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Designing the Structure of Photonic Crystal Fibers for the Generation of Broadband Single Photon States

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Abstract—Structures of photonic crystal fibers are proposed for the generation of broadband single photon states using the process of spontaneous four-wave mixing. New types of structures are modeled mathematically. The spectral and correlation characteristics of the generated states are calculated.

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INTRODUCTION

Devices that allow one-photon states to be generated with targeted and temporally stable characteristics are the basis for a large class of quantum information technologies. The possibility of using single photon sources results from its characteristics fitting the specified requirements [1]. The most promising applications of single-photon sources are associated with producing quantum computing algorithms, quantum memory, quantum repeaters, quantum communications (needed for building scalable quantum networks with absolute secrecy) and other applications of quantum metrology and quantum informatics.

Two effective and highly developed ways of generating two-photon and single-photon states are spontaneous parametric scattering (SPS) and spontaneous four-wave mixing (SFWM). Nonclassical two-photon states of light are generated during SPS and SFWM. A correlated pair of photons allows us to create a single-photon source with an alert tone. The probability of there being a second photon (the signal photon) at the output of a one-photon source at a certain point in time can be calculated when one photon from a pair (the alert photon) is detected. The main advantages of this approach are the stability of the generated states over time at room temperature; wide possibilities of tuning the wavelength and the width of the spectrum when controlling the parameters of laser pumping and the medium of generation; and a small contribution from multiphoton states at high spectral brightness (rates of photon generation per spectral interval). Its main disadvantages are the random nature of the generation of single-photon states over time (no determinism); and the correlation between the signal and idle photons (the generated one-photon state is not pure). This correlation is due to a feature of two-photon generation: mixed single-photon states are born during SPS and SFWM. This means a generated pair of photons has spatial, polarization, and frequency correlations. In order to obtain a pure one-photon state, the photons must be cleansed of all correlation parameters. Using fiber media to generate photon pairs allows us to eliminate all types of correlations, except for the frequency (spectral) correlation between signal and idle photons. This procedure requires us to select the parameters of (a) a nonlinear medium and (b) laser pumping to obtain special conditions of synchronization. It is a major problem when creating a single photon source.

Single-mode waveguide structures have several advantages over other media: the ability to generate one spatial mode; the possibility of using extended media (from one to several meters in length) to generate photon pairs, which allows us to increase the efficiency of generation; and a high degree of coordination with fiber networks and optic fiber quantum information devices. Photonic crystal fibers (PCFs) have great potential and are widely used to generate correlated photon pairs in SFWM using spectrally limited laser pulses [1, 2]. The structure of such fibers is usually designed to obtain specific profiles of dispersion and is used to generate, e.g., super continuums in femtosecond lasers. A new design for a PCF structure with a flat dispersion profile, optimized for generating broadband single photon states, is proposed and analyzed in this work. This structure can be used to generate ultrashort broadband single-photon states of light.

STATEMENT OF THE PROBLEM

From the viewpoint of quantum electrodynamics, spontaneous four-wave mixing (SFWM) can be defined as the virtual absorption of two pump photons p with the subsequent generation of a pair of photons (a biphoton): signal photon s and idle photon i [1]. Four-wave mixing is spontaneous if only one pair of photons is born in the medium at any one time. For the specified properties of a fiber's structure and the pumping of laser radiation, the signal and idle wavelengths generated during SFWM are determined by the conditions of phase matching and the law of the conservation of energy (formulas 1 and 4):

$$2w_p = w_s + w_i. \tag{1}$$

Nonlinear interaction in the photonic crystal fibers used to generate photon pairs via SFWM proceeds in the quartz core of the fiber, and the shell is a periodic two-dimensional structure that consists of holes of different shapes, filled with gas with a different refractive index.

The state of a two-photon field generated by spontaneous four-wave mixing in an optical fiber of length L is described by a function of state [3, 4]:

$$|\Psi\rangle = |0\rangle_s |0\rangle_i + \kappa \iint dw_s dw_i F(w_s, w_i) |w_s\rangle_s |w_i\rangle, \tag{2}$$

where κ is a constant characterizing the efficiency of generation; it is linearly proportional to the length of the fiber and the amplitude of the electric field for each pump field, and depends on the relative polarizations of the pump fields and the generated pairs). $F(w_s, w_i)$ is a function of the spectral amplitude of a biphoton (a signal and an idle photon) that describes the spectral and correlation properties of a generated photon pair. The function of the joint spectral amplitude can be expressed as

$$\begin{aligned} F(w_s, w_i) &= \int dw' \alpha_1(w')\alpha_2(w_s + w_i - w') \\ &\times \sin c\left[\frac{L}{2}\Delta k(w', w_s, w_i)\right] \exp\left[i\frac{L}{2}\Delta k(w', w_s, w_i)\right], \end{aligned} \tag{3}$$

where $\alpha_{1,2}$ (w) is the spectral pump amplitude; $\Delta k(w', w_s, w_i)$ is the phase matching function, which in the case of two-photon pumping of one polarization for the signal and idle field is determined by the formula

$$\begin{aligned} \Delta k(w_p, w_s, w_i) &= k(w_p) + k(w_s + w_i - w_p) \\ &- k(w_s) - k(w_i) - \gamma P, \end{aligned} \tag{4}$$

$$k_q = \frac{\omega_q n^{\mathrm{eff}}(\omega_q)}{c}, \quad q = \mathrm{p, s, i}, \tag{5}$$

where P is the peak power of a laser pulse, and γ is a nonlinear coefficient determined by the physical properties of the fiber and the parameters of its own mode [6]. The peak power of the pulse is normally low during SFWM, and the contribution from term γP is negligible in expression (4). The limit on the conservation of energy is determined by the argument of the second term for the phase mismatch in expression (3). The factorized state in which there are no correlations between photons in a pair is determined by spectral amplitude function $F(w_s, w_i)$. This function can be presented as the product of two functions: $F(w_s, w_i) = S(w_s)I(w_i)$, where functions $S(w_s)$ and $I(w_i)$ are eigenfunctions of the signal and idle photons, respectively.

EXPERIMENTAL

Exact values of the indices of refraction and dispersion of the eigenmodes of photonic crystal fibers at the lengths required for parametric processes are needed to determine the spectral and correlation characteristics generated during the SFWM of two photon fields. The complicated and bulky structure of photonic crystal fibers usually does not allow us to obtain analytical solutions for seeking and calculating eigenmodes. The values of the effective index of refraction, dispersion, and other characteristics of photonic crystal fibers are therefore calculated by numerically solving Maxwell's equations. In this work, modeling was done in the Lumerical MODE Solutions programming environment.

The results from modeling a photonic crystal fiber with zero dispersion at 800 nm (an analog of commercial fiber NL-800) that was promising from the viewpoint of generating factorized photon pairs during SFWM were presented in [7]. The parameters at which the spectral correlation was minimal were determined in that work.

The spectral width of the photon pairs generated during SFWM depends on the width of the pump pulse and the dispersion at the pump, signal, and idle wavelengths. Calculations show the spectral width of the signal and idle photons widens for the structure of a fiber with a flat dispersion profile (reduced dispersion in a wide range of wavelengths). The duration of a single-photon (spectrally limited) pulse in this case grows shorter.

A broad class of zero dispersion fibers at 750, 800, 890, and 1040 nm was modeled to produce structures with a flat dispersion profiles optimized for generating broadband photon pairs. Defects in the form of holes in the cores of fibers with different shapes and refractive indices were added to these structures. The eigenmodes (close to Gaussian) and variance were found for each structure. Certain parameters (the size and shape of holes, and the index of refraction inside a hole) thus changed during a simulation. The dispersion characteristics and the combined spectral amplitudes of the generated photons were calculated for different combinations of these parameters.

The most impressive result is shown in Fig. 1, where there are dispersion curves for three different structures (a commercial fiber with zero dispersion at 800 nm; a fiber similar in structure, but with a hole

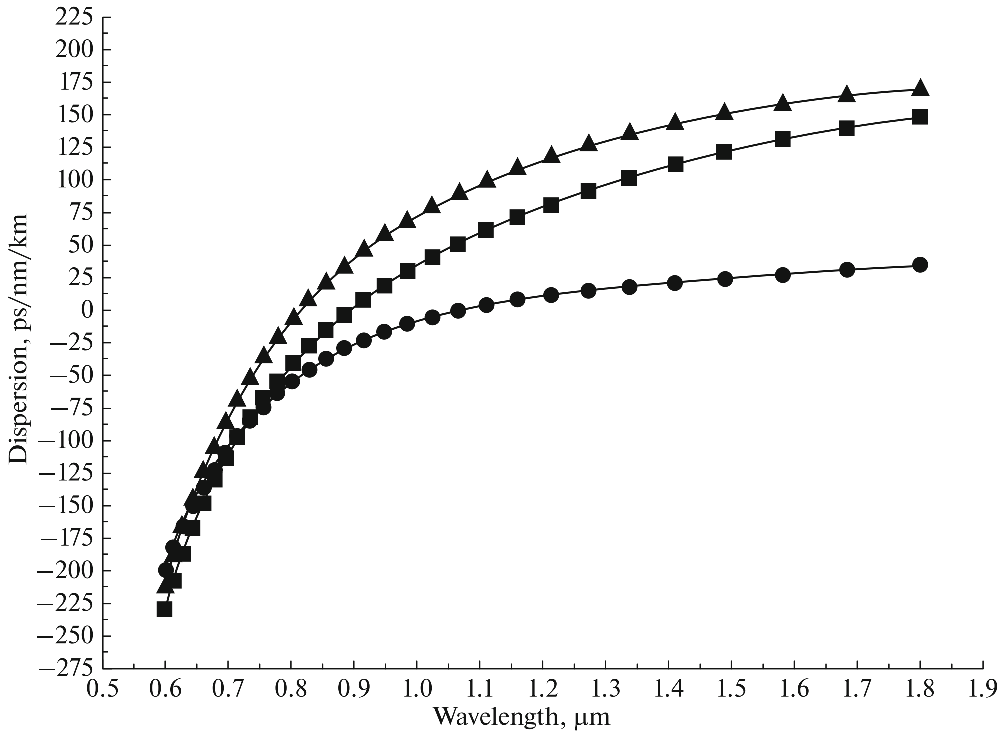

Fig. 1. Dispersion for different fiber structures. Triangles denote the standard fiber with zero dispersion at 800 nm; squares, the similar fiber with a hole 260 nm in diameter in the center of the core; dots, the similar fiber with a hole 500 nm in diameter.

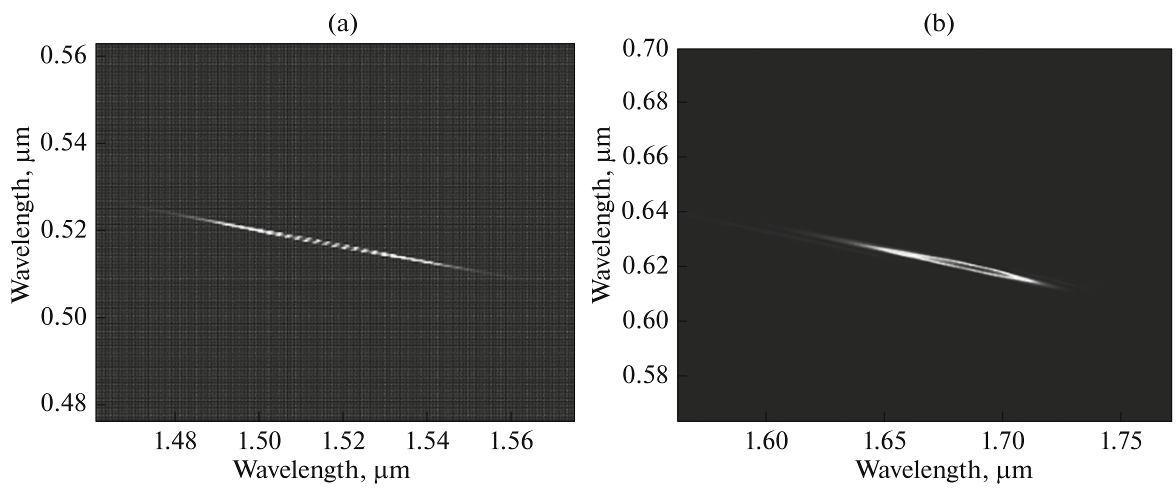

Fig. 2. Joint spectral amplitude for signal (ordinate axis) and idle (abscissa axis) photons. (a) Standard fiber; (b) fiber with a hole 500 nm in diameter.

260 nm in diameter in the center of the core; and a fiber similar in structure, but with a hole 500 nm in diameter). A considerable drop in the level of dispersion over a wide range of wavelengths is observed in the last case.

The combined spectral amplitude of a pair of photons, showing the dependence of the wavelength of the signal photon on the wavelength of the idle photon, is shown in Fig. 2. Figure 2a was obtained for a commercial fiber with zero dispersion at 800 nm and has a signal photon spectrum width of $\Delta\lambda = 3.4$ nm (for the specified pump laser parameters and a fiber length of $l = 1$ m). The joint spectral amplitude for a similar fiber with a hole 500 nm in diameter is shown in Fig. 2b. The width of the spectrum (with similar parameters) was in this case $\Delta\lambda = 12$ nm. This design of the fiber's structure allows us to increase the width

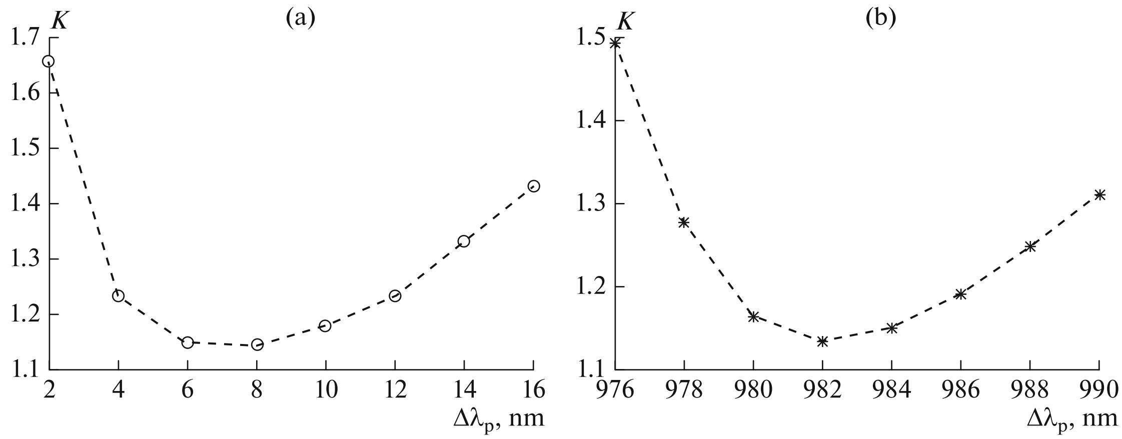

Fig. 3. Dependence of the Schmidt number on the (a) pump wavelength and (b) pumping spectral width for a photonic crystal fiber with zero dispersion at 1040 nm.

of the spectral line of the signal photon substantially. This dependence was also observed for fibers with zero dispersion at other wavelengths, but they were less broadened.

We also considered the possibility of factorizing the function of the signal and idle photons for a zero-dispersion fiber at 1040 nm (an analog of commercial fiber SC-1040). This fiber was modeled, and we obtained the dependence of the index of refraction and dispersion on the wavelength for the eigenmode of the fiber.

A way of decomposing spectral amplitude function F of the two-photon state in the Schmidt mode was developed in order to estimate the spectral correlation of single-photon states. If the initial state vector is

$$|\psi\rangle = |0\rangle + \iint F(\omega_i, \omega_s) a^+(\omega_i) a^+(\omega_s) d\omega_i d\omega_s, \quad (6)$$

the Schmidt decomposition has the form

$$F(\omega_i, \omega_s) = \sum_n \sqrt{\lambda_n} \alpha_n(\omega_i) \beta_n(\omega_s), \quad \sum_n \lambda_n = 1, \quad (7)$$

where $\alpha_n(\omega_i)$ and $\beta_n(\omega_s)$ are Schmidt functions (modes), and λ_n denotes expansion coefficients in the Schmidt modes [9]. Only one mode remains in the Schmidt decomposition of a pure (factorized) state. The Schmidt number in this case is 1. Calculating the Schmidt number for the SFWM mode of generation thus yields an estimate of the purity of the one-photon state. The dependence of Schmidt number K on the pump wavelength (with a pulse duration of 150 fs and a spectral width of 6 nm) and the width of the pump pulse are shown in Fig. 3. There is a local minimum on both graphs that corresponds to the minimum spectral correlation between a signal and an idle photon and is most promising from the viewpoint of generating factorized single photon states.

CONCLUSIONS

A design for the structure of photonic crystal fibers optimized for the generation of broadband pairs of photons in the process of spontaneous four-wave mixing was proposed for the first time. The structure corresponding to substantial broadening of the spectrum was found for a fiber with zero dispersion at 800 nm. The pump wavelength and pulse width were optimized for a fiber with zero dispersion at a wavelength of 1040 nm in order to reduce the spectral correlation and generate pure single-photon states.

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