Tunable quantum interference using a topological source of indistinguishable photon pairs

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Sources of quantum light, in particular correlated photon pairs that are indistinguishable for all degrees of freedom, are the fundamental resource for photonic quantum computation and simulation. Although such sources have been realized using integrated photonics, they offer limited ability to tune the spectral and temporal correlations between generated photons because they rely on a single component, such as a ring resonator. Here, we demonstrate a tunable source of indistinguishable photon pairs using dual-pump spontaneous four-wave mixing in a topological system comprising a two-dimensional array of resonators. We exploit the linear dispersion of the topological edge states to tune the spectral bandwidth (by about 3.5×), and thereby, to tune quantum interference between generated photons by tuning the two pump frequencies. We demonstrate energy–time entanglement and, using numerical simulations, confirm the topological robustness of our source. Our results could lead to tunable, frequency-multiplexed quantum light sources for photonic quantum technologies.

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in continuous-variable quantum computation and Gaussian boson sampling.\cite{23,24}

Our system consists of a 2D checkerboard lattice of ring resonators (Fig. 1a)\textsuperscript{35,36}. The rings (blue) at the lattice sites are coupled to their nearest and next-nearest neighbours using another set of rings, which we call the link rings.\textsuperscript{18,20} The gap between the link and the site rings is always zero, and that between nearest-neighbour site rings is zero. Our system also supports a pseudo-spin degree of freedom because of the two circulation directions (clockwise and counter-clockwise) in the ring resonators, and therefore experience opposite hopping phases and exhibit counter-propagating edge states\textsuperscript{36}. This coupled ring resonator configuration simulates the anomalous quantum-Hall model for photons\textsuperscript{35,36}, with a Haldane-like tight-binding Hamiltonian

\[
H = \sum_m a_m^\dagger a_m^\dagger + J \sum_{\langle m,n \rangle} a_m^\dagger a_n^\dagger e^{-i\phi_{m,n}} + \sum_m a_m^\dagger a_m + h.c.
\]

Here \(a_m^\dagger (a_m)\) is the photon creation (annihilation) operator at a lattice site \(m\) and h. c. indicates Hermitian conjugate. The summations \(\langle m,n \rangle\) and \(\langle (m,n) \rangle\) are over the nearest-neighbour and the next-nearest-neighbour lattice sites, respectively. \(J\) is the coupling strength between the lattice sites, and is the same for both nearest and next-nearest neighbour site rings. The resonance frequencies of the link rings are detuned from those of the site rings such that the link rings act as waveguides connecting site rings. More importantly, depending on their position, the link rings introduce a direction-dependent hopping phase between the site rings. In our system, the link rings are positioned such that the hopping phases between next-nearest-neighbour site rings is always zero, and that between nearest-neighbour site rings is \(\pm \pi/4\). This configuration effectively leads to the realization of a staggered synthetic magnetic field for photons such that the average magnetic flux through a unit cell of two plaquettes of the lattice is zero (shaded light green in the inset of Fig. 1a), but the flux through a single plaquette is non-zero. This coupled ring resonator configuration simulates the anomalous quantum Hall model for photons\textsuperscript{35,36}, with a Haldane-like tight-binding Hamiltonian

\[
H = \sum_m a_m^\dagger a_m^\dagger - J \sum_{\langle m,n \rangle} a_m^\dagger a_n^\dagger e^{-i\phi_{m,n}} + \sum_m a_m^\dagger a_m + h.c.
\]
In our experiment, we position the two pump frequencies in two different longitudinal modes of the lattice separated by two free-spectral ranges ($\Omega$, see Fig. 1d). The indistinguishable photon pairs are then generated in the longitudinal mode located midway between the two pump modes, that is, $\omega_{p1} + \omega_{p2} = \omega_{s} + \omega_{i}$ and $\omega_{s} = \omega_{i}$. Here $\omega_{\mu}$ with $\mu = p_1, p_2, s$ or $i$, is the resonance frequency of the respective longitudinal mode. We note that each of the two pump beams also generates distinguishable photon pairs via non-degenerate (single-pump) SFWM. However, because of energy conservation, these photon pairs are generated in longitudinal modes located symmetrically around the respective pump beams (Fig. 1d). Therefore, we use spectral filtering and time-resolved coincidence measurements between detected photon pairs to exclude the noise photons generated by single-pump SFWM (Fig. 1c).

To understand the nature of spectral correlations between the two pump fields and the generated photons, we first measure the number of indistinguishable photon pairs generated via dual-pump SFWM as a function of the two pump frequency detunings ($\delta \omega_{p1,2} = \omega_{p1,2} - \omega_{\mu}$), relative to their respective longitudinal mode centre frequencies. As mentioned earlier, we use time-resolved correlation measurements ($g^{(2)}(\tau)$) to post-select the photon pairs generated by dual-pump SFWM. Figure 2b shows the typical temporal correlation function with pump powers $P_1 = 1$ mW and $P_2 = 3$ mW at the input of the lattice. We measure a maximum $g^{(2)}(0) \approx 117$, which shows that the two photons are indeed correlated. We integrate over the correlation peak to get the total number of coincidence counts in a given acquisition time (here 10 s). Figure 2c shows the measured number of coincidence counts (normalized) as a function of the frequency detunings $\delta \omega_{p1,2}$.
Notably, we observe that the photon generation rate is maximum when both the pump frequencies are in the edge band, that is, when \( \delta \omega_{p1}, \delta \omega_{p2} = [-1, 1] \) (Fig. 2a). Furthermore, compared to the bulk band regions, the generation rate is relatively uniform throughout the edge band. We note that for a given choice of the two pump frequencies, energy and momentum conservation lead to spectral correlations between generated photons. However, our measurement of the number of generated photon pairs as a function of the pump frequencies does not resolve these spectral correlations.

To reveal the spectral correlations between generated signal and idler photons, we fix the input pump frequencies to be in the middle of the edge band, at \( \delta \omega_{p1}, \delta \omega_{p2} \approx 0 \), and measure the joint-spectral intensity (JSI), \( \phi(\delta \omega_{s}, \delta \omega_{i}) \) (Fig. 2d). This is the joint probability of detecting a signal photon at frequency \( \delta \omega_{s} \) and an idler photon at frequency \( \delta \omega_{i} \). Here \( \delta \omega_{s,i} \) are the frequency detunings of the signal and idler photons relative to their respective longitudinal mode resonances. The measured correlations show that, with the two pump fields in the edge band, the spectrum of generated signal and idler photons is also limited to the edge band. This is because of the linear dispersion of the edge states that leads to efficient phase matching (momentum conservation) when all four fields are in the edge band and the confinement of the edge states to the lattice boundary, which leads to a good spatial overlap between the fields. Furthermore, both the signal and idler spectra are centred around \( \delta \omega_{s,i} \approx 0 \), which shows that they are degenerate in frequency, that is, \( \phi(\omega_{s}, \omega_{i}) \equiv \phi(\omega_{s}, \omega_{i}) \). The JSI also shows that the signal and idler photons generated by our source are entangled, that is, \( \phi(\omega_{s}, \omega_{i}) \neq \phi_{s}(\omega_{s}) \phi_{i}(\omega_{i}) \). We note that we use continuous-wave pumps in our experiments and the apparent width of spectral correlations along the diagonal is because of the finite spectral resolution (\( \approx 10 \) GHz \( \approx 0.64/\) of our measurements.

The energy conservation and the linear dispersion of the edge states allows us to tune the spectral bandwidth of generated photons by tuning the input pump frequencies within the edge band region. This is because of the efficient momentum conservation in the edge band that limits the spectra of generated photons also to the edge band region. To show such tunability of the spectra of generated photons, we measure the signal–idler spectral correlations for different pump frequencies in the edge band (Fig. 2e,f). When both the pump frequencies are near the side of the edge band (\( \approx 0.8f \)) in Fig. 2f, we observe that the spectra of generated photons are substantially narrower (by about 4 times) than when both the pumps are in the centre of the edge band (Fig. 2d). Also, the spectra are centred around 0.8f, which shows that the two photons are degenerate in frequency, as expected. Similarly, when the two pump frequencies are at different locations in the edge band (\( \delta \omega_{p1}, \delta \omega_{p2} \approx 0.8f, \delta \omega_{p1,2} \approx 0 \)), we observe that the spectra of generated photons are centred around 0.4f, with a bandwidth larger than that with both the pumps in the side of the edge band (Fig. 2c).

Though our JSI measurements show that the signal and idler photons are degenerate in frequency, \( |\phi(\omega_{s}, \omega_{i})|^{2} = |\phi(\omega_{s}, \omega_{i})|^{2} \), these measurements do not confirm their indistinguishability, which requires phase-coherence such that \( \phi(\omega_{s}, \omega_{i}) = \phi(\omega_{s}, \omega_{i}) \phi_{s,i}(\omega_{s}, \omega_{i}) \). A way to unambiguously confirm the indistinguishability of generated signal and idler photons is to perform HOM interference between the two photons. In HOM interference, when two indistinguishable photons arrive simultaneously at the two input ports of a beamsplitter, they bunch together at the output of the beamsplitter. We emphasize that HOM interference between correlated signal and idler photons (generated by the same source) only requires the two-photon spectral function to be symmetric, \( \phi(\omega_{s}, \omega_{i}) = \phi(\omega_{s}, \omega_{i}) \), but not necessarily separable, \( \phi(\omega_{s}, \omega_{i}) = \phi_{s}(\omega_{s}) \phi_{i}(\omega_{i}) \).

In HOM interference the two photons arrive separately, one photon in each of the two input ports of the beamsplitter. However, in our topological source, both the photons are in a single spatial mode, they have the same polarization, and they are degenerately in frequency. Therefore, we cannot deterministically split the two photons into two spatial modes using a normal beamsplitter, which creates at its output a superposition of states where either one photon is in each port, or two photons are in the same port (see Supplementary section 3, and refs. 43,44). Nevertheless, when the input to the beamsplitter is a path-entangled two-photon state of the form \( |20\rangle_{A,B} + |02\rangle_{A,B} \), that is, when both the photons arrive either at the input port A or at port B of the beamsplitter, then the two-photon state at the output ports C, D of the beamsplitter is deterministic with one photon in each port, that is, \(|11\rangle_{C,D} \). Here the state \(|nm\rangle_{A(C),B(D)}\) refers to \( n \) photons in the input/output port A(C) of the beamsplitter and \( m \) photons in the input/output port B(D) (see Supplementary section 3, and refs. 43,44). This scenario, in fact, corresponds to time-reversed HOM interference of two photons.

To deterministically split the two photons, so that we can later perform HOM interference between them, we use our topological source in a Sagnac interferometer (formed by beamsplitter BS-1, Fig. 3a)45. In this configuration, both the pseudo-spins (up and down) associated with our source are simultaneously pumped. Because they are time-reversed partners, the pump beams corresponding to the two pseudo-spins propagate through the same edge state, but in opposite directions, and generate a path-entangled two-photon state \( |20\rangle_{A,B} + e^{-i\delta\omega} |02\rangle_{A,B} \) at ports A, B of the beamsplitter BS-1 (Fig. 3a). We note that the strength of SFWM interaction in our experiment is very weak, such that the probability of generating two photon pairs, one in each arm of the Sagnac interferometer, is small. The relative phase \( \delta \) of two-photons entangled state can be set to 0 or \( \pi \) by appropriately choosing the input ports for the two pump beams at the Sagnac beamsplitter (BS-1 in Fig. 3a). When both the pumps are in the same port of the BS-1 (port C or port D), the phase \( \delta = \pi \), and the two photons bunch at the output of BS-1, that is, they appear together at either port C or port D of BS-1 (Fig. 3c). In contrast, when the two pumps are in different ports of the beamsplitter BS-1 (one in port C, and the other in port D), the phase \( \delta = 0 \) and it leads to anti-bunching of photons such that the photons are deterministically separated at the output of the BS-1 (Fig. 3b). We use two circulators to collect the photons at ports C and D. For \( \delta = 0 \), we measure the total probability of bunching (in either port C or port D), \( g^{(2)}(0) = 0.05(1) \), which shows that the two photons are predominantly in the state \(|11\rangle_{C,D} \). For \( \delta = \pi \), we measure \( g^{(2)}(0) = 0.93(1) \), which shows that the two photons are still in the same spatial mode (port C or port D). We emphasize that the use of a Sagnac interferometer, with the two pump beams injected at different input ports, alleviates the need for any active stabilization of our source.

To demonstrate HOM interference we set \( \delta = 0 \) such that the two photons are deterministically separated in the ports C and D of the beamsplitter BS-1. We pump our source in the middle of the edge band, that is, \( \delta \omega_{p2} \approx 0 \approx \delta \omega_{p1} \). We introduce a relative delay \( \tau_{e} \) between the two photons, interfere them on another beamsplitter (BS-2), and measure the coincidence counts at the output of BS-2 as we vary the delay \( \tau_{e} \) (Fig. 3a). We see a HOM dip in the coincidence counts, with a visibility of 88(10)%, which confirms that the two photons are indeed indistinguishable (Fig. 3d). The visibility of the HOM interference observed using the topological source compares well with that observed using single waveguides and ring resonators44.

We note that the temporal width of the HOM interference dip is inversely related to the spectral width of the JSI (along the line \( \delta \omega_{s,i} = \delta \omega_{0} \)), which characterizes the two-photon state. As demonstrated in Fig. 2d–f, we can control the JSI of generated photons in our source by simply tuning the input pump frequencies (Fig. 2). To demonstrate similar control in the HOM interference, we set the two pump frequencies to be at one of the extremes of the edge band \( \delta \omega_{p1,2} \approx 0.8f \approx \delta \omega_{p1,2} \) such that the spectral width of the JSI is small (Fig. 2f). We now observe, in Fig. 3c, that the temporal width
of the HOM interference dip is indeed much larger (by a factor of $2.7 \pm 0.4$) compared to the case with both the pumps in the centre of the edge band. The discrepancy between this factor and the decrease in the spectral width (by a factor of $\approx 4$) can be accounted for by the limited spectral resolution of our JSI measurement.

Finally, we show that the two-photon state generated by our source is energy−time entangled. We use a fibre beamsplitter (Fig. 4a, Supplementary section 4) to split the two photons at the output of our source, and inject them into two Franson interferometers. The path length delay in the interferometer is about $800 \text{ ps}$, which is much longer than $\Delta T \approx 200 \text{ ps}$, the width of the second-order temporal correlation function $g^{(2)}(\tau)$ of the generated photons (see Fig. 2b). As we discussed earlier (also see Supplementary section 4), the fibre beamsplitter creates a superposition of states, with one photon in each output port or two photons in either of the output ports. However, our coincidence measurements at the outputs of the two interferometers post-select only the state where there is one photon in each output port of the beamsplitter. Furthermore, coincidence measurements that resolve the time delay in the arrival of two photons yield three peaks. The two side peaks correspond to the two cases $(\mid s \rangle, \mid l \rangle)$ when one of the photons took the shorter path $(s)$ in the interferometer, while the other took the longer path.
entanglement between generated photon pairs is because of the use of narrow-band continuous-wave pumps. By using pulsed pumps with broad-band spectra, it is indeed possible to generate indistinguishable photons pairs that are also nearly separable (see refs. 32,43 and Supplementary section 7), and can therefore be used to realize multi-photon interference schemes.

Because the edge states are topologically protected, we expect that the spectral correlations between generated photon pairs will also be robust against fabrication disorders when the two pump frequencies—and therefore the signal and idler frequencies—are in the edge band. Indeed, in ref. 32, we demonstrated the topological robustness of spectral correlations using a single-pump SFWM process. To show that this topological robustness holds for dual-pump SFWM process as well, we provide numerical simulation results in Supplementary section 5. We fix the input pump frequencies to be in the centre of the edge band and calculate the spectra of generated photons for random realizations of disorder. We compare these results against those for a one-dimensional array of ring resonators, which is topologically trivial, and therefore not robust against disorder. As expected, we observe that our topological source of indistinguishable photon pairs achieves much higher spectral similarity across devices when compared to topologically trivial sources.

In summary, we have demonstrated a topological source of indistinguishable photon pairs with tunable spectral–temporal correlations. Our demonstration could lead to on-chip generation of novel quantum states of light where topological phenomena are used for robust manipulations of the photonic mode structure and quantum correlations between photons. In particular, in the low-loss regime that can be easily accessed using the commercial silicon-nitride platform, our topological devices can achieve pair-generation rates that are an order of magnitude higher than that in single-ring sources (see Supplementary section 9). Low-loss topological devices would also allow the generation of spectrally engineered or spectrally multiplexed squeezed light44–46 for applications in continuous-variable quantum photon computation. On a more fundamental level, nonlinear parametric processes such as four-wave mixing are inherently non-Hermitian in nature (when treating the pump beam classically), that is, they do not conserve particle number. Therefore, our system paves the way for investigations of the rich interplay between topology, nonlinear and non-Hermitian physics, and quantum photonics processes to realize novel topological phases that are unique to photons.

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**Methods**

Our devices are fabricated using the complementary metal–oxide–semiconductor (CMOS) compatible silicon-on-insulator platform at a commercial foundry (IMEC Belgium). The ring waveguides are about 510 nm wide, about 220 nm high and, at telecommunications wavelengths (around 1,550 nm), they support a single transverse-electric polarized mode. The ring length is about 70 μm with a free-spectral range of around $2\pi J \approx 1$ THz. The coupling gap between the rings is 0.180 nm, and it results in a coupling strength of $J \approx (2\pi)15.6$ GHz. The lattice is coupled to input and output waveguides, as shown in Fig. 1. At the ends of the input/output waveguides, we use grating couplers to couple light from a standard single-mode fibre into the waveguide.

We use two tunable lasers (Santec TSL 710) to pump the lattice. The two pump lasers are amplified using two erbium-doped fibre amplifiers (Amonics), and two tunable filters (OzOptics) are used to reduce the noise photons generated by the erbium-doped fibre amplifiers. The pump lasers are combined using a 50:50 fibre beamsplitter, and coupled to the input port of the lattice using a grating coupler. The photons generated at the output port of the lattice are collected into a single-mode fibre using another grating coupler. We use cascaded wavelength-division multiplexing (WDM) filters to filter out the pump photons, and use two superconducting nanowire detectors (PhotonSpot) and a time-correlated single photon counter (HydraHarp) to perform time-resolved coincidence detection of photons. For demonstration of energy-time entanglement we used a single Michelson interferometer (see Supplementary Information for details).

**Data availability**

The data that support the findings of this study are available on reasonable request. Correspondence should be addressed to S.M. (mittals@umd.edu).

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**Author contributions**

S.M. and V.V.O. contributed equally. S.M. conceived and designed the experiment, and performed numerical simulations. V.V.O. and S.M. performed the measurements. E.A.G. contributed to source characterization. M.H. supervised the project. All authors contributed to analysing the data and writing the manuscript.

**Competing interests**

A US provisional patent application (no. 63/028,468) has been filed based on the results reported in this manuscript.

**Additional information**

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