Conditional coherence via phase-sensitive post-selection

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Abstract: A single beam of light created via spontaneous parametric down-conversion has a random phase. We show it is possible to induce a well-defined *absolute* phase in one beam by overlapping the other with a weak coherent state and conditioning on detection of a photon. This post-selection fixes the phase of the down-conversion even though stimulated emission is negligibly small.

Experiment has shown that interference fringes between a local oscillator (LO) and a beam created through spontaneous parametric down-conversion (SPDC) do not occur [1], and down-conversion beams are mutually incoherent [2]. One can understand this absence of coherence in terms of which-path information. It is well known that interference cannot occur if there exists information that can identify which path a system took to reach its final state. In the case of homodyne measurement between a LO phase-reference and the SPDC idler mode, a strong number correlation between the signal and idler beams makes it possible to know whether a detected photon came from down-conversion or from the reference laser: if there is a photon in the signal mode, then the detected photon was most likely the idler, if there is no signal photon, then the photon must have come from the LO. The mere existence of which-path information, whether or not it is actually measured, precludes the possibility of interference.

In this work, we overlap a second LO beam over the signal beam from SPDC, as represented in the experimental cartoon (fig. 1.)

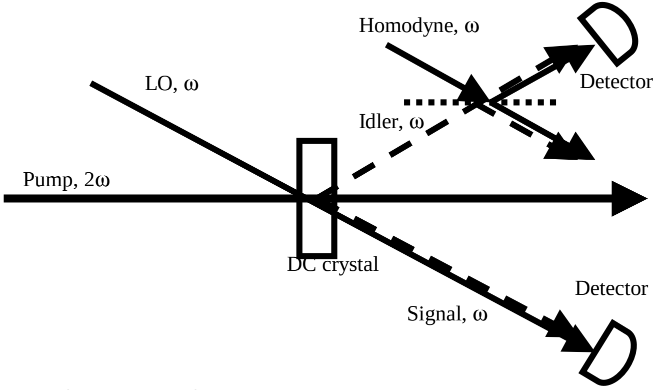

Figure 1. A simplified cartoon of the experiment. A LO beam is overlapped with the signal beam created via SPDC. The idler beam is mixed with a phase reference in an optical homodyne measurement.

Due to the number uncertainty of the LO beam, the correlations between beams 1 and 2 are thus weakened. This erases some of the which-path information; full erasure can be accomplished by conditioning on detection at D2. This detection collapses the state of the light in the idler mode to a particular superposition of the Fock states $|0\rangle$ and $|1\rangle$ that resembles a weak coherent state, $|\alpha\rangle \approx [|0\rangle + \alpha|1\rangle]$, where α depends on the experimental parameters. The optical phase of this state, $\varphi = \arg(\alpha)$, is set by the phase difference between the pump laser and the LO. In our setup, the LO, pump and homodyne laser are all phase-locked since they all originate from the same laser. The weak coherent state conditionally created in the idler mode can therefore create a stable interference pattern upon homodyne measurement. A state preparation technique of this type was considered by Hardy [3] and has more recently been generalized by Clausen et al. [4]. The interference effect studied here is closely related to studies of the phase correlations in SPDC [5]. This effect is also related to an experiment by Zou et al. [6], whereby overlapping idler modes from two different down-conversion crystals induced a well-defined *relative* phase between the two signal modes. The first-order interference effect reported in that experiment occurred without a conditional measurement. This work builds on some of our previous experiments that focus on effective nonlinearities at single photon intensities [7,8].

Light from an ultrafast Ti:Sa laser is frequency doubled to serve as the pump laser, and some of the fundamental is highly attenuated and used to create both the homodyne laser and the LO. We use type-II phase-matching for down-conversion and, after spatial and spectral filtering, send the vertically polarized beam to detector 2 and the horizontally polarized beam to the homodyne setup containing detector 1. The vertically polarized LO passes through the crystal into the signal mode and is sent, along with the signal, to detector 2. Motorized stages are placed in trombone delay arms in the pump laser path and the homodyne beam path. Fig. 2. shows the coincidence rate as a function of the delay introduced by the motor in the pump path (Fig. 2a.), and the motor in the homodyne path (Fig. 2b.).

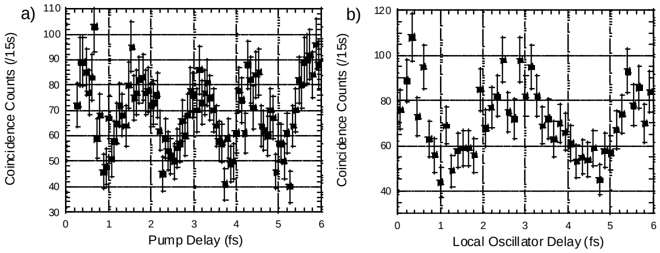

Figure 2. The conditional intensity (coincidence rate) vs time delay for a) the pump laser, and b) the homodyne laser.

This is the homodyne interference pattern conditioned on a photon in the signal mode. The fringe spacings in the two plots correspond to the pump laser frequency (Fig. 2a.) and the fundamental frequency (Fig. 2b.)

We have demonstrated that the idler beam created via SPDC can be collapsed to a state resembling a weak coherent state with a well-defined optical phase by performing a phase-sensitive measurement on the signal beam. While this setup brings to mind the classical nonlinear effect of difference frequency generation (DFG), this new effect differs in some very important respects. DFG occurs via stimulated emission and our LO is of insufficient intensity to produce a measurable amount of stimulated emission; our LO singles rate is only about 2×10^4 s^{-1}, which corresponds to 1 photon per 4000 pulses. Also, the light produced by classical DFG is first-order coherent regardless of the intensity in the signal mode; no conditional measurement would be required to observe intensity fringes. In our experiment, the detection of a photon in the signal mode is a phase-sensitive post-selection, that, upon success, collapses the idler to a weak coherent state.

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