Atomic spin-controlled non-reciprocal Raman amplification of fibre-guided light

Sebastian Pucher1,2, Christian Liedl1,2, Shuwei Jin1, Arno Rauschenbeutel1 and Philipp Schneeweiss1,✉

In a non-reciprocal optical amplifier, gain depends on whether the light propagates forwards or backwards through the device. Typically, one requires either the magneto-optical effect, temporal modulation or optical nonlinearity to break reciprocity. By contrast, here we demonstrate non-reciprocal amplification of fibre-guided light using Raman gain provided by spin-polarized atoms that are coupled to the nanofibre waist of a tapered fibre section. The non-reciprocal response originates from the propagation-direction-dependent local polarization of the nanofibre-guided mode in conjunction with polarization-dependent atom–light coupling. We show that this novel mechanism can also be implemented without an external magnetic field and that it allows us to fully control the direction of amplification via the atomic spin state. Our results may simplify the construction of complex optical networks. Moreover, by using other suitable quantum emitters, our scheme could be implemented in photonic integrated circuits and circuit quantum electrodynamics.

Non-reciprocal optical devices are paramount in optical technologies. They treat light differently when propagating forwards or backwards1–3, thereby enabling, for example, diodes and circulators for light. The established ways to break reciprocity are based on the magneto-optical effect1, temporal modulation4 or optical nonlinearities5–7. Recently, the internal spin of quantum emitters that are coupled to spin-momentum-locked nanophotonic modes has also been used to achieve non-reciprocity8. This enabled a novel class of non-reciprocal elements that, by now, comprises the experimental realizations of isolators9,10 and circulators11. However, a non-reciprocal amplifier is missing to date. For such amplifiers, the optical gain depends on whether the light propagates forwards or backwards through the gain medium. In terms of applications, non-reciprocal amplifiers for light facilitate the optical read-out of sensitive signal sources such as quantum systems without exposing the latter to spontaneous emission noise. Moreover, they simplify the construction of complex optical networks as there is no amplification of undesired reflections. Non-reciprocal gain also naturally lends itself to constructing unidirectional ring lasers.

Examples for the recent experimental realizations of non-reciprocal optical amplifiers include schemes based on Doppler shifts in hot atomic vapours12, on optomechanical effects13–15 and on stimulated Brillouin scattering in silicon16. For technical applications, optical Raman amplifiers are of particular importance. In this context, non-reciprocal amplification using the propagation-direction-dependent polarization overlap of Raman light fields guided in nanophotonic waveguides has been demonstrated17. Moreover, non-reciprocal amplification via spin-selective photon–phonon interactions enabled by stimulated Raman scattering was theoretically studied recently18.

Here we experimentally demonstrate the non-reciprocal amplification of light using laser-trapped, spin-polarized caesium (Cs) atoms, which are coupled to a nanophotonic waveguide. Taking advantage of the inherent link between the local polarization and propagation direction of guided light19–21, also referred to as spin-momentum locking, polarization interchange. In this context, non-reciprocal amplification using the propagation-direction-dependent polarization overlap of Raman light fields guided in nanophotonic waveguides has been demonstrated17. Moreover, non-reciprocal amplification via spin-selective photon–phonon interactions enabled by stimulated Raman scattering was theoretically studied recently18.

Here we experimentally demonstrate the non-reciprocal amplification of light using laser-trapped, spin-polarized Cs atoms, which are coupled to a nanophotonic waveguide. Taking advantage of the inherent link between the local polarization and propagation direction of guided light19–21, also referred to as spin-momentum locking, polarization interchange. In this context, non-reciprocal amplification using the propagation-direction-dependent polarization overlap of Raman light fields guided in nanophotonic waveguides has been demonstrated17. Moreover, non-reciprocal amplification via spin-selective photon–phonon interactions enabled by stimulated Raman scattering was theoretically studied recently18.

Figure 1 shows a schematic of the experimental setup. We work with a pair of counter-propagating fundamental modes of a cylindrical nanophotonic waveguide, which is realized as the waist of a tapered optical fibre. The Cs atoms are held at a distance of ~230 nm from the optical nanofibre surface using a two-colour optical dipole trap and coupled to the nanofibre-guided modes via their evanescent fields22. We launch the signal field at a wavelength of 852 nm from either one side (port 1) or the other side (port 2) into the tapered fibre. We note, however, that our scheme also works when two fields are simultaneously launched into ports 1 and 2 (Supplementary Section 1). We refer to the corresponding power transmission coefficients as T1→2 and T2→1, respectively. Due to the strong transverse confinement of the signal field in the nanofibre section, a strong component of the electric field along the direction of propagation occurs. This leads to a local polarization at the position of the atoms that is almost perfectly circular and lies in the plane containing the atoms and the nanofibre axis (x–y plane)23. Specifically, the calculated overlap of the signal field at the position of the atoms with σp (σp) polarization is 92% (8%) when propagating in the 1→2 direction (quantization axis, +z). When propagating in the 2→1 direction, these specified overlaps of the signal field with σ+ and σ– polarization interchange.

1Department of Physics, Humboldt-Universität zu Berlin, Berlin, Germany. 2These authors contributed equally: Sebastian Pucher, Christian Liedl.
2✉E-mail: philipp.schneeweiss@hu-berlin.de
We illuminate the atoms from the side with a π-polarized free-space pump laser field that propagates in the +x direction and hence cannot break reciprocity. In conjunction with the inherent link between the local polarization and propagation direction of the signal field, this then couples the states of different A configurations, depending on the signal propagation direction (Fig. 2a). For signal propagation from 1 to 2, the A configuration comprises a π and σ− transition and is denoted as A−. For the other propagation direction, it comprises a π and σ+ transition and is called A+. For the following, the relevant A− systems are formed by the following three states: |[6S1/2, F=4, m_F=±4⟩, |6S1/2, F=3, m_F=±3⟩ and |6P3/2, F=4, m_F=±4⟩], where F labels the hyperfine level and m_f labels the Zeeman level.

When the pump and signal fields fulfill the dressed-atom two-photon resonance, the dynamics that results from these A couplings only depends on the two-photon Rabi frequency and decoherence rates. For nanofibre-trapped cold atoms, Raman cooling has been shown recently, and the in-trap atomic motion has been measured using Raman coupling[23]. Generally, the resonant two-photon Rabi frequency is given by Ω_p=Ω\_p,Ω\_r/(2d), where Ω\_p and Ω\_r are the single-photon Rabi frequencies of the signal and pump field, respectively, and d is the one-photon detuning from the excited state. When the latter can be adiabatically eliminated[18] and when Ω\_p is much larger than the decoherence rates, the dynamics is coherent and two-photon Rabi oscillations of the ground-state populations occur. The underlying stimulated Raman scattering leads to an energy transfer from the pump to the signal field as population transfer from |F=4⟩ to |F=3⟩ of the 6S1/2 manifold takes place. In this case, the signal field experiences gain. Conversely, although population is transferred from |F=3⟩ to |F=4⟩, the signal field experiences loss. In this coherent regime, gain and loss thus vary periodically with time, with a period that is given by 2\sqrt\Omega\_p,\Omega\_r. In the incoherent regime, that is, when Ω\_p is much smaller than the decoherence rates, the dynamics can be described by rate equations. Here the gain is proportional to the population difference between |F=4⟩ and |F=3⟩, and the small-signal gain is independent of signal power. This is in contrast to the coherent regime where the maximum gain is inversely proportional to Ω\_p and thus proportional to 1/\sqrt\Omega\_p.

We now show that the elements introduced above allow non-reciprocal amplification that is controlled by the atomic spin. To this end, we prepare atoms on only one side of the nanofibre (Methods). This step is performed at an offset magnetic field along +z of ~0.5G and yields atoms cooled close to the motional ground state, dominantly in the state |6S1/2, F=4, m_F=−4⟩ (ref. 24). The offset magnetic field is then ramped to ~7G to stabilize the m_F state. We set the one-photon detuning of the pump laser to Δ ≈ −2π×82 MHz and tune the signal field to the light-shifted two-photon resonance, that is, Δ+δ=0. Here δ\_LS=|(\Omega\_p^2+\Delta^2)^{1/2}−|Δ||/2 is the pump-field-induced light shift of the |6S1/2, F=4, m_F=±4⟩ states and Ω\_p \approx 2π×20 MHz is the Rabi frequency of the pump field. We estimate a signal-field Rabi frequency of Ω\_p \approx 2π×1.6 MHz for atoms in the minimum of the trapping potential (Supplementary Table 1 provides an overview of the relevant parameters).

For reference, we first only switch on the signal field, which does not couple to the atoms in |6S1/2, F=4, m_F=−4⟩, and measure the optical power transmitted through the waveguide, yielding ~9 pW.
At time $t=0\mu s$, we then switch on the pump field and thereby establish the Raman coupling. Figure 2b shows the measured signal transmission for propagation from 1 to 2 and $\sim$1,400 trapped atoms (green circles). Initially, it increases linearly and then reaches a maximum of 2.38(6) after $t=0.9\mu s$, only slightly less than a quarter of a period of the two-photon Rabi oscillations at a frequency of $\Omega_{\text{R}} \approx 2\pi \times 200\text{kHz}$. Amplification of the signal field propagating from 1 to 2 prevails up to $t=2.5\mu s$. From $t=2.5\mu s$ onwards, we observe $T_{1\rightarrow 2} < 1$ (Supplementary Section 2). In combination, these two observations evidence that our system operates in a partially coherent regime. From the gain spectrum, we infer an amplifier bandwidth of $2\pi \times 0.78(6)\text{MHz}$ (Supplementary Section 3). For our settings, the main source of decoherence is off-resonant scattering of the pump field, which initially occurs at a rate of $\sim$500kHz and then decreases to $\sim$100kHz. The modelled evolution of the signal transmission is shown by the dashed line (Fig. 2b) and agrees well with the data. It is obtained by solving the time-dependent master equation for each atom (Methods).

In the other direction, we only observe a small increase in transmission (Fig. 2b, orange diamonds and dotted line), which reaches a maximum of $T_{2\rightarrow 1} = 1.20(5)$. This residual gain mainly arises from a small $\Lambda^-$ coupling of the 2$\rightarrow$1 signal field due to its $\sim$8% overlap with $\sigma^-$ polarization. We checked that the spontaneous Raman scattering of the pump laser beam into the nanofibre-guided mode contributes at the most 11% of the detected signals. We, thus, clearly observe non-reciprocal Raman gain.

In Fig. 2c, we plot the mean signal transmissions, namely, $T_{1\rightarrow 2}$ and $T_{2\rightarrow 1}$, averaged within $t=0.7$–1.2$\mu s$. The red bars are derived from the data shown in Fig. 2b, where the atoms are prepared in the $|F=4, m_F=4\rangle$ state of the $6S_{1/2}$ manifold. To reverse the direction of Raman gain, we now switch from $\Lambda^-$ to $\Lambda^+$ coupling by preparing the atoms in $|F=4, m_F=4\rangle$ (Methods). However, when only switching the initial atomic spin state, no gain is observed in either direction (Fig. 2c, blue bars). This is because of the Zeeman shifts in the energy levels of the $6S_{1/2}$ manifold, which leads to a large two-photon detuning, $\delta^*$, for the $\Lambda^+$ system (Fig. 2a). By adjusting the signal frequency to compensate for this Zeeman shift, we restore the two-photon resonance for the $\Lambda^+$ system; indeed, we observe non-reciprocal Raman gain in the opposite (2$\rightarrow$1) direction (Fig. 2d, blue bars). The difference in the non-reciprocal gain (Fig. 2c,d) stems from the different numbers of atoms that are prepared in the $|F=4, m_F=4\rangle$ and $|F=4, m_F=4\rangle$ states (Methods). For this setting of signal detuning, in turn, no gain is observed for either direction when atoms are prepared in the $|F=4, m_F=4\rangle$ state (Fig. 2d, red bars).

We now demonstrate that non-reciprocal Raman gain can also be achieved in our system without an applied magnetic field. However, in this case, we have to stabilize the $m_F$ states by means of another mechanism against depopulation and dephasing due to spin-motion coupling and stray magnetic fields. To this end, we employ an additional $\pi$-polarized laser field. This beam co-propagates with the pump beam, is about $2\pi \times 90\text{MHz}$ red-detuned to the $|6S_{1/2}, F=4\rangle \rightarrow |6P_{3/2}, F=3\rangle$ transition at a wavelength of 894nm and has an intensity of $\sim$380mWcm$^{-2}$. It induces a TLS for the $F=4$ manifold of the $6S_{1/2}$ ground state, whereas its effect on the $F=3$ ground state manifold is negligible (Fig. 3a). For our experimental parameters, we estimate the differential TLS between the $|F=4, m_F=4\rangle$ and $|F=4, m_F=4\rangle$ states to be about $2\pi \times 2\text{MHz}$, large enough to stabilize the $|F=4, m_F=4\rangle$ states. Crucially, the TLS is proportional to $m_F^2$; therefore, the two-photon resonances in the $\Lambda^-$ and $\Lambda^+$ configurations now coincide, that is, $\delta = \delta^*$ (Supplementary Section 3 provides the experimental confirmation).

We first demonstrate reciprocal gain in this setting. For this, we prepare atoms in a statistical mixture of $|6S_{1/2}, F=4, m_F=4\rangle$ and $|6S_{1/2}, F=4, m_F=4\rangle$ (Methods). The mean transmissions, $T_{1\rightarrow 2}$ and $T_{2\rightarrow 1}$, averaged within $t=0.15$–0.90$\mu s$ are shown in Fig. 3b (grey bars). They coincide within the error bars, confirming reciprocal amplification. In these measurements, the average gain is smaller than $\sim$10%, limited by the smaller number of atoms due to a less efficient state preparation as well as by the almost five times larger width of two-photon resonance (Supplementary Section 3). To obtain non-reciprocal gain, we now selectively prepare atoms in one of the two outermost Zeeman states, either $|F=4, m_F=4\rangle$ or $|F=4, m_F=4\rangle$ (Methods). For $|F=4, m_F=4\rangle$, we only observe gain in the 1$\rightarrow$2 direction (Fig. 3b, red bars). For $|F=4, m_F=4\rangle$, gain only occurs for the 2$\rightarrow$1 direction (Fig. 3b, blue bars). This confirms that the atomic spin rather than an applied magnetic field breaks reciprocity and allows us to control the direction of amplification in our experiment.

At the fundamental level, our results enable the investigation of cold-atom lasing with spin-controlled directionality of the atom-light coupling. Moreover, given the high level of control available with our experimental platform, it lends itself to study quantum thermodynamics in the presence of non-reciprocal interactions. The demonstrated gain mechanism is compatible with both pulsed and continuous-wave operation, where the latter only requires the addition of a suitable repump laser field. Finally, our amplification

---

**Fig. 3 | Magnetic-field-free non-reciprocal Raman gain.** a, We use a $\pi$-polarized laser field to stabilize the atomic spin state via the TLS. For this configuration, the two-photon detunings, namely, $\delta$ and $\delta^*$, coincide (see the main text). b, Setting the gain direction of the magnetic-field-free amplifier: at two-photon resonance, amplification occurs in both directions when the atoms are prepared in a statistical mixture of $|F=4, m_F=4\rangle$ and $|F=4, m_F=4\rangle$ of the $6S_{1/2}$ manifold (grey bars). For atoms prepared in the $|F=4, m_F=4\rangle$ state only, we observe gain exclusively for the 1$\rightarrow$2 direction. When the atoms are prepared in the $|F=4, m_F=4\rangle$ state, amplification occurs in the 2$\rightarrow$1 direction. Here the data are presented as transmission with error bars indicating the $\sigma$ uncertainty assuming Poissonian statistics for the underlying photon counting.
scheme could also be implemented using other quantum emitters with a suitable level scheme coupled to spin-momentum-locked waveguides. This encompasses applications in various frequency domains based on, for example, photonic integrated circuits or circuit quantum electrodynamics, where non-reciprocal magnetic-field-free amplification at the quantum level is a highly sought capability.

**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/s41566-022-00987-z.

Received: 5 August 2021; Accepted: 8 March 2022; Published online: 25 April 2022

**References**

1. Potton, R. J. Reciprocity in optics. *Rep. Prog. Phys.* **67**, 717 (2004).
2. Jalas, D. et al. What is—and what is not—an optical isolator. *Nat. Photon.* **7**, 579–582 (2013).
3. Asadchy, V. S., Mirmoosa, M. S., Díaz-Rubio, A., Fan, S. & Tretyakov, S. A. Tutorial on electromagnetic nonreciprocity and its origins. *Proc. IEEE* **108**, 1684–1727 (2020).
4. Caloz, C. et al. Electromagnetic nonreciprocity. *Phys. Rev. Appl.* **10**, 047001 (2018).
5. Sounas, D. L. & Alù, A. Non-reciprocal photonics based on time modulation. *Nat. Photon.* **11**, 774–783 (2017).
6. Fan, S., Shi, Y. & Lin, Q. Nonreciprocal photonics without magneto-optics. *IEEE Antennas Wireless Propag. Lett.* **17**, 1948–1952 (2018).
7. Khurgin, J. B. Non-reciprocal propagation versus non-reciprocal control. *Nat. Photon.* **14**, 711 (2020).
8. Kittlaus, E. A. Reply to ‘Non-reciprocal propagation versus non-reciprocal control’. *Nat. Photon.* **14**, 712 (2020).
9. Lodahl, P. et al. Chiral quantum optics. *Nature* **541**, 473–480 (2017).
10. Sayrin, C. et al. Nanophotonic optical isolator controlled by the internal state of cold atoms. *Phys. Rev. X* **5**, 041036 (2015).
11. Schuescher, M., Hiloço, A., Will, E., Volz, J. & Rauschenbeutel, A. Quantum optical circulator controlled by a single chirally coupled atom. *Science* **354**, 1577–1580 (2016).
12. Lin, G. et al. Nonreciprocal amplification with four-level hot atoms. *Phys. Rev. Lett.* **123**, 033902 (2019).
13. Ruesink, F., Miri, M.-A., Alù, A. & Verhagen, E. Nonreciprocity and magnetic-field-free isolation based on optomechanical interactions. *Nat. Commun.* **7**, 13662 (2016).
14. Fang, K. et al. Generalized non-reciprocity in an optomechanical circuit via synthetic magnetism and reservoir engineering. *Nat. Phys.* **13**, 465–471 (2017).
15. Shen, Z. et al. Reconfigurable optomechanical circulator and directional amplifier. *Nat. Commun.* **9**, 1797 (2018).
16. Otterstrom, N. T. et al. Resonantly enhanced nonreciprocal silicon Brillouin amplifier. *Optica* **6**, 1117–1123 (2019).
17. Krause, M., Müller, J. & Brinkmeyer, E. Measurement of nonreciprocal stimulated Raman scattering in silicon photonic wires. In *The 9th International Conference on Group IV Photonics (GFP)* 6–8 (IEEE, 2012).
18. Lawrence, M. & Dionne, J. A. Nanoscale nonreciprocity via photon-spin-polarized stimulated Raman scattering. *Nat. Commun.* **10**, 3297 (2019).
19. Petersen, J., Volz, J. & Rauschenbeutel, A. Chiral nanophotonic waveguide interface based on spin-orbit interaction of light. *Science* **346**, 67–71 (2014).
20. Mitsch, R., Sayrin, C., Albrecht, B., Schneeweiss, P. & Rauschenbeutel, A. Quantum state-controlled directional spontaneous emission of photons into a nanophotonic waveguide. *Nat. Commun.* **5**, 5713 (2014).
21. Blokh, K. Y., Rodríguez-Fortuño, F. J., Nori, F. & Zayats, A. V. Spin–orbit interactions of light. *Nat. Photon.* **9**, 796–808 (2015).
22. Vetsch, E. et al. Optical interface created by laser-cooled atoms trapped in the evanescent field surrounding an optical nanofiber. *Phys. Rev. Lett.* **104**, 203603 (2010).
23. Ostfeldt, C. et al. Dipole force free optical control and cooling of nanofiber trapped atoms. *Opt. Lett.* **42**, 4315–4318 (2017).
24. Markussen, S. B. et al. Measurement and simulation of atomic motion in nanoscale optical trapping potentials. *Appl. Phys. B* **126**, 73 (2020).
25. Brion, E., Pedersen, L. H. & Melmer, K. Adiabatic elimination in a lambda system. *J. Phys. A* **40**, 1033 (2007).
26. Meng, Y., Dareau, A., Schneeweiss, P. & Rauschenbeutel, A. Near-ground-state cooling of atoms optically trapped 300 nm away from a hot surface. *Phys. Rev. X* **8**, 031054 (2018).
27. Dareau, A., Meng, Y., Schneeweiss, P. & Rauschenbeutel, A. Observation of ultrastrong spin-motion coupling for cold atoms in optical microtraps. *Phys. Rev. Lett.* **121**, 253603 (2018).
28. Guerin, W., Michaud, F. & Kaiser, R. Mechanisms for lasing with cold atoms as the gain medium. *Phys. Rev. Lett.* **101**, 093002 (2008).
29. Braak, D. & Mannhart, J. Fermi’s golden rule and the second law of thermodynamics. *Found. Phys.* **50**, 1509–1540 (2020).
30. Loos, S. A. M. & Klapp, S. H. L. Irreversibility, heat and information flows induced by non-reciprocal interactions. *New J. Phys.* **22**, 123051 (2020).
31. Clerk, A. A., Devoret, M. H., Girvin, S. M., Marquardt, F. & Schoelkopf, R. J. Introduction to quantum noise, measurement, and amplification. *Rev. Mod. Phys.* **82**, 1155 (2010).
32. Gu, Z., Koekum, A. F., Miranowicz, A., Liu, Y. & Nori, F. Microwave photonics with superconducting quantum circuits. *Phys. Rep.* **718–719**, 1–102 (2017).

**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 2022
Methods

Nanofibre-based dipole trap. We trap laser-cooled Cs atoms in a nanofibre-based two-colour optical dipole trap. The nanofibre is implemented as the waist of a tapered step-index optical fibre. The nanofibre part is ~5 mm long and has a diameter of ~500 nm. The blue-deduced trapping light field has a free-space wavelength of λ = 760 nm, power of ~20.5 mW and is launched as a running wave into the fibre. The red-detuned standing-wave field with λ = 1,064 nm and total power of ~2.4 mW is also guided in the nanofibre. All the trapping light fields propagate as HE_1 modes and are quasi-linearly polarized. The blue-deduced trapping light field's polarization plane is orthogonal to the polarization plane of the red-detuned light field. As a result of these settings, two diametric arrays of optical trapping sites form along the nanofibre. These dipole-trap minima are located ~230 nm away from the nanofibre surface.

Preparation of the atomic ensemble. The atoms are loaded from a magnetic-to-optical transition into a nanofibre-based trap via an optical molasses stage. The collisional blockade effect limits the maximum number of atoms per trapping site to a maximum of one. The filling of the trapping sites is random, with an average filling factor of ~20% (ref. 35). To only work with atoms on one side of the fibre, we first have to remove the atoms stored in one of the two diametric arrays. We achieve this by side-selective degenerate Raman heating for 40 ms, after which the heated atoms leave the trap. Simultaneously, the atoms on the other side of the fibre are subject to degenerate Raman cooling (DRC) and thus stay in the trap. The cooling turns the 6S_1/2, F = 4, m_F = -4 state into a dark state. To demonstrate non-reciprocal amplification (Fig. 2), the magnetic field is first ramped from ~0.5G to ~7G over 7 ms. This guiding off-field ensures that the atoms remain in the F = 4, m_F = -4 state. From there, if the atoms are to be prepared in F = 4, m_F = -4, we perform optical pumping by means of a σ^+ polarized external laser beam that propagates in the z+ direction and couples to the Cs |6S_1/2, F = 4⟩ → |6P_{1/2}, F = 4⟩ transition. In this optical pumping process, we lose about 40% of the atoms from the trap due to heating. The resulting lower number of trapped atoms explains why the gain in Fig. 2d is lower than that shown in Fig. 2c.

For the experiment on non-magnetic non-reciprocal amplification (Fig. 3), the state preparation is performed differently. Here we ramp the magnetic field to zero after the DRC stage. Then, residual magnetic stray fields and spin–motion coupling distribute the atomic population over all the Zeeman states of the F = 4 ground-state manifold. Subsequently, we red-detune the TLS laser beam, which is 2×90 MHz red-detuned from the Cs |6S_1/2, F = 4⟩ → |6P_{1/2}, F = 3⟩ transition. In addition to inducing level shifts, it optically pumps the atoms into an incoherent mixture of the Cs |6S_1/2, F = 4, m_F = -4⟩ and |6S_1/2, F = 4, m_F = +4⟩ states within 100 μs. These two outermost Zeeman states are dark states for the TLS laser field. To exclusively prepare atoms in either |F = 4, m_F = -4⟩ or |F = 4, m_F = +4⟩ state, we simultaneously apply a σ^+ polarized optical pumping pulse onto the TLS beam. In this case, the dark-state condition for atoms in m_F = ±4 is lifted, they experience strong recoil heating and are removed from the trap, whereas atoms in |F = 4, m_F = ±4⟩ are nearly unaffected.

Measurement of signal gain and loss. For measuring the signal gain, we probe the atoms in an alternating fashion, that is, switching the signal’s propagation direction in every run as the transmitted optical power is measured using a single-photon counting modules (SPCMs). This reduces the influence of possible long-term drifts of the setup on, for example, the observed gain asymmetry. For reference, in every experimental run, we also record the photon counts for a guided signal beam that does not couple to atoms in the Cs |6S_1/2, F = 4⟩ ground state for a duration of 100 μs. In addition, we record the background count rate in the absence of signal and pump laser fields for 100 μs. In total, one experimental cycle takes ~3 s. We repeat the experiment until a good counting statistics is reached, typically involving >1,000 cycles. Supplementary Section 1 provides details on complementary measurements with the signal field simultaneously sent through the fibre in both directions.

Detection setup and data analysis. On each end of the tapered optical fibre, we employ two identical bandpass filtering systems with a centre wavelength of ~852 nm to suppress the trapping fields in the transmitted signal beam. Each system consists of a dichroic mirror and a variable Bragg grating. The filtered signal field hits a 50:50 beam splitter. To suppress any unbalanced part, it passes an additional bandpass filter and is guided to an SPCM via a multimode fibre. The count rate on each detector always stays below 2 MHz, minimizing SPCM saturation. The SPCM detection events are time tagged and then binned. From these raw data, we infer the signal transmission by correcting both signal and reference data for the background and then computing their ratio. The corresponding histogram is shown in Fig. 2b, displaying the dynamics of signal transmission.

Theoretical description. In our theoretical model, we propagate the signal field through an array of atoms that feature three energy levels in a Λ configuration and driven by the pump field. The atomic ground state (a) and an excited state (e) are associated with the states |6S_1/2, F = 3, m_F = -3⟩, |6S_1/2, F = 4, m_F = -4⟩ and |6P_{1/2}, F = 4, m_F = -4⟩ of atomic Cs, respectively (Fig. 2a). We model the signal transmission past each atom as T = |β|^2 with the transfer function

\[ h = \exp \left( \frac{1}{t_1} \right) \frac{OD_0}{1 + \frac{1}{t_2}} \]  

where OD_0 is the single-atom resonant OD of the signal-field-driven (a)→(e) transition in the absence of a pump field with all the atoms prepared in state (a) and

\[ \frac{\gamma_a}{\gamma_e} \frac{\rho_{ae}}{\rho_{ee}} \]  

Here γ_a is the decay rate of the excited-state population and \( \rho_{ee} \) is the time-dependent density matrix element of the atomic density operator, \( \rho \). The dynamics of \( \rho_{ee} \) is governed by the Lindblad master equation for \( \rho \), which we numerically solve using QuTiP.

We then numerically propagate the signal field through the ensemble. The signal-field amplitude launched into the fibre is assumed to be constant in time, thus driving the first atom with a fixed Rabi frequency. The second atom is then driven by the superposition of the initial signal field and the modulated field indicated by the first atom. More quantitatively, the Rabi frequency of the signal light field at the second atom is given by \( \Omega_2(t) = \Omega_1 h_1(t) \). Here \( \Omega_1 \) is the Rabi frequency of the signal light at the first atom and \( h_1(t) \) is the transfer function. The third atom is then driven by the superposition of the initial field and the modulated fields radiated by the first two atoms, and so on. The dashed line in Fig. 2b is the result of this calculation for the set of parameter values listed in Supplementary Table 1, which are chosen to obtain good agreement with the experimental data. For comparison, Supplementary Table 1 also lists independently determined values of the same parameters, which are in reasonable agreement.

Data availability

Source data for Figs. 2 and 3 are available in an open-access repository.

References

35. Kien, F. L., Liang, J., Hakuta, K. & Balykin, V. Field intensity distributions and polarization orientations in a vacuum-clad subwavelength-diameter optical fiber. Opt. Fiber. Commun. 242, 445–455 (2004).

Acknowledgements

We thank J. Finn, A. Husakou, F. Tebbenjohanns and J. Völz for stimulating discussions and helpful comments. We acknowledge funding by the Alexander von Humboldt Foundation in the framework of the Alexander von Humboldt Professorship endowed by the Federal Ministry of Education and Research. Moreover, financial support from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 800942 (ErBeStA) is gratefully acknowledged.

Author contributions

C.L. and S.P. adapted and extended the setup for this experiment and carried out the measurements. S.J. assisted in the early stages of the experiments. Data were analysed and modelled by C.L., S.P. and P.S. The experiment was conceived and supervised by A.R. and P.S. All the authors contributed to the writing of the manuscript.

https://zenodo.org/record/6242113 (2022).
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/s41566-022-00987-z.

Correspondence and requests for materials should be addressed to Philipp Schneeweiss.

Peer review information Nature Photonics thanks Karu Sinha, David Wilkowski and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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