Quantum superposition and entanglement of mesoscopic plasmons

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Abstract. Quantum superpositions and entanglement are at the heart of the quantum information science. There have been only a few investigations of these phenomena at the mesoscopic level, despite the fact that these systems are promising for quantum state storage and processing. Here, we present two novel experiments with surface plasmons propagating on cm-long metallic stripe waveguides. We demonstrate that two plasmons can be entangled at remote places. In addition, we create a single plasmon in a temporal superposition state: it exists in a superposition of two widely separated moments. These quantum states, created using photons at telecom wavelength, are collectively held by a mesoscopic number of electrons coding a single-quantum bit of information; they are shown to be very robust against decoherence.

Quantum superpositions and entanglement are widely recognized as the core of quantum physics, with all its counterintuitive features. They are also essential for the coming age of quantum technology, as needed for instance for quantum information processing. Entanglement of several photons [1]–[5] or ions [6]–[10] is nowadays common in laboratories, but not much is known at the mesoscopic level. Surface plasmons (SPs) are propagating charge density waves, involving about $10^{10}$ free electrons at the surface of metals [11, 12]. SPs can be excited using light, and are thus good candidates to test the robustness of quantum superpositions and entanglement at a mesoscopic level. Previous experiments focused on the conservation of entanglement for photon–plasmon–photon conversion using metallic subwavelength hole-arrays [13] and long-range SPs (LR-SPs) device [14]. In this paper, we use cm-long plasmon guides to experimentally investigate these aspects of quantum physics. To begin, we demonstrate for the first time

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entanglement between two remote SPs existing at the same time and without photons being present simultaneously. In a second experiment, we create temporal superposition states at extreme scales. SPs have a finite lifetime: they are created, propagate and eventually die. We create SPs with photons in superposition of two time-bins and consequently this plasmonic process is in a coherent superposition of occurring at two times that differ by much more than its lifetime. At a macroscopic level, this would superpose a cat living at two epochs that differ by much more than a cat’s lifetime. One should stress that the investigated system involves a mesoscopic number of electrons coding a single-quantum degree of freedom; hence they are not proper Schrödinger cat states.

SPs correspond to the propagation of an electromagnetic quantum field, but with major differences with respect to the propagation of photons in a fibre. The structure of the electric field is indeed very different (see figure 1) in the two cases. Moreover, the implication of the free electron plasma at the surface of the metal is essential for the generation of a SP state and its quantum properties are completely defined by the geometrical and electromagnetical characteristics of the solid state of matter that support them. Therefore the existence of SPs is a truly mesoscopic phenomenon and is very bound to matter, in contrast to the propagation of photons.

LR-SPs are symmetric low loss propagating modes, that can be excited on thin metallic stripes sandwiched between dielectrics. A particular geometry of these structures allows the direct in and out coupling of the 1550 nm light mode of a standard telecom fibre to the LR-SPs mode, with very low insertion losses [15]. These devices are called plasmonic stripe waveguides (PSWs).

In the first experiment presented in this paper, we focus on the entanglement of distant SPs that fulfil the following two criteria. Firstly, the two SPs being transient processes, care must be taken to excite them at the same time within the SPs lifetime. Secondly, the SPs propagation distance must be larger than the coherence length of the exciting photons, in order to clearly destroy the photon during the process. Hole-array-based experiments did not meet these requirements, but this is achieved in our experiment using LR-SPs.
We use two distant similar PSWs inserted in between an energy-time entangled photon pair source and two interferometers, to create and verify the entanglement of SP pairs. The corresponding setup is presented in figure 2.

The source is a spontaneous parametric down conversion (SPDC) source consisting of a periodically poled lithium niobate (PPLN) waveguide (HC Photonics) pumped with a continuous-wave laser diode. The phase matching conditions of the process are such that it takes place at the degeneracy point, i.e. the two photons are created around the same average central wavelength of about 1546 nm. Their spectral width is about 80 nm. The photon pairs and the remaining pump power are butt coupled into a single-mode fibre. By energy conservation, (and provided that the spectrum of the pump laser is of negligible width), whenever one photon is measured at a given wavelength, its twin photon can only be detected at a wavelength such that the sum of both energies are equal to the pump photons energy. We use this property to separate the paired photons with high efficiency and controllability. This is done with tunable fibred Bragg gratings (AOS GmbH) and circulators. Photons coming from the source with a first chosen wavelength are reflected by the first Bragg grating BG1 and launched into PSW1 via a first circulator C1. The remaining light passes through this filter and reaches the Bragg grating BG2. This filter is tuned such that only the photons that are energetically complementary of the first ones are in turn back-reflected, and then launched into the second PSW via circulator C2. This setup ensures
that only paired photons are injected into the PSWs. It also enables us to filter out the remaining pump light that is directed to a dump in order to avoid back reflections. The Bragg grating filters are tuned by stretching the fibre in which the grating is inscribed. The spectral width of these filters is 0.8 nm, thus the coherence length of the filtered photons is 0.9 mm (coherence time of 4.25 ps), i.e. much smaller than the PSWs. The optical lengths of the two paths from the source to PSW1 and PSW2 are equalized with less than 1 mm uncertainty using optical frequency domain reflectometry (OFDR) [16]. The uncertainty on the path lengths from the source to the PSWs is small compared to the length of the shorter PSW (5 mm). The simultaneous existence of both SPs is thus ensured since SPs on PSWs are not faster than photons in fibres.

Photons are collected back at the output of the PSWs into single-mode fibres and sent to two matched unbalanced fibre Michelson interferometers having a path length difference between the two arms corresponding to 1.2 ns. They are stabilized in temperature and the relative phase between the two arms of IF2 can be scanned by a piezoelectric actuator.

InGaAs APD detectors are connected at the output of each interferometer. Note that the first InGaAs APD (D1) (Epitaxx) is operated in passive mode [17, 18] and its detection signal triggers the detection gate of the second (D2), which is operated in gated mode (IdQuantique). In order to maximize the signal-to-noise ratio, which means maximizing the probability of getting a corresponding count at D2 conditioned on a photon detection at D1, the more lossy path is connected to the passive APD D1. The difference of the detection times is recorded using a time to amplitude converter (TAC). Using this setup, we performed a conventional Franson-type entanglement measurement [19] (details in figure 3).
Figure 4. Interference fringes measured with the two PSWs in the path of the photons. The visibility, obtained through sinusoidal fitting (solid curve), is $96.5 \pm 1.6\%$, while the visibility of the reference fringes measured without PSWs (fringes not shown) is $97.4 \pm 1.2\%$.

The result of this measurement is presented in figure 4. In the same way, we measured the entanglement of the original photon pairs emitted by the source as a reference. The interference fringes recorded after photon–plasmon–photon conversion and the reference exhibit the same high visibility (inside the error uncertainty) of about 97% in both cases.

This result demonstrates that the degree of entanglement is not lowered with respect to the initial two-photon entanglement. At some point, the entanglement is therefore entirely carried by two SPs since the experimental conditions fulfill the required criteria. To our knowledge, this is achieved for the first time. We demonstrated the creation of entangled SP pairs, and hence the entanglement of two distant mesoscopic systems (separated by about 1 m) constituted by the very large number of free electrons at the surface of the two PSWs. These systems, although consisting of many particles, could code entangled qubits (e.g. time-bin qubits [20]) in a simpler way than other experiments relying on different type of plasmonic devices [13] or atomic ensembles [21]–[23]. The present setup is working at standard telecom wavelength and with a form of entanglement which is robust for transmission in fibres [24].

In the second experiment, we create a single SP in a coherent superposition of two widely separated instants of existence. We verify whether the coherence is preserved even if the temporal separation of the two instants of existence is several orders of magnitude larger than the SP lifetime. For this purpose, we used the auto-compensating interferometer described in figure 5, consisting of an unbalanced Mach–Zehnder interferometer connected by a spool of fibre to a Faraday mirror.

The timescale for a change in the length of the interferometer due to temperature variation is slower than the time needed for the two-way travel of the light, and the whole system behaves like a single very large and symmetric interferometer (when applied to quantum cryptography, this configuration is known as the ‘Plug’ & ‘Play’ system) [25]. A PSW of 1 cm length is placed in the long arm of the Mach–Zehnder interferometer. Pulses can propagate following
Figure 5. Scheme of the experimental setup for the coherent superposition of plasmons at two instants of existence. All fibres are polarization maintaining, except the fibre spool and the fibres of the plasmon conversion part. L: pulsed laser at 1550 nm; repetition rate: 5 MHz; pulse length: 1.2 ns; A: variable attenuator; D: InGaAs peltier cooled photodiode single photon counter; BS: 50/50 beam splitter; PM: phase modulator; PC: polarization controller; PSW: surface plasmons stripe waveguide; PBS: polarization beam splitter; S: standard fibre spool of several kilometres; FM: Faraday mirror.

Two paths of equal lengths. One corresponds to pulses that first choose the Mach–Zehnder long arm, undergo photon–plasmon–photon conversion on the PSW (and thus achieve the full SP creation, propagation and recollection), travel back and forth through the fibre spool, and then take the short arm of the Mach–Zehnder. The other path corresponds to pulses that first choose the short arm, travel back and forth, and then excite a SP in the long arm. The SP conversion thus does not occur at the same time for the two paths, but at instants separated by the time needed for pulses to travel twice inside the fibre spool (i.e. twice 5 µs multiplied by the length of the fibre in kilometres). Pulses are finally detected at one output of the interferometer.

The two paths are undistinguishable and we are thus in presence of a coherent superposition, but only as long as the PSW does not introduce distinguishability between them. At this condition only, one can observe interference at the detector, and the detection probability is a sinusoidal function of the phase shift which is applied in synchronization with the returning pulses. These interference fringes are recorded by sending several light pulses and applying different phase values. The visibility of these fringes represents a direct indication of the coherence of the created superposition state for the path, and thus for the existence time of the plasmonic processes.

We recorded interference fringes with and without PSW in the path of the photons. We first recorded fringes with an average number of photons per pulse set to 1. More precisely, this value is adjusted (using the variable attenuator) so that the sum of the average number of photons in the short arm and in the long arm just before the PSW is 1. The results of this measurement for a short delay $\Delta t$ is presented in figure 6. For larger delays, we increased the launched pulse energy in order to obtain good statistics on the detection counts.

We repeated the experiment many times for various pulse powers and for several different delays ranging from 0.27 to 1.24 ms (corresponding to spooled fibre length from 27 to 124 km). In every cases, we consistently found visibilities higher than 99%. The time needed for a SP to propagate from the input to the output of the PSW (i.e. the ‘lifetime’ of the SP), is of the order of 50 ps. The maximal delay we used in our experiment (1.24 ms) is therefore more than $10^7$ times larger. We thus demonstrated that SPs can be in a coherent superposition state of existing at two times separated by a large delay, even if this delay is much larger than their lifetime.
The two presented experiments demonstrate that quantum superpositions and entanglement can be surprisingly robust. This adds to the growing experimental evidence that robust manipulation of entanglement is feasible [1]–[10] with today’s technology. It stresses that quantum bits can be carried by collective modes of a mesoscopic number of particles, here electrons. However, one should emphasize that in the reported experiments, as in similar ones [13], [21]–[23], the many particles collectively code for only a very limited number of degrees of freedom. These results are thus not in conflict with the well-established theory of decoherence. Entangling many degrees of freedom, or equivalently many quantum bits, remains a challenge; however, the present results are encouraging.

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