QUANTUM OPTICS

Topological protection of biphoton states

Andrea Blanco-Redondo[1]*, Bryn Bell[1]†, Dikla Oren[2], Benjamin J. Eggleton[1], Mordechai Segev[2]

The robust generation and propagation of multiphoton quantum states are crucial for applications in quantum information, computing, and communications. Although photons are intrinsically well isolated from the thermal environment, scaling to large quantum optical devices is still limited by scattering loss and other errors arising from random fabrication imperfections. The recent discoveries regarding topological phases have introduced avenues to construct quantum systems that are protected against scattering and imperfections. We experimentally demonstrate topological protection of biphoton states, the building block for quantum information systems. We provide clear evidence of the robustness of the spatial features and the propagation constant of biphoton states generated within a nanophotonics lattice with nontrivial topology and propose a concrete path to build robust entangled states for quantum gates.

Discoveries about topological states of matter have emerged over the past decade, affecting fields beyond condensed matter, such as electromagnetism (*1*) and photonics (*2*–*4*), acoustics (*5*), cold atoms (*6*, *7*), and mechanics (*8*). The reasons for the extensive research interest are twofold: The underlying concepts are fundamental and universal to many wave systems in nature, and the topological features of these systems offer the possibility of topological protection of transport for classical and quantum waves.

In photonics specifically, even though multiphoton quantum states have played a major role in testing quantum mechanics, quantum computing, and communications, the scalability to large quantum optical devices is limited by loss and fabrication imperfections (*9*). With the major progress in topological photonics, experiments examining the transport of quantum edge states with the use of single photons have recently been carried out (*10*–*12*) and are of clear interest for quantum simulation and sensing. These single-photon experiments investigated the physics of topologically protected bound states (*10*) and topological transitions (*11*) in photonic quantum walks, as well as demonstrating an interface between a quantum emitter and a photonic topological edge state (*12*). However, quantum information systems rely on multiphoton states, thus highlighting the importance of demonstrating topological robustness of multiphoton states. It has been suggested theoretically that topological features can provide robustness to the transport of biphoton states (*13*–*15*), and recent experiments have shown that topology can lead to robustness in the spectral correlations between photon pairs (*16*).

Our experimental system is a one-dimensional (1D) array of silicon nanowires (Fig. 1A) comprising alternating short and long gaps that modulate the coupling strength between adjacent nanowires, creating a Su-Schrieffer-Heeger (SSH) lattice (*17*, *18*). A long-long defect in the middle of the lattice acts as a topological interface between two mirror-reflection versions of the SSH lattice, yielding a topological edge state at the interface between both versions (*19*, *20*). Given the topological nature of the SSH lattice, two key features of this mode are protected against any disorder that preserves the chiral symmetry of the system: the propagation constant (analogous to the energy in condensed matter systems) and the zero amplitude of the wave function in every other site.

Intense picosecond pump pulses from a mode-locked laser (MLL) at 1550 nm are focused into the waveguide at the center of the lattice (Fig. 1A). As the pulses propagate in the lattice, they efficiently generate correlated signal and idler photons over a broad bandwidth via spontaneous four-wave mixing (SFWM) (*21*). At the output of the chip, we filter signal and idler photons at 1545 and 1555 nm, respectively. We detect individual photons by using superconducting single-photon detectors (SSPDs) and identify matching arrival times by using a time correlation circuit (TCC). In this way, we measure the spatial profile of the wave function and the biphoton correlations as a function of the lattice position.

Generally, photon pairs generated within a lattice have entanglement between the spatial modes of the lattice (in addition to frequency entanglement) (*22*). In our lattice, the nontrivial topology provides selection rules for the generation of the biphoton states (*23*) in addition to the phase-matching condition typical of trivial quantum walks of correlated photons using SFWM. Because the pump beam excites the topological defect mode, it stays confined to the defect. The biphotons thus strongly overlap with the wave function of the topological defect mode. This yields topological protection of several features of the biphototon wave function and, at the same time, makes the wave function close to—but not exactly—separable.

This underlies an important difference between the current experiments with biphoton states and previous topological photonic studies that used classical light. Although the eigenmodes of the structure are the same as those for classical states, the wave functions of multiphoton states exist in a higher-dimensional Hilbert space—in particular, the current experiments with two nonidentical photons in m waveguides exist in an m^2 dimensional Hilbert space. The presence of the topological defect state localizes the biphoton to a near-separable state, but an m^2 dimensional Hilbert space is still required to describe the state because the signal and idler cannot be described independently, even if the photons are nonidentical (*24*). In this context, previous topological experiments using single-photon states (*10*–*12*), which live in an m^1 dimensional Hilbert space, are similar to those using the corresponding classical states.

Figure 1A shows a scanning electron micrograph (SEM) of the fabricated topological lattice of silicon nanowires on a silica substrate (Fig. 1A), where height h = 220 nm, width w = 450 nm, short gap g_s = 173 nm, and long gap g_l = 307 nm (*21*). The lattice consists of 203 nanowires with length L = 381 μm. The center nanowires fan out at the output of the array to allow the collection of photons via grating coupling to a fiber array. For comparison, we also fabricated a nontopological lattice of equidistant nanowires with a wider center waveguide (Fig. 1B), giving rise to a localized, topologically trivial defect mode. Choosing a gap g = 100 nm and w_s = 465 nm, we achieved the same confinement at the five center waveguides for the topologically and trivially localized defect modes.

To experimentally demonstrate the robustness of the topological biphoton state against disorder, we fabricated and measured structures without disorder and with deliberately introduced random disorder in the position of the waveguides and thus in the coupling constants. In our nanophotonics platform, randomizing the positions of the center of each nanowire within a range of ±14 nm (±43 nm) results in disorder of 20% (60%) of the original coupling constant.

We measured biphoton correlations (Fig. 2) over 120 s at the output of the five center waveguides of the topological (Fig. 2, A to C) and the nontopological (Fig. 2, D to F) lattice for increasing levels of disorder. In this context, we measure individual structures exemplifying a particular instance of random disorder. The measurements agree with the quantum states resulting from the propagation simulations at each level of disorder

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(movies S1 and S2). The vertical scale is distinct for each measured structure and shows the true signal and idler coincidence counts between waveguides, with the background level of accidental coincidences subtracted. The coincidence-to-accidental ratio (CAR) is well above 10 for all significant points in the correlation matrix.

For the biphoton quantum state in the topological lattice, the strong center peak in Fig. 2, A to C, shows that, with high probability, both correlated photons are in waveguide 0 even for very high levels of disorder. This is evidence of the strong localization of the quantum state at the topological defect. However, the most crucial feature in this topological quantum state is that the counts remain zero in the odd waveguides. The robustness of this quantum state stems from its strong overlap with the topological edge mode of the lattice, whose wave function is immune to disorder (Fig. 3A). The Schmidt number (K) of the measured topological biphoton states, which essentially represents the mode entanglement, is not protected against disorder, as shown in Fig. 2. Nevertheless, K remains close to 1 because the topology guarantees the presence of a single localized mode, even with disorder, and the biphotons are well overlapped with this mode.

These measurements beg the question: Are the quantum correlations playing a crucial role, or is the robustness observed here just a logical consequence of the topological protection of classical light (*21*) or of single photons (*12*, *13*)

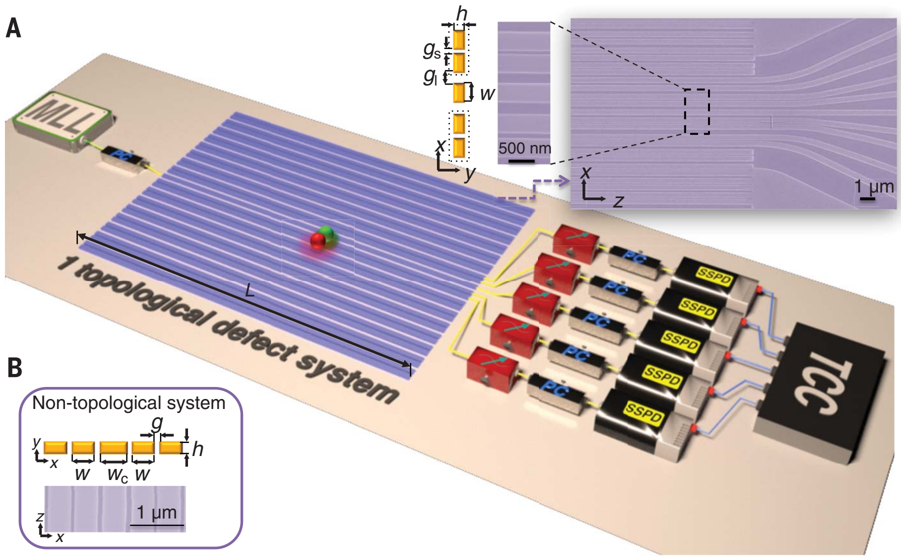


Fig. 1. Our nanophotonics topological system and experimental setup. (**A**) An MLL, a dimer chain of silicon nanowires with one topological defect, polarization controllers (PCs), tunable filters, SSPDs, and a TCC. (Inset) SEM of the topological defect. (**B**) SEM of the center waveguides of the structure providing nontopological (index-guiding) localization.

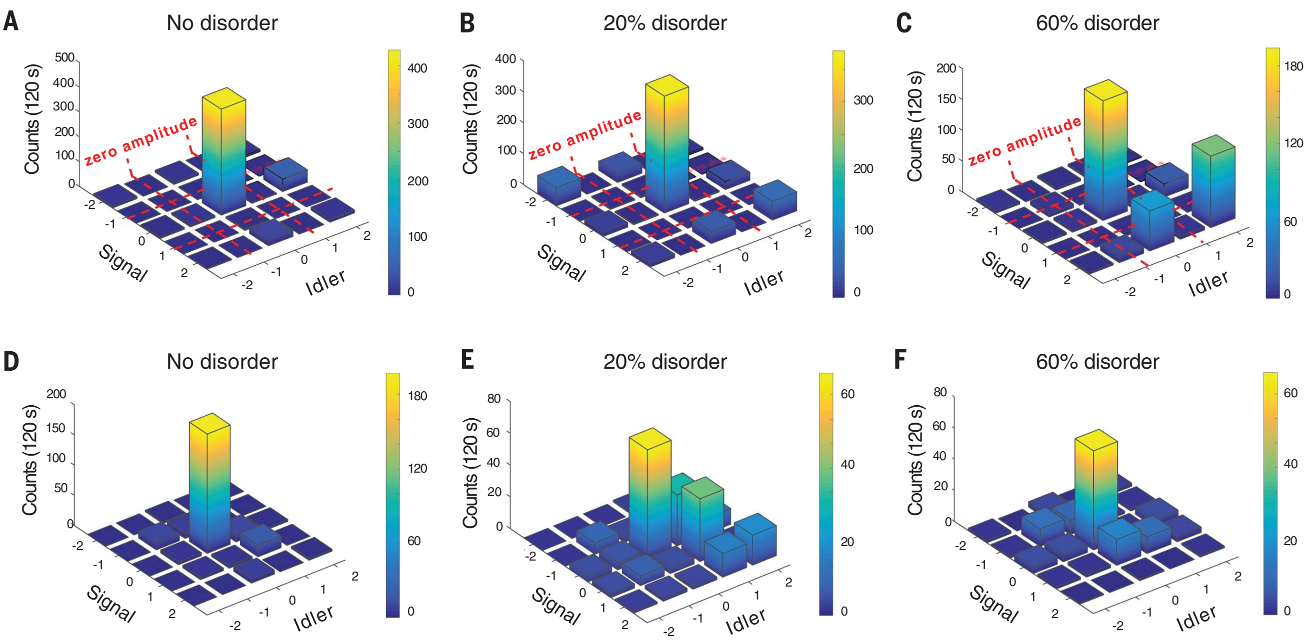


Fig. 2. Measured biphoton states with and without disorder. (**A** to **C**) Detected biphoton correlations of the topological quantum state for random disorder in a range of 0, 20, and 60% in the coupling constants. The probability amplitude remains zero in the odd waveguides. (**D** to **F**) Detected biphoton correlations of the nontopological quantum state under the same conditions of disorder. The disorder causes all coincidence amplitudes to vary, and no feature is preserved.

in the SSH model? We calculate the value of the quantity

$$\Gamma_{ij}^{\Delta,si} = \left\langle n_i^s n_j^i \right\rangle - \left\langle n_i^s \right\rangle \left\langle n_j^i \right\rangle$$

where $\langle n_i^s n_j^i \rangle$ denotes the signal (*s*)–idler (*i*) correlations and $\langle n_i^s \rangle \langle n_j^i \rangle$ denotes the product of the signal and idler intensities in waveguides *i* and *j*, respectively. Our calculation shows that $\Gamma_{ij}^{\Delta,si}$ is almost entirely determined by the biphoton correlation (*21*). Therefore, the measurements in Fig. 2 reveal an unexplored regime beyond the classical topological protection of electromagnetic states, with new quantities coming into play and new aspects of the wave function being protected.

The topological edge states in the SSH model are protected against any kind of disorder that preserves the chirality. In our nanophotonics SSH platform, this includes disorder in the position of the waveguides, environmental changes resulting in a *z*-axis uniform refractive index change, and wavelength fluctuations. However, a small amount of disorder in the width of the individual waveguides, which does not respect the lattice chirality, is inevitable because of fabrication precision limits. This is the cause of the only minor outlier in our measurements, the detection of a small but nonvanishing number of coincidences between waveguides 2 and −1 in Fig. 2C. Because of these fabrication imperfections, waveguide −1 is slightly wider than the rest in this particular device, leading to slight index localization.

For comparison, we repeated the same measurements on the nontopological lattice described above. The measured biphoton states in Fig. 2, D to F, show localization of the biphotons around the center waveguide but reveal severe delocalization even at low levels of disorder. More notably, no experimental observable is conserved, even though the pump is launched at a defect mode. Because the defect in Fig. 2, D to F, is nontopological, the emerging biphoton state does not exhibit any feature that is conserved in the presence of disorder (Fig. 3B).

The other prominent signature of topological protection in the SSH model is associated with the zeroes of the wave function: The energy of the topological edge mode (red dots in Fig. 3C) remains pinned at zero for all levels of disorder. In practice, this means that the propagation constant (k_z) of the topological mode does not change with disorder, which implies that the phase imparted by the lattice on the quantum state is robust. In contrast, the propagation constant of the index-guided mode (red dots in Fig. 3D) varies appreciably even for low levels of disorder, leading to phase errors that accumulate into very large phase variations at the lattice output. This highlights the importance of the results presented here in the context of quantum information systems with entanglement between different modes.

Simulations show that the nanophotonic platform for topologically protected waveguiding of biphoton quantum states demonstrated here can be used as the key building block of an entangled system. We put together two such building blocks in a two-topological-defect system (Fig. 4A). This yields two topological defect modes that are uncoupled from each other, provided that there is enough separation between defects *A* and *B*. The entanglement between these two modes can be generated in the same lattice, or alternatively, one can use entangled states generated outside the chip as the input to the topological modes. We simulated the generation of an entangled state between the two topological defect modes on-chip by using two intense pumps at the center of each topological defect and SFWM (*22*). This topological two-mode system can serve as the building block for a variety of quantum gates in a quantum information system. As an example, we demonstrate how it could be used for a quantum gate operating on 2 qubits.

The interference between the quantum states emerging from the two topological defect modes

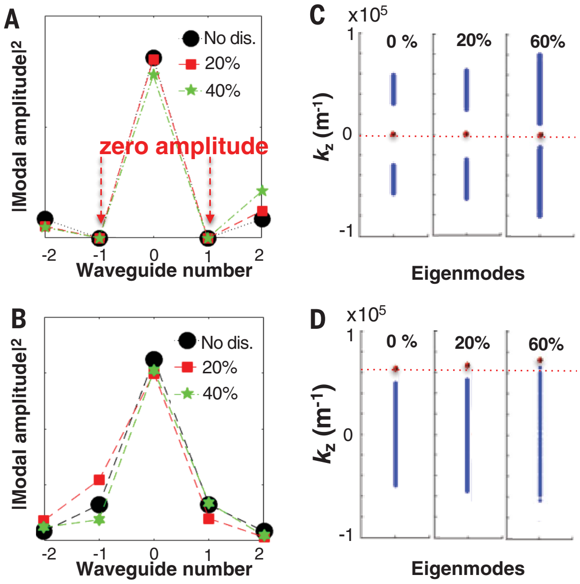
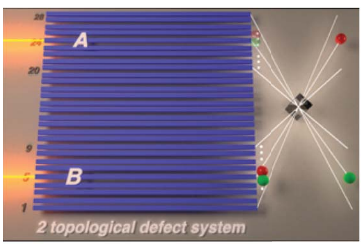


Fig. 3. Modal amplitudes and energies in the presence of lattice disorder. (**A**) The calculated amplitude squared of the topological defect mode with 0, 20, and 40% disorder. The modal amplitude remains zero in the odd waveguides for all levels of disorder. (**B**) Similar to (A) but for the trivial mode. Here, no feature is preserved. (**C** and **D**) Mode propagation constants (k_z), equivalent to mode energies, for topological and trivial systems, respectively. The red dot is k_z of the defect mode, which remains unchanged under disorder in the topological system but changes in the nontopological system.

A



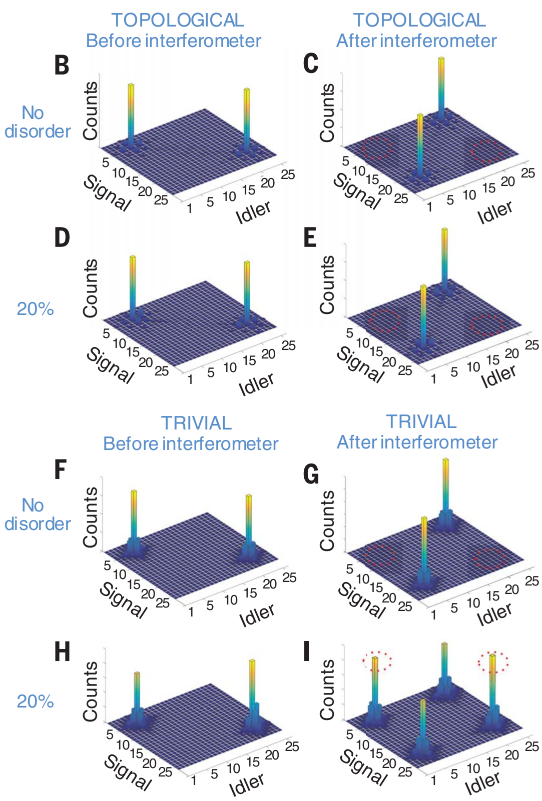


Fig. 4. Protection of entanglement in a simulated two-topological-defect system. (**A**) Nanophotonics platform with two topological defects for the generation and protection of entanglement. The output of modes *A* and *B* interfere in a beam splitter. (**B** to **E**) Simulated biphoton correlations before and after the beam splitter with 0 and 20% disorder for the two-topological-defect system. (**F** to **I**) Similar to (B) to (E) but for the two-trivial-defect system. The red circles in (I) indicate the (false) correlation peaks introduced by disorder.

of the lattice is robust against disorder. We simulated the biphoton generation and propagation with and without disorder and the interference of the defect modes A and B at the output (Fig. 4A) by using a beam splitter. This interference generates four peaks, $|A>_s|A>_i$, $|B>_s|B>_i$, $|A>_s|B>_i$, and $|B>_s|A>_i$, representing the presence of the signal and idler in defect modes A and B. At the output of the lattice but before the interferometer, we have $|A>_s|A>_i$, $|B>_s|B>_i$, corresponding to the entangled state in Fig. 4B. After the interferometer, these two peaks disappear because of destructive interference, and the peaks $|A>_s|B>_i$, $|B>_s|A>_i$ appear, experiencing constructive interference (Fig. 4C). This is similar to reverse Hong-Ou-Mandel interference, where entangled pairs of photons at the beam-splitter inputs are split and appear as one photon at each output.

In the presence of 20% disorder in the coupling constant, the propagation constants of the topological defect modes A and B, $k_{z,A}$ and $k_{z,B}$, remain unchanged, and thus the entanglement is preserved (Fig. 4, D and E). This robustness should be compared with an equivalent system of two trivial (nontopological) defects, such as the ones measured above. In the absence of disorder, our simulations show that the two peaks before (Fig. 4F) and after (Fig. 4G) the interferometer are similar to the topological case. However, in the presence of disorder, $k_{z,A}$ and $k_{z,B}$ change and the output phases are randomized, which leads to all four peaks being present in the biphoton correlation after the beam splitter (Fig. 4I). When the topological protection is absent, the entangled state takes on vastly different forms in the presence of disorder, such that on average (over multiple realizations of disorder), entanglement is lost. The concept of topology in this system, however, goes beyond making this platform more tolerant to fabrication defects. It offers a degree of freedom to generate new entangled quantum states in a multidimensional Hilbert space in a complementary metal-oxide semiconductor–compatible platform.

The results presented here provide definitive experimental evidence of the protection that the underlying topology of the structure can provide to the spatial features of states living in high-dimensional Hilbert spaces. We have shown how the topological nanophotonic platform can be used to enable scalable entangled quantum information systems robust to fabrication disorder. The multidimensionality of the wave function highlights new directions in topological physics, as new variables become relevant and can be affected by topology. This is also a versatile platform to investigate phenomena combining topological edge modes with nonlinear optics, with the ability to generate and manipulate quantum correlations. Lastly, the topological protection of the biphoton states demonstrated here for the 1D SSH lattice serves as an experimental proof of concept for any other topological photonic quantum system, including 2D lattices such as those described in (*2*–*4*), which should exhibit topologically protected transport around the perimeter of the lattice, with protection against any disorder that does not break time-reversal symmetry. These findings lead to many new avenues in conjunction with boson sampling (*25*, *26*), quantum simulations (*27*, *28*), quantum computing (*9*), and a variety of exciting possibilities related to the evolution of quantum states in photonic structures (*29*).

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/362/6414/568/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S3
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Movies S1 and S2

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Protecting entangled pairs

Photons are readily generated, are fast and can travel vast distances, and are ideal carriers of quantum information. Practical applications, such as quantum computing, will likely be based on an optical-chip platform and require the manipulation of multiphoton states. The inevitable scattering and loss of photons in such a platform would be detrimental for application. Blanco-Redondo *et al.* show how a specially designed optical circuit based on topology can offer protection for propagating biphoton states. The results show that topological design consideration could provide the desired robustness required for quantum optical circuitry.

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