Hybrid Integrated Photonics for On-Chip Heralded Photon-Number States

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Abstract: We show the potential of a hybrid technology for realizing highly complex circuits for quantum photonic applications. We demonstrate the most advanced chip enabling four photon generation and manipulation for heralding tunable two-photon states.

Integrated photonics plays a remarkable role in investigating fundamental quantum phenomena as well as a variety of disruptive quantum technologies [1]. More specifically, the ability of realizing complex and scalable quantum circuits finds repercussions in quantum sensing, secure communication, as well as in quantum computation and simulation, that would be otherwise inaccessible using bulk-optic approaches. Despite this attractive potential, only a few examples of on-chip multi-photon generation and manipulation based on monolithic platforms have been reported to date, due to fabrication challenges [2–4]. Currently, more complex devices are being considered exploiting hybridization of complementary technologies [5]. Following such a strategy, we demonstrate, for the first time, an integrated optical four-photon generator enabling the on-chip engineering of heralded two-photon states thanks to real-time manipulation capabilities.

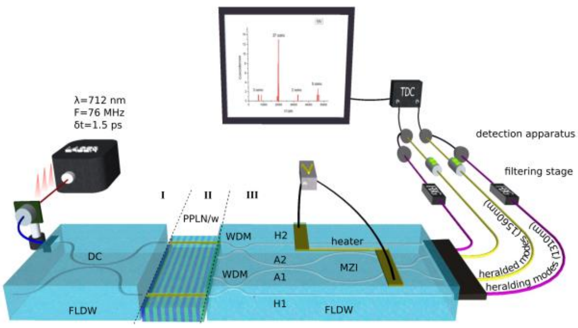

Fig. 1. Configurable two-photon state generator based on the hybridization of two complementary integrated optical technologies.

Lithium niobate (LN) stands as a key plateform for integrated quantum photonics mostly for its optical nonlinear properties. LN's optical-optical nonlinearity allows to efficiently produce photon pairs in low-loss waveguides, while its electro-optical nonlinearity permits to actively route the photons in desired spatial modes [4]. However, the fabrication steps are delicate, therefore limiting the complexity of the considered devices. On the other hand, the femto-second laser direct-writing (FLDW) technique on glass (SiO_2) has recently emerged for its fast prototyping of 3D low-loss circuits, despite the lack of efficient optical nonlinearities for photon-pair generation. In our realization, we combine those two complementary platforms for exploiting the best features of both technologies and to demonstrate an advanced photonic device [5].

Our demonstration enables on-chip manipulation of four photons for the generation of configurable two-photon states, for the first time in a heralded fashion. The heralding feature is an important functionality for next generation quantum systems, making it possible to implement efficiently series of quantum operations. More specifically, our device permits producing a variety of path-coded heralded two-photon states, ranging from product to entangled states, thanks to real-time configuration capabilities.

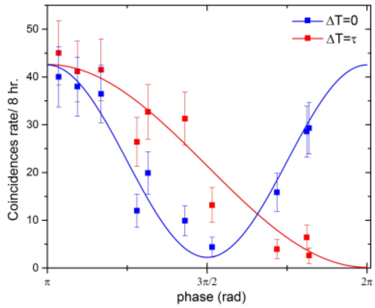

Fig. 2. 4-fold coincidences for single-(red) and two-(blue) photons interference.

Our realization consists of three photonic chips fabricated on either LN for photon generation or on SiO2 substrates for photon manipulation purposes (Figure 1). The input chip routes the pump laser pulses in two spatial modes coupled to two identical periodically poled lithium niobate waveguides (PPLN/w) allowing the simultaneous generation of paired photons spectrally distinguishable (at 1560 nm and 1310 nm) via the process of spontaneous parametric down-conversion. Integrated optical functions ensure the splitting of the photons of each pair and, thanks to an integrated, thermally tunable, Mach-Zehnder interferometer, the manipulation of heralded photon-number states is achieved. Coincidence detection of the two 1310 nm photons in the outer modes heralds the arrival of the two photons at 1560 nm in the inner modes, encoded in the following quantum state:

$$|\psi\rangle \sim \left(1 - e^{i2\varphi(V)}\right)\left(|20\rangle - |02\rangle\right)/\sqrt{2} + 2i\left(1 + e^{i2\varphi(V)}\right)|11\rangle, \quad (1)$$

where the phase $\varphi(V)$ from the interferometer can be tuned by adjusting the temperature gradient between the two arms thanks to the 3D capabilities of the FLDW waveguides. Therefore, the source can prepare on demand, either a two-photon N00N or a product state. By exploiting the capabilities of the time-to-digital converter (TDC) for coincidence counting, we can trace simultaneously the single-photon (red) as well as the two-photon (blue) interference fringes (Figure 2). Both the double phase sensitivity of the two-photon state and the absence of 4-fold coincidences for a given phase $\varphi(V) = 3\pi/2$, confirm the generation of the N00N state and prove that the states are engineered with high levels of purity. This elementary device is opening the route towards merging several key functionalities on a single chip for achieving more complex circuits dedicated to advanced quantum protocols.

References

[1] S. Tanzilli et al., *On the genesis and evolution of integrated quantum optics*, Laser Photon. Rev., vol. 6, pp. 115-143, 2012

[2] B. J. Metcal et al., *Multiphoton quantum interference in a multiport integrated photonic device*, Nat. Commun., vol. 4, pp. 1356, 2013

[3] J. Silverstone et al., *On-chip quantum interference between silicon photon-pair sources,* Nat. Phot., vol. 8, pp. 104–108, 2014

[4] H. Jin et al., *On-Chip Generation and Manipulation of Entangled Photons Based on Reconfigurable Lithium-Niobate Waveguide Circuits*, Phys. Rev. Lett., vol 113, pp. 103601, 2014

[5] T. Meany et al., *Hybrid photonic circuit for multiplexed heralded single photons*, Laser Photon. Rev., vol. 8, pp 42-46, 2014