Cross-polarized photon-pair generation and bi-chromatically pumped optical parametric oscillation on a chip

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Nonlinear optical processes are one of the most important tools in modern optics with a broad spectrum of applications in, for example, frequency conversion, spectroscopy, signal processing and quantum optics. For practical and ultimately widespread implementation, on-chip devices compatible with electronic integrated circuit technology offer great advantages in terms of low cost, small footprint, high performance and low energy consumption. While many on-chip key components have been realized, to date polarization has not been fully exploited as a degree of freedom for integrated nonlinear devices. In particular, frequency conversion based on orthogonally polarized beams has not yet been demonstrated on chip. Here we show frequency mixing between orthogonal polarization modes in a compact integrated microring resonator and demonstrate a bi-chromatically pumped optical parametric oscillator. Operating the device above and below threshold, we directly generate orthogonally polarized beams, as well as photon pairs, respectively, that can find applications, for example, in optical communication and quantum optics.
Following the ground-breaking demonstration of second-harmonic generation by Franken et al., nonlinear optical processes quickly rose to form the backbone of disciplines as important as spectroscopy, signal processing and quantum optics. With the goal of compact, more stable and scalable devices, the main platform for nonlinear optical architectures has rapidly evolved from bulk optics to fibre-based devices, and has more recently progressed towards integrated photonics. In particular, devices compatible with large-scale electronic chip complementary metal–oxide–semiconductor (CMOS) technology offer the potential for both mass production and low-cost commercial implementation. Since second-order nonlinear materials are very challenging to integrate and are typically not CMOS compatible, most integrated nonlinear devices rely on third-order processes. Various third-order nonlinear processes such as four-wave mixing (FWM), self- and cross-phase modulation, Raman and Brillouin scattering have been exploited on chip to achieve significant breakthroughs such as integrated broadband nonlinear parametric gain, optical parametric oscillation, frequency combs, third-harmonic generation, optical modulators, all-optical routing, mode-locked lasers, photon pair sources and many others. Most applications exploiting nonlinear processes in either bulk media or fibre-based devices have extensively relied on the electric field polarization as a fundamental degree of freedom to achieve novel nonlinear functionalities. There are several different types of FWM, as well as spontaneous parametric downconversion, which can be categorized, for example, by the frequency and polarization of the interacting fields. In general, the fields generated through parametric frequency conversion can either have identical (degenerate) or different (non-degenerate) frequencies and present different combinations of polarization, according to the following definitions: Type-0, the pump and generated fields are co-polarized; Type-I, the generated fields are co-polarized but different from the pump polarization; and Type-II, the generated fields have orthogonal polarizations. Table 1 summarizes the different types of FWM processes in terms of linear polarization for the different pump and generated fields (horizontal and vertical), as well as their efficiency assuming terms of linear polarization for the different pump and generated fields. The investigated device and the implementation of the novel bi-chromatically pumped integrated optical parametric oscillator (OPO). To achieve this, we introduce a method to suppress stimulated degenerate FWM while enhancing spontaneous non-degenerate FWM between two cross-polarized pumps inside a high-Q integrated nonlinear microring resonator. We show, on the one hand, that this novel kind of OPO emits high-purity orthogonally polarized photon pairs when operated below OPO threshold. On the other hand, it generates orthogonally polarized beams while running above the OPO threshold. The investigated device and the implementation of the cross-polarized FWM process can find various applications in quantum optics, as well as optical communications.

**Results**

Type-II SFWM. Here we demonstrate Type-II spontaneous FWM in a novel bi-chromatically pumped integrated optical parametric oscillator (OPO). To achieve this, we introduce a method to suppress stimulated degenerate FWM while enhancing spontaneous non-degenerate FWM between two cross-polarized pumps inside a high-Q integrated nonlinear microring resonator. We show, on the one hand, that this novel kind of OPO emits high-purity orthogonally polarized photon pairs when operated below OPO threshold. On the other hand, it generates orthogonally polarized beams while running above the OPO threshold. The investigated device and the implementation of the cross-polarized FWM process can find various applications in quantum optics, as well as optical communications.

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**Table 1 | Different types of FWM processes in terms of the polarization of the interacting fields.**

| P1 | P2 | S | I | Efficiency |
|----|----|---|---|------------|
| H  | H  | H | H | $\propto (\gamma L)^2 P_1 P_2$ |
| V  | V  | V | V | $\propto (\gamma L/3)^2 P_1 P_2$ |
| H  | V  | V | H | $\propto (\gamma L)^2 P_1 P_2$ |
| H  | V  | V | H | $\propto (\gamma L/3)^2 P_1 P_2$ |

FWM, four-wave mixing.

List of different FWM processes and their relative efficiencies (from Lin et al.) in terms of pump powers (P1 and P2), propagation length (L) and nonlinear parameter ($\gamma$). P1, P2, S and I represent the first pump, second pump, signal and idler photon, respectively. H denotes horizontal and V vertical polarization.
achieved by operating in a slightly anomalous dispersion regime for both modes 5 .

Below-threshold operation. When operated below the OPO threshold, our device directly generates orthogonally polarized photon pairs. To characterize them and confirm the nature of the underlying nonlinear process, we performed photon coincidence measurements (see Methods). The photon pairs generated in the TE and TM modes of the microring resonator were collected at the ring through port after appropriate filtering of both pump fields by means of a polarization-maintaining, high-isolation 200-GHz-wide notch filter (for example, by TeraXion Inc.). The device was pumped in a hybrid self-locked pump configuration (Fig. 3), where the TE pump laser (1,555.65 nm) was directly built around the resonator, while the TM resonance (1,556.24 nm) was pumped with an external laser (see Methods). The generated photons were then separated by a polarizing beam splitter and detected with single-photon detectors. We measured a clear coincidence peak (see Fig. 4a) with a coincidence-to-accidental ratio (CAR) of up to 12 without any background subtraction (see Fig. 4b). As photon pairs can only be generated via spontaneous nonlinear processes, the measured photon coincidences give a strong indication that the photon pairs are generated through Type-II spontaneous FWM, with stimulated processes being successfully suppressed. The power-scaling behaviour provides further insight into the process associated with the generation of the photon pairs. Only when one photon from each pump field is used to create two daughter photons does it become possible to directly generate orthogonally polarized photon pairs 20. Therefore, the coincidence counts (C) are expected to scale with the product of both pump powers 5 (C ∝ P_{TE} × P_{TM}). If the power of one pump field is kept constant, and the power of the second one is increased, a linear scaling behaviour is predicted for type-II spontaneous FWM, whereas if the power of both pump fields is simultaneously increased (with constant power ratio), a quadratic scaling is expected. As shown in Fig. 4c, no coincidences (within the noise) were measured when the ring was not pumped or pumped with the TE field alone, where the non-zero counts are
Heralded photon source. In addition to revealing the nature of the nonlinear process, photon pairs are of interest for several applications, such as quantum communications.25 Orthogonally polarized photon pair generation has recently been demonstrated in non-CMOS compatible second-order nonlinear integrated Bragg reflection waveguides using Type-II parametric downconversion.26 In third-order nonlinear media, orthogonally polarized photon pairs have been generated in specifically designed non-resonant microstructured fibres pumped at 800 nm (ref. 27). On a third-order nonlinear chip, the superposition of two Type-0 nonlinear waveguide sources has been achieved, where two straight waveguides were connected by a polarization rotation segment to generate photon pairs, which are either both TE or TM polarized28. In stark contrast, the source presented here directly generates orthogonally polarized photon pairs (one TE, one TM) on chip with a single third-order source presented here directly generates orthogonally polarized photon pairs, which is observed with increasing balanced pump powers. The presence of Raman scattering can be neglected, as the signal and idler frequencies do not overlap significantly with the Raman gain spectrum. This is also experimentally confirmed by the absence of any linear contribution to the power scaling arising from Raman scattering.

Due to the dark counts of the detector. A clear linear scaling behaviour is visible with increasing TM pump power and constant TE power, while a quadratic (without linear contribution) scaling is observed with increasing balanced pump powers. The presence of Raman scattering can be neglected, as the signal and idler frequencies do not overlap significantly with the Raman gain spectrum. This is also experimentally confirmed by the absence of any linear contribution to the power scaling arising from Raman scattering.

determined by the narrower resonance. From the coincidence measurement, shown in Fig. 4a, we extract a measured photon bandwidth of 320 MHz (black line), which is in good agreement with the resonator bandwidth of 410 MHz (red line), where the difference can be explained by the timing jitter of the detectors and electronics, resulting in a small temporal broadening of the measured peak. It is worth noting that the narrow bandwidth, required for several quantum applications, is intrinsically achieved inside the resonator and cannot be directly realised in non-resonant waveguides or fibre-based architectures. The measured CAR of up to 12 is limited by loss, dark counts and the quantum efficiency of the detectors (see Methods), as well as by the photons generated through Type-0 SFWM of the individual pumps, that is, issues which can in the future be addressed by optimized dispersion control. However, we note that a CAR > 10 already suggests the possibility for an immediate implementation of the source for quantum cryptography applications, see, for example, ref. 25. We measure a coincidence rate of ~4 Hz at 5 mW balanced pump power at the input of the chip (5 mW is the highest achievable pump power featured by a CAR > 10). Considering all losses of the detection system (8.5 dB for both signal and idler) as well as the quantum efficiency of the detectors (5% and 10%), this corresponds to a pair production rate (PPR) of 40 kHz and a pair production probability of 1.48 × 10^-12, accounting for the 1.6 dB coupling loss of the pump into the chip. The measured coincidence rate can be further increased to approach the production rate by using better detectors and implementing low-loss filtering on chip. To further characterize the performance of our device as a single-photon source, we measured the heralded autocorrelation function g^2(2) as well as the idler–idler autocorrelation function to estimate the purity of the state (see Methods). A clear dip of g^2(2)(0) ≈ 0.26 ± 0.11 < 0.50 was recorded (see Fig. 5a), showing that the source operates in a non-classical single-photon regime,29,30 while the idler–idler autocorrelation (see Fig. 5b) shows a clear peak with a maximum of 2.01 ± 0.03, resulting in N = 0.99 ± 0.03 ± 1 effective modes, underlining the high purity of the source. Finally, the production of cross-polarized photon pairs is not limited to only the adjacent resonances, but the generation of multiplexed cross-polarized photon pairs is also possible. Indeed, we measured cross-polarized photon pairs over 12 resonance couples, limited by the available filters, each with PPRs > 20 kHz at 5 mW balanced pump power (see Fig. 6 and Methods). All these characteristics highlight the potential of our device for quantum optical applications.

Above-threshold operation. The same pumping scheme and Type-II FWM process can, in principle, lead to above-threshold OPO. However OPO operation could not be reached at the available pump powers (up to 26 mW) with the resonator used in the experiments mentioned above. We therefore resorted to a second ring with higher Q-factors of 750,000 and 1,100,000 for the TE and TM modes, respectively, which was pigtailed to single-mode, non polarization-maintaining fibres, thus preventing us to use this device for the single-photon experiments. Instead of separating the beams by polarization, we detected all outputs (pump and generated fields) using an optical spectrum analyser. With a balanced pump power, a quadratic power-scaling behaviour was measured below threshold (Fig. 7), as also seen in Fig. 4c for the low-Q ring. At the OPO threshold, which was reached at 14 mW balanced pump power (see OPO spectrum in the inset of Fig. 7), the power scaling changed from quadratic to linear, confirming the transition from spontaneous emission to OPO (ref. 11). This device is a novel type of bi-chromatically pumped OPO operating on two orthogonally polarized beams.
combination with passive and easy-to-implement polarization quantum operations can be achieved by using the source in our cross-polarized source, polarization photon routing and (standard deviation of the 10 bin distribution). (averaged for each point, displayed together with the statistical error below the limit for classical correlations (equal to 0.5), confirming the

Figure 5 | Heralded and idler-idler autocorrelation measurement. (a) Measured heralded autocorrelation, showing a clear dip at zero delay below the limit for classical correlations (equal to 0.5), confirming the quantum nature and single-photon operation of the source. Ten bins were averaged for each point, displayed together with the statistical error (standard deviation of the 10 bin distribution). (b) Measured idler-idler autocorrelation, showing a clear peak with a maximum at $2.01 \pm 0.03$, confirming the single-mode operation and high purity of the source.

Figure 6 | Pair production rate at different resonances. Measured pair production rate (blue circles) associated to the Type-II process at different resonator lines symmetrically located with respect to the pumps at 5 mW balanced pump power, showing good agreement with the approximated predicted curve (red line), see Methods for details.

Discussion

We achieve Type-II spontaneous FWM in an integrated platform, thus providing more access to polarization as a degree of freedom for integrated third-order spontaneous nonlinear interactions. Using this process, we demonstrate a novel bi-chromatically pumped OPO, which below threshold directly generates orthogonally polarized photon pairs on a CMOS-compatible chip. The measured photon bandwidth, CAR and high purity single-mode operation in the non-classical single-photon regime underline the utility of the photon pair source for quantum applications. For example, on-chip wavelength photon routing was recently achieved using electronically controlled spectral filters. With our cross-polarized source, polarization photon routing and quantum operations can be achieved by using the source in combination with passive and easy-to-implement polarization elements such as polarizing beam splitters and waveplates.

Methods

Device fabrication. The microring resonators are fabricated using UV photolithography and reactive ion etching in a CMOS-compatible high refractive index silica glass deposited by chemical vapour deposition without the need for high temperature annealing. Hydex is featured by very low linear ($<0.06$ dB/cm)$^{-1}$ and negligible nonlinear optical losses (no nonlinear losses measured up to 25 GW cm$^{-2}$)$^{-1}$, and a high effective nonlinear ($g = n_{eff} / (A_{eff} C_{0}) \approx 233$ W$^{-1}$ km$^{-1}$)$^{-1}$). The etched waveguide cross-section is almost square ($1.5 \times 1.45$ μm), in turn enabling the desired slightly different dispersions in the TE and TM modes, which are low and anomalous at 1,535 nm for both polarizations (zero dispersion wavelengths at 1,560 nm and 1,590 nm, respectively)$^{8}$. The microring resonators are vertically coupled to two bus waveguides, forming a four-port configuration. The resonator used for the single-photon measurements exhibits 200.39 GHz and 200.51 GHz FSR with an offset of 85 GHz, as well as Q-factors of 750,000 and 410 MHz bandwidth) for the TE and TM modes, respectively. The input and output bus waveguides are featured with mode converters and are pigtailed to polarization-maintaining fibres, resulting in coupling losses of $<1.6$ dB per facet. The resonator used for the above-threshold OPO measurement exhibits 200.54 and 200.76 GHz FSR with an offset of 85 GHz, as well as Q-factors of 730,000 and 1,100,000 for the TE and TM modes, respectively. The input and output bus waveguides are pigtailed to single-mode fibres (non polarization maintaining), resulting in coupling losses of $<1.5$ dB per facet.

Type-II FWM and suppression of stimulated FWM. In addition to phase matching, the energy has to be preserved in all nonlinear processes. For the two pumps involved in the Type-II FWM process, the total input pump energy is given by the sum of both pump photon energies

$$E_p = h \cdot \left( \nu_{TE} + \nu_{TM} \right) .$$

$h$ being the Planck’s constant, and $\nu_{TE}$ and $\nu_{TM}$ the central frequencies of the two pump resonances.

As the pump resonances have a specific linewidth, and assuming a Lorentzian resonance (as in our case, see the spectrum in Fig. 11), the energy bandwidth is given by the convolution of both pump lines, which for two Lorentzian curves is also given by a Lorentzian

$$L_{\nu_e}(\nu) = \frac{2}{\pi} \frac{E_p}{\nu_e^2 + \left( \frac{\nu - \nu_e}{\Gamma_{\nu_e}} \right)^2} ,$$

where $\nu_e$ is the center frequency and $\Gamma_{\nu_e}$ the linewidth of the Lorentzian function.
featured by a full width at half maximum (FWHM) of:

\[ L_n(v) = \frac{2}{\pi} \times \frac{1}{1 + \left( \frac{v - \omega_n}{\Omega_{\text{FWHM}}} \right)^2} \]  

with \( \Omega_{\text{TE,TM}} \) being the frequency FWHM of the individual resonances. The same can be estimated for the \( n \)th adjacent resonances, where the signal and idler photons will be generated. The total output energy curve will be again a Lorentzian

\[ E_n(v) = h(v + n \cdot FSR) \]  

and complete suppression of the stimulated FWM between the two pumps.

\[ I_n = h(\Omega_{\text{TE}} + \Omega_{\text{TM}}) \]  

detector is triggered by the first and operated at 10% quantum efficiency, resulting with a FWHM of:

\[ \Delta \omega_{\text{FWHM}} = \frac{1}{2} \Omega_{\text{FWHM}} \]  

or \( \Delta \omega_{\text{FWHM}} \) which becomes 1 for equal FSRs in TE and TM, and decreases when the mismatch between FSRs with respect to the FWHM of the resonances increases.

In addition to the overlap, the resonator linewidth and Q-factor play an important role in the definition of the spontaneous FWM process efficiency. When the Q-factors of the resonances are the same, the FWM efficiency is expected to scale with the Q-factor to the power of 4 (ref. 35). In the case where the TE and TM resonances have different bandwidths and Q-Factors, the FWM process is expected to scale as \( Q_{\text{TE}} \cdot Q_{\text{TM}} \) to account for the possibility of generating multiple photon pairs, as well as for the visibility reduction. Due to the low visibility which is a maximum to the relative standard deviation is displayed in the error bars in Fig. 5a.

Using the measured values (see main text), the PPR for different resonances with respect to the offset can be approximated with

\[ \text{PPR}(\sigma) = \text{PPR}_{\text{max}} \left( 1 + \frac{2}{\pi} \arctan \left( \frac{n \cdot \Delta \omega_{\text{FWHM}}}{\Omega_{\text{FWHM}} + \Omega_{\text{TE}}} \right) \right) \]  

Note that this approximation does not include higher order dispersion and assumes a flat FWM gain spectrum. Even with these assumptions, the fit in Fig 6 shows good agreement to the measured data, resulting in a PPR_{\text{max}} = 40.92 ± 1.33 kHz extracted from the fit.

Stimulated FWM can be fully suppressed by designing the ring resonator in such a way that no ring resonance overlaps with the stimulated FWM bandwidth. With two pump frequencies \( v_{\text{TE}} \) and \( v_{\text{TM}} \) separated by \( \Delta \omega_{\text{TE,TM}} \) the frequencies for stimulated FWM are:

\[ v_{\text{TE}} - v_{\text{WM}} = v_{\text{TE}} + 2 \Delta \omega_{\text{TE,TM}} \]  

\[ v_{\text{TM}} - v_{\text{WM}} = v_{\text{TM}} - 2 \Delta \omega_{\text{TE,TM}} \]  

with a linewidth of

\[ \Omega_{\text{FSR}} = \Omega_{\text{TE}} + \Omega_{\text{TM}} \]  

The stimulated FWM bandwidths do not overlap, and thus stimulated FWM is suppressed, under the following assumptions:

\[ |2 \Delta \omega_{\text{TE,TM}} - FSR_{\text{TE}}| > 2 \Omega_{\text{TE}} + \Omega_{\text{TM}} \]  

\[ |2 \Delta \omega_{\text{TE,TM}} - FSR_{\text{TM}}| > 2 \Omega_{\text{TM}} + \Omega_{\text{TE}} \]  

The FSRs and \( \Delta \omega_{\text{TE,TM}} \) depend on the waveguide dispersion, while the FWHM depends on linear and bending losses together with the resonator coupling. Therefore, the above stated equations can be used to design the ring resonator to simultaneously achieve both cavity enhancement of the spontaneous Type-II FWM and complete suppression of the stimulated FWM between the two pumps.

For example, for the first (lower-Q) microring resonator, equations (12) and (13) are satisfied if

\[ |2 \Delta \omega_{\text{TE,TM}} - FSR_{\text{TE}}| > 60.39 \text{ GHz} > 1.64 \text{ GHz} = 2 \Omega_{\text{TE}} + \Omega_{\text{TM}} \]  

\[ |2 \Delta \omega_{\text{TE,TM}} - FSR_{\text{TM}}| > 60.51 \text{ GHz} > 2.05 \text{ GHz} = 2 \Omega_{\text{TM}} + \Omega_{\text{TE}} \]  

The same also holds for the second (higher Q) microring resonator.

### Single-photon measurements

The coincidence measurements were done using two single-photon detectors (idQuantique id210), one set to the free-running mode with 5% quantum efficiency leading to 1.6 kHz dark-count rates, while the second detector is triggered by the first and operated at 10% quantum efficiency, resulting in 0.3 Hz dark coincidence counts. Time tags from both detectors were collected using a time-to-digital converter with 81 ps timing resolution (idQuantique id800). To realistically assess the properties of our device, unless explicitly stated, all measurements were performed using raw data without background subtraction or correction for losses, detection efficiency or dark counts. For the heralded g^{(2)} measurement, the photons were separated using a polarizing beam splitter, followed by a second 50:50 beam splitter in the idler arm. A third single-photon detector (idQuantique id201) was used, also triggered by the first detector measuring the signal photon. The heralded autocorrelation function \( g^{(2)}(0) \) can be directly extracted from the time tags using the relation:

\[ g^{(2)}(t_1, t_2, t) = \frac{P_{\text{det}}(t_1 - t_2)}{P_{\text{det}}(t_1, t_2 - t) + P_{\text{det}}(t_1, t_2)} \]  

where \( t_{(1,2)} \) are the detection times of the idler photon at the first (second) output port of the beam splitter, respectively, \( t \) is the detection time of the heralding signal photon, \( P_{\text{det}}(t_1, t_2) \) are the normalized Glauber cross-correlation functions, \( P_{\text{det}}(t_1) \) is the triple coincidence rate and \( R \) is the PPR. To quantify the noise, 10 bins are averaged and the relative standard deviation is displayed in the error bars in Fig. 5a.

It is important to note that the method described above to measure the heralded autocorrelation is not valid for all experimental set-ups. It is for instance required that the photon coherence time is larger than the detection time-bin, the time jitter and the heralding time window, all necessary constraints which are fulfilled in our experiment.

For a perfect heralded photon source, it is expected that only one idler photon is present if a signal photon is detected, which results in a dip approaching zero in the conditional coincidence measurement \( g^{(2)}(0) = 0 \). In real systems, where we need to account for the possibility of generating multiple photon pairs, as well as for the fact that the dark count detection, the visibility is reduced. For a dip in the conditional coincidence function \( g^{(2)}(0) = 0.5 \) (not corrected for any losses or detection efficiencies) is sufficient to prove the quantum nature of a heralded photon source. The dominant source of error originates from the fluctuations in the triple coincidence measurement, which are often caused by detector dark counts. Despite the fact that this measurement lasted 3 weeks, the low number of observed triple coincidences resulted in a high relative error.

The idler–idler autocorrelation function, \( g^{(2)}(0) \), where the signal photon is not detected, can instead be used to reveal the purity of the state and the number of effective modes. After a photon pair is generated, there is a certain probability to stimulate the emission of a new pair. This results in an autocorrelation peak with a maximum related to the number of effective modes \( N \) through the relation \( g^{(2)}(0) = 1 + 1/N \). A pure state is thus characterized by \( g^{(2)}(0) = 2 \), corresponding to a single mode.

### Hybrid pumping scheme

The external pumping of high-Q microring resonators with a single pump laser usually requires thermal locking to follow the frequency shift of the resonances induced by cavity heating. Using two external CW lasers to simultaneously pump two resonances of the same device adds a significant degree of complexity leading to a very unstable operation. For this reason, we used a hybrid self-locked pumping approach, where the laser pumping the TE mode was directly built around the resonator, thus eliminating the need for active stabilization. The microcavity resonator was embedded inside an external cavity, with a fibre amplifier and a wavelength filter (nestved cavity design, see Fig. 3). The amplified spontaneous emission of the fibre amplifier was transmitted through a band-pass filter (100 GHz) centered at the desired TE ring resonance and was then coupled into the chip. Light coupled out of the drop port of the ring resonator was fed back to the amplifier, thereby closing the external pump cavity and promoting lasing on the TE mode. To allow self-locked lasing only on the TE polarization, while pumping the TM mode with an external laser (actively locked to the resonance using a feedback loop), polarizing beam couplers were placed before and after the ring resonator. This hybrid approach using one self-locked and one external pump permits pumping on both resonances in a very stable configuration and provides precise control over the individual pump powers.

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Author contributions

C.R., M.K. and L.C. developed the idea. B.E.L. and S.T.C. designed and fabricated the integrated devices. C.R., M.K., L.C., B.W., F.R., M.C., Y.J., M.F., M.P. and A.P. contributed to the development of the experiment and to the data acquisition and analysis. L.C., D.J.M. and R.M. supervised and coordinated the project. All authors contributed to the writing of the manuscript.

Additional information

Competing financial interests: The authors declare no competing financial interests.

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