

Postselection free time-bin entanglement on a thin-film lithium niobate photonic chip

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Time-bin entanglement is a commonly used form of entanglement for quantum communication protocols over fiber networks, due to the natural resilience of this encoding scheme to thermal phase fluctuations and to birefringence in optical fibers. Projective measurements on some bases in the time-bin encoding need, however, postselection in the time domain of the measured events, introducing a loophole in Bell tests and requiring high temporal resolution. In this work, we demonstrate chip-integrated receivers for time-bin entanglement certification, including a high-speed optical switch to remove the temporal postselection loophole. The receivers are realized using thin-film lithium niobate and operate at a switching frequency of 5 GHz. We demonstrate a Bell inequality violation by more than 24 standard deviations without the need for time resolution at the time-bin separation level.

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I. INTRODUCTION

Entangled states of light play a fundamental role in quantum information science and technology [1], with applications ranging from fundamental tests of quantum mechanics to quantum computing and quantum communication. Their use in conjunction with fiber-optic networks makes them a cornerstone of quantum communication protocols, where they are exploited in protocols such as quantum teleportation [2], entanglement swapping [3], entanglement-based quantum key distribution (QKD) [4], and quantum secure direct communication [5–7]. In this context, the encoding of quantum information in the discrete time basis, i.e., the time-bin (TB) encoding [8,9], has proven to be particularly favorable in fiber link field tests compared with other encoding schemes, such as path or polarization [10,11], and has also been demonstrated suitable for satellite-ground and free-space links [12–14]. Key

advantages of TB-entangled states include their robustness against noise over large distances, their ease of generation and manipulation, and the possibility to scale the data rates through hyperentanglement with other degrees of freedom [15–17] or by increasing the dimension of the Hilbert space (TB *qudits*) [18]. In addition, TB entanglement has a prominent role in high-efficiency entanglement purification [19,20], and TB-entangled state purification has been demonstrated by Yan *et al.* [21].

The correlated and nonlocal nature of the TB state is ensured by Bell’s theorem and can be assessed through a modified version of the well-known Franson interferometer [22], originally proposed by Brendel *et al.* [8,23]. On the other hand, two-photon interference in the TB basis only occurs on a subset of the detected photon pairs, associated with the indistinguishability of the interferometric path experienced. As was early pointed out by Aerts *et al.* [24], this opens a postselection loophole that affects local-realistic tests of quantum mechanics, hindering the security of QKD protocols. The need for temporal postselection also requires the use of detectors with high temporal resolution, capable of distinguishing between the TBs. This poses a trade-off in which larger time separations are desirable to distinguish the TBs, but these in turn entail limited bandwidth of the quantum communication protocols and long delay lines in the analyzing interferometers

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to perform projective measurements. Strategies proposed to overcome temporal postselection employed hyperentangled states combining the polarization and TB degrees of freedom, as demonstrated by Strekalov *et al.* [25], albeit at the expense of additional complexity. Another solution is the so-called “hug” interferometric configuration, as proposed by Cabello *et al.* [26]. A third solution, first proposed by Vedovato and co-workers [27], leverages active switching to remove the need for temporal postselection. Unlike in common Franson-type interferometry, here the TB paths are *deterministically* selected by active switches to grant two-photon interference for virtually any pair of photons detected, closing the temporal postselection loophole vulnerability and overcoming the need to resolve and discard detection events. In its first demonstration, this approach used a pair of fiber-based actively stabilized Mach-Zehnder interferometers, whose length matched the separation of the TB pairs, combined with commercial electro-optic (EO) modulators used as fast active switches. A comprehensive review on TB encoding and postselection loophole-free test has been recently published by Xavier *et al.* [28].

All of the approaches enumerated above have shown through proof-of-concept demonstrations how TB entanglement can still be regarded as a useful resource for quantum communication, although at the expense of the additional complexity required to overcome temporal postselection. However, to make TB entanglement scalable and practical, integrated photonics provides a promising avenue to reduce complexity, size, and cost while maintaining performance. A demonstration of the hug scheme, for example, has been recently reported on a silicon photonic chip [29].

Recently, the thin-film lithium niobate (TFLN) integrated photonic platform has emerged as a major player in the photonics technology landscape [30]. Combining the high second-order nonlinearity of this material with tight confinement and low propagation losses in etched waveguides, TFLN photonic integrated circuits enable the implementation of many nonlinear devices on the same photonic chip with high nonlinear efficiency and low bending losses. With regard to integrated quantum photonics, TFLN has proven suitable for nonclassical light generation on-chip through spontaneous parametric down-conversion [31–33] and its manipulation [34–36], unattainable in centrosymmetric media such as silicon and silicon nitride, and for high-speed modulation thanks to its high Pockels coefficient [37,38]. A high-speed QKD system has been recently demonstrated in which TFLN chips act as transmitter and receiver asymmetrical MZIs in a dual-polarization TB phase encoding scheme [39].

In this work, we leverage the industrial-grade TFLN photonic platform developed by Advanced Fiber Resources Milan to develop a turnkey device for the certification of temporal postselection loophole-free TB

entanglement. The device takes advantage of the $\chi^{(2)}$ properties of TFLN to achieve high-speed (5 GHz) active switching on-chip, effectively implementing the approach outlined in Ref. [27,36] in a centimeter-scale device, fully packaged and interconnected optically and electrically, overcoming the need for actively stabilized interferometers and bulky optical components. We benchmark the device by showing genuine TB entanglement of photon pairs generated by a standard on-chip spontaneous four-wave mixing source pumped with gigahertz-level repetition rates, with a pulse separation lower than or comparable with the detector jitter. Our results confirm a violation of the Bell inequality by more than 24 standard deviations without temporal postselection and subtraction of accidentals, showing how this approach allows for the certification of genuine TB entanglement even with low-resolution detectors.

II. THEORY AND OPERATING PRINCIPLE

We first describe the evolution of generic light pulses within the TFLN receiver, in order to straightforwardly outline the device operating principle. Figure 1(a) depicts a scheme of the TFLN device: pairs of early (*E*) and late (*L*) pulses are fed at the input of the device, pass through a balanced Mach-Zehnder modulator (MZM), or “optical switch”, and then through an unbalanced Mach-Zehnder interferometer (MZI). When operating the device in a “passive” configuration, namely in the absence of radio frequency (rf) modulation, the optical switch is set to operate as a 50:50 beam splitter [Fig. 1(b)(i)], randomly routing the incoming photons to the long or short arm of the unbalanced interferometer. Pulses traveling the long arm are delayed by $T_s = 100$ ps, where T_s is the optical path separation [Fig. 1(b)(ii)], resulting in the characteristic three-pulse pattern at detectors after recombination [Fig. 1(b)(iii)]. Interference arises only at the central measured peak, where two pulses temporally overlap. Conversely, when the device operates in an “active” configuration, the optical switch is biased at the quadrature point and fed with an electrical rf signal at frequency $f_m = 1/2T_s$ and peak-to-peak modulation amplitude V_π [Fig. 1(c)(i)]. Here, the early and late pulses are deterministically routed to the long and short arms of the MZI [Fig. 1(c)(ii)], respectively. This configuration allows for the complete temporal overlap of the pulses after recombination [Fig. 1(c)(iii)], thus the totality of input light is subject to interference.

So far, we have considered generic (classical) light pulses, i.e., temporally separated wave packets. We now focus on the evolution of correlated photon pairs: in particular, we are interested in TB-entangled biphoton states, which can be generated by injecting light pulses in a nonlinear medium through parametric fluorescence processes such as spontaneous four-wave mixing or spontaneous parametric down-conversion and then used as input to the

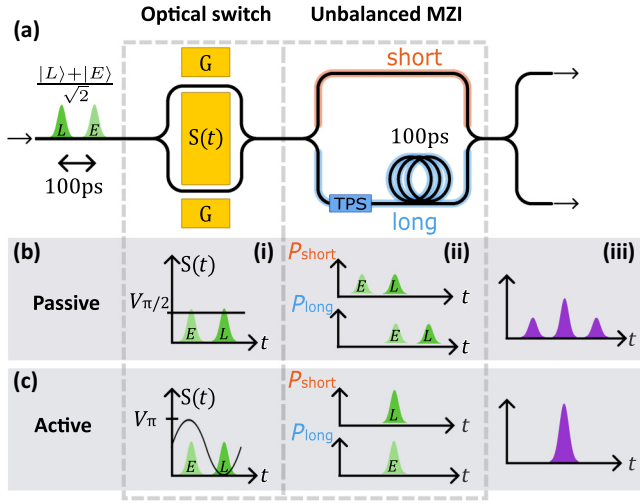


FIG. 1. (a) Schematic of the TFLN integrated photonic circuit. TPS: thermal phase shifter, S: rf signal, G: ground. A pair of laser pulses, separated by 100 ps, are injected in the device. (b),(c) Evolution of the input laser pulses in the integrated device for both passive (b) and active (c) configurations: (i) phase applied to the input state in the MZI. (ii) Evolution after propagation in the unbalanced MZI, before recombination. (iii) Light detection pattern at the device output.

device. Selecting a time separation between twin pulses much higher than the pulse temporal width and minimizing multipair emission from the crystal, the resulting state can be described as [8]

$$|\Phi\rangle = \frac{1}{\sqrt{2}} (|E\rangle_s |E\rangle_i + e^{i\varphi_p} |L\rangle_s |L\rangle_i), \quad (1)$$

where φ_p is a relative phase inherited from the pump pulses, while $|E\rangle_{s(i)}$ and $|L\rangle_{s(i)}$ describe the emission of a signal (idler) photon either in the early or late pump pulse wave packet, respectively.

In the “passive” configuration, signal and idler photons can be detected at three different time delays with respect to the pump trigger signal, yielding the characteristic three-peak delay histogram profile. Postselecting the central coincidence peak, the projection $\hat{P}_{s,i} = |\psi\rangle\langle\psi|_{s,i}$ is realized, where $|\psi\rangle_{s,i} = (|E\rangle_{s,i} \pm e^{i\varphi_{s,i}} |L\rangle_{s,i})/\sqrt{2}$. $\varphi_{s,i}$ are phase shifts that originate from analysis interferometers, i.e., the unbalanced MZI, and controlled by thermal phase shifter (TPS) Fig. 1(a). The probability of coincidence detection around the central peak is

$$\mathcal{P}(\varphi_s, \varphi_i) = \frac{1}{4} [1 \pm \mathcal{V}_{ps} \cos(\varphi_s + \varphi_i - \varphi_p)], \quad (2)$$

where $\mathcal{V}_{ps}$ is the postselected visibility of the two-photon interference fringe. The maximum value of the parameter S of the Clauser-Horn-Shimony-Holt (CHSH) inequality is $S_{\max} = 2\sqrt{2}\mathcal{V}$, hence the CHSH inequality ($S \leq 2$) is

violated if $\mathcal{V} > 1/\sqrt{2}$. Without central peak postselection, thus considering the whole coincidence pattern, coincidence detection probability is still similar to Eq. (2), while the global visibility becomes $\mathcal{V}_g = \mathcal{V}_{ps}/4$. The result is that the CHSH inequality cannot be violated, as the maximum achievable visibility is 25% [27].

Activating the optical switch, i.e., feeding the MZM with a synchronous electrical rf signal, the early and late TBs are deterministically routed to the long and short arms of the second interferometer, respectively. In this case, following the work by Vedovato *et al.* [27], the positive operator valued measure is implemented by the observer:

$$\hat{\Pi}_{s,i} = \frac{1}{2} \cos^2\left(\frac{\varphi_E}{2}\right) \mathbf{I} + \sin^2\left(\frac{\varphi_E}{2}\right) \hat{P}_{s,i}, \quad (3)$$

where $\mathbf{I} = |E\rangle\langle E| + |L\rangle\langle L|$ and $\hat{P}_{s,i}$ was defined earlier. Imposing $\varphi_E = \pi$ results in $\hat{\Pi}_{s,i} = \hat{P}_{s,i}$, and a single peak delay histogram is retrieved without postselection in the time domain. Data shedding is no longer necessary to exhibit quantum interference, since the CHSH inequality is violated, freed from the temporal postselection loophole.

III. DEVICE DESIGN AND LINEAR CHARACTERIZATION

The integrated device was fabricated at Advanced Fiber Resources Milan on a 4-in. lithium-niobate-on-insulator (LNOI) X-cut wafer with silicon substrate. The optical waveguides, featuring rib geometry, are defined by a deep UV (248 nm) stepper lithography (ASML PAS 5500/350C) on a 550 nm-thick LN layer via a 275 nm-deep etching process and are embedded in a silica matrix that provides full confinement of the optical mode within the LN layer. The waveguides ensure fundamental mode propagation in the standard C + L optical telecom bands, with optical propagation losses around 0.2 dB/cm. Additional design considerations are provided in Supplemental Material Note I [40] (see also Ref. [41] therein). Figure 2(b) illustrates a microscope image of a fabricated device: the input photons are coupled through one of the four edge couplers featuring an adiabatic inverse tapered LN waveguide. The light passes through a 50:50 multimode interferometer to form the balanced MZM that is used as optical switch. In the MZM, 1 cm-long electrodes form a ground-signal-ground coplanar rf line that applies the EO modulation to the two optical waveguides in a push-pull configuration. The two optical paths of the MZM are geometrically balanced, and each one has a TPS to control the MZM bias. The optical switch is completed by a 2×2 multimode interferometer, whose two outputs form an unbalanced interferometer with a fixed delay of 100 ps (1.31 cm). A 2%(0.1 dB) power splitter is placed in the shorter path of the unbalanced MZI to monitor the bias

of the MZM and to partially mitigate unbalanced propagation losses. The unbalanced interferometer phase can be controlled in the longer path via either a TPS or an EO phase modulator independently. Finally, it is closed by a third 2×2 multimode interferometer, where the two complementary outputs are routed to two edge couplers, which provide light out of the chip.

The balanced MZM is the key component of our integrated device, as it is designed for high-speed single-photon switching. The optical switch routes the early (late) photon to the longer (shorter) path of the unbalanced interferometer, thus eliminating the need of temporal post-selection. To do this, the optical switch must apply a phase difference of π within the temporal separation of the TB state [Fig. 1(c)], that is, 100 ps, which means applying a modulation with a fundamental frequency of the switch at 5 GHz. The electrode geometry was designed taking into account different aspects: (i) tailoring the rf line characteristic impedance to match the external signal generator impedance of 50Ω for maximum power transfer, (ii) matching the rf phase velocity with the optical group velocity to maximize the EO modulation bandwidth, and (iii) optimizing the rf and optical field overlap to minimize V_π [Fig. 2(a)]. More design and characterization details are provided in Supplemental Material Note II [40] (see also Ref. [42] therein).

Figure 2(c) displays some illustrative data from the linear characterization of the device: the optical switch extinction ratio is 40 dB, $V_\pi = 3.37$ V at 1 MHz (upper panel) and a measured 3 dB EO bandwidth of ~ 30 GHz. The transmissions of both MZI outputs are shown in the lower panel, showing extinction ratios of 18 dB and 21 dB and TPS π phase difference $P_\pi = 27.3$ mW.

To guarantee the portability of the proposed device, the fabricated TFLN chip is fully packaged in a metal case, as shown in Fig. 2(b). The packaging includes a

four-fiber (Nufern UHNA7) array unit pigtailed to the chip at maximum optical coupling. The chip is attached to the package using a thermally conductive adhesive to improve heat dissipation and thermal stabilization. A standard G3PO RF connector and precise wire bonding between the package and the chip feed the modulation signal to the MZM electrodes. All the TPSs and the EO electrodes of the unbalanced interferometer are connected to lateral package pins by wire bonding with the relative chip pads.

IV. EXPERIMENT

To demonstrate the device operating principle and assess its performance, we generate a TB-entangled state using an integrated spontaneous four-wave mixing source and route both signal and idler photons to one of the fabricated devices, where we perform measurements both in passive and active configurations. The experimental setup is depicted in Fig. 3. An actively mode-locked, infrared laser emits pump pulses 9 ps wide at 1550.92 nm wavelength, with a repetition rate of 500 MHz. The pulses pass through an optical isolator and are sent to an unbalanced MZI, with a free-space time delay that matches the 100 ps of the on-chip interferometer (light blue panel). Pulses are then amplified with an erbium-doped fiber amplifier and coupled via grating coupler to a silicon photonic chip, where signal and idler photons are generated via spontaneous four-wave mixing in a low-loss 16 mm-long silicon-on-insulator rib waveguide (orange panel). We chose for this experiment a silicon integrated waveguide for its practicality and the wide availability of the silicon photonic platform. We notice, however, that our receivers could work with a wide variety of TB entangled photons including bulk sources or even integrated poled LN sources [36,43]. Photons are collected and, after pump rejection,

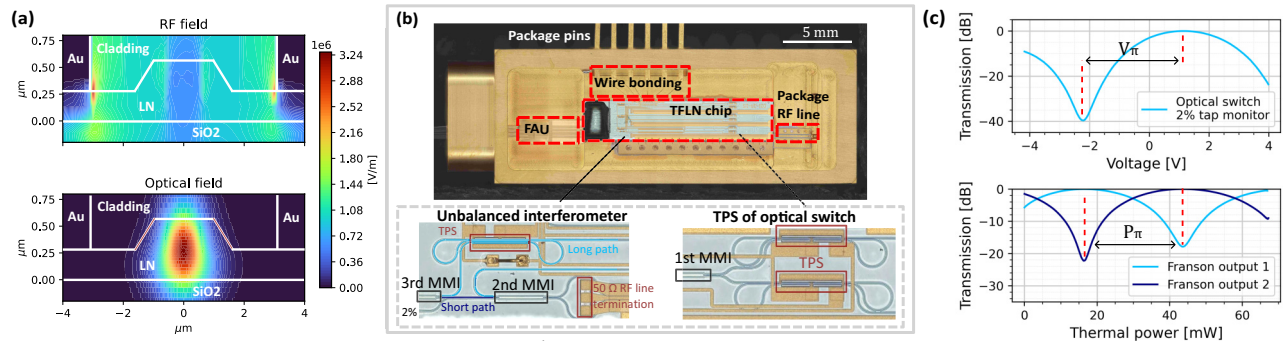


FIG. 2. (a) Simulated transverse component (parallel to the extraordinary optical axis) of the rf and optical electric field in the MZM cross section. (b) Micrograph of the packaged device. FAU: fiber array unit. The insets show details of the main components of the photonic integrated circuit: on the left the unbalanced MZI, the 2% optical tap monitor, and the integrated rf termination of the MZM; on the right the multimode interferometer (MMI) that feeds the MZM, together with the two TPSs in the interferometer arms. (c) Linear characterization. Upper panel: balanced MZM used as optical switch, V_π of 3.37 V. Lower panel: unbalanced MZI, P_π of 27.3 mW.

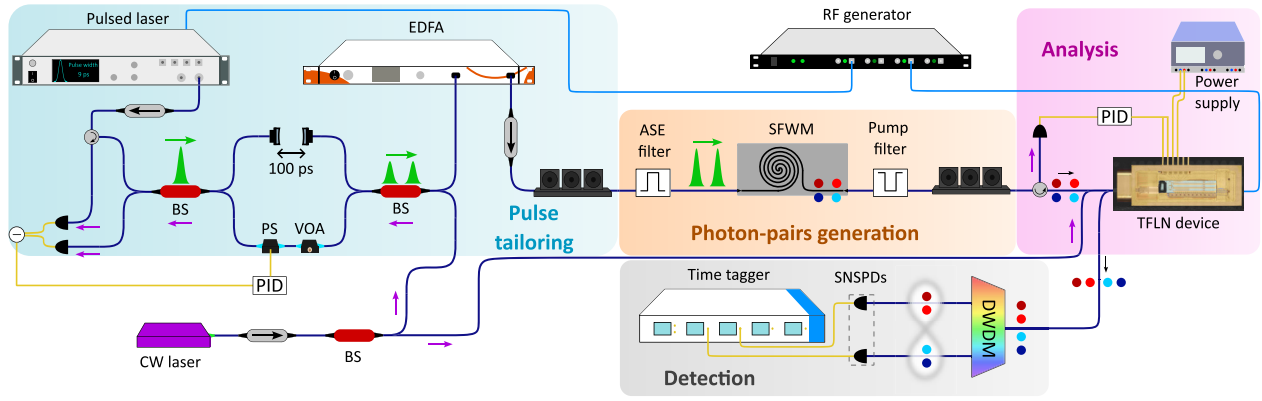


FIG. 3. Experimental setup: a mode-locked laser (Pritel) emits pulses at 1550.92 nm. Each pulse is delayed by an unbalanced fiber MZI to create the early/late pair and amplified by an erbium doped fiber amplifier (EDFA) (Keopsys). An in-fiber phase shifter, driven by a proportional-integral-derivative (PID), controls the phase difference between the two arms of the MZI, and a variable optical attenuator (VOA) equalizes the power of the pulses. After filtering of the amplified spontaneous emission (ASE), the tailored pump pulse pairs are coupled to a silicon waveguide, where photon pairs are generated via spontaneous four-wave mixing. The residual pump is then filtered and the generated photons are routed to the TFLN device for entanglement certification. Here, the unbalanced interferometer phase is controlled by a TPS, driven by an external power supply, while the optical switch is actuated by the same rf generator driving the pump laser. Light is demultiplexed with in-fiber filters (Opneti) and finally detected by SNSPDs (Photon Spot). A continuous-wave (CW) laser (PurePhotonics) counterpropagates in the first delay line and in the device MZM to stabilize the operating point.

routed to the TFLN device input to perform Franson interferometry in the passive or active TB configuration. The phase difference between short and long interferometer arms is set via an external power supply, which drives the TPS (violet panel). An rf source generates the modulation signals driving both the pulsed laser and the optical switch, hence they are synchronized. Signal and idler photons coming from a single output of the MZI are then demultiplexed via two Opneti bandpass filters centered at standard International Telecommunication Union (ITU) channels 38 (1546.92 nm) and 28 (1554.94 nm), with 100 GHz bandwidth and sent to superconducting nanowire single-photon detectors (SNSPDs), with an 85% efficiency and jitter of 50 ps for time-correlated single-photon counting (gray panel). Both the in-fiber MZI and the integrated balanced MZM are stabilized via a counterpropagating continuous-wave laser and proportional-integral-derivative feedback loops. The former fixes the phase difference between pump pulses, and the latter maintains the MZM at its quadrature working point. Light passing through the MZI is detected via a balanced photodiode in a dual-output monitor configuration, increasing sensitivity and improving the interferometer phase stability. The counterpropagating laser is injected into the 2% port of the TFLN device, allowing light to interact only with the balanced MZM; here, only one port is monitored with a photodetector, since the TFLN chip temperature is controlled via a Peltier module, thereby inhibiting long-term thermo-optic phase drifts. It is worth noting that the feedback loops are independent of each other, hence the same stabilization procedures could be performed with

two counterpropagating lasers. In addition, the active feedback loops can be removed, substituting the in-fiber MZI with an integrated interferometer and improving the temperature control over these photonic integrated circuits. This condition reduces the complexity of the connection between the parametric source and the users' TFLN receivers. The optical switch is modulated using a sinusoidal signal with a peak-to-peak voltage of the effective V_π at a frequency of 5 GHz. The optical losses from the silicon waveguide to photodetectors are listed as follows: silicon chip out-coupling 4.4 dB; pump rejection filters and routing toward the TFLN device 6.5 dB; TFLN insertion loss 6.1 dB due to coupling, propagation, and integrated component loss; and signal and idler demultiplexing and SNSPD detection efficiency 1.6 dB. Overall, the optical losses are 18.6 dB per signal and idler channel. Silicon photonic integrated circuit out-coupling and pump rejection filter losses can be shrunk by optimizing our setup.

To characterize the device operation on the generated quantum state, we first reconstruct the joint temporal intensity (JTI) of the two-photon state at the output of the device. This quantity, corresponding to the squared amplitude of the complex biphoton wave function in the temporal representation, can be experimentally assessed as a two-dimensional coincidence histogram between signal and idler photon arrival times (t_s, t_i) and the emission time of the pump pulses. Before entering the device, the JTI of the biphoton state consists of two mainlobes, associated with the two entangled TBs and with theoretical Schmidt number $K = 2$ [Fig. 4(a)]. The device then enacts a unitary

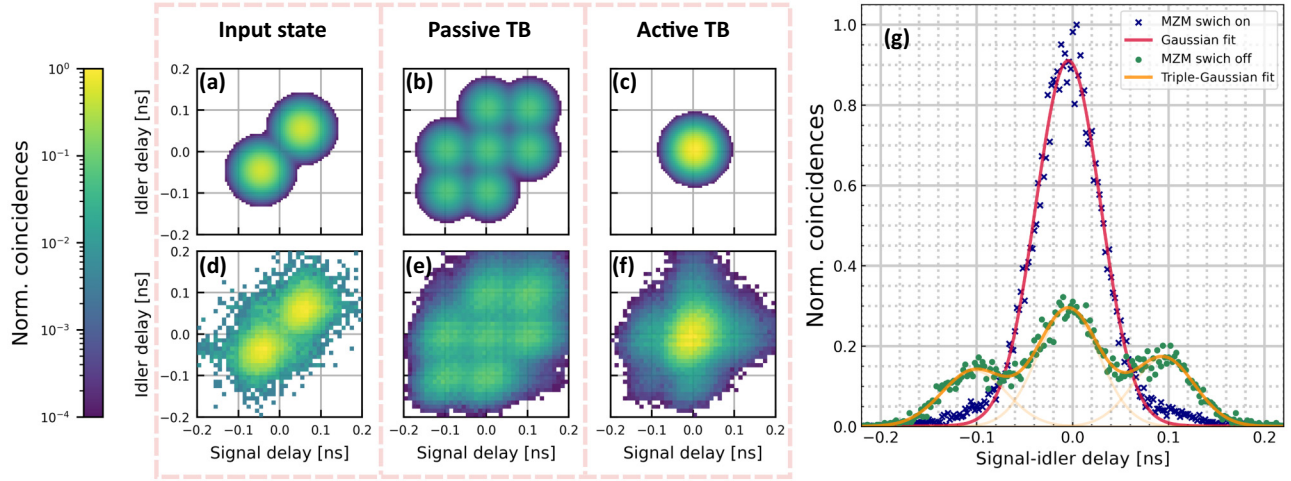


FIG. 4. (a)–(c) Simulated and (d)–(f) reconstructed JTIs for the input state and after undergoing evolution in the device, both in the passive and active-switching configurations. The amplitude of the passive-switching case is normalized to the peak of the active-switching one for consistency. The peak’s resolution is limited by SNSPDs jitter (50 ps) and the pulse delay is 100 ps. (g) Experimental time-correlated single-photon counting coincidence histograms for the passive- and active-switching cases. The same data can, in principle, be retrieved by integrating along the main diagonal of the JTIs.

evolution of the state, which in the passive configuration transforms it by creating, intuitively, four copies of each such lobe through temporal shift of the original pattern on the horizontal and vertical axes. The resulting pattern, depicted in Fig. 4(b), consists of seven lobes, of which only the central one displays quantum interference. A rigorous explanation of the mechanism behind TB interference goes beyond the scope of this work and can be found, for example, in Refs.[9,29]. The simulated pattern is well reproduced experimentally, as shown in Fig. 4(e), confirming that the device correctly performs the unitary transformation associated with such Franson-type interference. Conversely, when operated in active-switching configuration, the device deterministically shifts the two lobes along the main diagonal of the JTI ($t_i = t_s$), resulting in quantum interference for all photon pairs reaching the device. The experimental trace, shown in Fig. 4(f), well replicates the simulation [Fig. 4(c)], with only few residual counts in the secondary lobes, which we attribute to finite extinction ratio of the MZM stage, to small uncertainty in the bias control of the optical switch, and to a nonideal power of the rf driving signal.

The signal-idler time-correlated single-photon counting histogram [Fig. 4(g)], representing a measurement of the Glauber cross-correlation function $g_{s,i}^{(2)}(t_s, t_i)$, can be either directly retrieved from the photon arrival times or equivalently obtained from integration of the JTI along the $t_s = t_i$ axis. This operation effectively projects the measured JTI over the antidiagonal $t_i = -t_s$, and it is therefore a function of the arrival time delay at the detectors. As a consequence, the coincidence histogram trace associated with the passive-switching (green dots) regime displays three peaks, which can be only partially resolved due to the finite

resolution of our SNSPD (50 ps). Since the central peak originates from the three diagonal lobes, varying the interferometer phase only allows partial extinction. This results in a maximum theoretical visibility of 50% when postselecting only the central peak events, and 25% when also including the lateral histogram peaks, preventing temporal postselection loophole-free entanglement certification, as pointed out in Sec. II. Conversely, operating the device in active-switching regime provides a single-peak coincidence histogram (blue crosses). Since in this case all the incoming photons participate in quantum interference, the interference can here reach a maximum theoretical visibility of 100%, therefore allowing a temporal postselection loophole-free violation of Bell’s inequality.

We then perform a Bell test by collecting photons from one output channel of the device, without postselecting coincidences, namely summing all the coincidence events associated with the correlation histogram while varying the phase of the unbalanced MZI by acting on the TPS current. The result is shown in Fig. 5: two different experimental Bell curves, corresponding to the passive (light blue dots) and active (dark blue dots) configurations, clearly show an increase of the quantum interference visibility between the respective cases. Sinusoidal fits of the experimental data (each associated with a coincidence histogram, with 20 second integration time) yield a visibility of $(22.8 \pm 0.7)\%$ for the passive case and $(87.9 \pm 0.7)\%$ for the active case without accidental subtraction. With accidental correction the visibilities are, respectively, $(23.0 \pm 0.6)\%$ and $(88.9 \pm 0.7)\%$. The latter values exceed the theoretical bound for local realism ($1/\sqrt{2} \approx 70.7\%$) by more than 24 standard deviations, proving a temporal postselection loophole-free Bell

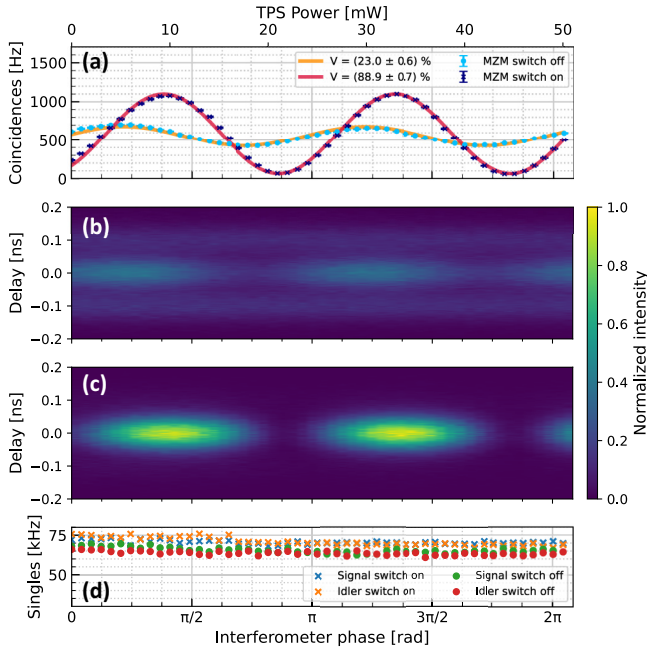


FIG. 5. (a) Measured quantum interference curves in both passive (MZM off) and active (MZM on) configurations. The solid curves are sinusoidal fits of the experimental data and are used to assess the visibility. Experimental intensity plots of the coincidence histograms for (b) the passive scheme, and (c) the active scheme. (d) Photon rate at the SNSPDs. All the data and visibilities are reported without subtraction of accidental counts.

violation for the TB-entangled state. Measurement data obtained by routing the entangled signal and idler photons toward two spatially separated devices are reported in Supplemental Material Note III [40].

V. DISCUSSION AND CONCLUSIONS

We demonstrated a chip-integrated receiver for the certification of genuine TB entanglement without temporal postselection. To the best of our knowledge, this is the first experimental implementation of the method outlined in Ref. [27,36] using an integrated device. To this end, we take advantage of an industrial-grade TFLN fabrication technology and develop fully packaged devices that prove the maturity of TFLN technology for the practical deployment of quantum protocols.

Unlike the scheme presented in Ref. [25], the active switching scheme implemented here does not exploit hyperentanglement or any additional degree of freedom to overcome the temporal postselection loophole. Instead, only the TB qubit encoding is required, enabling the exploitation of other degrees of freedom to encode useful quantum information. By deterministically selecting the long or short path, all photon pairs (excluding losses) can contribute to quantum interference. In contrast, the “hug” schemes [26,29] passively discard photons that do not

temporally overlap, reducing the number of useful photon pairs by half and limiting the maximum two-photon coincidences. We remark that our demonstration does not aim to provide a fully loophole-free violation of Bell inequalities, as achieved for instance in Ref. [44]. In the present experiment, the *fair-sampling* loophole remains open due to the overall optical losses of the setup [28]. Our goal here is instead to demonstrate an integrated receiver capable of closing the temporal postselection loophole inherent to TB encoding [24], using state-of-the-art integrated photonic technology. This represents an important step toward TB-based loophole-free experiments, as well as toward the implementation of practical entanglement-based QKD architectures based on TB encoding.

As shown in Fig. 4(f), the sidebands caused by spurious events are almost entirely suppressed during device operation. This greatly simplifies the measurement process, as the required temporal resolution is now less than the period between two pulses rather than the TB spacing. We leverage this feature to drive the device at a switching frequency of 5 GHz, among the highest reported so far for an integrated quantum device [37,38], and we operate the device at near gigahertz-level repetition rates, only limited in this demonstration by the repetition rate of our pump laser (500 MHz). Note that the theoretical maximum—in this device geometry set at 5 GHz—is only affected by the TB separation, and is in principle only limited by the pulse duration and detector jitter. However, we stress that this limitation is not directly inherited from the “active-switching” approach itself, but from the interferometer’s geometry. The ultimate TB separation is set by the pulse duration and the detector jitter, the latter increasing the measured pulse width by a detector-dependent amount. Recently, SNSPDs with time jitter of 15 ps and detection efficiency of 90.5% have been demonstrated [45], allowing for the discrimination of ≈ 30 ps separated events and a corresponding switching signal > 15 GHz. Consequently, it would be possible to operate at repetition rates exceeding 10 GHz, after setting the MZI unbalance accordingly and decreasing the pulse duration to less than 3 ps. With a switching peak-to-peak voltage as low as $V_\pi = 3.37$ V at 1 MHz and 30 GHz 3 dB EO bandwidth, the device operates at low rf power (< 17 dBm) and in a CMOS-compatible voltage range, making it suitable for cointegration with standard high-speed electronics. We note that similar modulation bandwidths can also be achieved using silicon-based modulators. However, compared with TFLN devices, they generally exhibit higher insertion loss [46]. In addition, the larger propagation losses in silicon waveguides can limit the achievable interferometric performance in unbalanced MZI configurations.

In terms of the visibility of quantum interference, the device reaches a maximum of $(87.9 \pm 0.7)\%$ without subtraction of accidentals and $(88.9 \pm 0.7)\%$ with subtraction of accidentals, when operated in the active-switching

regime. Although this result does not show the violation of the CHSH inequality, we can infer the value of the S parameter to be (2.49 ± 0.08) and (2.51 ± 0.08) without and with accidental subtraction, respectively. While Bell's inequality is undeniably violated, the visibility without accidental subtraction, which is a more realistic metric for practical field-deployed applications such as QKD, is limited by three main causes: the spontaneous four-wave mixing source coincidence-to-accidental ratio (CAR), the MZM and MZI extinction ratios, and TFLN device nonidealities. The CAR itself is mainly limited by the 100 GHz bandwidth of the dense wavelength division multiplexing filters and by the input pump power. In the active regime, with a CAR of approximately 60, the maximum achievable visibility can be estimated as $V_{\max} = \text{CAR}/(\text{CAR} + 2) \approx 96.8\%$. Although narrower filters or reduced pump power could increase CAR, this would reduce the coincidence rate, demonstrating a trade-off between visibility and secure key rate. Importantly, the use of standard dense wavelength division multiplexing filters in our setup allows for high coincidence rates without significantly degrading entanglement quality, showing the potential for telecom-compatible multiuser quantum communication [11,47,48].

In Sec. III we reported a MZM extinction ratio of 40 dB at 1 MHz and the best MZI extinction ratio of 21 dB. Further investigations (see Supplemental Material Note IV [40]), performed at the working rate of 5 GHz, show an overall extinction ratio of the TFLN photonic integrated circuit of 19.8 dB, a slight reduction with respect to the extinction ratio of the MZI alone. We believe that this is caused by limited performance of the modulator at high frequencies. As a consequence, the maximum achievable visibility is 97.8% and, taking into account $\text{CAR} \approx 60$, visibility is capped to 94.7%.

Residual device nonidealities represent the principal factor limiting the interference visibility, such as multi-mode propagation and polarization crosstalk in the TFLN photonic integrated circuit (see Supplemental Material Note V [40]). These effects could be mitigated in future designs by using Euler bends [49] and integrated polarization filters [50]. Further optimization may include improved control of the optical switch bias and of the rf driving signal, both of which can affect the visibility, as well as a reduction of component losses, which is particularly important for multiphoton applications.

While here we limit ourselves to showcasing the device operation with a demonstration of temporal postselection loophole-free entanglement certification, future works may include its application to quantum communication protocols, such as QKD, teleportation, and entanglement swapping, as well as for the automated tomography of TB qubits. For all of these applications, the use of TBs would be particularly favorable over fiber-optical links, owing to the inherent robustness of the TB encoding over long-haul

propagation. Future developments could also extend this approach to higher-dimensional TB states (qudits) [18]. With sufficient technological maturity, cascading multiple unbalanced interferometers with high-speed modulation and multiport switching could enable temporal postselection loophole-free operation with higher TB dimensionality and picosecond-separated TB states. We note that, for real-world implementations involving physically separated stations, precise timing synchronization between the users and the pulsed source represents an important practical difficulty. In the present demonstration, synchronization was inherently ensured by driving both the laser and the on-chip optical switch with the same rf source, thereby avoiding relative timing drifts. In a distributed scenario, accurate synchronization is necessary to properly align the modulation signal with the arrival times of the early and late photons, ensuring correct routing within the receivers. Recent demonstrations have, however, proven that picosecond-level synchronization over fiber links up to 50 km has already been demonstrated, even without additional dedicated communication channels [51–53].

In summary, we have demonstrated a fully engineered device for entanglement certification in TFLN integrated photonics. Operating at gigahertz-rate switching speed, and overcoming the need for temporal postselection, this result is a significant step toward the practical deployment of quantum communication protocols over actual quantum networks.

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The authors declare no conflicts of interest.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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