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# Programmable frequency-bin quantum states in a nano-engineered silicon device

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## Abstract

Photonic qubits should be compatible with easy on-chip manipulation and noise-tolerant transmission over optical networks to find practical use across the whole spectrum of quantum technologies. Furthermore, the source of qubits should grant programmable control over the emitted state and high brilliance, in order to provide quantum algorithms with resilience to losses. However, encoding schemes demonstrated so far only combine at most two of the aforementioned properties, restricting the full potential of photonic quantum technologies. In this work, we finally overcome this hurdle by demonstrating a programmable silicon nano-photonic chip capable of generating frequency-bin entangled photons, a type of qubit encoding compatible with long-range transmission over optical links. Our device emits quantum states that can be manipulated using existing telecommunication components, including active devices that can be integrated in silicon photonic technology. Remarkably, our design also overcomes the state-of-art trade-off between brightness and operation bandwidth. As a powerful demonstration, we programmed our chip to generate the four computational basis states, and the four maximally-entangled Bell states, of a two-qubit system. For each state we perform quantum state tomography, confirming high brightness, fidelity, and purity. Such a device combines all the key properties of on-chip quantum state reconfigurability and dense integration.

## 1 Introduction

Photons serve as excellent carriers of quantum information. They have long coherence times at room temperature, and are the inescapable choice for broadcasting quantum information over long distances, either in free space or through the optical fiber network. Quantum state initialization is a particularly important task for photonic qubits, since adjusting entanglement after emission is nontrivial. Initialization strategies depend on the degree of freedom used to encode quantum information, and the most common choice for quantum communication over optical channels is time-bin encoding [1]. Here the two qubit levels consist of the photon being in one of two time windows, generally separated by a few nanoseconds. Time-bin encoding is extremely resilient to phase fluctuations resulting from thermal noise in optical fibers, with qubits maintaining their coherence even over hundreds of kilometers [2, 3]. However, the control of the state in which time-bin-entangled photons are generated is challenging, and impractical in emerging nano-photonic platforms. For on-chip manipulation of qubit states, dual-rail encoding, in which the two states of a qubit correspond to the photon propagating in one of two optical waveguides, is a superior strategy [4, 5], and is thus a common choice for quantum computing and quantum simulation in integrated platforms. Yet this approach is not easily compatible with long-distance transmission links using either optical fibers or free space channels.

75 Recently frequency-bin encoding has been proposed, and experimentally  
 76 demonstrated, as an appealing strategy that can combine the best character-  
 77 istics of time-bin and dual-rail encodings [6–11]. In this approach, quantum  
 78 information is encoded by the photon being in a superposition of different  
 79 frequency bands. Frequency bins can be manipulated by means of phase modu-  
 80 lators, and are resistant to phase noise in long-distance propagation. Pioneering  
 81 studies have investigated the generation and manipulation of frequency-bin-  
 82 entangled photons in integrated resonators. They have considered quantum  
 83 state tomography of entangled photon pairs [12], qudit encoding [13], and  
 84 multi-photon entangled states [14]. The experimental results have all been  
 85 achievable thanks to the recent development of high-Q integrated resonators  
 86 in the silicon nitride and silicon oxynitride platforms.

87 Despite all this progress, there are obstacles that must be overcome in order  
 88 to exploit the full advantage of photonic integration. In frequency-bin encod-  
 89 ing today, the generation of photon pairs occurs via spontaneous four-wave  
 90 mixing in a single ring resonator, with the desired state obtained *outside* the  
 91 chip, by means of electro-optical modulators and/or pulse shapers. And since  
 92 commercial modulators have limited bandwidth, the frequency span separa-  
 93 ting the photons cannot exceed a few tens of gigahertz, which sets a limit to  
 94 the maximum free spectral range of the resonator. Finally, because sponta-  
 95 neous four-wave mixing efficiency scales quadratically with the resonator free  
 96 spectral range [15], there is also a significant trade-off between the generation  
 97 rate and the number of accessible frequency bins.

98 In this work, we show that these limitations can be overcome by utilizing  
 99 the flexibility of light manipulation in a nano-photonic platform and the dense  
 100 optical integration possible in silicon photonics. Our approach is based on  
 101 constructing the desired state by direct, on-chip control of the interference of  
 102 biphoton amplitudes<sup>1</sup> generated in multiple ring resonators that are coherently  
 103 pumped. States can thus be constructed “piece-by-piece” in a programmable  
 104 way, by selecting the relative phase of each source. In addition, since the fre-  
 105 quency bin spacing is no longer related to the ring radius, one can work with  
 106 very high-finesse resonators, reaching megahertz generation rates. These two  
 107 breakthroughs, namely high emission rates in combination with high values of  
 108 the free spectral range, together with output state control using on-chip com-  
 109 ponents, are only possible using multiple rings: they would not be feasible were  
 110 the frequency bins encoded on the azimuthal modes of a single resonator.

111 We demonstrate that with the very same device one can generate all super-  
 112 positions of the  $|00\rangle$  and  $|11\rangle$  states or, in another configuration with different  
 113 frequency bin spacing, all superpositions of the  $|01\rangle$  and  $|10\rangle$  states. One needs  
 114 only to drive the on-chip phase shifter and set the pump configuration appro-  
 115 priately. This means that all four fully-separable states of the computational  
 116 basis and all four maximally-entangled Bell states ( $|\Phi^\pm\rangle = (|00\rangle \pm |11\rangle)/\sqrt{2}$   
 117 and  $|\Psi^\pm\rangle = (|01\rangle \pm |10\rangle)/\sqrt{2}$ ) are accessible. Our high generation rate allows

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<sup>1</sup>See *Supplementary Information* for a detailed discussion.

118 us to perform quantum state tomography of all these states, reaching fidelities  
 119 up to 97.5% with purities close to 100%.

## 120 2 Device characterization and principle of 121 operation

122 The device is schematically represented in Fig. 1a. The structure is operated by  
 123 exploiting the fundamental transverse electric (TE) mode of a silicon wave-  
 124 guide, with a  $600 \times 220 \text{ nm}^2$  cross section, buried in silica. Two silicon ring  
 125 resonators (Ring A and Ring B) in all-pass configuration act as sources of  
 126 photon pairs. Their radii are some  $30 \mu\text{m}$  to ensure high generation rates, and  
 127 they are not commensurate so that the two free spectral ranges are different:  
 128  $\text{FSR}_A = 377.2 \text{ GHz}$  and  $\text{FSR}_B = 373.4 \text{ GHz}$ , respectively. The two rings are  
 129 critically coupled to a bus waveguide and their resonance lines can be tuned  
 130 independently by means of resistive heaters. The device also contains a tun-  
 131 able Mach-Zehnder interferometer (MZI), whose outputs are connected to the  
 132 input of two tunable add-drop filters that allow one to control the field inten-  
 133 sity and relative phase with which Ring A and Ring B are pumped in the  
 134 spontaneous four-wave mixing experiment [16].

135 Linear transmission measurements through the bus waveguide are shown  
 136 in Figs. 1b-g. In a first configuration (Figs. 1b-d), which we will later refer  
 137 to as “ $\Phi$ ”, two resonances of Ring A and Ring B are spectrally aligned to be  
 138 later used for pumping, thus only one transmission dip is observed at 194 THz  
 139 (1545 nm) in Fig. 1c. Since Ring A and Ring B have different free spectral  
 140 ranges, the other resonances are not aligned, and one observes double dips,  
 141 with spacing  $\Delta(m) = |m|(\text{FSR}_A - \text{FSR}_B)$ , with  $m$  being the azimuthal order  
 142 with respect to the pump resonance. In Figs. 1b and d we plot the transmission  
 143 double dip corresponding to  $m = -5$  and  $m = +5$ , named “idler” and “signal”,  
 144 respectively. For both the signal and idler bands the resonances of Ring A  
 145 and Ring B are separated by  $\Delta = 19 \text{ GHz}$ . Later, the two frequencies will  
 146 be used to encode the two states of the qubits, with signal and idler pairs of  
 147 frequencies representing the two qubits. For this reason, in Figs. 1b and d,  
 148 we name  $|0\rangle_{s,i}$  the two frequency bins closer to the pump, and  $|1\rangle_{s,i}$  the two  
 149 bins further away from the pump, in line with previous works on frequency-  
 150 bin entanglement [6]. Our device can also operate in a different configuration,  
 151 which we will refer as “ $\Psi$ ”. Here Ring A and Ring B are thermally tuned so that  
 152 the resonances corresponding to the states  $|0\rangle_i$  and  $|1\rangle_s$  belong to Ring B and  
 153 those corresponding to  $|0\rangle_s$  and  $|1\rangle_i$  belong to Ring A (see Fig. 1e-g). As can be  
 154 seen from all panels in Figs. 1b-g, the resonances of the two generating rings  
 155 have quality factors  $Q \approx 150,000$  (Full width at half maximum  $\Gamma \approx 1.3 \text{ GHz}$ ),  
 156 which guarantee well-separated frequency bins and high generation rates.

157 The basic principle of operation of the device is the following: (i) Ring A and  
 158 Ring B are set in the proper configuration (e.g.,  $\Phi$ ) by controlling the thermal  
 159 tuners; (ii) The pump power is coherently distributed between the two rings  
 160 with the required relative phase and amplitude set either through the MZI or

161 directly through the bus waveguide; (iii) Photon pairs are collected in the bus  
 162 waveguide, with the desired state resulting from a coherent superposition of  
 163 the two-photon states that would be generated by each ring separately.

## 164 3 Results

### 165 Spontaneous four-wave mixing

166 The photon generation efficiency through spontaneous four-wave mixing  
 167 (SFWM) was assessed for the two rings by setting the device in configuration  
 168  $\Psi$ , which is convenient to pump each ring individually through the bus wave-  
 169 guide. The two resonators were pumped with an external tunable laser, and the  
 170 chip output was separated in the signal (194.7–197.2 THz), pump (192.2–194.7  
 171 THz), and idler (189.7–192.2 THz) bands by means of a telecom-grade coarse  
 172 wavelength division multiplexer (see Fig. S1 in the *Supplementary Informa-*  
 173 *tion*). The generated signal and idler photons were then narrowband filtered  
 174 using tunable fiber Bragg gratings with an 8 GHz stop-band, and routed to  
 175 a pair of superconductive single-photon detectors. The overall insertion losses  
 176 from the bus waveguide to the detectors are 6 dB and 7 dB for signal and  
 177 idler channels, respectively. The results of the experiment are summarized in  
 178 Fig. 2. The two rings exhibit similar generation efficiency  $\eta = R/P_{\text{wg}}^2$ , with  
 179  $\eta_{\text{A}} = 57.6 \pm 2.1 \text{ Hz}/\mu\text{W}^2$  for Ring A and  $\eta_{\text{B}} = 62.4 \pm 1.7 \text{ Hz}/\mu\text{W}^2$  for Ring B  
 180 [15]. The internal pair generation rate  $R$  can exceed 2 MHz for both ring res-  
 181 onators (Fig. 2a). A high coincidence-to-accidental ratio (CAR) exceeding  $10^2$   
 182 was obtained for any value of the input power, a necessary condition to ensure  
 183 a high purity of the generated state (Fig. 2b).

184 We now turn to the spectral properties of the generated photon pairs and  
 185 the demonstration of entanglement. We set our device to operate in the  $\Phi$   
 186 configuration, which will later be used to generate the maximally entangled  
 187 state

$$|\Phi(\theta)\rangle = \frac{|00\rangle + e^{i\theta}|11\rangle}{\sqrt{2}}, \quad (1)$$

188 where  $|00\rangle = |0\rangle_{\text{s}}|0\rangle_{\text{i}}$ ,  $|11\rangle = |1\rangle_{\text{s}}|1\rangle_{\text{i}}$ , and the phase  $\theta$  can be adjusted by acting  
 189 on the thermoelectric phase shifter after the interferometer (see *Supplementary*  
 190 *Information*);  $\theta = 0$  and  $\theta = \pi$  correspond to the well-known Bell states  $|\Phi^+\rangle$   
 191 and  $|\Phi^-\rangle$ , respectively. The corresponding SFWM spectrum of the signal and  
 192 idler bands is shown in Fig. 3 a and b (upper panels); the device was electrically  
 193 tuned to set  $\theta = 0$ , with the pump power split equally between Rings A and  
 194 B by means of the MZI. Here we focus on the azimuthal order  $m = \pm 5$ , with  
 195 the generated frequency bins clearly distinguishable in the marginal signal and  
 196 idler spectra.  
 197

### 198 Two-photon interference

199 In order to demonstrate entanglement, the demultiplexed signal and idler  
 200 photons were routed (see Fig. S1 in the *Supplementary Information*) to

201 two intensity electro-optic modulators (EOMs), coherently driven at  $f_m =$   
 202 9.5 GHz, which corresponds to half the frequency bin separation of the  
 203 selected azimuthal order  $m = \pm 5$ . The modulators operate at the mini-  
 204 mum transmission point (i.e. at bias voltage  $V_\pi$ ) to achieve double-sideband  
 205 suppressed-carrier amplitude modulation. The amplitude of the modulating  
 206 RF signal was chosen to maximize the transferred power from the carrier to  
 207 the first-order sidebands, with a modulation efficiency of around  $-4.8$  dB, cor-  
 208 responding to a modulation index  $\beta \approx 1.7$ . These losses can be reduced by  
 209 integrating the modulators on chip. Furthermore, our approach allows the use  
 210 of frequency bin spacings potentially much lower than the frequency cut-off of  
 211 the modulators. This will allow the use of complex wavelength shifting modu-  
 212 lation techniques [17, 18] to avoid the generation of double sidebands and the  
 213 consequent 3 dB in added losses.

214 The resulting spectrum is shown in the lower panels of Fig. 3a and b, in  
 215 which one can clearly recognize three peaks. Indeed, given the chosen modu-  
 216 lated frequency, the central one results from the overlap of the down- and  
 217 upper-converted original bins. From a quantum optics point of view, this oper-  
 218 ation achieves quantum interference of the original frequency bins [12] in a  
 219 similar fashion to what can be done with time bins in a Franson interferometer  
 220 [19, 20]. Here the achievable visibility of quantum interference depends on the  
 221 correct superposition of the spectra of the modes encoding the two frequency  
 222 bins for the signal and idler photons respectively, as outlined in Fig. 4a.

223 For coincidence counting, the modulated signal and idler photons were  
 224 filtered using narrowband fiber Bragg gratings to select only the central line at  
 225 the output of the corresponding modulator, and routed to the single-photon  
 226 detectors. The results of this experiment are shown in Figs. 4b and c as a  
 227 function of the modulation frequency. The rapid oscillation of the correlation  
 228 is due to the different phase acquired by the photons during their propagation  
 229 from the device to the EOMs. If the resonances share the same  $Q$  factor and  
 230 coupling efficiency, the coincidence rate is proportional to the cross-correlation  
 231 function (see *Supplementary Information*)

$$G_{s,i}^{(2)}(f_m) = 1 + \frac{\Gamma^2}{(f_m - \Delta/2)^2 + \Gamma^2} \cos(4\pi(f_m - \Delta/2)\delta T + 2\varphi_s - 2\varphi_i - \theta), \quad (2)$$

232 where  $\delta T = t_i - t_s$  is the difference between the idler and signal arrival times  
 233 at the EOMs, and  $\varphi_{s(i)}$  is the signal (idler) modulator driving phase. Fig. 4b  
 234 shows good agreement between the experimental results and curve described  
 235 by Eq. (2) for  $\varphi_s - \varphi_i = \theta/2$  and  $\delta T = 8.5$  ns, which corresponds to the  $\sim 2$  m  
 236 path difference between the idler and signal EOMs in our setup (see *Supple-*  
 237 *mentary Information*). The curve visibility obtained from a least-square fit of  
 238 the model is  $V = 98.7 \pm 1.2\%$ . The two-photon correlation reaches its maximum  
 239 value  $G_{s,i}^{(2)}(f_m) \approx 2$  when  $f_m = \Delta/2$ , as shown other work on frequency-bin  
 240 entanglement [12]. Thanks to the high brightness of the source, coincidence  
 241 counts on the detectors remain well above the noise level even with the added

242 losses from the modulators, with a CAR level  $> 50$  and detected coincidence  
 243 rate  $> 2$  kHz, thus implying an interference pattern with a high visibility.

244 With these results in hand, we set  $f_m = \Delta/2$  and varied  $\varphi_s$  to perform  
 245 a Bell-like experiment. The corresponding quantum interference curves are  
 246 reported in *Supplementary Information*.

## 247 Quantum state tomography

248 Finally, we show that our device can be operated to generate, directly on  
 249 chip, frequency bin photon pairs with a controllable output state. For each  
 250 of the explored configurations we performed quantum state tomography. First  
 251 we kept the device in configuration  $\Phi$ , in which Ring A and Ring B generate  
 252 photon pairs in the state  $|0\rangle_{s,i}$  and  $|1\rangle_{s,i}$ , respectively. Thus, the two states of  
 253 the computational basis  $|00\rangle = |0\rangle_s |0\rangle_i$  and  $|11\rangle = |1\rangle_s |1\rangle_i$  can be generated by  
 254 selectively pumping only the appropriate resonator, as shown in Fig. 5a and  
 255 b. The states were characterised via quantum state tomography [12, 21, 22],  
 256 as detailed in the *Methods* section. In both cases the states are accurately  
 257 reproduced, with fidelity and purity exceeding 90%.

258 In a second experiment, the MZI was operated to split the pump power so  
 259 that the probabilities of generating a photon pair in Ring A and in Ring B are  
 260 equal. If the pump power is sufficiently low that the probability of emitting  
 261 two photon pairs is negligible, then the generated frequency bins are in the  
 262 state  $|\Phi(\theta)\rangle$  described by Eq. (1), where the phase factor  $\theta$  is controlled by the  
 263 phase shifter after the MZI. By setting  $\theta = 0$  or  $\pi$ , we were able to generate  
 264 the two Bell states  $|\Phi^+\rangle$  and  $|\Phi^-\rangle$ , respectively (see Fig. 5c and d). The real  
 265 and imaginary parts of the density matrix are shown in Fig. 5g, h, k, and  
 266 l. As expected, we found non-zero off-diagonal terms in the real part of the  
 267 density matrix, which indicate entanglement. In these cases as well the device  
 268 is capable of outputting the desired with purity and fidelity exceeding 90%.  
 269 The entanglement of formation, a figure of merit to quantify the entanglement  
 270 of the generated pairs [23], was extracted from the measured density matrices,  
 271 yielding values  $> 80\%$  for the two Bell states, in contrast with values  $< 20\%$  for  
 272 the two separable states  $|00\rangle$  and  $|11\rangle$ .

273 Our device can also operate in the  $\Psi$  configuration, with the ring resonances  
 274 arranged as shown in Fig. 1e-g. In this case one is able to generate also the  
 275 two remaining computational basis states  $|01\rangle$ ,  $|10\rangle$  and the two remaining Bell  
 276 states  $|\Psi^+\rangle$  and  $|\Psi^-\rangle$ . Note that in this configuration, the pump resonances  
 277 for the two ring resonators are not aligned (Fig. 1f).

278 When generating the two separable states, either Ring A (to generate  $|01\rangle$ )  
 279 or Ring B (to generate  $|10\rangle$ ) was pumped through the bus waveguide by simply  
 280 tuning the pump to the corresponding resonance (see Figs. 6a and b). To  
 281 generate the two Bell states, the pump pulse spectrum (which is tuned to  
 282 be in the middle of the two resonances) is shaped using an external EOM  
 283 operated at the frequency corresponding to half the difference between the  
 284 two pump resonances ( $f_{m,p} = \Delta_p/2 = 19$  GHz) (see Figs. 6c and d and the  
 285 *Methods* section). The pumping ratio and the phase between the two rings were



adjusted by tailoring the modulation to obtain an equal probability amplitude of generating a single photon pair for the states  $|01\rangle$  and  $|10\rangle$  respectively, while still keeping the probability of double pair generation negligible. The relative phase of the superposition can be controlled by adjusting the EOM driving phase to select either  $|\Psi^+\rangle$  or  $|\Psi^-\rangle$ .

The four generated state were characterized via quantum state tomography as in the previous case. However, we stress that here two different values of bin spacing for the signal ( $\Delta_s = 19$  GHz) and idler ( $\Delta_i = 3\Delta_s = 57$  GHz) qubits were used. While this does not constitute a problem for the generation of entanglement, as the Hilbert space of the two qubits is built from the tensor product of Hilbert spaces of two qubits with different values for  $\Delta_s$  and  $\Delta_i$ , it offered us the opportunity to demonstrate, for the first time, frequency bin tomography for uneven spacing. This is done by operating the signal and idler EOMs (see Fig. S1 of the *Supplementary Information*) at different frequencies equal to half the frequency spacing of the corresponding resonances.

The experimental results are shown in Figs. 6e-l. All four states were prepared with fidelity close to or exceeding 90%, and purity between 85% and 100%. The entanglement of formation is below 5% for the separable states  $|01\rangle$  and  $|10\rangle$ , while above 80% for the Bell states  $|\Psi^+\rangle$  and  $|\Psi^-\rangle$ , as expected. The reconstructed density matrices show increased noise with respect to those reported in Fig. 5, because the modulation efficiency of our idler modulator was significantly reduced at such a high frequency, resulting in additional losses lowering the count rate on the detectors (see the *Methods* section).

## Scalability to higher-dimensional states

Our approach can be generalized to frequency bin qudits by scaling the number of coherently excited rings. We give a proof of principle demonstration of this capability by using a different device hosting  $d = 4$  rings and add-drop filters. The four sources,  $j = 0, \dots, d - 1$ , have radii  $R_j = R_0 + j\delta R$ , where  $R_0 = 30 \mu\text{m}$  and  $\delta R = 0.1 \mu\text{m}$ , which leads to a bin spacing of approximately 9 GHz at 7 FSR from the pump. The spectral response of the device at the output of the bus waveguide, indicated in Fig. 7a, shows the four equidistant bins ( $A, B, C, D$ ) associated with the signal and with the idler photons, and the overlapping resonances of the rings at the pump frequency. As in the case of qubits, we used an MZI tree to split the pump into four paths, each feeding a different add-drop ring filter that is used to control the field intensity at the photon pair sources. We focused on the capability to generate the four computational basis states and the two-dimensional Bell states formed by adjacent frequency bins pairs. First, the add-drop filters are tuned on resonance one at a time. This selects the computational basis state that is generated. We characterized those states by performing a  $Z$ -basis correlation measurement, i.e., by projecting the signal and the idler photon on the  $Z$ -basis  $\{|j\rangle_s |m\rangle_i\}$ ,  $j(m) = A, B, C, D$  in order to measure the uniformity and the cross-talk between the four frequency bins. From the correlation matrices, shown in Fig. 7b-e, it was possible to measure the ratio of the coincidence

330 counts  $n_{jj}$  in the frequency-correlated basis  $|j\rangle_s |m\rangle_i$  to that in the uncorrelated  
 331 basis  $\sum_{j \neq m} n_{jm}$ , and it is about two orders of magnitude. We could compen-  
 332 sate for the slightly different amplitude of the different basis states by acting  
 333 on the MZI tree at the input. Second, the add-drop filters associated with the  
 334 adjacent frequency bin pairs A-B, B-C and C-D are tuned on resonance one at  
 335 a time, thus generating the Bell states  $|\Phi\rangle_{AB}$ ,  $|\Phi\rangle_{BC}$  and  $|\Phi\rangle_{CD}$ . The visibil-  
 336 ity of quantum interference is assessed by mixing the corresponding frequency  
 337 bins with the electro-optic modulator. Unlike in the qubit experiment, here we  
 338 choose a modulation frequency that matches the spectral separation between  
 339 the bins. We used phase modulators configured to create first order sidebands  
 340 of amplitude equal to that of the baseband, and recorded the coincidences in  
 341 signal/idler bins B,C and D. The resulting Bell curves, shown in Fig. 7f, have  
 342 visibilities  $V_{AB} = 0.831(5)$ ,  $V_{BC} = 0.884(6)$  and  $V_{CD} = 0.81(1)$ , indicating the  
 343 presence of entanglement between the bin-pairs in all cases. It is worth not-  
 344 ing that, as in the two-dimensional case, the relative phase between the three  
 345 Bell curves in Fig. 7f could be adjusted using on-chip phase shifters in order  
 346 to realize maximally entangled high-dimensional Bell states.

## 347 4 Conclusions

348 We demonstrated that a rich variety of separable and maximally entan-  
 349 gled states, including any linear superposition of  $\{|00\rangle, |11\rangle\}$  or  $\{|01\rangle, |10\rangle\}$ ,  
 350 can be generated using frequency-bin encoding in a single programmable  
 351 nano-photon device, fabricated with existing silicon photonic technologies  
 352 compatible with multi-project wafer runs. This guarantees that these devices  
 353 can be available for widespread use in applications, ranging from quantum  
 354 communication to quantum computing.

355 Our approach constitutes a new paradigm for the integration of frequency-  
 356 bin devices that goes well-beyond a miniaturization of bulk strategies. Indeed,  
 357 unlike previous implementations, the states are all generated inside the device,  
 358 without relying on off-chip manipulation of a single initial state. Controlla-  
 359 bility of the generated state was shown to be readily accessible on-chip, via  
 360 electrical control of thermo-optic actuators in one configuration ( $\Phi$ ), and by  
 361 tailoring the pump spectral properties in another ( $\Psi$ ). In a future version of  
 362 the device the use of more than two rings for the definition of the state will  
 363 allow the two configurations to have the same frequency spacing for the qubits.  
 364 As a result, the device will be capable of generating all four Bell states with  
 365 the same physical characteristics, as recently demonstrated using an external  
 366 periodically-poled lithium niobate crystal [24]; it will also be used to explore  
 367 more of the Hilbert space of the two qubits.

368 Since in our approach the frequency bin spacing is only limited by the resonator  
 369 linewidth, the requirements for the electro-optic modulators are greatly  
 370 relaxed with respect to previous implementations. Indeed, as demonstrated in  
 371 this work, the frequency bin separation is compatible with existing silicon inte-  
 372 grated modulators [25]. Thus, one can foresee a future evolution of our device

that will involve modulators integrated on-chip. This will further increase its suitability for practical applications, such as quantum key distribution and quantum communications in general. In addition, the ability to independently choose the bin spacing  $\Delta$  for both qubits, as shown in Figs. 1b-g, demonstrates an additional flexibility in choosing the basis for frequency-bin encoding that can be exploited for the engineering of the source.

The approach demonstrated here is scalable, for one can design and implement devices with more than two generating rings by taking advantage of silicon dense integration, opening the possibility of using frequency qudits instead of simple qubits. As demonstrated in a number of theoretical proposals, such an ability will be of pivotal importance for multiple applications in quantum communication, sensing, and computing algorithms [26].

Finally, our approach allowed us to overcome the trade-off between the frequency bin spacing and the generation rate that characterized previous work. This was instrumental in achieving a comprehensive assessment of the properties of the generated states, which could be performed using only telecom-grade fiber components – with the sole exception of single-photon detection – with an overall low loss ( $< 4$  dB) ensured by the all-fiber technology. The accuracy and the precision that have been achieved in our measurements are state-of-the-art for frequency-bin encoding, even considering results obtained with bulk sources. well-beyond any other reported so far on frequency-bin encoding. All these results will usher in the use of frequency bin qubits as a practical choice for photonic qubits, capable of combining easy manipulation and robustness for long haul transmission.

## Acknowledgements

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## Methods

**Sample fabrication.** The device was fabricated at CEA-Leti (Grenoble), on a 200-mm Silicon-on-Insulator (SOI) substrate with a 220-nm-thick top device layer of crystalline silicon on 2- $\mu$ m-thick SiO<sub>2</sub> buried oxide. The patterning process of the silicon photonics devices and circuits combines deep ultraviolet (DUV) lithography with 120-nm resolution, inductively coupled plasma etching (realized in collaboration with LTM – Laboratoire des Technologies de la Microélectronique) and O<sub>2</sub> plasma resist stripping. Hydrogen annealing was performed in order to strongly reduce etching-induced waveguide sidewalls roughness [27]. After high-density plasma, low-temperature oxide (HDP-LTO) encapsulation - resulting in a 1125-nm-thick SiO<sub>2</sub> layer - 110 nm

415 of titanium nitride (TiN) were deposited and patterned to create the ther-  
 416 mal phase shifters, while an aluminium copper layer (AlCu) was used for the  
 417 electrical pad definition. Finally, a deep etch combining two different steps  
 418 -  $C_4F_8/O_2/CO/Ar$  plasma running through the whole thickness of both sil-  
 419 ica upper cladding and buried oxide, followed by a Bosch deep reactive ion  
 420 etching (DRIE) step to remove 150  $\mu\text{m}$  of the 725- $\mu\text{m}$ -thick Si substrate - was  
 421 implemented to separate the sub-dice, thus ensuring high-quality optical-grade  
 422 lateral facets for chip-to-fiber edge coupling.

423 **Linear spectroscopy.** The experimental apparatus is schematically repre-  
 424 sented in Fig. S1 of the *Supplementary Information*. The linear characteriza-  
 425 tion of the sample shown in Fig. 1 was realized by scanning the wavelength  
 426 of a tunable laser (Santec TSL-710), with its polarization controlled by a  
 427 fiber polarization controller (PC). Light was coupled to the sample at the  
 428 input of the bus waveguide and collected at the output using a pair of lensed  
 429 fibers (nominal mode field diameter: 3  $\mu\text{m}$ ), with an insertion loss lower than  
 430 3 dB/facet. The output signal was detected by an amplified InGaAs photodi-  
 431 ode and recorded in real time by an oscilloscope. The resonance configuration  
 432 was adjusted by addressing each ring resonator's phase shifter with electric  
 433 probes driven by multi-channel power supply.

434 **Nonlinear characterization.** The SFWM efficiency for each resonator was  
 435 assessed through power-scaling experiments (Fig. 2). The flux of generated  
 436 idler and signal photons was measured by varying the pump power coupled  
 437 to each microring, while keeping the resonances in place by acting on the  
 438 thermo-electric phase shifters. The tunable laser source spectrum was filtered  
 439 by a band-pass (BP) filter in order to reduce the amount of spurious photons  
 440 at signal and idler frequencies coming from the launching part of the setup,  
 441 mainly associated with amplified spontaneous emission of the laser diode and  
 442 Raman fluorescence from the fibers. The collected signal and idler photons  
 443 were first separated using a coarse wavelength division multiplexer (CWDM),  
 444 with 2.5 THz (20 nm) nominal channel separation and measured inter-channel  
 445 crosstalk  $< -80$  dB. The frequency bins of interest were then narrowband  
 446 filtered (3 dB-bandwidth: 8 GHz) by a pair of tunable fiber Bragg gratings  
 447 (FBG): besides selecting the frequency bins with high accuracy, this procedure  
 448 also suppresses any spurious broadband photon falling outside the bandwidth  
 449 of the input bandpass filter and not eliminated by the CWDM.

The resulting signal and idler photons were routed, using circulators,  
 towards two superconductive single-photon detectors (SSPDs), where time-  
 correlated single photon counting (TCSPC) was performed with a precision  
 of about 35 ps, mainly determined by the detectors jitter. A coincidence  
 window of  $\tau_c = 380$  ps was chosen by selecting the average full-width at  
 half-maximum (FWHM) of the histogram peak. Accidental counts were esti-  
 mated from the background level; note that this value is not subtracted  
 from the number of coincidences counted, but was used only to estimate the

coincidence-to-accidental ratio, according to the formula:

$$CAR = \frac{\text{total counts in coinc. window} - \text{accidental counts in coinc. window}}{\text{accidental counts in coincidence window}}.$$

450 **Quantum state tomography.** Two-photon interferometry and tomography  
 451 of the generated quantum states were performed by including a pair of intensi-  
 452 ty EOMs (iXblue MX-LN) at the signal and idler demultiplexer outputs,  
 453 coherently driven by a multi-channel RF generator (AnaPico APMS20G). The  
 454 sidebands of interest were selected by tuning the central stop-band wavelength  
 455 of the FBGs. The tomography of each quantum state involved 16 individual  
 456 measurements, each performed in an acquisition time of 15 s. For each measure-  
 457 ment, each FBG was tuned to one of the three sideband frequencies obtained  
 458 from the modulation of the signal (idler) bins, and the EOM's relative phase  
 459 was adjusted appropriately. Estimation of the density matrices was performed  
 460 via maximum-likelihood technique [21, 22]. For the generation of states in the  
 461  $\{|01\rangle, |10\rangle\}$  basis ( $\Psi$  configuration), we added a phase EOM at the input of  
 462 the setup, coherently driven by the same RF source used for tomography, and  
 463 we entered the chip at the bus waveguide. The two generation rings were then  
 464 pumped by the first-order sidebands, while their relative phase was fixed by  
 465 the phase of the modulation.

466 **Measurement of qudits.** For the  $Z$ -basis correlation measurement, a total  
 467 set of different projectors (for each photon) is used for each basis state. The  
 468 projector  $|j\rangle_s |m\rangle_i$  is implemented by setting the signal(idler) FBG to reflect  
 469 only the frequency bin  $j(m)$ . For those combinations carrying negligible counts  
 470 (corresponding to frequency uncorrelated bins), the central frequency of the  
 471 two FBGs cannot be determined by simply maximizing the coincidence rate or  
 472 the flux of singles in each bin. To circumvent this, we coupled a secondary laser  
 473 beam in the counter-propagating direction with respect to that of the pump,  
 474 and recorded the back reflected light from the sample. The spectra of the latter  
 475 are monitored after being transmitted by the FBGs, and simultaneously reveal  
 476 the spectral location of the stop band of the FBG and the four resonance  
 477 frequencies of the rings. In this way, the stop band can be overlapped with the  
 478 desired frequency bin with high precision.

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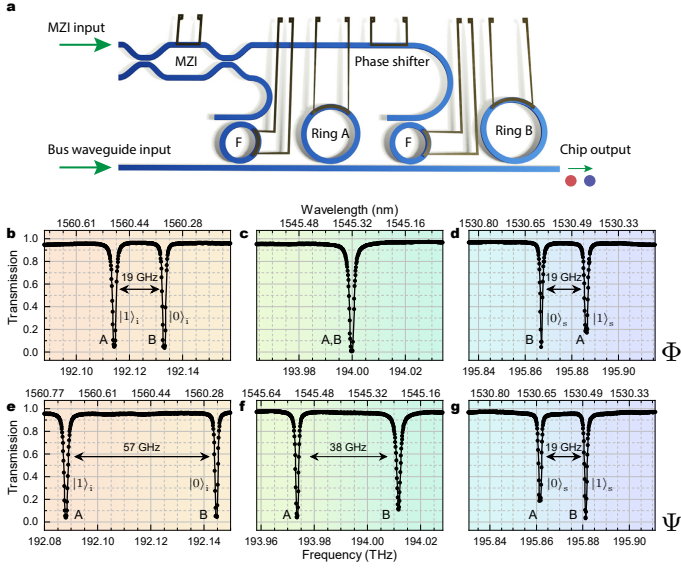
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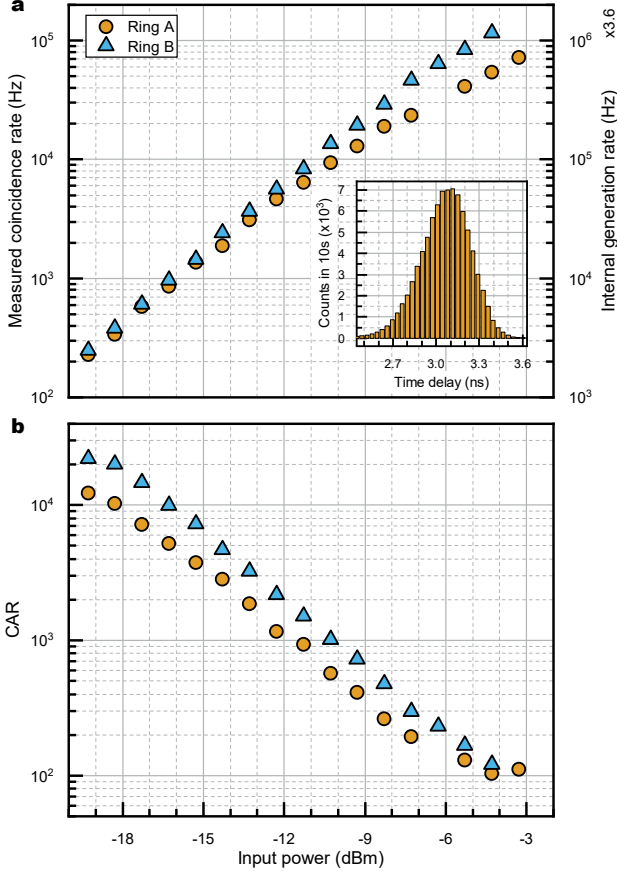
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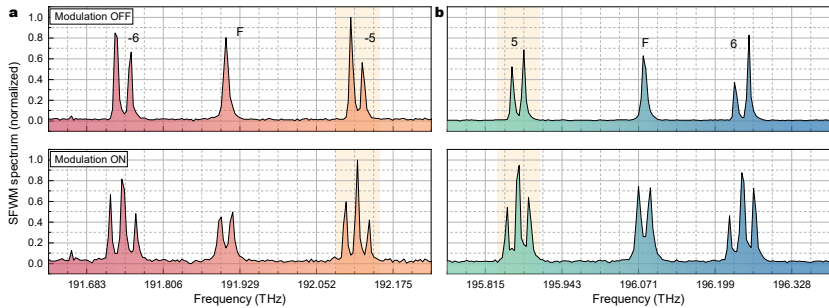




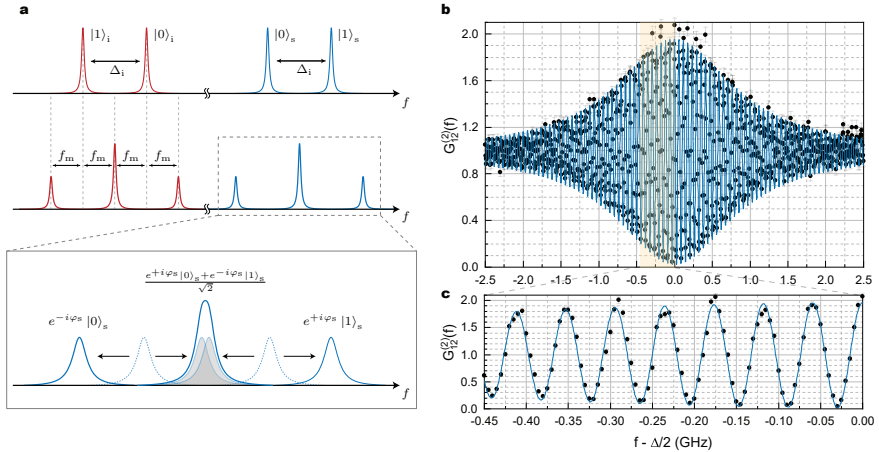
**Fig. 1** Device layout and transmission spectra. **a**. Schematic of the device, in which a Mach Zehnder Interferometer (MZI) is used to route optical pumping power to the two generating rings (Ring A and Ring B) via two add-drop filters (F). The pump relative phase for the two rings is controlled by a thermo-electric phase shifter. **b-d**. Linear characterization of the sample through the bus waveguide, with the device operated in configuration  $\Phi$ . A detail of the transmission spectrum around the idler (panel **b**,  $m = -5$ ), pump (panel **c**,  $m = 0$ ), and signal (panel **d**,  $m = +5$ ) bands shows resonances belonging to both ring resonators, identified by labels A and B respectively. In this configuration, Ring B is associated to the  $|0\rangle_{s,i}$  frequency bins for both signal and idler, while Ring A is associated to the  $|1\rangle_{s,i}$  resonances for both signal and idler. **e-g**. Same as panels **b-d**, respectively, but with the device set in configuration  $\Psi$ . Here, Ring A corresponds to the  $|0\rangle_s$  resonance for the signal and  $|1\rangle_i$  resonance for the idler, Ring B corresponds to the  $|1\rangle_s$  resonance for the signal and  $|0\rangle_i$  resonance for the idler.



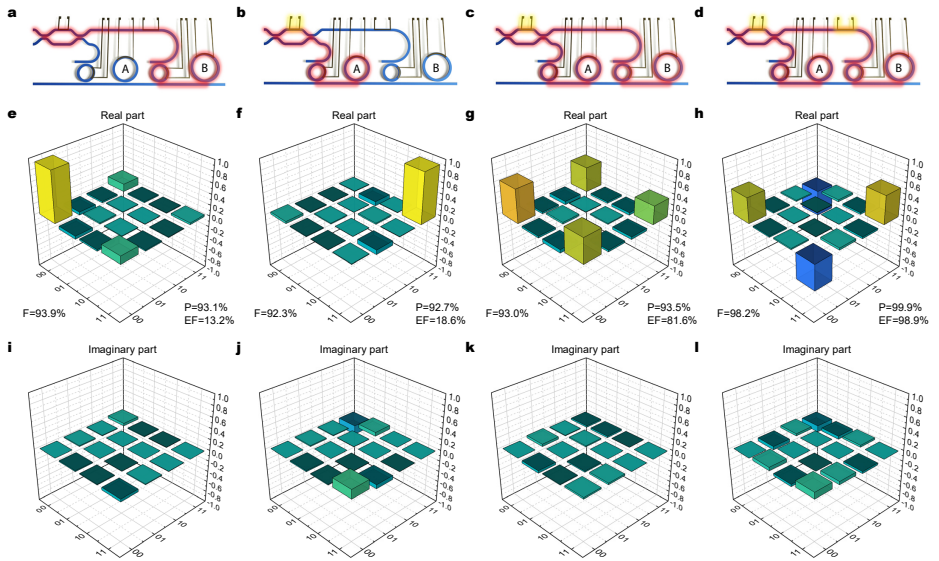
**Fig. 2 Spontaneous four-wave mixing.** Generation of pairs through spontaneous four-wave mixing using the two rings of the device. The two sets of resonances are shifted such that all the resonances are separated (configuration  $\Psi$ ). A tunable laser is tuned on resonance with either Ring A or Ring B, and the related signal and idler photons are detected. Similar coincidence rates (panel **a**) are observed, proving that the two rings have similar generation efficiencies. Inset shows an example histogram of the photon arrival time delays. Panel **b** shows the calculated CAR, which exhibits the typical reduction for the higher values of the input power due to the generation of higher-order photon states.



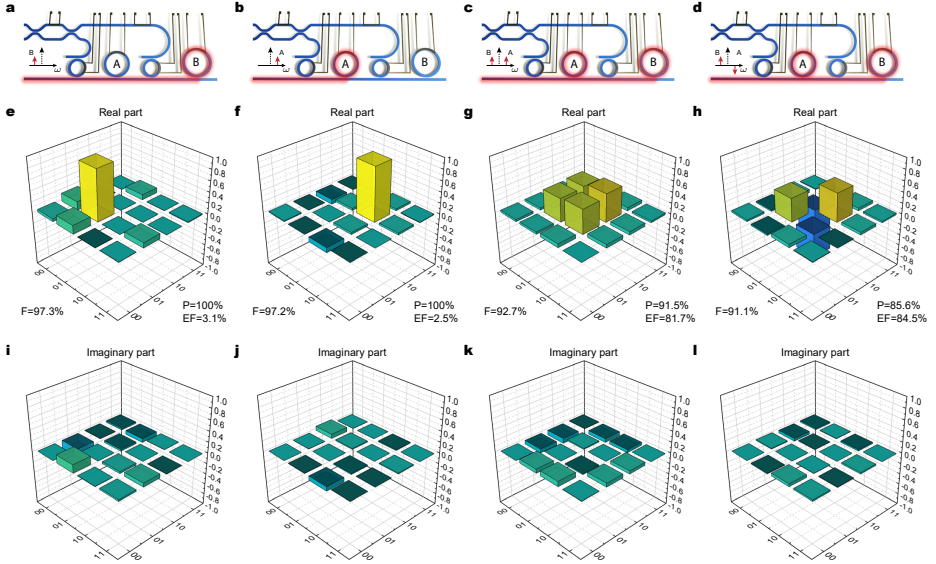
**Fig. 3 Effect of modulation on spontaneous four-wave mixing spectra.** Normalized spontaneous four-wave mixing spectra for the **a.** idler and **b.** signal channels after demultiplexing both in the absence (upper panels) and presence (lower panels) of modulation. The bin pair order  $m$  with respect to the pump resonances is marked, while spontaneous four-wave mixing generated in the add-drop filter rings is marked as F. Note that, despite the different out-coupling efficiency for each resonance and the limited resolution of the spectrometer, it is still possible to observe the expected symmetry in the intensity of the generated bins, and how the bin spacing increases with the azimuthal order  $m$ . Lower panels show the effect of the double-sideband suppressed-carrier modulation on the signal and idler spectra, where only the first-order sidebands are preserved. The spectra shown here are associated with generation of the state described by Eq. (1), where we chose  $\theta = \pi$  (Bell state  $|\Phi^-\rangle$ ). Analogous spectra are attainable for any of the device configurations discussed in this work.



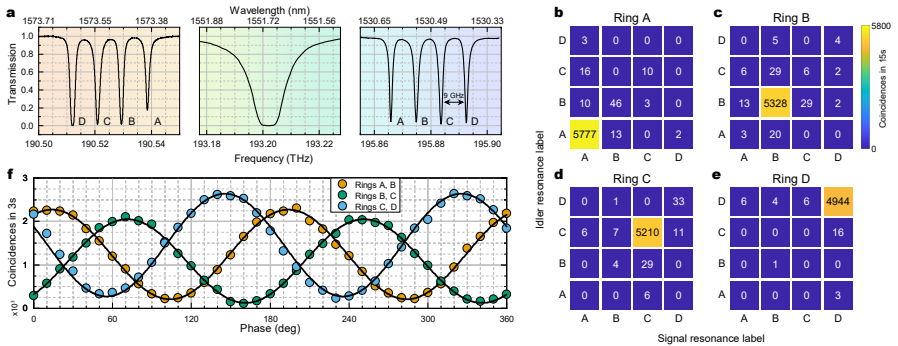
**Fig. 4 Frequency mixing and two-photon interference.** **a.** Schematic of the effect of modulation on the generated idler (red) and signal (blue) frequency bins. The frequency mixing produces maps each of the signal and idler states in a superposition of three frequency components: the outermost ones are reminiscent of the probability amplitude proportional to  $|0\rangle_{s,i}$  or  $|1\rangle_{s,i}$ ; while the “central” bin results in a superposition of the two. Each frequency-shifted bin also acquires a phase  $\pm i\varphi_{s,i}$  due to the modulation. The superposition of the generated bins is regulated by the modulation frequency, and the overlap is ideally maximized when  $f_m = \Delta/2$ , when perfect indistinguishability of the generated bins is achieved. **b.** Two-photon correlation  $G_{1,2}^{(2)}$  of the frequency-mixed bins as a function of the detuning  $f_m - \Delta/2$ . The experimental points (black dots) were obtained by counting coincidences between frequency-mixed bins at varying modulation frequency, while keeping fixed the modulation phase, and normalizing. Error bars (light gray) were estimated assuming Poissonian statistics. Blue curve represents the best-fit of the curve according with Eq. (2), showing good agreement (panel c) with theoretical predictions.



**Fig. 5 Quantum state tomography in the  $\{|00\rangle, |11\rangle\}$  basis ( $\Phi$  configuration).** Columns from left to right refer respectively to states:  $|00\rangle$ ,  $|11\rangle$ ,  $|\Phi^+\rangle$ , and  $|\Phi^-\rangle$ . **a-d.** Device pumping scheme for each of the generated state. The path covered by the pump laser is highlighted in red. The generation rings A and B are selectively addressed by acting on the tunable MZI, while the relative phase of the pump is varied through a thermal phase shifter. **e-h.** Real and **g-l.** imaginary part of the reconstructed density matrices for each of the generated states, estimated through the maximum-likelihood method.  $F$ ,  $P$  and  $EF$  indicate respectively fidelity, purity and entanglement of formation of each reconstructed state.



**Fig. 6 Quantum state tomography in the  $\{|01\rangle, |10\rangle\}$  basis ( $\Psi$  configuration).** Columns from left to right refer respectively to states:  $|01\rangle$ ,  $|10\rangle$ ,  $|\Psi^+\rangle$ , and  $|\Psi^-\rangle$ . **a-d.** Device pumping scheme. The bus waveguide is used as input for the pump, whereas the generation rings' resonances are addressed by spectral shaping (modulation) of the pump, performed before coupling to the chip. The relative generation phase between rings A and B is tuned by adjusting the phase of the input modulator driver. **e-l.** Reconstructed density matrices for each of the generated states (see caption of Fig. 5 for details).



**Fig. 7 Higher-dimensional states (qudits).** **a.** Normalized transmission spectrum of the device used for the generation of higher-dimensional states. The device layout is analogous to the one shown in Fig. 1a, but four generation rings (labeled A, B, C, D) are involved. Panels from left to right show respectively the idler, pump, and signal resonances associated to the correspondent four rings involved. **b-e.** Correlation matrices showing coincidence counts for each pair of resonators while pumping respectively rings A, B, C, D. **f.** Bell-type quantum interference measurements performed on the generated states  $|\Phi\rangle_{AB}$  (orange dots),  $|\Phi\rangle_{BC}$  (green dots) and  $|\Phi\rangle_{CD}$  (blue dots).