Topologically-Protected Single-Photon Sources with Topological Slow Light Photonic Crystal Waveguides

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Slow light waveguides are advantageous for implementing high-performance single-photon sources required for scalable operation of integrated quantum photonic circuits (IQPCs), though such waveguides are known to suffer from propagation loss due to backscattering. A way to overcome the drawback is to use topological photonics, in which robust waveguiding in topologically-protected optical modes has recently been demonstrated. Here, single-photon sources are reported using single quantum dots (QDs) embedded in topological slow light waveguides based on valley photonic crystals. Purcell-enhanced single-photon emission is demonstrated from a QD into a topological slow light mode with a group index over 20 and its robust propagation even under the presence of sharp bends. These results pave the way for the realization of robust and high-performance single-photon sources indispensable for IQPCs.

1. Introduction

High-performance single-photon sources are recognized as a key element for scalable operation of integrated quantum photonic circuits (IQPCs) based on discrete variables. To implement such a quantum light source, it is essential to incorporate solid-state quantum emitters, such as semiconductor quantum dots (QDs), into photonic nanostructures for efficiently funneling their radiation into IQPCs. Among various platforms, slow light waveguides in photonic crystals (PhCs) are particularly attractive. The slow light modes largely enhance light–matter interactions, which accelerate the emission of quantum emitters into the modes via the Purcell effect and thereby boost the performance of the single-photon source. In addition, the photonic bandgap effect in the PhCs strongly suppresses unwanted radiation into nonguided modes and thus further improves the source efficiency. Importantly, the slow light waveguides in PhCs have also been employed for studying nonlinear optics at single-photon levels and chiral light–matter interactions. However, PhC waveguides are known to often suffer from non-negligible propagation loss due to backscattering, which becomes more prominent when approaching the slow light regime. Since the backscattering is induced by structural imperfections, which are inevitably accompanied with nanofabrication processes, a rather different approach might be necessary to solve the issue.

One possible strategy for mitigating the scattering loss in the slow light PhC waveguides is the use of topological photonics. Topologically-protected modes have been demonstrated to exhibit robust waveguiding immune to disorders. Among reported topological waveguides, those based on valley photonic crystals (VPhCs) have attracted much attention, since they can be realized using simple dielectric slabs. Therefore, VPhCs can be naturally implemented in conventional photonic integrated circuit platforms and hence can be combined with QDs. So far, the coupling of single QDs to topological waveguides have been demonstrated. However, all these demonstrations utilized fast light modes that naturally emerge in topological bandgaps. In contrast to slow light modes, such fast light modes could exhibit only moderate enhancement in light–matter interactions.

In this article, we report single-photon sources based on single QDs embedded in topological slow light VPhC waveguides. Single QDs coupled to the topological slow light waveguide exhibit large Purcell enhancement of spontaneous emission rate up to a factor of ≈12. The generated single-photons robustly propagate through the slow light mode with a high group index of over 20 even with sharp waveguide bends. These results pave the way
which utilize complex materials or structures,\,[20–26] the VPhC
pared to previously reported topological slow light waveguides,
paredtoconventionalPhCwaveguides.\,[14,27]
significantly mitigate propagation loss and backscattering com-

Figure 1c shows a bearded interface formed using the two
VPhCs with large and small triangles with \( L_1 = 1.3a/\sqrt{3}\) and \( L_2 = 0.7a/\sqrt{3}\) (\( a\) is lattice constant). Figure 1d shows a calculated
band diagram of the VPhC waveguide with the bearded interface
by the 3D plane wave expansion (3D PWE) method. We consider
a slab with the refractive index of \( n = 3.4\) and thickness of \( d = 130\) nm. We set the lattice constant \( a\) to be 310 nm. In stark con-
trast to conventional zigzag interfaces with fast light modes,\,[29]
the bearded interface used in this work supports two different
slow light modes in the bandgap. They are degenerate at the Bril-
loin zone (BZ) edge due to glide plane symmetry across the
interface.\,[29] The lower frequency mode corresponds to a topo-
logical edge state (light green curve), while the higher frequency
one originates from a trivial state (black curve). The detailed dis-
cussion of the origin of these modes can be found in our previous
work.\,[18,19] Figure 1d shows the corresponding group indices of
the in-gap modes, showing high \( n_g\) over 100 near the BZ edge.

3. Sample Fabrication and Basic Optical
Characterization

We fabricated straight and Z-shaped topological slow light wave-
guides into a 130-nm-thick GaAs slab by standard semiconductor
processes based on electron beam lithography and reactive ion
inght. Air-bridge structures were finally formed by removing
a 1-\( \mu \)m-thick Al\(_{0.7}\)Ga\(_{0.3}\)As sacrificial layer under the slab using
hydrofluoric acid. A single layer of InAs QDs with a low areal
density of \( \approx 10^6 \) cm\(^{-2}\) is contained in the middle of the slab. Pho-
toluminescence (PL) peaks of individual QDs were observed in a
spectral range from 900 to 1000 nm. Figure 2a,b shows scanning
electron microscope (SEM) images of one of the fabricated 52a-
long straight and Z-shaped waveguides. Both ends of the wave-
guides are terminated with grating ports for light out-coupling to
free space. We slightly shifted the position of the grating ports
from the center of the waveguides to control the reflectance of
light at the waveguide ends. For high reflective cases, we can
observe Fabry–Pérot (FP) fringes in transmission spectra, enabling
the extraction of \( n_g\) of the waveguide modes.\,[29]

First, we performed PL measurements to characterize the fab-
ricated waveguides. The sample was placed in a liquid helium
cryostat and pumped using a 775 nm pulse laser with a repeti-
tion rate of 80 MHz and a pulse duration of 1 ps. In order to
clearly observe FP fringes in PL spectra, the sample temperature
was kept at 60 K where confusing spectral peaks from single QDs
are largely suppressed. We used a 50x objective lens to focus the
laser light onto one grating port so as to excite the QDs embedded
therein. The PL emission from the QDs was used as an internal
light probe for measuring transmission spectra\,[9] and was col-
clected from the other grating port via the same objective lens for
analyzing with a spectrometer equipped with a Si CCD camera.
Figure 2c shows the PL spectra of both straight and Z-shaped
waveguides taken at a high average excitation power of 30 \( \mu \)W.
We observed sharp peaks in the PL spectrum originating from FP
resonances sustained by reflection at both waveguide ends. The
FP fringes were observed from 910 to 1000 nm in the straight
waveguide, while we did not see clear FP fringes in the shorter
wavelength region below \( \approx 934 \) nm in the Z-shaped waveguide.
The shorter wavelength band is the trivial mode with a high
scattering loss when transmitting through the sharp waveguide bends. On the other hand, the longer wavelength band above 934 nm corresponds to the topological mode and thus can support robust light waveguiding even with the 120° bends. These interpretations for the observations are consistent with our previous results of numerical and experimental investigations on the VPhC slow light waveguides. From the observed FP fringes, $n_g$ of both modes were estimated for the straight and Z-shaped waveguides (see Section S1, Supporting Information), and were plotted in Figure 2d. The measured $n_g$ for both waveguides show similar values in the topological band and rapidly increase near the wavelength of $\approx$934 nm. The highest $n_g$ extracted from the measured FP fringes for the straight and Z-shaped waveguide are $\approx$40 in the topological band. It is noted that we obtained higher $n_g$ of up to $\approx$56 for topological modes in a different waveguide which exhibits a clearer FP spectrum particularly near its high $n_g$ region. These results demonstrate robust propagation of light emitted from QDs through topological slow light waveguides even under the presence of the sharp bends. The observed contrast between trivial and topological modes in PL spectra also highlights the impact of the topological protection in slow light waveguides. For the estimation of the BZ edge position of the fabricated topological waveguides, we fitted the measured $n_g$ for 11 different samples with the same design using theoretical curves computed by the 3D PWE method (solid lines in Figure 2d). From the fitting, we deduced the wavelength of the BZ edge to be 934.0 ± 0.45 nm. The fitting curve was plotted in Figure 2d and shows a good agreement with the measured $n_g$. Hereafter, using the extracted $n_g$ curve, we estimate $n_g$ of the waveguide mode only from its wavelength of operation, after taking into account a wavelength redshift of $\approx$0.8 nm from 6.5 to 60K.

4. Observation of Slow Light Enhanced Radiative Decay of Single QDs

Next, we optically investigated single QDs in straight waveguides at 6.5K. For inspecting each single QD, we excited a QD in a waveguide by impinging 775 nm laser pulses and measured its PL emission guided through the waveguide modes from the right-side output port one by one, as depicted in the inset of Figure 3a. Figure 3a shows an emission spectrum of a QD (labeled as QD-A) emitting at 936.17 nm. From the theoretical curve in Figure 2d, the emission wavelength can be translated into a high $n_g$ of 24 ± 3 in the topological waveguide band. We also performed time-resolved PL measurements on QD-A using a time-correlated single-photon counting system with a superconducting single-photon detector (SSPD). The measured system time resolution was 33 ps, which is dictated by the timing jitter of our SSDP. We selectively measured the QD emission using a spectrometer as a band-pass filter (bandwidth $\approx$180 μeV). Figure 3b shows the time-resolved PL spectra measured for the QD-A (red) and a QD in an unpatterned area on the same chip (black). We fitted the measured PL curves using a single exponential function convolved with a peak function reflecting the measured system time resolution. The QD lifetime for QD-A was measured to be 0.6 ns, which is $\approx$2 times shorter than the average lifetime for 10 QDs measured in unpatterned area ($\approx$1.2 ns). The observed lifetime reduction suggests that the emission rate of QD-A was
Figure 3. a) PL spectrum for a QD (labeled as QD-A) in a straight waveguide. Inset shows the SEM image of a waveguide, overlaid with the positions of the laser excitation (cross marker) and QD emission detection (circle marker). b) Measured PL decay curves of QD-A (red) and a bulk QD (black). The blue and green lines are fitting curves. c) Normalized decay rates measured for 49 QDs. The black (light green) solid line indicates calculated decay rates for the electric field ($F_p$) of trivial (topological) modes. d) Distribution of calculated Purcell factor ($F_p$) when a slow light mode with $n_g \approx 25$ is coupled to linear dipoles ($d_x$ or $d_y$) and circularly polarized dipoles ($d_+\text{ or } d_-$).

enhanced by the Purcell effect in the topological slow light mode. Note that we also confirmed single-photon emission from the QD-A by intensity autocorrelation measurements.

We also investigated wavelength dependence of QD spontaneous emission rates for 49 different QDs in 10 different straight waveguides. Figure 3c shows the summary of the QD emission rates normalized by that of bulk QDs. Overall, the measured decay rates tend to increase as approaching the BZ edge of $\approx 934$ nm, which is consistent with the trend of measured $n_g$. We observed the highest enhancement of $\approx 12$ in the topological band (see Section S2, Supporting Information). We compared the measured decay rate with a theoretical model (see Section S3, Supporting Information), assuming the QD dipole moment is coupled to the $x$ component of the electric field dominant in the dielectric region (see Figure 3d). The theoretical decay rate was overlaid in Figure 3c with the same offset in the horizontal axis as that used for the theoretical curves in Figure 2d. The experimental data points with high decays agree well with the theoretical curves, further confirming the Purcell-enhanced emission of the QDs in the VPhC slow light modes. Meanwhile, many data points in Figure 3c were found below the theoretical curves. This observation indicates that the majority of the investigated QDs are located away from the field maxima of the waveguide modes and/or their polarization mismatched with those of the optical modes. This is quite common when using randomly-formed self-assembled QDs.

Finally, we investigate single-photon generation from a single QD in a Z-shaped waveguide. As depicted in Figure 4a, we measured QD emission from the grating port located at the top left, while pumping a QD in the waveguide located far away from the grating port. Thus, we only detect PL signals that efficiently passed through the sharp corners. Figure 4b shows a PL spectrum of a QD (labeled QD-B) emitting at 936.03 nm (corresponding to $n_g \approx 25 \pm 3$). Figure 4c shows a measured time-resolved PL spectrum for QD-B, showing a large reduction in PL lifetime due to the Purcell effect by coupling to the slow light mode. By fitting...
Figure 4. SEM image of a Z-shaped waveguide. a) The cross and circle makers indicate the positions of the excitation and detection. b) PL spectrum of a QD (labeled as QD-B) measured at an averaged excitation power of 100 nW. c) Time-resolved PL spectra measured for QD-B (red) and a bulk QD (black). d) Measured second-order correlation function of QD-B. 

In order to confirm the single-photon nature of the QD emission, we performed intensity autocorrelation measurements on QD-B using a Hanbury Brown–Twiss setup equipped with two SSPDs. Figure 4d shows a measured second-order correlation function, $g^{(2)}(t)$, measured using the output port. We observed a clear antibunching behavior with $g^{(2)}(0) = 0.26$. The nonzero value at $t = 0$ could be attributed to background emission from the FP fringes supplied by other QDs inside the waveguide. These results demonstrate Purcell-enhanced single-photon generation from a single QD in a topological slow light waveguide and its efficient propagation even under the presence of sharp bends.

5. Conclusion

In summary, we have demonstrated QD-based single-photon sources embedded in topological slow light VPhC waveguides. We observed a large reduction in PL lifetime of a single QD by a factor of up to $\approx 12$ due to the Purcell effect in the topological slow light modes. In the slow light regime with a high $n_\gamma$ of $\approx 25$, we demonstrated Purcell-enhanced single-photon generation from a QD and its robust propagation even under the presence of sharp waveguide bends. These results will be of importance for the development of topologically-protected IQPCs with robust and high-performance single-photon sources.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The authors thank Prof. M. Lončar, M. Nishioka, Dr. S. Ishida, T. Yamaguchi, and Dr. W. Lin for their technical support and helpful discussions. This work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (15H05700); KAKENHI (17H06138, 18J13565, 19K05300); JST-CREST (JPMJCR19T1); Asahi Glass Foundation; New Energy and Industrial Technology Development Organization (NEDO); JSPS Overseas Research Fellowships (202160592).

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.
Keywords
photonic crystals, quantum dots, single-photon sources, topological photonics