INVESTIGATION OF POSSIBILITIES TO CONTROL FEMTOSECOND SUPERCONTINUUM CHARACTERISTICS

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The generation of a supercontinuum in the spectral range 530–1100 nm in a series of photon-crystal fibers pumped by a femtosecond Ti:S laser Mira Optima 900-F is obtained. The evolution of spectral characteristics of the femtosecond supercontinuum depending on the pump pulse wavelength and the power radiation is studied. The polarization characteristics of spectral components of the supercontinuum are analyzed. The possibility of a control over the femtosecond supercontinuum generation is experimentally demonstrated.

1. Introduction

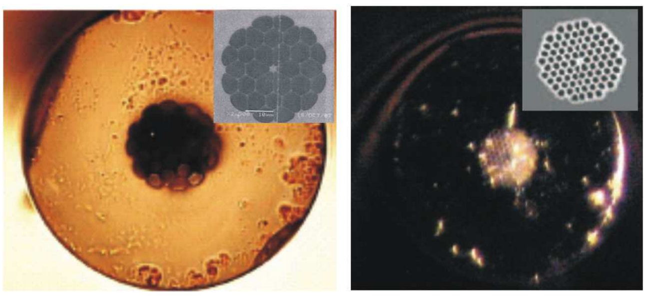
The generation of a supercontinuum (SC) is a spectrum broadening after the propagation of high energy pulses in a nonlinear medium. It was first observed by Alfano and Shapiro in 1970 [1, 2]. The term "supercontinuum" is not associated definitely with some effect, because it is a combination of various nonlinear phenomena which produce the strong broadening of the spectrum of an input pulse after mutual interaction of phenomena, with the properties of laser beam. In other words, SC is a continuous collection of spectral components of the electromagnetic wave with properties of the laser radiation, i.e., it is a spatially coherent "white" light.

The SC generation can be observed in a drop of water at the pumping with appropriate input pulse power, but the nonlinear effects participating in the formation of a spectral broadening strongly depend on the medium dispersion. In such a case, the development of materials with high nonlinear properties can reduce the requirements for the input power. The broadest spectrum is observed in the case where a pumping pulse wavelength is close to the zero-dispersion wavelength of a nonlinear medium. The input of the femtosecond laser radiation into a nonlinear photonic-crystal fiber (PCF) with a wavelength close to the zero-dispersion wavelength of the fiber leads to the generation of a femtosecond SC [3]. The first report on the SC generation in optical fibers was made in [4]. The fundamental physical processes which underlie the SC generation in a PCF include the stimulated Raman scattering [5], four-wave mixing [6], self-phase modulation [7], decay of solitons [8], and others. The need for a broadband coherent radiation appears, while solving various problems in nanotechnology, metrology, biomedicine, spectroscopy, near-field microscopy, *etc.* However, different applied problems pose different requirements for characteristics of SC. For example, the optical frequency metrology requires SC within at least one octave and with a high stability of the amplitude and the phase. A narrow stable frequency interval of the intensive SC radiation is enough for a realization of femtosecond coherent anti-Stokes Raman spectroscopy (CARS). One approach to the construction of a universal SC generator is to develop the methods using a dynamic change of parameters. In the course of studies, we have obtained the SC generation in microstructured fibers with the input radiation from a femtosecond Ti:S laser Mira Optima 900-F and investigated its properties (see Fig. 1).

2. Microstructured Fibers

To obtain the supercontinuum generation, we used photonic crystal fibers. Such a fiber belongs to a class of microstructured optical fibers with a solid quartz core

Fig. 1. Sketches of a microstructured PCF



a **b**

Fig. 2. Photos of the cross sections of PCFs: *a* — Thorlabs NL–2.4–800 and *b* — H 071015_125 obtained by a polarization microscope Olimpus BX-51 (magnification of 400 times) not long after the operation, in insertion – given by the manufacturer

surrounded by a periodic pattern of cylindrical quartz tubes fulfilled with air.

In conventional optical fibers, the total internal reflection is ensured under conditions when the refractive index of a fiber cladding is less than the refractive index of a core. As for microstructured optical fibers, the waveguide modes are formed by reflection and scattering on the microinhomogeneities of the refractive index. For a wide class of microstructured optical fibers, the condition of existence of waveguide modes in a fiber core, which can be regarded as a defect in the microstructure, can be written in the form similar to that in the case of the existence of the complete internal reflection in a conventional fiber: $n_{\rm clad} < n_{\rm core}$. Along with the conventional waveguide modes, which are ensured by complete internal reflection, the microstructured optical fibers possess waveguide modes of the electromagnetic field which are formed due to a high reflective ability of the fiber cladding in the field of a two-dimensional periodic microstructure (two-dimensional photonic crystal).

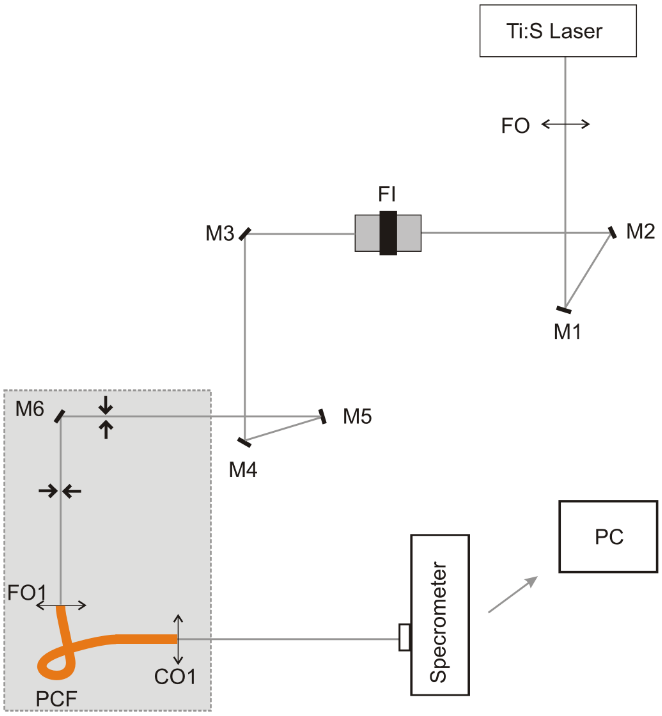


Fig. 3. SC generation scheme: a femtosecond Ti:S laser 900 Mira Optima-F, FI – Faraday optical isolator, M – mirrors, PCF – photonic-crystal fiber, FO – focusing lenses, CO – collimating lens, PC – personal computer

The microstructured optical fibers have unique properties, especially in the dispersion characteristics. With an appropriate choice of fiber parameters (refractive index of a fiber material, sizes of a core and a shell), the zero group velocity dispersion for a given wavelength can be attained. This leads to an increase of the efficiency of nonlinear interactions and allows observing the new nonlinear optical phenomena. In our work, we used PCFs Thorlabs NL–2.4–800 and H 071015_125 which have a zero-dispersion wavelength of 800 nm and core diameters of 2.4 and 2.5 μm, respectively (see Fig. 2).

3. Experimental Setup

The laser femtosecond radiation was supplied by a femtosecond laser complex (Coherent Mira Optima 900-F) at the Institute of Physics of the NAS of Ukraine. A typical scheme of the experimental setup is shown in Fig. 3.

Basic functional parameters of the complex:
– minimum pulse duration $\tau = 70$ fs;
– maximum pulse power $W = 2.5$ MJ;
– maximum pulse peak power $P = 3 \times 10^{11}$ W;
– maximum radiation intensity $I_0 = 10^{15}$ W/cm^2;
– 76-MHz pulse repetition rate.

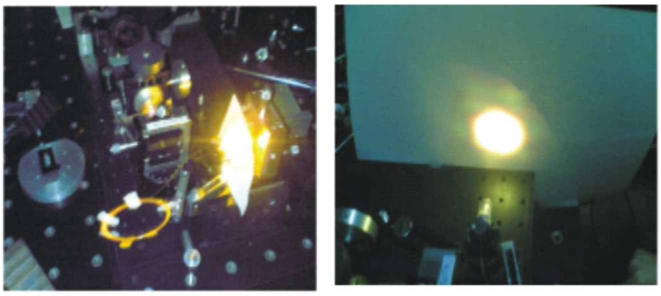


Fig. 4. Multiplex transformation of the frequency in a microstructured fiber of mark H 071015_125

In Fig. 4, we present a typical view of the near-field radiation at the output of a microstructured fiber.

4. Supercontinuum Generation in Photonic-Crystal Fibers

The main factors for the SC generation are: dispersion properties of a fiber with respect to the wavelength of a pump laser, pulse duration, and peak pulse power. The dispersion and especially its sign determine the type of nonlinear effects and the nature of the spectrum – its shape and stability.

The fibers Thorlabs NL–2.4–800 and H 071015_125 are designed with a zero-dispersion wavelength of 800 nm. In the normal dispersion region, where the pumping wavelength is less than the zero-dispersion wavelength, the self-phase modulation and the Raman scattering are dominant nonlinear processes which broaden a spectrum into the long-wave side. Fast pulses are broadened in the first few centimeters of a fiber; this limits the peak output power and the spectral broadening. In the anomalous dispersion region, where the pumping wavelength is more than the length corresponding to the zero dispersion, a soliton is formed. In this region, the efficient conversion of the incoming energy into the SC output radiation energy should be expected. The output spectra for different pumping powers and pumping wavelengths are presented in Figs. 5 and 6.

As is seen, the SC spectrum is narrowed at 780 nm (the normal dispersion region), and the most share of energy is concentrated around the pumping wavelength. At 800 nm (zero-dispersion region), the spectrum is wide and can be used in various tasks. At 820 nm, we used pumping pulses with their wavelengths in the anomalous dispersion region and obtained a very wide spectrum.

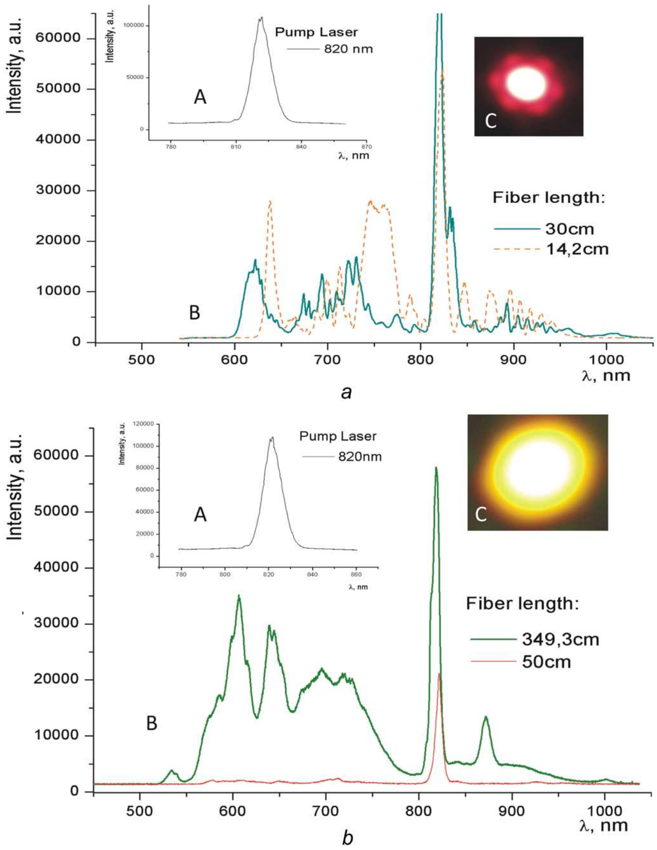


Fig. 5. Emission spectra of a supercontinuum generated by femtosecond pulses of a Ti:S laser at a wavelength of 820 nm, a power of 500 mW (A) in microstructured photonic-crystal fibers: *a* – Thorlabs NL–2.4–800 with lengths of 14.2 cm and 30 cm (B); *b* – H 07101_125 50 cm and 349.3 cm in length (B). Insertion (C) – experimentally recorded intensity distribution of radiation leaving a fiber

5. Polarization Characteristics of SC

We investigated the polarization characteristics of SC by using a Glan–Taylor prism and showed that the femtosecond laser radiation changes its linear polarization to the elliptic one after passing through a photonic crystal fiber. The ellipticity of polarization is 0.33. Experimental data are shown in Fig. 7.

We have analyzed the spectral broadening for each component of the polarization. It is shown that the maximal spectral broadening was equal to 385 nm at the minimum power after a polarizer, and the minimum spectral broadening was 310 nm with a maximum power after a polarizer. For the central component of the emission as a function of the rotation angle of a polarizer, we get a maximum shift (94 nm) at the minimum power

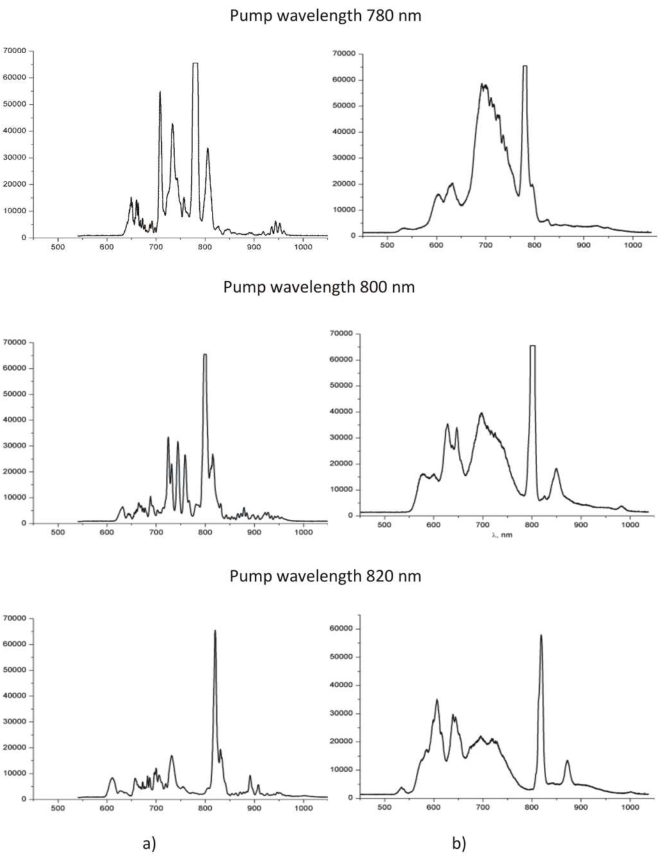


Fig. 6. Supercontinuum spectra at a pumping power of 400 mW: *a* – Thorlabs NL–2.4–800 14.2 cm in length; *b* – H $07101_1 25$ 50 cm in length

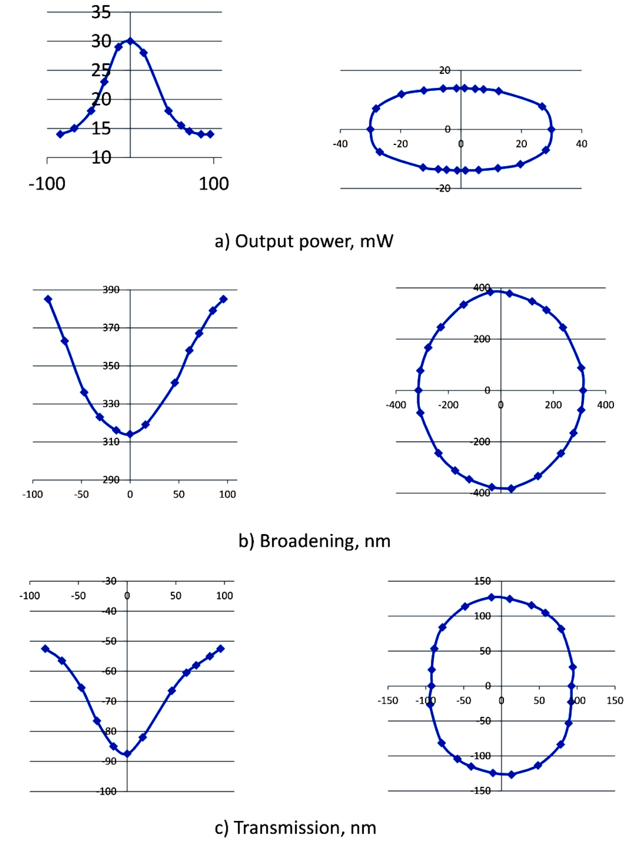


Fig. 7. Polarization at the output of a fiber. Relative changes of the emission characteristics as functions of the rotation angle of a Glan–Taylor prism: *a* – emission power; *b* – broadening of the spectrum; *c* – shift of the central component of the emission relative to the pumping wavelength

after a polarizer and a minimum shift (48 nm) at the maximum power after a polarizer.

6. Conclusion

We report the results of the supercontinuum generation in microstructured photonic-crystal fibers pumped by the radiation of a femtosecond Ti:S laser Mira Optima 900-F at 820 nm. The SC generation covers the intervals 580–1000 nm for fibers Thorlabs NL–2.4–800 (30 cm in length) and 525–1100 nm for fibers H $071015_1 25$ (349.3 cm in length). We have studied the dependence of spectral characteristics of the femtosecond supercontinuum on the pumping wavelength within the interval 770-830 nm. We have observed that the SC spectrum width increases from 150 to 350 nm with the pump laser wavelength. We have studied also the evolution of the femtosecond SC spectral characteristics at changing the pumping power. We have shown that it is possible to control the amplitude and frequency positions of the lateral component in the SC spectrum by changing the pumping power. The polarization characteristics of SC are investigated with the use of a Glan–Taylor prism. It is shown that, as the femtosecond laser radiation has passed through a photonic-crystal fiber, its linear polarization changes to the elliptic one with an ellipticity of about 0.3. Thus, we have experimentally demonstrated the possibility of the control over femtosecond supercontinuum characteristics.

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ДОСЛІДЖЕННЯ МОЖЛИВОСТЕЙ КЕРУВАННЯ ХАРАКТЕРИСТИКАМИ ФЕМТОСЕКУНДНОГО СУПЕРКОНТИНУУМУ

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Р е з ю м е

Отримано генерацію суперконтинууму в спектральному інтервалі 530–1100 нм у типоряді мікроструктурованих фотоннокристалічних волокон при накачці випромінюванням фемтосекундного Ti:S лазера Mira Optima 900-F. Досліджено еволюцію спектральних характеристик фемтосекундного суперконтинууму від довжини хвилі та потужності випромінювання накачки, а також поляризаційні характеристики суперконтинууму. Експериментально продемонстровано можливості керування характеристиками фемтосекундного суперконтинууму.