PARAMETRIC PROCESSES AS A VERSATILE TOOL TO HARNESS QUANTUM LIGHT

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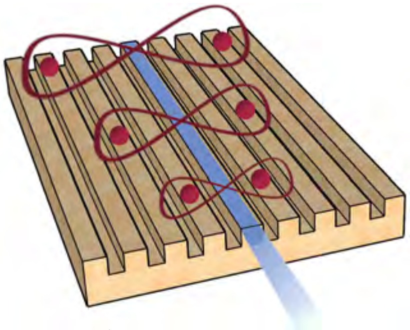

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The parametric generation of quantum states of light holds a central position across various fields of quantum technologies. Starting from the seminal experiments in the 1970's, we retrace the history of this powerful approach for creating and tailoring entangled photon pairs or squeezed states of light from the interaction of strong laser fields with optically nonlinear media. From its inception to its latest applications, this technique not only continues to play a pivotal role in the burgeoning fields of quantum computation, communication, and metrology, but shares also fundamental links with general concepts of quantum field theories in curved space-times.

In our childhood, all of us had great fun in experiencing that a periodic motion of our legs and feet can induce a wildly wide oscillation of the swing on which we are sitting. In this article we explore how similar parametric processes can be a powerful tool to generate quantum light and also underlie fundamental phenomena in many fields of physics, from quantum optics to gravitation.

When a dielectric material is illuminated by strong light fields, a number of novel optical phenomena can be observed thanks to the nonlinear optical response of the medium, such as harmonic generation, frequency conversion, or parametric amplification. While many such processes are well captured by Maxwell equations with suitable nonlinear polarization terms, other nonlinear phenomena require a quantum description of light-matter interaction including the vacuum fluctuations of the quantized electromagnetic field. This is the case of spontaneous parametric down-conversion (SPDC) and spontaneous four-wave mixing (SFWM) phenomena. In SPDC, a photon from an intense pump laser gets converted into a pair of photons, called signal and idler (Fig. 1a), while in SFWM two pump photons collide and get converted into a photon pair (Fig. 1b). These nonlinear processes are fully general and only require a nonlinear optical response of the medium, so that they are observed both in dilute atomic vapors and in dense solid-state materials.

FOUNDING EXPERIMENTS

The first experimental demonstration of SPDC was reported in 1970 by Burnham & Weinberg using a barium borate (BBO) crystal [1], whose birefringence was exploited to achieve the phase-matching (wavevector conservation) of the nonlinear process. Following this seminal demonstration, several striking peculiarities of the photons generated by SPDC were successively evidenced. In 1986, Hong & Mandel demonstrated that thanks to the simultaneity of emission of the two down-converted photons, one photon of the pair can be used to herald the emission of its twin. This allows realizing so-called heralded sources of single-photons which, despite their probabilistic nature, still play a central role today in quantum technologies thanks to their simplicity and ability to operate at room temperature.

The intrinsically quantum nature of the emitted photon pairs was soon after highlighted by Hong, Ou & Mandel who made the two photons forming an SDPC pair to interfere on a 50/50 beamsplitter. In symmetric configurations the two photons are indistinguishable, so their bosonic nature implies that processes where they would emerge from different ports undergo destructive interference, leaving only scenarios where the two photons exit together from the same port. This intriguing two-photon interference effect is experimentally evidenced by measuring the coincidence counts between detectors placed at the two outputs of the beamsplitter and manifests itself as a dip when varying the time delay between the two incident photons. The visibility of this dip around zero delay is a direct measure of the indistinguishability of the interfering SPDC photons and can reach very high levels (>99%) in state-of-the-art experiments.

The next milestone was the demonstration of entanglement between photons created by SPDC. Using a BBO crystal, for a careful pump configuration the signal and idler photons turn out to be emitted along two cones, which support photons with orthogonal polarizations and intersect at two points in a given detection plane (Fig. 1c). Placing oneself at one of these intersection points, it is therefore impossible to predict the polarization of the emerging photon, which can randomly change from horizontal to vertical from measurement to measurement; however, the polarization of the photon emerging at one intersection must be orthogonal to the one of the other photon, which corresponds to having a polarization-entangled state of the two photons. A slight improvement of this general principle was exploited by Kwiat et al. to demonstrate in 1995 a strong violation of Bell inequalities by over 200 standard deviations in less than 3 min [2].

At the turn of the 20th century, SPDC continued to make crucial contributions to the demonstration of foundational concepts of quantum information. These include the first demonstration of quantum teleportation (1997), entanglement-based quantum key distribution (2000), as well the first realization of an optical controlled-not gate (2003) soon after the landmark proposal of linear optical quantum computing by Knill, Laflamme and Milburn.

In parallel, another branch of quantum information has been actively explored since the mid-80's, pushing

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parametric generation beyond the single photon-pair regime by increasing the pump power or/and the nonlinear interaction length. In this situation, the probability of generating double, triple, etc. photon pairs becomes sizable and the generated quantum state of the field is a squeezed state involving the superposition of many photon-number states. This marks the transition into the continuous-variable regime, where quantum information is encoded within the quadratures of quantum electromagnetic fields rather than in individual photons. The first forays into this realm were realized by placing a nonlinear crystal in a cavity so as to resonantly reinforce the parametric processes. For instance, a degenerate parametric down conversion (PDC) process operated below the oscillation threshold leads to the generation of single-mode squeezed vacuum states, while nondegenerate PDC operated above the oscillation threshold leads to two-mode squeezed coherent states, also called twin beams as they feature strong mutual intensity correlations in the form of a strong squeezing of their amplitude difference [3].

APPLICATIONS TO QUANTUM TECHNOLOGIES

In the early 2000s, progresses in microfabrication techniques made parametric generation possible also in integrated optical structures. This provided a strong reduction in the device footprint, but also a large increase of the process efficiency: the strong modal confinement of the three fields in microscopic waveguides allows indeed for a diffractionless propagation as well as a reinforced nonlinear overlap of the fields. The on-chip parametric generation of quantum states of light was demonstrated by SPDC in periodically poled lithium niobate (PPLN) and in AlGaAs waveguides, as well as by SFWM in optical fibers, silicon-based and glass microresonators. While these early demonstrations operated in the photon pair regime, recent years have seen a significant progress towards the on-chip generation of squeezed states (Fig. 2b).

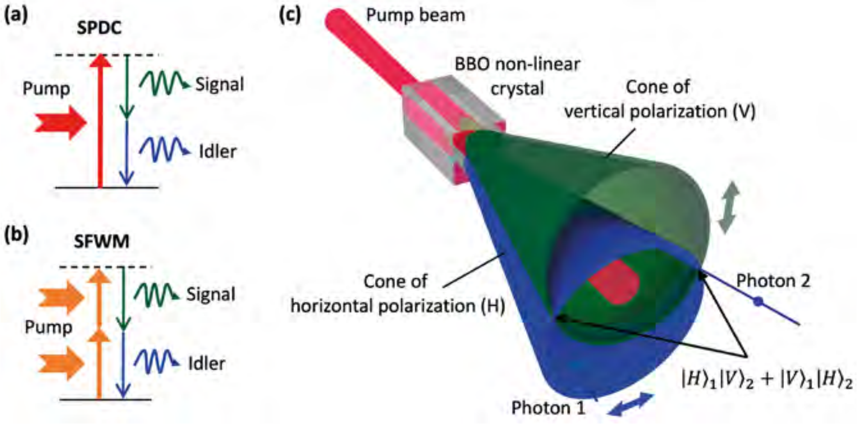

Figure 1. (a) Energy diagram for Spontaneous Parametric Down-Conversion (SPDC) and (b) for Spontaneous Four-Wave Mixing (SFWM). (c) Sketch of an SPDC experiment in a Barium Borate (BBO) crystal, leading to the generation of polarization-entangled photon pairs (modified from open-access Wikimedia Commons CC BY-SA 4.0).

Concurrently, another layer of complexity was introduced into the quantum optics landscape by the emergence of quantum photonic circuits, which allowed in 2008 the first on-chip demonstration of two-photon quantum interference and controlled-NOT gate operations using a combination of passive waveguides and beamsplitter elements. This area of research has then experienced rapid evolution, transitioning from centimeter-scale static circuits, manipulating a small number of photons with only few optical components, to millimeter-scale reprogrammable circuits, capable of processing multiphoton states with hundreds of components.

Initially, these two research trajectories progressed independently, with a separate development of parametric sources and of passive optical circuits. Recently though, the convergence of these streams has led to remarkable integrated photonic devices combining the on-chip generation and manipulation of quantum states of light (Fig. 2a), in particular on the Silicon, PPLN and AlGaAs platforms. The high fabrication reproducibility of integrated parametric sources is here exploited to realize of a large number of identical sources on the same chip (*e.g.* 16 SFWM sources in Ref. [4], with a mutual indistinguishability > 90%). Photons emitted by these integrated sources can then interfere in the following elements of the optical circuit to produce high-dimensional entangled states, paving the way to scalable applications in linear optical quantum computing, boson sampling or quantum simulation. An alternative strategy for these tasks is based on continuously-coupled systems such as the nonlinear waveguide arrays illustrated in Fig. 2c. Here, photons are generated and interfere along the entire propagation length rather than solely at discrete optical elements. This allows to unveil novel phenomena stemming from an intertwined instead of sequential combination of the generation and manipulation steps of photonic quantum states [5].

In addition to the spatial degrees of freedom, further possibilities are offered by the spectral ones. For instance, by pumping SPDC with a multi-frequency laser, complex networks of multi-mode squeezing can be generated: an optical comb pump source containing a lattice of equispaced frequencies simultaneously generates squeezing in all pairs of frequencies that sum up to a comb tooth [6]. In the same way as entanglement in waveguide arrays can be manipulated via the coupling of neighboring waveguides, techniques inspired by synthetic dimensions provide manipulation tools in the spectral domain. Combining together all degrees of freedom, and possibly exploiting also topological protection effects [7], complex high-dimensional entanglement lattices can be generated with high interest for quantum information applications.

While in the late 1990s, parametric sources supplanted atomic cascades as flexible and user-friendly sources of quantum states of light, in the recent years they are encountering an increasing competition from high-quality two-level emitters such as semiconductor quantum dots, which can emit single photons in a deterministic manner without trade-off between brightness and photon purity. In spite of this, parametric sources still play a pivotal role nowadays thanks to various practical assets, including their room temperature operation, high fabrication reproducibility, and quality and versatility of the emitted quantum states, including the generation of squeezed states. These assets underlie a number of recent breakthrough advances in quantum technologies, from fundamental tests of quantum mechanics (where parametric sources were used to close loopholes in Bell tests), to quantum computation and simulation (leading *e.g.* to the demonstration of a quantum advantage in the Boson sampling problem), to metrology (where the use of squeezed states as an input improves the sensitivity of the LIGO interferometer for gravitational wave detection) [8].

FURTHER PERSPECTIVES

From a wider perspective, it is interesting to note that spontaneous parametric processes are at the heart of a number of exciting phenomena that are attracting a strong interest in many other areas of physics. A simplest such example is the dynamical Casimir effect, that can be straightforwardly understood as the spontaneous parametric emission of photon pairs when a neutral body (*e.g.* a dielectric or a mirror) is accelerated in space: here, the role of the optical pump beam is played by the mechanical motion and, most remarkably, the electromagnetic emission takes place even though no net currents are present in the set-up.

At a higher level of complexity, parametric processes play a crucial role also in cosmology and gravitation: the parametric generation of particles during and right after the fast

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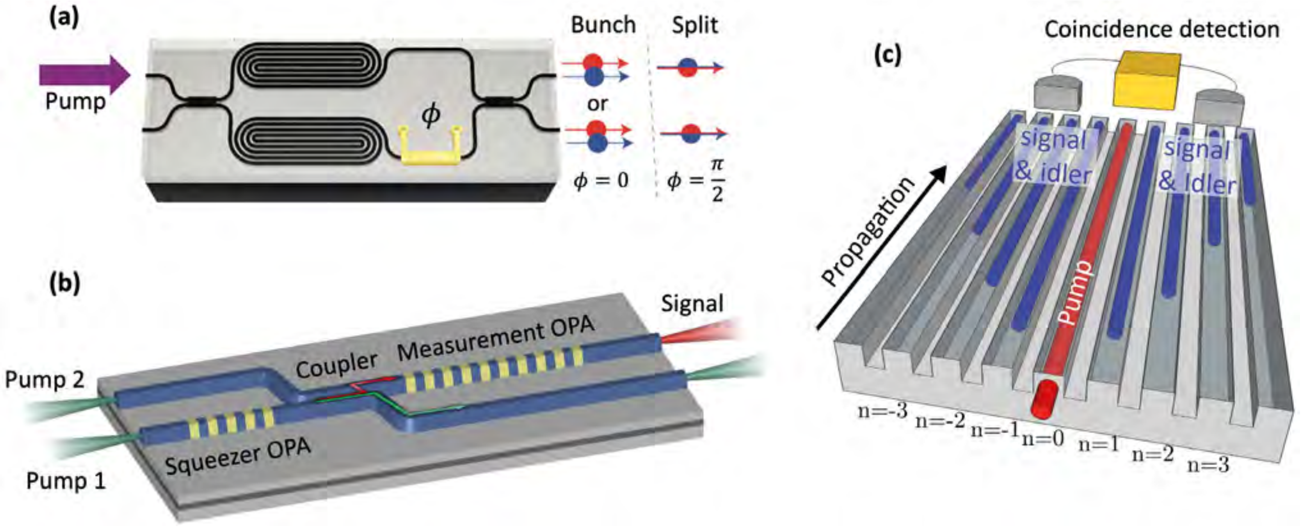

Figure 2. (a) Silicon photonic circuit embedding two SFWM sources, beamsplitters and a phase shifter: depending on the phase shift ϕ, one can switch from a regime where bunched photons are generated in the same output arm to a regime where the photon pairs are split into the two arms (adapted with permission from Silverstone *et al.*, Nature Photonics **8**, 104 (2014)). (b) Lithium niobate circuit allowing the generation and all-optical measurement of squeezed states within a single chip: the pump beam 1 injected into a squeezer optical parametric amplifier (OPA) generates a squeezed vacuum state, which is coupled into an adjacent waveguide and amplified by a second OPA (seeded by the pump beam 2) for measurement (adapted with permission from Nehra *et al.*, Science **377**, 1333 (2022)). (c) Nonlinear waveguide array for the controlled generation of spatially entangled states of light: the pump beam (sketched in red) continuously generates photon pairs that undergo quantum walks (blue), resulting in spatial entanglement over the whole lattice [5].

inflationary expansion of the early Universe has contributed to the generation of visible matter. And also the Hawking radiation from black holes can be physically understood as the result of the parametric emission of photon pairs traveling on either side of a black hole horizon: here, the role of the pump is played by the curved black hole space-time and entanglement ends up being shared between the black hole and the emitted radiation. In spite of the harsh experimental difficulty of investigating these phenomena in their original contexts, first experimental evidences are coming from the so-called analog models of gravity, namely table-top condensed matter systems whose dynamics is ruled by quantum field theories on effective curved space-times. Here, evidences of Hawking radiation and dynamical Casimir emission are available, as well as hints of their quantum entanglement properties [9,10].

This exciting on-going research highlights the generality of the parametric emission concept and further confirms the importance of its full understanding in view of quantum technology applications as well as for fundamental science to get a deeper insight into the mysteries of our Universe. ●

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