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.

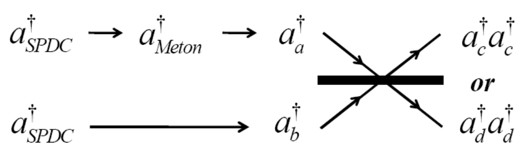

Fig. 5. Schematic of the quantum experiment.

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

This work is supported by the State Key Program for Basic Research of China (Nos. 2012CB921501 and 2010CB630703) and the National Natural Science Foundation of China (Nos. 11021403, 51001059, and 11004096).