Hong-Ou-Mandel interference mediated by the magnetic plasmon waves in a three-dimensional optical metamaterial

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Abstract: We studied the quantum properties of magnetic plasmon waves in a three-dimensional coupled metamaterial. A Hong-Ou-Mandel dip of two-photon interference with a visibility of *86 ± 6.0%* was explicitly observed, when the sample was inserted into one of the two arms of the interferometer. This meant that the quantum interference property survived in such a magnetic plasmon wave-mediated transmission process, thus testifying the magnetic plasmon waves owned a quantum nature. A full quantum model was utilized to describe our experimental results. The results showed that the metamaterials could not only steer the classical light but also the non-classical light and they might have potential application in the future quantum information.

OCIS codes: (160.3918) Metamaterials; (270.0270) Quantum optics.

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Metamaterials as a new kind of micro-structure materials are composed of many artificial resonant units, which can be called as "meta-atoms" or "meta-molecules," with their intrinsic electric and magnetic resonance. When propagating in metamaterials, the classical EM (electromagnetic) waves excite the resonances in these resonant units, which usually leads to various exotic properties that do not occur in natural materials, such as artificial magnetism [1], negative refraction [2], superlensing [3], cloaking [4] and optical illusion [5] *etc*. In previous works, most of researches focused on two-dimensionally planar metamaterials. Due to the recent progresses of nano-fabrication technology, the 3D optical metamaterials can be realized, exhibiting bulk negative index [6], extremely high refractive index [7] and even a 3D cloaking [8].

Besides, the variety of spatial distributions and symmetries of arrangement of "meta-atoms" or "meta-molecules" in the 3D metamaterials enable various coupling effects, which attracts wide attentions due to their interesting properties. Many novel applications are introduced by these coupling, such as stereometamaterials [9], Fano resonance [10], toroidal dipolar modes [11], optical Mobius symmetry [12], *etc*. Especially, in 3D magnetic metamaterials, the strong interaction between magnetic resonators leads to magnetic plasmon waves (MPWs) [6,9], which is analog to the spin waves in natural ferromagnetic materials. However, due to the excitation at low frequency range, the spin waves cannot interact with near infrared photons. MPWs in metamaterials can be coherently excited by photons in microwave and even optical region. Therefore, the MPWs can be considered as "optical spin waves" that can be possibly tried to mimic spin-photon coupling quantum processes in metamaterials.

Up to now, although some new progresses about MPWs in optical metamaterials have recently been achieved in classical regime, there is a lack of the experimental work on their quantum counterpart to reveal the quantum properties of the waves in these materials, and their excellent properties have not been utilized in quantum researches. Therefore, the investigation on the quantum characteristics of the excitation of MPWs in the metamaterials is quite necessary and essential. In this paper, we carry out a two-photon interference experiment to verify the quantum characteristic of the MPWs in a 3D optical metamaterial by using the photon pairs produced from the spontaneous parametric down-conversion (SPDC) process. An obvious Hong-Ou-Mandel dip is detected, which means that the quantum property survives in such a MPW-assisted transmission process, so testifying the MPWs have a quantum nature. The concept of quasi-particle is used to describe the excitation of MPWs in the 3D optical metamaterial based on the second quantized of Hamiltonian.

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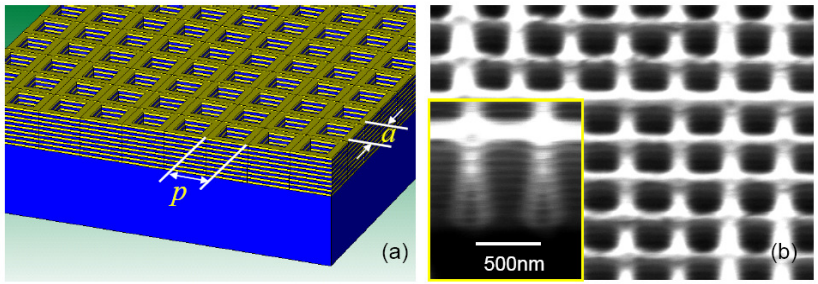

Fig. 1. The diagram and FIB image of the multilayer fishnet sample are presented in (a) and (b), respectively. Here, $p = 580nm$ and $a = 340nm$, the thickness of the silver layer and glass layer are *30nm* and *35nm*. The total size of the sample is $80\mu m \times 80\mu m$. A cross-section of the *17*-layer fishnet structure is shown in the inset of (b).

As a typical structure of optical metamaterial, the fishnet structure has been widely used to provide negative phase and negative index [13]. By introducing the vertical coupling between adjacent magnetic resonators, the MPWs, the collective magnetic resonances, composed by the resonators in the multilayer fishnet structure can be formed. The diagram of this structure is depicted in Fig. 1(a). The sample is fabricated on a *17*-layer metal/dielectric stack on the quartz substrate by using focused ion beam milling (FIB) (FEI Co. USA). Silver and SiO_2 are chosen to work as the metallic and dielectric components in the 3D optical metamaterial. An FIB image of the sample is shown in Fig. 1(b). A cross-section of this multilayer fishnet sample is presented in the inset, in which an evident *17*-layered structure can be observed.

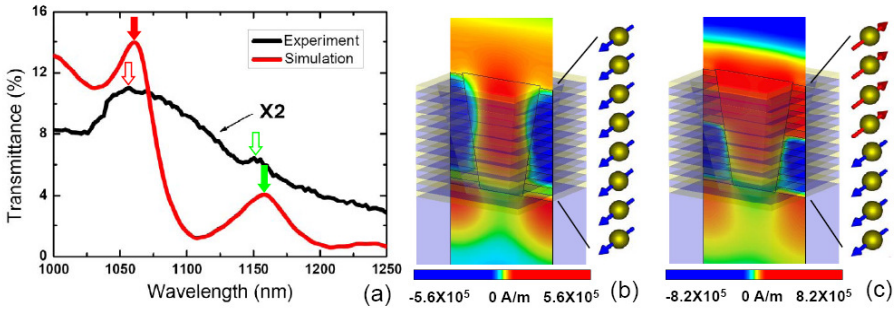

Fig. 2. The transmittance and magnetic field distribution. a, The transmittance in both experiment and numerical simulation of the multilayer fishnet sample are shown, with the transmittance of experiment being multiplied by two for clarity. b, c, The magnetic field distributions of the first order and second order of MPWs remarked by the colored arrows are plotted, with solid arrows denoting the numerical results and hollow arrows denoting the experimental results.

Firstly, we measure the transmittance of the 3D optical metamaterial sample. Figure 2(a) depicts the measured transmittance with normal incidence (black line), as well as the numerical simulation result (red line) by using the commercial software package CST MICROWAVE STUDIO. In the numerical simulation, the permittivity of silver is defined with Drude model with $\omega_p = 1.37 \times 10^{16} rad/s$ and $\gamma_m = 12.24 \times 10^{13} s^{-1}$ [14]. It should mentioned that the imperfections introduced from the thickness of each layer during the deposition and from the size of holes milled in FIB etching may be the main causes leading to the broadening the band width of the magnetic plasmon resonance and increasing the transmittance at the frequency where supposed to have low transmittance. In both experimental and simulated results, an evident transmittance peak resulted from the MPW formed by vertical coupling between magnetic resonators in the sample can be observed around *1064nm* marked by the red arrows in Fig. 2(a). This peak corresponds to the first MPW mode with the phase differences through the whole thickness being π. The magnetic field distribution of this MPW mode obtained from numerical simulation is plotted in

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Fig. 2(b), which gives out the phase relation of the field in the multilayer sample. The wavelength difference of the transmittance peaks between experimental and simulated result is smaller than 10nm, indicating that the sample is able to provide the required properties belonging to the designed model. Additionally, a small peak can also be found at about *1155nm* pointed by the green arrows in both experimental and stimulated result. This mode correspond to the second MPW with the phase difference equal to 2π, which can also be regarded as the second excited spin wave-like mode. Its magnetic field distribution is shown in Fig. 2(c). The observation of such mode can further confirm the MPW properties of the main peak around *1064nm*, where the following quantum experiment is carried out.

The excitation of these MPW modes can be considered as the most crucial property of this 3D optical metamaterial, which indicates its coupling nature that does not exist in the previously studied surface plasmonic systems [15]. And, the various couplings in the 3D metamaterial system present many novel properties that the simple 2D surface plasmonic systems cannot provide, such as bulk index and complicated spatial couplings [6–9]. The transmission peaks directly result from the exciting of the MPWs in the 3D optical metamaterial sample, because the theoretical transmittance through the slab of silver with same thickness and same size of holes has lower than *0.1%* transmittance at these frequencies. Additionally, if we mill the rectangle holes on the sample, we can obtain the transmittance peak or dip corresponding to the different MPW excitation with the polarization of the incident photons rotating. This method is also efficient to judge whether the MPW is excited in the system.

In order to reveal the quantum nature of the 3D optical metamaterial, we then verify the quantum characteristic of the MPWs in it by measuring the two-photon interference of the reradiating photons from the sample. If this quantum properties survive, quantum characteristic of the mediated state, MPWs in 3D optical metamaterial, can be confirmed because the states before and after both have the quantum characteristic. This method has been used to demonstrate the quantum property of surface plasmons in 1D and 2D plasmonic structures [15].

The Hong-Ou-Mandel (HOM) interference is utilized in our experiment. The HOM interference, first observed by Hong, Ou, and Mandel [16], is a widely used two-photon interference effect in quantum optics community for its simplicity in geometry and clarity in physics. When two single photons overlap at a *50:50* beam splitter from different inputs, the two photons will bunch together in either output of the beam splitter, giving rise to a null coincidence count of the two outputs, if and only if the two photons are identical, *i.e.*, they are indistinguishable in polarization, spatial, temporal and spectral modes. Classical optical fields can also have a similar destructive interference, but the visibility of the interference has an upper bound of *50%* [17]. Therefore, the HOM interference is often used to demonstrate the quantum property of a light field against its classical description [18]. Moreover, HOM interference has wide applications in high-resolution time measurement [16,17,19], quantum-optical coherence tomography [20], and in quantum information science, for example, quantum teleportation [21], quantum repeater [22] and quantum computation [23].

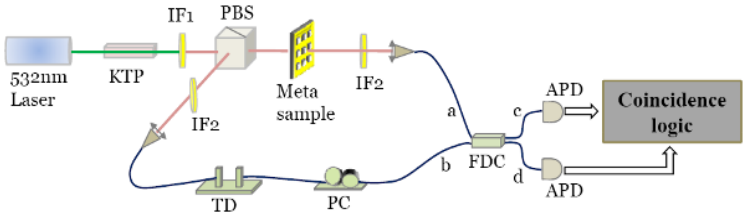

Fig. 3. Experimental set-up. IF: interference filter; PBS: polarizing beam splitter; TD: time delay; PC: polarization controller; FDC: fiber directional coupler; APD: avalanche photodiode.

The experimental setup is shown in Fig. 3. A *1cm* long $KTiOPO_4$ (KTP) cut for type II spontaneous parametric down-conversion (SPDC) is pumped by a *532nm* continuous laser to produce a pair of orthogonally polarized photons at *1064nm,* horizontally (H) and vertically

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(V) polarized photons. The SPDC photons are divided into two beams by a polarizing beam splitter (PBS). One beam irradiates the 3D optical metamaterial sample and excites the MPWs in it. At the other side of the sample, the MPWs reradiates as photons, which are collected by a single mode fiber. The other beam is directly collected by a single mode fiber. Then the two fibers are coupled into a single mode fiber coupler (Thorlabs) which serves as a *50:50* beam splitter. The time delay between the two beams can be adjusted by a time delay line (OZ delay line driver) with a single step of *0.7μm*. The difference of the location of coincidence dips in Fig. 4(a) and Fig. 4(b) is due to the thickness of *0.5mm* SiO_2 substrate. Together with the careful modulation of polarization controller, the best overlap of the two beams can be achieved. After the coupler, the photons are detected by two silicon APDs (Perkin Elmer). The coincidence measurement is performed by using a photon correlator card (DPC-230, Becker & Hickl GmbH), with the coincidence time window of *3ns*. To get a better visibility we use a *2nm* bandwidth interference filter IF1 centered at *1064nm* before the PBS. We also use two 10nm bandwidth interference filters IF2 centered at *1064nm* before the fiber couplers to block the background light.

The result of coincidence measurement after noise background subtracted versus time delay in the absence of the sample is presented in Fig. 4(a), with least-squares fit to a Gaussian function (red solid curve). A Hong-Ou-Mandel dip is obtained with the visibility of *89 ± 3.0%*, indicating the quantum properties of the photons produced by SPDC process. The noise background is measured by shifting the relative delay of the signals given by the two APDs to avoid detection of photon pairs. So the noise background subtracted is the sum of the dark count rate and the double pair emission rate of the SPDC source which can lead to uncorrelated detections. The uncorrelated fiber collection positions can also induce unwanted coincidence detections, resulting in reduced visibilities. Furthermore, the very low single-photon detection efficiency of the silicon APD at *1064nm* (*~1%*) leads to low single-to-noise ratio, contaminating the experimental results. However, the visibilities of both with and without 3D metamaterial sample surpass the upper bound of *50%* predicted by the classical light field theory [18]. And, the visibilities higher than *71%* can be used to test quantum non-locality in the experiment [24]. Therefore, the quantum property of the two-photon interference of the photon pairs produced from SPDC has been confirmed, which is easy to understand.

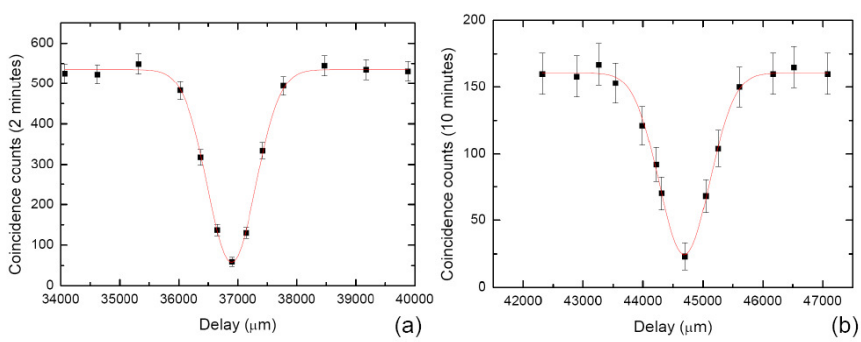

Fig. 4. The coincidence counting results. The coincidence counts without and with 3D optical metamaterial sample are shown in (**a**) and (**b**), respectively. The black dots correspond to the experimental data and red line is the fitting result. Error bars are plus or minus one standard deviation derived from the Poisson distributed counting statistics.

Then, the 3D optical metamaterial sample is inserted into one of the two arms of the interferometer. The coincidence measurement result after noise background subtracted is shown in Fig. 4(b). A solid curve fitted with a Gaussian function gives a visibility of *86 ± 6.0%*, which means that the reradiated photons from the sample also presents the quantum property of the two-photon interference. Moreover, the profile of the coincidence curve is almost the same as that of the free space in Fig. 4(a). This indicates the almost complete survival of the quantum property in the conversion from two-photon state to MPWs to two-

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photon state. Therefore, the mediated state, MPWs in 3D optical metamaterial, is shown to carry the quantum characteristic, and it could be described in a quantum language, consequently [15]. It should also be mentioned that such HOM interference only exists while the MPWs is excited in the 3D optical metamaterial, otherwise, almost no photon can leak through the sample according to the numerical calculation, and almost no photon will be collected and enter the interferometer, which is not consistent with the coincidence counts shown in Fig. 4(b) with the pumping power keeping unvaried.

Because of the quantum nature of the optical metamaterial verified above, a full quantum treatment can be used to describe it, based on our theoretical Lagrangian method [25]. The Hamiltonian of the 3D optical metamaterial can be obtained and its number representation,

$$\hat{H} = \sum_k \left(\hat{a}_k^\dagger \hat{a}_k + \frac{1}{2} \right) \hbar \omega_k , \tag{1}$$

can be derived through second quantization. Here, $\hat{a}_k^\dagger$ and $\hat{a}_k$ are the creating and annihilating operators with the momentum k. By borrowing the concepts of elementary excitation and quasi-particle in Solid State Physics [26], the quantum description of the excitation of the 3D optical metamaterials, the quasi-particle named as 'meton', could be introduced. This may be used as an institutive picture of studies on quantum property of such meta-solid. With the aid of the concept of meton, the quantum description of the conversion from photon to meton is much more understandable by using a total Hamiltonian including the interaction information as

$$\hat{H}_{Total} = \hbar \omega \hat{a}_{PDC}^\dagger \hat{a}_{PDC} + \hbar \omega \hat{a}_{Meton}^\dagger \hat{a}_{Meton} + i\hbar \left(\eta \, \hat{a}_{PDC}^\dagger \hat{a}_{Meton} - \eta^* \, \hat{a}_{Meton}^\dagger \hat{a}_{PDC} \right). \tag{2}$$

Here, the third term corresponds to the interaction between meton and photon, and the suffix k and the summation of it are omitted for convenience. The amplitude of coupling coefficient η is determined by the conversion efficiency from photon to meton and also largely influences the total transmittance of the sample [27]. Eq. (2) is also valid in the reradiating process. A schematic of the whole quantum interference experiment is shown in Fig. 5.

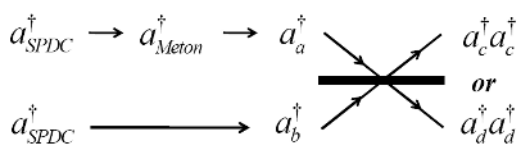

Fig. 5. Schematic of the quantum experiment.

In summary, we fabricated a 3D optical metamaterial sample with multilayer fishnet structure and performed a two-photon interference experiment to verify the quantum nature of the MPWs as they were excited by single photon in 3D optical metamaterial. This experiment can be used to fill the blank of the quantum properties of 3D optical metamaterials, which has been predicted in our previous theoretical work. Furthermore, the quasi-particle, meton, is also introduced to describe MPWs in the 3D optical metamaterial based on the second quantized of Hamiltonian, providing more convenience in understanding.

Acknowledgments

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