Indistinguishable photon pair generation using two independent silicon wire waveguides

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Abstract. We performed a Hong–Ou–Mandel interference experiment with 1.5 $\mu$m band photon pairs generated through spontaneous four-wave mixing (SFWM) in two independent silicon wire waveguides (SWWs). To maintain the long-term stability of the coupling between the SWWs and optical fibers without a fiber alignment system, we employed fiber module SWWs installed in a rigid metallic case with fiber array interfaces. In addition, those signal photons that passed through a beam splitter (BS) were detected by high-speed single-photon detectors that used InGaAs avalanche photodiodes operated in a gated mode with a high gate frequency of 500 MHz. With these novel technologies, we successfully observed a quantum interference with a visibility of 73\% without subtracting accidental coincidence counts in the fourfold coincidence measurement.
1. Introduction

The generation of entangled photon pairs is essential for realizing quantum communication systems such as a quantum key distribution (QKD) system [1] and a quantum computer (QC) [2]. Entangled photon pairs in the 1.5 µm band are especially advantageous for scalable quantum communication networks over optical fibers. However, even with 1.5 µm band entangled photons, the maximum transmission distance over an optical fiber has been limited to 200 km [3] because of fiber transmission loss and detector noise. To overcome this problem, a quantum repeater (QR) has been proposed by Briegel et al [4], by which we can realize scalable quantum communication in theory. One of the technologies essential for achieving a QR is entanglement swapping, which involves the generation of indistinguishable photon pairs from independent sources and has been proposed and implemented in [5–7].

Currently, two sources are widely used to create indistinguishable photon pairs in the 1.5 µm band. Spontaneous parametric down-conversion in a periodically poled lithium niobate (PPLN) waveguide is the most widely used technique for the generation of 1.5 µm band photon pairs [6], [8–10]. However, timing jitter induced by the walk-off between a pump and a photon pair occurs in photon-pair sources based on a PPLN waveguide. As timing jitter leads to the degradation of quantum interference with photon pairs, very narrow filters are required in order to overcome this problem. As a result, it is generally hard to perform a Hong–Ou–Mandel (HOM) interference experiment with photon pairs generated from two independent PPLN waveguides. On the other hand, there have also been reports describing the generation of indistinguishable photon pairs by using near-degenerate spontaneous four-wave mixing (SFWM) in a dispersion shifted fiber (DSF) [7, 11, 12]. With the photon pairs generated via near-degenerate SFWM, timing jitter does not occur because the wavelengths of the pump and photon pairs generated by the SFWM process are almost the same; hence an interference experiment is relatively easier to perform with fiber devices than with photon pairs generated from PPLN devices. However, fiber-based photon pair sources are affected by the noise photons generated by spontaneous Raman scattering (SpRS), which degrade the degree of quantum correlation and two-photon interference. Although it is possible to suppress the generation of SpRS photons by soaking DSF in liquid nitrogen [13], the need for such cooling devices complicates the experimental system, which is undesirable.
Recently, a silicon wire waveguide (SWW) made using silicon nanophotonics technology has attracted considerable attention, and it is considered a good alternative for the generation of correlated and entangled photon pairs. The effective cross-section of an SWW is much smaller than that of a standard optical fiber. Therefore, in SWWs the third-order nonlinear effects are noticeably enhanced. As a result, we can generate photon pairs efficiently in a waveguide with a length of a few centimeters using SFWM unlike the few hundreds of meters required with DSF. In the SFWM process, the photon timing jitter is generally negligible because the group velocity matching and the refractive index matching are achieved simultaneously. Moreover, the Raman spectrum of single-crystal silicon is 15.6 THz from the pump frequency and it has a width of about 100 GHz as reported by Claps et al. As a result, we can avoid SpRS photons getting generated in an SWW by selecting signal and idler frequencies away from the Raman peak and obtain high-purity correlated photon pairs as we have already reported. Thus, the SWW-based sources are expected to be useful for a quantum interference experiment with photon pairs. The reason for applying silicon photonics technologies to quantum information tasks is to realize high-function photonic quantum circuits. Since the bending radius of an SWW is much smaller than that of conventional silica waveguides, we can significantly reduce the size of quantum circuits. In addition, we can include active functions (including photon pair sources) in quantum circuits, so that we may realize a quantum gate that requires entanglement sources on a chip (see e.g. [20]). To achieve this, the generation of indistinguishable photons from independent SWW is an important step.

In this paper, we report an HOM interference experiment with photon pairs generated from the SFWM process in two independent SWWs. Here, the SWWs installed in a rigid metallic case were directly connected to optical fibers on both sides. In our previous work, a fiber alignment system was needed to adjust the coupling between the SWW and the optical fiber. However, the fiber module SWWs allow easy injection of laser lights into waveguides, and also maintain the long-term stability of the coupling between them without fiber alignment systems. In addition, we used InGaAs avalanche photodiodes (APDs) operated in a gated mode whose gate frequency was as high as 500 MHz for the twofold coincidence measurement. With these novel technologies, we achieved quantum interference with a visibility of 73% in a fourfold coincidence measurement. Here, we would like to emphasize that we have not subtracted accidental coincidence counts.

2. Theory: Hong–Ou–Mandel interference with multi-photon pairs generated from independent sources

In this section, we theoretically consider the HOM interference with multi-photon pairs generated in two independent sources. In previous studies, events involving the simultaneous generation of more than three pairs in two independent sources were disregarded. However, it is important to include the higher-order generation of photon pairs for the accurate evaluation of visibility. The correlated photon pairs were created in source1 and source2 as shown in figure 1. As in [23, 24], the interaction Hamiltonian for the correlated photon pair generation by SFWM in source $y (= 1, 2)$ is described as

$$ \hat{H}_y = i\hbar \chi (a_{iy}^\dagger a_{sy}^\dagger - a_{iy} a_{sy}) $$

where $\chi$ is proportional to the square of the pump photons and $a_{iy}^\dagger$ ($a_{iy}$) and $a_{sy}^\dagger$ ($a_{sy}$) are the creation (annihilation) operators for idler and signal photons emitted from source $y$, respectively.
Figure 1. Scheme showing the principle of HOM interference. Two independent sources, source1 and source2, emit two correlated photon pairs, pair idler1 ($i_1$)–signal1 ($s_1$) and pair idler2 ($i_2$) and signal2 ($s_2$). Two signal photons are transformed to $s_1'$ and $s_2'$ on a 50 : 50 BS.

respectively. Here, we assume that the pump light is strong and can be treated as a classical oscillator. The time evolution of the quantum state is given by

$$|\Psi\rangle = e^{-i\hat{H}/\hbar t}|0\rangle_{i_1}|0\rangle_{s_1}|0\rangle_{i_2}|0\rangle_{s_2}. \quad (2)$$

$\hat{H}$ represents the total Hamiltonian defined as $\hat{H}_1 + \hat{H}_2$, and $|m_y\rangle_{iy}$ and $|n_y\rangle_{sy}$ are the number states, where $m_y, n_y$ are the numbers of idler and signal photons emitted from source $y$. By using the disentangling theorem shown as equation (5.63) in [23], equation (2) can be re-expressed as follows,

$$|\Psi\rangle = \frac{1}{C^2} e^{i(\hat{a}_{i_1}^{\dagger}a_{i_1}^{\dagger} + \hat{a}_{s_1}^{\dagger}a_{s_1}^{\dagger})}|0\rangle_{i_1}|0\rangle_{s_1}|0\rangle_{i_2}|0\rangle_{s_2},$$

$$= \frac{1}{C^2} \left(1 + \hat{\Gamma} + \frac{1}{2!} \hat{\Gamma}^2 + \frac{1}{3!} \hat{\Gamma}^3 + \cdots \right)|0\rangle_{i_1}|0\rangle_{s_1}|0\rangle_{i_2}|0\rangle_{s_2}, \quad (3)$$

where $\hat{\Gamma} = (\Gamma (a_{i_1}^{\dagger}a_{i_1}^{\dagger} + a_{s_1}^{\dagger}a_{s_1}^{\dagger}))$, $C = \cosh \chi t$, and $\Gamma = \tanh \chi t$.

The $x$-order term in equation (3) can be written as

$$|\Psi_x\rangle = \sqrt{x + 1} \frac{\Gamma^x}{C^x} |\psi_x\rangle. \quad (4)$$

Here, $x$ and $|\psi_x\rangle$ represent a positive integer and the normalized quantum state of an $x$ pair, respectively. $|\psi_x\rangle$ is given by

$$|\psi_x\rangle = \frac{1}{\sqrt{x + 1}} \sum_{k=0}^{x} |x - k\rangle_{i_1}|x - k\rangle_{s_1}|k\rangle_{i_2}|k\rangle_{s_2}. \quad (5)$$

From equation (4), the probability of generating the $x$ pair $P(x)$ is described as

$$P(x) = \langle \Psi_x | \Psi_x \rangle = \frac{(x + 1) \Gamma^x}{C} = \frac{(x + 1) \tanh^x \chi t}{\cosh^x \chi t}. \quad (6)$$

When we then define $\mu_y$ as the average photon pair number generated from source $y$, the total average photon pair number $\mu$ in the system becomes $\mu_1 + \mu_2$. Thus, the probability of generating $x$ pairs is rewritten as a function of $\mu$ from equation (6),

$$P(\mu, x) = \frac{(\mu/2)^x}{(1 + (\mu/2))^{x+2}}. \quad (7)$$
Therefore, the quantum state for the overall system is expressed as

$$|\Psi\rangle = \sum_{x=0}^{\infty} \sqrt{P(\mu, x)} |\psi_x\rangle.$$  \hspace{1cm} (8)

2.1. Probability of fourfold coincidence counts inside dip

Let us consider the case when the signal photons emitted from both source1 and source2 arrive simultaneously at a 50 : 50 beam splitter (BS). Here, we note that the two photons are indistinguishable in the spectrum, spatial and temporal modes, so they are always emitted from the same output port together due to the interference effect. As a result, the twofold and fourfold coincidence counts cannot be observed, in principle. We estimate the overall probability of fourfold coincidence counts $R_{4id}(\mu, \alpha)$ inside the dip (id) for a multi-pair emission event using the following equation:

$$R_{4id}(\mu, \alpha) = \sum_{x=2}^{\infty} P(\mu, x) f_{id}(x).$$  \hspace{1cm} (9)

Here, $f_{id}(x)$ is defined as the probability of fourfold coincidence counts for $x$ pairs, which is obtained by taking only the relevant terms in $|\psi_x\rangle$. $\alpha$ denotes the collection efficiency of each photon, which includes the coupling efficiency between the nonlinear medium and fiber, the optical loss caused by the filter and the detection efficiency. The transformation from input modes $s_1$ and $s_2$ to output modes $s_1'$ and $s_2'$ of a BS is as follows:

$$a_{s_1} = \frac{1}{\sqrt{2}} (a_{s_1'} - a_{s_2'}),$$  \hspace{1cm} (10)

$$a_{s_2} = \frac{1}{\sqrt{2}} (a_{s_1'} + a_{s_2'}).$$  \hspace{1cm} (11)

Using these transformations, equation (5) is expressed as

$$|\psi_x\rangle_{id} = \frac{1}{\sqrt{x+1}} \sum_{k=0}^{x} \frac{1}{(x-k)!k!} (a_{11}^\dagger)^{x-k} (a_{s_1}^\dagger)^{x-k} (a_{s_2}^\dagger)^{k} |\text{vac}\rangle$$

$$= \left( \frac{1}{\sqrt{2}} \right)^x \frac{1}{\sqrt{x+1}} \sum_{k=0}^{x} \frac{1}{(x-k)!k!} \times (a_{11}^\dagger)^{x-k} (a_{s_1}^\dagger - a_{s_2}^\dagger)^{x-k} (a_{s_2}^\dagger)^{k} (a_{s_1}^\dagger + a_{s_2}^\dagger) |\text{vac}\rangle,$$

where $|\text{vac}\rangle$ represents a vacuum state.

2.2. Probability of fourfold coincidence counts outside dip

In this case, as the signal photons emitted from both source1 and source2 arrive at a BS at different times, there is no interference between them. Thus, the temporal modes of $s_1$ and $s_2$ transform to two different modes at the BS as

$$a_{s_1} = \frac{1}{\sqrt{2}} (a_{s_1'} - a_{s_2'}),$$  \hspace{1cm} (13)

$$a_{s_2} = \frac{1}{\sqrt{2}} (a_{s_1'} + a_{s_2'}).$$  \hspace{1cm} (14)

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Using these transformations, equation (5) is described as

$$|\psi_\text{od}\rangle = \left(\frac{1}{\sqrt{2}}\right)^x \frac{1}{\sqrt{x+1}} \sum_{k=0}^{x} \frac{1}{(x-k)!} x^{x-k} (a_{11}^{\dagger})^{x-k} (a_{21}^{\dagger} - a_{2}^{\dagger})^{x-k} (a_{12}^{\dagger})^{k} (a_{21}^{\dagger} + a_{2}^{\dagger})^{k} |\text{vac}\rangle. \quad (15)$$

The overall probability of fourfold coincidence counts \( R_{4\text{od}}(\mu, \alpha) \) outside the dip for a multi-pair emission event is obtained from the following equation:

\[
R_{4\text{od}}(\mu, \alpha) = \sum_{x=2}^{\infty} P(\mu, x) f_{\text{od}}(x). \quad (16)
\]

Here, \( f_{\text{od}}(x) \) represents the probability of fourfold coincidence counts for \( x \) pairs outside the dip.

2.3. Visibility

We define the visibility of an HOM dip for a multi-pair emission event by using \( R_{4\text{id}} \) and \( R_{4\text{od}} \), which were calculated in sections 2.1 and 2.2, as follows:

\[
V(\mu, \alpha) = \frac{R_{4\text{id}}(\mu, \alpha) - R_{4\text{od}}(\mu, \alpha)}{R_{4\text{id}}(\mu, \alpha)}. \quad (17)
\]

The visibility for a two-pair emission event reported in [21, 22] is

\[
V_{2p}(\mu) = \frac{1 + 8\mu}{1 + 12\mu}. \quad (18)
\]

We compared the visibilities of multi-pair and two-pair emission events using equations (17) and (18) assuming \( \alpha = 0.04 \) and considering the generation of up to 10 photon pairs in the calculation of equation (17). The result is shown in figure 2. This indicates that the visibility in the case of a multi-pair emission event becomes poor when compared with that of a two-pair emission event as the average photon pair number increases. The visibility given by equation (18) is a good approximation of that given by equation (17) from figure 2 when \( \mu \leqslant 0.01 \) (96.4% at \( \mu = 0.01 \)), but the difference between their visibilities gradually increases when \( \mu > 0.01 \) because of the effect of multi-photon pair generation. In previous studies, e.g. [22], there are very few HOM interference experiments with a reported visibility of more than 95% performed using independent sources. Therefore, equation (17) is useful in evaluating the degree of visibility more accurately.

3. Experimental setup

The experimental setup is shown in figure 3. We employed a single-frequency tunable laser source (HP 81682A) with a wavelength of 1551.1 nm. The laser light was modulated into a 19 ps-wide pulse with a repetition frequency of 500 MHz by using an intensity modulator. The pulse was amplified by an erbium-doped fiber amplifier (EDFA) and filtered to eliminate amplified spontaneous emission noise from the EDFA. This pulse was then divided into two paths by a 50 : 50 fiber coupler. One of the paths passed through an attenuator and was connected to an optical delay line that is used in adjusting the path length of the light. Its length was controlled by using a personal computer. The pump pulses from each path were precisely
Figure 2. Theoretical calculation of visibilities as a function of the average photon pair number $\mu$. The solid line represents improved visibility, which includes the generation probability of up to 10 photon pairs in the system. The dashed line shows the visibility reported in [21]. The inset shows plots of both visibilities up to $\mu = 0.2$.

adjusted to a horizontal polarization by using polarization controllers (PC) and then injected into fiber module SWWs where photon pairs were generated through SFWM. Each waveguide was fabricated on a silicon-on-insulator wafer with a Si top layer on a 3 $\mu$m SiO$_2$ layer. Both SWWs were 460 nm wide and 200 nm thick; however, their lengths were 0.97 cm (SWW1) and 1.60 cm (SWW2). The peak input pump powers injected into SWW1 and SWW2 were 280 and 180 mW, respectively. We plot the excess losses of light in different waveguides with lengths of 0.97, 1.60 and 2.80 cm in figure 4(a). It is evident that there is an excess loss of about 1.4 dB cm$^{-1}$ in each of the waveguides considered. The spot size converters were constructed on both sides of the waveguides to reduce the coupling losses between the optical fibers and the waveguide; its effective cross-sectional area was estimated to be about one-thousandth of that of a single-mode fiber. The spot size converters had Si adiabatic tapers, and the second low-index waveguides that were 3 $\mu$m$^2$ covered the taper [25]. With this technology we achieved an outcoupling loss of only 1.9 dB. Moreover, in the experiment we employed fiber module SWWs, in which optical fiber pigtails were connected to the waveguide by using ultraviolet glue. A photograph of the module is shown in figure 4(b). A centimeter-square chip with a number of waveguides was installed in a rigid metallic case with fiber array interfaces. The case was 45 mm wide, 25 mm deep and 7 mm thick. By employing these modules, we were able to obtain long-term stability of the setup, which is advantageous in a long measurement such as a quantum interference experiment with photon pairs. This device required no temperature control.

After the photons from the SWWs had passed through the PCs, they were input into fiber Bragg gratings (FBG) to suppress the pump photons and were then separated into signal and

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idler photons by using arrayed waveguide gratings (AWG), which transmitted signal and idler photons with a 25 GHz full-width at half-maximum (0.2 nm). This narrow bandwidth of the AWG extended the photon pair coherence time to 18 ps. The wavelengths of the selected signal and idler photons were 1546.3 and 1555.9 nm, respectively. The photons were then input into band pass filters (BPF) to further reduce the number of pump photons. The signal photons from two independent SWWs were input into a 50:50 fiber coupler whose output ports were connected to single-photon detectors (SPD2 and SPD3). The transmittance and reflectance of

Figure 3. Experimental setup. IM, intensity modulator; PC, polarization controller; ATT, optical attenuator; ODL, optical delay line; SWW, silicon wire waveguide; FBG, fiber Bragg grating; AWG, arrayed waveguide grating; BPF, optical band pass filter; SPD, single-photon detector.

Figure 4. (a) The excess loss of light in the fiber module SWWs as a function of waveguide length. The solid line in the figure is a linear curve fit for the data. (b) A photograph of the fiber module SWW. SWWs of different lengths are installed in the rigid metallic case with fiber array interfaces.
the coupler were $-3.3$ and $-3.1$ dB, respectively. To ensure that the signal photons had the same polarization, a polarizer was installed in front of SPD2. SPD2 and SPD3 used an InGaAs APD (Epitaxx EPM239BA) whose gate frequency was 500 MHz. This fast gated mode operation was made possible by using the sine-wave gating reported in [26, 27]. With this scheme, we apply a sinusoidal signal as a gate. The avalanche signals, which are observed as electrical pulses in the time domain, have broad spectra in the frequency domain. On the other hand, the APD capacitive response to the gate signal is approximated to be a delta function in the frequency domain. We can easily suppress the APD capacitive response by using band rejection filters and so we can detect avalanche signals that are smaller than those observed in the conventional gating schemes. This means that we can reduce the afterpulse probability by setting the avalanche signals small (which can be realized by using a reduced gate voltage). Or if we accept a similar level of afterpulse probability to that of conventional gated mode detectors, we can significantly increase the gate frequency.

The quantum efficiency and dark count probability per gate of the photon detectors were, respectively, 11.5% and $1.6 \times 10^{-5}$ for SPD2 and 9.2% and $1.6 \times 10^{-5}$ for SPD3. The afterpulse probabilities of the photon counters were 3.9% for SPD2 and 6.9% for SPD3. On the other hand, the idler photons were detected by id-200 single-photon detection modules (id Quantique) operating with a 2.5 ns detector gate width (SPD1 and SPD4). The signals detected from SPD2 and SPD3 were used as triggers for SPD1 and SPD4, respectively. The losses of the setup, including those of the PC, FBG, AWG and BPF, were estimated to be approximately 5.8 and 6.4 dB for the idler1 and idler2 photons and 5.6 and 7.5 dB for the signal1 and signal2 photons, respectively. The coincidence rate obtained from the photon pair source based on SWW1 was about 5 kHz, which was measured using SPD1 and SPD2.

4. Experimental results and discussion

Figure 5 shows the twofold and fourfold coincidence count rates as a function of the relative delay time between two signal photons. HOM dips were clearly observed in twofold (squares) and fourfold (circles) coincidence measurements when the relative delay was zero. As the spectral shape of the photon pairs was determined by the spectral transmission of the AWG, it was approximated by a Gaussian. Thus, the coincidence count rates in figure 5 can be fitted by the following equation:

$$N = C \left[ 1 - \frac{2 V T R}{T^2 + R^2} \exp\left(\frac{-\delta \tau^2}{2 \sigma^2}\right) \right].$$

(19)

Here, $V$, $T$, $R$, $\delta \tau$ and $\sigma$ represent the visibility, the transmittance of the BS, the reflectance of the BS, the delay time and the $1/\sqrt{\pi}$ half-temporal width of the photon field, respectively, and $C$ is a constant. The visibilities estimated using equation (19) were 22 and 73% for the twofold and fourfold measurements, respectively. Thus, we observed quantum interference in the fourfold coincidence measurement since the visibility in this case is $>50\%$. We note that the measurement of the fourfold coincidence counts for each delay took approximately an hour. The measured temporal width of the fourfold coincidences was 38 ps, which is close to the full-width of the spectral transmission of the AWG.

In this experiment, the average photon pair numbers generated from SWW1 and SWW2 were estimated to be approximately 0.02 and 0.03, respectively. Therefore, the maximum visibility is calculated as 92% for $\mu = 0.05$ from equation (17).
Figure 5. Twofold and fourfold coincidence count rates as a function of the delay of a signal photon. The squares and circles represent twofold and fourfold coincidences, respectively. The HOM visibilities were 22 and 73% for the twofold and fourfold measurements, respectively. Statistical error bars are shown for fourfold coincidences. The error bars were smaller than the symbols for twofold coincidences.

There are other possible reasons for the visibility degradation. One such possibility is the timing jitter caused by the relatively broad pump pulse. When the pump pulse width is comparable to or broader than the coherence time of the photon pair, we observe the timing jitter of the generated photons, which results in the temporal distinguishability. In our experiment, the photon pair coherence time (18 ps) is close to the pump pulse width (19 ps), so a slight degradation of visibility is expected. If the ratio between the pump pulse width and the photon pair coherence time is given by $r$, the expected visibility of an HOM dip obtained with SFWM-based sources is expressed as $[7, 22]$

$$V = \frac{\sqrt{1 + r^2}}{1 + r^2 / 2}.$$  

With the parameter values stated above, the visibility is calculated to be $\sim 93\%$.

Another cause of the visibility degradation could be the large leakage of pump photons. To suppress the pump power, we employed filters, including an FGB, an AWG and a BPF, whose total attenuation was around 100 dB. The pump power at the SPD was estimated to be around $9 \times 10^{-12}$ W from the overall pump power attenuation. A pump power larger than that used in our previous report [19] was needed to obtain reasonably large coincidence counts and to shorten the measurement time required for the fourfold coincidence measurement. As a result, the imperfect suppression of pump power increased the accidental coincidence count, which reduced the visibility.

We believe that a combination of the above reasons may have resulted in the moderate visibility of 73%. The spectral purity of the heralded photons is also an important factor that determined the visibility in the previous HOM experiment using a photon pair source based on bulk crystals [28]. Since we use very tight spectral filtering (0.2 nm bandwidth), we consider that this effect is not the dominant factor for the visibility degradation.
We would like to note that there are other ongoing studies with which one may be able to realize high-quality heralded single-photon sources. For example, Mosley et al have reported a source with high spectral purity based on engineered phase-matching conditions in potassium-dihydrogen-phosphate \cite{28}. Sources based on SFWM in birefringent fibers are also being studied as heralded single-photon sources \cite{29,30}. A photon pair source based on the chalcogenide glass waveguide \cite{31} is another interesting candidate for a highly efficient photon pair source.

5. Conclusion

We have reported an HOM interference experiment with photon pairs originating from two independent SWWs. The photon pairs were generated through an SFWM process in each SWW. We successfully obtained a visibility of 73\% for the fourfold coincidence measurement by using fiber module SWWs. The fiber module SWWs may be employed in integrated photonic quantum information devices that use silicon photonics technologies, and may also be useful for QKD, QC and QR systems over optical fiber networks in the future.

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