A micrometer-scale integrated silicon source of time-energy entangled photons: supplementary material

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1. SAMPLE FABRICATION

The devices were fabricated on a silicon-on-insulator (SOI) wafer from SOITEC with a 220 nm-thick silicon core layer. The 5 mm-long and 500 nm-wide single-mode silicon waveguides for TE-polarized light were fabricated comprising spot-size converters (SSCs) for efficient input and output coupling. SSCs consist of 300 μm -long silicon inverse tapers with a 20 nm tip width and $1.5 \times 2.0 \mu\text{m}^2$ polymer (SU8) waveguides. Ring resonators with radii of 5, 10, 20 and 30 μm were fabricated side-coupled to a single bus waveguide at different coupling distances for each radius. The pattern of the silicon waveguide structures was defined in negative tone resist via electronic beam lithography, and then transferred into the silicon layer by using inductively coupled plasma reactive ion etching. Polymer waveguide-couplers were written in SU8 material using a second e-beam lithography step. The silicon chip was finally coated with a protective PMMA layer. We chose a ring resonator with radius $R=10 \mu\text{m}$ and a coupling distance of 150 nm for the experiments reported in this paper based on its efficiency in the generation of photon pairs.

2. DETAILED EXPERIMENTAL SET-UP

Figure S1, gives a detailed scheme of the actual setup we employed. Light from a tunable cw pump diode laser (Santec, TSL-510), whose wavelength can range through 1500-1630 nm, comes through a polarization maintaining (PM) single-mode

optical fiber. The pump laser light is collimated to free-space by means of an aspheric lens and then it passes through a half wave plate (HWP) and some pass band interferometric filters (PBFs) to achieve more than 120 dB of side-band suppression at the frequency of the spontaneously generated photons. The collimated and filtered pump laser is then injected into the silicon wire waveguide (SWW) by means of a second aspheric lens, which focuses the beam to a diffraction limited spot (diameter $\sim 2 \mu\text{m}$) onto the waveguide's edge. The HWP is turned to align the pump polarization to the TE-like single mode SWW. The sample has polymeric field mode converters to couple the silicon wire waveguides to the optical fibers.

The output from the sample is collected by a PM lens tapered fiber mounted on a high precision fiber rotator. In-coupling and out-coupling losses are estimated to be the same, and they sum up to a measured value of about 7 dB. Then two band pass filters (BPFs), tuned at the signal and idler frequencies, are employed at the output of a 50:50 fiber beam splitter in order to separate the signal from the idler.

A. Characterization and Four Wave Mixing measurements

Linear transmission spectra with a resolution of 5 pm were taken using a tunable continuous wave laser modulated through an optical chopper for injection and an InGaAs photodiode coupled to a lock-in amplifier for detection. The experimental setup used to test spontaneous four wave mixing uses a Santec TSL-510 tunable cw laser. Spectral filtering of the

Fig. S1. Complete scheme of the experimental set-up. The acronyms stand for: PMF, polarization maintaining fiber; SMF, single mode fiber; BPF, band-pass filter; FP, fiber polarizer; Piezo, piezoelectric actuator.

laser beam is performed before injection to filter out the fluorescence background emitted from the laser because of amplified spontaneous emission. The pump beam is collimated to free-space using an aspheric lens, its polarization is aligned to the TE-like single-mode of the silicon waveguide, and finally the pump light is coupled to the sample using an aspheric lens. The output from the sample is collected with a PM lensed-fiber mounted on a high-precision fiber rotator. The total insertion losses of the silicon chip are estimated around 7 dB. The output containing the transmitted pump beam and the photon pairs is sent, through a 50:50 fiber beam-splitter, to two band pass filters (BPF) tuned to the signal and idler frequencies in order to reject the remaining pump. Using a 50:50 fiber beam-combiner, the output of both band pass filters is finally conveyed to a monochromator coupled to a nitrogen-cooled CCD.

B. Measurement of the generation and output rates

The output rate was measured in an ad-hoc set-up: we calibrated the response of the LN-cooled CCD camera using a power-meter with sub-pW sensitivity, so that the CCD could be then used as a power-meter itself. Between the sample and the CCD we have placed only a filtering stage (to select only signal or idler photons and completely rejecting all other resonances including the pump). The insertion loss of the filtering stage was directly measured to be 3.5 dB. To extract the internal generation efficiency, we have back-traced this flux to the ring by adding an additional 3.5 dB of coupling losses (half of the 7 dB insertion loss of the whole sample).

C. Coincidence measurements

After the signal and idler filters, collimators couple the photons from the optical fibers to free space. Signal and idler photons then enter the two separate, equally unbalanced, Michelson interferometers. The path length difference is about $\Delta L \simeq 18$ cm, well above the coherence length of the generated photons ($l_c \simeq 3$ mm). The mirrors on the short path of the interferometers are positioned using an open loop piezo actuator (Attocube series 101) with resolution better than 1 nm. The piezo actuator is connected to a computer-based feedback system that allows the stabilization of the interferometers and the control of their relative phase (see the next section). The collimated photons exiting from the interferometers are then coupled to two single mode fibers by which signal and idler photons are sent to two superconducting single photon detectors from Scotel.

Losses were directly measured for all components of the set-up. In-coupling and out-coupling losses of the sample are estimated to be the same, and they sum up to a measured value of about 7 dB. So the outcoupling losses from the sample are $L_{out} = 3.5$ dB, then the beamsplitter introduces another $L_{bs} = 4$ dB, while losses from the filters have been measured to be $L_{filter} = 3.5$ dB. Since we are only collecting from one of the two outputs of each interferometer (with the second output coinciding with the input), half of the signal and idler photons are lost. Moreover, for every interferometer, nonunitary mirror reflectivity, beam splitter imperfections, and coupling losses from fiber to free-space, and viceversa, result in a total loss $L_{Interf} \simeq 10$ dB for both the short and the long paths. Detector 1 has a detection efficiency of 10%, so $L_{D1} = 10$ dB, while detector 2 has a detec-

tion efficiency of 5%, so $L_{D2} = 13$ dB. In total we have a loss $L_s = L_{out} \cdot L_{bs} \cdot L_{filter} \cdot L_{interf} \cdot LD1 = 31$ dB for signal photons, and a loss of $L_i = L_{out} \cdot L_{bs} \cdot L_{filter} \cdot L_{interf} \cdot LD2 = 34$ dB for idler photons. The detected coincidence rate is then given by $R_{coinc} = R \cdot L_s \cdot L_i$ where R is the internal generation rate, so on R_{coinc} there is a loss of about 65 dB.

A very important condition to fulfill in a Franson type experiment is the following relation between the relevant time quantities: $\tau_c \ll \Delta T \ll \tau_p$, where τ_c is the coherence time of signal and idler photons, $\Delta T = \Delta L/c$ is the time difference between the two paths of each interferometer, and τ_p is the pump laser coherence time. The second fundamental condition is that both interferometers must have the same path difference to within the coherence length of signal and idler photons. In order to align the path difference of the two interferometers we used the following procedure. The first interferometer (at Alice's side) was aligned using a highly coherent laser beam. The second interferometer (at Bob's side) is then roughly aligned (to within about one centimeter) by means of a measuring tape. Then, a pulsed laser (spectral width ~ 8 nm, and pulse coherence time ~ 0.5 ps) is injected in Alice's interferometer whose output is connected in cascade to the input of Bob's device. Finally, the output of Bob's interferometer is sent to a slow detector. Then, the piezo actuator controlling Alice's mirror is scanned with an excursion larger than the laser wavelength. Since the coherence length of the laser pump pulses ($\delta l_p \simeq 150 \mu\text{m}$) is much shorter than ΔL , interference arises when $\Delta L_A \simeq \Delta L_B$. Note the interference involves only two of the four paths a pump pulse can take, and thus its visibility is limited to 50 %. By maximizing the interference's amplitude oscillation, we were able to set the same value of ΔL for both interferometers to within $\sim 150 \mu\text{m}$, well below the coherence length on the generated photons (estimated to be about 3 mm).

3. STABILIZATION OF THE INTERFEROMETERS

Fig. S2. Scheme of the stabilized interferometer comprising a control red beam and a target (measured) IR beam. The inset shows the transmission of the red and IR beams through the wedge beam-splitter, the effect is intentionally exaggerate to better show the effect.

In order to verify time-energy entanglement between photon pairs produced by our silicon microring resonators, it is necessary to relate the coincidence rate at the output of two separate interferometers, while varying their phases ϕ_A and ϕ_B . The period length of the interference is about half the pump wavelength (~ 775 nm). Because of the sub micrometric period

Fig. S3. (a) Interferometer output with and without the feedback as a function of the acquisition time. (b) Statistical distribution of the phase errors δ during the stabilization.

of the interference, together with the need of long integration time in coincidence measurements, environmental noise, due for example to thermal fluctuation or mechanical stresses on the optical table, can seriously affect the results of the measurement. This configuration therefore requires very accurate control and stabilization of the path length difference between the arms of each interferometer. To achieve this aim we have developed a new stabilization method by which it is possible to actively stabilize an interferometer at an arbitrary phase with subnanometric resolution. The scheme of our set-up is reported in Figure S2: a He:Ne laser ($\lambda_p = 632.8$ nm) (depicted in red in Figure S2) is used as a reference beam, while signal and idler photons follow the controlled IR beam path (in green). One of the two mirrors (M1) is slightly tilted and forms an angle α with the plane P, which is parallel to the wavefront of the incoming light (y -direction), so that the two parts of the reference laser beam traveling in the two arms exit the interferometer at a slightly different angle and the interfering beams are no more collinear. This angle results therefore in vertical spatial interference fringes along the y -direction.

In order to obtain a collinear geometry on the controlled IR beam while preserving the spatial interference fringes along the y -direction on the red reference beam, we injected the reference and controlled beams into the interferometer following two spatially separated parallel directions, and we employed a UV fused silica wedged (wedge angle: 30 arcmin) beam splitter, with an antireflection coating ranging from 600 nm to 1700 nm. The optical dispersion of silica ($dn/d\lambda < 0$), together with

the wedge angle, cause the transmitted beam of this beam splitter to exit with an angle dependent on its wavelength. Thus, if we adjust the mirror M1 on the reflected in studies that have been arm (see Figure S2) such that it is perpendicular to the IR beam, this mirror reflects the red beam at a certain angle with respect to the incoming wave. Remembering that the mirror on the reflected arm is perpendicular to both beams, this leads to a spatial interference fringe for the reference beam, while the controlled beam conserves a homogeneous phase over its transverse area. In practice, the wedge angle of our beam splitter is sufficient to create about three spatial fringes on the red output beam.

The fringes on the reference beam are measured using a line CCD camera. The phase of the fringe pattern is directly correlated to the phase of the IR beam, so in essence this methods converts a temporal modulation to a spatial modulation. The camera signal is used as an input for PID control algorithm driving the piezo actuators in the interferometers. We have checked that the interferometers can be set and stabilized at an arbitrary phase. An example of stabilization is shown in Figure S3, where the phase has been kept stable for 48 hours and then the PID control algorithm was switched off. Analysis of the data confirms that both stability and positioning accuracy are about 0.8 nm, limited by the piezo positioning accuracy. This corresponds to a precision in phase of about one third of a degree, for the signal and idler wavelengths.

A full description of the stabilization method and further details can be found in ref. [1].

4. THE FULL EXPERIMENTAL DATASET OF FIGURE 4 (E)

All the coincidence curves measured for a coupled pump power of 1.5 mW (Fig. 4 in the paper) are shown in Figures S4 and S5. The curves are reported as measured from the event timer, without any treatment of the data (and thus with no error bars). The time window of 75 ps coincides with the time resolution of the detectors.

5. FRANSON EXPERIMENTS FOR DIFFERENT VALUES OF THE PUMPING POWER

The second order interference experiments were performed for different values of the pump power. The values of the coincidence rates of the central peak are shown as dots in Figure S6 together with the best fit with a sinusoidal function (red line). These data correspond the values reported in Table 1 of the main text.

6. SNR AND VISIBILITY FROM THE DATA

Levenberg-Marquardt nonlinear regression of the function

$$F(\varphi, (A, \vartheta, y_0)) = A * \cos(\varphi + \vartheta) + y_0 \quad (\text{S1})$$

to the experimental data was performed using Mircocal Origin-lab plotting and analysis software; here φ is the sum of the phases of the two interferometers, while A , ϑ and y_0 are the fit parameters. The measured visibility is extracted from the best fit of the experimental data:

$$V_{Meas} = \frac{\max - \min}{\max + \min} = \frac{A}{y_0}, \quad (\text{S2})$$

where $\max$ and $\min$ are respectively the maxima and the minima of the curve. The SNR can itself be extracted from the best

fit parameters, $\text{SNR} = y_0 - A$. SNR can however be directly extracted from the measured coincidence curves: as the side peaks of the coincidence curves do not depend on φ , we can define

$$\text{SNR} = 2 \times \frac{C_{LS} + C_{SL}}{C_A}, \quad (\text{S3})$$

where C_{LS} is the count rate for events in which the signal photon has taken the long path and the idler photon has taken the short path in the interferometers (vice versa per C_{SL}), while C_A is the accidentals count rate. We have chosen to extract the SNR directly from the data as outlined equation S3: the obtained values are consistent with the SNR measured in direct coincidence experiments (i.e. without interferometers).

A. Error analysis

The errors are taken into account using standard error propagation theory. The statistical distribution of coincidence counts, including C_{LS} , C_{SL} and C_A , is assumed to be Poissonian. The interferometers stabilization procedure lets us set the value of φ to better than 0.4° , nonetheless we estimate the error on φ to be about 10° due to phase inhomogeneity on the beam profiles. The uncertainty on the derived quantities A and y_0 is obtained from the fitting routine. The error on the visibility is thus:

$$\sigma_{V_{Meas}} = V_{Meas} \sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_{y_0}}{y_0}\right)^2}. \quad (\text{S4})$$

The error on the S parameter of the CHSH inequality is

$$\sigma_S = 2\sqrt{2}\sigma_V. \quad (\text{S5})$$

The error on the SNR is

$$\sigma_{\text{SNR}} = \text{SNR} \sqrt{\left(\frac{\sqrt{\sigma_{C_{LS}}^2 + \sigma_{C_{SL}}^2}}{C_{LS} + C_{SL}}\right)^2 + \left(\frac{\sigma_{C_A}}{C_A}\right)^2}. \quad (\text{S6})$$

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Fig. S4. Time correlation spectra for $P=12$ mW, $\varphi = 0$ to $\varphi = 165^\circ$.

Fig. S5. Time correlation spectra for $P=12$ mW, $\varphi = 180^\circ$ to $\varphi = 345^\circ$.

Fig. S6. Two photon interference curves with varying the coupled pump power P