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REVIEW ARTICLE

On-chip frequency combs and telecommunications signal processing meet quantum optics

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Abstract Entangled optical quantum states are essential towards solving questions in fundamental physics and are at the heart of applications in quantum information science. For advancing the research and development of quantum technologies, practical access to the generation and manipulation of photon states carrying significant quantum resources is required. Recently, integrated photonics has become a leading platform for the compact and cost-efficient generation and processing of optical quantum states. Despite significant advances, most on-chip non-classical light sources are still limited to basic bi-photon systems formed by two-dimensional states (i.e., qubits). An interesting approach bearing large potential is the use of the time or frequency domain to enabled the scalable on-chip generation of complex states. In this manuscript, we review recent efforts in using on-chip optical frequency combs for quantum state generation and telecommunications components for their coherent control. In particular, the generation of bi- and multi-photon entangled qubit states has been demonstrated, based on a discrete time domain approach. Moreover, the on-chip generation of high-dimensional entangled states (quDits) has recently been realized, wherein the photons are created in a coherent superposition of multiple pure frequency modes. The time- and frequency-domain states formed with on-chip frequency comb sources were coherently manipulated via off-the-shelf telecommunications components. Our results suggest that microcavity-based entangled photon states and their coherent control using accessible telecommunication infrastructures can open up new venues for scalable quantum information science.

Keywords nonlinear optics, quantum optics, entangled photons

1 Introduction

In the last few decades, research has greatly intensified towards realizing universal quantum computers as well as simulators, with the promise of being able to perform calculations that are beyond the capability of conventional classical computers. To implement a quantum computer, or quantum information processing in general, physical systems are required that can support the preparation, manipulation, and measurement of quantum information [1]. Technologies that provide these characteristics are being advanced in several platforms including electronic, trapped ions, solid state, nuclear magnetic resonance, and

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superconducting systems [2]. What all these platforms have in common is that quantum states are very delicate, can quickly deteriorate, and are highly sensitive towards noise. This characteristic usually requires highly sophisticated experimental facilities, a core technological challenge towards achieving quantum computers. Among the many quantum platforms, photons (particles of light) are very promising, as they exhibit very high noise tolerance [3]. Indeed, the low decoherence of light, which has already been exploited for classical telecommunications [4], transfers to very high noise tolerance in quantum applications. Additionally, photons are ideally suited to interact with other quantum platforms, while information can be encoded into their different degrees of freedom, such as polarization, phase, path, frequency, time, and more, which in the classical domain has enabled multiplexing in current telecommunication networks. In addition, photons exhibit excellent transmission properties through e.g. free-space or optical fibers, which in turn enables the possibility to create quantum communication networks [5]. However, optical states with significant quantum resources (i.e., large Hilbert spaces), which are a key cornerstone for realizing optical quantum computers, remain difficult to prepare and control, in large parts because of increasing experimental complexity and the need of operations that act probabilistically.

To address these issues, optical quantum research has focused on two main directions: 1) increase the quantum resource, and 2) reduce the device complexity to achieve scalable systems. In the first case, an immediate approach would be to boost the number of photons, which will in turn lead to larger entangled states [6–8], similarly to the approach used for other quantum platforms [9,10]. However, this comes with significant drawbacks, since the generation of optical entangled states is commonly achieved with photon pairs in probabilistic processes. As such, increasing the number of photons means incrementing the number of probabilistic sources, which lowers their efficiency. Furthermore, multi-photon states are highly sensitive towards losses and noise. The combination of these drawbacks has so far limited the generation of optical states to ten entangled photons [6]. A different approach, that is unique and ideally suited for optical system, is to simultaneously exploit multiple modes (polarization, spatial, temporal, spectral) of fewer photons to achieve large optical quantum states [11–13]. Optical frequency combs, which are broadband optical sources that have equidistantly-spaced spectral modes, directly suit this direction. Due to their well-defined spectral locations, frequency combs have served as extremely precise optical rulers, enabling a revolution in high-precision metrology and spectroscopy [14]. Recently, the classical frequency comb concept has been extended to the quantum world for the preparation of non-classical states [15,16]. This approach brings about many benefits, especially for the creation of large states. First, optical combs offer many experimentally-accessible frequencies within a single spatial mode, where photons of different wavelengths are transmitted together in a single waveguide. Furthermore, the intrinsic multi-frequency-mode characteristics enable the generation of many entangled quantum states simultaneously, with the density of these quantum channels controllable via the spectral mode separation. Finally, the frequency domain is complementary to other degrees of freedom, enabling the creation of even larger-scale quantum states. Quantum frequency combs have until now been utilized for the generation of heralded single photons [17–21], as well as two-photon entangled states via the time [22–25], path [26] and frequency [27] degrees of freedom. In addition, very complex states, e.g. cluster states [28,29], and multipartite entangled states [16,30], have been predicted and achieved for applications in quantum signal processing, including quantum logic gates [27], and spectral linear optical quantum computation [31].

2 Quantum optical frequency combs

The first investigations of quantum frequency combs were based on large free-space cavities embedding bulk nonlinear crystals. In this approach, the resulting optical parametric oscillator (OPO), is operated below the lasing threshold. In the nonlinear process, a photon from an excitation field splits into a pair of photons (signal and idler) satisfying both energy and momentum conservation (phase-matching). In cases where the nonlinear crystals have a large phase-matching bandwidth, a broadband quantum frequency comb of entangled photon pairs is created by the OPO at the resonant wavelengths. In particular, each cavity mode of a frequency comb can be described by a quantum harmonic oscillator and, analogous to the position and momentum observables, the field's continuous-variable Hilbert space can be represented by its amplitude or phase-quadrature observables. Quantum state preparation using so-called squeezed states, where quantum information is encoded in continuous quadratures of the optical fields, has been remarkably successful, allowing the generation of many complex states. Examples include the simultaneous realization of quadripartite entangled quantum states [29]. Richer excitation spectra and more tailored nonlinear optical interactions have been predicted to enable larger states [30] including an experimentally demonstrated multipartite entangled state covering up to 115974 nontrivial partitions of a 10-mode state [32].

Although large complex quantum states have been widely investigated, bulk-optic based approaches require large, expensive, and very complex setups, not suitable for out-of-the lab applications. Furthermore, the quantum states that have been demonstrated with such OPO approaches have not yet achieved the level of squeezing required (with a threshold value of 20.5 dB) for fault-tolerant optical quantum computation [33], being typically limited by loss which degrades the squeezed states. In addition, the spectral modes of a large OPO cannot be individually addressed due to their small spectral separation. Reducing the size of the resonant cavities would allow access to individual frequency modes and, in turn, also allow one to exploit single or entangled photons instead of (or in addition to) squeezed states. Therefore, the miniaturization of optical frequency combs will bring not only more compact devices but may open up novel opportunities.

In order to address the second main challenge of realizing compact and scalable devices, integrated (on-chip) photonics has established itself as a promising platform for quantum optics [34,35]. Compact and mass-producible photonic chips (particularly those compatible with the silicon chip industry) enabled compact, cost-efficient, and stable devices for the generation and processing of non-classical optical states. This is highlighted by the demonstration of on-chip single photon sources [36,37], generation of entangled states [25,26,38], as well as the realization of basic algorithms [39–41]. Integrated quantum photonics is ideally suited to generate quantum optical frequency combs. Certainly, the on-chip realization of optical combs is a very active research field [42,43], and many of its principles are reflected in the first demonstrations of on-chip quantum combs. As materials used for on-chip integration typically exhibit third-order optical nonlinearity, spontaneous four-wave mixing (SFWM) can be used for the generation of integrated quantum frequency combs [21].

3 On-chip comb of heralded single photons

In SFWM, the nonlinearity mediates the annihilation of two photons from an excitation field and the simultaneous generation of two daughter photons named signal and idler. By optically exciting a single cavity resonance, SFWM symmetrically populates neighboring resonances with photon pairs, creating a highly stable source of heralded single photons distributed over several channels (where the measurement of the signal heralds the presence of the idler, and vice versa) [17]. First realizations showed that a broadband frequency combs can be generated, spanning the full infrared telecommunications bandwidth, see Fig. 1. Using photon auto-correlation measurements, it was verified that a pure single frequency mode photon was produced in the signal and idler resonances, respectively, and that the bi-photon state has a Schmidt mode number close to 1 (corresponding to a pure separable state), see Fig. 2 [17,27]. In contrast to free-space OPOs, where the spectral mode spacing is very narrow, on-chip resonators enable mode separations compatible with standard telecommunication filters. Spectrally selecting one pair of signal and idler photon resonances has enabled heralded sources in silicon-based microrings [18,19] and microdisks [44], as well as amorphous silicon microrings [45]. The excitation of such on-chip frequency combs can be achieved in different manners. First, an external continuous-wave laser can be used, however this usually requires active locking of the laser to the resonance due to thermal bistability [46] and is also associated with a reduced purity of the generated photons. Another approach is to use pulsed excitation, which has several advantages in terms of synchronization. Furthermore, in the pulsed excitation scheme, no active feedback is required, since a broadband laser is filtered to match the full resonance, and small thermal drifts are not an issue. However, the filtering results in a very inefficient excitation, and most of the optical power is lost [22,27]. A very elegant approach to solve both locking and power issues can be achieved by placing the resonator within a self-locked laser cavity [47,48]. This approach immediately compensates for any drifts in the resonance, and only frequencies within the resonator bandwidth can lase, leading to an energy-optimized excitation. By adjusting the external lasing

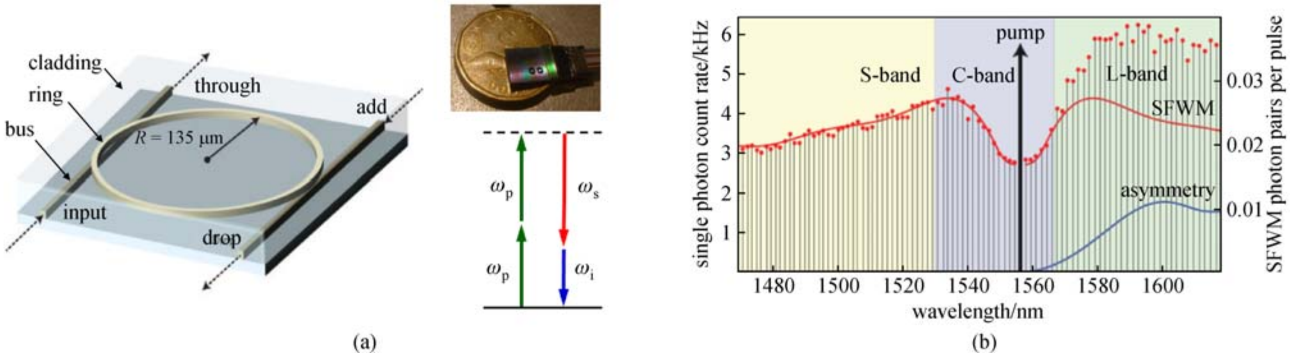

Fig. 1 Quantum frequency comb generation in integrated microring resonators. (a) Via spontaneous four-wave mixing inside the nonlinear microcavity [48], two pump photons at frequency (ω_p) are converted to one signal and one idler photon at frequencies ω_i and ω_s, with energy conservation demanding $\omega_i + \omega_s = 2\omega_p$. Inset: an integrated Hydex photonic chip (based on a high refractive index glass with similar properties to silicon oxynitride) compared to a Canadian one-dollar coin. (b) A broad measured quantum frequency comb spectrum spanning from the S to the L telecommunications band [22]

cavity, both CW [17], as well as stable pulsed excitation [47] can be achieved.

4 On-chip comb of entangled multi-photon states

An important step following the realization of correlated photon pairs is achieving entanglement. Entangled photon pair generation has been demonstrated in silicon and silicon nitride microring resonators by means of energy-time [23–25], or path-entanglement [26] approaches. In addition, because of the multi-channel property, these on-chip entangled quantum sources exhibit compatibility with telecommunications wavelength multiplexing techniques [17,22]. With respect to quantum frequency combs, their multimode nature can be used here to achieve highly parallel generation of entangled states. In particular, a double-pulse excitation of a single resonance was used to demonstrate the realization of time-bin entangled photon pairs over the entire frequency comb spectrum [22]. The phase-locked double pulses were prepared using stabilized fiber-interferometers, and the excitation power was chosen such that the double pulses only emit one photon pair, which is then in a superposition of two temporal modes, see Fig. 3. For their characterization, the photons were sent to a set of unbalanced interferometers, which enables the implementation of projection measurements for quantum interference and tomography measurements, see Fig. 4. Most remarkably, due to the resonance characteristics of the cavity, the coherence time of the excitation field is matched to that of the photons. This configuration enables the generation of multiple entangled photons pairs simultaneously over multiple spectral lines. This distinctive multimode characteristic of the frequency comb allowed the demonstration of the first four-photon entangled states on a chip, by post-selecting two signal and idler pairs on different resonances simultaneously. The realization of this four-photon entangled state was confirmed through quantum interference as well as quantum state tomography, see Fig. 5 [22].

5 On-chip comb of high-dimensional entangled photon states

From a different point of view, photon pairs (signal and idler) can be generated in a quantum superposition of many frequency modes [27]. This was achieved by injecting a nonlinear resonator with a spectrally-filtered mode-locked laser to excite a single resonance of the microring at ~1550 nm wavelength, in turn producing pairs of correlated signal and idler photons spectrally-symmetric to the excitation field covering multiple resonances, see Fig. 6. Considering

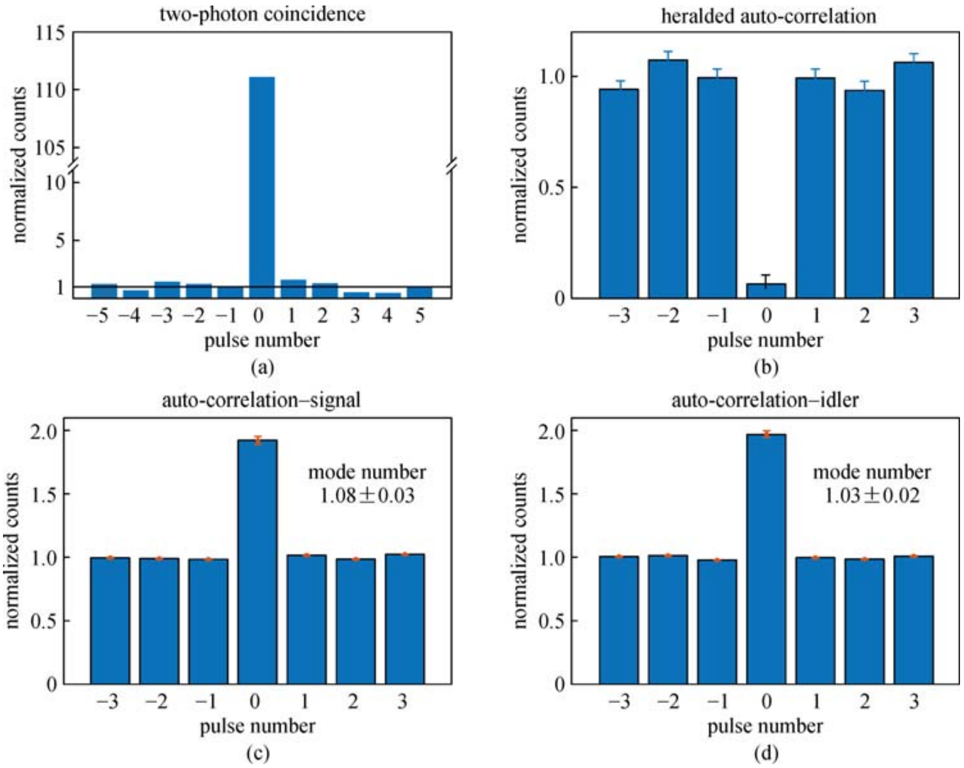

Fig. 2 Photon coincidence, and auto-correlation measurement. The high coincidence to accidental ratio in the photon coincidence peak (a) shows that the source can be used as a good quantum source. The dip in the heralded auto-correlation peak (b) confirms that the photons can be used as heralded single photons. The single photon auto-correlation peaks for both signal (c) and idler (d) photons are reaching two, confirming that the photons are emitted into pure states

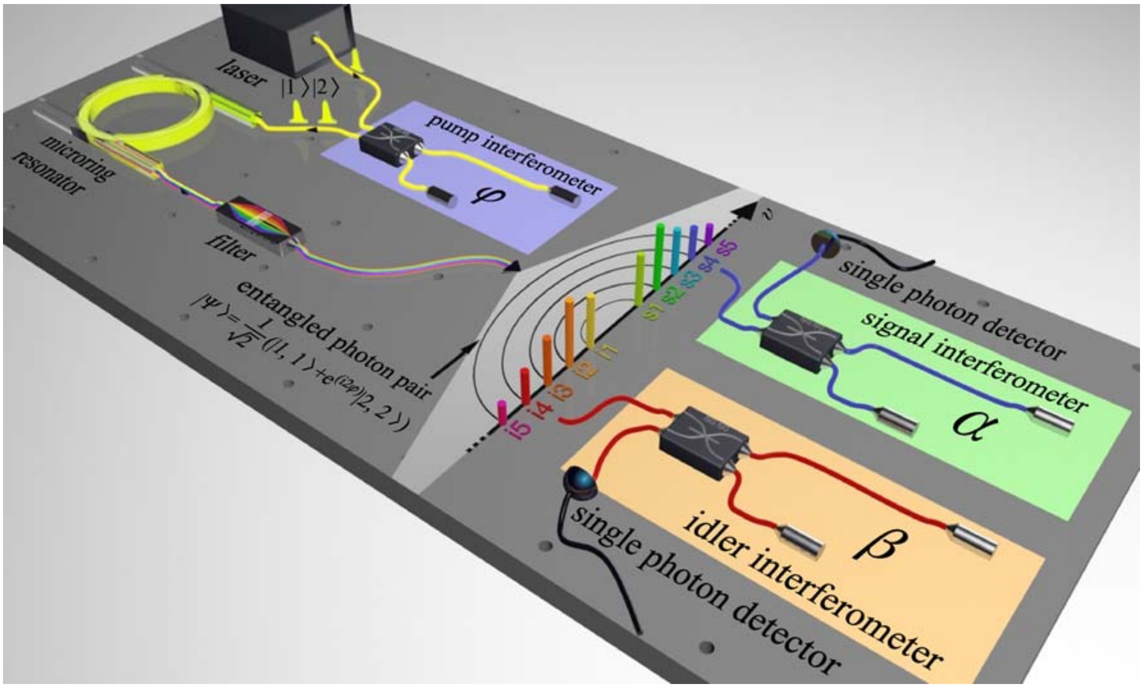

Fig. 3 Experimental setup for the generation and characterization of time-bin entangled quantum frequency comb. Double-pulses are generated by means of an unbalanced interferometer, and are then used to excite the microring resonator for photon pair generation, emitting a time-bin entangled frequency comb. Another set of interferometers is then used for state characterization [22]

the quantum nature of this process, the individual photons were intrinsically generated in a superposition of multiple frequency modes [27]. Due to the energy conservation of SFWM, this approach leads to the realization of a two-photon high-dimensional frequency-entangled state. To characterize the high-dimensional states, a novel manipulation scheme was developed, which is capable to perform basic gate operations for coherent state control. The quantum gate was realized using a configuration composed of two programmable filters and one electro-optic phase modulator, as schematized in Fig. 6 and explained in more detail in Fig. 7. The first programmable filter was used to impose an arbitrary spectral amplitude and phase mask on the high-dimensional state, see Fig. 7 (b). The manipulated state was then sent to an electro-optic phase modulator, which was driven by a radio frequency (RF) synthesizer. The imposed optical phase modulation generated coherent sidebands from the input frequency modes. When the sideband frequency shift was chosen to match the spectral mode separation of the quantum state, i.e., the ring's free spectral range (FSR), these input frequency modes were coherently mixed. Then, a second programmable filter (Fig. 7(d)) was used to select different, individual frequency components of the manipulated state through the application of a second amplitude mask. Finally, each of the two photons was routed to a separate single photon detector for coincidence detection. High-visibility measured quantum interference and state tomography (Fig. 8) confirmed the first generation of high-dimensional entangled states on a photonic chip.

6 Conclusion and outlook

On-chip quantum optical frequency combs have been shown to generate complex entangled optical states, which were not realized by other means, such as on-chip path or polarization entanglement. Considering how successful the quantum frequency comb approach is even in bulk systems (emitting squeezed states), it is conceivable that the potential of on-chip quantum combs is extremely significant, and the here reviewed experiments only represent the first steps [49,50]. Furthermore, merging the fields of quantum optical frequency combs with telecommunications signal processing will enable even more functionalities and has the potential to advance the field of quantum optics towards large-scale implementation. Indeed, following our first realizations of multi-photon and high-dimensional entanglement on a chip, several other groups have achieved significant and related breakthroughs. These include the realization of frequency-bin entangled combs with 50 GHz spacing [51], using the same coherent manipulation scheme reviewed here. Reducing the mode spacing is particularly interesting once the spacing reaches frequencies achievable by electronics, which will enable more versatile quantum state control. Indeed, using an extension of the basic manipulation scheme depicted in Figs. 6 and 7, it has been shown that by employing two phase modulators and an additional amplitude/phase filter, more complex quantum gates such as Pauli and Hadamard gates can be implemented in the frequency domain [52,53]. This indicates that the processing of optical quantum

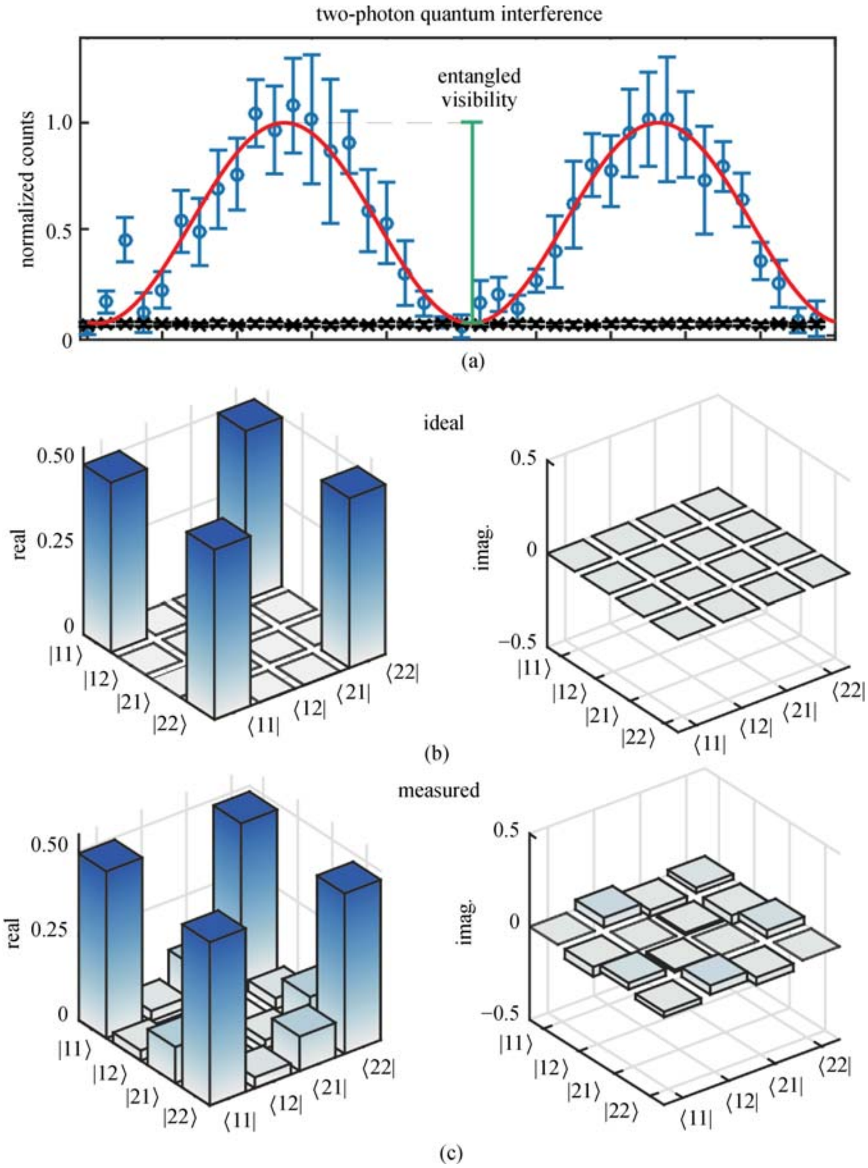

Fig. 4 Two-photon quantum interference (a) and quantum state ((b) ideal and (c) measured) tomography. By changing the phases of the characterization interferometers, two-photon quantum interference and quantum state tomography can be performed. The quantum interference has a visibility exceeding the limit for a Bell inequality violation, and the tomography confirms that a state close to the maximally entangled ideal Bell state is generated [22]

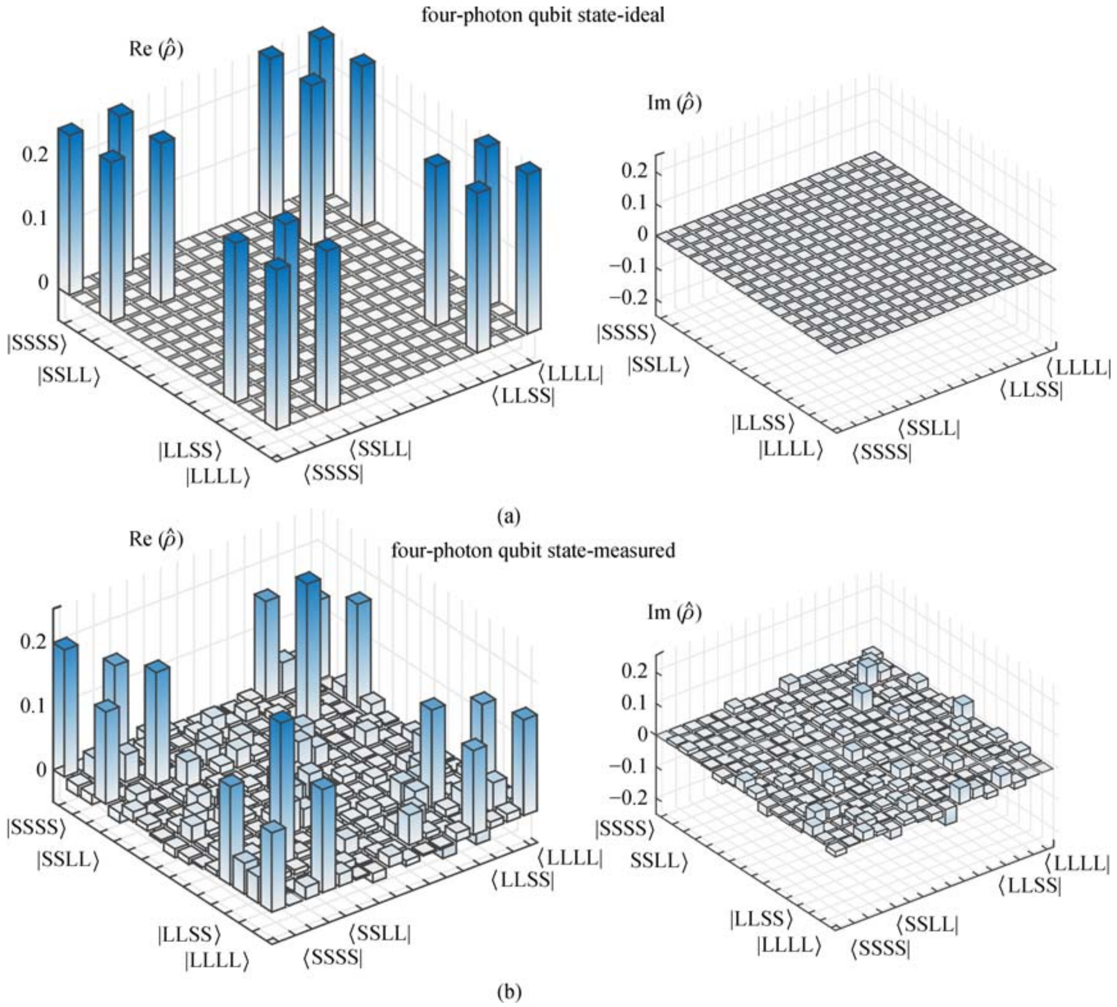

Fig. 5 Four-photon quantum state tomography. (a) Ideal; (b) measured. By performing tomography on the four-photon state, the first generation of a multi-photon entangled state on a photonic chip was confirmed [22]

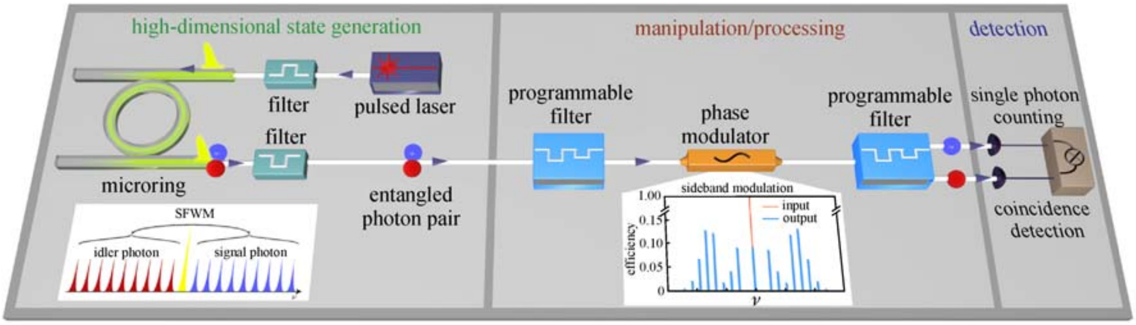

Fig. 6 Experimental setup for the generation and characterization of high-dimensional quantum states with on-chip optical frequency combs. The microring resonator is excited with single pulses from a mode-locked laser, generating photon pairs in a superposition of frequency modes. Using a combination of programmable filters and an electro-optic phase modulator, the quantum states can be coherently manipulated and projection measurements can be performed [27]

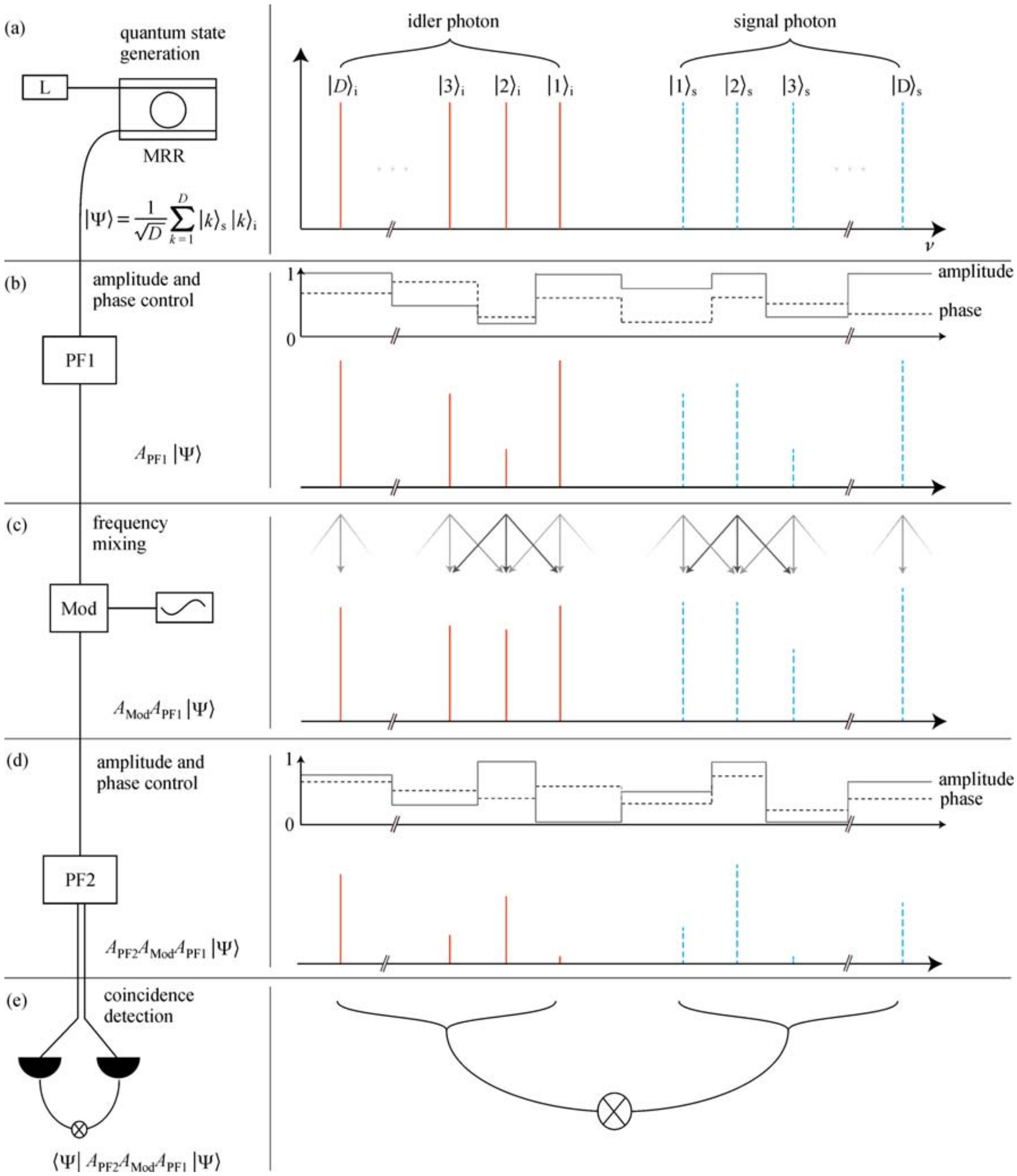

Fig. 7 Experimental realization of coherent manipulation of high-dimensional frequency-bin entangled quantum states. Individual steps to control, manipulate and characterize the high-dimensional quantum states are displayed. (a) The initial states $|\Psi\rangle$ were generated using the micro- ring resonator (MRR)-based operational principle illustrated in Fig. 1. (b) Using a programmable filter (PF1), any arbitrary spectral phase and amplitude mask can be imposed on the quantum states for manipulation. (c) An electro-optic modulator (Mod) driven by a radio-frequency synthesizer was used to coherently mix different frequency components of the high-dimensional states. (d) A second programmable filter (PF2) can impose an amplitude and phase mask and route the signal and idler to two different paths. (e) The photons were then detected using single photon counters and timing electronics [27]

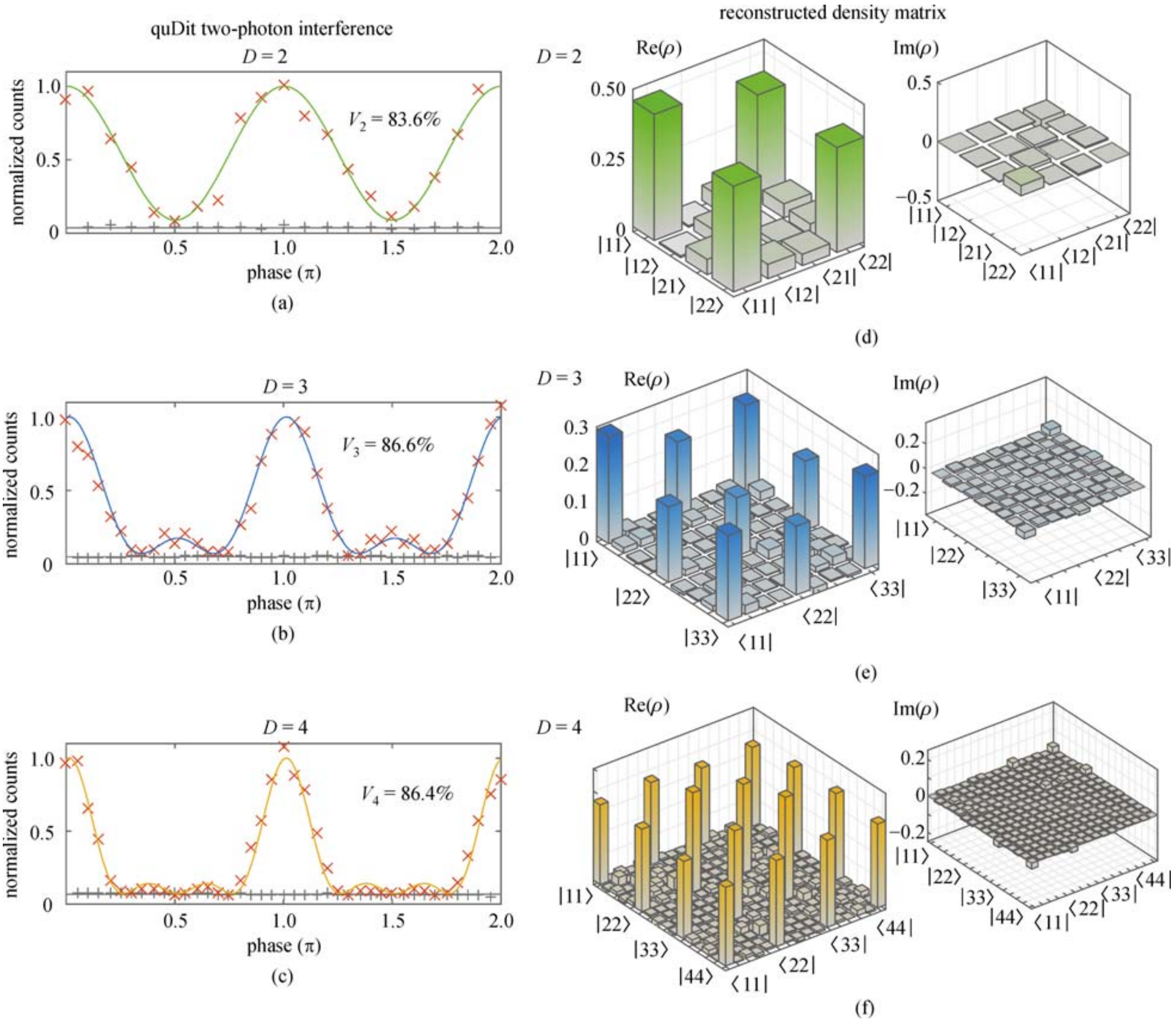

Fig. 8 Quantum interference and quantum state tomography of high-dimensional entangled photon states. The visibilities of the quantum interference of quDits with (a) $D = 2$, (b) $D = 3$ and (c) $D = 4$, exceed the visibilities required to violate a Bell inequality for $D = 2$, $D = 3$ and $D = 4$ states. Full quantum state tomography revealed that the experimentally reconstructed density matrix of the entangled quDit states are in very good agreement with the expected maximally entangled states [27]

information by means of telecommunications infrastructure is a very promising direction. In parallel, significant work has also been dedicated towards further scaling time-bin encoded schemes. In particular, fully integrated interferometers have been realized, which will enable compact state preparation and characterization on a photonic chip.

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