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A hybrid quantum eraser scheme for characterization of free-space and fiber communication channels

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A B S T R A C T

We demonstrate a simple projective measurement based on the quantum eraser concept that can be used to characterize the disturbances of any communication channel. Quantum erasers are commonly implemented as spatially separated path interferometric schemes. Here we exploit the advantages of redefining the *which-path* information in terms of spatial modes, replacing physical paths with abstract paths of orbital angular momentum (OAM). Remarkably, vector modes (natural modes of free-space and fiber) have a non-separable feature of spin–orbit coupled states, equivalent to the description of two independently marked paths. We explore the effects of fiber perturbations by probing a step-index optical fiber channel with a vector mode, relevant to high-order spatial mode encoding of information for ultra-fast fiber communications.

1. Introduction

The concept of *which-way* information has profound implications in the study of coherence of light, giving a different scope to the historical wave-particle duality. The most revered demonstration of the wave-like nature of photons was performed by Young in 1804, in his famous double-slit experiment [1], followed by modern variations [2–6]. The double-slit experiment is a two-path interferometer in which a light source blocked by a screen with two slits is split into two new sources traveling along different paths. Upon propagation, these two new sources interfere with each other to produce an interference pattern of spatial fringes. Remarkably, interferometric phenomena are not restricted to two-path interferometers; it is also possible to observe interference of beams traveling along the same path, but using different degrees of freedom (DoF).

The combination of two DoF, orbital angular momentum (OAM) and polarization in a non-separable fashion, known as vector beams, allows to perform novel versions of the two-slit experiments. Here, the physical paths are replaced by two components of one degree of freedom, e.g., two values of OAM. Vector beams have gained significant amount of interest in a great variety of research fields at both the classical and the quantum levels. In particular, in the field of optical communication and quantum information, their high dimensional encoding capabilities have raised attention [7–10] due to their potential applications in free-space and optical fibers [11–13]. In quantum optics, photons entangled in OAM and polarization have been demonstrated to violate a Bell-like inequality [14], being able also to tune its entanglement or photon indistinguishability [15], similarly to the analogous version of a quantum eraser scheme using OAM and polarization [16]. Other DoF can also be found to demonstrate this particular type of correlations, e.g., in the case of generating entanglement between momentum and polarization in a single photon [17], or even using intense beams [18,19].

The modern view of wave-particle duality has opened new research avenues, for example in the development of novel measurement schemes, as the ones based on quantum non-demolition [20]. The traditional quantum eraser experiment [21–29], and its delayed choice versions [29–32] are related to the complementarity principle formulated by Bohr in 1928 [33], which states that photons can behave indistinctly as particles or waves but cannot be observed as both simultaneously.

Importantly, the double-slit experiment and its modern variations allows to link the *which-way* information provided by the whole system with the interference pattern produced at the detection plane [34]. Thus, the visibility of the interferometric pattern can be directly related to the properties of the system. For example, the decrease of quality in the interferometric measurement can be associated to the perturbations introduced by the system. This approach provides a useful tool for applications in optical communication in both free-space and optical fibers [11–13], a hot topic nowadays due to the realization of a pending bandwidth "capacity crunch".

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Here we report on the comparison of a quantum eraser in free-space and a step-index fiber using the OAM and polarization DoF provided by vector modes. This work establishes the basis for a simple detection technique to quantify perturbations introduced by the environment, particularly in the communication channel, between the source and the detection section. In our particular case, a fiber optic link is formed by many different channels, introducing some kind of perturbation depending on the DoF that carries the encoded information. That is to say, the results presented give a fast probing method to characterize the different channel's perturbation, and would be useful for determining in an easy measurement what would be feasible for a quantum communication channel down fiber.

2. Concept

2.1. Revisiting the traditional which-way quantum eraser

Previous demonstrations of the quantum eraser experiment were performed with the aid of path interferometers. We revisit a variation of the experiment based on Thomas Young's double-slit interferometer. Single photons traversing the two slits form interference fringes due to each photon's paths interfering (wave-like behavior). However, the lack of interference fringes is associated with path distinguishability (particle-like behavior). In the quantum eraser experiment, the interference fringes and *which-way* information cannot be observed simultaneously. Quantitatively, this is associated with the complementarity inequality [35–38],

$$V^2 + D^2 \leq 1, \tag{1}$$

where D is the amount of path information in the system while V is the visibility of interference fringes. Thus, gaining knowledge of path information ($D \neq 0$), reduces the visibility of the fringes ($V < 1$). In quantum eraser experiment, the path information can be obtained (minimal V) and subsequently erased (maximal V). To illustrate this effectively with the aid of Eq. (1), consider a double-slit marked with orthogonal polarizers. The quantum state of the system, is given by

$$|\Phi\rangle = \frac{1}{\sqrt{2}} \left(|H\rangle \left|s_1\right\rangle + |V\rangle \left|s_2\right\rangle\right), \tag{2}$$

with $\left|s_1\right\rangle$ and $\left|s_2\right\rangle$ the states upon traversing the independent paths s_1 and s_2, respectively, and $|H\rangle$ and $|V\rangle$ represent the horizontal and vertical polarization states that mark the two paths. Note that without the markers and taking into account perfect conditions, the two paths are allowed to interfere, which leads to the trivial case of interference fringes appearing at the detection plane, with $D = 0$ (minimal path information) and $V = 1$ (maximal fringe visibility), due to path indistinguishably (wave-like behavior). On the contrary when the slits are marked, the probability distribution of the photons is $|\langle\Phi|\Phi\rangle|^2 = \sum_i |\langle\psi_i|\psi_i\rangle|^2/2$, which signals the presence of path information in the system when projecting the polarization of the system onto the $|H\rangle$ or $|V\rangle$ states. Thus, $D = 1$ (maximal path information) and $V = 0$ (minimal fringe visibility), meaning that there is a full knowledge of the *which-path* information (particle-like behavior).

However, the interference fringes can be recovered with a complimentary projection of the polarization, in the diagonal basis ($|H\rangle \pm |V\rangle$), which acts to remove the path information and hence erase it from the system. Again, $D = 0$ (minimal path information) and $V = 1$ (maximal fringe visibility), showing a mutually exclusivity between the two cases. Intriguingly, partial visibility and partial distinguishability are permitted, where the result cannot be explained exclusively by a wave-like or particle-like interaction although the inequality in Eq. (1) is maintained [38].

2.2. Redefining the quantum eraser with spatial modes

Equation (2) represents a general state of a non-separable or entangled path and polarization DoF of a single photon, a trait of non-separable DoF of a photon [17]. Similarly, vector modes are a class of spatial modes with non-separable polarization and OAM DoF with the following general form

$$|\psi\rangle = \frac{1}{\sqrt{2}} \big(|R\rangle\,|\ell\rangle + e^{i\zeta}\,|L\rangle\,|-\ell\rangle\big). \tag{3}$$

Here, $e^{i\zeta}$ is a relative phase, the states $|\pm\ell\rangle$ are the OAM eigenstates with ℓ representing the topological charge of the spatial field, characterized by a helical phase of $e^{i\ell\phi}$, and $|R\rangle$ and $|L\rangle$ the right and left circular polarization states, respectively. In Eq. (3) the OAM eigenstate of the photon are marked with orthogonal circular polarisation states. Through polarization control, the OAM information can be determined and erased. For example, by projecting the photon onto the polarization state $|R\rangle$ or $|L\rangle$, the photon collapses onto the state $|\ell\rangle$ or $|-\ell\rangle$, respectively ($D = 1, V = 0$), where the spatial fields are azimuthal donut-like rings with opposite helicities. An example is illustrated in Fig. 1(e) for $\ell = \pm 10$. Analogously, the OAM eigenstates act as abstract paths in contrast to the double-slit experiment. The OAM modes can be interfered with a complimentary projection of the polarization, i.e, $|R\rangle \pm |L\rangle$, thus collapsing the spatial mode onto a superposition state, $|\ell\rangle \pm |-\ell\rangle$, where the interference fringes appear in the azimuthal direction with a frequency proportional to $2|\ell|$ (see Fig. 1(e)). Hence this erases the OAM information of the photon ($D = 0, V = 1$). Accordingly, the non-separability is exploited to demonstrate the quantum eraser with a single photon described by a vector mode. Interestingly, these spatial modes are natural modes of free-space and fiber, the basic media of quantum information and communication.

2.3. Vector mode propagation in step-index fibers

Step-index fibers have cylindrical symmetry and a refractive index with a step-like profile, as can be seen in Fig. 2. The full vector wave equation for a step-index fiber is given by

$$\{\nabla_t^2 + n^2k^2\ \nabla_t\}\mathbf{u}_t + \nabla\{\mathbf{u}_t \cdot \nabla_t \ln(n^2)\} = \beta^2\mathbf{u}_t, \tag{4}$$

where $k = 2\pi/\lambda$ is the wave vector, n is the index of refraction which has a radial dependence, $\mathbf{u}_t$ is the transverse component of the electric field while β is the propagation constant for each solution. The radial component of the fields are described as follows,

$$u_{\ell p}(r) = \begin{cases} J_{|\ell|}\left(\dfrac{\beta_{\ell p}}{a}\right)/J_{|\ell|}(\beta_{\ell p}) & r < a, \\[2ex] K_{|\ell|}\left(\dfrac{\sigma_{\ell p}}{a}\right)/J_{|\ell|}(\sigma_{\ell p}) & r \geq a, \end{cases} \tag{5}$$

with a being the fiber core radius and the functions $J_{|\ell|}$ and $K_{|\ell|}$ representing the higher-order Bessel and modified Bessel functions. The $\beta_{\ell p}$ and $\sigma_{\ell p}$ are the respective propagation constants for the Bessel functions in the different regions of the fiber. Eq. (5) is a consequence of the step-index fibers cylindrical symmetry and refractive index profile. The first four cylindrically symmetric higher-order vector solutions, which are nearly degenerate, take the form of Eq. (3). They are known as the transverse electric (TE_{01}), transverse magnetic (TM_{01}), hybrid electric odd (HE_{21}^{odd}) and hybrid electric even (HE_{21}^{even}), where the two indices represent the number of half-wave patterns across the width and the height of the waveguide, respectively.

In this paper, we consider the propagation of the TM_{01} mode which is also known for its radial polarization profile and is defined by Eq. (3) for $\ell = 1$ and $\zeta = 0$ (see Fig. 1 for intensity profiles).

3. Implementation

To generate the spatial modes marked with orthogonal polarization states we make use of a q-plate [39,40], a Pancharatnam–Berry phase element with a locally varying birefringence. A q-plate couples the

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