Bell's Inequality Tests and Quantum Communication with Entangled Photon Holes

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Abstract: We report on experimental work towards the realization of quantum communication with entangled photon holes. These experiments involve two-photon interferometry and photon hole states generated through quantum interference effects.

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1. Introduction

Entangled pairs of photons serve as a valuable resource in a number of quantum information processing protocols. Depending on the application, the entanglement is typically based on polarization, momentum, or energy-time variables. However, it has recently been shown that in addition to entanglement of the various physical properties of the photon pairs, optical entanglement can also arise from the absence of the photon pairs themselves [1]. These correlated absences, which we call "entangled photon holes", can also lead to violations of Bell-type inequalities, and may be useful for quantum communications.

2. Entangled Photon Holes

The concept of entangled photon holes can be understood by comparing it with entangled photon pairs generated by continuous-wave non-collinear parametric down-conversion (PDC), which is illustrated in Figure 1a. In PDC, there is a small probability amplitude for an individual pumping photon to be split into two lower energy photons. The photons are known to be created at the same time, but that time is completely uncertain, and there exits a uniform probability amplitude to find the photon pair at any location in the outgoing beams.

One way to envision the generation of entangled photon holes is by passing two (different frequency) weak coherent state beams through an idealized two-photon absorbing material that does nothing to the system but simultaneously remove one photon from each beam. In analogy to the creation of PDC pairs, here the two photons are known to be removed from the beams at the same time, but that time is completely uncertain. In this sense, entangled photon holes can essentially be thought of as the "negative image" of the PDC process in Figure 1a.

Entangled photon holes can also be generated through a variety of two-photon interference effects [2]. A particularly robust method is illustrated in Figure 1b. This type of set-up was first used by

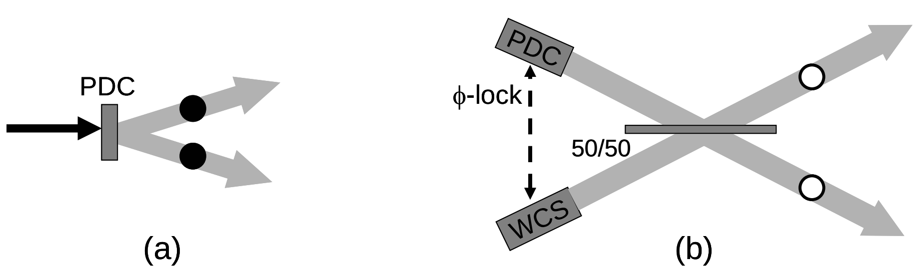

Figure 1. (a) A method for generation of entangled photon pairs based on CW non-collinear parametric down-conversion. (b) A method for generation of entangled photon holes based on quantum interference between PDC pairs and a weak coherent state [2].

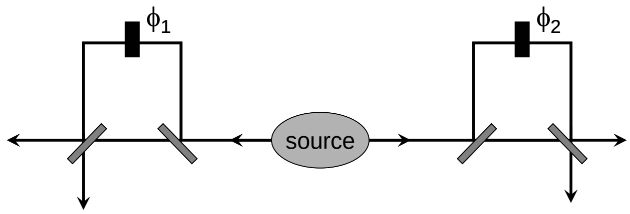

Figure 2. Violation of Bell's inequality and quantum communication using two-photon interferometry [5]. The source is typically entangled photon pairs from PDC. The focus of this work is on using a source of entangled photon holes instead.

Koashi et.al. to explore the phase-coherence of the PDC process [3,4]. Here a weak coherent state source (laser beam) is phase locked to a PDC source which emits pairs of photons in a single beam. The two sources impinge upon a 50/50 beam splitter and (in the limit of weak sources) the probability of simultaneously finding a single photon in each output beam is only due to an amplitude corresponding to a PDC pair being split by the beam splitter, and an amplitude corresponding to the two-photon term of the weak coherent state being split by the beam splitter. If these two amplitudes have equal magnitude, but are out of phase, they will destructively interfere.

For our purposes, the end result is that the emerging beams essentially contain background photons from the weak coherent state, but the probability of simultaneously finding one photon in each beam has vanished. We recently performed an experimental demonstration of the generation of entangled photon holes in this way [2]. The experiment used a master mode-locked laser, pulsed PDC, and single-mode fibers for mode-matching and phase-locking the two sources of Figure 1b. That apparatus forms the basis of our current work towards quantum communication with entangled photon holes.

3. Bell tests and Quantum Communication with Entangled Photon Holes

Bell tests can be done by using a source of PDC photon pairs and two distant unbalanced Mach-Zehnder interferometers as shown in Figure 2 [5]. Because the photons are created at the same time, coincident detections at the outputs of the interferometers must be due to both photons taking the longer paths (LL) or the shorter paths (SS). There are no contributions corresponding to LS and SL events, and quantum interference between the LL and SS amplitudes results in a coincidence counting rate proportional to $\cos^2(\phi_1+\phi_2)$, which can be used to violate Bell's inequality [5]. This arrangement can also be used as the basis of a quantum communication system, where Alice and Bob choose the phase settings of the distant interferometers [6].

The focus of our current work in on using the system shown in Figure 2 with a source of entangled photon holes, rather than entangled photon pairs. In this case contributions to the coincidence counting rate can only arise from LS and SL terms. Quantum interference between these two indistinguishable amplitudes results in a coincidence rate proportional to $\cos^2(\phi_1-\phi_2)$, which can also be used in Bell tests and quantum communication. Here the required coherence originates from the properties of the mode-locked laser used to generate the photon holes.

An experimental implementation of a quantum communication system based on the entangled photon hole source of reference [2] is in progress. Independent users will control the phase settings in two distant fiber-based interferometers, and correlations between their measurements can be used to generate a secret key through the Ekert protocol [6].

4. References

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