

## Monolithic Integration of Polarization-entangled Photon Pair Source Using Silicon Photonics Technology

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### Abstract

Quantum entanglement is an essential resource for quantum information processing technologies, including quantum communication and quantum computation. In this article, we present the world's first-ever monolithically integrated polarization-entangled photon pair source on a silicon chip.

### 1. Introduction

Quantum entanglement, or in other words, nonlocal quantum correlation between two or more quantum-mechanical objects, is a quintessential feature of quantum mechanics. At the same time, quantum entanglement is a substantial resource for quantum information processing (QIP) technologies including quantum cryptography, quantum metrology, and quantum computation [1]–[4].

A number of physical systems are being investigated for their potential application in the development of QIP. Among them, photons are excellent media to generate, process, and distribute entanglements. This is because quantum states encoded in physical quantities of light are highly robust, thanks to an inherent weakness in the interactions between light and electromagnetic environments. The physical freedom of light includes polarizations, optical paths, frequencies, and time bins. Of these quantum states, polarization is particularly important, since polarization is a true two-level photonic system, which is easy to manipulate with conventional bulk optics such as wave plates. Thus, many QIP protocols have been proposed [3], [5] and experimentally demonstrated

[4], [5] using polarization-encoded quantum states of light. In such experiments, sources of polarization-entangled photons have been inevitably playing a key role [6], [7].

Very recently, integrated optical circuits have been attracting much attention as the next platform of QIP using photons [8]. Such an approach promises to scale up the experiments by exploiting the miniature physical size and highly stable interferometers of integrated waveguides. To achieve such integrated photonic QIP systems, it is essential to develop integrated subsystems to generate, manipulate, and measure the quantum states on a chip. In particular, an integrated polarization-entanglement source, which generates polarization-entangled photons into a waveguide mode on a chip, is necessary in order for us to utilize the wealth of QIP protocols. However, no such demonstration of an integrated polarization-entanglement source has been reported to date; nevertheless, it is necessary for a practical integrated QIP system. In this article, we present the world's first ever polarization-entanglement source, which NTT achieved using silicon photonics technology [9] (**Fig. 1**). We have implemented the source as a simple and stable silicon-on-insulator photonic circuit so the

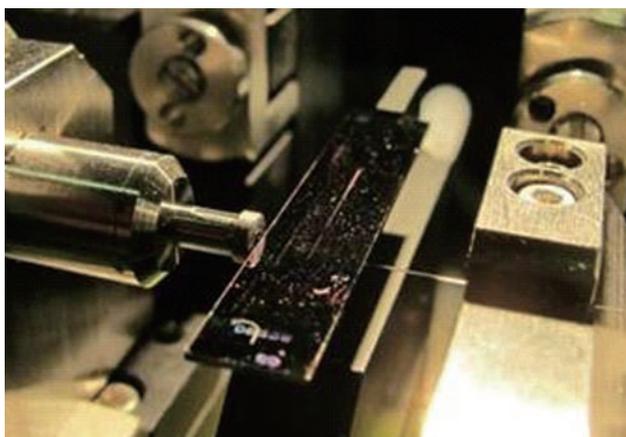


Fig. 1. Picture of the chip of monolithic polarization-entangled photon pair sources. By injecting pump pulses from the left hand side, we can obtain polarization-entangled photon pairs to be collected by the output optical fiber on the right hand side.

source could successfully generate a high degree of polarization entanglement.

## 2. Building blocks of polarization-entangled photon pair source

An entangled photon pair source requires two building blocks: a source to generate photon pairs having a time correlation, and a device to manipulate the polarization state of photons to ensure that photon pairs are entangled in the polarization degree of freedom. NTT has already realized both components by using on-chip silicon photonics technology.

A silicon-wire waveguide is a highly efficient source of time-correlated photon pairs (**Fig. 2(a)**) [10]–[15]. The silicon-wire waveguide is a single-mode waveguide whose core is made of single-crystalline silicon with a typical cross-sectional size of 400 nm (width) and 200 nm (height). Thanks to this extremely small core, the optical power density in the waveguide becomes very high, and as a result, we can observe a huge nonlinear optical effect. The nonlinear coefficient of our silicon-wire waveguide is five orders of magnitude larger than that of a silica optical fiber. This coefficient represents the optical-nonlinearity strength of a waveguide.

When we input a telecom-wavelength pump light whose frequency is  $\nu_p$  into the silicon-wire waveguide, we can generate a photon pair with frequencies of  $\nu_s$  and  $\nu_i$  through spontaneous four-wave mixing (SFWM), which is one of the third-order nonlinear

effects. The process occurs under the energy conservation of photons as follows

$$2\nu_p = \nu_s + \nu_i \quad (1)$$

This indicates that two pump photons are annihilated, and subsequently a signal-idler photon pair is created. Since the two photons are created simultaneously, we can generate time-correlated photon pairs. In addition, the use of the single-crystalline silicon core enables us to avoid background noise photons caused by spontaneous Raman scattering, which has been a serious problem for photon pair sources based on other types of nonlinear waveguides such as fused silica [1] whose core has an amorphous structure. A single-mode waveguide supports two propagating modes with orthogonal polarization states of light: transverse-electric (TE) and transverse-magnetic (TM) fields. In the silicon wire waveguide, TE-polarized photon pairs are efficiently generated by a TE-polarized pump field. This is because the waveguide has a field confinement of TE-polarized light into the core that is stronger than that of TM-polarized light [13].

The second building block is a silicon polarization rotator [16], which is used in polarization-diversity optical circuits for telecommunication applications [17]. The device has an off-axis double-core structure consisting of a 200-nm<sup>2</sup> silicon wire core and a second 840-nm<sup>2</sup> silicon-oxynitride (SiON) core on the silicon core (**Fig. 2(b)**). The structure exhibits two orthogonal eigenmodes, which have different effective refractive indices and eigen-axes tilted at 45° to the normal with respect to the silicon substrate. The birefringence in the eigenmodes provides an integrated wave plate, which causes the polarization plane to rotate by an amount that depends on the length of the rotator. We show the measured polarization rotation characteristics of a 30- $\mu$ m-long polarization rotator in **Fig. 2(c)**. A TE-polarized input field was successfully converted to TM polarization with the rotator. The polarization rotation angle was estimated to be  $86.7 \pm 0.1^\circ$  with a polarization extinction ratio as high as 30 dB. Thus, we obtained a polarization rotation angle of almost 90° with a high polarization extinction ratio. This high performance of the rotator enabled us to generate a high degree of polarization entanglement as we show later.

## 3. On-chip polarization-entanglement source

We combined the two building blocks fabricated on

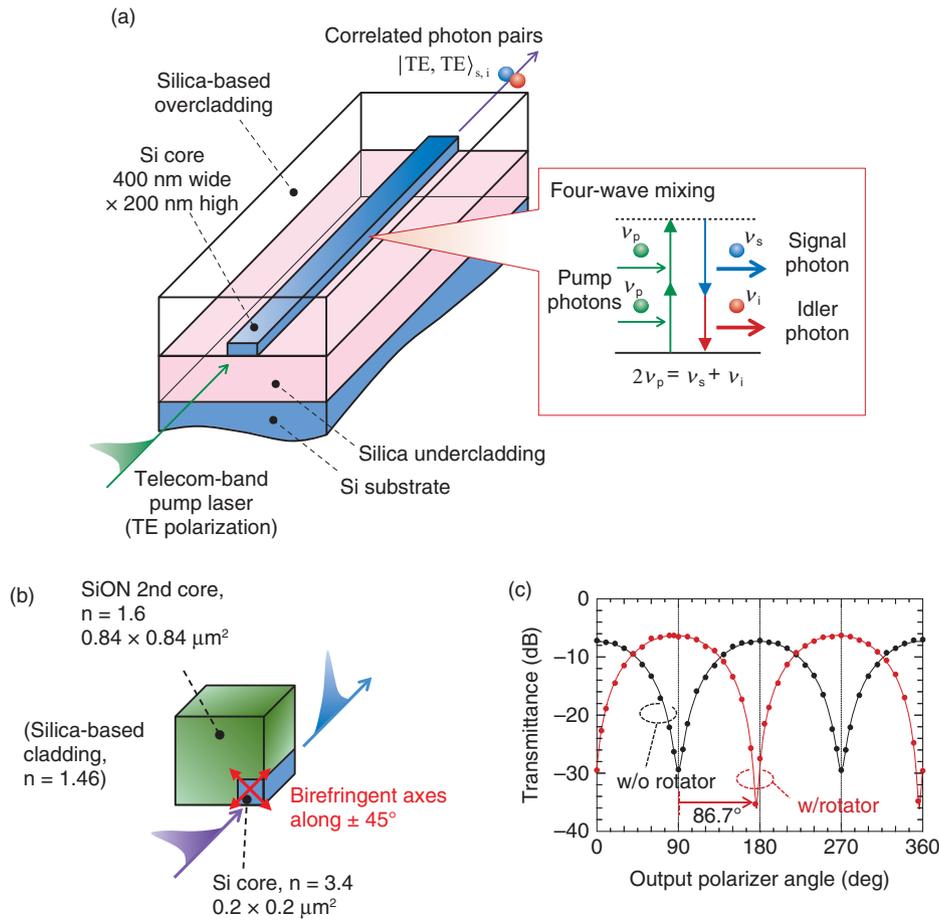


Fig. 2. Building blocks of polarization-entanglement source. (a) Silicon-wire waveguide source of correlated photon pairs. (b) Ultrasmall silicon polarization rotator. Claddings are not shown for clarity. (c) Characterization of polarization rotation angle at the silicon polarization rotator.

the same silicon photonics platform to implement the monolithic polarization entanglement source on a chip [9]. Our polarization-entanglement source (**Fig. 3**) consists of two silicon-wire waveguides connected by a silicon-wire polarization rotator. Both silicon wire waveguides and the silicon polarization rotator are connected by 10- $\mu\text{m}$ -long tapered silicon wires. The over- and under-cladding of the silicon wire waveguides and the silicon polarization rotator were made of silica (not shown).

The operating principle of the device is as follows. We use a pump beam with  $+45^\circ$  linear polarization, which is a 1:1 combination of the TE and TM modes in the silicon wire waveguides. In the first silicon wire waveguide, the TE component of the pump creates a photon pair in the  $|\text{TE}\rangle_s |\text{TE}\rangle_i$  state, which means that there is one TE-polarized photon in the signal

frequency channel and one TE-polarized photon in the idler frequency channel. In the following, we rewrite the state as  $|\text{TE}\rangle_s |\text{TE}\rangle_i$  for simplicity. Then, the silicon polarization rotator rotates this state to the  $|\text{TM}\rangle_s |\text{TM}\rangle_i$  state as a result of  $90^\circ$  polarization rotation. Here, the subscripts denote the frequency modes of the signal and idler photons. At the same time, the silicon polarization rotator rotates the TM component of the pump field to provide it with TE polarization, and the second silicon wire waveguide creates other  $|\text{TE}\rangle_s |\text{TE}\rangle_i$  photons. Since we cannot distinguish whether the pair was generated in the first or second silicon waveguides, we obtain the maximally polarization-entangled state:

$$|\psi\rangle = (|\text{TE}\rangle_s |\text{TE}\rangle_i + e^{-i\phi} |\text{TM}\rangle_s |\text{TM}\rangle_i) / \sqrt{2}, \quad (2)$$

at the output of the polarization-entanglement source.

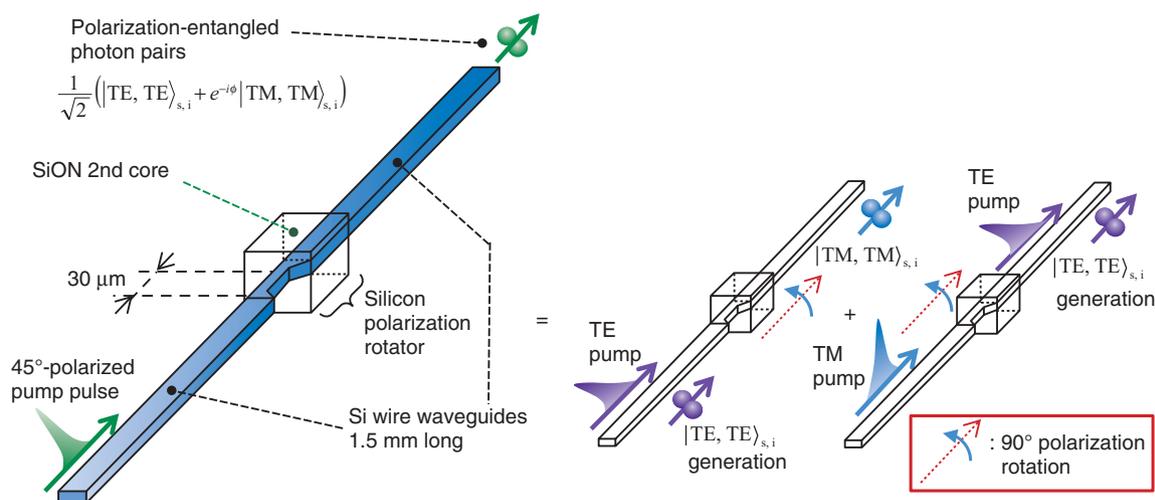


Fig. 3. Monolithically integrated polarization-entangled photon pairs. The source, fabricated on a silicon-on-insulator substrate, consists of a silicon 90° polarization rotator sandwiched by two nonlinear silicon wire waveguides. The device generates the polarization entanglement as a superposition of the two events shown on the right hand side.

Here, the relative phase difference  $\phi$  is a fixed value and depends on the difference in length between the first and second silicon waveguides.

Generally, it is difficult to precisely control a birefringence of nonlinear waveguides with an ultrasmall core. The residual birefringence causes significant polarization-mode dispersion (PMD), which degrades the degree of polarization entanglement. To avoid this degradation, the conventional polarization-entanglement sources adopt off-chip PMD compensators such as birefringent crystal or polarization-maintaining fiber. In those cases, photons cannot be polarization-entangled inside the waveguide chip. In our case, since the polarization-entanglement source is designed to be symmetric about the polarization states with respect to the midpoint of the device, the polarization-mode dispersion of the pump pulses and photon pairs are completely cancelled out. Therefore, our polarization-entanglement source generates a polarization-entangled state inside the waveguide chip. This feature enables us to directly integrate the source with quantum-state controllers and detectors to construct a quantum information processor on a chip. Moreover, the device can automatically balance the amplitude of the two terms in Eq. (2) even in the presence of practical waveguide losses, leading to highly robust polarization entanglement (see Ref. [9] for details).

#### 4. Experiment

We generated and analyzed polarization-entangled photon pairs using the setup shown in **Fig. 4**. We injected optical pump pulses whose polarization was set at +45° linear polarization and a wavelength centered at 1551.1 nm into the polarization-entanglement source. The photons generated from the chip were introduced into the wavelength-division-multiplexing (WDM) filter, which suppressed the residual pump light and separated the signal and idler photons into different fiber channels. Each output port had a center wavelength of 1546.4 nm (signal) and 1556.0 nm (idler) with a channel bandwidth of 0.14 nm. Then, the photons passed through the polarization analyzers, each of which consisted of a half and a quarter wave plate, and a polarizer. Finally, the photons were received by InGaAs (indium/gallium/arsenide) single photon detectors. The detection signals from the two detectors were input into the time interval analyzer (TIA), with which we carry out time-correlation measurement of photon pairs.

We first reconstruct the density matrix of the generated polarization-entangled state to evaluate the degree of entanglement. The density matrix  $\rho$  of the state in Eq. (2) can be expressed as

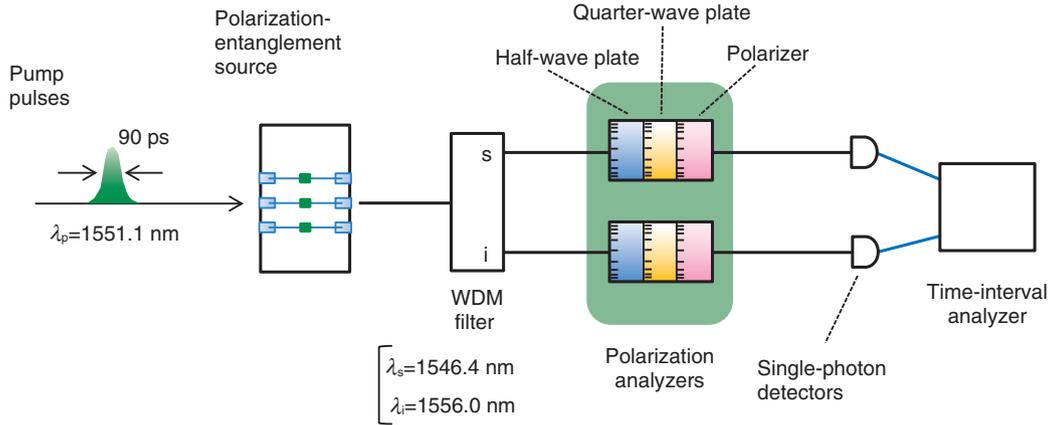


Fig. 4. Experimental setup.

$$\begin{aligned}
 \rho &= \sum |\psi\rangle\langle\psi| \\
 &= \frac{1}{2} (|TE\rangle_s |TE\rangle_i + e^{-i\phi} |TM\rangle_s |TM\rangle_i) \\
 &\quad \langle\langle TE|_s \langle TE|_i + e^{i\phi} \langle TM|_s \langle TM|_i, \\
 &= \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & e^{-i\phi} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ e^{i\phi} & 0 & 0 & 1 \end{pmatrix}
 \end{aligned} \tag{3}$$

when the state is purely in the maximally entangled state. Here, the summation takes over all the generated photon pairs. In this representation, we used  $|TE\rangle_s |TE\rangle_i$ ,  $|TE\rangle_s |TM\rangle_i$ ,  $|TM\rangle_s |TE\rangle_i$ , and  $|TM\rangle_s |TM\rangle_i$  as a basis set. Each diagonal element represents the probability (population) of the system, and the off-diagonal elements represent the quantum coherence. If the generated system has no coherence, the density matrix becomes

$$\rho = \sum |\psi\rangle\langle\psi| = \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{4}$$

Therefore, the density matrix that has the off-diagonal elements whose absolute values are as high as those of the diagonal elements shows the full coherence of the entanglement.

To experimentally obtain the density matrix of the

two-photon polarization state, we first carried out the correlation measurement of the photon pairs under 16 different polarization combinations that were selected based on the angles of the four wave plates in the polarization projection units [18]. This is analogous to the measurement of the polarization state of classical light, in which projection measurements of four different polarization states are at least required to estimate Stokes vectors. In the present case with the two-photon state, we require  $4^2 = 16$  projection measurement. Then, using a procedure called quantum state tomography, we can reconstruct the density matrix. The reconstructed density matrix is shown in **Fig. 5**. For simplicity, we have only displayed the absolute values of each matrix element. The result exhibits off-diagonal amplitudes as high as 0.5, which represent a high coherence of the system. Note that the results include any background (noise) counts.

Regarding the degree of entanglement, we evaluate the fully entangled fraction  $F(\rho) = \max_{|\Psi\rangle} \langle\Psi|\rho|\Psi\rangle$ , where the maximum is taken over all maximally entangled states  $|\Psi\rangle$ . From the measured  $\rho$  values in accordance with the procedure described by Badziag et al. [19], we obtained an  $F(\rho)$  value of  $(94 \pm 2)\%$ . This value is much higher than the classical limit of 0.5. Furthermore, the  $F(\rho)$  value is much greater than  $1/\sqrt{2} \sim 71\%$ , implying that the generated state has strong nonlocal correlation. Hence, we successfully generated photon pairs with a high degree of polarization entanglement from the chip.

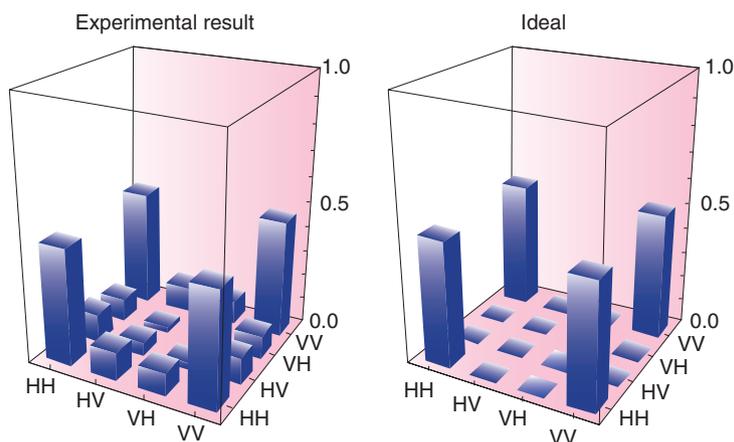


Fig. 5. Reconstructed density matrix. Here, the absolute values of each element are shown. H and V represent the TE and TM bases, respectively.

## 5. Conclusion

We have demonstrated the world's first ever source of polarization-entangled photon pairs on a chip. The device we constructed is capable of generating a high degree of polarization entanglement thanks to nanofabrication technology of silicon photonic devices. To achieve a photonic QIP system on a chip, it is necessary to integrate our source with subsequent quantum processors, which manipulate or project the polarization-encoded quantum state of photons. Such integration would also be possible, since our source is equipped with spot-size converters, which can be a versatile interface with other types of integrated waveguide platforms [20]. Our monolithic polarization-entangled photon pair source helps pave the way to the full-scale implementation of a photonic quantum information system on a chip.

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