Optical simulation of photon-pair generation in nonlinear lossy waveguides

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Integrated optical circuits enable stable and scalable realization of quantum logic devices, which can form a basis for the mass production of photonic chips for quantum communications and computations. An important challenge is the integration of single-photon sources, which should provide on-chip generation and preparation of quantum photon states. Spontaneous parametric down-conversion (SPDC) provides an attractive solution for experimental generation of correlated and entangled photon pairs [1,2]. However, internal losses in the waveguides may still be present, affecting nontrivially the emerging photon state [3].

The establishment of quantum-classical analogies is an active research topic due to the cross-fertilization of ideas, with recent examples including simulated quantum walks of entangled photons [4] and development of new device characterization methods [5]. In this work, we demonstrate that photon-pair generation through SPDC in a nonlinear lossy waveguide can be simulated in a specially designed linear lossless waveguide array.

We consider the process of SPDC in a lossy $\chi^{(2)}$ nonlinear waveguide pumped by a quasi-CW laser, where a pump photon at frequency ω_p spontaneously splits into signal and idler photons with corresponding frequencies ω_s and ω_i, such that $\omega_p = \omega_s + \omega_i$ [Fig. 1(a)]. We reveal that this process can be simulated by a classical linear light propagation in a semi-infinite array of weakly coupled single-mode optical waveguides with the different coupling coefficients controlled by waveguide spacing [Fig. 1(b)]. At the input, the laser is coupled to the first waveguide, which propagation constant is detuned from the second waveguide to account for the phase mismatch (Δβ). Then the output intensity in the second waveguide, $I_s^{(0)}(z)$, is proportional to the number of generated signal-idler photon pairs, and total intensity in the other waveguides, $\tilde{I}_s(L)$, determines the signal photon count when idler photons are absorbed. The effective loss of idler photons is determined by the waveguide coupling coefficients as $\gamma = C_2^2/C_3$. The theoretically calculated (lines) and experimentally simulated (dots) dependencies of the photon pair generation on phase mismatch are presented in Figs. 1(c,d) for different losses. In the absence of loss, we observe the well-known sinc-shape dependence [Fig. 1(c)], whereas at higher losses it is transformed into Lorentzian shape [Fig. 1(d)].

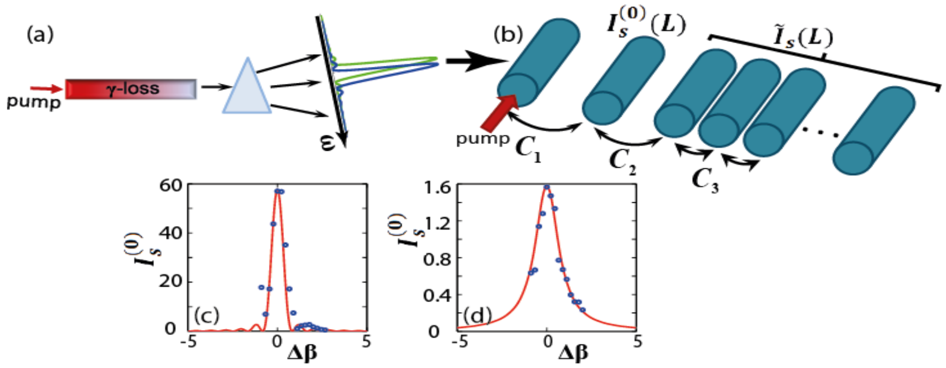

Fig. 1 (a) Scheme of photon-pair generation through SPDC in a nonlinear waveguide with loss; the photon states are defined by frequency-dependent phase mismatch and losses. (b) Corresponding classical optical simulator based on a waveguide array. (c,d) Normalized number of photon pairs $I_s^{(0)}$generated through SPDC in a single waveguide vs the phase mismatch Δβ at the propagation distance L=7.6cm. Solid (red) line theoretical calculations and dots (blue) experimental data for different losses: (c) $\gamma_s=\gamma_i=0$ and (d) $\gamma_s=\gamma_i=0.397$.

The demonstrated waveguide platform can be further applied to optically simulate the effects of non-Markovian losses and quantum decoherence phenomena [6], which are important for nano-plasmonic circuits.

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