# Chapter 6

# Summary

In this work, nonlinear processes with the ultrabroadband radiation in photonic crystal, tapered, and hollow fibers were studied. Since standard methods are not applicable for the study of processes with ultrabroadband radiation, methods which do not rely on the slowly-varying envelope approximation, were necessary. Starting from the Maxwell equation for the electric field, a novel first-order equation was derived, which is valid for media in which the refractive index is a smooth function of the coordinate. This is the only limitation for this equation, and it can be used for the study of processes of radiation with arbitrary spectral width, dispersion and refractive index. Comparison of the results obtained by this equation with the results obtained by the FDTD method is done, and good correspondence was shown. Linear dispersion plays a very important role in nonlinear processes in photonic, tapered, and hollow fibers, therefore an accurate model for its description was necessary. For the photonic fibers, effective cladding model for the description of the wavenumber dependence on the frequency was used. The dispersion relation was derived for the fundamental space-filling mode in the

PCF cladding, and its solution used to obtain the effective refractive index of the cladding. The full vectorial step-index fiber model was used to calculate the dispersive properties of the photonic crystal and tapered fibers. The dependence of the nonlinear coefficient was studied using the mode distributions for the photonic fibers. The propagation of light pulses through the waveguides was done with a global account for dispersion using the split-step Fourier method with a novel boundary condition.

The SC generation in PCF's is a fascinating phenomenon, which was already used in applications. The explanation of this puzzling effect, which can not be the result of SPM due to low intensity, was given in this work. Spectral broadening in PCF's was studied in different input frequency regimes. It was shown that supercontinuum generation is possible only if the input frequency is in the anomalous dispersion regime near the zero-dispersion point. Pulses in the anomalous dispersion regime form a higher-order soliton. Each of the constituent solitons experiences a shift toward the infrared due to the action of third-order dispersion. During this shift they emit non-solitonic radiation until the effect of third-order dispersion becomes small and the shift stops. The phase-matching condition in accordance with the numerical calculations showed that the generated radiation covers a wide spectral range up to doubled input frequency and is thus responsible for the supercontinuum generation. The comparison with experimental data, performed for different intensities, confirms this mechanism of spectral broadening.

Four-wave mixing plays an important role in the generation of the supercontinuum as well. Due to the possible applications, to study the peculiarities of FWM in the PCF's is an important task, which is undertaken in this work. If the pulse is at the zero dispersion frequency or in the normal dispersion range, the soliton fission is impossible. However, the process in which two pump photons are transformed into two photons with shifted frequencies can lead to the creation of sidebands and spectral broadening as well. The peculiarity of dispersion in PCF's manifests itself in the modified phase-matching condition, which shows that generation of sidebands far from the pump frequency is possible for PCF's and tapered fibers, in contrast to standard fibers. It was shown that control over the positions of the sidebands can be achieved by changing the input intensity or (and) frequency. To obtain effective phase-matching for the pump far in the normal dispersion regime, ps-duration pulses were necessary. This process was studied by the application of a slowly varying envelope approximation. It was shown that the idler pulse can reach the intensity of the pump pulse. The effect of birefringence on the phase matching was also studied. The control of birefringence, which can be achieved e.g. by the temperature change, allows shifting the idler wavelengths in the range around $1.3\mu$m which is interesting for applications.

The broadband radiation generation in gas-filled hollow fibers was studied with the aim to optimize the waveguide propagation parameters and pulse shortening by phase compensation. It was shown that it is possible to optimize the gas pressure in the fiber to suppress the dispersion-induced spectral broadening and to obtain larger effective nonlinear length, thus obtaining broader output spectra. It was predicted that such optimization allows achievement of the ultrashort ($\sim$ 1 fs) subcycle pulses by using a liquid crystal spatial light modulator.