Remote preparation of single-plasmon states

Marie-Christine Dheur,1 Benjamin Vest,1 Éloïse Devaux,2 Alexandre Baron,3 Jean-Paul Hugonin,1 Jean-Jacques Greffet,1 Gaëtan Messin,1 and François Marquier1,∗

1Laboratoire Charles Fabry, Institut d’Optique, CNRS, Université Paris-Saclay, 91127 Palaiseau cedex, France
2Institut de Science et d’Ingénierie Supramoléculaires, CNRS, Université de Strasbourg, 67000 Strasbourg, France
3Centre de Recherche Paul Pascal, CNRS, 33600 Pessac, France

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Quantum entanglement is a stunning consequence of the superposition principle. This universal property of quantum systems has been intensively explored with photons, atoms, ions, and electrons. Collective excitations such as surface plasmons exhibit quantum behaviors. We report the remote preparation of a single plasmon state through the projective measurement of a photon entangled with the plasmon. We achieved photon-plasmon entanglement by converting one photon of an entangled photon pair into a surface plasmon. The plasmon is tested on a plasmonic platform in a Mach-Zehnder interferometer. A projective measurement on the polarization of the photon allows the remote preparation of the interference state of the plasmon. Entanglement between particles of various nature paves the way to the design of hybrid systems in quantum information networks.

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I. INTRODUCTION

Surface plasmon polaritons (SPPs) are collective excitations of electrons with a mixed mechanical and electromagnetic character [1,2]. Their quantum nature has been demonstrated by Powell and Swan [3] in the 1960s. The fast development of nanophotonics and the need for compact integrated devices for quantum communication applications has revived the interest for SPPs in the quantum regime. Testing the pioneering quantum optics experiment with plasmons has then become a motivation to challenge the limits of plasmonics [4–10]. Among the fundamental quantum features, quantum entanglement [11] has raised much interest [12–18] as entangled pairs are a fundamental resource in quantum teleportation [19], in entanglement-based cryptography [20], and in other protocols [21]. The effect of plasmonic conversion has first been investigated by Altewischer et al. where the plasmon-assisted transmission of entangled photons was studied [22]. Since then, several groups have explored the plasmonic coherence properties and confirmed that polarization entanglement between two photons could be preserved when at least one of the energy quanta had had a plasmonic character onto a metallic device [23–27]. Such experiments prove that quantum correlations should exist between photons before/after the plasmonic chip and a—mainly unknown—plasmonic state.

Here we observe quantum nonlocality. We report remote state preparation [28,29] of a well-defined single SPP state. More precisely, we entangle the two polarization modes of a photon with two spatial modes of a single SPP propagating along a metal-dielectric interface on a plasmonic chip. In order to probe the quantum state of the single SPP, we recombine both paths on a plasmonic beam splitter. The quantum state of the single plasmon is revealed by the resulting single plasmon interferences. The visibility of the interference fringes can be remotely controlled by postselecting different heralding photon polarization states. To further check the role of the photon-SPP entanglement, we perform a control experiment using a nonentangled photon-plasmon pair.

II. SOURCE OF ENTANGLED PHOTON PAIRS

The experimental setup is based on a source of entangled photon pairs, one of the photons being thereafter converted into a single plasmon (see Fig. 1). The source is a postselected entangled photon pair source (PSEPPS). It consists in a spontaneous parametric down-conversion source delivering 1-nm-spanned frequency-degenerate pairs of photons at 806 nm with linear orthogonal polarizations [30]. The photons of the pair are indistinguishable except in polarization and are sent at each input of a fibered 50:50 beam splitter (BS) as in Ref. [31]. The photonic state can then be written considering the initial horizontal (H) or vertical (V) polarizations from the down-conversion process on the one hand, and the output modes α and β of the fibered splitter, on the other hand:

$$|\psi_{\text{in}}\rangle = \frac{1}{\sqrt{2}}(|H_\alpha; V_\alpha\rangle + |H_\beta; V_\beta\rangle - |H_\beta; V_\alpha\rangle - |H_\alpha; V_\beta\rangle).$$

(1)

By postselecting the coincidences between the output modes α and β of the splitter, we reduce the state to an entangled state that can be cast in the form

$$|\psi_{\text{out}}\rangle = \frac{|H_\alpha; V_\beta\rangle - |V_\alpha; H_\beta\rangle}{\sqrt{2}}.$$ 

(2)

Note that if the photons do not hit the beam splitter simultaneously, the arrival time of the photons on the last beam splitter contains information on the polarization so that the state is no longer an entangled state.

We can introduce a delay δ_{Bell} between the two photons by mechanically translating one fiber’s input along the photon path. This allows us to control the temporal indistinguishability of the photons. Optimal entanglement between photons is obtained for a delay that maximizes overlap of the photon wave packets when impinging on the beam splitter. Therefore, the degree of quantum entanglement can be progressively reduced by slightly moving the translation stage from this position.

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To evaluate the quantum state produced by the PSEPPS, we estimated the violation of the Clauser, Horne, Shimony, and Holt form of Bell’s inequality by measuring the Bell parameter $S_{\text{Bell}}$ of our source for different delays between the arrival times of the photons on the fibered beam splitter [32]. We found the highest value $S_{\text{Bell}} = 2.44 \pm 0.04$ for the maximal temporal overlap of the photons. As $S_{\text{Bell}} > 2$, this value indicates that we clearly measure quantum correlations from a polarization entangled state [33]. It is useful to note that such a state leads to strong correlations between photons in orthogonal polarizations: $H$ and $V$. But more importantly, this property extends to correlations between any orthogonal linear polarizations in any other linear basis.

III. EXPERIMENTAL SETUP

We will now describe the setup to manipulate the photon pairs and achieve photon-SPP entanglement. A simplified picture is shown in Fig. 2, where each photon of the entangled pair is sent into opposite directions. The photon in mode $\alpha$ goes through a polarizer before being detected by the single photon counting module (SPCM) C and is used to herald the arrival of the other particle on SPCMs A and/or B. The particle is detected around $13 \pm 1$ ns after its emission by the entangled photon source. The photon in mode $\beta$ goes through a beam splitter at the entrance of a Mach-Zehnder (MZ) interferometer, about 5 ns after its emission, and exits around $15 \pm 0.35$ ns after its emission (uncertainties in detection times are related to the single photon timing resolution of SPCMs C or A/B). Hence we note that when the projective measurement takes place, the particle in mode $\beta$ is already in a quantum superposition state of the two spatial states of the interferometer. The MZ interferometer first separates polarizations $H$ and $V$ using the input polarizing beam splitter (PBS). The vertical (respectively, horizontal) component of polarization is reflected (respectively, transmitted), thus exciting the photonic mode $\beta_1$ (respectively, $\beta_2$). We can now rewrite the state of the photon pair:

$$|\psi_{\alpha\beta}\rangle = \frac{|H_\alpha;1_\beta;0_\beta\rangle - |V_\alpha;0_\beta;1_\beta\rangle}{\sqrt{2}}. \quad (3)$$

Modes $\beta_1$ and $\beta_2$ are sent onto a plasmonic chip. It is composed of five elements that are etched on a gold 300-nm-thick film on top of a silica substrate: two SPP directional launchers that convert photonic modes $\beta_1$ and $\beta_2$ to plasmonic modes SPP1 and SPP2 [see Fig. 2(b)]. The detailed design of the launchers can be found in Ref. [34]. The photon-to-SPP couplers send freely propagating SPPs onto a surface plasmon beam splitter (SPBS) made of two diagonal grooves. Two slits placed at the output of the SPBS convert the SPPs back into photons [black rectangles in Fig. 2(b)] which can be finally detected on SPCMs A and B. The dimensions of all the components of the platform have been optimized with rigorous coupled wave analysis simulations [35]. The out-coupling slits dimensions are 10 $\mu$m in width and 20 $\mu$m long. The dimensions of the beam splitter (BS) have been optimized to produce similar amplitude and a $\frac{\pi}{2}$ phase shift between the reflection and transmission factors $r$ and $t$. The SPBS grooves are identical and their dimensions have been designed to be 180-nm width and 140-nm depth separated by a 140-nm gap. Measurement using a scanning electron microscope (SEM) gives 171-nm width and 145-nm spacing. Due to the roughness of the gold at the bottom of the grooves, we can only provide an estimation of the depth of about 140 nm. We measured the SPBS intensity reflection and transmission factor $R = 17\%$ and $T = 20\%$, respectively, leading to similar amplitudes $|r| \approx |t|$. The losses $P = 1 - R - T$ are deduced to be $63\%$ and are mainly due to scattering processes. The phase difference between $r$ and $t$ has been measured using the difference between two fringe patterns recorded on SPCMs A and B. This phase difference is $100^\circ \pm 6^\circ$, which is close to the expected value $90^\circ$ although slightly different due to the lack of accuracy in the depth of the SPBS grooves. Just after
the conversion of the photonic modes to plasmonic modes, the state of the photon-SPP system before impinging on the SPBS can be finally written

$$|\psi_{\alpha\beta}'\rangle = \frac{|H_\alpha;1_{\text{SPP}},0_{\text{SPP}}\rangle - |V_\alpha;0_{\text{SPP}},1_{\text{SPP}}\rangle}{\sqrt{2}}.$$  \hspace{1cm} (4)

In other words, the state corresponds to a single photon entangled with a SPP. Note that the polarization degree of freedom of the photon in mode $\beta$ is converted into a path degree of freedom for the SPP. The photon in mode $\alpha$ is a heralding photon, and is sent into an ad hoc channel. It will first fall onto a linear polarizer POL that projects the polarization of the photon before its detection by SPCM C. The photodetection on SPCM C opens a coincidence time window to detect photodetection events on SPCMs A and B. The SPCMs A and B are blind the rest of the time. This projective measurement on $\alpha$ is used to postselect the polarization of the particle in mode $\beta$ detected by SPCMs A and B. This polarization, which is thus orthogonal to the polarization of the photon in mode $\alpha$, excites photonic and plasmonic modes $[\beta_1 - \text{SPP} ]$ and $[\beta_2 - \text{SPP} ]$ with different amplitudes. A motorized translation stage introduces mechanically a delay $\delta_{\text{MZ}}$ in one arm of the MZ interferometer.

IV. RESULTS

In a first experiment we measure the postselected count rates on SPCMs A and B while rotating the heralding channel polarizer POL along different polarization directions $\theta$. Writing the polarization state of the photon in mode $\alpha$ polarized along the direction $\theta$ in the $(H_\alpha, V_\alpha)$ basis leads to

$$|\theta_\alpha\rangle = \cos(\theta)|H_\alpha\rangle + \sin(\theta)|V_\alpha\rangle.$$  \hspace{1cm} (5)

The projective measurement of the photon in mode $\alpha$ allows us to write the state of the particle in mode $\beta$ as

$$|\psi_\beta'\rangle = \langle \theta_\alpha | \psi_{\alpha\beta}' \rangle = \cos(\theta)|1_{\text{SPP}},0_{\text{SPP}}\rangle + \sin(\theta)|0_{\text{SPP}},1_{\text{SPP}}\rangle.$$  \hspace{1cm} (6)

We study how this projective measurement on the photon in mode $\alpha$ affects the correlations with the output signal of the interferometer. Figure 3 highlights two particular configurations. First, the direction $\theta$ of the heralding channel polarizer is chosen along one of the neutral axes of the input PBS [denoted as $H$ or $V$ in Fig. 3(a)]. Let us choose direction $V$ (respectively, $H$). Thus, the photon in mode $\beta$ will be measured in a polarization orthogonal to state $V$ (respectively, $H$), meaning $H$ (respectively, $V$): the photon will be, for instance, only transmitted by the PBS and will follow the path $\beta_2$ (respectively, $\beta_1$) with 100% probability: from the detection point of view, the which-path information is completely known. At the output of the SPBS, interferograms do not exhibit any visible fringes [see Fig. 3(a)]. We measure a stable heralding counting rate with respect to the path difference $\delta_{\text{MZ}}$. The fluctuations of the heralded counts that are observed are mainly attributed to the photon detection noise.

We now rotate the polarizer POL by 45° and align it along a diagonal direction $D$, so the test photon $\beta$ is now measured along the antidiagonal direction $A$, at 45° with respect to the neutral axis of the input PBS. In this configuration, the photon has a 50% probability to be either reflected or transmitted by the PBS, and both modes of the interferometer are excited with similar amplitudes: the PBS behaves like a 50:50 BS. Recombining the modes on the balanced SPBS allows one to
A perfect entangled source would have given no more than 80% for the visibility of the SPP fringes. The second source of degradation comes from the plasmonic interferometer in terms of fringes visibility. However, the visibility of the fringes is limited to 50 ± 7% [36]. We explain this value by several origins. The previous results show a strong correlation between the choice of \( \theta \)' and the appearance of plasmonic fringes. The projective measurement on particle \( \alpha \) allows a remote preparation of the outcome of the plasmonic interferometer which is an indication of the entanglement between the photon and the plasmon.

As a further confirmation of the role of entanglement in the observation of interferences, we repeated the interference experiment for a lower degree of quantum entanglement. The polarizer POL is still aligned in the diagonal/antidiagonal basis. As no relative time dependence between the particles is necessary, Eq. (5) suggests that the SPP state could be controlled in a delayed-choice experiment using the orientation of POL. However, the visibility of the fringes is limited to 50 ± 7% [36]. We explain this value by several origins. The first source of degradation comes from the plasmonic platform itself. The nonguided plasmonic modes on the film do not offer a perfect control of SPP modes overlap on the platform itself. The nonguided plasmonic modes on the film do not offer a perfect control of SPP modes overlap on the platform itself. The nonguided plasmonic modes on the film do not offer a perfect control of SPP modes overlap on the platform itself. The nonguided plasmonic modes on the film do not offer a perfect control of SPP modes overlap on the platform itself. The nonguided plasmonic modes on the film do not offer a perfect control of SPP modes overlap on the platform itself.

In summary, we have reported the generation of a hybrid entangled state consisting of a photon and a surface plasmon. This state is generated by exciting a plasmon with one of the photons of an entangled photon pair. Measurements performed...
on the state of polarization of the photon affect the visibility of single plasmon interferences. We have observed this nonlocal behavior by postselecting detection counts at the output of a plasmonic Mach-Zehnder interferometer. We have further checked that when replacing the polarization entangled photon pair by a nonentangled photon pair, the nonlocal behavior is suppressed. These results pave the way to the development of hybrid plasmon-photon systems for quantum protocols.

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