Quantum State Filtering of Dual-rail Photons with Fiberized Plasmonic Metamaterial

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Abstract:
We demonstrate quantum state filtering of dual-rail photons through single-photon interference on a fiberized plasmonic metamaterial, exploiting different optical response of the metamaterial to symmetric and anti-symmetric superpositions of double-path wavefunction of single-photons.

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1. Introduction
Coherent interaction of light with nanostructured materials provides new possibilities for manipulation of photons in quantum communication systems [1, 2]. In this process, the interaction of two coherent beams of light on a layer of a plasmonic metamaterial is exploited so that one beam modulates the intensity of the other. Here we demonstrate that such subwavelength thick plasmonic metamaterials can also be used to modify wavefunctions of single photons. We demonstrate quantum state filtering of dual-rail photons in a stabilized fiber network by using a metamaterial, which has different optical responses to symmetric and anti-symmetric superpositions of double-path wavefunction of single-photons.

2. Experimental Setup

In our experiments, we adopted a double interferometer design as shown in Fig. 1(a), where one interferometer is used to prepare dual-rail superposition input states of single photons and the other one is used to perform projective measurements on photon output states. In the first interferometer, the phase retardation between two arms is controlled via a phase modulator \( \phi_1 \). After a single-photon interacts with the metadevice, the state measurement on the output state is performed through single-photon interference in the second interferometer, where phase delay between interfering arms is controlled via \( \phi_2 \). We implement this double interferometer design in a more compact way as shown in Fig. 1(b). In our setup, an incoming photon to the metadevice will traverse the first...
After its first pass through the 50:50 beam splitter (BS), the single-photon wavefunction takes the form of a double-path superposition \(|\psi_{in}\rangle \sim |1\rangle_a |0\rangle_b + e^{i\phi} |0\rangle_a |1\rangle_b\) because the photon spatial mode occupies both arms simultaneously. Then the photon impinges on the metadevice, which is designed to have different optical response to the wavefunctions of opposite superposition states: It is completely opaque for a wavefunction which is symmetric in Fock basis \(|\psi^{(S)}\rangle \sim (|1\rangle_a |0\rangle_b + |0\rangle_a |1\rangle_b)/\sqrt{2}\), whereas it is transparent for an anti-symmetric wavefunction \(|\psi^{(A)}\rangle \sim (|1\rangle_a |0\rangle_b - |0\rangle_a |1\rangle_b)/\sqrt{2}\). Therefore, \(|\psi_{in}\rangle\) will be modified by the metadevice in such a way that only \(|\psi^{(A)}\rangle\) part will be transmitted and \(|\psi^{(S)}\rangle\) part will be filtered out via dissipation of the photon energy to the plasmon mode, and the output state will collapses to \(|\psi_{out}\rangle \sim |1\rangle_c |0\rangle_d - |0\rangle_c |1\rangle_d\).

3. Results

The experimental results agree well with the expected photon detection probabilities at two output arms of the interferometer [Fig. 2(a)]. At one output arm (i.e. blue curve), the photon detection probability changes with \((1 - \sin(\phi))^2/4\), whereas it changes with \((1 + \cos(2\phi))/8\) at the other arm (i.e. red curve) due to the double phase \(\phi\) accumulation. Moreover, the phase \(\phi\) between interfering arms also controls the probability amplitudes of the symmetric and anti-symmetric parts of the input wavefunction \(|\psi_{in}\rangle \sim (1 + e^{i\phi}) |\psi^{(S)}\rangle + (1 - e^{i\phi}) |\psi^{(A)}\rangle\).

Thus, phase modulation provides a way of controlling the probability of a single photon to pass through the metadevice. For a proof-of-concept experiment, we drive the metadevice between coherent absorption and transmission regimes and change the number of detected photons between a mean values of 1 and 8, respectively [Fig. 2(b)]. The distribution of photon counts detected for these regimes [Fig. 2(c) left] agrees well with the Poisson statistics of incoming photons for the same mean photon number [Fig. 2(c) right]. The non-zero photon number at the coherent absorption regimes is due to the fabrication imperfections of the fiber-metadevice. Our work may be utilized in optical quantum information protocols such as dual rail encoding. As future work, we further investigate other metamaterial designs for processing of other forms of quantum light and study waveguide-based metadevices for scalable implementations.

References