Single-Photon Nonreciprocity with an Integrated Magneto-Optical Isolator

Shang-Yu Ren, Wei Yan, Lan-Tian Feng, Yang Chen, Yun-Kun Wu, Xiao-Zhuo Qi, Xiao-Jing Liu, Yu-Jie Cheng, Bo-Yu Xu, Long-Jiang Deng, Guang-Can Guo, Lei Bi,* and Xi-Feng Ren*

Nonreciprocal photonic devices are essential components of classical optical information processing. It is interesting and important to investigate their feasibility in the quantum world. In this work, a single-photon non-reciprocal dynamical transmission experiment has been performed with an on-chip silicon nitride (SiN)-based magneto-optical (MO) isolator. The measured isolation ratio for single photons achieved is 12.33 dB, consistent with the result of the classical test, which proves the functionality of our on-chip isolator. The quantum coherence of the passing single photons is further verified using high-visibility quantum interference. This work will promote on-chip nonreciprocal photonic devices within the integrated quantum circuits and help introduce novel phenomena in quantum information processes.

1. Introduction

Photonic integrated circuits (PICs) possess inherent advantages over space and fiber optics owing to their small footprint, scalability, programmability, and stability against the environment.[1–4] These advantages also become quite important for large-scale quantum information processing.[5–7] As quantum information processing becomes much more complicated, requiring larger number of optical components,[8] the demand for quantum photonic integrated circuits (QPICs) will significantly increase. Although many photonic elements, such as phase shifters, directional couplers, and even high-Q cavities, have already been integrated on QPICs, till date, the nonreciprocal optical isolator has not been used for on-chip quantum circuits.

Nonreciprocal photonic devices, which break the time-reversal symmetry, play key roles in optical information processing. They work as essential isolators and circulators to protect the laser source and eliminate the Fabry–Perot effect. In quantum information processing, non-reciprocal devices can be used to explore quantum transfer in optical systems.[9] Further, by designing networks for nonreciprocal devices, it is possible to construct directional, quantum-limited amplifiers.[10]

Many nonreciprocal devices have been reported in bulk structures,[11,12] and nanostructures[13,14] and are widely used in commercial optical fibers. Recently, integrated optical isolators based on magneto-optical effects,[15–18] nonlinear photonic effects[19–21] and spatio-temporal modulation[22–24] have also been reported. Among them, silicon-on-insulator (SOI) and SiN-based MO isolators are particularly promising owing to their wide optical isolation bandwidth, low insertion loss, and passive operation capability.[16,17] This provides us an opportunity to integrate the isolator onto a quantum chip. Moreover, the permittivity tensor of the MO materials allows a linear relationship between the polarization P(\(\omega\)) and the incident electric field E(\(\omega\)). While it should be noted that the function of the classical device may not be valid in quantum world. For example, a plasmonic beam splitter can cause unusual anti-coalescence Hong–Ou–Mandel (HOM) interference curve, which is totally different from the general cases.[25] Thus, it is necessary and important to test the quantum coherence preservation property of the isolator before we find its applications in quantum photonics.

Here, by taking a single-photon-level transmission test, we prove the functionality of an on-chip magneto-optical isolator with an isolation ratio of 12.33 dB at 1550 nm wavelength. Further, the HOM interference experiments with high visibility also indicate that the coherence of transmitted photons can be well preserved, which excluded the destruction of mode crosstalk, filter property of isolator and other potential mechanisms in nonlinear materials on coherence. These results reveal the potential utility of nonreciprocal photonic devices in QPICs.
Figure 1. a) Scanning electron microscopy (SEM) image of the cross-section of a fabricated MO/SiN waveguide in the SiN optical isolator. The white arrow indicates the direction of the external magnetic field. b) Classically measured transmission spectra of the TM mode SiN optical isolator, together with a reference SiN waveguide (TM mode) on the same chip. At 1544 nm wavelength, the maximum isolation ratio reached 25 dB, with an insertion loss of 2.3 dB. The 10 dB isolation bandwidth of this device was 13 nm, and across the entire 10 dB isolation bandwidth, the device experienced an insertion loss increasing to 3 dB. The interference ripples in the transmission spectrum are due to Fabry–Pérot interferences between the coupling fiber and the waveguide facet, which can be further minimized by optimizing spot-size converters.[17]

2.2. Experiment of Single-Photon Nonreciprocal Transmission

A schematic of the experimental setup for the quantum test is shown in Figure 2. A continuous-wave laser centered at 775 nm was used as the pump (Topical DL Pro) to generate photon pairs at 1550 nm through a spontaneous parametric down-conversion (SPDC) process in a 3 cm long potassium titanyl phosphate (PPKTP) crystal. The temperature of the crystal was controlled to achieve frequency-degenerate photon pairs and the wavelength was fixed via a wavelength meter (Angstrom WS/6 IR; HighFinesse). The generated photon pairs had orthogonal polarizations; thus, they were divided into two paths by a polarization beam splitter (PBS) and then coupled into SM-28 single-mode fibers. Fiber lenses (Chuxing Optical Fiber Application Technologies Ltd.) were used for the on-chip coupling. In our experiment, one photon of each pair was coupled into and passed through the on-chip isolator. The other photon was directly inserted into one detector and acted as a reference. Both photons were detected by superconducting nanowire single-photodetectors (SNSPDs, Scontel). The output electric signals were imported into the TCSPC system for the correlation analysis.

The core of the on-chip MO isolator is the MZI with four ports. We studied four propagation situations of the signal photons. A: From port 1 to 2, A': from port 2 to 1, B: from port 3 to 4, and B': from port 4 to 3 of the isolator. The polarization of the signal photons must be fixed by a polarization controller to excite them into a TM mode to match the working polarization of the device because only the TM mode induces NRPS under the classical test. A magnet was placed parallel to the device, producing an in-plane external magnetic field perpendicular to the propagation direction of the light. The magnitude of the generated magnetic field affects the strength of the non-reciprocal phase shift effect.

In the experiment (Figure 3a), the magnet was fixed on a self-made scaled displacement stage, which could move forward and backward to observe the influence of the magnetic field waveguide in each arm of the MZI structure was designed to be 670 μm in length, and the propagation loss of the MO/SiN waveguide was measured to be 31.7 dB cm⁻¹ as mentioned in ref. [16]. The propagation loss of the SiN waveguide was measured to be 0.5 dB cm⁻¹. The Faraday rotation of YIG and Ce:YIG thin films was set as 500 deg cm⁻¹ and ~5900 deg cm⁻¹, respectively. The refractive index of the MO thin film was 2.3. During the classical measurement, an in-plane magnetic field (1000 Gs) was applied perpendicular to the propagation direction of light to saturate the magnetization of the MO thin films. Figure 1(b) shows the transmission spectra of the TM mode SiN optical isolator, together with a reference SiN waveguide (TM mode) on the same chip. At 1544 nm wavelength, the maximum isolation ratio reached 25 dB, with an insertion loss of 2.3 dB. The 10 dB isolation bandwidth of this device was 13 nm, and across the entire 10 dB isolation bandwidth, the device experienced an insertion loss increasing to 3 dB. The interference ripples in the transmission spectrum are due to Fabry–Pérot interferences between the coupling fiber and the waveguide facet, which can be further minimized by optimizing spot-size converters.[17]

2. Experimental Section

2.1. Fabrication and Classical Characterization of the Magneto-Optical Isolator

This process was begun by fabricating a SiN transverse magnetic (TM) MO isolator based on the Mach–Zehnder interferometer (MZI) structure,[17,26,27] using standard silicon photonics foundry processes for fabricating SiN PICs and pulsed laser deposition (PLD) for MO thin films. 3 dB directional couplers were introduced at both ends of the MZI. The reciprocal and nonreciprocal phase shifters on both arms of the MZI allowed a 0 (±π) phase difference for the forward (backward) propagating light, thus achieving isolation. The nonreciprocal phase shifter was an MO/SiN waveguide with Ce:YIG/YIG thin films on top of the SiN waveguide, providing a non-reciprocal phase shift (NRPS) for TM-polarized light.[18,28] Figure 1(a) shows the cross-sectional scanning electron microscope (SEM) image of the fabricated MO/SiN waveguide in the SiN device. The structure consisted of a planar Ce:YIG (150 nm)/YIG (50 nm) thin-film stack deposited on the SiN channel waveguide, where only TM polarized light experiences NRPS with an in-plane external magnetic field H (1000 Gs) applied perpendicular to the propagation direction of light to saturate the magnetization of the MO thin films.[29] The MO/SiN waveguide in each arm of the MZI structure was designed to be 670 μm in length, and the propagation loss of the MO/SiN waveguide was measured to be 31.7 dB cm⁻¹ as mentioned in ref. [16]. The propagation loss of the SiN waveguide was measured to be 0.5 dB cm⁻¹. The Faraday rotation of YIG and Ce:YIG thin films was set as 500 deg cm⁻¹ and ~5900 deg cm⁻¹, respectively. The refractive index of the MO thin film was 2.3. During the classical measurement, an in-plane magnetic field (1000 Gs) was applied perpendicular to the propagation direction of light to saturate the magnetization of the MO thin films. Figure 1(b) shows the transmission spectra of the TM mode SiN optical isolator, together with a reference SiN waveguide (TM mode) on the same chip. At 1544 nm wavelength, the maximum isolation ratio reached 25 dB, with an insertion loss of 2.3 dB. The 10 dB isolation bandwidth of this device was 13 nm, and across the entire 10 dB isolation bandwidth, the device experienced an insertion loss increasing to 3 dB. The interference ripples in the transmission spectrum are due to Fabry–Pérot interferences between the coupling fiber and the waveguide facet, which can be further minimized by optimizing spot-size converters.[17]
Figure 2. Schematic of the experimental setup and non-reciprocal optical resonator structure. a) The experimental setup. HWP: half-wave plate, used to adjust the input polarization; DM: dichroic mirror to filter out the pump laser; PPKTP: nonlinear crystal, used to generate frequency-degraded photon pairs; PBS: polarization beam splitter, used to split photons pairs into different paths. LPF: long-pass filter to filter out the residual pump laser; SNSPDs: superconducting nanowire single-photon detectors for coincidence measurement. PC: the polarization controller is also used to maximize the coupling efficiency. b) Schematic of the non-reciprocal optical resonator structure.

Figure 3. a) Experimental setup of single-photon nonreciprocal transmission test. The magnet approaches and then moves away from the chip to observe the variation of coincidence counts with the strength of magnetic field. b) The measured coincidence. Blue dots: for Case B, signal photons pass from port 3 to port 4. Red dots: for Case B’, signal photons pass from port 4 to port 3. Negative abscissa axis indicates the process of the magnet moving away from the chip. The curves only show the changing trend of the coincidence counts. Error bar comes from the Poisson statistical distribution. The initial magnetization is opposite to the magnetic field direction of the moving magnet. Finally, the magnetic field in chip was initialized again in the grey zone.

magnitude on single-photon transmission. The signal photons passed through the chip and were received by Channel I of the SNSPDs. The idler photons were directly received by Channel II, and the coincidences between the two channels were recorded. Figure 3(b) shows the experimental results. The horizontal axis coordinates denote the distance between the magnet and the end face of the chip. The blue dots indicate the measured coincidence counts for Case B. The red dots denote the case in which we reversed the direction of propagation of the photons, that is, Case B’.

At the beginning of the test, the magnet was placed 26 mm away from the saturation magnetization point. In the description, this position was denoted as –26 mm. This distance guaranteed that the magnetic field had no influence on the MO materials. Focusing on the red curve (Case B’), when the magnet is moving from –26 to –10 mm, the transmission is steady because the external magnetic field is still too weak to induce an obvious non-reciprocal phase shift effect. When the distance between the magnet and the device reduces sufficiently, the number of transmitted photons decreases quickly. At the saturation magnetization point (0 distance), the coincidence reaches a minimum. When the magnet is pulled back, the coincidence increases but is not as fast because of the magnetic remanence magnetization in the MO materials. For the blue curve (Case B), the phenomenon is the opposite. These two curves present nonreciprocal characteristics. It is worth noting that when we applied a magnetic field initialization operation with the direction of the magnetic field opposite to the direction of saturation magnetization in MO materials and the magnet was pulled back to 23 mm away from the saturation magnetization point, the coincidence rises or falls sharply and returns to the initial value (shown in the gray zone in Figure 3b). The classical transmittance at 1550 nm wavelength that consists of the above single-photon test method can be found in the Supporting Information.

Classical and single-photon tests for Cases A and A’ were also conducted (see Supporting Information) and the results were consistent with those in Case B and B’. We additionally measured the coincidence of photons passing through a straight SiN waveguide as a comparison with the isolator (also see Supporting Information). The result proves that the trend of coincidence is not caused by the magnet’s effect on the coupling. The maximum isolation ratio for the single photons was approximately 12.33 dB for B’. This is lower than that in classical characterization at 1544 nm wavelength, because our source needed to be fixed at 1550 nm wavelength. Even though it is not the best working wavelength of the isolator, the result was basically consistent with the classical one in Section 2.1 at 1550 nm wavelength. Thus, the single-photon transmission characteristics have been verified. However, it is not sufficient to guarantee practical utility in QPICs yet.
The form is reduced to \(-FBS\). Only when photons are indistinguishable, the interference matrix of the FBS:

\[
\begin{pmatrix}
1 & 1 \\
1 & 1
\end{pmatrix}
\]

was imported into the FBS at ports a and b. A 50/50 fiber beam splitter (FBS) was used to perform the interference (Figure 4a). A single photon passed through the chip and the reference photon was imported into the FBS at ports a and b.

The interference process can be derived using the transformation matrix of the FBS:

\[
a^\dagger b^\dagger |0 \rangle \rightarrow_{FBS} \frac{1}{2} (c^\dagger + d^\dagger)(c^\dagger - d^\dagger) |0 \rangle \\
= \frac{1}{2} (c^\dagger + d^\dagger)(c^\dagger - d^\dagger) |0 \rangle
\]

which means the photon pairs can be detected either at c or d port of FBS with one-half probability respectively. Therefore, if two indistinguishable photons arrive FBS simultaneously, they will always go together and there will be no coincidence between ports c and d.

Without loss of generality, it was assumed that the spectrum transmitted by the interference filter is Gaussian. The coincidence count of HOM interference can be expressed as 

\[
C \propto 1 - e^{-\Delta \tau^2/2w^2},
\]

where \(\Delta \tau\) refers to the time delay of two photons on the FBS and \(2w\) is the spectral width of the photons. The visibility \((V)\) of the HOM interference is defined as 

\[
V = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}}},
\]

where \(C_{\text{max}}\) is the maximum coincidence and \(C_{\text{min}}\) is the minimum coincidence. When \(C_{\text{min}} = 0\), the perfect coincidence visibility is \(V = 1\), which indicates that the two photons are identical.

In the experiment, the arrival time of the photon pair was synchronized by adjusting the path-length difference between them. The time delay was introduced and controlled by a group of two fiber port collimators. The polarization controllers were used to ensure that the photons had the same polarization before interfering in the FBS. Before testing on the non-reciprocal isolator, we characterized our SPDC source. The HOM interference visibility was up to 95.61\(\pm\)0.94\%. The experimentally measured interference visibility in Case B was 91.16\(\pm\)1.05\%, which indicates that the photons maintain their coherence after the function of the MO isolator. This result proved that the quantum property of the single photons transmitted through the isolator was not influenced. HOM interference tests for the source, waveguide and other cases have been discussed in the Supporting Information.

### 2.3. HOM Experiment on the Magneto-Optical Nonreciprocal Isolator

To prove the validity of the device for QPIcs, it was necessary to verify whether the coherence of the transmitted photons can be preserved, in other words, whether the quantum property of the single photon is influenced in this process. To achieve this, the HOM interference was implemented, which can tell the indistinguishability of two photons. Experimentally, a 50/50 fiber beam splitter (FBS) was used to perform the interference (Figure 4a). A single photon passed through the chip and the reference photon was imported into the FBS at ports a and b.

The process can be derived using the transformation matrix of the FBS:

\[
a^\dagger b^\dagger |0 \rangle \rightarrow_{FBS} \frac{1}{2} (c^\dagger + d^\dagger)(c^\dagger - d^\dagger) |0 \rangle \\
= \frac{1}{2} (c^\dagger + d^\dagger)(c^\dagger - d^\dagger) |0 \rangle
\]

which means the photon pairs can be detected either at c or d port of FBS with one-half probability respectively. Therefore, if two indistinguishable photons arrive FBS simultaneously, they will always go together and there will be no coincidence between ports c and d.

Without loss of generality, it was assumed that the spectrum transmitted by the interference filter is Gaussian. The coincidence count of HOM interference can be expressed as 

\[
C \propto 1 - e^{-\Delta \tau^2/2w^2},
\]

where \(\Delta \tau\) refers to the time delay of two photons on the FBS and \(2w\) is the spectral width of the photons. The visibility \((V)\) of the HOM interference is defined as 

\[
V = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}}},
\]

where \(C_{\text{max}}\) is the maximum coincidence and \(C_{\text{min}}\) is the minimum coincidence. When \(C_{\text{min}} = 0\), the perfect coincidence visibility is \(V = 1\), which indicates that the two photons are identical.

In the experiment, the arrival time of the photon pair was synchronized by adjusting the path-length difference between them. The time delay was introduced and controlled by a group of two fiber port collimators. The polarization controllers were used to ensure that the photons had the same polarization before interfering in the FBS. Before testing on the non-reciprocal isolator, we characterized our SPDC source. The HOM interference visibility was up to 95.61\(\pm\)0.94\%. The experimentally measured interference visibility in Case B was 91.16\(\pm\)1.05\%, which indicates that the photons maintain their coherence after the function of the MO isolator. This result proved that the quantum property of the single photons transmitted through the isolator was not influenced. HOM interference tests for the source, waveguide and other cases have been discussed in the Supporting Information.

### 3. Discussion

In this work, we did not use any additional filters to manipulate the bandwidth of SPDC photon pair because PPKTP crystal itself played a filtering role. However, the bandwidth of quasi-phase matching in PPKTP crystal is still over 100 GHz. That means although the single-photon isolation is consistent with the result of the classical test, it is actually determined by the combined effect of the photons around 1550 nm. As described above, 3 dB directional couplers were introduced to the characterized device at both ends of the MZI structure, forming a four-port optical circulator. Therefore, the device we showed above can also achieve the function of optical circulation. The classical characterization of the optical circulator can be found in [16]. Although the device worked under the TM polarization which mismatched most integrated photonic devices designed for the TE polarization, TE-TM polarization rotators (PRs) can be introduced at both ends of the TM devices for constructing optical isolators and circulators operating for the TE polarization.[18] To minimize the insertion loss, polarization rotators based on the mode evolution mechanism to rotate the fundamental TE mode into the fundamental TM mode have been practical realized.[30] There is also an issue that cannot be ignored on the edge coupling loss during the test, both classically and quantumly. The high fiber-to-chip test loss is mainly caused by the high edge coupling loss, which was over 5 dB for each end. It can be further optimized by designing trident spot-size converter (SSC) combining three misplaced tapers or other high-efficiency couplers with air trenches.[12]

### 4. Conclusion

Our experiment proved unambiguously that the fabricated on-chip isolator works well at the single-photon level. In addition,
the quantum properties of photons passing through the device are well maintained. Our work shows the potential of the integrated non-reciprocal device as an on-chip isolator and for its use in quantum algorithms and quantum computing circuits. For example, it can be integrated with on-chip lasers\cite{33} and other photonic components such as filters\cite{34,35} photon sources\cite{36} and quantum circuits. It can serve as a feasible photonic isolator, and join and support the full on-chip generation of arbitrary quantum states,\cite{37} teleportation\cite{38} and quantum computation.\cite{39}

Supporting Information

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

Acknowledgements

S.-Y. R., W. Y. and L.-T. F. contributed equally to this work. The work was supported by National Natural Science Foundation of China (NSFC) (Grant Nos. 61590932, 11774333, 62061160487, 12004373, 51972044, 52021001), the Anhui Initiative in Quantum Information Technologies (Grant No. AHY130300), the Fundamental Research Funds for the Central Universities. This work was partially carried out at the USTC Center for Micro and Nanoscale Research and Fabrication.

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

integrated optics, magneto-optics, nonreciprocal, quantum optics

Received: October 20, 2021
Revised: January 28, 2022
Published online: March 6, 2022

[1] M. Zhang, C. Wang, Y. Hu, A. Shams-Ansari, T. Ren, S. Fan, M. Lončar, Nat. Photonics 2018, 13, 36.
[2] M. Li, H. Liang, R. Luo, Y. He, J. Ling, Q. Lin, Optica 2019, 6, 860.
[3] B. Machielse, S. Bogdanovic, S. Meesala, S. Gauthier, M. J. Burek, G. Joe, M. Chalupnik, Y. I. Sohn, L. Shao, S. Maity, M. D. Lukin, M. Lončar, Phys. Rev. X 2019, 9, 031022.
[4] L. Zhang, L. Jie, M. Zhang, Y. Wang, Y. Xie, Y. Shi, D. Dai, Photonics Research 2020, 8, 684.
[5] M. Reck, A. Zeilinger, H. J. Bernstein, P. Bertani, Phys. Rev. Lett. 1994, 73, 58.
[6] A. Politi, J. C. F. Matthews, L. O’Brien, Science 2009, 325, 1221.
[7] L.-T. Feng, M. Zhang, Z.-Y. Zhou, M. Li, X. Xiong, L. Yu, B. S. Shi, G. P. Guo, D.-X. Dai, X.-F. Ren, G.-C. Guo, Nat. Commun. 2016, 7, 11985.
[8] H. S. Zhong, H. Wang, Y. H. Deng, M. C. Chen, L. C. Peng, Y. H. Luo, J. Qin, D. Wu, X. Ding, Y. Hu, P. Hu, X. Y. Yang, W. J. Zhang, H. Li, Y. Li, X. Jiang, L. Gan, C. Yang, L. You, Z. Wang, L. Li, N. L. Liu, C. Y. Lu, J. W. Pan, Science 2020, 370, 1460.
[9] E. Mascarenhas, F. Damante, S. Flannigan, L. Tagliacozzo, A. J. Daley, J. Goold, I. De Vega, Phys. Rev. B 2019, 99, 245314.
[10] A. Metelmann, A. A. Clerk, Phys. Rev. X 2015, 5, 021025.
[11] R.-Y. Zhang, Y.-W. Zhai, S.-R. Lin, Q. Zhao, W. Wen, M.-L. Ge, Sci. Rep. 2015, 5, 1.
[12] X.-X. Hu, Z.-B. Wang, P. Zhang, G.-J. Chen, Y.-L. Zhang, G. Li, X.-B. Zou, T. Zhang, H. X. Tang, C.-H. Dong, G.-C. Guo, C.-L. Zou, Nat. Commun. 2021, 12, 2389.
[13] Z. Shen, Y.-L. Zhang, Y. Chen, C.-L. Zou, Y.-F. Xiao, X.-B. Zou, F.-W. Sun, G.-C. Guo, C.-H. Dong, Nat. Photonics 2016, 10, 657.
[14] C. Z. Chai, H. Q. Zhao, H. X. Tang, G. C. Guo, C. L. Zou, H. Dong, Laser Photonics Rev. 2020, 14, 1900252.
[15] L. Bi, J. Hu, P. Jiang, D. H. Kim, C. F. Dionne, L. C. Kimerling, C. A. Ross, Nat. Photonics 2011, 5, 758.
[16] W. Yan, Y. Yang, S. Liu, Y. Zhang, S. Xia, T. Kang, W. Yang, J. Qin, L. Deng, L. Bi, Optica 2020, 7, 1555.
[17] Y. Zhang, Q. Du, C. Wang, T. Fakhrl, S. Liu, L. Deng, D. Huang, P. Pintus, J. Bowers, C. A. Ross, J. Hu, L. Bi, Optica 2019, 6, 473.
[18] P. Pintus, D. Huang, P. A. Morton, Y. Shoji, T. Mizumoto, J. E. Bowers, J. Lightwave Technol. 2019, 37, 1463.
[19] L. Fan, J. Wang, L. T. Varghese, H. Shen, B. Niu, Y. Xuan, A. M. Weiner, M. Qi, Science 2012, 333, 447.
[20] J. Wang, Y. Shi, S. Fan, Opt. Express 2020, 28, 11974.
[21] L. Ren, X. Xu, S. Zhu, L. Shi, X. Zhang, ACS Photonics 2020, 7, 2995.
[22] E. A. Kittlaeus, N. T. Otterstrom, P. Kharel, S. Gertler, P. T. Rakich, Nat. Photonics 2018, 12, 613.
[23] D. B. Sohn, S. Kim, G. Bahl, Nat. Photonics 2018, 12, 91.
[24] C. Liang, B. Liu, A.-N. Xu, X. Wen, C. Lu, K. Xia, M. K. Tey, Y.-C. Liu, L. You, Phys. Rev. Lett. 2020, 125, 123901.
[25] B. Vest, M.-C. Dheur, Eloïse Devaux, A. Baron, E. Rousseau, J.-P. Huigonin, J.-J. Greffet, G. Messin, F. Marquier, Science 2017, 356, 1373.
[26] Y. Shoji, A. Fujie, T. Mizumoto, IEEE J. Sel. Top. Quant. 2016, 22, 264.
[27] D. Huang, P. Pintus, C. Zhang, Y. Shoji, T. Mizumoto, J. E. Bowers, IEEE J. Sel. Top. Quant. 2016, 22, 271.
[28] D. Huang, P. Pintus, Y. Shoji, P. Morton, T. Mizumoto, J. E. Bowers, Opt. Lett. 2017, 42, 4901.
[29] H. Yokoi, Opt. Mater. 2008, 31, 189.
[30] Y. Yin, Z. Li, D. Dai, J. Lightwave Technol. 2017, 35, 2227.
[31] N. Hatori, T. Shimizu, M. Okano, M. Ishizaka, T. Yamamoto, Y. Urino, M. Mori, T. Nakamura, Y. Arakawa, J. Lightwave Technol. 2014, 32, 1329.
[32] X. Wang, X. Quan, M. Liu, X. Cheng, IEEE Photonics Technol. Lett. 2019, 31, 349.
[33] C. Xiang, W. Jin, J. Guo, J. D. Peters, M. J. Kennedy, J. Selvidge, P. A. Morton, J. E. Bowers, Optica 2020, 7, 20.
[34] N. C. Harris, D. Grassani, A. Simbula, M. Pant, G. Galli, T. Barbiere-Jones, M. Hochberg, D. England, B. J. Dale, C. Galland, Phys. Rev. X 2014, 4, 041047.
[35] D. Liu, M. Zhang, D. Dai, Opt. Lett. 2019, 44, 1304.
[36] H. Jin, F. M. Liu, P. Xu, J. L. Xia, M. L. Zhong, Y. Yuan, J. W. Zhou, Y. X. Gong, W. Wang, S. N. Zhu, Phys. Rev. Lett. 2014, 113, 103601.
[37] S. Paesani, Y. Ding, R. Santagati, L. Chakhmakhchyan, C. Vigilars, K. Rottwitt, L. K. Oxenløwe, J. Wang, M. G. Thompson, A. Laing, Nat. Physics 2019, 15, 925.
[38] B. J. Metcalfe, J. B. Spring, P. C. Humphreys, N. Thomas-Peter, M. Barbieri, W. S. Kolthammer, X.-M. Jin, N. K. Langford, D. Kundys, J. C. Gates, B. J. Smith, P. G. R. Smith, I. A. Walmsley, Nat. Photonics 2014, 8, 770.
[39] E. Knill, R. Laflamme, G. J. Milburn, Nature 2001, 409, 46.