Coherence properties of entangled two-photon states in quantum interferometry

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Abstract: We study first- and second-order coherence properties of entangled two-photon states of both type-I and type-II spontaneous parametric down-conversion (SPDC) in standard quantum interferometry. Our results suggest that care must be taken not to over-estimate the two-photon bandwidth of type-I SPDC in applications in which variables other than polarization, such as, energy and momentum, are utilized.

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The two-photon state generated via spontaneous parametric down-conversion (SPDC), spontaneous splitting of a pump photon into a pair of daughter photons in a nonlinear optical crystal, is one of the most well-known examples of two-particle entangled states. If the phase matching is perfect, assuming monochromatic plane wave pump, it is not hard to see that the state of SPDC should be written as

$$|\Psi\rangle = \sum_{s,i} \delta(\omega_s + \omega_i - \omega_p)\delta(\mathbf{k}_s + \mathbf{k}_i - \mathbf{k}_p) a_s^\dagger(\omega(\mathbf{k}_s)) a_i^\dagger(\omega_i(\mathbf{k}_i))|0\rangle.$$

Here, the signal-idler photon pair is perfectly entangled in energy and momentum and such a perfectly entangled state (in energy and momentum) naturaly has an infinite coherence time.

In reality, perfect phase matching can never occur, most notably, due to pump beam divergence, limited pump beam size, and limited thickness of the nonlinear crystal. Therefore, the above delta functions should be replaced by two-photon spectral functions that are sharply peaked around $\omega_s = \omega_i$ and $\mathbf{k}_s = \mathbf{k}_i$ and have some bandwidths. This means that given an energy or momentum of the signal photon, there are some ranges of energies and momentum available for the idler photon: the entanglement between the photon pair is less-than-perfect. As a result, the two-photon state of SPDC has finite coherence time and the shape of the correlation function is determined by the two-photon spectral functions, which depend on the types of phase matching.

In this paper, we are interested in these coherence properties of the two-photon entangled state generated from cw-pumped SPDC under different phase matching conditions. Both first-order and second-order coherence properties of the entangled two-photon state in standard quantum interferometry are studied. Frst-order coherence properties of the SPDC fields are considered for a Michelson interferometer and, for second-order coherencce, the usual Shih-Alley type-I SPDC [1] and Shih-Sergienko type-II SPDC [2] setups are considered.

In the case of first-order coherence, the measurable quantity is the single-detector count rate and it can be calculated as [3]

$$R_s = \frac{1}{2}(1 + g^{(1)}(\tau)\cos(\Omega\tau)),$$

and for the second-order coherence, the the measurable quantity is the coincidence count rate which can be written as

$$R_c = \frac{1}{2}(1 \pm g^{(1)}(2\tau)),$$

where $g^{(1)}(\tau) = G^{(1)}(\tau)/G^{(1)}(0)$, $G^{(1)}(\tau) = \int_0^\infty d\omega |S(\omega - \Omega)|^2 e^{-i\omega\tau}$, and Ω is the central frequency of the SPDC field. Note that both the first- and second-order interference involve $G^{(1)}(\tau)$. As a result, the first and second order interference should have the same envelope structure but the first-order interference envelope is twice bigger than that of the second-order one.

The above predictions were first tested using a Michelson interferometer and a Shih-Sergienko two-photon interferometer setup for type-II SPDC . The pump photon was at 351.1 nm and the SPDC photons were centered at 702.2 nm. The experimental data, not shown, confirms that both the first- and second-order interference have triangular (or diamond shape if peak to min is considered) interference envelopes and the first-order interference shows twice bigger interference envelope than the second-order one. This is exactly what the results of calculation shows and good agreement between theory and experiment is observed.

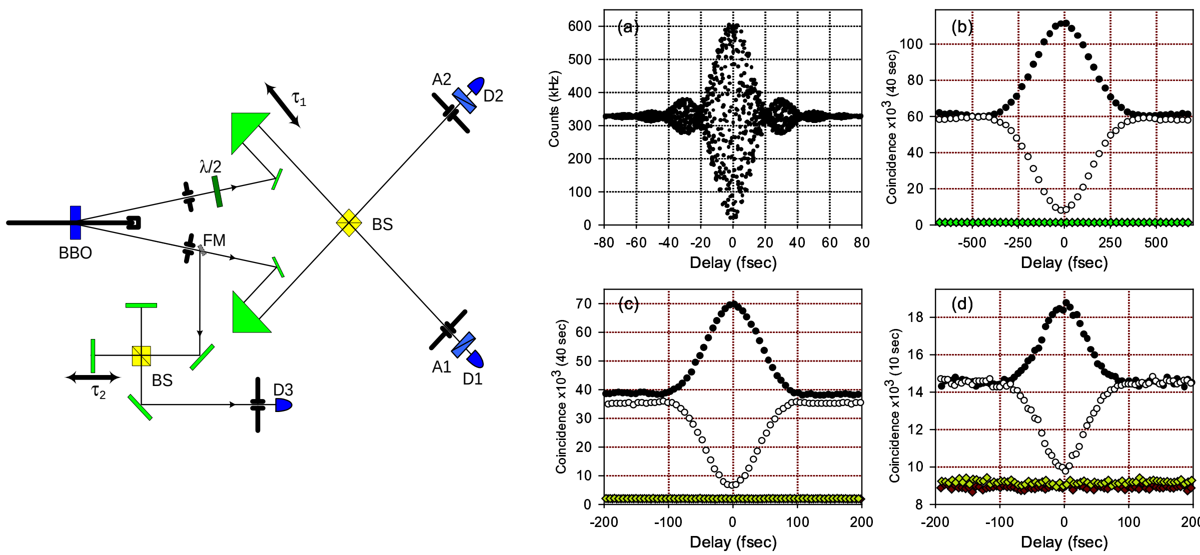

Fig. 1. Experimental setup and data for type-I SPDC first-order (observed at D3) and second-order coherence measurements (observed at D1-D2 coincidence). (a) First-order interference observed at D3 with no spectral filters. Second order interference shown in (b), (c), and (d) are for 3 nm, 20 nm, and 80 nm spectral filters, respectively. Diamond data points show the background or accidental coincidence level, which becomes significant for the broadband case.

For type-I SPDC, we used the Shih-Alley type-I setup shown in Fig. 1. The flipper mirror (FM) allows us to measure the first-order coherence property by using a Michelson interferometer. The first-order interference measured without using any spectral filtering is show in Fig. 1(a) and the data agrees quite well with the theory. The second-order interference data are presented in Fig. 1(b) (d) for different spectral filters. For 3 nm and 20 nm filters, the measured envelopes simply correspond the photon wavepackets determined solely by the bandwidth of the filters. This is an expected result since type-I SPDC bandwidth is much bigger than both filters. However, when broadband filters which do not affect the bandwidth of the type-I SPDC are used, we still observe much greater coherence time (than the calculated one) for the second-order interference. In fact, the two-photon envelope width, which is supposed to be the half of the data shown in Fig. 1(a), is actually more than five times bigger.

We will discuss the source of this discrepancy in type-I SPDC in detail [4]. Our results imply that care must be taken not to over-estimate the two-photon bandwidth when using entangled two-photon states from type-I SPDC in applications in which variables other than polarization, such as, energy and momentum, are utilized.

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