to silicon, silicon nitride has advantages in its low linear and nonlinear losses at 1.5 μm and its high transparency in VIS-NIR range, but it has lower Kerr nonlinearity and weaker mode confinement compared to Silicon (see Table I). Photon pair generation has also been demonstrated via SFWM in double-stripe and silicon-rich SiN waveguides achieving a 144 kHz/mW/nm brightness with CAR larger than 10. Time-bin entangled photon pairs were generated in SiN double-stripe spiral channel waveguides with a $V_{\text{TPP}}$ of 88.4%. (the double-stripe waveguide structure is shown in Fig. 4(c)).

III-V semiconductor photon pair sources based on SPDC have been developed in channel waveguides demonstrating correlated photon pair generation and frequency-bin entanglement with integrated super-lattices for quasi phase-matching. Other works using BRW structures for phase-matching are discussed in the following subsection ‘other waveguide structures’. SFWM-based photon pair generation was also investigated in channel waveguides made with III-V semiconductors since they also possess large Kerr coefficients. Correlated photon pairs and subsequently polarization-entangled states were demonstrated in dispersion engineered AlGAs waveguides exploiting their strong third-order nonlinearity.

Correlated photon pairs were also demonstrated in channel waveguides on other material platforms, for example, via SFWM in As$_2$S$_3$ glass channel waveguides. Although possessing a high nonlinearity, this chalcogenide glass material faces similar obstacles posed by SpRS noises as silica glass for achieving high CAR.
2. Microresonators

In the last decade, following the rapid development of micro-ring resonators, they have become a new option to further improve on-chip SFWM photon-pair sources. With their ultra-high Q-factor, they are naturally suited for many other applications including filtering\textsuperscript{224}, active modulation,\textsuperscript{225} sensing\textsuperscript{226} and frequency comb generation\textsuperscript{226}. Due to the high Q-factor of low-loss ring resonators and the possibility of resonant enhancement of all the three wave components (pump, signal and idler) in the FWM process. The pair generation rate $r$ could enhanced according to the following relation\textsuperscript{136}:

$$r = (F_p^2F_sF_i)r_{ch},$$

(27)

where $F_{p,s,i}$ are the field enhancement factors for pump, signal and idler frequencies and $r_{ch}$ is the pair generation rate in a channel waveguide with length equal to the perimeter of the ring resonator. This relation implies that the pair generation rate could be strongly enhanced by the resonant FWM process in a properly designed MRR.

Early works of MRR-based photon pair generation demonstrated a significant improvement of efficiency by 2 orders of magnitude compared to simple channel waveguides, achieving a high brightness of 5 MHz/mW/nm and CAR larger than 250\textsuperscript{136,144}. Reverse biasing of the silicon waveguide was demonstrated to mitigate the effects of free-carrier absorption, further improving the PGR to 123 MHz (corresponds to a brightness of 640 MHz/mW/nm)\textsuperscript{145}. In a MRR with a Q-factor of 9 × 10\textsuperscript{5}, at a low pump power of 10 µW, CAR up to 12000 was demonstrated\textsuperscript{157}. Exploiting multiple resonances of the MRR and broad phase-matching range, correlated photon pairs could be generated via SFWM in multiple neighboring channels\textsuperscript{151}. The potential of photon pair sources based on silicon photonics for QPIC has been shown in its...
compatibility with standard CMOS fabrication processes \cite{148} and capability for advanced functionalities such as spectral filtering systems \cite{150,152}. Two-photon entanglement was also demonstrated in silicon MRR using energy-time/time-bin entanglement \cite{154-157,159} and path entanglement \cite{153,158,160} schemes with $V_{\text{TPI}}$ up to 98\% \cite{155} (an example of entangled photon pair source with an integrated interferometer is shown in Fig. 5(a)).

With SiN MRRs, time-bin/energy-time \cite{171,173} and high-dimensional frequency-bin \cite{172} entangled states were also generated with a brightness of 150 MHz/nm/mW \cite{171}. Thanks to the wider bandgap and ultra-low losses of SiN, time-energy entangled photon pairs were generated also in the visible range with a CAR as high as 3780 \cite{174}.

Besides the aforementioned platforms that attracted more attention, photon pair generation has been also demonstrated in other materials based MRRs. For example, MRRs were also realized in AlN demonstrating photon pair generation via SPDC with a brightness up to 102 kHz/mW/nm \cite{196}. Entangled photon pairs were also generated in InP membrane MRRs achieving a brightness of 91 MHz/mW/nm \cite{203}. Furthermore, correlated pair generation was also demonstrated in amorphous hydrogenated silicon channel waveguides \cite{210} and MRR \cite{211} showing higher PGR compared to silicon MRRs with a similar design due to the higher Kerr nonlinearity of the hydrogenated silicon. Multi-channel correlated photon pairs were demonstrated in Hydex MRRs which have a low nonlinearity ($n_2 \approx 1.15 \times 10^{-19}$ m$^2$/W) and low linear loss (<0.07 dB/cm) \cite{62}. Employing SFMW in high-Q MRRs, correlated photon pairs with a moderate brightness of 3.5 MHz/mW/nm in multiple frequency channels of the comb structure and high-dimensional frequency-bin entangled states were also generated \cite{204-207}.

3. Other waveguide structures

For their strong second-order nonlinearities, III-V semiconductors such as GaAs and AlGaAs are also suited for photon pair generation via SPDC processes. However, in a simple channel waveguide structure the phase-matching condition cannot be easily satisfied. To this end, BRWs have been employed to enable phase-matching between transverse-electric and transverse-magnetic modes for SPDC \cite{34,193,194}, achieving CAR as high as 141 and brightness up to 102 kHz/mW/nm \cite{196}, polarization-entangled \cite{198,200,201} and time-energy entangled states were demonstrated in (Al)GaAs Bragg reflection waveguides via SPDC with a highest $V_{\text{TPI}}$ of 95\% and Bell state fidelity of 97\% \cite{65,192,196}.

Photon pair generation can also be enhanced by slow-light structures, such as photonic crystal waveguides and coupled-
resonator optical waveguides. These structures are shown to possess much higher nonlinear coefficients than simple channel waveguides and MRRs\cite{163,227}. Both correlated photon pairs\cite{162,164-167}, time-bin entangled\cite{168} and path entangled\cite{228} two-photon states have been demonstrated in silicon slow-light structures. Although at the moment their performances in terms of PGR (13 kHz)\cite{229}, CAR (80)\cite{229} and $V_TPI$ (74%)\cite{168} do not compare favorably towards other types of waveguide structures, these devices have very small footprints and high efficiencies, beneficial for dense large-scale integration.

IV. PERSPECTIVES

Although research on integrated photon-pair sources with nonlinear optics has seen rapid growth and great success, further improvements in efficiency and strategies to overcome the limitations imposed by the probabilistic nature of the parametric process at a system level are in urgent need before they can be ready for realistic applications. Moreover, the development of high-performance on-chip photon pair sources can potentially lead to various exciting technological applications.

A. New material platforms

For future implementation of complex QPICs, the reduction of losses in each of the active and passive components, such as directional couplers, modulators, detectors etc., are of significant importance and have seen tremendous advances. At the same time, new materials other than those previously discussed are also under investigation. For example, with the availability of quantum memories based on nitrogen-vacancy (NV) centers, diamond has attracted considerable attention in recent years\cite{231}. With the advance of laser inscription of waveguide\cite{232}, diamond has also been considered for integrated nonlinear optics\cite{233} and mid-IR applications\cite{234}. Lithium niobate with micrometer level thickness has been considered for phase-matching-free photon pair generation\cite{235}. Other materials (such as AlN\cite{58} and metal chalcogenides\cite{236}) also have potentials as platforms for integrated photon pair sources.

In recent years, low-dimensional nanomaterials (for example 1D materials such as carbon nanotubes\cite{237} and nanowires\cite{238}, 2D materials such as graphene, transition metal dichalcogenide monolayers\cite{239-241}) have attracted considerable research efforts. Their interesting potential in nonlin-
ear optics and quantum photonics is being gradually discovered and investigated (e.g., optical parametric generation\textsuperscript{242} and gate tunable nonlinearity\textsuperscript{244}). Their hybrid integration in conventional photonic waveguide platform is also under active research (as illustrated in Fig.6(c))\textsuperscript{230}. With graphene and graphene oxide\textsuperscript{244} deposited on top of silicon\textsuperscript{245,246} and silicon nitride\textsuperscript{247} waveguides and optical fibers\textsuperscript{248,249}, the effective Kerr nonlinearity of the composite waveguide structure were shown be strongly enhanced. Photon pair generation in graphene-covered silicon waveguide were also investigated.

Although the nonlinearity of the waveguide was enhanced by a factor up to 10, the linear propagation loss due to absorption in graphene limits its performance in terms of PGR and CAR of the device\textsuperscript{250}. These losses can be avoided by using transition metal dichalcogenide monolayers which are absent of the wavelength-independent absorption characteristic of semi-metallic graphene. Besides the enhancement in nonlinearity, these atomically-thin materials could also bring new functionalities such as ultrafast modulators\textsuperscript{251} and broadband photodetectors\textsuperscript{252}.

### B. Novel integrated structures

Various techniques have been investigated to further enhance the conversion efficiency of the photon-pair generation processes. Resonant cavities and structures are among the most evident solution for passive field enhancement which directly leads to increased efficiency. MRRs, photonic crystal waveguides and coupled-resonator optical waveguides have been the most widely used solution for their ultra-high Q-factor and facile integration with on-chip photonic waveguides, deserving further investigation for practical applications.

Microcavities other than MRRs such as microtoroids\textsuperscript{253} and microdisks\textsuperscript{146,149,254,255} could provide even higher Q-factors and potentially can further improve the efficiency of photon pair sources. Linear cavities realized with dielectric mirrors could also be employed for channel waveguides\textsuperscript{187,256,257}.

Novel metamaterials and metasurfaces\textsuperscript{258,259} including plasmonic nanostructures\textsuperscript{260} have also been considered for photon pair generation to take advantage of their sub-wavelength field localization. Photon pair generation via SPDC has been demonstrated in AlGaAs dielectric nanoantenna\textsuperscript{261} and hybrid nanoantenna\textsuperscript{262}. Metasurfaces are also being investigated for the enhancement of photon pair generation via SPDC process\textsuperscript{263}.

### C. Emerging technological innovations

The utmost challenge for photon-pair sources at the moment is how they can meet the need of quantum sources with on-demand emission. The maximum probability of one single pair being emitted from a SPDC process is shown to be 25\%\textsuperscript{100}. As a result, the parametric photon pair source cannot behave as a deterministic quantum light source (as opposed to sources based on e.g. quantum dots\textsuperscript{264}). The solution to this limitation is one of the focuses of active research endeavors in the field. Currently temporal\textsuperscript{99,265–267}, spatial\textsuperscript{98,266} and frequency\textsuperscript{269} multiplexing techniques are among the most common solutions, realized in free space, fibers or on-chip PICs (shown in Fig.6(a)). By multiplexing 40 channels actively in the time-domain, a single-photon probability up to 66.7\%\textsuperscript{99} was achieved recently, with the potential to maintain high purity of entanglement states\textsuperscript{267}. With the rapid advances of large-scale photonic integration\textsuperscript{270,271} and ultra-low
loss waveguides near-ideal on-chip multiplexed photon-pair sources should be fathomable in the near future.

The generation of high-dimensional photon states is also one of the forefronts. With the ability of generating frequency-bin high-dimensional entangled states, the quantum frequency combs based on MRRs have great potentials for the generation and the control of complex photon states on a scalable integrated platform.

With the advance in integrated near-deterministic photon pair source development, the implementation of many proposals of quantum technologies on integrated photonic platforms will become closer to reality. The simulation of quantum mechanical problems could be achieved on integrated photonic platforms. Quantum computation using quantum qubit/quantum states can be implemented with quantum walk, boson sampling, linear optics, or with cluster states in a measurement-based one-way photonic quantum computer.

V. CONCLUSION

In conclusion, we reviewed the recent advances in integrated photon-pair sources based on nonlinear parametric processes. Developments in the hybrid integration of multiple materials will bring new degrees of freedom and functionalities to the current QPIC platforms. With large-scale integration of spatial and temporal multiplexing systems, near-deterministic entangled multi-photon states can be implemented with high brightness and high-fidelity entanglement. These scalable and efficient integrated quantum light sources will be instrumental for the development and application of quantum technology in quantum key distribution for secure communication, quantum information processing, quantum metrology and sensing.

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DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.


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