EPJ Web of Conferences **161**, 03018 (2017) DOI: 10.1051/epjconf/201716103018
PECS-2017

Generation of single-photon states with orbital angular momentum in the process of spontaneous parametric down-conversion in a cavity

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Abstract. We consider the generation of single-photon states with orbital angular momentum in the process of spontaneous parametric down-conversion in a nonlinear crystal placed in a cavity. For creating optical beams with an orbital angular momentum, a ring resonator with a Dove prism is proposed to be used.

Light beams with orbital angular momentum (OAM) are currently the subject of active research. In contrast to the spin angular momentum, which is associated with the polarization of light, OAM arises due to the spatial distribution of the intensity and phase of the optical field. Promising applications of OAM are associated with manipulation of microparticles [1], increasing the capacity of optical communication channels [2], increasing the stability of quantum communication through the atmosphere [3] and a number of other applications.

One of the simplest ways of generating single photons is the process of spontaneous parametric down-conversion (SPDC) of light, during which a photon from the pump beam incident on a nonlinear crystal is annihilated with creating two photons called idler and signal. This process satisfies the energy and phase matching conditions: $\boldsymbol{\omega_p = \omega_i + \omega_s}$ and $\vec{\mathrm{k}}_{\boldsymbol{p}} = \vec{\mathrm{k}}_{\boldsymbol{i}} + \vec{\mathrm{k}}_{\boldsymbol{s}}$, where ω и $\vec{\mathrm{k}}$ are the frequency and wave vector of signal (*i*), idler (*s*) and pump (*p*) photons. In addition, for collinear SPDC we have the following conservation condition [4]:

$$\ell_{\boldsymbol{pump}} = \ell_{\boldsymbol{s}} + \ell_{\boldsymbol{i}} , \tag{1}$$

where ℓ_{pump}, ℓ_s and ℓ_i are the values of OAM for the pump, signal and idler photons, respectively. The sum of OAM values of the created photons is equal to OAM value of the pump. This is confirmed by coincidence measurements with detecting photons of the signal and idler SPDC fields, when the crystal is pumped by Laguerre-Gaussian beams with different OAM. The probability of coincidence is calculated by the formula $P_{p_s,p_i}^{\ell_s,\ell_i} = |C_{p_s,p_i}^{\ell_s,\ \ell_i}|^2$, where the probability amplitude $C_{p_s,p_i}^{\ell_s,\ \ell_i}$ is given by the integral [5]

$$C_{p_s,p_i}^{\ell_s,\ \ell_i} \sim \int dr_\perp \, \Phi(r_\perp) \left[LG_{p_s}^{\ell_s}(r_\perp)\right]^* \left[LG_{p_i}^{\ell_i}(r_\perp)\right]^*, \tag{2}$$

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where $r_\perp$ is the radial coordinate in the transverse X–Y plane, $\Phi(r_\perp)$ is the distribution of the amplitude of the pump field, $LG_{p_s}^{\ell_s}(r_\perp)$ and $LG_{p_i}^{\ell_i}(r_\perp)$ are the distributions of the amplitude of the signal and idler fields, respectively. Figure 1 shows the theoretical simulation of the coincidence probability.

In this paper, we consider the generation and detection of single photons with OAM via the SPDC process in a nonlinear crystal placed in a cavity. A cw neodymium laser at 532 nm is assumed to be used as a pump, while a PPLN crystal in which correlated photon pairs are produced at 810 nm and 1550 nm can be used as a nonlinear material. The nonlinear crystal is placed in a cavity whose mirrors have a high reflection coefficient for one of the emitted fields, say signal, and are transparent for the second emitted field and pump field. Beams of the signal field with OAM can be created in a ring cavity consisting of one planar and two spherical mirrors [6]. Such geometry of the resonator in the form of an obtuse triangle allows one to reduce the influence of astigmatism of the spherical mirrors. Rotation of the field around the beam axis is realized by means of a Dove prism. If the cavity creates specific value of OAM for the signal field, the corresponding OAM value for the idler field satisfying the conservation law (1) should be observed. When the cavity field proves to be a superposition of Laguerre-Gaussian modes, the corresponding superposition should be observed for the conjugated field.

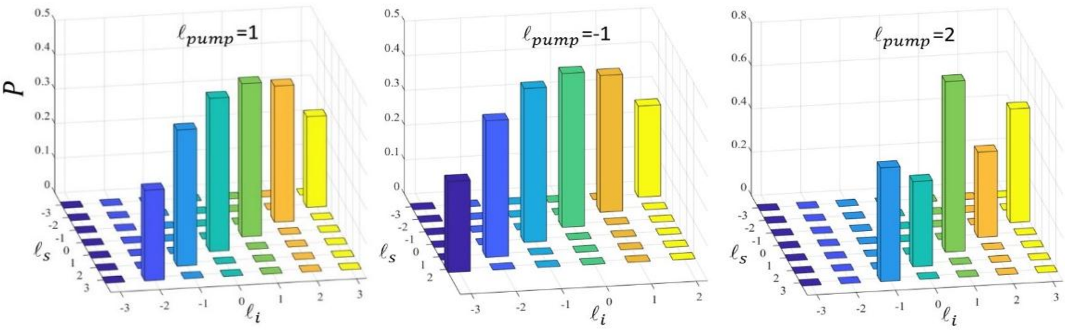

Fig. 1. The coincidence probability *P* for the orbital angular momenta of the signal and idler photons for $\ell_p = 1$, –1, and 2. The result of simulation using Eq. (2).

This work was supported by the Russian Foundation for Basic Research (grant № 16-02-01055).

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