Quantum entanglement is one of the most extraordinary phenomena borne out of quantum theory [1], and lies at the heart of quantum information and future quantum technologies. From a fundamental aspect, it is used to prove the Copenhagen interpretation of quantum mechanics, against the famous EPR paradox [2, 3]. Quantum entanglement has powerful applications in information processing and communications, as well as in the enhanced precision of measurement [4]. Among various systems, photonic entanglement has been extensively studied owing to the high-speed transmission and outstanding low-noise properties of photons [5]. However, applications based on photonic entanglement are restricted due to the diffraction limit, and a bridge between free space quantum optics and nanophotonics is in demand. In this work, we demonstrate for the first time the maintaining of quantum polarisation entanglement in both a nanoscale dielectric tapered fibre and a plasmonic waveguide. Entangled photons are coupled into these waveguides, and quantum state tomography [6] is used to verify that the transmitted states have fidelities of 0.958 and 0.932 with the maximally polarisation entangled state $\Phi^+$, respectively. Furthermore, the Clauser, Horne, Shimony, and Holt (CHSH) inequality [3] tests performed, resulting in values of $2.588 \pm 0.141 > 2$, and $2.495 \pm 0.147 > 2$, respectively, demonstrate the violation of the hidden variable model. Our investigations pave the way toward a quantum near-field micro/nano-scope, which can realize high spatial resolution, ultra-sensitive, fibre-integrated, and plasmon-enhanced detection, as well as bridge nanophotonics and quantum metrology.

Quantum metrology [3] is the measurement of physical parameters with enhanced resolution and sensitivity, enabled by taking advantage of quantum theory, particularly by exploiting quantum entanglement. For example, phase measurement with super-sensitivity beyond the standard quantum limit (SQL) can be realized by using entangled $N$-particles entangled state $(N \geq 2)$ [7, 10]. This has many important applications, including gravitational wave detection, measurements of distance and optical properties of materials, and chemical and biological sensing. Very recently, entanglement-enhanced microscopes, which give a signal-to-noise ratio better than that limited by the SQL [11, 12], have been realized. In these experiments, structures were measured using the far field method, and the entangled photons were focused by an objective lens onto the sample surface. The spatial resolution of this type of optical imaging system was fundamentally limited by the well-known Abbe diffraction limit.

To overcome this limitation, near field optics, such as a near-field scanning optical microscope (NSOM), were developed. Typically, dielectric tips (silica taper or nano-aperture) are used to probe nano-structures beyond the diffraction limit. An alternative method is to utilise surface plasmon polaritons (SPPs) [13], where the collective oscillations of free electrons are unlimited by the diffraction. Not only can SPPs confine light beyond the diffraction limit, but they can also enhance the light-matter interaction [14]. Among various plasmonic structures, silver nanowires are a natural choice for practical applications for several reasons: they are easy to prepare, have regular and uniform geometry, and undergo relatively low losses. Recently, great progress has been achieved in implementing silver nanowire photonics for various applications [15, 16], such as waveguides, compact logic gates, single-photon sources, nanoscale sensing and even single-photon-level quantum transistors.

In this work, we studied the transmission of a photonic quantum-entangled state through nanoscale waveguides, including a silica tapered fibre and a silver nanowire. By performing quantum state tomography and a CHSH inequality test, preservation of the quantum polarisation entanglement in these waveguides is demonstrated unambiguously, providing additional experimental evidence of quantumness in photon-SPP-photon conversion processes [17, 19]. More importantly, these quantum entanglement-maintaining nano-scale waveguides are fibre integrated, highly efficient, broadband, robust and free to move. Therefore, they are perfect candidates to be used as near-field quantum probes for NSOMs and endoscopes [20, 21], and may also be useful for quantum photonic integrated circuits [22, 23].

In our experiment, the polarisation entangled two-photon state

$$\Phi^+ = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle),$$  

was used to investigate the preservation of the quantum entanglement in nanoscale waveguides. $\Phi^+$ is a maximally polarisation entangled Bell state, where $H(V)$ denotes horizontal (vertical) polarisation. The entangled photon pairs were generated via a type-I spontaneous parametric down conver-
Experimental set-up. (a) The polarisation entangled photon source generated by a degenerate type-I non-collinear spontaneous parametric down-conversion (SPDC) process. The produced photon pairs (808 nm) are separated in free space by a 6° angle based on the phase-matching condition and directed to different optical single-mode fibres. (b) One of the single mode fibres is connected with a tapered fibre or further coupled with a silver nanowire, output photons are collected by an objective lens and sent to the quantum state tomography (QST) apparatus, and the other fibre is directly connected to the QST. QP: Quartz plate; HWP: half-wave plate; QWP: quarter-wave plate; BBO: $\beta$-BaB$_2$O$_4$. (c) Schematic illustration of the maintaining of polarisation entanglement of photons in nanoscale waveguides. (d) Scanning electron microscope (SEM) image of a tapered fibre with a tip radius of about 60 nm. Scale bar: 5 µm. (e) SEM image of a fibre taper coupled with a 160 nm radius silver nanowire. Scale bar: 5 µm.

The silica fibre taper used as the nanoscale dielectric waveguide was fabricated and then characterised [25]. As shown in Fig. 1(d), the taper has a very smooth surface, and the diameter is adiabatically decreased from 125 µm to about 120 nm with a cone angle of about 3 ~ 5°. Therefore, the photons can be adiabatically focused into the nanoscale taper tip with negligible loss. Due to the perfect cylindrical symmetry of the taper, the polarisation of the photons should be preserved during the focusing process. The maintaining of the quantum entanglement in the taper was verified by sending one of the two entangled photons into the tapered fibre and the other through a single mode fibre, as illustrated in Fig. 1(b). The re-radiated photon from the fibre taper was collected using an objective lens (NA = 0.8), and a confocal system composed of two lenses and one pinhole. The pinhole was used to block the background scattered light and enhance the signal to noise ratio. The quantum correlation between the two photons was then investigated by quantum state tomography. The real and imaginary parts of the measured density matrix are shown in Figs. 2(a) and 2(b), and exhibit good agreement with the corresponding parts of $\Phi^+$ (Figs. 2(c) and 2(d)). Further calculations showed that the quantum concurrence was 0.852 and the fidelity of the output state with $\Phi^+$ was 0.958.

Additionally, CHSH inequality tests were performed to examine the non-local feature of the output photons. A hidden variable model requires that

$$|S| = |E(\hat{A}_1, \hat{B}_1) - E(\hat{A}_1, \hat{B}_2) + E(\hat{A}_2, \hat{B}_1) - E(\hat{A}_2, \hat{B}_2)| \leq 2,$$

where $E(\hat{A}_i, \hat{B}_j)$ is the expectation value of operator $\hat{A}_i \hat{B}_j$, and $\hat{A}_i$ and $\hat{B}_j$ are the measurement operators on the two photons, respectively. The maximal value of $S$ in our experiment was 2.588 ± 0.141, which definitely violates the hidden variable model. This further confirmed that the output photons were still entangled after emerging from the taper.

A fibre taper is unique for the efficient coupling with other photonic micro/nano-structures, because there is strong evanescent field around the taper (see the Supplementary Information). Therefore, it is natural to hybridise this dielectric waveguide with an SPP nano-structure. Here, a silver nanowire was adapted, which outperforms other plasmonic waveguides, such as the dielectric load SPP waveguide [27] and the metal strip waveguide [28], for which SPPs can only...
be excited with transverse magnetic (TM) mode light. As shown in Fig. 1(d), the silver nanowire was adhered to the tip of the fibre taper. In addition to the nano-scale photonic confinement, there are several other benefits gained by using such a hybrid dielectric-metal nanotip: (1) Compactness. The highly efficient light coupling between the silica taper and silver nanowire can be achieved within the wavelength scale coupling region, avoiding harmful absorption loss in metal [29,30]. (2) In-line geometry. Photons from a single mode fibre can be efficiently focused to the tip of the silver nanowire. The transmission coupling efficiency from the fibre to the silver nanowire was estimated to be as high as 40% in our experiment. (3) Robustness. The structure is very robust and free to move; therefore, it has the potential to be used in a quantum endoscope [20–21].

Before testing the preservation of the quantum entanglement, we first investigated the transmission of the hybrid tip using single photons. The reason for doing so was that the coupling between the fibre taper and the silver nanowire was a two-mode to three-mode process (see the Supplementary Information) and the contact region of the silver nanowire and the silica fibre tip was not cylindrically symmetric (see Fig. 1(e)), which influences the coupling between the dielectric waveguide mode and the SPPs. First, H-polarised single photons were sent into the hybrid tip, and the polarisation of the transmitted photons were analysed by a half wave plate (HWP) and a polariser. The results are shown in Fig. 3(a). The extinction ratio was measured to be 25 : 1, which indicates that the H-polarisation was preserved throughout the entire process (propagation of the photons in the silica fibre, adiabatic focusing of the photons in the taper, conversion between the photons and plasmons, propagation of the plasmons in the silver nanowire, and scattering of the plasmons into free space photons at the end of the nanowire). Secondly, the coupling efficiencies for photons with different polarisation were measured (Fig. 3(b)). Due to the asymmetric structure in the contact area, the coupling efficiency changed with the polarisation of the input photons and the ratio between the \( H \) and \( V \) polarised photons was approximately 1.78, close to the calculated result of 1.59 (see the Supplementary Information). The oscillations in the curve will be eliminated if the coupling efficiency is identical for \( H \) and \( V \) polarised photons.

Entangled photons were then used to test the hybrid tip, using an experimental set-up similar to that used for the fibre taper. To show the entanglement of the output photons intuitively, we measured the coincidence rate by projecting one photon to a fixed state, while scanning the projection state of the other. If the photons are entangled, we can always find special projection states to make the coincidence be 0. For example, for the maximally entangled state \( \Phi^+ \), when one photon is projected to \( \ket{D} = \frac{1}{\sqrt{2}}(\ket{H}+\ket{V}) \), the other photon will be correspondingly collapsed to \( \ket{D} \). Therefore, the coincidence rate will become 0 when we measure the other photon using the \( \frac{1}{\sqrt{2}}(\ket{H}−\ket{V}) \) basis. Similarly, if we project the first photon to state \( \ket{H} \), the coincidence rate will become 0 with the other measured basis as \( \ket{V} \). The experimental biphoton fringes are shown in Fig. 3(c), which can be treated as intuitive evidence of entanglement. Furthermore, QST and CHSH inequality tests were also performed. The density matrix is shown in Figs. 4(a) and 4(b). It has a concurrence of 0.700 and a fidelity of 0.924 with the eigenstate \( \Phi^+ \) [22]. This mode area can be even smaller if we use the fundamental mode [31].

In summary, we have experimentally proven that quantum polarisation entanglement can be maintained in nanoscale waveguides, including fibre taper and silver nanowire. Both of the devices confine the effective mode area to subwavelength scale and can be applied as quantum probes to realise high spatial resolution and highly sensitive measurements, or to perform remote excitation and remote sensing with the help of quantum entanglement. Our studies encourage further investigations of the quantum effect in nanostructures through the coupling of these waveguides, thus bridging free space quantum optic techniques and nanophotonics. For example, we can envision a quantum nanoscope that simultaneously beats the diffraction limit and SQL by using the techniques exploited here.
FIG. 3: **Single and biphoto fringes for the case of the silver nanowire.** The points are experimentally measured data and are fitted with a sinusoidal function. (a) Single photon polarisation property of the fibre-nanowire structure. After injecting horizontally-polarised photons, we measured the output counts while changing the orientation of the polariser in steps of 10°, where 0° corresponds to measurement of the H state. (b) Transmission property of the fibre-nanowire structure for different linearly polarised photons. We measured the output counts while changing the polarisation of the input photons in steps of 10°, where 0° denotes the H state. (c) Biphoto fringes corresponding to fourth-order quantum interference. Blue and red dots are coincidence rates when one photon was projected to a different polarisation state, while the other is projected to the H and $\frac{1}{\sqrt{2}}(H) + |V\rangle$ states, respectively. Error bars are calculated from Poissonian statistics.

FIG. 4: **Density matrix of the output state for the case of the silver nanowire.** (a) and (b) Real and imaginary parts of the density matrix of the original state from the silver nanowire. (c) and (d) Real and imaginary parts of the density matrix of the output state after an operation on the input state. The output state has a fidelity of 0.932 with the maximally entangled state $\Phi^+$. Forming a dilution process, we dripped the solution onto an edge area of a side-polished substrate. A fibre taper was used to move the nanowire to the edge with half of the nanowire free-standing in air. We then used a three-dimensional stage to control another fibre taper and moved it close to the nanowire. Due to the Van de Waals forces between the fibre taper and the nanowire, the silver nanowire adhered onto the surface of the fibre taper and was quite stable in several hours. The stability can further be improved by attaching the nanowire to the fibre taper with glue [20]. The overall efficiency, $P$, the ratio of the number of output photons from the confocal system to the number of input photons from the single mode fiber was approximately 7.5%. Taking into account the collecting efficiency of the objective lens, the transmission of the confocal system, and the propagation loss from the silver nanowire, the calculated coupling efficiency from the fibre taper to the silver nanowire was about 40%. An even higher efficiency can be achieved by carefully adjusting the fibre tapering angle [20].

**Method**

**Sample fabrication and coupling method**

In our experiment, the fibre taper was fabricated by heating a single mode fibre while stretching it from opposite ends. The cone angle of the fibre taper was dependent on the stretching force. The silver nanowire was synthesised using a chemical reaction between silver nitrate ($AgNO_3$) and ethylene glycol in the presence of polyvinyl pyrrolidone (PVP). After purifying the silver nanowires from the reaction product and performing a dilution process, we dripped the solution onto an edge area of a side-polished substrate. A fibre taper was used to move the nanowire to the edge with half of the nanowire free-standing in air. Due to the Van de Waals forces between the fibre taper and the nanowire, the silver nanowire adhered onto the surface of the fibre taper and was quite stable in several hours. The stability can further be improved by attaching the nanowire to the fibre taper with glue [20]. The overall efficiency, $P$, the ratio of the number of output photons from the confocal system to the number of input photons from the single mode fiber was approximately 7.5%. Taking into account the collecting efficiency of the objective lens, the transmission of the confocal system, and the propagation loss from the silver nanowire, the calculated coupling efficiency from the fibre taper to the silver nanowire was about 40%. An even higher efficiency can be achieved by carefully adjusting the fibre tapering angle [20].

**Photon source**

The polarisation-entangled photon source was generated via a type I spontaneous parametric down-conversion process (opening angle of 6°) by focusing a 404 nm laser onto two 0.5 mm thick $\beta - BaB_2O_4$ (BBO) crystals with orthogonal axes. Photon pairs were filtered using 650 nm long-pass filters and 3 nm interference filters centred at 808 nm. The photons were then coupled to single mode fibres followed by polarisation controllers to reduce the impact of the fibre on the polarisation of the photons. Because the laser had a wavelength bandwidth of 1.6 nm, resulting in the incoherence of the generated states on the two crystals, we used a quartz plate to make a time compensator to ensure that the output state was a pure state.
Quantum state tomography and CHSH inequality test

For the quantum state tomography measurements, we used 16 complete bases $\langle HH, HV, VH, VH, RH, RV, DV, DH, DR, DD, RD, HD, VH, VL, HL, RL \rangle$, where $H$ (V) denotes horizontally (vertically) polarized state $|H\rangle$ ($|V\rangle$), $D$ denotes $\frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$, $R$ denotes $\frac{1}{\sqrt{2}}(|H\rangle - i|V\rangle)$ and $L$ denotes $\frac{1}{\sqrt{2}}(|H\rangle + i|V\rangle)$, to make projection measurements on the two-photon state. All of the bases can be realized with a half wave plate, a quarter wave plate and a polariser. By searching for the density matrix closest to the experimental results, we can reconstruct the density matrix of the output state. For the CHSH inequality test, we chose $0^\circ$, $45^\circ$ measurements on one photon and $22.5^\circ, 67.5^\circ$ measurements on the other photon. These degrees correspond to the orientation of the measuring polarisers.

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Author contributions

All authors contributed extensively to the work presented in this paper. M.L., X.F.R and L.M.T prepared the fiber tip and silver nanowire. M.L., X.F.R. and Y.J.C. performed the measurements and data analysis. C.L.Z., X.X., M.L., G.P.G.
and G.C.G. conducted theoretical analysis. X.F.R, C.L.Z and M.L. wrote the manuscript. X.F.R. supervised the project.

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

**Additional information**

**Supplementary Information** Supplementary information is available in the online version of the paper.