Optomechanical quantum teleportation

Nicolò Fiaschi, Bas Hensen, Andreas Wallucks, Rodrigo Benevides, Jie Li, Bas Hensen, Thiago P. Mayer Alegre and Simon Gröblacher

Quantum teleportation, the faithful transfer of an unknown input state onto a remote quantum system, is a key component in long-distance quantum communication protocols and distributed quantum computing. At the same time, high-frequency nano-optomechanical systems hold great promise as nodes in a future quantum network, operating on-chip at low-loss optical telecom wavelengths with long mechanical lifetimes. Recent demonstrations include entanglement between two resonators, a quantum memory and microwave-to-optics transduction. Despite these successes, quantum teleportation of an optical input state onto a long-lived optomechanical memory is an outstanding challenge. Here we demonstrate quantum teleportation of a polarization-encoded optical input state onto the joint state of a pair of nanomechanical resonators. Our protocol also allows to store and retrieve an arbitrary qubit state onto a dual-rail encoded optomechanical quantum memory. This work demonstrates the full functionality of a single quantum repeater node and presents a key milestone towards applications of optomechanical systems as quantum network nodes.

High-frequency nano-optomechanical systems, besides their appeal for probing fundamental quantum physics, also hold great promise as nodes in a future quantum network. First, their optical characteristics can be designed to match the particular application, including operation at low-loss telecom wavelengths and matching resonances with other systems (for example atomic transitions). Second, the mechanical modes can be designed to coherently store quantum information for more than ten microseconds, unparalleled for systems natively operating at telecom wavelength. Third, the mechanical mode offers a direct interface to other quantum systems operating in the gigahertz frequency regime, such as superconducting qubits or spin quantum systems.

Quantum teleportation of an unknown input state from an outside source onto a quantum node is considered one of the key components of long-distance quantum communication protocols. It has been demonstrated with pure photonic quantum systems as well as atomic and solid-state spin systems linked by photonic channels. While quantum teleportation involving the vibrational modes of a diamond has previously been demonstrated, the extremely short lifetimes of the system required the mechanical state to be measured before the teleportation protocol was completed. This reverse time-ordering, as well as operation in the visible wavelength regime, makes the protocol unsuitable for long-distance quantum communication.

Here we demonstrate the quantum teleportation of an arbitrary input state onto a long-lived optomechanical quantum memory. In particular, we teleport a polarization-encoded photonic qubit at telecom wavelength onto a dual-rail encoded optomechanical quantum memory. The memory is composed of two mechanical resonators, where the quantum information is stored in the single-excitation subspace of the two resonators. The teleportation we perform implements all components of first-level entanglement swapping. Together with the remote generation of a single-excitation, or Duan–Lukin–Cirac–Zoller (DLCZ)–type entanglement, which has been shown individually before, this current experiment demonstrates the combined requirements for a fully functional quantum repeater node. Besides the impact this has on quantum technologies, it also opens the way to create single-phonon arbitrary qubit states of massive, mechanical oscillators, which can be used for testing quantum physics itself and potential decoherence mechanisms leading to quantum-to-classical transition.

Our optomechanical register consists of two silicon photonic crystal nanobeams, A and B, on two separate chips. Both the nanobeams support a co-localized optical and mechanical mode with resonance frequencies in the optical telecom C-band around 1,550 nm and the microwave C-band around 5 GHz, respectively. The optical and mechanical modes are coupled through the radiation pressure force and photoelastic effect with a single-photon coupling rate $g_p/2\pi \approx 900$ kHz. The chips are placed 20 cm apart from each other inside a dilution refrigerator, and the nanobeam resonators are cryogenically cooled close to their quantum ground state of motion. Optical control pulses of 40 ns length that are either blue- or red-detuned by one mechanical frequency $\Omega_m$ from the optical resonance give rise to linearized optomechanical interactions, addressing the Stokes and anti-Stokes transitions of the system, respectively.

Our teleportation protocol is based on the proposal described in refs. 26,27, which is schematically shown in Fig. 1a, while a sketch of the experimental setup can be seen in Fig. 1b. Each optomechanical device is placed in one of the arms of an actively phase-stabilized fibre interferometer (see Supplementary Section 5 for more details). The paths are recombined using a fibre-based polarizing beamsplitter such that the photons from the devices are cross-polarized. A single blue-detuned pulse is injected into the interferometer, exciting each nanobeam with the same probability $p_b$ and the which-path information of the Stokes scattered light is encoded in the polarization state of the optical mode. Light from device A is vertically polarized, while light from device B is horizontally polarized. The joint state of the two mechanical resonators AB and the optical field are described as

$$|\Psi_{\text{EPR}}\rangle \propto |0\rangle_b |0\rangle_{AB} + \sqrt{p_b} \left( |H\rangle_a |01\rangle_{AB} + e^{i\phi} |V\rangle_a |10\rangle_{AB} \right) + O(p_b).$$

(1)
where $|0\rangle,|1\rangle$ denote the number states containing 0 and 1 excitation, respectively, $\phi$ is the phase, which can be set by controlling the relative phase of the light coming from each nanobeam using an electro-optic modulator (EOM) in arm A of the interferometer, and $p_h\ll 1$ is the Stokes scattering probability set by the blue-detuned control pulse energy. Conditional upon the presence of a Stokes scattered photon, equation (1) is the Einstein–Podolsky–Rosen (EPR) state, $|\Psi_{EPR}\rangle$, that forms our basic resource for teleportation (as shown in Fig. 1a, top left).

After passing a narrow-band (~40-MHz) Fabry–Pérot optical cavity filter to reject the excitation pulse light, the optical part of our EPR-state wave-packet is sent to a (potentially remote) Bell-state measurement (BSM) apparatus. The arbitrary input qubit state, $|\psi_{in}\rangle$, to be teleported is encoded into the polarization of a weak coherent state obtained from a heavily attenuated independent laser (Fig. 1a, top right)

$$|\psi_{in}\rangle \propto |0\rangle + \alpha \left( \cos \frac{\theta_{in}}{2}|H\rangle + e^{i\phi_{in}}\sin \frac{\theta_{in}}{2}|V\rangle \right) + O(|\alpha|^2) \tag{2}$$

where $|\alpha|$ is the coherent state amplitude and the input angles $\theta_{in}$ and $\phi_{in}$ can be chosen by setting the appropriate angles $\theta_{in}$ and $\phi_{in}$, respectively, on the waveplates shown in Fig. 1b.

We then implement a polarization-based BSM by combining $|\psi_{in}\rangle$ with the optical part of $|\Psi_{EPR}\rangle$ using a 50/50 beamsplitter (Fig. 1a, bottom left) and further analysing the output polarization using polarizing beamsplitters and single-photon detectors. From equations (1) and (2) we can see that both the conditional EPR state and the photonic state to be teleported are close to the single-excitation ideal case, and, by operating in the suitable regime, $\sqrt{p_h} \ll |\alpha| \ll 1$, we can beat the classical threshold despite the higher-order terms that reduce the teleportation fidelity (see ref. 26 and Supplementary Section 3). In this limit, a coincidence between polarizations $H$ and $V$ in the BSM projects the state of the mechanical resonators onto

$$|\psi_{out}\rangle_{AB} = \cos \frac{\theta_{in}}{2}|10\rangle_{AB} + e^{i\phi_{in}}\sin \frac{\theta_{in}}{2}|01\rangle_{AB} \tag{3}$$

where the $+(-)$ corresponds to cases where the coincidence occurs on the same (different) output port of the BSM beamsplitter. This event corresponds to the input state $|\psi_{in}\rangle$ being teleported onto the single-excitation subspace of the two mechanical resonators. We note that, as also stated in ref. 26, the teleported mechanical state has the probability amplitudes of the two eigenstates exchanged (bit flip) and has a possible $\pi$-phase difference (phase flip) compared with the conditional EPR state of equation (1). We take this into account in post-processing.

Finally, we can verify that the teleportation was successful by mapping the joint state of the mechanical resonators back onto an optical polarization state using a red-detuned pulse (Fig. 1a, bottom right). We can choose an arbitrary measurement basis for the polarization analysis setup by pulsing the EOM in arm A to adjust the relative phase $\theta_{out}$ between the $H$ and $V$ components, and setting the rotation of a Pockels cell (PC) pulsed at its half-wave voltage to adjust $\theta_{out}$, the relative amplitude between the $H$ and $V$ components. Conditional upon a successful teleportation event, the fidelity of the teleported state can be measured from the number of readout events with the polarization equal to the one in the input, divided by the total number of readout events (see Supplementary Section 8 for more).

For the above protocol to work, the nanobeams must meet very stringent criteria. In particular, the emitted photons from each device must be completely indistinguishable in all degrees of freedom except for their polarization, which in principle requires the nanobeams to have identical mechanical and optical resonance
To accurately predict the $g^{(2)}$ of the mechanical state, we measure the cross-correlation between the Stokes and anti-Stokes scattered photons: $g^{cc}_{\Delta n} = \frac{p_{\Delta n}(\Delta n)}{p_{\Delta S}(\Delta S)}$, where $p_{\Delta n}$ is the probability of detecting both a Stokes (S) and an anti-Stokes (aS) scattered photon $\Delta n$ experimental repetitions apart, and $p_{\Delta S}$ and $p_{\Delta a}$ are the probability of detecting individual Stokes and anti-Stokes photons, respectively. The measurement results shown in Fig. 2c demonstrate cross-correlation values far above the classical bound of 2 (ref. 25) by more than 9 (5) standard deviations for device A (B), proving that we can store our teleported state with little added noise. We also use this measurement to estimate the total thermal population added by the optical pulses. We infer a total thermal excitation of $0.24(4) \times 100$ ns (ref. 29) for device A (B) using a fixed delay between the pulses of $(0.10(1))$ for device A (B), proving that the anti-Stokes process of $2.6\%$ (2.9%) for device A (B), which correspond to a pulse energy of $22\, \mu J$ (18\,\mu J) and $50\, \mu J$ (40\,\mu J) for device A (B) (see Supplementary Sections 2 and 3 for more details).

We then confirm that the mechanical modes of the nanobeams can individually be prepared close to a single-phonon Fock state. To accurately predict the $g^{(2)}$ of the mechanical state, we measure the cross-correlation between the Stokes and anti-Stokes scattered photons: $g^{cc}_{\Delta n} = \frac{p_{\Delta n}(\Delta n)}{p_{\Delta S}(\Delta S)}$, where $p_{\Delta n}$ is the probability of detecting both a Stokes (S) and an anti-Stokes (aS) scattered photon $\Delta n$ experimental repetitions apart, and $p_{\Delta S}$ and $p_{\Delta a}$ are the probability of detecting individual Stokes and anti-Stokes photons, respectively. The measurement results shown in Fig. 2c demonstrate cross-correlation values far above the classical bound of 2 (ref. 25) by more than 9 (5) standard deviations for device A (B), proving that we can store our teleported state with little added noise. We also use this measurement to estimate the total thermal population added by the optical pulses. We infer a total thermal excitation of $0.24(4) \times 100$ ns (ref. 29) for device A (B) using a fixed delay between the pulses of $(0.10(1))$ for device A (B), proving that the anti-Stokes process of $2.6\%$ (2.9%) for device A (B), which correspond to a pulse energy of $22\, \mu J$ (18\,\mu J) and $50\, \mu J$ (40\,\mu J) for device A (B) (see Supplementary Sections 2 and 3 for more details).

Having chosen the most suitable pair of optomechanical devices using the above criteria, we then proceed to characterize their suitability as a conditional EPR source to produce the state $|\Psi_{EPR}\rangle$ in equation (1). We test the full conditional EPR source by proving the non-separability of the Stokes field with the phononic state in the nanobeams, verifying it with the visibility after readout, similarly to ref. 1. We first measure the polarization of the optical output state of $|\Psi_{EPR}\rangle$ in a rotated, diagonal basis. This projects the state of the nanobeams onto $|\psi\rangle_{AB} = \frac{1}{\sqrt{2}} \left( |01\rangle_{AB} \pm e^{i\theta} |10\rangle_{AB} \right)$ (4)

where the sign $\pm$ depends on whether a diagonal $|D\rangle \propto |H\rangle + |V\rangle$ or an anti-diagonal $|A\rangle \propto |H\rangle - |V\rangle$ photon was detected. We then map the joint state of the mechanical resonators back onto an optical polarization state and measure it in the same diagonal basis.

Fig. 2 EPR source characterization. a, Characterization of the optical resonances of device A (blue) and device B (orange) measured in reflection. The devices have a small mismatch of about 0.01 GHz. b, Mechanical spectra of the devices using optomechanically-induced transparency (or OMIT; see Supplementary Section 1 for details) for device A (blue) and device B (orange). The difference in the mechanical frequencies shown here, equal to 8 MHz, is compensated by using a serrodyne technique to frequency shift the light going to device A, to ensure that the emitted photons are fully indistinguishable. c, For the same repetition $\Delta n = 0$, the Stokes and anti-Stokes fields of each device show strong cross-correlations $g^{cc}_{\Delta n}$, violating the bound for classical emitters (dashed line), while for different repetitions the detections are fully uncorrelated. Data are blue for device A and orange for device B. d, Characterization of the entangled states produced by the EPR source. The second-order coherence $g^{\langle 2\rangle}_{\Delta n}$ is in green for $i \neq j$ and in red for $i = j$, with $i,j \in (D,A)$ the detected polarization state of the Stokes and anti-Stokes photons, respectively (D for diagonal, A for anti-diagonal, see the main text), as a function of the phase shift induced in one arm of the interferometer by applying a pulsed voltage to the EOM. The solid line is a sinusoidal fit to guide the eye. The shaded regions are the expected values from simulation (see the main text for details). The error bars in c and d are one standard deviation.
Letters | Nature Photonics

Obtain a visibility between the Stokes and anti-Stokes pulses of respectively. As shown in Fig. 2d, the cases where detected polarization state of the Stokes and anti-Stokes photons, polarization is detected for Stokes and anti-Stokes photons) exhibit more robust Agresti–Coull interval 30, which is above the threshold significantly above the classical threshold of 2/3 by 4.8 standard deviations. The grey bars are the expected fidelities for each basis from our simulation of the full teleportation protocol, taking only independently measured parameters as input, with the shaded area the statistical confidence interval based on the uncertainty in those parameters and the black line the expected value.

As a function of \( \phi \) set by the EOM voltage in arm A. This yields the second-order coherence \( g^{(2)}(\phi) = \frac{F_{\text{meas}}}{F_{\text{total}}} \), with \( i,j \in \{ H, V \} \) the detected polarization state of the Stokes and anti-Stokes photons, respectively. As shown in Fig. 2d, the cases where \( i=j \) (the same polarization is detected for Stokes and anti-Stokes photons) exhibit an opposite correlation compared with the cases where \( i \neq j \). We obtain a visibility between the Stokes and anti-Stokes pulses of \( \mathcal{V} = \frac{g^{(2)}(\phi=0) - g^{(2)}(\phi=\frac{\pi}{4})}{g^{(2)}(\phi=0)} = (74 \pm 3)\% \) for the EOM voltage of 6 V, which shows the suitability of the optomechanical system as the EPR source for the teleportation. From this measurement we also calculate our readout angle \( \phi_{\text{read}} \) as a function of the applied EOM voltage. Finally, we compare the measured visibility against a numerical simulation of the entanglement experiment, taking as the input only the independently measured thermal occupations and lifetimes of the two nanobeams (see Supplementary Section 2), the detector dark count probability, the control pulse leakage and the interferometer dephasing. The values expected from the simulation are shown as the shaded region in Fig. 2d, also taking into account the statistical uncertainties in the measured simulation input parameters (see Supplementary Section 3 for more details).

Since our scheme is symmetric around a change of \( \pi \) in the phase of the teleported state, we verify our teleportation for the input states \( H, V, D = (H+V) \) and \( L = (H+V) \), only. To estimate our teleportation fidelity we set our EOM readout phase \( \phi_{\text{read}} \) and PC angle such that the ideal teleported state is mapped to \( H (V) \) for cases where the coincidence occurred on the same (different) output port of the BSM beamsplitters. We can then estimate the fidelity of the teleported state as the fraction of correct readout results \( F = \frac{N_{\text{correct}}}{N_{\text{total}}} \), with \( i \in \{ H, V, D, L \} \) (see Supplementary Section 8). Note that this fidelity estimation includes the fidelity of our readout process, and therefore provides a lower bound to the true teleportation fidelity. After around 100 successful measurement runs for each basis we obtain an average fidelity of \( \langle F \rangle = \frac{(F_H + F_V + 2F_D + 2F_L)}{6} = (75.0 \pm 1.7)\% \) (see Fig. 3), which is significantly above the classical threshold of 2/3 by 4.8 standard deviations. We obtain very similar results even when using the more robust Agresti–Coull interval 30, which is above the threshold by more than four quantiles of a standard normal distribution. The average probability of the measured teleportation event is \( 4.3 \times 10^{-5} \) (one event every 1.3 hours).

Using our simulated version of the protocol, which agrees well with the measured fidelities, we can estimate the errors induced by various parts of the protocol. Excluding the readout error from the thermal population added by the red-detuned pulse, we estimate the teleportation fidelity to be \( \langle F \rangle_{\text{meas}} = (77 \pm 1)\% \). By replacing the input weak coherent state with a true single-photon state, our expected fidelity increases to \( (86 \pm 1)\% \), with all the other parameters unchanged.

Our experiment marks the realization of quantum teleportation of an arbitrary qubit input state onto a dual-rail-encoded long-lived optomechanical quantum memory. In contrast to previous experiments, our fully engineered system directly functions as a basic quantum repeater node for a future quantum network with an integrated memory component at telecom wavelengths. Even though the experiment was performed at the laboratory scale, in our current implementation we already separate the weak coherent state (and the BSM polarizing beamsplitter) from the mechanical oscillators by several tens of metres of fibre. A logical further extension to the teleportation protocol will be to demonstrate a full first-level entanglement-swapping operation 23, where previously distributed entangled states between distant nanobeams are combined to produce robust dual-rail-encoded entanglement. In the present form this would require four compatible nanobeam resonators. An attractive alternative would be to use nanobeams with two distinct frequency mechanical modes coupled to a single optical mode, combined with photonic dual-rail frequency encoding.

Our experiment also paves the way for transferring arbitrary qubit quantum states onto a mechanical system, which could lead to new tests of fundamental quantum physics 13. Another exciting possibility for our system is the potential to directly interface with various different quantum systems, such as superconducting microwave circuits, for example 14. In this context the demonstrated teleportation could function as a quantum-state transfer between photonic and microwave qubits. Moreover, we show that the system can be easily mode matched to an outside source, making it suitable to connect a large variety of optical systems that emit in the near-infrared regime.

### Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at [https://doi.org/10.1038/s41566-021-00866-z](https://doi.org/10.1038/s41566-021-00866-z).

Received: 14 April 2021; Accepted: 20 July 2021; Published online: 7 October 2021

### References

1. Bennett, C. H. et al. Teleporting an unknown quantum state via dual classical and Einstein–Podolsky–Rosen channels. *Phys. Rev. Lett.* 70, 1895–1899 (1993).
2. Sangouard, N., Simon, C., de Riedmatten, H. & Gisin, N. Quantum repeaters based on atomic ensembles and linear optics. *Rev. Mod. Phys.* 83, 33–80 (2011).
3. Rauschenfeld, R. & Briegel, H. J. A one-way quantum computer. *Phys. Rev. Lett.* 86, 5188–5191 (2001).
4. Barz, S. et al. Demonstration of blind quantum computing. *Science* 335, 303–308 (2012).
5. Chan, J. et al. Laser cooling of a nanomechanical oscillator into its quantum ground state. *Nature* 478, 89–92 (2011).
6. Kimble, H. J. The quantum internet. *Nature* 453, 1023–1030 (2008).
7. Riedinger, R. et al. Remote quantum entanglement between two micromechanical oscillators. *Nature* 556, 473–477 (2018).
8. Wallucks, A., Marinković, I., Hensen, B., Stockill, R. & Gröblacher, S. A quantum memory at telecom wavelengths. *Nat. Phys.* 16, 772–777 (2020).
9. Forsch, M. et al. Microwave-to-optics conversion using a mechanical oscillator in its quantum groundstate. *Nat. Phys.* 16, 69–74 (2020).
10. Jiang, W. et al. Efficient bidirectional piezo-optomechanical transduction between microwave and optical frequency. *Nat. Commun.* **11**, 1166 (2020).
11. Mirhosseini, M., Sipahigil, A., Kalae, M. & Painter, O. Superconducting qubit to optical photon transduction. *Nature* **588**, 599–603 (2020).
12. Aspelmeyer, M., Kippenberg, T. J. & Marquardt, F. Cavity optomechanics. *Rev. Mod. Phys.* **86**, 1391–1452 (2014).
13. Briegel, H.-J., Dür, W., Cirac, J. I. & Zoller, P. Quantum repeaters: the role of imperfect local operations in quantum communication. *Phys. Rev. Lett.* **81**, 5932–5935 (1998).
14. Bouwmeester, D. et al. Experimental quantum teleportation. *Nature* **390**, 575–579 (1997).
15. Furusawa, A. et al. Unconditional quantum teleportation. *Science* **282**, 706–709 (1998).
16. Ma, X.-S. et al. Quantum teleportation over 143 kilometres using active feed-forward. *Nature* **489**, 269–273 (2012).
17. Valivarthi, R. et al. Quantum teleportation across a metropolitan fibre network. *Nat. Photon.* **10**, 676–680 (2016).
18. Olmschenk, S. et al. Quantum teleportation between distant matter qubits. *Science* **323**, 486–489 (2009).
19. Pfaff, W. et al. Unconditional quantum teleportation between distant solid-state quantum bits. *Science* **345**, 532–535 (2014).
20. Hou, P.-Y. et al. Quantum teleportation from light beams to vibrational states of a macroscopic diamond. *Nat. Commun.* **7**, 11736 (2016).
21. Jiang, L., Taylor, I. M. & Lukin, M. D. Fast and robust approach to long-distance quantum communication with atomic ensembles. *Phys. Rev. A* **76**, 012301 (2007).
22. Duan, L. M., Lukin, M. D., Cirac, J. I. & Zoller, P. Long-distance quantum communication with atomic ensembles and linear optics. *Nature* **414**, 413–418 (2001).
23. Bassi, A., Lochan, K., Satin, S., Singh, T. P. & Ulbricht, H. Models of wave-function collapse, underlying theories, and experimental tests. *Rev. Mod. Phys.* **85**, 471–527 (2013).
24. Fröwis, F., Sekatski, P., Dür, W., Gisin, N. & Sangouard, N. Macroscopic quantum states: measures, fragility, and implementations. *Rev. Mod. Phys.* **90**, 025004 (2018).
25. Riedinger, R. et al. Non-classical correlations between single photons and phonons from a mechanical oscillator. *Nature* **530**, 313–316 (2016).
26. Li, J. et al. Proposal for optomechanical quantum teleportation. *Phys. Rev. A* **102**, 032402 (2020).
27. Pautrel, S., Denis, Z., Bon, J., Borne, A. & Favero, I. An optomechanical discrete variable quantum teleportation scheme. *Phys. Rev. A* **101**, 063820 (2020).
28. Meenehan, S. M. et al. Silicon optomechanical crystal resonator at millikelvin temperatures. *Phys. Rev. A* **90**, 011803 (2014).
29. Hong, S. et al. Hanbury Brown and Twiss interferometry of single phonons from an optomechanical resonator. *Science* **358**, 203–206 (2017).
30. Brown, L. D., Cai, T. T. & DasGupta, A. Interval estimation for a binomial proportion. *Stat. Sci.* **16**, 101–133 (2001).
31. Chu, Y. & Gröblacher, S. A perspective on hybrid quantum opto- and electromechanical systems. *Appl. Phys. Lett.* **117**, 150503 (2020).

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2021
Data availability
Source data for the plots are available via Zenodo at https://doi.org/10.5281/zenodo.5079912.

Code availability
The QuTiP code used for the simulations in the Supplementary Information is available at https://github.com/GroeblacherLab/Optomechanical_Quantum_Teleportation.

Acknowledgements
We would like to thank K. Hammerer and R. Stockill for valuable discussions. This work is supported by the Foundation for Fundamental Research on Matter (FOM) Projectruimte grant (16PR1054), the European Research Council (ERC StG Strong-Q, 676842 and ERC CoG Q-ECHOS, 101001005) and by the Netherlands Organization for Scientific Research (NWO/OCW), as part of the Frontiers of Nanoscience programme, as well as through Vidi (680-47-541/994) and Vrij Programma (680-92-18-04) grants. R.B. and T.P.M.A. acknowledge funding from the Fundação de Amparo à Pesquisa do Estado de São Paulo (2019/01402-1, 2016/18308-0, 2018/15580-6 and 2018/25339-4) and from the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Finance Code 001). B.H. also acknowledges funding from the European Union under a Marie Skłodowska-Curie COFUND fellowship.

Author contributions
N.F., B.H., A.W., J.L. and S.G. devised and planned the experiment. R.B. and B.H. fabricated the sample, and N.F., B.H., R.B. and A.W. built the setup and performed the measurements. B.H. developed the code for the simulations. N.F., B.H. and S.G. analysed the data and wrote the manuscript with input from all authors. T.P.M.A. and S.G. supervised the project.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41566-021-00866-z.
Correspondence and requests for materials should be addressed to Simon Gröblacher.

Peer review information Nature Photonics thanks the anonymous reviewers for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.