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Corresponding Author:	Stefan Preble, Ph.D. Rochester Institute of Technology Rochester, New York UNITED STATES
Corresponding Author Secondary Information:	
Corresponding Author E-Mail:	sfpeen@rit.edu
Corresponding Author's Institution:	Rochester Institute of Technology
Corresponding Author's Secondary Institution:	
First Author:	Jeffrey A Steidle
First Author Secondary Information:	
Other Authors:	Jeffrey A Steidle
	Michael L Fanto
	Christopher C Tison
	Gregory A Howland
	Zihao Wang
	Paul M Alsing
Order of Authors Secondary Information:	
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TITLE:

Measurement of Quantum Interference in a Silicon Ring-Resonator Photon Source

AUTHORS:

Jeffrey A. Steidle¹, Michael L Fanto^{1,2}, Stefan F. Preble¹, Christopher C. Tison^{2,3,4}, Gregory A. Howland², Zihao Wang¹, Paul M. Alsing²

¹Microsystems Engineering
Rochester Institute of Technology
Rochester, New York, United States

²Air Force Research Laboratory
Rome, New York, United States

³Florida Atlantic University
Boca Raton, Florida, United States

⁴Quanternion Solutions Incorporated
Utica, New York, United States

Steidle, Jeffrey A.
jas2518@rit.edu

Fanto, Michael L.
fantom1580@gmail.com

Preble, Stefan F.
sfpeen@rit.edu

Tison, Christopher C.
christopher.tison.ctr@us.af.mil

Howland, Gregory A.
greg.a.howland@gmail.com

Wang, Zihao
zw4491@rit.edu

Alsing, Paul M.
alsingpm@gmail.com

CORRESPONDING AUTHOR:

Jeffrey Steidle
jas2518@rit.edu

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SHORT ABSTRACT:

Silicon photonic chips have the potential to realize complex integrated quantum systems. Presented here is a method for preparing and testing a silicon photonic chip for quantum measurements.

LONG ABSTRACT:

Silicon photonic chips have the potential to realize complex integrated quantum information processing circuits, including photon sources, qubit manipulation, and integrated single-photon detectors. Here, we present the key aspects of preparing and testing a silicon photonic quantum chip with an integrated photon source and two-photon interferometer. The most important aspect of an integrated quantum circuit is minimizing loss so that all photons that are generated are detected with the highest possible fidelity. Here, we describe how to perform low-loss edge coupling by using an ultra-high numerical aperture fiber to closely match the mode of the silicon waveguides. By using an optimized fusion splicing recipe, the UHNA fiber is seamlessly interfaced with a standard single-mode fiber. This low-loss coupling allows the measurement of high-fidelity photon production in an integrated silicon ring resonator and the subsequent two-photon interference of the produced photons in a closely integrated Mach-Zehnder interferometer. This paper describes the essential procedures for the preparation and characterization of high-performance and scalable silicon quantum photonic circuits.

INTRODUCTION:

Silicon is showing great promise as a photonics platform for quantum information processing¹⁻⁵. One of the vital components of quantum photonic circuits is the photon source. Photon-pair sources have been developed from silicon in the form of micro-ring resonators made via a third-order nonlinear process, spontaneous four-wave mixing (SFWM)⁶⁻⁸. These sources are capable of producing pairs of indistinguishable photons, which are ideal for experiments involving photon entanglement⁹.

It is important to note that ring resonator sources can operate with both clockwise and counter-clockwise propagation, and the two different propagation directions are generally independent from one another. This allows a single ring to function as two sources. When optically pumped from both directions, these sources generate the following entangled state:

$$|\psi\rangle_{ring} = \frac{1}{2} \left[\hat{a}_{cw}^{\dagger 2} + \hat{a}_{ccw}^{\dagger 2} \right] |vac\rangle$$

where \hat{a}_{cw}^{\dagger} and \hat{a}_{ccw}^{\dagger} are the independent creation operators for clockwise- and counterclockwise-propagating bi-photons, respectively. This is a very desirable form of entangled state known as a NOON state (N=2)¹⁰.

Passing this state through an on-chip Mach-Zehnder interferometer (MZI) results in the state:

$$|\psi\rangle_{out} = \frac{1}{4} e^{-i\theta} \left[\hat{a}_{cw}^{\dagger 2} - \hat{a}_{ccw}^{\dagger 2} + 2i\hat{a}_{cw}^{\dagger} \hat{a}_{ccw}^{\dagger} + \left(-\hat{a}_{cw}^{\dagger 2} + \hat{a}_{ccw}^{\dagger 2} + 2i\hat{a}_{cw}^{\dagger} \hat{a}_{ccw}^{\dagger} \right) e^{i2\theta} \right] |vac\rangle$$

This state oscillates between maximum coincidence and zero coincidence at twice the frequency of classical interference in an MZI, effectively doubling the sensitivity of the interferometer¹⁰. Here, we present the procedure used to test such an integrated photon source and MZI device.

PROTOCOL:

Note: This protocol assumes that the photonic chip has already been fabricated. The chip described here (shown in **Figure 1A**) was fabricated at the Cornell University NanoScale Science & Technology Facility using standard processing techniques for silicon photonic devices¹¹. These include the use of silicon-on-insulator wafers (composed of a 220 nm-thick silicon layer, a 3-μm layer of silicon dioxide, and a 525 μm-thick silicon substrate), electron-beam lithography to define the strip waveguides (500 nm-wide), and the plasma-enhanced chemical vapor deposition of the silicon dioxide cladding (~3 μm-thick). The micro-ring resonators were designed with an inner radius of 18.5 μm and a waveguide-to-ring gap of 150 nm. Figures of merit for this device include loss, quality factor, free spectral range, and dispersion.

1. Photonic Chip Preparation

1.1) Place a small amount of wax on a cross-sectioning polishing mount and heat it to ~130 °C.

Note: The amount of wax to be used depends upon the size of the sample being mounted. There must be enough wax to keep the chip immobile, while too much will result in wax on the chip facets.

1.2) Place the photonic chip on the portion of the polishing mount with the wax. Ensure that the wax is melted completely so that the chip is flat against the mount. Use plastic tweezers when handling the chip to avoid damaging the facets.

1.3) Allow the mount to cool in ambient air so that the wax solidifies. Cooling faster than this may result in damage to the chip.

1.4) Polishing the chip facets.

Note: It is important to choose the correct lapping pad, as starting with a pad that is too aggressive can result in polishing away more of the chip than desired.

1.4.1) Attach the polishing mount to the polisher and polish for only a few seconds. A pad with a 3-μm roughness has shown to be a good starting point for silicon chips with facet lengths of ~1 cm.

1.4.2) Remove the polishing mount and inspect the chip facet to determine how level the chip is mounted.

Note: A microscope is useful for measuring the distance between the ends of the waveguides

and the facet of the chip. These measurements allow for the angle between the facet and the waveguide to be determined.

1.4.3) Make the necessary adjustments to the micrometers on the polisher in order to improve the leveling of the chip.

1.4.4) Repeat steps 1.4.1-1.4.3 until the facet of the chip and the waveguides are within 0.15° of being orthogonal to each other.

1.4.5) Polish the chip in steps of $\sim 50\text{ }\mu\text{m}$, inspecting the chip between each step to monitor the distance remaining, until there is $\sim 100\text{ }\mu\text{m}$ left to polish. If at any point the cladding appears to be delaminating from the surface, ensure that the pad is rotating so as to polish from the top of the chip to the bottom.

Note: It may also help to use green lube instead of water. This delamination is an effect of stress in the cladding and is an indication that the fabrication process needs to be optimized.

1.4.6) Change to a $1\text{-}\mu\text{m}$ lapping pad and polish until there is $\sim 20\text{ }\mu\text{m}$ remaining.

1.4.7) Change to a $0.5\text{-}\mu\text{m}$ pad and continue polishing for another $15\text{ }\mu\text{m}$.

1.4.8) Use a $0.1\text{-}\mu\text{m}$ pad for the final $5\text{ }\mu\text{m}$ to ensure a smooth facet. Microscope images of the facet of a silicon photonic chip before and after polishing are shown in **Figure 2**.

1.5) Heat the mount with the attached chip to $\sim 130^\circ\text{C}$ to allow the wax to melt.

1.6) Once the wax is completely melted, remove the chip from the mount and allow it to cool slowly.

1.7) Clean any of the remaining wax from the chip using acetone, isopropanol, and water.

2. Preparation of Fiber Pigtailed

2.1) Strip any buffer or coating from the end of a single mode fiber (SMF) pigtail and from one end of an ultra-high numerical aperture (UHNA) fiber.

2.2) Clean the bare ends of the fibers with a mixture of acetone and methanol.

2.3) Cleave the bare ends of both fibers with a commercial fiber cleaver.

2.4) Fusion splice the cleaved end of the fibers. A recipe for splicing SMF to UHNA fiber is shown in **Table 1**.

2.5) Slide a protective sleeve over the splice and place it in the sleeve oven to permanently attach it to the fiber.

2.6) Repeat steps 2.1-2.5 to prepare a total of three fibers.

3. Configuration of the Testing Setup

Note: A diagram of the testing setup is shown in **Figure 1B**.

3.1) Place a small amount of wax on the chip mount and apply voltage to the thermo-electric cooler (TEC) to melt the wax.

3.2) Place the chip on the melted wax, ensuring that it is sitting flat on the mount.

3.3) Remove the voltage from the TEC and allow the mount and chip to cool slowly.

3.4) Attach each of the spliced fibers to a fiber v-groove with polyimide tape and mount a single v-groove to each of the 3-axis stages using the manufacturer-supplied mounting hardware.

3.5) Fiber edge coupling.

3.5.1) Connect the three fibers to their respective components: one to the optical output of the laser and the other two to optical power meters.

3.5.2) Adjust the microscope so that it is focused on the chip where the waveguides reach the edge.

3.5.3) Position the fibers close to the chip edge so that they are in the view of the infrared (IR) camera and adjust their heights so that the core of each fiber is in focus.

3.5.4) Adjust the horizontal positioning of the fibers with the stage micrometers so that they are lined up with the waveguides.

3.5.5) Turn on the optical output of the laser and tune the horizontal and vertical micrometer positions of the input fiber until the light is coupling into the waveguide. This will show up on the IR camera as scattering along the input waveguide and as a bright spot at one of the output waveguides.

3.5.6) Tune the wavelength of the laser to a point where the micro-ring resonator is lit up on the camera. This indicates that the resonance condition is being satisfied and that the light is reaching the output waveguides.

3.5.7) Adjust the horizontal and vertical micrometer positions of the output fibers until there is a measurable amount of light extending from the waveguides to the power meters.

3.5.8) Maximize the power to both detectors by manipulating the horizontal and vertical micrometer positions of the three fibers.

3.5.9) Further maximize the power to the detectors by making fine adjustments to the horizontal and vertical fiber positions using the piezo controllers.

3.5.10) Use the piezo controllers to move the fibers slightly closer to the chip. Make sure not to use the micrometers to push the fibers onto the chip, as doing so will likely damage the cleaved ends of the fibers.

3.5.11) Repeat steps 3.5.9 and 3.5.10 until the fibers are firmly pressed against the sides of the chip.

Note: Excessive scattered light from the waveguides, coupled with poor waveguide transmission, can be an indication of waveguide defects. These can include, but are not limited to, material defect sites, stitching boundaries, and excessive waveguide roughness.

3.6) Place a fiber-based polarization controller between the laser and the chip. This allows for control of the polarization state that makes it to the chip. The waveguides, being wider than they are tall, aid in minimizing any on-chip polarization rotation.

3.7) Dispersion characterization.

3.7.1) Tune the polarization of the laser output to maximize the coupling to the chip. This device was designed for transverse-electric (TE) polarization and, as such, the transverse-magnetic (TM) polarization has a much higher loss.

3.7.2) Scan a tunable laser over the wavelength range of interest (1,510 nm to 1,600 nm in this case) and monitor the power meters. Any artifacts in the transmission spectra are likely due to a combination of the TM component of the polarization and etalon effects from the fiber-chip interface.

3.7.3) Locate the resonant wavelengths in the spectrum and also extract the bandwidth of each resonance. This particular chip had bandwidths as small as 65 pm, which translates to quality factors (Q) of up to 23,000.

3.7.4) Determine the free spectral range (FSR), the separation between resonances, for each adjacent pair of resonances. This particular device had an FSR of ~5 nm.

3.7.5) Calculate the group index (n_g) of the guided mode for each value of the FSR using the following equation:

$$n_g \cong \frac{\lambda^2}{FSR * 2\pi * r}$$

where λ is the wavelength and r is the radius of the micro-ring resonator. The above equation is a first-order approximation of the group index.

3.7.6) Use the bandwidth of each resonance to determine a width (Δn_g) associated with each value of the group index.

3.7.7) Choose the wavelengths for the two pump lasers such that they coincide with resonances in the spectrum and have an odd number of resonances between them (**Figure 1C**).

3.7.8) Determine the wavelength of the degenerate bi-photons using the following equation:

$$\lambda_{Bi-Photons} = 2 \left(\frac{1}{\lambda_{Pump\ 1}} + \frac{1}{\lambda_{Pump\ 2}} \right)^{-1}$$

where $\lambda_{Pump\ 1}$ and $\lambda_{Pump\ 2}$ are the wavelengths of the pump photons.

3.7.9) Add a horizontal line on the plot of group index versus wavelength that extends between the two pump wavelengths (**Figure 3**). If it is possible for the line to sit within $n_g \pm \Delta n_g$ at all three wavelengths of interest simultaneously, the phase-matching condition is satisfied and photons can be generated via SFWM. If it is not possible, try choosing pump wavelengths that are closer together and check again.

3.8) Add a second tunable laser source and polarization controller to the setup and combine the optical outputs from both lasers with a 1 x 2 fiber combiner.

3.9) Add a series of fiber-based notch filters (enough of them achieve ~120 dB of attenuation) immediately before the chip.

Note: The filters allow both pump wavelengths to pass but reject the bi-photon wavelength. They help to remove excess noise (*i.e.*, broadband Raman scattering in the optical fiber) before coupling to the chip. The filter spectrum is shown in **Figure 1B**.

3.10) Add a series of fiber-based bandpass filters (enough of them to achieve ~150 dB of attenuation) immediately after the chip.

Note: The filters should be wide enough to allow the bi-photons to pass but narrow enough to reject the pump photons. Two sets of these are needed, one set for each output. The filter spectrum is shown in **Figure 1B**.

3.11) Send the rejected photons from each set of filters to separate power meters.

Note: These power meters are used to monitor the optical coupling to the chip and can also be used to determine if the pump lasers are remaining on-resonance.

3.12) Connect the individual optical output from each set of fiber-based filters to a single photon detector (SPD) and connect the electrical signal output from each SPD to a coincidence correlator.

3.13) Cross a pair of tungsten probes and set the tips down on one of the spiral legs (~1 mm in length) of the MZI.

3.14) Connect a power supply to the two crossed probes such that they generate heat when voltage is applied. This will act as the phase-shifter for the MZI.

Note: See the discussion for a description of the more standardized method for the thermal tuning of photonic devices.

4. Measuring Two-Photon Interference

4.1) Tune both of the pump lasers to the chosen wavelengths. Use the power meters that are monitoring the rejected pump photons to ensure that both lasers are tuned to the resonances. When the lasers are properly tuned to the desired resonances, the rejected signal from the filters will be maximized.

4.2) Set the optical power output from each laser to -3 dBm.

Note: This will result in $<100\text{ }\mu\text{W}$ at the chip. It is important to keep the pump power this low in order to minimize loss (from multi-photon absorption and free-carrier absorption) and maintain stability (by minimizing light-induced thermal shifts). PN junctions can be used to remove carriers from the waveguide to better accommodate higher pump powers.

4.3) Determine a sufficient integration time.

4.3.1) Monitor the coincidence counts (synchronous singles across two ports) by integrating over 224 ps about the peak of the data. Choose the integration window to account for the timing jitter of the SPDs.

4.3.2) Monitor the accidental coincidence counts (incoherent uncorrelated noise) by integrating over 320 ns (far away from the coincidence peak) and, from that, determine the number of accidentals contributing to the noise in the 224-ps coincidence window.

4.3.3) Calculate the coincidental-to-accidental ratio (CAR) from the measured value in steps 4.3.1 and 4.3.2. The CAR is the signal-to-noise ratio equivalent for time-correlated measurements.

4.3.4) Monitor the CAR during the measurement until it stabilizes. At that point, the integration time is determined to be sufficiently long.

4.4) Set the power supply for the phase-shifter to the initial voltage (*e.g.*, 0 V).

4.5) Scan one of the tunable lasers over the entire wavelength range and use the power meters that are collecting the rejected pump photons to confirm the location of the resonances of interest. Set the pump lasers to the wavelengths corresponding to the desired resonances.

4.6) Collect the single-photon counts from both detectors, as well as the coincidence counts, for an integration time of 90 s, with a timing resolution of 32 ps.

4.7) Increase the voltage applied to the phase-shifter by 5 mV.

4.8) Repeat steps 4.4-4.6 until data has been collected for the desired range of voltages.

Note: The maximum voltage was limited to 2.4 V due to rapid degradation of the probes above this voltage.

4.9) Integrate the coincidence peaks for each power-supply voltage over 224 ps to determine the total number of coincidences (**Figure 4**).

4.10) Integrate over 320 ns away from the coincidence peak to obtain the accidental coincidences. Use this result to calculate the number of accidentals in the coincidence peak.

4.11) Fit the singles counts from each detector with the following modified sine function:

$$f(V) = A * \sin[(B * e^{C*V} + D) * (V + E)] + F$$

where A, B, C, D, E, and F are the fit parameters. This fit is necessary due to the nonlinear relationship between the voltage and the induced thermal shift (relative phase).

4.12) Convert the independent variable to relative phase for all three sets of data (the singles counts from each detector and the coincidence counts) with the following equation:

$$\theta(V) = (B * e^{C*V} + D) * (V + E)$$

where B, C, D, and E are the fit parameters from step 4.11. This conversion is possible due to the well-known sinusoidal transfer function of an MZI¹².

4.13) Fit the coincidence data (with the relative phase as the independent variable) with the following sine function:

$$f(\theta) = A * \sin(2 * \theta) + B$$

where A and B are the fit parameters.

4.14) Calculate the visibility of each interference pattern with the following equation:

$$V = \frac{f(\theta)_{max} - f(\theta)_{min}}{f(\theta)_{max} + f(\theta)_{min}}$$

where $f(\theta)_{max}$ and $f(\theta)_{min}$ are the maximum and minimum values of $f(\theta)$, respectively. A visibility of 1 corresponds to a perfect interference pattern.

REPRESENTATIVE RESULTS:

Individual photon counts from each detector, as well as the coincidence counts, were collected as the relative phase between the two paths was tuned. The individual counts (**Figure 5A**) show the classical interference pattern from an MZI with visibilities of $94.5 \pm 1.6\%$ and $94.9 \pm 0.9\%$. The coincidence measurements (**Figure 5B**) show the quantum interference of the entangled state, as is evident by the oscillation at twice the frequency of the classical interference pattern, with a visibility of $93.3 \pm 2.0\%$ ($96.0 \pm 2.1\%$ with the accidentals subtracted). To confirm that the photons are primarily being generated in the ring, the pumps were configured into two resonances that would require the bi-photons to be generated at a wavelength not supported by the ring. The orange line in **Figure 5B** confirms that, with such a configuration, there are no significant coincidences. **Figure 6** shows the coincidence counts for the available resonance pairs that are symmetric in frequency about the resonance corresponding to the desired bi-photons. In all cases, the 2θ dependence of the relative phase is evident.

Figure 1: Experimental Testbed for the Silicon Waveguide Circuit

(a) Image of the silicon photonic quantum chip indicating the propagation direction of the photons. The inset is an energy conservation diagram for the four-wave mixing process that occurs within the ring. (b) Experimental setup used to test the silicon photonic circuit. (c) Transmission spectrum of the micro-ring cavity, with arrows indicating the pumping configuration as well as the wavelength of the generated bi-photons.

Figure 2: Facet Improvement from Polishing

Images of the facet of a silicon photonic chip (a) after fabrication but before polishing and (b) after polishing.

Figure 3: Characterization of Waveguide Dispersion

Plot of the wavelength dependence of the group index. The red-shaded region is representative of the bandwidth of the resonances and allows for the easy evaluation of the phase-matching condition. The green dashed line is horizontal and lies completely within the shaded region, demonstrating that the phase-matching condition is satisfied. The fact that the data is flat across the entire range is confirmation of zero dispersion.

Figure 4: Measurement of Coincident Photons

Plot of the coincidence peak measured with the time-correlator with an integration time of 90 s and a timing resolution of 32 ps. The red dashed lines indicate the edges of the coincidence window, in which there are a total of 459 coincidences.

Figure 5: Classical and Quantum Interference Measurements

(a) Classical light demonstrating the typical interference pattern from an MZI as the relative phase between the two paths is varied. (b) Coincidence correlation measurements showing the 2θ dependence of the relative phase.

Figure 6: Bi-Photon Visibility for Various Pump Wavelength Configurations

Plots of the coincidences correlation measurements and calculated visibilities for the pumping wavelengths of (a) 1,513.5 nm and 1,592.0 nm, (b) 1,518.2 nm and 1,586.9 nm, (c) 1,522.9 nm and 1,581.8 nm, (d) 1,527.7 nm and 1,576.7 nm, (e) 1,532.4 nm and 1,571.6 nm, and (f) 1,537.2 nm and 1,566.6 nm. In all cases, the 2θ dependence of the relative phase is evident.

Table 1: Settings for Fusion Splicing SMF to UHNA Fiber

DISCUSSION:

There are multiple challenges for the field of integrated photonics to overcome in order for complex and scalable systems of photonic devices to be feasible. These include, but are not limited to: tight fabrication tolerances, isolation from environmental instabilities, and minimization of all forms of loss. There are critical steps in the above protocol that help to minimize the loss of photonic devices.

One of the most crucial requirements in minimizing loss is closely matching the optical modes of the fibers and the waveguides. Part of the difficulty stems from the large mode field diameter (MFD) of SMF ($\sim 10\text{ }\mu\text{m}$). On the integrated device side, there is a 500 nm-wide silicon waveguide with a much smaller MFD ($< 1\text{ }\mu\text{m}$). This mode transition between the fiber and the waveguide can be improved in two ways: the SMF to a length of UHNA fiber or placing an inverse taper to the edge of the photonic chip. The spliced region between the SMF and UHNA fiber acts as a mode converter, reducing the size of the mode to $\sim 3\text{ }\mu\text{m}$. The inverse taper is used to expand the mode on the chip by reducing the width of the waveguide as it approaches the facet. This chip uses a linear taper from the 500-nm waveguides to the 150-nm tips (at the chip facets), with a transition length of $300\text{ }\mu\text{m}$. The tapering of the waveguide width to the edge of the chip results in a decrease in the effective index of the optical mode and, in turn, the mode expands.

The polishing of the chip facet is also very important in mitigating optical loss. Two concerns while polishing are stopping at the desired surface and delaminating the upper cladding material. Ideally, the final position of the facet would be precisely at the end of the taper. However, this is quite difficult to achieve, and for that reason, the tip of the taper is extended by $100\text{ }\mu\text{m}$ so that the polishing can be stopped a few microns before the taper starts. If too little material is removed, the mode will not be captured as efficiently by the taper. If too much material is removed, there will be a larger mode mismatch at the fiber/chip interface, and more of the light will be lost. The other main concern is the delamination of the upper cladding. If there are problems with fabrication (cleanliness or excessive stress in the cladding), the cladding may not adhere to the substrate at the edge of the chip. When delamination happens to occur at one of the waveguides, it will result in very poor coupling efficiencies. If it is noticed during polishing, a polishing lubricant other than water can often improve results.

There is room for improvement in the above protocol. The largest improvement would come from using a more standard method for thermally tuning the device. The method used here was a result of a simplified fabrication process that did not include any metal layers. Typically, a resistive metal layer is used for heater elements, and a highly-conductive metal layer is used for contact pads and wires from the pads to the heater elements. A stage can then be used to set down probes onto the pads, allowing voltage to be applied to the heaters. This enables a greater level of control and stability.

There are other methods of coupling light to the photonic chip. For this work, edge coupling was used. Other common methods include free space coupling and grating coupling. Free space coupling relies upon bulk optical elements to align and focus the beam into the waveguide at the edge of the chip. The drawback with coupling in this manner is that it can be very difficult to optimize the alignment of the beam, and there will always be a reflection at the interface due to the index difference. Grating couplers scatter the light from the waveguide vertically, so that the end of a fiber can be placed at the surface of the cladding to couple to the device. These also have some issues, including difficult alignment (the fiber is often in the line of sight of the microscope) and higher losses. Fiber edge coupling is not perfect either. Pressing the fibers against the chip can damage the ends of the fibers, and both the fibers and the chip edge need

to be cleaned frequently. The benefit of fiber edge coupling is that the alignment is far easier than the other two methods and is capable of achieving lower losses.

As the complexity of optical systems increases, the only feasible way for them to scale into a stable platform is in an integrated system, much like the path of electronic technology. The challenge is merging the integrated photonics platform with the bulk and fiber-based optical systems that are already deployed. With the utilization of photon-based quantum information systems, where the information space scales exponentially (compared to the linear scaling of classical systems), phase stability and low-loss integrated photonic technologies are paramount for success. The protocol we have described serves as an initial path forward for advancing this emerging technology.

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DISCLOSURES:

We have nothing to disclose.

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Figure 1

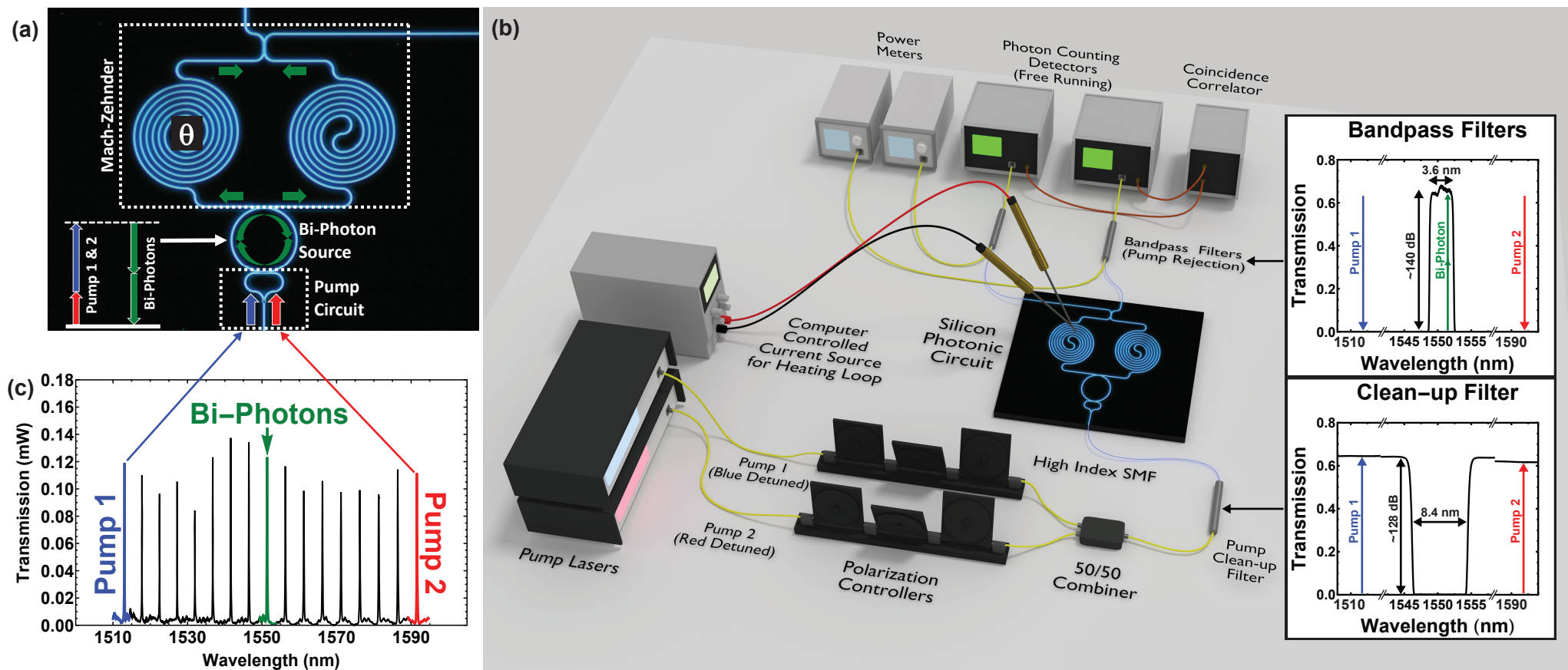
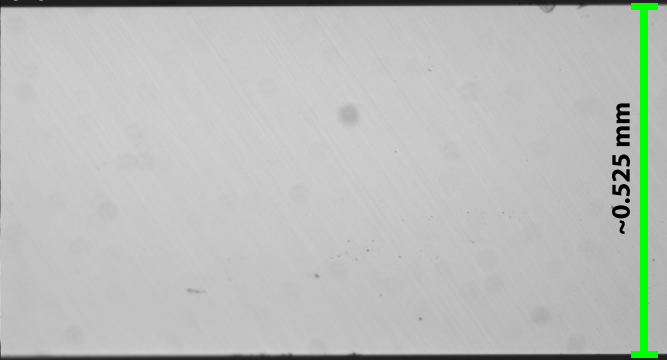
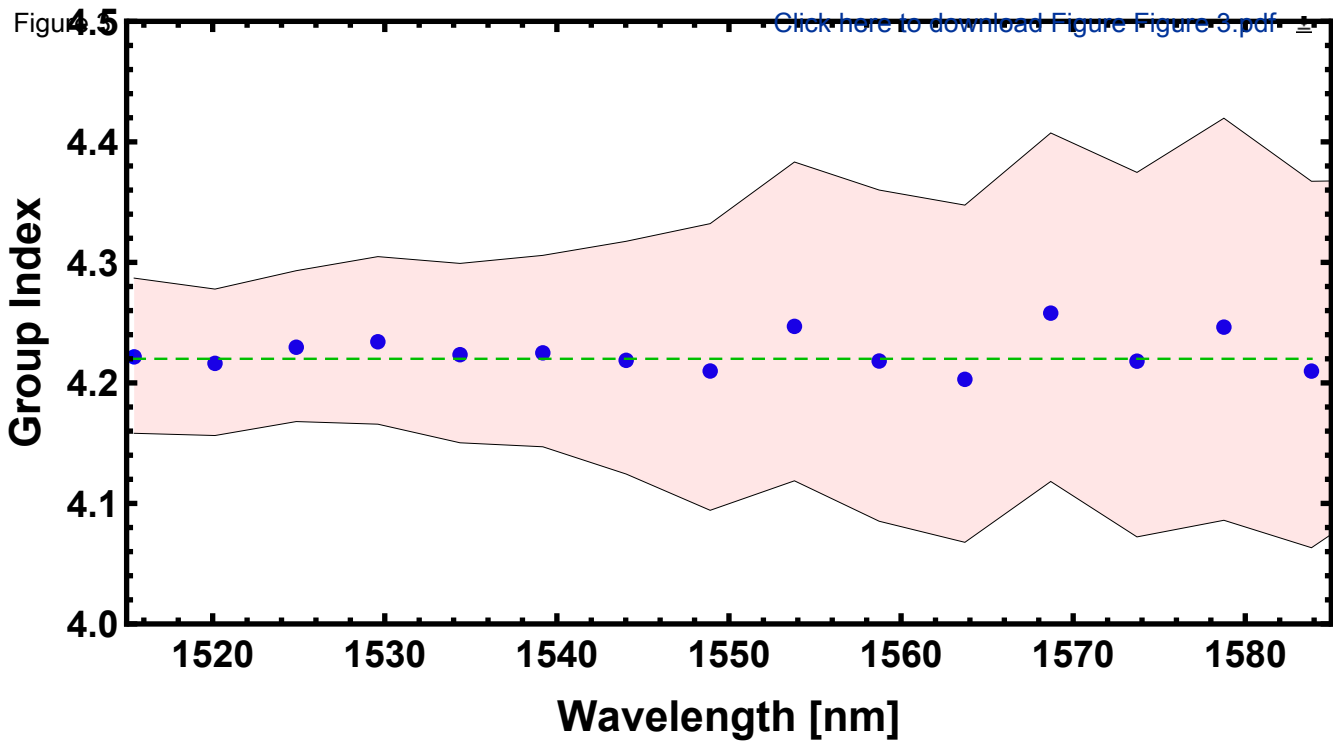


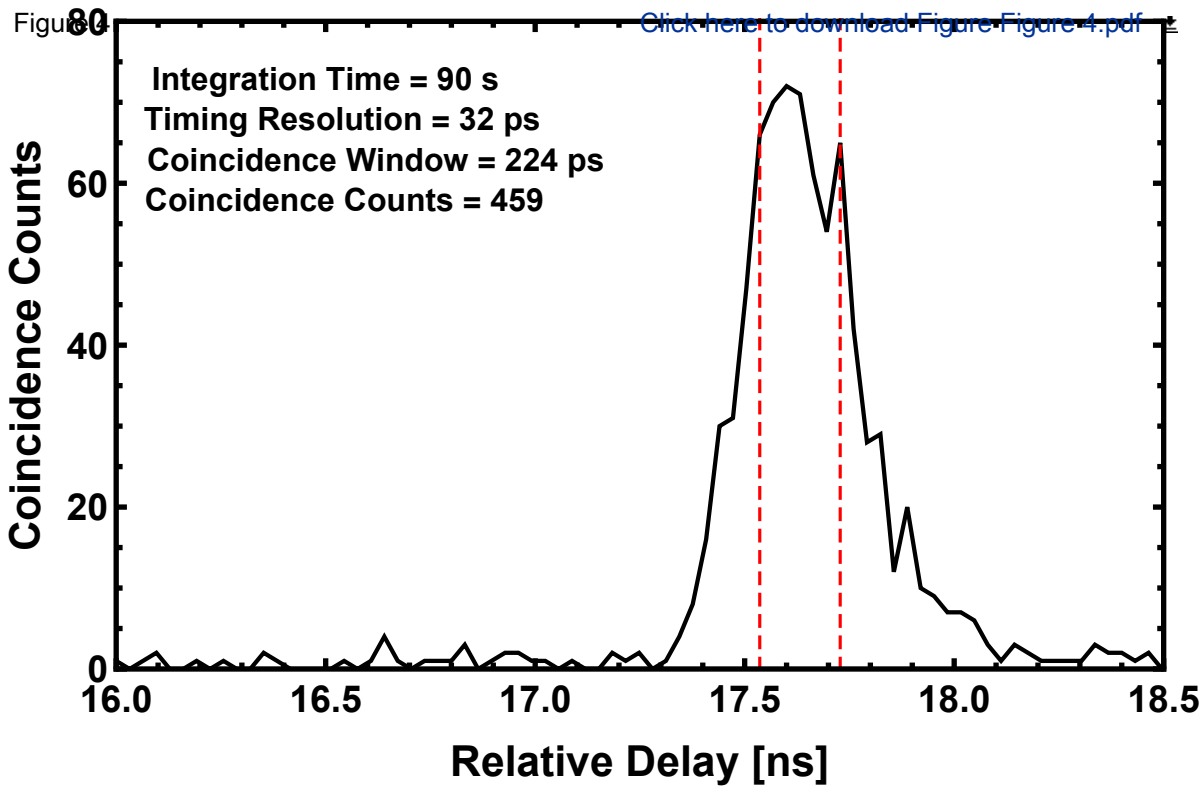
Figure 2



(b) [Click here to download Figure Figure 2.pdf](#)







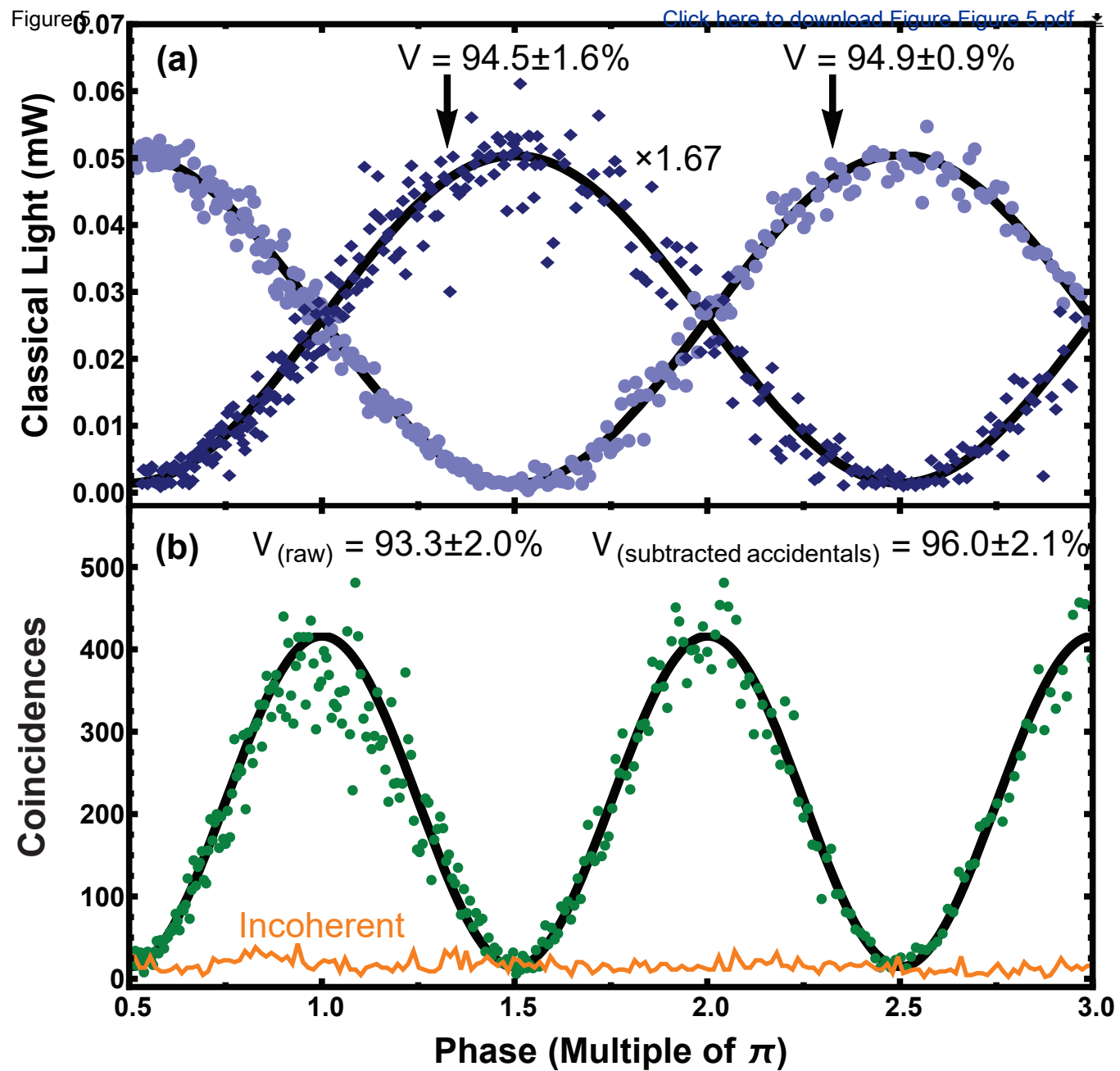
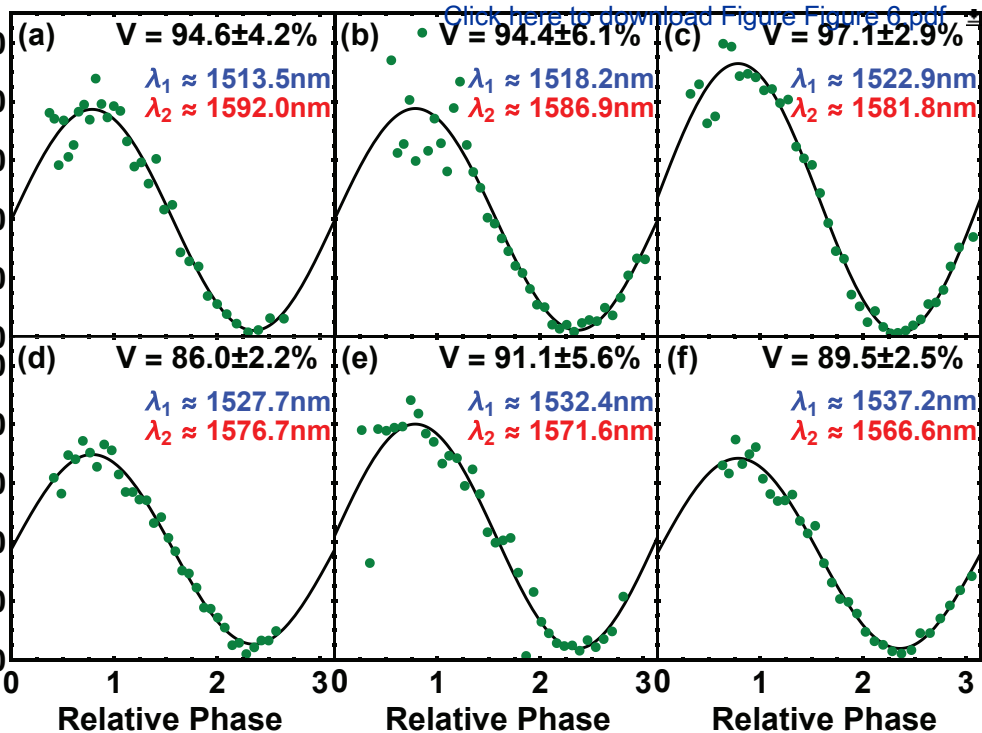


Figure 6

[Click here to download Figure 6.pdf](#)

Coincidence

Coincidence



SMF to UHNA Fiber Splicing Parameters	
Align: Core	Focus: Auto
ECF: Off	Auto Power: Off
Cleave Limit: 1°	Core Angle Limit: 1°
Cleaning Arc: 150 ms	Gap: 15 μm
Gapset Position: Center	Prefuse Power: 20 bit
Prefuse Time: 180 ms	Overlap: 10 μm
Arc1 Power: 20 bit	Arc1 Time: 18000 ms
Arc2: Off	Rearc Time: 800 ms
Taper Splice: Off	

Name of Reagent/ Equipment	Company	Catalog Number	Comments/Description
3-Axis NanoMax Flexure Stage	Thorlabs	MAX312D	Precision 3-axis stages
Three Channel Piezo Controller	Thorlabs	MDT693B	Piezo controllers for NanoMax stages
Fiber Polarization Controller	Thorlabs	FPC562	3-Paddle fiber-based polarization control
Fiber Cleaver	Thorlabs	XL411	Fiber cleaver
Standard V-Groove Fiber Holder	Thorlabs	HFV001	standard v-groove mount
Tapered V-Groove Fiber Holder	Thorlabs	HFV002	tapered v-groove mount
Right-Angle Top Plate for NanoMax Stage	Thorlabs	AMA011	right-angle bracket
50:50 Fiber Optic Coupler	Thorlabs	TW1550R5F1	50/50 combiner
Optical Fiber Fusion Splicer	Fujikura	FSM-40S	Fusion splicer
MultiPrep Polishing System - 8"	Allied High Tech	15-2100	Chip polisher
Cross-Sectioning Paddle with Reference Edge	Allied High Tech	15-1010-RE	Polishing mount
Lightwave Measurement System	Keysight	8164B	Mainframe for tunable laser
Tunable Laser Source	Keysight	81606A	Tunable laser
Optical Power Sensor	Keysight	81634B	Power meter
NIR Single Photon Detector	ID Quantique	ID210	Single photon detectors
NIR Single Photon Detector	ID Quantique	ID230	Low noise, free-running single photon
PicoHarp	PicoQuant	PicoHarp 300	Time-correlated single photon counting
WiDy SWIR InGaAs Camera	NIT	640U-S	IR Camera
WDM Bandpass Filter	JDS Uniphase	30055053-368-2.2	pump cleanup filters
WDM Bandpass Filter	JDS Uniphase	1011787-012	pump rejection filters
Ultra-High Numerical Aperture Fiber	Nufern	UHNA-7	high index fiber
Ultra Optical Single Mode Fiber	Corning	SMF-28	standard single mode fiber

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ng



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Author(s):

Jeffrey A. Steidle, Michael L. Fanto, Stefan F. Peck, Christopher C. Tison, Gregory A. Howland
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Name: Jeffrey A. Steidle
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Editorial comments:

The manuscript has been modified by the Science Editor to comply with the JoVE formatting standard. Please maintain the current formatting throughout the manuscript. The updated manuscript (55257_R0_072616.docx) is located in your Editorial Manager account. In the revised PDF submission, there is a hyperlink for downloading the .docx file. Please download the .docx file and use this updated version for any future revisions.

Changes to be made by the Author(s):

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues. The JoVE editor will not copy-edit your manuscript and any errors in the submitted revision may be present in the published version.

[Spelling and grammar issues have been addressed.](#)

2. Please abbreviate all journal titles.

[Completed.](#)

3. Please define all abbreviations before use.

[Completed.](#)

4. All tables should be uploaded separately to your Editorial Manager account in the form of an .xls or .xlsx file.

[Completed.](#)

5. Please provide titles for each Figure.

[Completed.](#)

6. Formatting:

-Please convert Table 1 to an Excel file. The .png cannot be used, and looks to have been obtained from a manual.

[The table has been converted into an excel file. The .png was obtained from a prior document that the authors had written for Nufern.](#)

-3.5.10 – The wrong steps are cited here. Please correct them.

[Steps have been corrected.](#)

-Please define all abbreviations at first occurrence (ie TEC, TM, TE, etc.).

Completed.

-The reference 9 citation is incomplete.

Reference 9 has been completed.

7. Please copyedit the manuscript for numerous grammatical errors, some of which are listed below. Such editing is required prior to acceptance.

-Line 71 – “One...are...”

-1.4.3 – “my” typo

-1.4.4 – “is indicates”

-3.4 – “3-axis stages” – are these multiple stages?

-3.5.2 – “core...are”

-Table 1 should be titled “Settings for...” rather than “Recipe”.

These editing fixes have been noted and fixed in the manuscript.

8. Additional detail is required:

-1.3 – How is cooling controlled?

Now addressed in text of 1.3.

-1.4.3 – How are these adjustments made?

Now addressed in 1.4.3 and 1.4.4.

-2.3 – Cleave how and by how much?

Now addressed in 2.3. Length will be set by the commercial cleaver of one’s choosing.

-3.1 – What is a TEC?

Now addressed in 3.1, thermo-electric cooler (TEC).

-3.4 – Are the fibers mounted to the stage or is the chip? How? How many fibers are used?

Which are input and which are output?

Now addressed in 3.4. and 3.5.

-3.5.5 – What ring?

Now addressed in 3.5.6. Ring refers to the micro-ring resonator.

-3.5.6 – When were fibers attached to the power meters?

Now addressed in 3.5.1.

-4.4 – Please provide a citation. It there is insufficient detail.

Additional details were added in section 3.7.

How is this done?

-4.6, Now addressed in 3.8.

4.9, Now addressed in 3.11 and 3.12

4.10 Now addressed 3.13 and 3.14.

9. Please remove commercial branding: Table 1 – Fujikura

Completed.

10. Results: Figure 3 – Please describe each of the plots individually. What are their differences?

Completed, differences were the choices of pump wavelengths used to generate the bi-photons.

11. Discussion: Please discuss the future applications of the protocol.

Added a discussion section for future applications.

Reviewers' comments:

Reviewer #1:

Manuscript Summary:

The manuscript describes the measurement of quantum interference in an integrated silicon device, where both source (four wave mixing parametric downconversion) and interferometer (an inscribed MachZender interferometer) are monolithically fabricated on a Silicon chip. Authors describe in details the polishing phase, and the coupling in and out to a fiber, as well as the optical configuration used to measure the interference. They finally show figures clearly displaying quantum interference, featuring a period double the classical fringes, indication of the generation of NOON state photon at the source.

Major Concerns:

My major issue with the manuscript is the inconsistency between the title and the technique presented. Indeed the authors present an quantum interference measurement, but the larger part of the methods focuses on the chip preparation and optical coupling, that is more of a general issue.

The manuscript has been modified to more closely reflect the title.

The authors should address better the steps that are more related to the experiment (or in general for performing quantum optics on Si devices), i.e. part 4 should be extended. Here are few technical issue that could be addressed

- Indicate the pump power levels, state if amplification is needed, and if care has be taken to tune the laser into resonance (e.g. if thermal shift plays a role)
- Stress the importance of noise and pump filtering and how to achieve 120 db noise suppression.
- Indicate other possible sources of noise (i.e. multi-pairs generation or stray light from the top of the chip)
- Show the photon-pair temporal characterization and how you determine the gating window
- Since the platform is Si, a comment on the 2-photon absorption should be given, including way to manage it via PN junction

Sections 3 and 4 of the manuscript have been extended with a more in depth discussions of these issues to address all of the above points.

Minor Concerns:

I believe the discussion of losses and taper coupling is a little confusing: the inverse taper is not well described in the text, especially in relation with the polishing. Maybe a figure/close up could clear the explanation.

A clearer description of the taper is now added to the discussion section of the paper. This section details the purpose of the taper on both sides, in fiber and on the chip. The tapering of the waveguide itself is slow enough over a long enough distance that an image would not capture the taper.

Also, little details on the photonics structure are given: what are the property of the source (Q-factor, free spectral range..) and of the interferometer (arms length, $d\phi/dt$). What are the figure of merits that are optimized when designing the structure?

These quantities have been added to the section 3.7.3, 3.7.4, 3.13. The figures of merit are the loss, Q, FSR, and dispersion of the device to be constructed and are addressed in the note section at the beginning of the protocol section.

Additional Comments to Authors:

The work is well described, with clean results. It just need to be more on focused on the integrated quantum optics aspect of the experiment.

Reviewer #2:

Manuscript Summary:

Firstly this is probably not the part of the experiment that needs a tutorial. The procedure of measuring entanglement, data processing, correcting for accidentals and dark counts etc. would be much more useful (especially since there is a lot of mis-understanding in that area from non-experts). That is what the title seems to suggest. But the "protocol" details are about polishing chips and basics of coupling light to them - something that is pretty simple for even a one-hour undergraduate lab. Does this really need to be in a paper?

Section 4 and the discussion have been expanded to include more of the measurement analysis of the quantum state. The polishing and setup for the experiment are just as crucial though to the experiment as they add to the loss of the entire circuit. This loss is squared when measuring coincidence, so a minimization in the loss is crucial.

Even in that area, there are too many unanswered questions to create a reliable "recipe" ...

"place a small amount of wax on a polishing mount": what is a "small amount"? What is a "polishing mount"? Was it provided by the equipment manufacturer or made? How smooth, what material, what hardness, what thermal properties etc. ? These details are crucial for polishing (as any packaging researcher will always point out).

"so that the chip will be firmly attached to the mount": what is "firmly"? How much force? How is it handled / attached without damaging the surface or the edges?

"do not cool the mount too quickly": how quickly is "too quickly"?

"Correct for any misalignment by making adjustments to the micrometers on the polisher." How is a misalignment noticed - visually, or measuring microscope or interferometer? Is there a recipe / procedure for the tip-tilt adjustment, or just trial and error? How good an accuracy can be achieved?

"to ensure a smooth facet." What is a "smooth facet" - how smooth? How is that quantified - how does the experimentalist know when to stop?

These points have now been addressed in an expansion of section one and figure 2 which shows the unpolished and polished chip facet.

"Choose the wavelengths for the two pump lasers. They must coincide with resonances in the spectrum and ..."

This is addressed in section 3.7.5 to 3.7.9.

Much harder than it seems, because of light-induced heating and thermal resonance shifts. "soft-locking" from the red side of the deformed resonance, etc. Moreover, silicon is an indirect band-gap semiconductor, which generates free carriers ...

These are valid points and have been addressed in 4.2.

There are many more unanswered questions ... I am afraid that the amount of provided information is simply not enough for a non-expert researcher to learn how to do this experiment accurately, efficiently and correctly. And the experts do not need this.

These comments have now been addressed with the expansion of sections 3 and 4.

Section 3 is far too simple. It says nothing about all the challenges in ensuring the light remains in the correct polarization state, in quantifying the amount of scattered light, in explaining the various artifacts in the transmission spectra etc.

Section 3 of the manuscript has been significantly expanded to include details addressing these issues.

Polarization state in sections 3.6, and 3.7.1

Scattered light in note immediately after section 3.5.11

Artifacts in the transmission spectrum in section 3.7.2

Major Concerns:

N/A

Minor Concerns:

N/A

Additional Comments to Authors:

N/A

Reviewer #3:

Manuscript Summary:

The authors describe a method for the preparation of a silicon quantum photonic chip and the

experimental set-up for on-chip photon state generation and quantum interferometric measurements. In this work they present the experimental set-up and the data shown in their previous work from 2015 (PHYSICAL REVIEW APPLIED 4, 021001), adding some of the experimental details and methods not presented in that article.

In this new work submitted to JoVE they focus more on the preparation of the sample for the minimisation of losses, one of the most important aspects in this kind of experiment.

Major Concerns:

No Major concerns, except maybe to modify slightly the abstract.

Completed. Abstract has been slightly modified as well as additions to sections 3 and 4 of the manuscript.

They actually describe only some of the key aspects of such preparation, focusing mainly on the minimization of losses for a particular kind of device. Furthermore loss is probably one of the fundamental problems in this kind of experiment but there are also other that could limit the feasibility.

These points are now addressed in the discussion section.

Nonetheless the information on this work are useful and should be published on JoVE.

Minor Concerns:

1. More informations on the silicon photonic device fabrication would be beneficial (e.g. size of the waveguide, is it a strip waveguide? What kind of tapers? was it fabricated with UV lithography or e-beam lithography? depth of the substrate and so on). I request this since some of the steps described by the authors will depend on the particular fabrication used.

This is now addressed in the note at the beginning of the protocol section.

2. In point 1.7 of the protocol the authors describe the use of acetone, isopropanol and water, for cleaning residual wax from the chip. This is ok in their case but in some silicon photonic devices the in/out tapers can be fabricated using polymer waveguides, in these cases acetone can damage the device. Are there any alternatives to the use of wax or acetone?

The chips can be mounted with epoxy, or a low stick double sided tape which would not expose the chip to the wax. This would be more friendly for devices which have polymer portions. This was not explicitly addressed in the paper as polymers are not the material system that is described in this specific paper, though these are valid questions addressed by the reviewer.

3. Missing integration time information for the data plots. The reader has to search for their previous work to get this information and get the count rate observed in their experiment. It would be good to report here again this information.

This data has been added to the plots.

4. Filters information missing in table of materials, it would be beneficial to know if these are commercially available filters or specifically fabricated for this experiment

Filter information is added to the table of materials.

Additional Comments to Authors:

N/A