Fully On-chip Laser-integrated Entangled Photon Pair Source

(Student paper) / (Invited paper)

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We demonstrate the first electrically-pumped laser-integrated quantum light source of entangled photons. The hybrid InP-SiN source emits frequency-bin entangled two- and high-dimensional states in the telecommunications band. It is fully integrated, compact, and field-deployable, bringing the required scalability to photonic quantum information processing.
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INTRODUCTION

Integrated photonic platforms can realize and process optical entangled quantum states in highly compact, robust, and scalable chips, enabling the implementation of long-distance quantum-secured communication, quantum-accelerated information processing, and non-classical metrology [1]. Notably, all previous on-chip entangled quantum photonic sources and the pioneering on-chip demonstrations of nonclassical functionalities were dependent on external excitation lasers, thereby making these systems overall non-reproducible, bulky, impractical, and thus precluding out-of-lab use as well as production at large scale [2].

To address this drawback, it is critical to realize a fully integrated quantum light source of entangled photons, where the laser is integrated. Such a system will allow all stages of quantum information processing to be on a single chip, bringing ultimately the required stability and scalability.

However, to date, the major technical challenge inhibiting a fully on-chip quantum light system was to integrate a stable and tunable laser together with a high rejection filter that eliminates laser sideband noise [3, 4], and a nonlinear parametric source of entangled photons. The absence of a unique material platform that is superior in all quantum photonic functionalities (i.e., low-loss guiding, filtering, efficient parametric generation of entangled

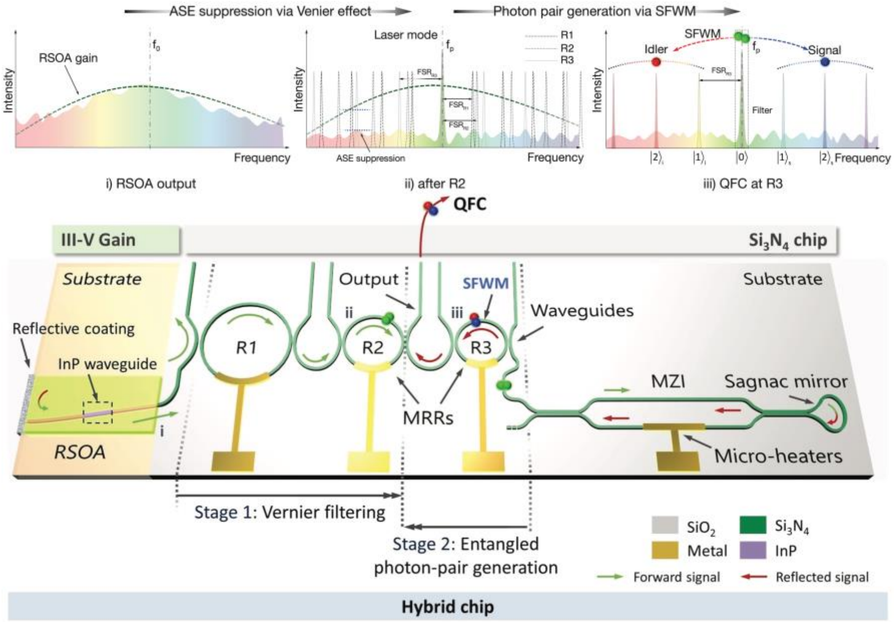

Figure 1 Laser-integrated photonic quantum light source of frequency-bin entangled photon pairs: An electrically pumped InP gain-section, i.e. a reflective semiconductor optical amplifier (RSOA) providing optical gain is coupled to a Si_3N_4 chip containing a three microring resonator (R1, R2, and R3) Vernier filter and a Mach-Zehnder interferometer (MZI) with a Sagnac loop mirror.

photons pairs, and their active manipulation) while providing at the same time optical gain, mainly impedes monolithic integration.

Here, we demonstrate for the first time a fully laser-integrated quantum light source that is capable of addressing these challenges by using an elaborated chip design and exploiting hybrid integration technologies [5]. The source directly generates frequency-bin entangled photons, i.e., high-dimensional quantum frequency comb (QFC).

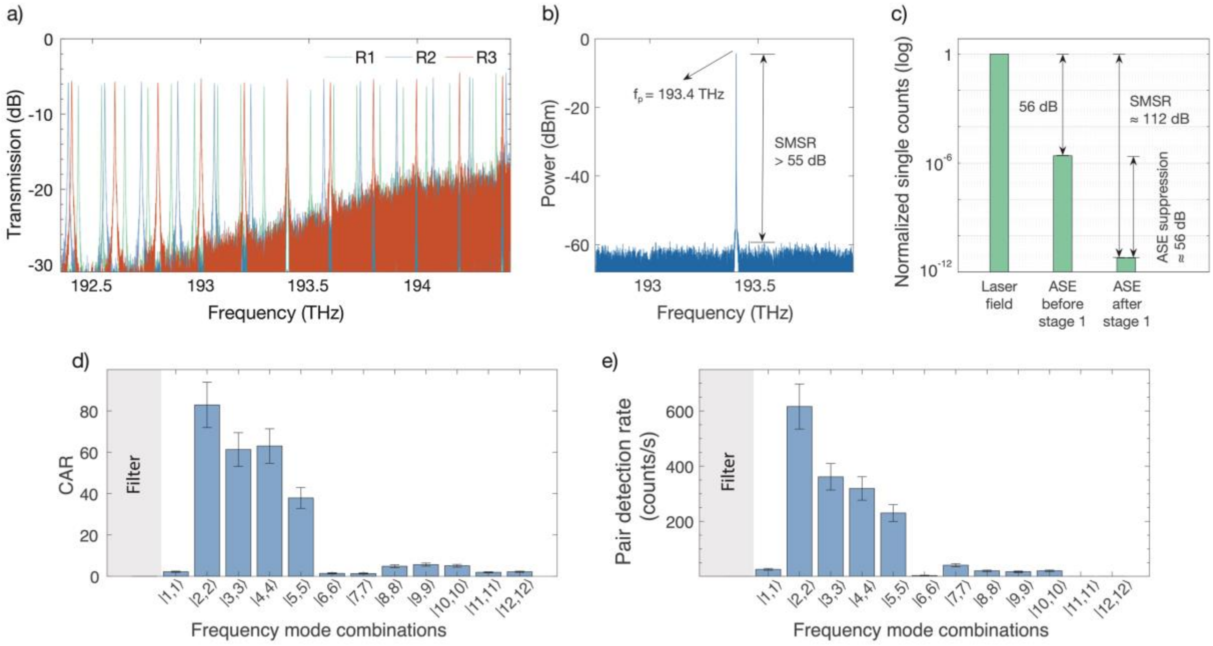

Figure 2 a) Measured transmission spectra of Si_3N_4 microrings R1, R2, and R3. b) Classical output spectrum showing the laser line at a frequency of 193.4 THz with a side-mode suppression ratio (SMSR) of >55 dB (Measurement limited by the dynamic range of the OSA). c) Measurements utilizing single photon detectors allowed to determine an SMSR ≈ 112dB, and an amplified spontaneous emission (ASE) suppression of ≈ 56 dB. d) Coincidence-to-accidental ratio (CAR) for respective frequency pairs for a detected excitation power of 3.9mW. e) Detection rate, i.e., the number of the coincidence counts per second, for the respective frequency pairs.

RESULTS

The hybrid quantum source, as shown in Fig. 1a, comprises an electrically-pumped InP gain section and a Si_3N_4 low-loss microring filter. It has a size comparable to a one-euro coin [5]. The three rings, i.e. R1, R2, and R3 form a Vernier filtering stage, which is further connected to an MZI and a Sagnac loop. The Sagnac loop mirror together with the reflecting coating at the RSOA forms a lasing cavity. Resonances of R1, R2, and R3 are aligned at f_p = 193.4 THz through the microheaters (see Fig. 2a).

Providing optical gain, the system starts lasing on this frequency mode (see Fig. 2b). The backward propagating laser field from the loop mirror acts as the excitation signal for a spontaneous four-wave mixing process within the third ring R3 producing signal/idler photons on the resonances and thus a quantum frequency comb. The Venier filter stage is central to this design as it was not only used to define the laser mode but more importantly to suppress amplified spontaneous emission (ASE) emerging from the gain medium. The ASE would otherwise introduce noise on the frequency components the photon pair signal is generated, which decrease the signal to noise ratio usually to a level where the photon correlations are not detectable. An ASE suppression of 56dB was demonstrated via single photon level leasurements, leading to a laser's side-mode suppression ratio (SMSR) of 122dB (see Fig 2c).

This highly efficient noise suppression Vernier filtering stage facilitated high-performance parameters such as a high coincidence-to-accidental ratio (CAR) of ~80 with a remarkable pair detection rate of ~620 Hz and a pair emission bandwidth of ~1 THz over four resonant modes in the telecom band (see Fig. 2d,e). We performed quantum interference measurement and quantum state tomography (QST) on frequency modes 2-3, 3-4, and 2-3-4 to verify the direct creation of two- and high-dimensional frequency-bin entangled quantum states (qubits/qudits) (see Fig. 3). Quantum interference measurements with visibilities > 96%, and QST with fidelities from 0.99 to 0.85 for two and three-dimensional Bell states, respectively, affirmed the generation of excellent-quality entangled photon states from this nonclassical light source.

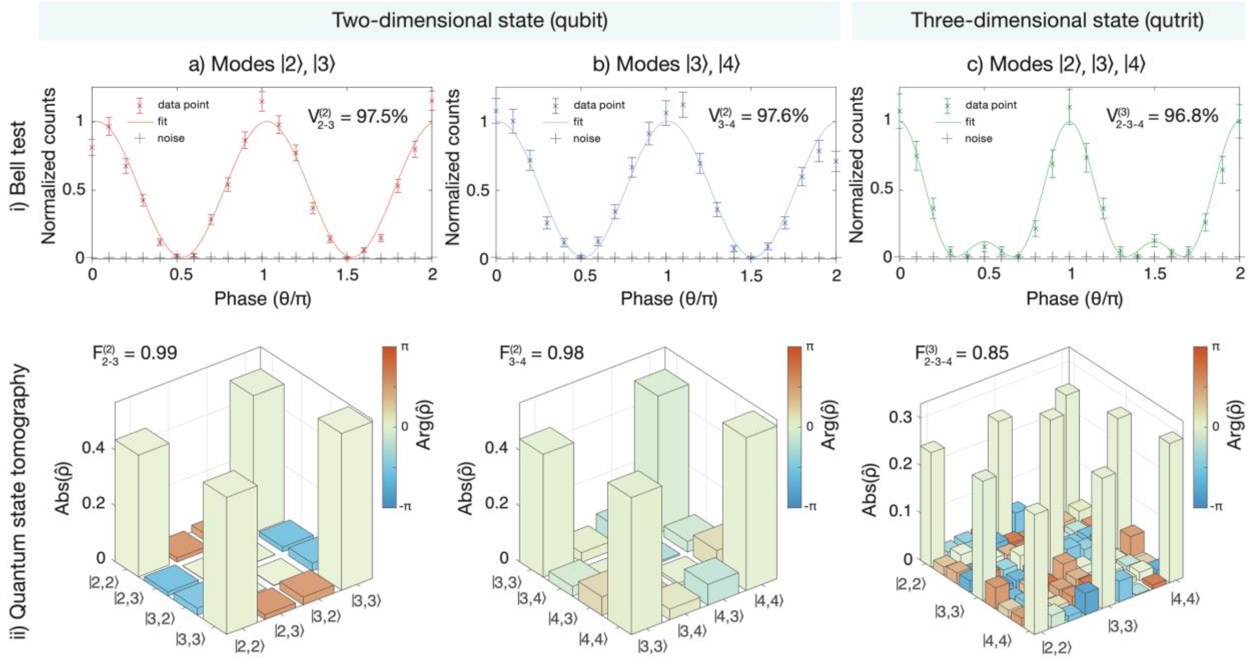

Figure 3 Performance of the quantum photonic source. Bell inequality violation and quantum state tomography of frequency-entangled qubit and qutrit states. First line (i), Bell test characterization of qubit and qutrit states. The error bars show the root of the absolute count numbers; the error of the noise background is smaller than the marker size. Second line (ii), quantum state tomography for qubit and qutrit QFC states. First column a), two-qubit state (composed of 2nd and 3rd resonances). Second column b), two-qubit state (composed of 3rd and 4th resonances). Third column c), bi-photon qutrit state (composed of 2nd, 3rd and 4th resonances).

DISCUSSION

In conclusion, our work is the first demonstration of an on-chip, scalable, light-weight, and readily deployable quantum light source. The novel architecture of this chip, i.e., the integration of a laser-cavity that includes a tunable Vernier filter, allows the required suppression of amplified spontaneous emission and thus furnishes high-quality entangled photons. This work facilitates necessary technological advancements for building quantum processors, quantum internet devices, and quantum satellite systems in a fully-integrated, stable, and field-deployable format meeting industrial requirements.

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