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Single-photon spontaneous parametric down-conversion in quadratic nonlinear waveguide arrays

Diana A. Antonosyan, Alexander S. Solntsev*, Andrey A. Sukhorukov

Nonlinear Physics Centre, Research School of Physics and Engineering, Australian National University, Canberra, ACT 0200, Australia

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ABSTRACT

We describe spontaneous parametric down-conversion of a single-photon pump in quadratic nonlinear waveguides and waveguide arrays, taking into account spectral broadening of the signal and idler photons. We perform a detailed analysis of the photon-pair intensities, spectra and spatial correlations for different types of phase-matching conditions and identify suppression of Rabi-like oscillations due to spectral dispersion. We also discuss distinct features of signal and idler photon correlations related to the single-photon nature of the pump.

1. Introduction

Spontaneous parametric down-conversion (SPDC) in quadratic nonlinear crystals, where a pump photon is spontaneously split into a pair of signal and idler photons, has become a source of choice for experimental generation of entangled photons [1]. The optical nonlinearity on a few-photon level is relatively small, and a conventionally SPDC process is realized with a relatively strong classical laser pump. However, investigation of nonlinear effects in a few-photon regime can lead to fundamental and ultimately technological advances. Important experimental results include two-photon sum-frequency generation [2,3] and SPDC with a single-photon pump [4]. Recently, coherent single-photon conversion has been demonstrated based on a four-wave-mixing interaction which mimicked the SPDC process in quadratic crystals [5], which can lead to optically switchable quantum circuits with a complete control over individual photons.

The photons generated through SPDC can feature nontrivial spatial entanglement, which is essential for realization of quantum simulations and processing [6]. For integrated quantum chips, the entanglement is required between different waveguides. Such entangled photons can be used to realize quantum walks through coupling between waveguides [7] and implement boson sampling machine [8–11]. It was suggested that on-chip generation of entangled photons is possible with nonlinear waveguide arrays (WGAs), which can efficiently produce entangled photon pairs and simultaneously shape their spatial correlations through quantum walks [12]. So far, only the regime of a strong classical pump coupled to a nonlinear WGA was studied [12–15].

In this work, we describe SPDC in a nonlinear WGA for a single-photon pump, applying quantum pump description and taking into account possible pump depletion. First, in Section 2 we present results for a single waveguide. Then, in Section 3 we generalize the analysis to a periodic array of coupled waveguides. We present conclusions in Section 4.

2. Single-photon SPDC in one waveguide

First we study the properties of the SPDC process in a single nonlinear waveguide [Fig. 1(a)]. The Hamiltonian of the system can then be written as follows [1,16]:

$$\hat{H} = \int d\omega_p \int d\omega_s \int d\omega_i \left[\chi a_p(\omega_p) a_s^\dagger(\omega_s) a_i^\dagger(\omega_i) + \chi^* a_p^\dagger(\omega_p) a_s(\omega_s) a_i(\omega_i)\right] + \int d\omega_p \beta_p(\omega_p) a_p^\dagger(\omega_p) a_p(\omega_p) + \int d\omega_s \beta_s(\omega_s) a_s^\dagger(\omega_s) a_s(\omega_s) + \int d\omega_i \beta_i(\omega_i) a_i^\dagger(\omega_i) a_i(\omega_i), \quad (1)$$

where a_j ($a_j^\dagger$) are annihilation (creation) operators for pump, signal and idler modes ($j = p, s, i$), ω_j and β_j are the corresponding frequencies and mode propagation constants in a waveguide, and χ is the effective nonlinear susceptibility coefficient.

We analyze the process when a single pump photon is converted into a signal photon and an idler photons. We consider

* Corresponding author. Tel.: +61 2 6125 2042; fax: +61 2 6125 8588.
E-mail address: Alexander.Solntsev@anu.edu.au (A.S. Solntsev).

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the case of a pump photon with long temporal duration, and accordingly narrow spectrum. However, the spectra of signal and idler photons can be much broader. Then, we seek the wave function describing the evolution of photon states in a form similar to Refs. [5,17], but accounting for spectra of photons:

$$|\psi\rangle = e^{i\beta_U z}\int d\omega_p\Big[U(z)S(\omega_p)a_p^\dagger(\omega_p) + \int d\Omega V(\Omega,z) \times S(\omega_p)a_s^\dagger(\omega_p/2+\Omega)a_i^\dagger(\omega_p/2-\Omega)\Big]|0\rangle, \quad (2)$$

Here U is the pump amplitude, V is the biphoton amplitude, $S(\omega_p)$ is the pump spectral distribution that is normalized as $\int d\omega_p|S(\omega_p)|^2 = 1$, Ω is the detuning of signal and idler photons as $\omega_s = \omega_p/2+\Omega$ and $\omega_i = \omega_p/2-\Omega$, $\beta_U = \beta_p$ at the central pump frequency, and $|0\rangle$ is the vacuum state. Note that U and V are considered to be independent on ω_p for a narrowband single-photon pump.

The wavefunction $|\psi\rangle$ for the SPDC obeys the Schrödinger equation for a traveling wave [1]:

$$i\frac{|\psi\rangle}{dz} = \hat{H}|\psi\rangle. \quad (3)$$

We substitute Eq. (2) into Eq. (3), and obtain the coupled-mode equations while neglecting the dependence of mismatches β_j on ω_p for a narrowband pump photon:

$$\frac{dU(z)}{dz} = -\chi\int d\Omega V(\Omega,z),$$
$$\frac{dV(\Omega,z)}{dz} = \chi^* U(z) + i\Delta\beta(\Omega)V(\Omega,z), \quad (4)$$

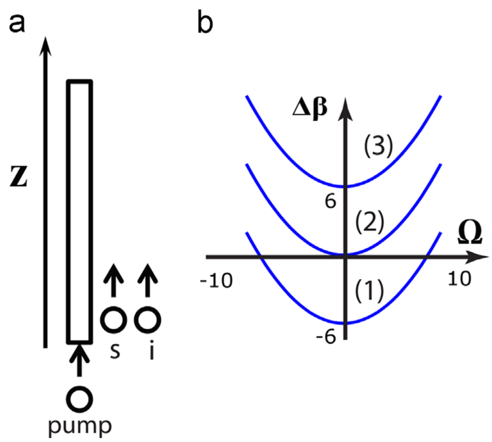

Fig. 1. (a) Scheme of SPDC for single-photon pump in a quadratic nonlinear waveguide. (b) Three kinds of possible phase-matching conditions : (1) $\Delta\beta_0 = -6$, non-degenerate SPDC favoring $\omega_s \neq \omega_i$, (2) $\Delta\beta_0 = 0$, degenerate SPDC favoring $\omega_s \simeq \omega_i$, and (3) $\Delta\beta_0 = 6$, phase-mismatched SPDC.

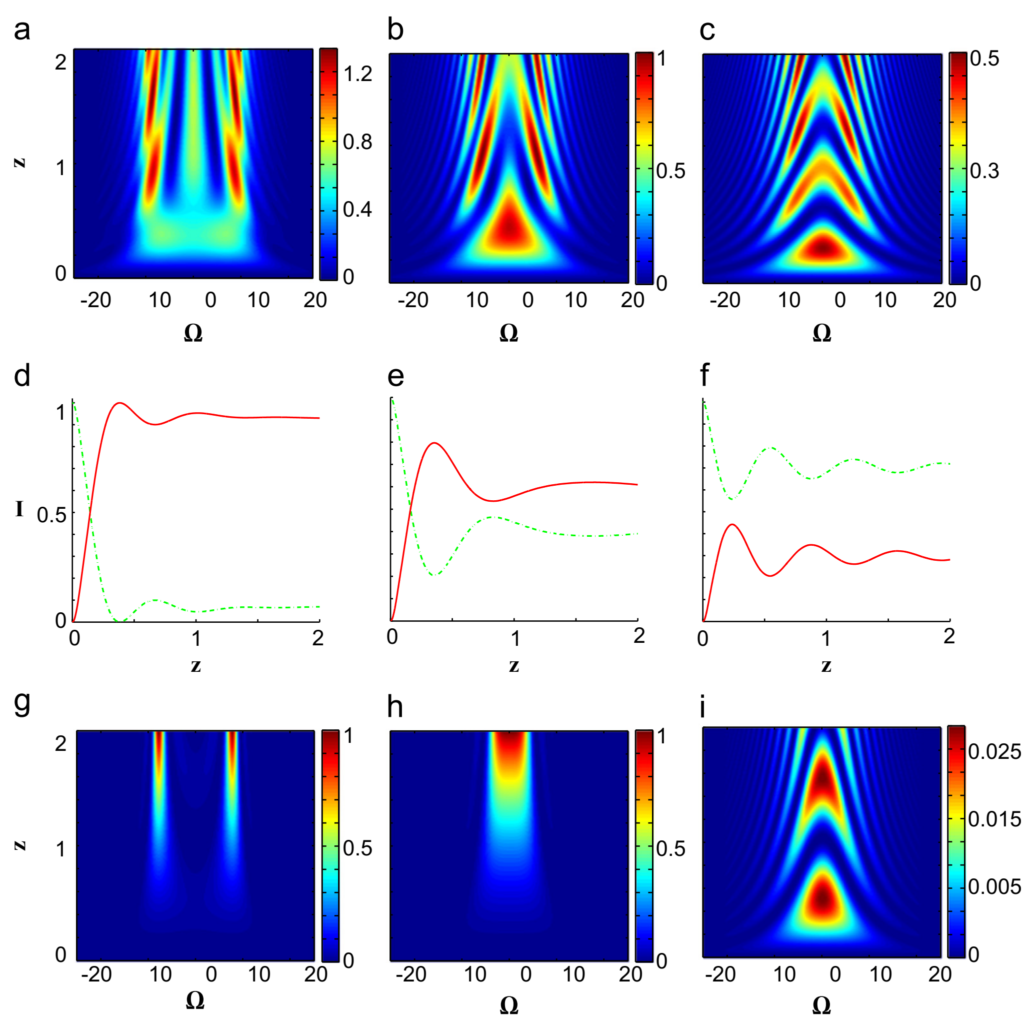

Fig. 2. (a)–(c) Biphoton intensity I_V depending on propagation distance and frequency for different phase-matching conditions; (d)–(f) pump intensity I_p (dashed line) and signal (or idler) intensity $\tilde{I}_V$ (solid line); (g)–(i) biphoton intensities depending on propagation distance and frequency for classical undepleted pump $U(z) \equiv$ const. The phase-matching parameters are (a), (d), (g) $\Delta\beta_0 = -6$; (b), (e), (h) $\Delta\beta_0 = 0$; and (c), (f), (i) $\Delta\beta_0 = 6$.