Quantum Electronics **39** (7) 634 – 637 (2009)

PACS numbers: 42.65.Ky; 42.65.Re; 42.65.Tg; 42.70.Qs; 42.81.Dp
DOI: 10.1070/QE2009v039n07ABEH014080

Multisoliton supercontinuum from a photonic-crystal fibre as a source of frequency-tunable megawatt femtosecond pulses in the infrared

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Abstract. **We demonstrate a new method of generation of frequency-tunable megawatt femtosecond pulses in the infrared based on multisoliton supercontinuum generation in a large-mode-area photonic-crystal fibre (PCF) followed by the temporal compression of the PCF output. Photonic-crystal fibres with a core area of about 710 μm^2 are employed to convert microjoule femtosecond laser pulses with a spectrum centreed at 1.39 μm into pulses with a central wavelength of 1520 nm, a pulse width of 210 fs, and a peak power of about 1 MW.**

Keywords: *nonlinear optics, ultrashort pulses, photonic-crystal fibres, optical solitons.*

Development of reliable, efficient, and compact sources of high-power ultrashort pulses in the infrared range is one of the key problems in laser physics and optical technologies [1]. Such sources are needed for highly efficient sensor elements [2], as well as for systems for trace impurity detection in liquid- and gas-phase media, including remote sensing of harmful and biothreat species in the atmosphere [3, 4], exhale diagnostics [5, 6], and biosensing [7]. Reliable and efficient frequency-tunable front-end sources of ultrashort pulses are critical for the creation of ultrahigh-power laser systems of new generation [8]. Akhmanov's legacy underlies many recent advances in the generation of high-power ultrashort pulses in the infrared.

The most commonly used approaches to the generation of frequency-tunable ultrashort infrared pulses are based on optical parametric amplification [1, 9], involving complex and expensive laser systems. Here, we demonstrate that frequency-tunable megawatt femtosecond infrared pulses can be produced by using the multisoliton regime of supercontinuum generation in a large-mode-area (LMA) photonic-crystal fibre (PCF) [10] followed by temporal compression of the PCF output. Large-mode-area PCFs are capable of supporting single-mode delivery of large-diameter light beams [11], allowing transmission, amplification, and nonlinear-optical transformation of high-energy laser fields without degradation of their beam quality. Due to this unique option, LMA PCFs are gaining growing applications in high-power fibre laser systems [12 – 16] and are employed for the spectral broadening of high-power pulses from solid-state lasers [17] and generation of high-energy supercontinuum [18, 19]. In experiments presented in this paper, PCFs with a core area of about 710 μm^2 are employed to convert microjoule femtosecond laser pulses with a spectrum centreed at 1.39 μm into pulses with a central wavelength of 1520 nm, a pulse width of 210 fs, and a peak power of about 1 MW.

The fibres used in our experiments were fabricated by a standard technology based on drawing specific performs, consisting of arrays of silica capillaries with a solid silica rod at the centre of the structure. A family of PCFs with a hexagonal array of air holes in the cladding (the inset in Fig. 1) with different air-hole diameters and different distances Λ between the centres of the holes was fabricated for the purposes of our experiments. The best results were achieved with PCFs with such d/Λ ratios that, rigorously

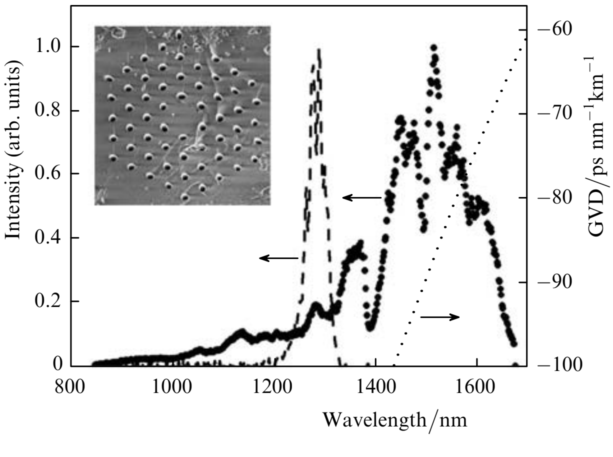

Figure 1. Spectrum of the input laser pulse (dashed line), spectrum of the PCF output (filled circles), and wavelength dependence of group-velocity dispersion (GVD) for the tellurite glass plate used for pulse compression (dotted line). The fibre length is 20 cm. The input pulse energy is 1 μJ. The inset shows the cross-section image of the PCF.

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Received 15 December 2008
Kvantovaya Elektronika **39** (7) 634 – 637 (2009)
Translated by A.M. Zheltikov

speaking, do not provide single-mode guiding. However, the number of modes supported by such PCFs is much less than the number of modes in fibres with the same core diameter, but with a solid cladding. The propagation-constant mismatch for the adjacent modes in our PCFs is much larger than a similar mismatch in fibres with a solid cladding. This stabilises isolated guided modes in the PCF and prevents nonlinear-optical cross-talk between the waveguide modes. The spectral – temporal dynamics of light pulses in the PCFs was analysed through a numerical solution of the generalised nonlinear Schrödinger equation (see, e.g., Refs 20, 21), including dispersion effects up to the seventh-order dispersion terms, Kerr- and Raman-type optical nonlinearities, as well as optical shock waves.

Ultrashort light pulses were generated in our experiments with a femtosecond laser system consisting of a mode-locked Ti : sapphire master oscillator pumped by the second harmonic of a neodymium garnet laser, a Ti : sapphire amplifier, and an optical parametric amplifier. The laser system can deliver light pulses with a central wavelength of about 800 nm, a pulse width of 50 fs, and an energy up to 1 mJ along with frequency-tunable pulses within the range of wavelengths from 1100 to 1500 nm with a pulse width of 70 – 190 fs and an energy up to 50 μJ.

The spectral and temporal properties of laser pulses transmitted through the PCF were analysed by using standard spectrometers, as well as cross-correlation frequency-resolved optical gating (XFROG) [22, 23]. The XFROG technique was used to measure parameters of the PCF output, including the retrieval of the spectral phase and the chirp of the light field. In our experiments, XFROG measurements were implemented by mixing the PCF output with a reference field (50-fs, 800-nm Ti : sapphire-laser pulses) in a thin BBO crystal. The full spectral – temporal profile of the PCF output was retrieved from the frequency-resolved sum-frequency signal generated in the nonlinear-optical crystal as a function of the delay time τ between the reference pulse and the PCF output.

The energy of laser pulses coupled into the PCF in our experiments ranged from 0.01 to 2.0 μJ. Propagation of laser pulses with such energies in an anomalously dispersive fibre (the zero-group-velocity-dispersion wavelength for the PCF used in our experiments was 1.25 μm) is accompanied by the formation of multiple solitons. High-order dispersion induces an instability of solitons with respect to the emission of dispersive waves in the visible spectral range [24]. The retarded part of optical nonlinearity gives rise to a continuous red shift of solitons – phenomenon known as soliton self-frequency shift (SSFS) [20, 25]. Solitons that feature such a spectral – temporal dynamics are readily identified as well-resolved peaks in the spectra of the PCF output (filled circles in Fig. 1) and as isolated maxima in XFROG traces of radiation transmitted through the fibre (Figs 2 and 3a). Results of numerical simulations presented in Fig. 2 suggest that laser pulses with an initial energy of the order of 100 nJ can be converted into solitons with an energy in excess of 10 nJ, a pulse width of about 50 fs, and a central wavelength of about 1670 nm in a 60-cm-long piece of PCF. Dispersive-wave emission gives rise to the high-frequency part of the output spectrum (Fig. 2). With the growth in the energy of laser pulses launched into the fibre, the number of solitons increases. In the multisoliton regime, the spectra of individual solitons tend to merge together, giving rise to a broadband radiation with a continuous spectrum in the visible and infrared spectral ranges (Fig. 3b). As can be seen from the results of measurements presented in Figs 1 and 3b, the nonlinear-optical transformation of laser pulses in the PCF in this regime can generate intense radiation with a broad spectrum stretching from 800 to 2200 nm.

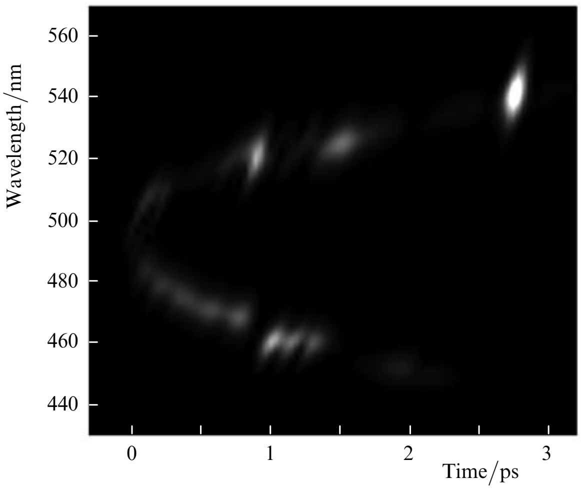

Figure 2. The spectral – temporal profile of the PCF output calculated by numerically solving the generalised nonlinear Schrödinger equation. The fibre length is 60 cm. The input pulse energy is 100 nJ.

The temporal structure of multisoliton supercontinuum radiation is generally quite complicated, making it difficult to compress the field as a whole to an isolated high-contrast, high-peak-power ultrashort light pulse. A certain part of the field, however, can be efficiently compressed, allowing a

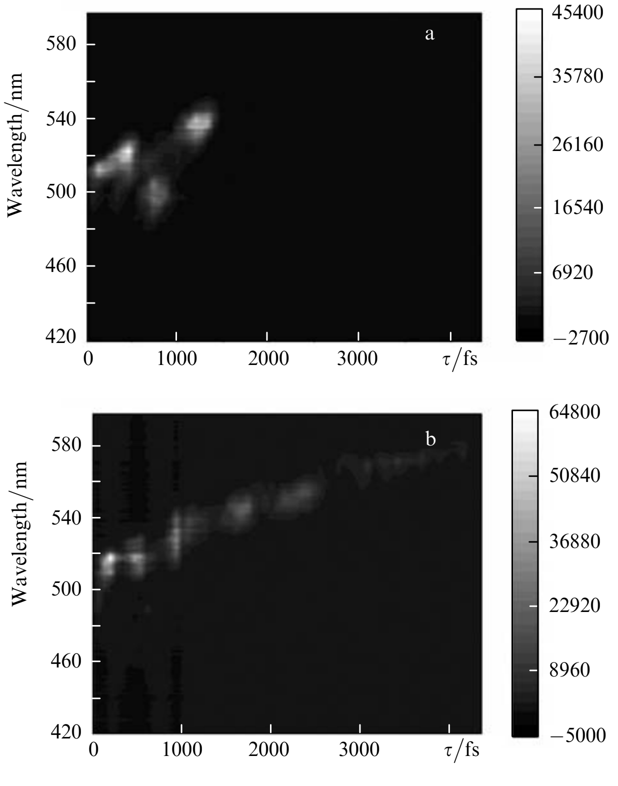

Figure 3. XFROG traces of the PCF output for input pulse energies of 0.2 μJ (a) and 1.0 μJ (b). The input central wavelength is 1390 nm. The fibre length is 18 cm.

sequence of light pulses with a sufficiently high peak power to be produced. In our experiments, such a compression was implemented with the use of a 8-cm-thick tellurite glass plate, which provided a partial chirp compensation for the output of the 60-cm PCF. The group-velocity dispersion for the glass plate is shown by the dotted line in Fig. 1. The XFROG trace shown in Fig. 4 indicates that, with a partial chirp compensation, multisoliton supercontinuum radiation is transformed into a sequence of light pulses, where the most powerful pulse has a central wavelength of 1520 nm, a pulse width of 210 fs, and a peak power of about 1 MW, carrying 20 % of the total radiation energy at the output of PCF. Parameters of light pulses produced with the use of this technology can be controlled by varying dispersion, nonlinearity, and length of the PCF, as well as by shaping input laser pulses. This method of supercontinuum pulse compression can be thus employed for the synthesis of optimal sequences of ultrashort light pulses for coherent control and single-beam microscopy of coherent Raman scattering.

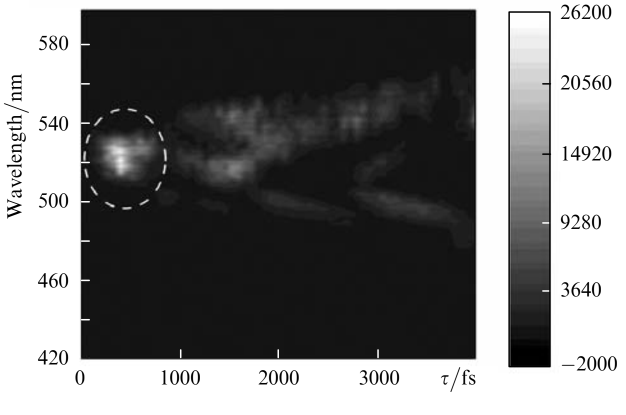

Figure 4. An XFROG trace of the field transmitted through the 60-cm PCF upon chirp compensation using the tellurite glass plate. The dashed contour highlights the pulse with a central wavelength of 1520 nm, a pulse width of 210 fs, and a peak power of 1 MW.

Spatial self-action of light in a PCF can lead to the excitation of higher order waveguide modes. This effect is one of the key factors limiting the peak power of light pulses that can be generated with the use of the multisoliton supercontinuum pulse compression technology. As mentioned above, experiments described here were performed with a multimode PCF. At a low peak power of laser radiation, however, only the fundamental mode of this fibre can be easily excited. Within fibre lengths less than 1 m, almost no energy exchange occurs between the waveguide modes in the regime of low peak powers. When the peak power P of laser pulses is increased, roughly, up to the level of $P \approx |\Delta\beta|/\gamma$, where $\Delta\beta$ is the propagation-constant mismatch for the relevant waveguide modes and γ is the nonlinearity coefficient, these waveguide modes become strongly coupled through a parametric nonlinear-optical interaction. In this regime, energy is transferred from the fundamental mode to higher order modes, opening an additional channel of waveguide loss. The $P \approx |\Delta\beta|/\gamma$ condition thus gives an estimate for the maximum peak power of laser pulses that still allows the above-described technology of short-pulse transformation to be implemented using multisoliton supercontinuum generation in LMA PCFs.

Generation of higher order waveguide modes is readily detected in our experiments, starting with peak powers of about 3 to 4 MW, from distortions of the beam profile of the PCF output, as well as from typical features appearing in XFROG traces of the PCF output. Since the waveguide modes differ in their dispersion profiles, XFROG traces of the multimode fibre output display several branches with turning points around the respective zero-group-velocity-dispersion wavelengths. Due to the difference in group velocities of the waveguide modes, such branches can be resolved in time given a sufficient fibre length (Fig. 5). In experiments, the beam profile of the sum-frequency signal used in XFROG measurements had a structure typical of the fundamental mode when the delay time between the PCF output and the reference pulse was $\tau \approx 200$ fs. Beam patterns typical of different higher order modes were observed with $\tau \approx 1300$ and 2700 fs. Fiber components capable of generating high-power ultrashort infrared pulses in higher spatial modes can be used for fibre-format implementation of high-resolution microscopy, including microscopy based on stimulated emission depletion [26] and coherent Raman scattering [27], where the spatial resolution is improved through the use of a pair of properly shaped light beams [26, 28].

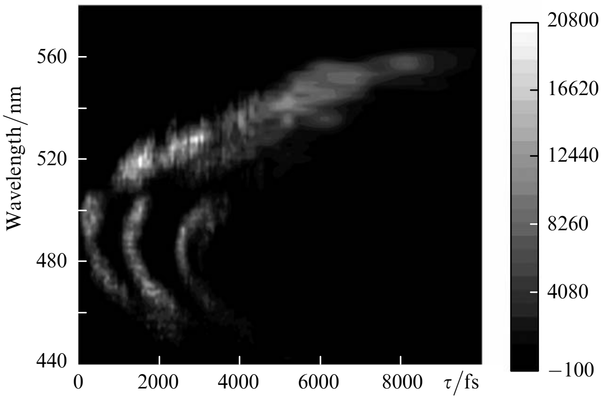

Figure 5. An XFROG of a light pulse transmitted through the PCF in the multimode regime. Input laser pulses have a central wavelength of 1290 nm, a pulse width of 160 fs, and an energy of 1 μJ.

We have thus experimentally demonstrated a new method for the generation of frequency-tunable megawatt femtosecond pulses in the infrared based on multisoliton supercontinuum generation in an LMA PCF followed by the temporal compression of the PCF output. Photonic-crystal fibres with a core area of about 710 μm^2 were employed to convert microjoule femtosecond laser pulses with a central wavelength of 1.39 μm into pulses with a spectrum centreed at 1520 nm, a pulse width of 210 fs, and a peak power of about 1 MW.

Acknowledgements. We are grateful to A.D. Savvin and A.A. Lanin for valuable help. This study was supported in part by the Russian Foundation for Basic Research (Project Nos 07-02-12175, 06-02-16880, 06-02-39011, 07-02-91215, 08-02-90061, and 08-02-91756) and the Federal Science and Technology Program of Russian Federation.

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