Random nonlinear layered structures as sources of photon pairs for quantum-information processing

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Abstract. - Random nonlinear layered structures have been found to be a useful source of photon pairs with perfectly indistinguishable un-entangled photons emitted into a very narrow spectral range. Localization of the interacting optical fields typical for random structures gives relatively high photon-pair fluxes. Superposing photon-pair emission quantum paths at different emission angles, several kinds of two-photon states (including states with coincident frequencies) useful in quantum-information processing can easily be generated.

Since the pioneering generation of photon pairs by Mandel and coworkers [1] photon pairs have been generated in many nonlinear materials using different configurations and geometries. Their properties are determined by their source. In general photon pairs can be divided into entangled and un-entangled pairs in a given degree of freedom. While entangled photon pairs have been found useful in many physical experiments testing quantum mechanics, demonstrating quantum teleportation, etc., un-entangled photon pairs have been found extraordinarily suitable for quantum-information protocols [2, 3]. The reason is perfect indistinguishability of two photons comprising a photon pair that is not ‘spoilt’ by entanglement and that guarantees perfect visibility in any interferometric setup. Moreover if pulsed pumping generates simultaneously N photon pairs we have 2N indistinguishable photons localized in a very sharp time window. This is ideal for quantum-information processing.

The first attention to un-entangled photon pairs has been attracted when two-photon states coincident in frequencies [4–6] were studied. It has been shown that nonlinear bulk crystals pumped by a spatially chirped beam [7–9] can serve as a source of such states. Also assuming non-collinear geometry, crystal of a given length and pumping with a suitable waist the theory [10, 11] predicts an un-entangled state at the output of a nonlinear crystal. Wave-guiding structures with perpendicular pumping and counter-propagating signal and idler beams ( [12, 13], [14] and references therein) also provide un-entangled states but they suffer from low photon-pair generation rates [15]. Here we offer an alternative way of generating photon pairs using random nonlinear layered structures. Easy and fault-tolerant fabrication represents a great advantage of this source of un-entangled photon pairs that is able to deliver sufficient photon fluxes. Moreover its integration into optoelectronic circuits is possible.

Considering the generation of photon pairs at the fiber-optics communication wavelength 1.55 µm we assume layered structures made of LiNbO₃ with etched strips filled by SiOₓ and pumping of spontaneous parametric down-conversion at the wavelength around λ₀/2 = 775 nm using a pulse 250 fs long. We note that production of photon pairs in regular layered structures has been studied in Refs. [16–19] where the details of the used model can be found. Structures under investigation are composed of 300 elementary layers with the mean layer optical thickness equal to λ₀/4 and material of each elementary layer is randomly chosen. Typical lengths of these structures lie around 60 µm. Numerical simulations for the used materials have revealed that suitable numbers of layers are in the interval from 200 to 400. It holds in general that the greater the contrast of indexes of refraction of two materials the smaller the number of needed layers. In order to include fabrication imperfections additional random Gaussian shifts of boundary positions with variance λ₀/40 are assumed. Nonlinear material LiNbO₃ is oriented
such that s-polarized signal, idler, and pump fields can efficiently interact. The optical axis of LiNbO$_3$ is parallel to the planes of boundaries and coincides with the directions of fields’ polarizations. We note that similar structures have been investigated from the point of view of second-harmonic generation [20, 21].

orders of magnitude (for central frequencies) is observed as a consequence of high signal- and idler-field amplitudes occurring in localized states (see fig. 2 where the enhancement one order of magnitude is in agreement with wider signal- and idler-field spectra). However high enhancement of photon-pair generation rates is at the expense of dramatic narrowing of the emission bandwiths and so only from 10 to 10$^3$ photon pairs per 100 mW of pumping is expected in the whole emission cone. The wider the transmission peak the higher the number of the generated photon pairs. Similar effects can also be observed in second-harmonic generation [21].

A two-photon state $|\psi\rangle_{\theta_s, \theta_i}$ describing a photon pair emitted into the signal- and idler-field radial emission angles $\theta_s$ and $\theta_i$ can be written as follows:

$$|\psi\rangle_{\theta_s, \theta_i} = \int d\omega_s \int d\omega_i \phi_{\theta_s, \theta_i}(\omega_s, \omega_i)|1\rangle_{\theta_s, \omega_s}|1\rangle_{\theta_i, \omega_i},$$

(1)

where the Fock state $|1\rangle_{\theta_j, \omega_j}$ contains one photon at frequency $\omega_j$ in the form of a plane wave propagating along radial angle $\theta_j$ ($j = s, i$). Two-photon spectral amplitude $\phi_{\theta_s, \theta_i}(\omega_s, \omega_i)$ gives us a probability amplitude of emitting a signal photon at frequency $\omega_s$ and its idler twin at frequency $\omega_i$. Its typical shape with contour plot resembling a cross (see fig. 3) is found in random layered structures. This shape reflects nearly perfect separability of the two-photon state as can be revealed in the Schmidt decomposition of the two-photon amplitude $\phi$. Two photons in a pair are perfectly indistinguishable owing to identical emission conditions. This can be experimentally verified, e.g., in Hong-Ou-Mandel interferometer giving visibility one. Wave-packets with durations in tens or hundreds of ps characterize these states in time domain.

Linear dependence of the signal- and idler-field central frequencies $\omega_s^{\text{rel}}$ and $\omega_i^{\text{rel}}$ on the radial emission angles $\theta_s$ and $\theta_i$ of this source of un-entangled photon pairs (see fig. 2)
allows to create easily new two-photon states by superposing photon pairs emitted into different radial emission angles. The fact that the shapes of two-photon spectral amplitudes $\phi$ corresponding to different emission angles $\theta_s$ ($\theta_i$) are nearly identical is a great advantage and allows to generate well defined two-photon states. Several kinds of two-photon states needed in quantum-information protocols can conveniently be generated this way as the following two examples demonstrate. If two-photon states emitted into a certain interval of radial emission angles $\theta$ are superposed (with a suitable phase compensation) two-photon states with coincident frequencies can be reached (see fig. 4a). In this case, the larger the range of the included emission angles, the broader the intensity spectra of the signal and idler fields and the higher the entanglement. Similarly, if two-photon amplitudes propagating from $M$ equidistantly positioned pinholes at increasing emission angles $\theta_s$ and $\theta_i$ are added two-photon states composed of $M$ independent collective modes (defined by the Schmidt decomposition) are obtained (see fig. 4b).

Random layered structures can also be used for spectrally non-degenerate emission of photon pairs though the generation of a suitable structure is an order of magnitude more difficult compared to the spectrally degenerate case. For example, un-entangled two-photon states with considerably different signal- and idler-field spectral widths can be obtained and then exploited in heralded single-photon sources.

In conclusion, nonlinear random layered structures in which an optical analog of Anderson localization occurs have been discovered as sources of photon pairs containing perfectly indistinguishable photons. Their spectral bandwidths may vary from 0.001 nm up to 1 nm for different realizations of a random structure. Special two-photon states useful in quantum-information processing can easily be generated superposing states occurring at different emission angles.

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