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Comprehensive Study of Entanglement Photon Source: Bulk Optics, Waveguides and Integrated Photonic Chip Hardware

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Abstract. In quantum technology, entanglement is the key resource to perform experiments in quantum computing, quantum communication, quantum sensing and metrology. Generation, characterization and distribution of entanglement deterministically is still an active research area. In contemporary, probabilistic entanglement sources based on parametric down-conversion process remain the workhorse for experimental demonstrations and practical applications, despite their inherent limitations of on-demand entangled photon generation. Over the years, three main technological architectures have evolved for generating probabilistic entangled-photon source; bulk-optics, waveguides and integrated photonic chips, each comprising several distinct architectural approaches tailored to different applications. This review article talks about the state of the art in probabilistic entangled photon source, examining the advancement from free space bulk non-linear optics to fiber based waveguides and scalable photonic chips with their current limitations, presenting a road map for researchers to choose the most appropriate platform for their quantum photonic applications.

1 Introduction

Quantum technology has developed from theoretical research to experiments in last century , and entanglement is one of the important quantum resources that has applications in all verticals of quantum field like quantum information theory [1], quantum computing [2], quantum imaging [3], quantum sensing and metrology [4].

Generating entanglement with high quality is an absolute necessity for many practical quantum applications. At present bi-partite entanglement is demonstrated on various technological platforms, here we mainly discuss on nonlinear crystals with bulk optics, waveguides, and integrated photonic chips. For all the above mentioned platforms the approach remains the same, probabilistic photon sources based on nonlinear parametric processes (SPDC/SFWM) [5] [6]. In nonlinear optics we have a diverse toolkit for engineering wave-mixing process to obtain a variety of photonic degrees of freedom with efficient entanglement pairs. Three wave or four wave mixing techniques that use the $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearity are the most commonly used techniques to generate the photon pairs. At present spontaneous four wave mixing based on $\chi^{(3)}$ process is implemented in photonic chip components like ring resonator but due to technological maturity in bulk based setups the $\chi^{(2)}$ spontaneous

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parametric down conversion process is the most preferred photon source for quantum experiments at present.

A qubit is counterpart of the classical bit and it can be extended to higher dimensions, which are known as qudits [7]. Qudits improves security, good error correction capabilities and large state space to process and represent quantum information. In this paper, we summarize the experimental progress of generation, manipulation, and measurement of entanglement photon source in bulk optics, fiber integrated waveguides and integrated photonic chip hardware that encode information in qubits and qudits space. In sec.2 we will give a detailed overview of experimental setup using bulk optics for entanglement photon source and the various degrees of freedom that are used to encode the quantum states [8]. Sec.3 we will see how waveguide and fiber optics are used to generate the entanglement photon pairs[9]. Sec.4 will be a summary of Photonic chip entanglement sources [10]. Sec.5 A detailed comparison table of all the above architectures that gives readers an overview on which source architecture will suit their applications based on their infrastructure and skill set.

2 Generation of Entangled Photon Pairs via Bulk Optical Nonlinearity

Quantum entanglement lies at the core of modern quantum technologies, among the various methods for generating entangled photons, spontaneous parametric down-conversion (SPDC) stands out as a widely used and experimentally accessible process for quantum photon source. There are three ways based on the polarization relationship between pump and down-converted photons (Type 0, Type 1 and Type 2) to generate entanglement using SPDC process [8] [11]. Entanglement can be engineered for multiple degrees of freedom (DOFs), such as polarization, spatial mode, time–energy, and orbital angular momentum [8]. SPDC can further be classified as degenerate or non-degenerate on the basis of the wavelength of down-converted photons. The spatial emission configuration may also vary, resulting in collinear or non-collinear geometries depending on the phase-matching conditions and crystal orientation [8]. In this section, we focus on Type-1 SPDC architecture, specifically degenerate non-collinear configuration implemented using paired beta barium borate (BBO) nonlinear crystals [12] .

Table 1. Types of SPDC process [8] [11]

Type	Pump, Signal and Idler	Description
Type 0	$o_p = o_s + o_i$ $e_p = e_s + e_i$	All photons have identical polarizations.
Type I	$o_p = e_s + e_i$ $e_p = o_s + o_i$	Signal and idler share polarization, orthogonal to pump.
Type II	$o_p = o_s + e_i$ $e_p = e_s + o_i$	Signal and idler have orthogonal polarizations.

Type-I SPDC, produces polarization entangled photon pairs through coherent superposition of $|HH\rangle$ and $|VV\rangle$ states, once phase matching conditions(energy conservation and momentum conservation) are satisfied. Traditionally, this setup is implemented using a pair of thin BBO nonlinear crystals with orthogonal optical axes, where both down-converted photons share the same polarization orthogonal to the pump. A continuous-wave pump at 405 nm is directed onto the nonlinear crystal where pump polarization is prepared in $|H\rangle + |V\rangle$ state using a sequence of Quarter wave plate and half wave plate, ensuring equal excitation of down-converted photons $|\Phi^{+}\rangle$ bell state [12] [2].

$$|\Psi^{+}\rangle = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle) \tag{1}$$

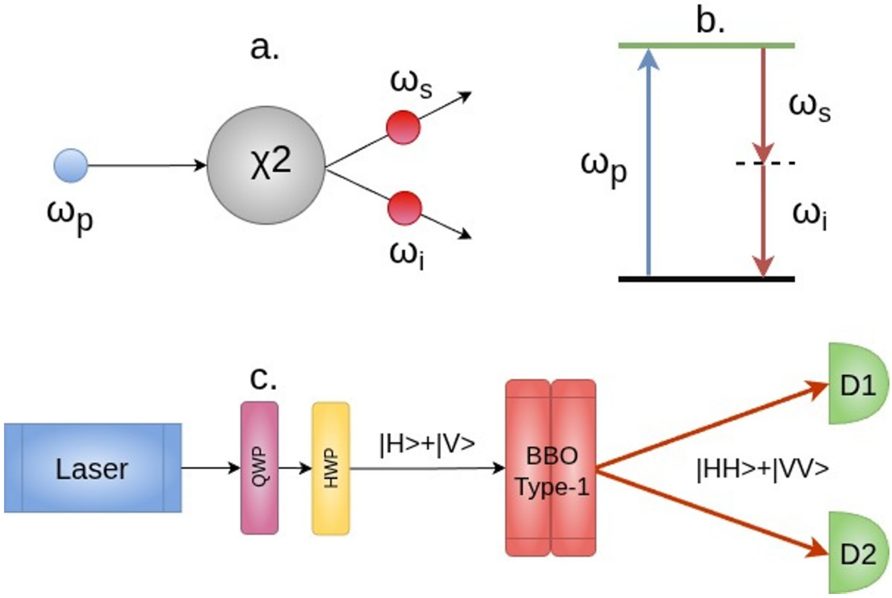

Figure 1. (a) $\chi^{(2)}$ nonlinear down-conversion process where a pump photon splits into signal and idler photons. (b) Energy conservation diagram of the down-conversion process[8]. (c) Bulk-optics entanglement setup using Type-I SPDC in a BBO crystal. Schematic adapted from [12].

In a sandwiched crystal configuration, the $|HH\rangle$ and $|VV\rangle$ components are generated in two orthogonally oriented crystals. Due to differing group velocities and walk-off angles, these components do not perfectly overlap in time and space. This mismatch leads to an effective relative phase between the two terms in the entangled state. It significantly affects interference measurements on the diagonal basis and limits the visibility of quantum correlations when left uncorrected. Traditionally, spatial and temporal walk-off in nonlinear crystals is addressed using pre and post compensation nonlinear crystals.

Type-I source has achieved $98.8 \pm 0.2\%$ visibility in both bases, Clauser-Horne-Shimony-Holt inequality test $S = 2.7007 \pm 0.0029$ (CHSH violation), confirming polarization entanglement for the $|\phi^{+}\rangle$ state via 16-angle measurements [13].

Implementing quantum networks via ground-to-satellite requires compact, robust entangled photon sources that exhibit high brightness and entanglement purity. Out of various architectures type-0 quasi-phase-matching (QPM) in periodically poled potassium titanyl phosphate(PPKTP) crystal is more favored over other phase-matching geometries to produce bright entangled photons [14].

This high-brightness entangled photon source achieved visibilities of $97.4 \pm 0.2\%$ and $96.9 \pm 0.3\%$ in the rectilinear/diagonal bases, along with a CHSH inequality parameter of $S = 2.63 \pm 0.02$ and fidelity of 0.975 for the Bell state $|\Psi\rangle = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$ [14].

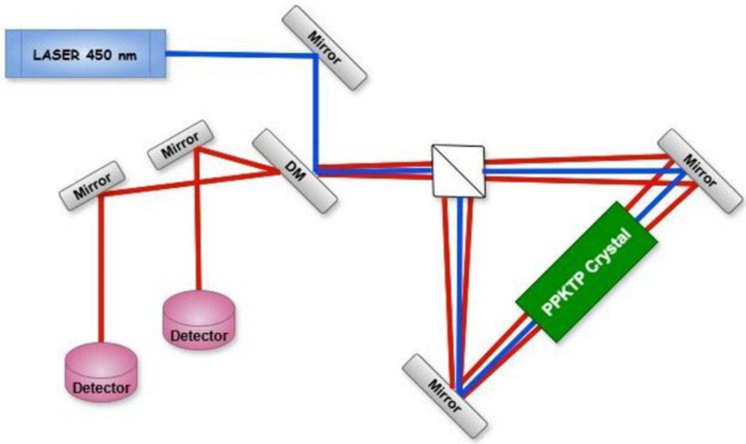

Figure 2. Sagnac-interferometer-based architecture for entangled photon generation using a PPKTP nonlinear crystal. Schematic adapted from [15] [16]

3 Fiber-Coupled Waveguide-Based Entangled Photon Sources

One of the main challenges in the advance of quantum photonic experiments from laboratory demonstrations to real-world deployable technologies is the need for compatibility with existing classical infrastructure. For instance, most of the entanglement photon source developed in lab falls on near infrared region (NIR) as it offers high spatial mode quality and are compatible with well-established single-photon detectors(SPAD) with high efficiency and low noise, neglecting the standard fiber loss of 2.5 - 3 dB/Km for this wavelength [17]. In contrast, real-world quantum communication must operate in the telecom bands, particularly near 1310 nm and 1550 nm, where standard optical fiber losses drop to 0.35 dB/km in the O-band and 0.2 dB/km in the C-band [17]. These telecom bands also align with the existing global fiber-optic infrastructure, allowing quantum and classical signals to coexist.

Fiber-based waveguide sources for entangled photons have emerged as a promising platform to operate in the o-band and c-band. A widely adopted fiber-integrated quantum light source at the telecommunication wavelength uses a periodically poled lithium niobate (PPLN) waveguide for SPDC process. Notably, the mentioned source can be used over the existing global fiber optic network coexisting in the classical and quantum field for advanced applications like quantum communication networks, quantum internet.

A compact and fiber-integrated entanglement source has been demonstrated using a 4-cm MgO-doped PPLN ridge waveguide in a Sagnac configuration, enabling stable Type-0 SPDC at telecommunication wavelengths. The device produces a broadband output centered at 1550 nm with a full-width at half-maximum (FWHM) of approximately 52 nm and achieves a high spectral brightness of roughly 2×10^8 pairs/s/mW/nm. The unfiltered polarization-entangled state exhibits strong quantum interference, with fringes exceeding 86% visibility on mutually unbiased bases. The corresponding raw concurrence and fidelity values reach ~ 0.83 and > 0.89, improving to ~ 0.88 and $\sim 92\%$ after background correction. The quality of entanglement is further confirmed by a CHSH parameter of $S = 2.49$, representing a violation by approximately 29 standard deviations [9].

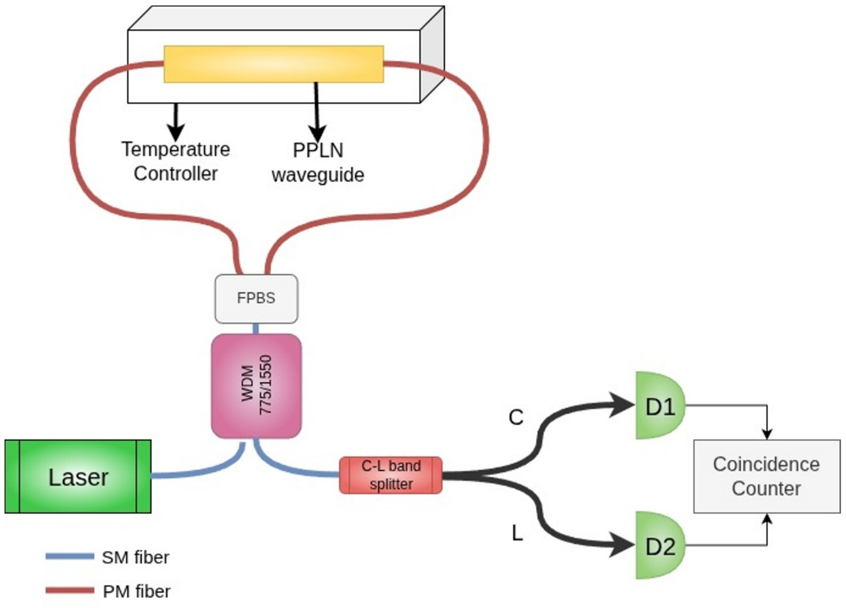

Figure 3. Experimental setup of a fiber-coupled PPLN waveguide implemented in a Sagnac interferometer architecture. Schematic adapted from [9].

Overall, the demonstrated performance highlights the strengths of PPLN waveguide architectures in generating high-brightness, broadband entanglement within the telecom window.

4 Scalable Entangled Source on Photonic Chips

The quantum sources reviewed in the above sections come with nonlinear bulk materials that limits a large scale implementation of quantum photon sources for applications like quantum processor and quantum computers. In this section, we present two architectures that showcase qubit and qudit encoding capabilities on photonic chip for entanglement source using SFWM in microrings [18] and frequency bin encoding [10].

Generally, qubit entanglement is generated with bulk or fiber based quantum optical systems. Here, using two coherently pumped photon-pair sources, a path entanglement is generated using a silicon-on-insulator photonic chip in central telecommunication band. A picosecond pump pulse is coupled into the silicon chip and it generates a superposition of photon pairs via spontaneous four-wave mixing (SFWM). On-chip de-multiplexers and waveguide crossovers transform this source superposition into path-encoded photonic qubit entanglement by separating the superposition into signal (blue) and idler (red) path qubit. In this architecture, pump laser, pump suppressing filters and detectors are all fiber integrated, off the chip.

The generated entanglement was characterized by a visibility of $94.7 \pm 1.0\%$ and a strong CHSH violation of $S = 2.686 \pm 0.026$.

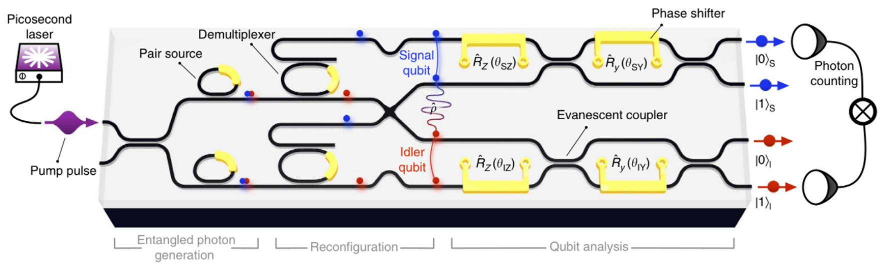

Figure 4. Fiber-coupled photonic chip entanglement source architecture. Reprinted from [18] under the Creative Commons CC BY 4.0 license.

Advancing toward full integration to monolithic sources, a photonic chip with a fully integrated light source combining a laser cavity with an advanced tunable noise-suppression filter (>55 dB rejection via the Vernier effect) and a nonlinear micro-ring resonator enabling entangled photon-pair production through spontaneous four-wave mixing has been fabricated. The setup features an electrically driven InP-based III-V reflective semiconductor optical amplifier (RSOA) that delivers optical gain and is butt-coupled to a low-loss Si_3N_4 waveguide feedback structure. A laser cavity is formed by a reflective coating on the RSOA facet and a Sagnac mirror at the far end. Following the gain section, three micro-ring resonators (MRRs) of progressively smaller radii (R1 > R2 > R3) and correspondingly distinct free spectral ranges (FSRs) are cascaded to implement a tunable Vernier filter, controlled via integrated micro-ring phase shifters.

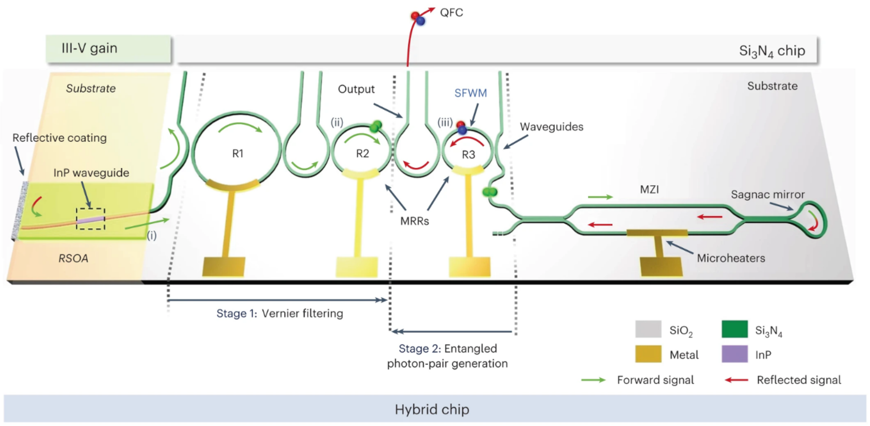

Figure 5. Integrated photonic chip-based entanglement source architecture. Reprinted from [10] under the Creative Commons CC BY 4.0 license.

This architecture employs frequency-bin encoding, distinguishing it from traditional SPDC sources in BBO/PPLN waveguides that utilize polarization (H/V) for qubit entanglement. Spontaneous four-wave mixing in a Si_3N_4 micro-ring generates a quantum frequency comb with photon pairs at discrete resonances spanning 1 THz around the 193.4 THz pump. This enables high-dimensional states qubits across mode pairs {2,3}, {3,4} and qutrits spanning {2,3,4}, verified by 97.5% visibilities and 99% fidelity. Unlike polarization-limited systems $d = 2$, frequency-bin encoding accesses qudit Hilbert spaces in a chip-integrated platform compatible with telecoms [10].

5 Comparative Analysis

Table 2. Comparison of representative entangled photon-pair sources.

Setup	Material	Architecture	DoF	Wavelength	Characterization	Applications
Bulk Optics[12]	BBO crystal	$\chi^{(2)}$, Type-I SPDC	Polarization, Qubit	Visible/NIR	Visibility=98.8 ± 0.2%, Pair Rate = 10,000 s^{-1} mW^{-1}, $S = 2.7007 \pm 0.0029$	Foundational Experiments, Quantum Imaging
Bulk Optics[14]	PPKTP crystal	$\chi^{(2)}$, Type-0 SPDC, Sagnac	Polarization, Qubit	Visible/NIR	Pair Production Rate=39.13 ± 0.04 MHz/mW, Fidelity=96%, $S = 2.39 \pm 0.04$, Visibility=96.9 ± 0.4% / 75.3 ± 0.3%	High-brightness, Satellite Quantum Key Distribtuion
Fiber Optics[9]	PPLN waveguide	Type-0 SPDC, Sagnac	Polarizations, Qubit	Telecom	Spectral Brightness=2×10^8 pairs/s/mW/nm, $S = 2.49 \pm 0.017$, Fidelity=92.2%, Visibility=86%	Quantum Networks, Quantum Internet, Fiber Communication.
Integrated Chip[18]	SOI platform	Microring, SFWM	Path, Qubit	Telecom	$S = 2.686 \pm 0.026$, Visibility= 94.7 ± 1.0%, Fidelity=92 ± 1%	Quantum Walks, Linear Optical Quantum Computing
Hybrid Chip[10]	InP III-V / Si_3N_4	Microring, SFWM	Frequency-bin, Qudit	Telecom	Visibility=97.5%, Fidelity=99%, $S = 2.793$	Boson sampling, quantum ML

Bulk optics entanglement source using BBO crystal is well suited for foundational experiments like quantum interference studies, validation of bell states and experiments like ghost imaging [19], serving as a testbed for early researchers in entanglement field. PPKTP crystal in free space optics is used for experiments where high brightness entanglement is required like entanglement distribution and QKD in satellite communication [20], this architecture demands active temperature control and highly alignment sensitive.

Fiber-coupled waveguide source is less alignment sensitive compared to the bulk optical source, and it is well suited for experiments like quantum internet and cosmopolitan quantum key distribution systems that need to be integrated to the existing optical fiber infrastructure.

Both bulk optics and fiber-coupled architectures inherently come with scalability issues, as both are mounted on the optic table and in a controlled environment. Although photonic chip sources are scalable and deployable, at present this architecture has limitations with mode-field mismatch, coupling loss, insertion loss and on chip cryogenic detectors like SNSPD(superconducting nanowire single-photon detectors) are few engineering bottlenecks that researchers must carefully consider while choosing photonic chip entangled source.

6 Conclusion

In this review paper, we have seen a comparison of entanglement photon source architectures their applications and trade-offs that one should consider when choosing an architecture. The future for both bulk optics and fiber-coupled waveguides is to move from probabilistic entanglement photon source to deterministic entanglement source. Development of motor controlled optical equipment helps in precise alignment and coupling of photons to fibers and detectors.

At present for entanglement photon source the bulk nonlinear optics and fiber-coupled waveguide outweigh the scalable photonic chips in reliability. Progress in silicon photonics that are compatible with CMOS processes along with silicon nitride platforms has transformed quantum photonic chips from theoretical concepts into practical devices. Moving ahead, the integrated photonic chip platform will be crucial for building robust, error-corrected Quantum Communication Networks and Quantum Photonic Processors.

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