On-chip transverse-mode entangled photon pair source

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Integrated entangled photon pair source is an essential resource for both fundamental investigations and practical applications of quantum information science. Currently, there have been several types of entanglement, among which the transverse-mode entanglement is becoming attractive because of its unique advantages. Here, we report an on-chip transverse-mode entangled photon pair source via the spontaneous four-wave mixing processes in a multimode silicon waveguide. Transverse-mode photon pairs are verified over multiple frequency channels within a bandwidth of \( \sim 2 \text{ THz} \), and a maximally entangled Bell state is also produced with a net fidelity of 0.96 ± 0.01. Our entangled photon pair source is the key element for quantum photonics based on transverse-mode, and also has the possibility to extend to higher-dimensional Hilbert space. Furthermore, the transverse-mode entanglement can be converted coherently to path and polarization entanglement, which paves the way to realizing highly complex quantum photonic circuits with multiple degrees of freedom.

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INTRODUCTION

Quantum photon pair sources are not only critical to advancing our fundamental understanding of quantum mechanics, but also play a key role in many applications for quantum technologies. Compared with free-space ones, integrated photon pair sources have attracted much attention owing to their compactness, scalability, and stability. For example, path or polarization entangled photon pairs were demonstrated by using the nonlinear processes in a single-mode waveguide or in a micro-ring cavity. Aside from these degrees of freedom, transverse-mode entanglement can be converted coherently to path and polarization entanglement, which paves the way to realizing highly complex quantum photonic circuits with multiple degrees of freedom.

RESULTS

Entangled photon pair source chip

As shown in Fig. 1a, the device includes three parts: part I, the mode modulator; part II, the multimode waveguide; and part III, the output analyzer. The mode modulator is used to modulate the pump power ratio for different transverse-modes, and the output state analyzer is used to export the state for measurement. The multimode waveguide is 3 mm long, with a cross-section of \( \sim 760 \times 220 \text{ nm}^2 \), so that it can support two transverse-electric (TE) modes, i.e., TE_0 and TE_1. The pump light is coupled to the device through a directional coupler, with one part being converted to TE_0, and the other to the transverse-mode TE_1 through a mode multiplexer. After nonlinear interactions in the
multimode waveguide, a mode demultiplexer is used to separate
the generated photons into different paths, which are then
coupled out using two identical grating couplers for further
measurement.

The SFWM processes in our device can be divided into three
types (see Supplementary Materials, Section 1). For Type I, the four
photons involved are in the same transverse-mode. For Type II, the
two pump photons are in the same transverse-mode, while the
signal and idler photons are in the other transverse-mode. For
Type III, the two pump photons are in different transverse-modes
(i.e., one in TE\(_0\) and the other in TE\(_1\)), and the signal and idler
photons are also in different transverse-modes. The SFWM process
of Type I is intramodal, while the SFWM processes of Type II and
Type III are intermodal. Here, the phase mismatching for the Type
II process is so large that it hardly occurs. Therefore, we focus on
Type I and Type III processes, where the signal and idler photon
pairs have four combinations of transverse-modes, i.e., \(|TE_0TE_0\rangle, |TE_0TE_1\rangle, |TE_1TE_0\rangle\) and \(|TE_1TE_1\rangle\) (Fig. 1b). We calculated the first-
order dispersions \(\beta_1\) and second-order dispersions \(\beta_2\) of the
multimode waveguide for the TE\(_0\) and TE\(_1\) modes, respectively
(Fig. 1c). The signal gain \(S\) of the generated photon pairs for those
four transverse-mode combinations is shown in Fig. 1d. All data
are normalized to the maximum value. The signal and idler
photons are time correlated, and their frequencies are equally
separated from the central pump frequency.

Photon pair source verification

According to the size of waveguide at different parts, we
measured the photon pair counts mainly came
from the multimode waveguide part (see Materials and Methods).

To ascertain the generated quantum states, we measured the
photopair coincidence for different combinations of the
frequency and transverse-mode. The experimental setup is shown
in Fig. 2a, an amplified continuous-wave (CW) laser (central
wavelength 1550.11 nm) was coupled to the device via a grating
coupler by a single-mode fiber array after passing through two
cascaded 100 GHz bandwidth pre-filters. At the output end, the
pump light was blocked by two cascaded off-chip 200 GHz
bandwidth post-filters. Two 40-channel dense-wave-division-
multiplexers (DWDMs) were used to separate the signal and idler
photons. Each channel has a 100 GHz bandwidth, such that we
can select any frequency- and transverse-mode combinations for
photopair emissions with a frequency detuning of \(\pm 2\) THz from the central
pump frequency (see Supplementary Materials, Table S3). The
generated photon pairs were finally detected by two
conducting nanowire single photon detectors (SCONTEL, dark
count rate 100 Hz, detection efficiency 85%).

We measured single photon counts in different frequency
channels, as shown in Fig. 2b, c. The differences in single photon
count arise from the different gains for the SFWM processes and the
uneven Raman scattering and losses for different DWDM
channels. To further characterize the photon source in the
multimode waveguide, we also measured the coincidence counts
for the processes of Type I (Fig. 2d, e) and Type III (Fig. 2f, g)
processes. All coincidences are the raw data without subtracting
the background and accident counts. As seen, the coincidences
for the Type I processes are almost constant but accompanied by
oscillation and the coincidences for the Type III processes
decrease as the frequency detuning increases, which agrees well
with the theoretical calculations (curves in Fig. 2d–g). The minor
discrepancy may originate from the correlation between intramo-
dal and intermodal SFWM processes and the difference in
propagation loss of different transverse-modes that we ignored in
theoretical calculation. Note that the photon pairs were
collected with a longer integral time for the Type III process due
to its lower collection efficiency.

Coincidence-to-accidental ratio (CAR) and source brightness are
two key parameters for characterizing the photon pair source. We
measured CARs for correlated photon pairs in different transverse-
mode combinations (see Supplementary Materials, Fig. S1). Intramodal (Type I) photon pairs show high CARs (generally higher than 200 for \(|TE_0TE_0\rangle\) and 100 for \(|TE_1TE_1\rangle\), while the CARs for the intermodal photon pairs (Type III) are not high (lower than 10 in most cases) because of the large phase mismatching. It is possible to obtain higher CARs by broadening the frequency spectra with a wider multimode waveguide, benefiting from a smaller difference in the first-order dispersion between signal and idler photons.

In a multimode waveguide, the lower energy density enables a better tolerance to nonlinear noise; thus, one can simultaneously achieve high brightness and CARs by simply increasing the input pump power. In the experiment, we measured the intramodal photon pair \(|TE_0TE_0\rangle \langle TE_1TE_1|\) for channel ±8 with a calculated generation rate ranging from 19 kHz (5.5 kHz) to 530 kHz (180 kHz). The CARs did not suffer severe reduction even at the highest generation rates (see Supplementary Materials, Fig. S2). It also applies for the intermodal photon pair \(|TE_0TE_1\rangle \langle TE_1TE_0|\) for channel ±14, with a calculated generation rate ranging from 2.7 kHz (2.9 kHz) to 54 kHz (53 kHz) (see Supplementary Materials, Fig. S3). These results show that the present device provides a flexible platform for quantum information processing. It is worth pointing out that our multimode photon pair source could also be used as heralded single photon sources. Second-order correlation measurements show \(g^{(2)}(0) = 0.13 \pm 0.02\) for photon pair \(|TE_0TE_0\rangle\) and \(g^{(2)}(0) = 0.19 \pm 0.06\) for photon pair \(|TE_1TE_1\rangle\), respectively. More details are provided in the Supplementary Materials (Section 3 and Fig. S4).

In fact, silicon platform has been used for photon source generation with various structures.\(^{29,30}\) A brief summary is provided in Supplementary Materials (Table S4). Compared to those single mode ones, the multimode waveguides have similar performance and could be further improved. Additionally, we also calculated the nonlinear efficiencies in a multimode waveguide as a function of the waveguide width (see Supplementary Materials, Fig. S5). For a waveguide with larger size, although the nonlinear efficiencies are decreased, a series of SFWM processes involving higher-order modes occur, and provides extra dimensions in quantum state generation.

### Entanglement verification and Bell state generation

After demonstrated the photon pair source generation, we then went further to demonstrate the generation of quantum entanglement, which lies at the heart of quantum information studies.\(^1\) As described above, the quantum state in the multimode waveguide is given as

\[
|\Phi\rangle = \frac{1}{\sqrt{1 + \delta_1^2 + \delta_2^2 + \delta_3^2}} (|TE_0TE_1\rangle + \eta_1 e^{i\delta_1}|TE_1TE_0\rangle + \eta_2 e^{i\delta_2}|TE_0TE_1\rangle + \eta_3 e^{i\delta_3}|TE_1TE_0\rangle),
\]

where \(\eta_1, \eta_2, \eta_3\) are relative proportions of different components; \(\delta_1, \delta_2, \delta_3\) are the phase differences, which come from the mode dispersions in the multimode waveguide. By using a two-dimensional (2D) grating coupler,\(^{32,33}\) the transverse-mode entangled state is coherently converted into the polarization entangled state, which is expressed as

\[
|\Phi\rangle = \frac{1}{\sqrt{1 + \delta_1^2 + \delta_2^2 + \delta_3^2}} (|HH\rangle + \eta_1 e^{i\delta_1}|HV\rangle + \eta_2 e^{i\delta_2}|VH\rangle + \eta_3 e^{i\delta_3}|VV\rangle).
\]

According to Figs. 1d and 2d–g, when the frequencies of the signal and idler photons are close to the pump frequency, all four transverse-mode combinations are generated. As an example, we performed the quantum state tomography measurement with the experimental setup shown in Fig. 3a for the photon pairs in the frequency channels ±2. Using \([H, V, D, R]\)\(^{35}\) as the measuring basis, total 16 combinations are required to reconstruct the state density matrix, where \(|H\rangle = (1, 0)^T\), \(|V\rangle = (0, 1)^T\), \(|D\rangle = \frac{1}{\sqrt{2}} (1, 1)^T\), \(|R\rangle = \frac{1}{\sqrt{2}} (1, i)^T\), and \(T\) is the transpose operator. Here we used the maximum-likelihood-estimation method\(^{34}\) to reconstruct the density matrix \(\rho_{\text{near}}\) as shown in Fig. 3b. Assuming the state is pure, the experimental data are fitted with the state expressed as \(|\Phi\rangle = 0.60 |TE_0TE_1\rangle + 0.29 e^{-2.8i} |TE_1TE_0\rangle + 0.48 e^{0.29i} |TE_0TE_1\rangle + 0.57 e^{-0.40i} |TE_1TE_0\rangle\). According to the definition \(F = Tr(\rho_{\text{near}}|\Phi\rangle\langle\Phi|)\), where \(Tr\) represents the trace and \(\rho_{\text{pure}} = |\Phi\rangle\langle\Phi|\), the net fidelity between these two density matrices is estimated to be 0.99 ± 0.02 (raw fidelity 0.93 ± 0.02). The high fidelity unambiguously shows that both intramodal and intermodal photon pairs are generated and that they constitute a complex but pure quantum state. The errors in fidelity were obtained by 100 times Monte Carlo calculation, with the experimental data subject to Gaussian statistics.
More interestingly, in some channels, intermodal photon pairs are negligible such that the entangled state
\[
\rho = \frac{1}{\sqrt{1 + \eta_3^2}} (|\text{TE}_0\text{TE}_1\rangle + \eta_3 e^{i\phi} |\text{TE}_0\text{TE}_0\rangle)
\]
(2)
can be acquired. Furthermore, by adjusting the energy ratio and the phase difference between the TE_0 and TE_1 terms for the pump light, one can achieve a maximally transverse-mode entangled state as follows:
\[
\rho = \frac{1}{2} (|\text{TE}_1\text{TE}_1\rangle + |\text{TE}_0\text{TE}_0\rangle).
\]
(3)

We took the frequency channels ±8 to test the quality of the entanglement. First, we remove the QWPs, and adjust the HWP in signal path to 0° or 45°, respectively. Then, we rotate the HWP in idler path from 0° to 360°. In this way, we obtained the coincidence between signal and idler photons and quantum state tomography. The photons are collected by two detectors and analyzed by controllers (FPCs). The quarter-wave plate (QWP), half-wave plate (HWP) and polarization beam splitter (PBS) are tuned to measure quantum state tomography. The polarizations of signal and idler photons exported from the DWDM are controlled by quantum state tomography. The coincidence fringes can be fitted as $V = (d_{\text{max}} - d_{\text{min}})/(d_{\text{max}} + d_{\text{min}})$, where $d_{\text{max}}$ and $d_{\text{min}}$ are the maximum and minimum of the fitted data, respectively. The net visibilities for $\phi_s = 0°$ (solid black line) and $\phi_s = 45°$ (solid red line) bases are 97 ± 2% (raw visibility 95 ± 2%) and 100 ± 2% (raw visibility 99 ± 2%), which are both greater than $\eta_s \approx 71\%$ and show the presence of Bell nonlocality between the signal and idler photons.

Then, quantum state tomography was performed to measure the state density matrix $\rho$. The ideal density matrix of the maximally entangled state in Eq. (3) and the measured density matrix of the output state from frequency channels ±8 are shown in Fig. 4b, c, respectively. The fidelity is defined as $F = \text{Tr}(\rho_{\text{meas}} \rho_{\text{ideal}})$, where $\rho_{\text{ideal}}$ is the ideal density matrix. We obtained a net fidelity of 0.96 ± 0.01 (raw fidelity 0.93 ± 0.01), confirming that the generated quantum state is of high quality and very close to the ideal maximally entangled state. The deviation of the fidelity from unity was mainly due to the errors in rotating the angles of the wave plates. Through use of a cascading on-chip Mach-Zehnder interferometer with thermal tuning to regulate the energy distribution and phase of different transverse-modes, any level of biphoton entanglement can be achieved.

**DISCUSSION**

We have shown the photon pair and entangled Bell state generation based on transverse-mode in a multimode waveguide. Using larger waveguide that support more transverse-modes enables high-capacity information processing within a more compact chip than single-mode ones. Very recently, we have successfully demonstrated a 10-channel transverse-mode (de) multiplexer in a 2.3 μm-wide waveguide. We believe that a higher-dimensional entangled state preparation will become feasible in the near future, even though several issues need to be addressed. For example, the efficiency of Type III SFWM processes have very narrow bandwidth and decreases sharply. And the dispersion of different transverse-modes also leads to the decoherence of the quantum superposed state. Nevertheless, for higher-dimensional Bell state generation, we just need to use Type I SFWM processes, and should avoid the cross terms induced by the Type III processes by selecting frequency channels. As for the dispersion, it can be compensated using delay line or by switching the transverse-modes with gratings. Taking a 4-dimensional quantum state preparation as an example, we discussed about the feasibility of realizing higher-dimensional entangled quantum state with one multimode waveguide (see Supplementary Materials, Section 4 and Figs. S6–S8). Also, we could hybridize the degrees of freedom of both path and transverse-mode for higher-dimensional quantum state generation. For example, a 16-dimensional spatial mode requires only 4 multimode waveguides that support 4 transverse-modes.

The fact that transverse-mode entangled state can be coherently converted into path and polarization entanglement provides convenience for large-scale quantum photonic integrated circuits (QPICs) and hyper-entanglement generation. Due to the non-uniform intermodal nonlinear process, photon pairs in different frequency channels are in different quantum states; thus, we can choose the quantum state as desired by selecting frequency channels, which is unimaginable for single-mode ones. This frequency-multiplexed transverse-mode entangled photon pair source in a multimode waveguide offers high selectivity and flexibility for realizing quantum applications. In principle, we can excite and measure arbitrary transverse-modes with the mode multiplexing technique, special quantum state also could be engineered with the intermodal nonlinear processes.

The intermodal SFWM process, where both the first-order and second-order dispersions can be engineered for phase matching, also can be used to realize frequency conversion between widely separated wavelengths. According to our calculations, in a multimode silicon waveguide with a cross-section of ~1600 × 220 nm², conversion between wavelengths separated by 600 THz (~800 nm) can be achieved (see Supplementary Materials, Fig. S9). On the other hand, the high quality cavities with multiple transverse-modes have also been explored to enhance the SFWM processes.
In conclusion, we have demonstrated the transverse-mode entangled photon pairs and quantum states generation using a multimode silicon waveguide, which has potential in extending further to higher-dimensional space. Combined with previous studies on coherent conversion and manipulation of transverse-mode entanglement, the present work shows the potential for realizing complex quantum information processing with high dimensionality and multiple degrees of freedom. Moreover, the multimode waveguide enables to tailor quantum state with mode multiplexing technique and shows much richer nonlinear phenomena than the single-mode one, thus providing an attractive platform for quantum information applications.

**METHODS**

**System efficiency**

We ascertained the efficiencies for all components using laser light measurements (see Supplementary Materials, Fig. S10). The one-dimensional grating coupler and 2D grating coupler show coupling losses of 5 dB and 8 dB, respectively. The chip excess losses in our device are 5 dB.
Photon pairs generated in different parts
Using the photon pair (TE$_2$TE$_2$), as example, we estimated the contribution of the finally detected photon pairs from parts I, II, and III. In our device, the part I and part III consist of single-mode waveguides with length of about 450 and 250 μm, respectively. Assuming that the pump power is the same and the conversion processes are lossless, the ratio of photon counts is C$_2$ : C$_I$ : C$_{II}$ = 1 : 188 : 0.1. When a transmission loss of 2 dB/mm is considered in the multimode waveguide (part II), the ratio became C$_2$ : C$_I$ : C$_{II}$ = 1 : 2.3 x 10$^4$ : 5.6 x 10$^{-6}$. Therefore, the photons generated in part I is mostly dissipated as propagation loss in part II. And in both cases, the contribution from single-mode waveguide (parts I and III) is negligible.

Optical apparatus
We used a CW tunable laser (linewidth 10 kHz, central wavelength 1550.11 nm) as the pump light. The laser was amplified by an erbium-doped fiber amplifier and filtered (100 dB extinction ratio). The remaining power, which was coupled to the device after a single-mode fiber and an on-chip grating coupler, was 6.96 mW, which was then divided into two parts by an on-chip directional coupler to excite the two transverse-modes. Fiber alignment was maintained using a piezo-controlled four-dimensional displacement table for the adjustment of the position, as well as the coupling angle. The coupling angle was set at 15° and 4° for the one-dimensional grating coupler and 2D grating coupler, respectively. Two off-chip post-filters (100 dB extinction ratio) were used to remove the pump photons, and two DWDMs (with an extinction ratio of 30 dB for adjacent channels and 50 dB for non-adjacent channels) were used to separate the signal and idler photons. The correlated photons were recorded by two superconducting nanowire single photon detectors. The electrical signals were collected and analyzed through a time-correlated single photon counting (TCSPC) system, with the coincidence window set as 0.8 ns.

Device fabrication
Chips were fabricated on the most commonly used 220 nm SOI platform. The pattern of the waveguides was exposed on ma-N 2403 negative tone photoresist by an inductively coupled-plasma etcher and transferred to the top silicon layer by an on-chip directional coupler. Finally, 1.2 μm plasma enhanced chemical vapor deposition (PECVD) SiO$_2$ was deposited on the top of the waveguide to form the upper-cladding.

DATA AVAILABILITY
Data are available from the authors upon reasonable request.

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AUTHOR CONTRIBUTIONS
All authors contributed extensively to the work presented in this paper. M.Z. and D.X. D. prepared the samples. L.T.F., M.Z., D.X.D., and X.F.R. performed the measurements, data analyses and discussions. X.X., Y.C., H.W., M.L., G.P.G., and G.C.G. conducted theoretical analysis. X.F.R. and D.X.D. wrote the manuscript and supervised the project.

ADDITIONAL INFORMATION
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