Parametric down-conversion photon-pair source on a nanophotonic chip

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Quantum-photonic chips, which integrate quantum light sources alongside active and passive optical elements, as well as single-photon detectors, show great potential for photonic quantum information processing and quantum technology. Mature semiconductor nanofabrication processes allow for scaling such photonic integrated circuits to on-chip networks of increasing complexity. Second-order nonlinear materials are the method of choice for generating photonic quantum states in the overwhelming majority of linear optic experiments using bulk components, but integration with waveguide circuitry on a nanophotonic chip proved to be challenging. Here, we demonstrate such an on-chip parametric down-conversion source of photon pairs based on second-order nonlinearity in an aluminum-nitride microring resonator. We show the potential of our source for quantum information processing by measuring the high visibility anti-bunching of heralded single photons with nearly ideal state purity. Our down-conversion source yields measured coincidence rates of 80 Hz, which implies MHz generation rates of correlated photon pairs. Low noise performance is demonstrated by measuring high coincidence-to-accidental ratios. The generated photon pairs are spectrally far separated from the pump field, providing great potential for realizing sufficient on-chip filtering and monolithic integration of quantum light sources, waveguide circuits and single-photon detectors.

Light: Science & Applications (2017) 6, e16249; doi:10.1038/lsa.2016.249; published online 5 May 2017

Keywords: nanofabrication; quantum photonic chip; second-order nonlinear material; single-photon source
of visible-wavelength (775 nm) pump photons to telecom-wavelength (1550 nm) photon pairs. The high refractive index contrast between the AlN waveguides and a silicon-dioxide (SiO₂) cladding layer allows for small device footprint and enables dense integration on silicon handles. The generated photon pairs are characterized by waveguide-coupled superconducting single-photon detectors (SSPDs) integrated on a dedicated chip. Apart from high source brightness, we also observe high-visibility anti-bunching of heralded single photons. The suitability of our source for quantum information applications is further highlighted by the nearly ideal purity of the heralded photons, which we demonstrate in self-correlation measurements of the idler photons.

MATERIALS AND METHODS
Experimental setup and device engineering

The device is shown in Figure 1a. We realize the down-conversion source as a high-quality-factor AlN-microring resonator, which enhances the pump-photon interaction with the material’s χ(2) nonlinearity⁴⁰. This allows for the production of down-conversion photon pairs with long coherence times at low optical-pump power. Here, the visible-wavelength pump laser field is guided into the microring resonator via a narrow wrap-around waveguide, while the generated IR-photon pairs are coupled out via a wider bus waveguide. We design an on-chip wavelength-division multiplexer (WDM), which guides IR photons back into the optical fiber towards the detectors. After passing through a fiber-coupled silicon filter, the residual visible pump photons are rejected while IR photons are guided to waveguide-coupled SSPDs, which are integrated on a separate chip⁷,₂⁸,⁴¹ inside a cryostat. Waveguide directional couplers on this detection chip allow for 50/50 splitting of photon pairs before detection with the SSPDs and signal analysis with time-correlated single-photon counting (TCSPC) electronics.

The lower left inset in Figure 1b shows a cross-section of the AlN chip. AlN forms the core of the waveguide while SiO₂ acts as a low refractive index cladding layer, on top of the silicon substrate. A degenerate (non-degenerate) SPDC process involves one optical-pump mode in the visible-wavelength band and one (two) signal and idler mode(s) in the IR-wavelength band. Energy conservation implies the condition ωvis = ωIR, while momentum conservation requires mvis = mIR, where ωvis and mvis (vis = vis, IR, 1 or IR, 2) are the frequencies and azimuthal numbers of the visible and IR modes, respectively (for degenerate down-conversion, ωIR,1 = ωIR,2 and mIR,1 = mIR,2). To fulfill these two conditions and realize efficient nonlinear conversion, it is necessary to match the effective refractive indices n_eff = c/ωvisr (where c is the speed of light in vacuum and r is the radius of the microring) of the visible pump and IR signal and idler modes. This phase-matching condition can be satisfied for a higher-order transverse-magnetic (TM) visible-wavelength pump

![Figure 1](image-url)

Figure 1 On-chip SPDC photon-pair source. (a) Schematic illustration of an on-chip photon-pair source based on a χ(2) nonlinearity connected to SSPD on another chip. Higher-energy pump photons (visible wavelengths) are coupled to a microring resonator and the generated lower-energy photon pairs (IR wavelengths) are randomly split on the detector chip for coincidence measurements with integrated SSPDs. A fiber-coupled silicon filter (labeled as off-chip filter) is used to reject the remaining pump light reflected back from the fiber-to-chip interface. (b) Effective refractive indices of modes in microring. The phase-match condition is satisfied with waveguide width around 1.10 μm. (c) Cross-section of the AlN waveguide. (d) Device images of AlN down-conversion photon-pair source. The white dashed box shows the enlarged region. (e) Optical image of an array of microring photon-pair sources with on-chip WDMs. (f) SEM picture showing the coupling region of visible light bus waveguide (narrow) with microring resonator (wide).
mode and fundamental TM (TM0) signal and idler modes in the IR. In Figure 1b, we show how this effective refractive-index matching is achieved for a 775-nm TM2 mode and a 1550-nm TM0 mode by engineering the waveguide width of the AlN microring. In the right two insets of Figure 1b, the corresponding mode profiles in a 1.10 μm width waveguide are shown.

The high refractive-index contrast between waveguide (AlN) and cladding (SiO2) materials allows for a small device footprint and dense lithography. After development in an MF312 developer, Cl2/BCl3/Ar with a 2.5-to-1 ratio, the detector chip, where SSPDs are integrated with a 50/50 degenerate down-conversion photon pair. The photons are then sent through a waveguide. Adjusting the gap between the ring and the wrap-around waveguide as well as the wrap-around waveguide width, it is possible to adiabatically couple the TM0 pump mode of the feed waveguide to the TM2 mode of the microring under critical coupling conditions. As long as the gap between the wrap-around waveguide and the microring is large enough, the existence of this narrow waveguide will not cause deterioration of the quality factor for the ring resonator’s IR modes (see Supplementary Section I). The wrap-around waveguide is tapered down to 100 nm, as shown in the SEM image of the coupling region (Figure 1e), while the coupling gap between the wrap-around waveguide and microring is 500 nm.

**Device fabrication and measurement**

A 1-μm thin AlN film is sputtered on a commercial oxide-on-silicon wafer. We use FOX-16 resist and define patterns in electron-beam lithography. After development in an MF312 developer, Cl2/BCl3/Ar chemistry is used to etch into the AlN layer. The chip is then coated with a 2.5-μm PECVD-oxide cladding layer for protection during subsequent polishing steps. The device is finally annealed in an O2 atmosphere for 5 h at 950 °C to improve the quality of the PECVD oxide. The detector chip is fabricated from a commercial 330-nm SiN-on-insulator wafer, onto which we sputter an 8-nm thin film of NbTiN. Electrode pads are defined in PMMA resist via electron-beam lithography followed by gold deposition and lift-off in acetone. In a second electron-beam lithography step, the SSPD nanowires are patterned in HSQ negative-tone resist and transferred into the NbTiN layer using CF4 chemistry. In the third and final electron-beam lithography step, the SiN waveguides are written in ZEP positive-tone resist followed by a timed reactive-ion etch in CHF3/O2 chemistry.

We use a continuous-wave visible-wavelength laser (TLB-6712) to pump the SPDC source. A fiber-coupled silicon absorber (OZ optics) is used to filter out the pump light reflected from the fiber-to-chip interface. We achieve 80-dB attenuation for pump light at 3-dB insertion loss for IR light. For the degenerate SPDC coincidence measurement, a band-pass tunable filter is used to spectrally select the degenerate down-conversion photons. For the measurements of the SPDC thermal state, a dense wavelength-division multiplexer (DWDM) is used to select the idler branch from the nearest non-degenerate down-conversion photon pair. The photons are then sent to the detector chip, where SSPDs are integrated with a 50/50 directional coupler for self-correlation measurements. Electrical signals from the on-chip detectors are sent into a TCSPC system (Picoharp 300, Rudower Chaussée 29, 12489 Berlin, Germany) for time tagging. For non-degenerate cross-correlation measurements, a DWDM is used to separate signal and idler photons, which are then sent to two separate on-chip detectors for coincidence measurement.

**RESULTS AND DISCUSSION**

**Characterization of on-chip down-conversion source**

We first characterize the classical performances of the microring resonator. Figure 2a shows the microring transmission spectrum for visible light in a slightly under-coupled configuration (a critically matched mode pair (TM2,2) for SHG and degenerate SPDC, whose resonances are aligned within the linewidth of IR-mode resonance. (a) Visible light transmission spectrum, with TM2 mode resonances emphasized by red lines. The quality factor of the visible optical mode (TM2,2) is 1.1×106. (b) IR-light transmission spectrum, with TM0 modes identified by the azimuthal mode number. The typical quality factor of the IR mode is 2×106. (c) Difference frequency generation (DFG) measured by optical spectrum analyzer. Peaks due to input IR pump lasers are shown in the light orange region and generated DFG signals are shown in the light green region. Visible pump laser with 1.9 mW power on chip is fixed on resonance with TM2,2 for SHG. (d) Single-photon flux arriving at the detector chip from the degenerate and nearest three groups of non-degenerate down-conversion. The counts are calibrated by the wavelength-dependent detection efficiency (Supplementary Section II).
coupled spectrum is shown in Supplementary Section I). The visible
resonance near 775 nm, which is used in the following experiment, has
a quality factor of $1.1 \times 10^8$. Figure 2b shows the transmission
spectrum of IR light when the bus waveguide is critically coupled to
the microring resonator. The IR resonances show a typical quality
factor of $2 \times 10^5$. The two spectra illustrate how the TM$_{2,2N}$ mode at
775 nm aligns with the TM$_{0,2N}$ mode at twice the wavelength according
to energy conservation ($\omega_{\text{vis}} = 2\omega_{\text{IR}}$). Here, $N$ (2N) stands for the
azimuthal mode number, which is determined by momentum
conservation ($m_{\text{vis}} = 2m_{\text{IR}}$) in the degenerate SPDC process. To
perfectly fulfill the energy conservation ($\omega_{\text{vis}} = 2\omega_{\text{IR}}$), we vary the
global temperature of the chip and determine the optimized working
temperature using second-harmonic generation (SHG)$^{38,39}$ as a figure of
merit, which is directly related to SPDC efficiency (see the
theoretical derivation in Supplementary Section III). By pumping in
TM$_{0,2N}$ mode and monitoring the output SHG from TM$_{2,2N}$ mode, we
observe a maximum SHG efficiency of $\eta_{\text{SHG}} = \frac{P_{\text{SHG}}}{P_{\text{p}}} = 1.16$ W$^{-1}$,
where $P_{\text{SHG}}$ ($P_{\text{p}}$) is the optical power of the generated second-
harmonic light (pump laser). Due to the group-velocity mismatch
between the visible and IR modes, energy conservation cannot be
satisfied for SHG in other modes, as can be seen in Figure 2a and 2b,
where no pairs of IR- and visible-light modes are aligned, except for
the TM$_{2,2N}$ and TM$_{0,2N}$ modes. However, the group-velocity dispersion
is relatively small in the IR region, and energy conservation can be
fulfilled for IR modes over a wide wavelength range for difference/sum
frequency generation (DFG/SFG) and, conversely, for non-degenerate
SPDC. We verify this by fixing the visible-wavelength pump laser at
the resonance of the TM$_{2,2N}$ mode and sweeping the IR probe laser
over a wavelength range covering the neighboring resonances (for
example, TM$_{0,2N-1}$/TM$_{0,2N}$/TM$_{0,2N-3}$ modes). We observe DFG
of various modes, as shown in Figure 2c. The fact that both SHG and
various DFG configurations can be observed indicates the possibility of
generating both degenerate and non-degenerate photon pairs in
wavelength bands spaced similarly to a frequency comb.

We use SSPDs to characterize the statistical properties of photons
generated by the SPDC source. In Figure 2d, the photon flux for
different ring resonances is shown for fixed power and wavelength of
the visible-light pump laser. The variation in the detected photon
rates for different resonance wavelengths can be explained by the difference
in the quality factors of the IR resonator modes because the photon-
pair generation rate is linearly dependent on the quality factor. As
discussed in the Supplementary Information, the bandwidth for non-
degenerate SPDC can be as large as 40 nm.

**Correlated photon-pair generation**

The statistical properties of the generated photon pairs can be analyzed
in terms of the second-order correlation function ($g^{(2)}$), which we
measure using two detectors at the outputs of a beam splitter and
normalize to photon flux$^{44}$

$$g^{(2)} = \frac{R_{cc}}{R_1 R_2 t_b}$$

where $R_{cc}$ is the coincidence count rate, $R_1$ ($R_2$) is the count rate of
detector 1 (2), and $t_b$ is the coincidence time window. Here, the
coincidence rate $R_{cc}$ is a function of the photon-photon arrival-time
delay $\tau$, while $R_1$, $R_2$ and $t_b$ are constant, which are combined to
obtain the accidental coincidence rate $R_{ac} = R_1 R_2 t_b$. We note that the
$g^{(2)}(\tau)$ function is a rescaling of coincidence rate $R_{cc}(\tau)$ by accidental
coinidence rate $R_{ac}$. While the values of $R_{cc}$ and $R_{ac}$ are both
dependent on the losses of the measuring systems, the value of $g^{(2)}(\tau)$
is independent of system losses, allowing us to directly extract the pair-
generation rate and SPDC photon bandwidth from the measured
$g^{(2)}(\tau)$ function.

For degenerate SPDC photon pairs, we measure the self-correlation
function with two waveguide-coupled SSPDs integrated with a 50/50
directional coupler, as sketched in the left inset of Figure 3a. We
observe a clear coincidence peak centered at zero delay time, which
indicates strong temporal correlations between the photons emitted
from the SPDC source. The second-order self-correlation function for
degenerate SPDC photon pairs is given by$^{45-47}$

$$g^{(2)}_{\text{self}}(\tau) = 1 + \frac{1}{4R_{cc} \tau e^{-|\tau|/\tau_c}}$$

where $\tau$ is the delay time between two photons, $\tau_c$ is the coherence
time of the SPDC photons and $R$ is the photon-pair generation
rate. Here, random fluctuations in the arrival time $(\delta \tau)$ of photons
have to be taken into account because the detector jitter $(\tau_j = 18$ ps; see Supplementary Section V) and the coincidence
time window $(\tau_w = 70$ ps) are not negligible compared with the
photons’ coherence time $(\tau_c)$. Assuming the arrival-time fluctuations $(\delta \tau)$ follow a normal distribution $\frac{1}{\sqrt{2\pi}\tau_c} e^{-\delta \tau^2/2\tau_c^2}$, with standard
deviation $\tau_c = \sqrt{2\tau_j^2 + (\frac{\tau_j}{2})^2} = 43$ ps, the correlation function can be
expressed as (see Supplementary Section V)

$$g^{(2)}(\tau) = 1 + \frac{1}{RR\tau_c} e^{\frac{\tau^2}{2\tau_c^2}} [f_+ (\tau) + f_- (\tau)]$$

(3)

where $f_\pm (\tau) = \left[ 1 \mp \text{erf} \left( \frac{\pm \sqrt{2\tau_c}}{\sqrt{2\tau_c}} \right) \right] e^{\mp \tau_c}$, and erf(x) is the error function. From a fit to the data in Figure 3a, we obtain the degenerate photon-pair generation rate $R = 5.9$ MHz for a 1.9 mW pump power on chip. The bandwidth of the photons extracted from the fit to the data is $\Delta \nu = \frac{1}{2\tau_c} = 1.1$ GHz ($\tau_c = 145$ ps), which agrees with the measured linewidth of the IR resonator mode. This indicates that the coherence time of the generated photon pairs is determined by the lifetime of the signal/idler mode. The photon-pair generation rate as a function of pump power is shown in the inset of Figure 3a. We obtain a generation rate of 3.0 MHz mW$^{-1}$ for degenerate SPDC.

For non-degenerate SPDC photon pairs, the photons of a pair may have different wavelengths. If we discard all the signal photons and only measure the emission of idler photons, thermal-state statistics is expected. We measure the self-correlation function for the nearest idler (TM$_{0,N-1}$) photons, as shown in the inset of Figure 3c. We obtain $g^{(2)}(0) = 2.07 \pm 0.12$ from a fit to the data in Figure 3c, which is in agreement with the expected value of $g^{(2)}(0) = 2$ for a single-mode thermal state.

We then separate signal and idler photons using a DWDM and use two independent waveguide-coupled SSPDs to measure the second-order cross-correlation function between signal and idler, as shown in the inset of Figure 3b. For non-degenerate photon pairs, the cross-correlation function is given as

$$g^{(2)}_{\text{cross}}(\tau) = 1 + \frac{1}{4R\tau_c} e^{\frac{\tau^2}{2\tau_c^2}} [f_+ (\tau) + f_- (\tau)]$$

(4)

From a fit to the data in Figure 3b, we extract the photon-pair generation rate of $R = 11.0$ MHz for 1.9 mW pump power (5.8 MHz mW$^{-1}$), and the bandwidth $\Delta \nu = \frac{1}{2\tau_c} = 1.1$ GHz, which is similar to the degenerate SPDC case. We conclude that non-degenerate SPDC is approximately two times more efficient than degenerate SPDC, which matches well our theoretical calculation and originates from the different coefficients of the interaction Hamiltonian for degenerate and non-degenerate SPDC processes (Supplementary Section III). Additional cross-correlation measurements for photon pairs emitted into other microring resonance modes are shown in the Supplementary Information. The total (including degenerate and different groups of non-degenerate) photon-pair generation rate for this AlN microring source is more than 20 MHz mW$^{-1}$, which is comparable or even higher than the state-of-the-art SPDC photon-pair source using bulk or waveguide-based $\chi^{(2)}$ crystals. Regarding the spectral brightness, the AlN microring source is much brighter due to the microring’s narrow linewidth.

Source of heralded single photons

Single-photon sources are a critical component for quantum information processing. Quantum-dot systems have recently been explored for the on-demand generation of single photons with non-classical correlations. However, SPDC sources, such as the one used in this work, produce photon pairs probabilistically. Nevertheless, single-photon generation can be realized with an SPDC source by applying a heralding technique, i.e. one of the generated photons of a pair is detected, thus heralding the presence of its partner photon in a single-photon state. In our experiment, with 1.9-mW on-chip pump power, the photon-pair generation rate for the nearest non-degenerate modes (TM$_{0,N+1}$ and TM$_{0,N-1}$) is 11.0 MHz. As stated above, the signal or the idler beam itself is in a thermal state, showing bunching statistics with $g^{(2)}(0) = 2$. However, one can use the signal photon to herald the appearance of the idler photon, in which case the heralded idler photon shows non-classical anti-bunching behavior. To verify that our photon-pair source can be used as a heralded single-photon source, we measure the normalized idler-idler self-correlation function conditioned on the detection of a signal photon:

$$g^{(2)}_{h0}(t_1, t_2 | t_s) = \frac{P_{\text{in}}(t_1, t_2, t_s)}{r(0) g^{(0)}_{h0} | t_1 - t_s | g^{(0)}_{h0} | t_2 - t_s |}$$

(5)

where $P_{\text{in}}$ is the coincidence rate of detecting one idler and two signal photons, $g^{(2)}_{h0}$ is the second-order cross-correlation function and $r(\tau)$ is the first-order correlation function. Here, three detectors are needed. One detector is used to measure the signal photon as the heralding trigger, while the other two detectors measure the self-correlation of the heralded idler photons. We are interested in the special case in which $g^{(2)}_{h0}(\tau) \equiv g^{(2)}_{h0}(0, \tau)$. For an ideal photon-pair source, we expect to detect at most one idler photon upon detection of one (heralding) signal photon. Thus, an anti-bunching dip around zero delay time ($\tau = 0$) is expected. In our experiment, we split up the nearest non-degenerate photon pairs deterministically using a DWDM. We then use the signal photon as a herald for the detection of its partner photon and measure the autocorrelation function for the latter. The inset of Figure 4 shows a schematic diagram of the experimental setup. Figure 4 shows the measurement result with no background noises or dark counts subtracted. A clear anti-bunching dip near zero delay time is observed. We extract $g^{(2)}_{h0}(0) = 0.088 \pm 0.004 < 0.5$ from the data, which confirms that our SPDC source indeed yields heralded single photons.

Device losses and measuring efficiencies

The raw data of the coincidence measurements are shown in the Supplementary Information. The measured coincidence rate is approximately 80 Hz. For a pump power of 1.9 mW on chip, we infer an emission rate of photon pairs in the nearest non-degenerate modes of 11.0 MHz from a fit to the coincidence data in Figure 3b. The difference between these rates arises from losses at the various
device interfaces, that is, microring-to-waveguide interface (3 dB) and fiber-to-chip interface (3.5 dB), at the silicon filter (3 dB), at the DWDM (6 dB) and due to non-ideal detector efficiency (10 dB). Without subtracting any background noise or dark counts, we find a coincidence-to-accidental ratio of 560 for a minimum pump power of 0.6 mW, at which the on-chip generation rate amounts to 3.5 MHz.

We expect that, in future experiments, high-efficiency waveguide-coupled SSPDs and semiconductor avalanche single-photon detectors will be integrated alongside the source on the same chip. This will greatly increase the measured coincidence rate because the optical loss at photonic interfaces is minimal in such implementations.

**On-chip WDM**

The significant difference between the pump and signal/idler wavelengths in the SPDC process allows for a variety of design choices to separate pump light from the generated photons. One could choose to exploit wavelength-selective material absorption, for example, silicon will strongly absorb visible light but transmit IR light. Another approach is to design WDM waveguide circuits. In this work, we choose to realize the latter option because a WDM structure has the additional benefit of simplifying the fiber-to-chip coupling interface: (i) When characterizing the IR and visible performances of the microring, only one optical fiber at each side of the photonic chip is needed. (ii) When characterizing the down-conversion photon pairs, a single optical fiber is simultaneously used to send the pump light into and collect generated photon pairs from the chip (as shown in Figure 1a). The designed WDM structure employs tapered waveguide couplers, as shown in Figure 5a and 5b. In dielectric waveguides, the optical mode confinement decreases as wavelength increases, such that IR light will have a longer-range evanescent field outside the waveguides compared to visible light. For two waveguides in close proximity, the resulting coupling is stronger for IR than for visible light. We hence adjust the coupling length such that IR light is efficiently transferred from one waveguide to another (Figure 5a) while visible light remains unaffected and is transmitted through the coupling region without coupling to the neighboring waveguide (Figure 5b).

Here the adiabatic-taper WDM design is realized with high fabrication tolerances and broadband working wavelength. The relationship between coupling efficiency and coupling length is shown in Figure 5c for \( \lambda = 1550 \text{ nm} \) and 775 nm. The design shown in Figure 5a and 5b corresponds to a coupling length of 350 \( \mu \text{m} \) and a gap of 0.4 \( \mu \text{m} \). With increasing coupling length, the cross-port coupling for IR light increases monotonically and saturates at 100\%, while the visible-light transmission into the drop port decreases linearly with coupling length but remains above 99\% over the entire range. The inset of Figure 5c shows that coupling efficiencies into the cross and drop ports of more than 99\% are achieved simultaneously for IR and visible light, respectively, for coupling lengths ranging from 250 to 400 \( \mu \text{m} \). This performance corresponds to 20-dB suppression of visible pump light with less than 0.044-dB insertion loss for IR light for each of the on-chip WDM structures. In future implementations, a cascade of such WDMs could be used for realizing sufficient suppression of guided pump light. Note that, in the current experimental configuration, a portion of the pump light is directly reflected back into the optical fiber from the fiber-to-chip interface and is thus guided towards the detectors. To suppress these residual pump photons, we use an additional off-chip fiber-coupled silicon filter.

**Discussion**

The high-visibility anti-bunching of heralded single photons shown in Figure 4 confirms the non-classical character of our SPDC source. However, for quantum information processing, it is desirable to generate photons in a pure state. We use the Schmidt number, \( K \), to describe any remaining entanglement between optical modes of an SPDC pair. The Schmidt number \( K \), heralded single-photon state purity \( P \) and second-order self-correlations are related via \( g^{(2)}(0) = 1 + 1/K = 1 + P \). Ideal heralded purity \( (P = 1) \) is obtained if all measured photons are found in the same optical mode \( (K = 1) \). Conversely, if photons are found in multiple output modes \( (K \gg 1) \), the correlation function \( g^{(2)}(0) \) approaches 1 and the heralded purity approaches 0. In our experimental configuration, down-conversion photons will only be emitted into TM\(_0\) modes because other spatial modes do not fulfill the phase-matching condition. These TM\(_0\) modes are spectrally separated by at least one free spectral range, as shown in Figure 2d. Selecting one of these modes with a bandpass filter thus yields single-mode emission. The measured \( g^{(2)}(0) = 2.07 \pm 0.12 \) \( (P = 1.07 \pm 0.12) \) in Figure 3c confirms that our SPDC source indeed achieves single-mode emission and nearly ideal (unit) heralded purity.

In addition to the purity of generated photons, sufficient on-chip pump rejection is a key requirement for achieving source-detector integration on the same chip. Here, we discuss the prospects of realizing sufficient on-chip filtering. (i) Suppressing guided pump light in photonic waveguide circuits: The filtering of pump photons propagating inside a waveguide could, for example, be achieved by depositing a thin layer of silicon on top of the waveguide-interfacing source (circuit) and detector. Silicon has an absorption coefficient of 1740 dB cm\(^{-1}\) for the pump wavelength (775 nm) at cryogenic temperatures, while being transparent for down-conversion photons (approximately 1550 nm). The hybrid AlN:silicon waveguide hence results in significant selective absorption of pump photons. Alternatively, five cascaded on-chip WDMs (as described above) could also...
provide efficient pump-light rejection. (ii) Suppressing unguided pump photons propagating in free space and in substrate and cladding materials: Photons incident from free space can efficiently be absorbed in a metal layer covering the area where the detectors are located\(^3\). Pump photons scattered into a transparent substrate, however, pose a significant challenge in SPWFM experiments, where the pump light in the telecom band near 1550 nm can propagate losslessly in the cladding (usually SiO\(_2\)) and substrate (usually silicon) materials and finally couple to the detection region, which limits the on-chip filter’s performance\(^5,6\). In our case, however, the visible pump photons scattered into the silicon substrate layer are efficiently absorbed due to the large material absorption. Pump photons coupled directly from the input fiber into SiO\(_2\) slab modes may propagate for somewhat longer distances before leaking into the underlying silicon substrate of higher refractive index. Numerical simulations show that the attenuation of slab modes is >90 (200) dB cm\(^{-1}\) for a 3 (2) \(\mu\)m thick SiO\(_2\) buffer layer. Hence, detectors can be efficiently shielded from pump photons propagating inside the cladding layer if they are separated by a centimeter from the fiber-to-chip interface.

Entanglement\(^6,35,36\) is an important resource for quantum information processing and quantum communications\(^57,58\). Entangled photon pairs produced via SPDC in nonlinear bulk crystal\(^4\) and SFWM in silicon chips.\(^59\) We see the potential for further enhancement of the nonlinear conversion efficiency for AlN microring resonators by decreasing the ring radius and improving the quality factor of the microring resonator. We believe that a fivefold increase in quality factors and a threefold decrease in radius are achievable in future AlN devices, which would bring SHG efficiencies of 400 W\(^{-1}\) within reach.

**CONCLUSION**

In conclusion, the demonstrated photon-pair source based on the \(\chi^{(2)}\) nonlinearity of AlN microring resonators and the quantum-correlation measurement with waveguide-integrated single-photon detectors constitute an exciting step towards fully integrated photonic quantum circuits. Compared to photonic circuits fabricated from more traditional semiconductor materials, for example, silicon-on-insulator, AlN permits high-quality (high-brightness, high-purity, low-noise) correlated photon-pair emission that is spectrally far separated from the pump light. AlN-on-insulator therefore holds great potential for realizing efficient pump suppression and monolithic integration of non-classical light sources with single-photon detectors on the same chip. Additionally, high-speed phase modulation via the electro-optic effect will enable real-time circuit reconfiguration. In combination with high-efficiency single-photon detectors, it will thus be possible to generate non-classical photonic states and implement feed-forward schemes as well as quantum logic operations in a scalable manner.

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