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Orbital angular momentum filter of photon based on spin-orbital angular momentum coupling

Dong-Xu Chen, Pei Zhang *, Rui-Feng Liu, Hong-Rong Li, Hong Gao, Fu-Li Li

MOE Key Laboratory for Nonequilibrium Synthesis and Modulation of Condensed Matter, Department of Applied Physics, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

Determination of the orbital angular momentum (OAM) of vortex beams has been hotly discussed. We propose a new type of method to determine the orbital angular momentum of photons, filtering. We present an OAM filter scheme which consists of a cavity with a polarization-based Mach–Zehnder interferometer inside. Our scheme can purify the specific OAM with unitary efficiency theoretically without the pre-knowledge of the OAM spectrum of the input light. We also implemented a proof-of-principle experiment to demonstrate the feasibility of our scheme by cascading three interferometers. Our method offers a new way to determine the OAM spectrum of a light and this method can also be exploited to prepare the eigenstate of vortex beams.

1. Introduction

The orbital angular momentum (OAM) of photons has been drawning more and more attention since it was discovered by L. Allen et al. in 1992 [1]. The infinite dimension of this degree of freedom of photons has critical applications in many fields [2,3], for example, high dimensional entanglement [4–7], optical tweezers [8–10], high capacity communication [11–13], quantum algorithm [14–16]. The OAM of photons is characterized by the spiral phase $\exp(i\ell\phi)$ in the transverse plane, where ℓ specifies the topological number of the vortex beams, ranging from $-\infty$ to ∞, ϕ is the azimuthal phase. A common example of such beams is the Laguerre–Gaussian (LG) beam.

There are many ways to generate LG beams. A mode converter converts Hermite–Gaussian (HG) beams to LG beams by use of two cylindrical lens [17–20]. A vortex phase plate (VPP) adds an $\exp(i\ell\phi)$ phase to the fundamental TEM_{00} ($\ell = 0$) mode from laser [21–23]. A computer generated hologram can also generate specific OAM [24,25]. However, as the imperfection of the devices, the beams generated are usually not perfect as expected. Given a beam, without the knowledge of the OAM spectrum, how does one extract the specific OAM one needs or purify the spatial mode? Here we propose an OAM filtering scheme which will solve this problem.

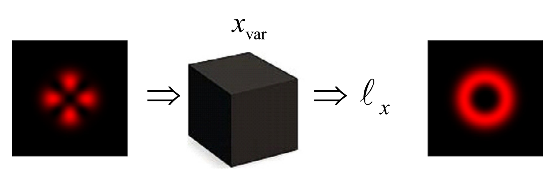

Fig. 1. Schematic of the OAM filter. When input an LG beam in mixed state or pure state, a black box with an external control variable x_{var} will filter out the desired mode with OAM of ℓ_x. Changing the variable x_{var}, the output LG beam changes.

Considering a device as depicted in Fig. 1, an OAM filter can be a black box which has an external control variable x_{var}. If we input LG beam in whatever pure state or mixed state, this box will output LG beam with $\ell = \ell_x$ which is related to x_{var}. In other words, an OAM filter can output only one specific OAM light as desired, which is analogous to polarizer for polarization.

To realize such an OAM filter, we need to consider the determination of OAM. So far, the principle of the determination of OAMs can be generally classified into three categories. The first one is projection-based schemes. Photons to be measured incident on a device that performs a translation to the state from non-zero ℓ to $\ell = 0$. Following by a spatial filter (a single mode fiber, for example), only photons with $\ell = 0$ will arrive at the detector. The second one is diffraction-based schemes [26–34] in which the diffraction pattern of the photons through an obstacle is observed. The magnitude of ℓ can be decided according to the patterns. The third one is the interferometer-based schemes [35–38]. Photons enter an interferometer in which different modes undergo different

* Corresponding author.
E-mail address: zhangpei@mail.ustc.edu.cn (P. Zhang).

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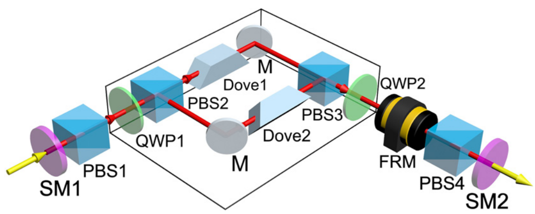

Fig. 2. The cavity scheme of our experiment. Two switchable mirrors (SM) form a cavity where photon cycles inside. The solid line frame is the polarization-based interferometer which rotates the polarization of the photon. A Faraday rotation material (FRM) compensate the polarization of the desired OAM back to horizontal. The detailed description is shown in article. M: mirror, PBS: polarization beam splitter, QWP: quarter wave plate, Dove: Dove lens.

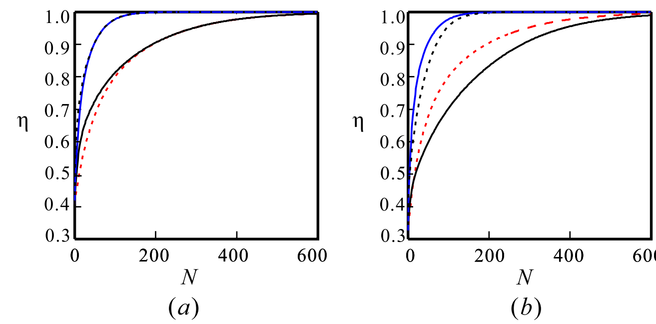

Fig. 3. Theoretical results of the loops of the photon passing through the interferometer *vs.* the purity of the requested modes for initial state in (a) ±1, ±2 and ±3 equally superposed initial state and (b) ±1, ±2, ±3, ±4 and ±5 equally superposed initial state with different α and requested modes, with $\alpha = 5°$, $\ell_0 = 1$ (dotted red line), $\alpha = 5°$, $\ell_0 = 3$ (solid black line), $\alpha = 10°$, $\ell_0 = 1$ (solid blue line), and $\alpha = 10°$, $\ell_0 = 3$ (dotted black line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

phase differences and interfere at different outputs of the interferometer.

In the first two categories, the spatial mode of the photons is destroyed due to the projection process or the diffraction. Although the OAM is successfully measured the photons cannot be used in future, which makes these two types of measurement fail to be candidates for OAM filter. In the third category, the OAM of light is unchanged, so the photons can be used after then. We will briefly introduce the interferometer-based scheme and put forward our method to construct an OAM filter which is based on an interferometer.

In Refs. [35,36], the OAMs of photons were sorted by Mach–Zehnder interferometer with Dove prisms inserted. However, to filter out one specific OAM, one needs to know the OAM spectrum previously to avoid degeneracy. In Ref. [37] W. Zhang et al. proposed an experiment sorting the OAM in a polarization-based Mach–Zehnder interferometer. The device mimics the Faraday effect in the spatial mode degree of freedom of photons, rotating the polarization of photons by $\ell\alpha$, α is the relative angle of the Dove prisms in the interferometer. The net result is that vortex beams with different OAMs in the same polarization turn into different polarizations with OAMs unchanged. By choosing appropriate α, the polarizations in the output port of the interferometer can be discriminated by a polarization beam splitter (PBS). The device transforms the problem of discriminating different OAMs into the issue of discriminating different polarizations. Because of the binary dimension of polarization, the polarization-based interferometer can only distinguish two different OAMs one time. In the following, we shall propose a scheme of OAM filter based on the method of Ref. [37], and show how it works.

2. Scheme description

Fig. 2 shows the cavity scheme of our OAM filter. In the beginning, the first switchable mirror (SM1) is OFF and the second switchable mirror (SM2) is ON. When photon enters the cavity, SM1 is ON. The solid line frame is the polarization based interferometer in Ref. [37]. Let the initial state be horizontal polarized and the magnitude of the OAM equal to ℓ, so the input state can be written as $|\psi_0\rangle = |H, \ell\rangle$. The relative angle of the two Dove prisms is set to be α. After passing through the interferometer, the polarization of photon is rotated by $\ell\alpha$, and the spin-orbital angular momentum state is:

$$|\psi_1\rangle = [\cos(\ell\alpha)|H\rangle + \sin(\ell\alpha)|V\rangle]|\ell\rangle. \tag{1}$$

Then the Faraday rotation material (FRM) rotates the polarization by $\theta = -\ell_0\alpha$, where ℓ_0 is the OAM number of light we want. The polarization of the requested OAM photon will be compensated by FRM, that is, in horizontal polarization, while for other photons with different OAMs, the polarization will be $(\ell - \ell_0)\alpha$ shifted from horizontal. After PBS4, the requested spatial mode will undergo without loss, while other modes will be projected onto horizontal polarization by $\cos[(\ell - \ell_0)\alpha]$ attenuation in amplitude. What should be noted is that unlike the PBS3 in Ref. [37], we don't aim to rotate the polarizations of different modes to orthogonal states, the PBS4 in our scheme is to rotate the specified mode to horizontal polarization. To this stage, the spin-orbital angular momentum state of photons becomes $|H, \ell\rangle$ again. Then SM2 reflects photon back and reverse OAM to $-\ell$. When passing through the FRM the second time, the polarization becomes $-\theta = \ell_0\alpha$ shifted from horizontal, so the spin-orbital angular momentum state is:

$$|\psi_2'\rangle = [\cos(\ell_0\alpha)|H\rangle + \sin(\ell_0\alpha)|V\rangle]|-\ell\rangle. \tag{2}$$

The interferometer rotates polarization by $-\ell\alpha$ when photon with $-\ell$ is injected inversely. So when the photon gets out of the interferometer the second time, the spin-orbital angular momentum state is:

$$|\psi_2\rangle = [\cos(\ell_0 - \ell)\alpha|H\rangle + \sin(\ell_0 - \ell)\alpha|V\rangle]|-\ell\rangle. \tag{3}$$

Accompanied by PBS1, it decays by $\cos[(\ell_0 - \ell)\alpha]$ once again. After being reflected by SM1, the spin-orbital angular momentum of photon becomes $|H, \ell\rangle$, the same as the initial state except for different attenuation coefficients of different OAMs. Then the photon experiences next cycle. After passing through the interferometer N times, the photons will be attenuated by $\cos^N[(\ell - \ell_0)\alpha]$. Then SM2 is OFF, the photon gets out of the cavity. Suppose the input is a superposition state, different modes will undergo different polarization rotation angles:

$$\begin{aligned}|\psi_0\rangle &= \sum_\ell c_\ell |H\rangle|\ell\rangle \\ \rightarrow |\psi_0\rangle &= \sum_\ell c_\ell[\cos(\ell\alpha)|H\rangle + \sin(\ell\alpha)|V\rangle]|\ell\rangle,\end{aligned} \tag{4}$$

where $c_\ell = |c_\ell|\exp(i\theta_\ell)$ is the relative complex coefficients of different modes, $|c_\ell|$ is the relative amplitude, θ_ℓ is the relative phase. After being attenuated by the post-selection of polarization, the amplitude is attenuated by factor $\cos[(\ell - \ell_0)\alpha]$. Repeating this process N times, the final state is:

$$|\psi_f\rangle = \sum_\ell c_\ell \cos^N[(\ell - \ell_0)\alpha]|H\rangle|\ell\rangle \quad \text{unnormalized.} \tag{5}$$

With $n \to \infty$, $c_\ell \cos^N[(\ell - \ell_0)\alpha] \to 0$ if $\ell \neq \ell_0$. Thus $|\psi_f\rangle \to c_{\ell_0}|H\rangle|\ell_0\rangle = |H\rangle|\ell_0\rangle$. The derivation is also adaptable when the input is in mix state.

Fig. 3 plots the loops N of the photon passing through the interferometer *vs.* the purity η of the specific mode with different α,