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Selecting the pre-detection characteristics for fiber coupling of parametric down-converted biphoton modes

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ABSTRACT

Photon modes have an important role in characterizing the quantum sources of light. The two main pre-detection factors affecting the biphoton mode coupling in SPDC are the pump beam focusing parameter and the crystal thickness. We present the numerical and experimental results on the effect of pump focusing on conditional down-converted photon modes for a Type-I BBO crystal. We experimentally verify that biphoton coupling efficiency decreases asymptotically with pump beam focusing parameter. We attribute this behaviour to (a) the asymmetry in the spatial distribution of down-converted photons with the pump beam focusing parameter and (b) the ellipticity of biphoton modes introduced due to the focusing of the pump beam. We also show the ellipticity experimentally as well as quantify it with the focusing parameter. These results may be useful in selecting optimum conditions for generating efficient fiber coupled sources of heralded single photons and entangled photons for quantum information applications.

1. Introduction

Spontaneous parametric down conversion (SPDC) is one of the most popular methods used to generate heralded single photons as well as entangled photon pairs [1]. In this second order non-linear optical process, a pump photon of higher energy, when interacting in a non-linear medium, down-converts to two lower energy photons. It is governed by the conservation laws of energy and momentum. The momentum conservation is apparently called as phase matching condition [2]. The twin photons generated by SPDC are primarily used as 'heralded' single photon sources [3]. The properties of the correlated photon pairs in these sources has been exploited in testing fundamental quantum mechanics such as quantum eraser [4]. Also, photon pairs that are entangled in different degrees of freedom such as polarization [5] and orbital angular momentum [6] are experimentally realized using SPDC process. Photon-based quantum information schemes such as quantum teleportation [7], quantum cryptography [8], quantum metrology [9] and super dense coding [10] demand the biphoton modes generated in SPDC to be coupled into a single spatial mode defined by an optical fiber.

There have been many theoretical studies on effective fiber coupling of SPDC sources [11–15]. The main parameters that control the collection efficiency of photon pairs are thickness of the crystal used for down-conversion, spatial walk-off, and mode field diameter of the optical fibers effectively imaged onto the crystal plane [11]. Coupling of SPDC photons with single-mode and multi-mode fibers were investigated [12] as a function of pump beam diameter, crystal thickness and walk-off. They observed entirely different behaviour between the coupling of SPDC photon pairs to the single-mode and multi-mode fibers by varying the pump beam diameter [13]. It was analytically shown that the coincidence spectrum becomes inseparable under strong pump focusing conditions so that the coincidence efficiency can be optimized [14]. It has been claimed that the important parameters for mode coupling in collinear parametric down conversion are the photon wavelength, the focal length of lens and the fiber diameter [15]. Use of single mode fiber attached detectors over direct spatial filtering of SPDC photons using a small slit is more advantageous, as in the former case, fringes smaller than the mode field diameter can be observed [16]. The results of numerical simulation [17] of heralded single photon purity and source brightness for pulsed pump source shows that an unengineered, pump focused, and filtered source gives higher number of fiber coupled photon pairs per pulse for smaller fiber collection mode radii. Similar work has been carried out for quasi-phase matched crystals, but coupling was investigated by considering the down-converted output as a classical beam [18]. A numerical study was carried out for choosing birefringent crystals with appropriate cut angles for efficient down-converted output in type-I phase-matching [19].

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Dependence of photon coupling ratio on focusing parameter of pump and collection modes, and the crystal length in the case of periodically-poled crystals has been studied [20] with an emphasis on grating defects. A method for optimizing the collection of entangled photon pairs in type-II SPDC by controlling angular divergence of the collection modes has been discussed [21]. The theoretical framework of [22] shows that the optimum focusing conditions for maximum efficiency of collinear PDC are precisely same as that of sum frequency generation and parametric amplification using Gaussian beams [23]. This was experimentally verified using a collinear phase matched PPKTP crystal with collimating pump, signal and idler [24]. On the contrary, in [25], it has been shown that there is no significant change in the coupling efficiency of conditional biphoton modes with the focusing parameter. Also, it was experimentally shown that focusing of the pump beam enhances the photon pair detection efficiency in non-collinear type-II birefringent phase-matched [26] and collinear type-I quasi phase-matched [27] crystals.

Here, we study the effect of pump focusing on biphoton coupling efficiency of photon pairs obtained in a non-collinear SPDC process. We have experimentally verified that the coupling efficiency decreases asymptotically with the focusing parameter of the pump beam. We give theoretical explanation on how crystal thickness influences the behaviour of biphoton modes in pump focusing. We also give a physical reason for this decrease in coupling efficiency based on our experimental observation using the matching of conditional optical modes of down-converted photons. We show that a loosely focused pump beam and a thin crystal are the best pre-detection conditions for the effective fiber coupling of entangled photons, as the former reduces the effect of SPDC ring asymmetry and the later reduces the walk-off effects inside the crystal. We also verify that the role of collection mode diameter on mode coupling to the fibers is more significant in tight pump focusing than in loose pump focusing.

2. Theory of SPDC: Semi-classical treatment

In the multi-mode perturbative treatment of SPDC, we consider the electric field of a pump beam as classical and the down-converted photons as quantum. Their respective electric fields can be written as [28]

$$E_p(\mathbf{r}, t) = \frac{1}{2}\left[\alpha_p \mathbf{e}_p E_p^0 g_p(\mathbf{r}) e^{-i\omega_p t} + c.\,c\right] \tag{1}$$

$$\hat{E}_{s,i}(\mathbf{r}, t) = \frac{i}{2}\sum_{k_{s,i}} \alpha_{s,i}\mathbf{e}_{s,i}\sqrt{\frac{\hbar\omega_{s,i}}{2n_{s,i}^2\epsilon_0 V_Q}}\, g_{s,i}(\mathbf{r}) e^{-i\omega_{s,i}t}\hat{a}_{k_{s,i}}(t) + h.\,c \tag{2}$$

where $\alpha_j = \sqrt{2/\pi w_j^2}$, ($j = p, s, i$), w_j is the beam waist, $\mathbf{e}_p$ is the polarization vector of pump, $\hat{a}_{k_{s,i}}(t)$ is the annihilation operator, $E_p{}^0$ is the amplitude of the pump beam and V_Q is the quantization volume. $\mathbf{e}_{s,i}$, $n_{s,i}$ and $\omega_{s,i}$ are respectively the polarization vectors, refractive indices and angular frequencies of target modes (*s*-signal, *i*-idler). $g_j(\mathbf{r})$ is the spatial mode function for the electric field and ϵ_0 the dielectric constant. Here, *c.c* and *h.c* represent the complex conjugate and the hermitian conjugate respectively. The Hamiltonian governing the interaction of pump with the non-linear crystal is given by [29]

$$\hat{H}_I(t) = \int 2\epsilon_0\left(\chi^{(2)}(\mathbf{r}){:}\ E_p^{(+)}(\mathbf{r}, t)E_s^{(-)}(\mathbf{r}, t)E_i^{(-)}(\mathbf{r}, t) + h.\,c\right)d^3\mathbf{r} \tag{3}$$

where $E_p^{(+)}(\mathbf{r}, t)$ is the positive frequency part of the pump field, $E_s^{(-)}(\mathbf{r}, t)$ & $E_i^{(-)}(\mathbf{r}, t)$ are the negative frequency parts of signal & idler modes respectively. $\mathbf{r} = (x, y, z)$ is the position vector in spatial coordinate system, $\chi^{(2)}(\mathbf{r})$ is the non-linear susceptibility tensor. For an interaction time τ, the quantum state of photon pairs generated in the process can be obtained by applying a time evolution operator $\exp[(-i/\hbar)\int_0^\tau H_I(t)dt]$ on the initial state. By truncating the above exponential function to the first order, the state is given by

$$|\Psi(t)\rangle \approx \left(1 - \frac{i}{\hbar}\int_0^\tau H_I(t)dt\right)|\Psi(0)\rangle \tag{4}$$

where $|\Psi(0)\rangle$ is the initial joint state of signal and idler. For a spontaneous process, the initial states are the vacuum states in the momentum space.

3. Biphoton modes in SPDC

In general, output of a parametric down conversion process is represented by a joint biphoton mode function. The two down-converted photons are correlated in several degrees of freedom including space, time, frequency, polarization and momentum. The correlated biphotons may or may not be entangled in those degrees of freedom depending on whether their mode function is separable into individual mode functions of each photon. A correlated photon pair can be a separable pair state, i.e. it need not be entangled. A biphoton mode function of momentum and frequency, derived from the quantum state of down-converted output is given in Eqn. (4) [30]. The mode function gives the information about the process such as pump beam characteristics and crystal phase matching conditions. Using the mode function, we can quantify spatial and spatio-temporal correlations among the down-converted modes without actually doing the state tomography [30]. The mode function has a one-to-one correspondence with the coincidence counts that we measure in experiment. A typical two-photon mode function [31] in transverse momentum coordinates $\mathbf{k}_s^\perp$ & $\mathbf{k}_i^\perp$ is given by

$$\Phi(\mathbf{k}_s^\perp, \mathbf{k}_i^\perp, \Delta k) = E_0(\mathbf{k}_s^\perp + \mathbf{k}_i^\perp)\mathrm{sinc}\left(\frac{\Delta kL}{2}\right)\exp\left(i\frac{\Delta kL}{2}\right) \tag{5}$$

where $E_0(\mathbf{k}_s^\perp + \mathbf{k}_i^\perp)$ represents the pump transverse wave vector amplitude distribution, Δk is the phase mismatch, and L is the thickness of the crystal. The exponential factor in the Eqn. (5) is a global phase term. Better sources of single photons by parametric down-conversion require the efficient coupling of optical modes involved in the process, into the fiber. Before coupling, the down-converted photons are spatially and spectrally filtered. The functions that represent the spatial and frequency (ω_c) filtering of down-converted photons are given by

$$\Gamma_{spatial} = \exp\left(-\frac{w_c^2}{2}|\mathbf{k}_c^2|\right) \tag{6}$$

$$\Gamma_{frequency} = exp\left(-\frac{(\omega_c - \omega_{c0})^2}{2B_c^2}\right) \tag{7}$$

where w_c and $\mathbf{k}_c$ are respectively the spatial collection mode width and the transverse momentum coordinate of collection mode. ω_{c0} and B_c are the central angular frequency and the bandwidth of the frequency filter respectively. In biphoton mode coupling, first we define a reference mode by imaging the single mode fiber-coupled idler photons onto the crystal. i.e., we project them into a single mode Gaussian.