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Coherent Perfect Absorption in Metamaterials with Entangled Photons

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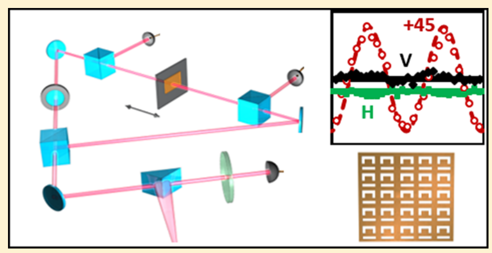
ABSTRACT: Quantum nonlocality, i.e., the presence of strong correlations in spatially separated systems that are forbidden by local realism, lies at the heart of quantum communications and quantum computing. Here, we use polarization-entangled photon pairs to demonstrate a nonlocal interaction of light with a plasmonic structure. Through the detection of one photon with a polarization-sensitive device, we can prevent or allow absorption of a second, remotely located photon. We demonstrate this with pairs of entangled photons in polarization, one of which is coupled into a plasmon of a thin metamaterial absorber in the path of a standing wave of an interferometer. Thus, we realize a quantum eraser experiment using photons and plasmonic resonances from metamaterials that promises opportunities for probabilistic quantum gating and controlling plasmon−photon conversion and entanglement. Moreover, by using the so-called coherent perfect absorption effect, we can expect near-perfect interaction.



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One of the quintessential aspects of quantum mechanics is the existence of entangled states, whereby the classical description of a particle being in a well-defined state is replaced with a quantum description based on superposition of states. Moreover, quantum entanglement provides a unique route for nonlocal correlations between remote particles such as photons. Beyond the relevance to the fundamental questions of quantum physics,[1−4] nonlocality is a resource for a number of applications such as quantum teleportation, quantum erasure, and interaction-free measurements.[5−11] In addition to demonstrating a new application of nonlocality, our work presented here is also relevant to the field of quantum plasmonics. This rather recent field emerged in 2002 when Altewischer et al.[12] showed that light passing through a metallic nanohole array conserved the quantum state of entangled photons. In parallel, Lukin and co-workers demonstrated that single plasmons can be generated from single photons as a process that can be deterministic.[13,14] More recently, Hong−Ou−Mandel two-photon quantum interference with plasmons was theoretically studied,[15] and experiments were carried out,[16−18] thereby providing experimental proof that propagating plasmons retained the quantum coherency of the photons that launched them.

In this work, we demonstrate that entangled photons can be used to achieve a remote interaction of photons, in the form of a quantum eraser, with the excitation of plasmonic modes resulting in coherent perfect absorption of light. In order to do so with polarization-entangled photons, we constructed a polarization-sensitive "quantum eraser" interferometer, for which we show that the conditions for interference can be nonlocally modified through a polarization-sensitive detection of the entangled photons. We previously demonstrated that the level of coupling to plasmons by using a thin metamaterial placed in a single-photon interferometer can be varied from nearly 0% ("perfect transmission") to 100% ("perfect absorption"), depending on the position in the standing wave, whereas only 50% absorption is observed when the standing wave is not formed.[19,20]

■ THE CONCEPT

In a simplified Sagnac interferometer, an input beamsplitter creates two optical paths, A and B (see Figure 1). To render the device polarization-sensitive, we introduce a half-wave plate

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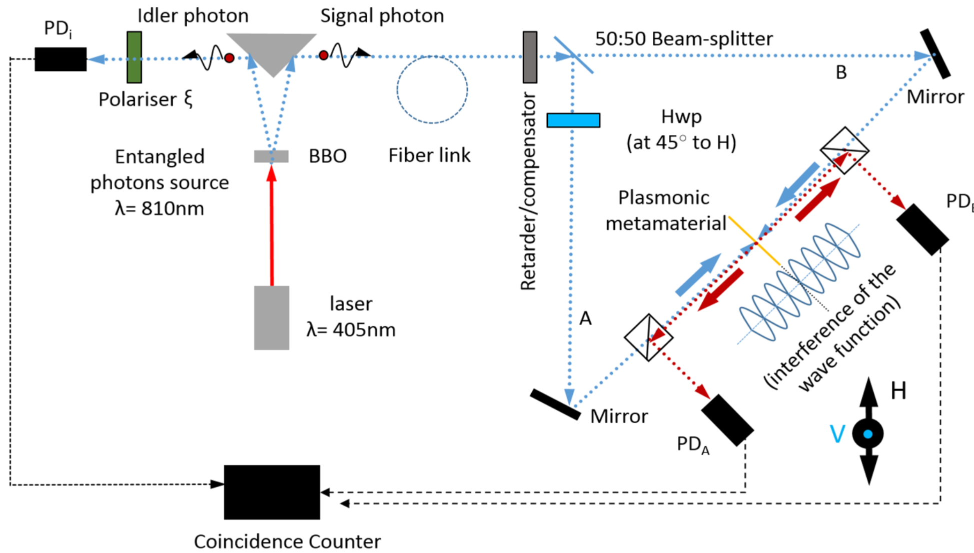

Figure 1. Nonlocal dissipation management with entangled photons. Polarization-entangled photon pairs are generated by a type II spontaneous parametric down-conversion process (laser at 405 nm impinging on a BBO nonlinear crystal). One photon of the pair is introduced in the interferometer (the "signal" photon at the 50/50 beamsplitter) and can take two paths (A and B) with a fiber link and a compensator for synchronization issues. Hwp is a half-wave plate in arm A. A thin metamaterial plasmonic absorber is introduced in the polarization-sensitive interferometer. By detecting the idler photon outside the interferometer with the help of a polarizer (ξ), one can nonlocally prevent or allow deterministic absorption of the signal-entangled photon that dissipates through coupling into a plasmon of the absorber placed in the interferometer. PD_A, PD_B, and PD_i are photon detectors.

only in path A and orient its main axis to be 45° to the plane of the interferometer.[21] In what follows we will refer to light linearly polarized in the plane of the interferometer as horizontally polarized (H-polarized) light and light polarized perpendicular to the plane as vertically polarized (V-polarized) light. Such an interferometer creates standing waves only for light polarized along the fast and slow axis of the wave plate. Input linear polarizations of +45° or −45° to the plane of the interferometer will not be affected by the wave plate and will evolve through both paths A and B as identically polarized traveling waves forming two standing waves in the interferometer with the antinode for +45° corresponding to the node for −45°. Conversely, the half-wave plate converts a vertical polarization into a horizontal one, and vice versa: so if vertically or horizontally polarized light is launched in the interferometer, optical paths A and B will contain counterpropagating orthogonal waves that do not interfere: a standing wave is not formed in the interferometer.

Now, with polarization-entangled photon pairs (denoted idler i and signal s photons for each pair; see Figure 1) it is possible to nonlocally select the state of the signal photons inside the interferometer, through a measurement on the idler photons outside (and that never enter) the interferometer. This is achieved by adding a polarizer on the idler channel. When the idler polarizer is set to an angle of either +45° or −45° to the plane of the interferometer, the polarization state of the polarization-entangled signal photon will be polarized at −45° or +45° correspondingly. The signal photon's path-entangled wave function will form a standing wave in the interferometer, and strong dissipation in the "coherent absorption" regime and zero dissipation in the "coherent transmission" regime can be observed.[22] Conversely, when the polarizer in the idler channel is set vertically or horizontally, the polarization state of the signal photon will be necessarily projected to the horizontal or vertical polarization, correspondingly. Therefore, due to distinguishability of optical paths,[7,8] no standing wave will be formed in the interferometer and the coherent absorption process is no longer visible.

Therefore, the scheme described here is a dissipative form of a quantum eraser: the interferometer polarizer rotated to the horizontal or vertical polarizations introduces a "which-path" information and hence removes any standing-wave effects at the metamaterial. By selecting idler photons (i.e., outside the interferometer) at 45°, the "which-path" information is nonlocally erased and coherent control of absorption is observed at the metamaterial.

■ THE EXPERIMENT

The experimental setup is shown in Figure 1. We generated pairs of polarization-entangled photons at a wavelength of 810 nm by spontaneous parametric down-conversion (SPDC). A 200 mW laser diode with emission centered at the wavelength of λ_p = 405 nm was used to pump a 2-mm-thick type II beta-barium borate (BBO) nonlinear crystal, producing noncollinear, degenerate photon pairs. Polarization entanglement is achieved by adding 1-mm-thick BBO compensation crystals and half-wave plates set at 45°. The photon pairs collected from the areas of intersections of phase-matching cones were coupled to single-mode fibers with collimation lenses. A 10 nm bandpass filter centered at 810 nm was used to block the pump radiation and select "twin" SPDC photons. As detailed in Figure 1, the idler channel was connected to a photon-counting avalanche photodiode detector and a coincidence counter (IDQuantique ID800). It was used to control the presence of the signal photon within the interferometer. The signal photons were coupled to the interferometer. A variable retarder was used to compensate for the polarization change in the signal fiber. The photons enter the interferometer through a lossless (50:50) nonpolarizing beam splitter. The thin metamaterial absorber was placed at the center of the interferometer between two 10× microscope objectives producing a spot size of ~10 μm in diameter. The absorber's position was scanned using a

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piezoelectrically actuated linear translation stage over a few optical wavelengths. The sum of the photon counts was detected by the two avalanche detectors (PD_A and PD_B) in coincidence with the idler photon PD_i within a 10 ns time window.

The SPDC source creates a quantum superposition of polarized photons of orthogonal basis. The wave function's general form for polarization-entangled states of this type is[23]

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_i|V\rangle_s - |V\rangle_i|H\rangle_s) \tag{1}$$

where indices i and s denote the idler and signal photons, respectively, and $|H\rangle$ and $|V\rangle$ denote the horizontal and vertical polarization states, respectively.

The path entanglement wave function of a single photon that enables interference has the general form

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|1\rangle_A|0\rangle_B - e^{i\phi}|0\rangle_A|1\rangle_B) \tag{2}$$

By integrating the path entanglement wave function (eq 2) into the polarization entanglement wave function (eq 1), in representation of our optical scheme, we obtain

$$|\Psi\rangle = \frac{1}{2}[|H\rangle_i(|H\rangle_A|0\rangle_B - e^{i\phi}|0\rangle_A|V\rangle_B) - |V\rangle_i(|V\rangle_A|0\rangle_B - e^{i\phi}|0\rangle_A|H\rangle_B)] \tag{3}$$

By expanding, we arrive at the path entanglement of two polarization wave functions:

$$|\Psi\rangle = \frac{1}{2}[(|H\rangle_i|H\rangle_A - |V\rangle_i|V\rangle_A)|0\rangle_B - e^{i\phi}|0\rangle_A(|H\rangle_i|V\rangle_B - |V\rangle_i|H\rangle_B)] \tag{4}$$

We first measured the degree of polarization entanglement of the generated photons. These measurements were performed for two different polarization basis sets, $|H, V\rangle$ and $\pm 45\rangle$, which correspond to (1) horizontal and vertical polarizations and (2) polarizations at +45° and −45° to the plane of the interferometer. The Bell parameter was then found to be $S = \sqrt{2}(V_1 + V_2) = 2.66 \pm 0.01$, where $V_{1,2}$ are visibilities calculated from the correlation curves for the two basis sets. Here, according to the Clauser−Horne−Shimony−Holt inequality,[23−25] a value of S greater than 2 implies nonlocal quantum correlations. We note that our measured value of the Bell parameter of $S = 2.66$ is close to the maximum value of $S = 2\sqrt{2} \approx 2.88$ that is expected for perfectly entangled states.

The plasmonic metamaterial absorber made of split-ring resonators was designed to provide a nearly 50% traveling wave absorption, similarly to work reported in ref 22. We fabricated a freestanding gold film of subwavelength thickness nano-structured to create polarization-independent plasmonic absorption at the operational wavelength of 810 nm.

To demonstrate the nonlocal interaction with polarization-entangled photons, we introduce one photon of the entangled pair (signal) in the polarization-sensitive interferometer, where it interacts with the plasmonic metamaterial absorber. We placed the absorber on a piezo-driven actuator in the center of the interferometer (see Figure 1). We then detected the level of light intensity at the interferometer output by taking the sum of the photon counts registered by photodetectors PD_A and PD_B that are heralded by the detection events of the idler photons on PD_i. We then normalized these to the total level of photon counts when the absorber is removed from the interferometer and recorded the normalized level as a function of absorber's position along the standing wave. The results of these measurements are presented in Figure 2.

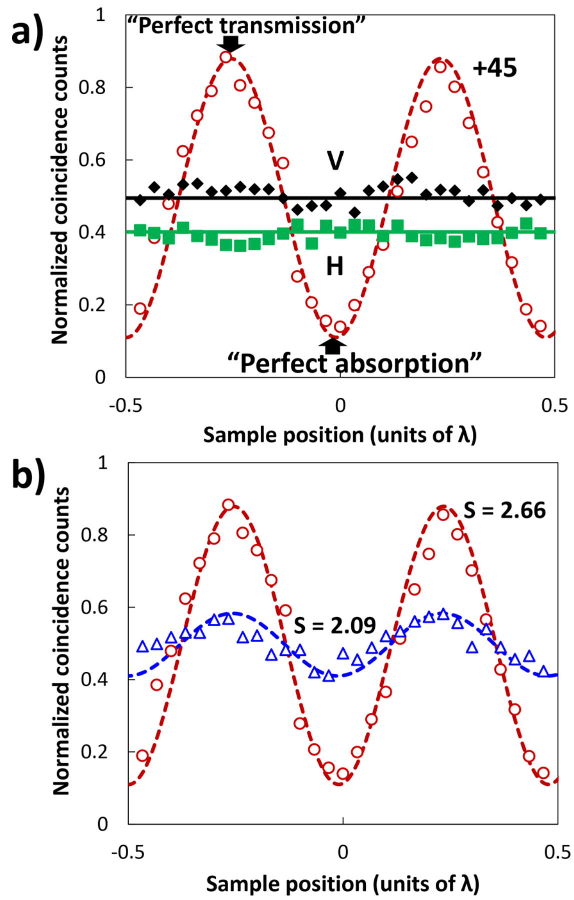

Figure 2. Normalized transmission of the plasmonic thin absorber placed in the interferometer, (a) registered for different polarization states of the photons detected in the idler channel with vertical polarization (black diamonds), with horizontal polarization (green squares), and with polarization at 45° to the plane of interferometer (red circles). (b) Photons detected in the idler channel with polarization at 45° to the plane of interferometer for two different levels of polarization entanglement of the idler and signal photons: "strong" entanglement with $S = 2.66$ (red circles) and "weak" entanglement with $S = 2.09$ (blue triangles).

No dependence of photon counts jointly registered by photodetectors PD_A and PD_B on the position of the plasmonic metamaterial was seen if the heralding was performed with an idler polarization set (with polarizer ξ in Figure 1) to vertical or horizontal (curves with black diamonds for V and green squares for H in Figure 2a). This measurement and distinguishability of "which-path" information derived from eq 1 can be described by

$$\langle H|\Psi\rangle = \frac{1}{2}(|H\rangle_A|0\rangle_B - e^{i\phi}|0\rangle_A|V\rangle_B) \tag{5}$$

Thus, the single-photon wave function does not interfere or form a standing wave in the interferometer: coherent control of absorption is lost and photons entering the metamaterial film suffer probabilistic absorption of approximately 50%. A small

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difference in the level of absorption between curves for vertical and horizontal polarizations is explainable by residual anisotropy of the plasmonic absorber.

On the contrary, if heralding is performed with the idler polarization set to +45° with respect to the plane of the interferometer, we observe a clear oscillation of absorption as a function of the absorber's position in the standing wave (curve with red circles in Figure 2a). The "which-path" information has been erased and the path-entangled single photon wave function forms a standing wave in the interferometer:

$$\langle +45|\Psi\rangle = \frac{1}{2}(|-45\rangle_A|0\rangle_B - e^{i\phi}|0\rangle_A|-45\rangle_B) \quad (6)$$

The corresponding modulation of the absorption/transmission is shown in Figure 2a. We note that when absorption is achieved for +45°, transmission is correspondingly observed for −45°. Each entangled photon entering the interferometer is therefore deterministically absorbed and converted into a plasmon in the nanostructure.

Finally, in order to underline the role of polarization entanglement, we compared the results from experiments performed with two levels of polarization entanglement. We adjusted our photon source from the regime when it generated entangled states close to the maximum Bell parameter S = 2.657 ± 0.004 to a rather low degree of entanglement with S = 2.087 ± 0.004. The source of photons with a lower degree of entanglement yielded absorption modulation of approximately 14% (see Figure 2b, curve with blue triangles) compared to the 80% (see Figure 2b, curve with red circles) attainable with strongly entangled photons.

The reduction of the absorption modulation visibility in the experiments performed with photon pairs with high and low values for the Bell parameter is relevant to the fundamental differences in polarization properties of the generated photons. The regime of high Bell parameter implies that photons traveling in the same direction but emerging from the intersections of two phase-matching cones of the parametric down-conversion crystal can create arbitrary superpositions of vertically and horizontally polarized states defined by the nonlinear down-conversion process. As a result, entangled, orthogonally polarized pairs of photons are generated with arbitrary polarization basis. In contrast, in the regime of low values of the Bell parameter, quantum superpositions of vertically and horizontally polarized states are not formed and the parametric device generates orthogonally polarized photons where idler and signal photons can either be horizontally or vertically polarized. This mixed state produced is thus not sufficient to produce interferences, unlike an entangled state. Therefore, this underlines a relationship between coherent perfect absorption and quantum states of light. First of all, it is possible to show that the visibility of modulation of absorption scales with the purity p of the quantum state, $V_{CPA} = p$, and that the Bell parameter may be described as $S = \sqrt{2}(1 + p)$. These two relations then combine to give the dependence of the modulation of absorption visibility on the Bell parameter, $V_{CPA} = \frac{S}{\sqrt{2}} - 1$. For the case of our highly entangled state with S = 2.66, we therefore predict V_{CPA} = 0.88, which is in very good agreement with the experimentally reported value of V_{CPA} = 0.8. This slight difference may be ascribed to a minor decoherence effect caused by the metamaterial.

CONCLUSION

In conclusion, we have demonstrated a regime of nonlocal interaction of polarization-heralded photons with plasmonic resonances from a metamaterial via the so-called coherent perfect absorption process with a fairly high efficiency. By selecting the idler photon polarization that never entered the interferometer, we can switch the metamaterial from the regime of traveling-wave absorption to the regime of coherent absorption. This quantum eraser experiment with plasmons can be seen as a new type of quantum gate with "a posteriori knowledge"[26,27] for which the output signal can be switched nonlocally in the "coherent transmission" regime from unitary transmission to a probabilistic 50% transmission. Alternatively, in the "coherent absorption" configuration, the system can be switched nonlocally from zero transmission to a probabilistic 50% transmission.[28,29]

It should be noted that in our experiment we do not nonlocally control the total dissipation of light energy on the absorber. Indeed, photons with other polarization states are always simultaneously present and also enter the energy balance, making the total dissipation independent from the heralding or remote interaction. In a broad sense, our results show that plasmonic losses, while certainly detrimental for many applications, can also be harnessed as a resource, in line with other recent work in quantum plasmonics aimed at controlling quantum states via a loss mechanism.[30,31] The approach shown here not only can be used for the nonlocal coupling of photons to localized plasmons but can also be exploited for entangling photons with plasmon polaritons in polarization-sensitive schemes. Experiments such as plasmon teleportation[5] or entanglement swapping[32] can thus be envisaged in the future since our method based on coherent perfect absorption can be made quasi-perfect by optimizing the experimental parameters.[19] Currently, one cannot "use" the single or entangled plasmons created due to their fast decaying behaviors, but in the close future it would be interesting to study plasmons created at a metamaterial's interface through pump−probe measurements or to convert them back to photons with a photonic structure, for instance with a waveguide.

All experimental data are available at http://dx.doi.org/10.17861/39643814-5752-4a30-9db1-6f5d65b5c174.

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Notes

The authors declare no competing financial interest.

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