PACS numbers: 42.65.Re; 42.70.Qs; 42.81.Qb; 42.62.Eh
DOI: 10.1070/QE2001v031n10ABEH002068

Generation of a supercontinuum in fibres by a continuous train of ultrashort pulses*

E M Dianov, P G Kryukov

***Abstract*. The generation of a supercontinuum in fibres required for precision metrology and fibreoptic communications is considered.**

Keywords: *femtosecond lasers, supercontinuum, optical fibre, wavelength-division multiplexing, optical frequency metrology*.

1. Introduction

The generation of extremely short radiation pulses is one of the most important problems of laser physics and quantum electronics. The shortening of the laser-pulse duration opens up the possibilities for achieving extremely high radiation intensities, measurements of extremely short time intervals, and the study of ultrafast processes in a variety of fields of science and technology.

Since the advent of first lasers, a tremendous progress has been achieved in the shortening of the laser pulse duration and increasing its power and intensity. Modern lasers can produce pulses of duration of no more than 5 fs, i.e., less than two cycles of a light wave. In this case, the peak intensity of laser radiation exceeds 1 PW and the intensity of focused radiation achieves 10^{21} W cm^{-2}. Femtosecond studies are discussed in more detail in review [1].

The possibility of generation of pulses of duration of less than 100 fs is mainly caused by the fact that modern femtosecond lasers operate in the cw mode. This allows one to use the unique features of their emission spectrum and obtain the limiting time coherence, which opens up new and very important prospects of applications of these lasers.

A combination of ultrashort-pulse lasers with fibreoptic elements of a special structure permits the fabrication of devices capable of generating a huge number of narrow, strictly equidistantly spaced emission lines of the same intensity (the so-called comb generator). Such comb generators provide a direct comparison of optical frequencies with frequencies of microwave frequency standards, thereby solving the problem of creation of optical frequency standards.

Another important application of comb generators is the dense wavelength-division multiplexing (DWDM) in fibreoptic communications. The DWDM is considered as a revolutionary breakthrough in informatics [2]. Both these applications require the use of narrow-band cw lasers, while the application of ultrashort-pulse lasers for these purposes seems rather unexpected.

We consider the features of the spectrum and time coherence of ultrashort-pulse lasers, the possibility of using these features in practice, and present the results of studies of the generation of a supercontinuum by femtosecond pulses from a cw Cr : forsterite laser.

2. Features of the spectrum and time coherence of radiation from cw femtosecond lasers

Continuous-wave femtosecond lasers emit a strictly periodic train of ultrashort pulses (Fig. 1a). The spectrum of such a pulse train represents a comb of equidistant discrete lines (modes) separated by intervals equal to the pulse repetition rate (Fig. 1b). The dependences of the radiation intensity on time and frequency are related by the Fourier transform, so that $\Delta F \approx 1/T$, $\delta f \approx 1/\Delta t$, $\Delta f \approx 1/\tau$, where ΔF is the pulse repetition rate; δf is the linewidth; Δt is the pulse-train duration; Δf is the full width of the spectrum; and τ is the pulse duration. It follows from these relations that the ultra-

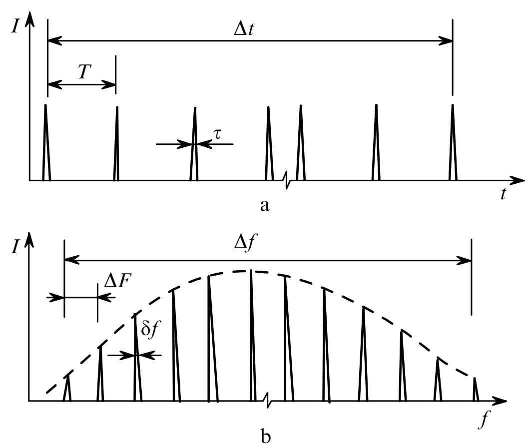

Figure 1. Dependences of the ultrashort-pulse intensity on time t (a) and frequency f (b).

*Reported at the seminar on 'Ultrafast Processes in Materials and Laser Technologies' (Institute of Applied Physics, Russian Academy of Sciences, Nizhnii Novgorod, Russia, 7 – 8 December 2000).

E M Dianov, P G Kryukov Fiber Optics Research Center, General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: kryukov@fo.gpi.ac.ru

Received 1 March 2001
Kvantovaya Elektronika **31** (10) 877 – 882 (2001)
Translated by M N Sapozhnikov

short-pulse laser emits during sufficiently stable and long operation the narrow lines of constant intensity.

Consider two experimental situations. Let us assume that a single pulse is separated from a continuous train of ultrashort pulses with the help of an electrooptical gate (Fig. 2a). Then, the emission spectrum becomes continuous, and the time coherence is determined by the pulse duration (the pulses are assumed to be transform-limited, i.e., they have no chirp). A single line (mode) can be separated from the continuous emission spectrum (Fig. 2b) using a monochromator with an appropriate diffraction grating. In this case, the intensity of the separated line becomes constant, while the time coherence is determined by the duration of the stable operation of the laser. Thus, a cw femtosecond laser is a source of both ultrashort pulses and extremely narrow emission lines.

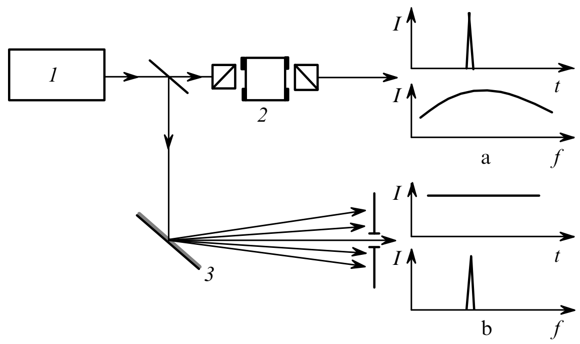

Figure 2. Dependences of the ultrashort-pulse intensity I on time t and frequency f upon separation of a single pulse (a) and a single line (b) from radiation of a cw self-mode-locked laser (*1*) with the help of an electrooptical gate (*2*) and a monochromator (*3*).

These properties of a cw femtosecond laser are manifested in experiments of two types. For example, in optical coherent tomography, extremely low time coherence is required because it determines the spatial resolution. Indeed, with the shortest pulses of duration of 5 fs, the spatial resolution close to the diffraction limit in optical microscopy has been achieved [3]. On the other hand, femtosecond lasers have found applications in precision metrology of optical frequencies [4, 5] and in wavelength-division multiplexing in fibreoptic communications [6–8], where cw radiation at discrete frequencies is necessary.

3. Fibreoptic supercontinuum generators

In both applications considered above, however, the width of the comb spectrum emitted by a laser proves to be insufficient. The bandwidth of modern fibreoptic communication systems operating at 1.5 μm is of about 3 THz. This corresponds to the pulse duration of ~ 100 fs, which can be comparatively easily obtained in modern lasers. However, the technical and operation characteristics of these lasers do not satisfy the requirements imposed on lasers used in fibreoptic communications.

The width of the comb spectrum required for metrology of optical frequencies should cover an octave, i.e., the maximum frequency of the comb should be twice as large as its minimum frequency. However, such width cannot be obtained even for the shortest pulse duration (5 fs at 0.8 μm). This raises the problem of a substantial increase in the width of the comb spectrum by retaining the strictly equidistant spacing of the spectral lines in the comb.

It is well known that using high-power ultrashort pulses, lasing with a continuous spectrum can be achieved, the width of the spectrum, which is called a supercontinuum, being many times larger than the width of the spectrum of these pulses [9]. It is important that such lasing can be obtained only upon pulsed pumping. The lasing mechanism represents a sophisticated combination of nonlinear effects such as self-phase modulation, four-photon mixing, stimulated Raman scattering, etc. It has been shown experimentally that the phase of the supercontinuum is coherently coupled to that of the pump pulse [10]. Therefore, if a supercontinuum is generated by a train of equidistantly spaced pulses, the supercontinuum pulses will have the same repetition rate. This means in turn that the supercontinuum will consist of the comb of equidistantly spaced lines.

However, there exists a fundamental problem. The supercontinuum width depends on the peak power and the length of nonlinear interaction. The average power of modern femtosecond lasers is determined by the power of a pumping laser. Typically, it does not exceed 1 W, while the pulse repetition rate is ~ 100 MHz, i.e., the energy of a single pulse does not exceed 10 nJ. The pulse repetition rate (the comb interval) in fibreoptic communication systems should be even higher, up to 10 and even 100 GHz. Of course, this reduces the peak intensity and, thereby, the efficiency of the supercontinuum generation. It seems that this fundamental problem can be overcome by compensating a decrease in the peak power by increasing the length of nonlinear interaction resulting in the supercontinuum generation.

The use of optical fibres allows one to achieve all the above-mentioned aims. The radiation launched into a single-mode fibre and, therefore, having a high intensity can propagate over large distances in the fibre. However, because of the group velocity dispersion (GVD), the duration of the pulse increases during its propagation in the fibre, resulting in a decrease in its intensity. To provide the required length of nonlinear interaction, it is necessary to have the opportunity to change the GVD in a desired way at the given wavelength of ultrashort pulses. Because the GVD in optical fibres is determined not only by the dispersion of the fibre material but also by its waveguide properties, which depend on the refractive index of the fibre core and cladding, it is possible in principle to change GVD by manufacturing fibres with a special structure. In addition, the nonlinear effect can be increased using strongly concentrated radiation.

Consider some examples.

3.1 Hole fibres (of the photonic crystal type)

A hole fibre is a single-mode fibre whose cladding contains a set of closely packed air holes with diameters smaller than the core diameter. Examples of such structures are shown in Fig. 3. The holes can form a periodic two-dimensional structure. Because of a periodic arrangement of the air holes (the refractive index $n = 1$) in glass ($n = 1.5$), the transmission spectrum of such a structure for certain directions of the light propagation has the wavelength regions, the so-called forbidden photonic bands, in which radiation cannot penetrate into the cladding. For this reason, such structures were called photonic crystal fibres. The fabrication of such fibres was first reported in paper [11]. To generate a supercontinuum, one layer of holes is sufficient, so that along with the term 'photonic crystal fibres', the term 'hole fibres' is also used, which refers to a broader class of fibres with a complicated cladding structure [12].

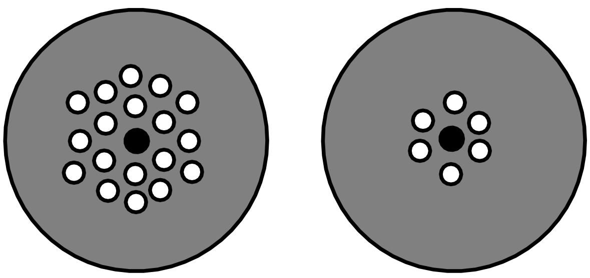

Figure 3. Types of microstructure fibres: a photonic crystal (a) and a hole fibre (b).

One of the main advantages of hole fibres is the possibility of obtaining in them a single-mode (over transverse modes) propagation of radiation in a very broad spectral region covering the emission spectrum of a Ti : sapphire femtosecond laser (0.8 μm). Due to a mutual compensation of the waveguide and material components of the dispersion, hole fibres allow one to shift the zero dispersion of group velocities to the visible region.

The use of hole fibres for the supercontinuum generation upon pumping by a continuous train of femtosecond pulses from a Ti : sapphire laser with energy of no more than 10 nJ was experimentally demonstrated in paper [13]. Fig. 4 shows the laser and supercontinuum emission spectra. One can see that the supercontinuum spectrum covers more than an octave. Because of this, the hole fibre supercontinuum generators have become an important component of femtosecond laser setups on which excellent results have been obtained, which produced a real revolution in the optical frequency metrology.

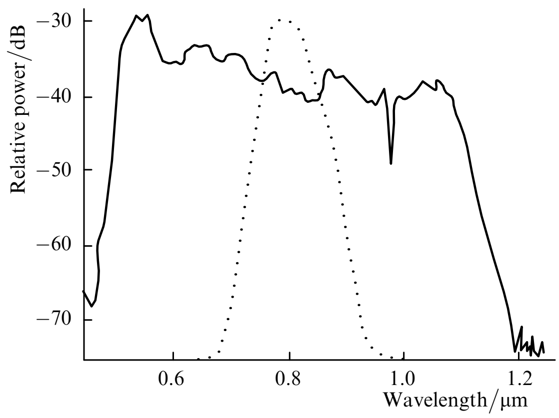

Figure 4. Supercontinuum spectrum at the output of a hole fibre (solid curve) and the laser spectrum (dashed curve) [11].

3.2 Tapered fibres

Recently [14], the generation of supercontinuum covering the spectral range from UV to near-IR region (i.e., more than two octaves) was demonstrated. The supercontinuum was excited by a continuous train of femtosecond pulses from a Ti : sapphire laser in fibres of another type, shown in Fig. 5.

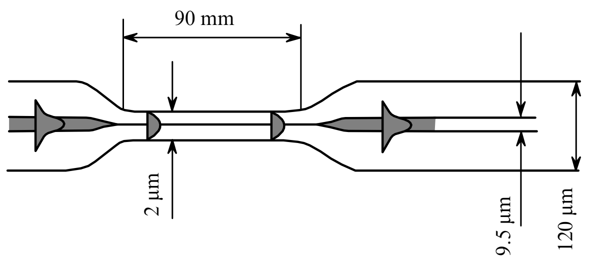

Figure 5. Tapered fibre [14].

A Corning SM-28 fibre with a cut-off wavelength of 1250 nm and a numerical aperture of 0.1 was drawn using controllable heating. A thread of diameter of about 2 μm was obtained, which was connected with the original fibre by tapered junctions. Such a tapered fibre provided the blue shift of the GVD zero. The thread length was 90 mm.

The supercontinuum spectrum excited by a train of 3.9-nJ femtosecond pulses covered the spectral range from 370 to 1545 nm at a level of 20 dB. This spectrum and the laser spectrum are shown in Fig. 6. In this way, an intense source of single-transverse mode 'white' light was obtained. Because the supercontinuum is generated by a continuous pulse train, the spectrum of 'white' light represents a comb of equidistant lines.

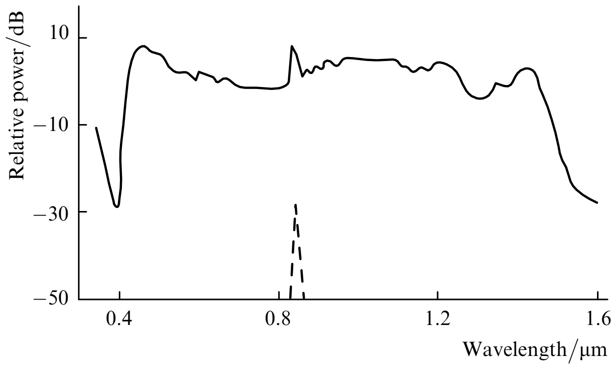

Figure 6. Supercontinuum spectrum at the output of a tapered fibre (solid curve) and the laser spectrum (dashed curve) [14].

3.3 Dispersion-shifted fibre

There is no need to generate supercontinuum with a very broad spectrum for fibreoptic communications, the width of the spectrum of about 3 THz at 1.5 μm being sufficient. However, this width should be obtained using compact and efficient fibre and semiconductor lasers emitting pulses of duration from 0.3 to 5 ps, with peak powers substantially lower than for vibronic crystal lasers. The supercontinuum is generated using semiconductor and fibre lasers in combination with single-mode fibres of length 1 – 3 km with special dispersion parameters [6 – 8].

4. Applications of cw femtosecond lasers based on their ability to emit continuous frequencies

4.1 Multiplexing in fibreoptic communication systems

To increase the bit rate in fibreoptic communication systems, the signal multiplexing of two types is used. In the first case (Fig. 7a), time-division multiplexing (TDM) is employed by using sufficiently short pulses. Modern electronics ensures handling of pulses of duration as short as 10 ps, providing the bit rate from 2.5 to 40 Gbit s^{-1}. To further increase the bit rate, parallel spectral channels are used with different carrier frequencies, the so-called wavelength-division multiplexing (WDM) (Fig. 7b).

In the WDM, radiation at different wavelengths (at present, as a rule, from independent light sources), carrying its own information at each of the wavelengths, is launched into one optical fibre with the help of a special device (multiplexer), amplified by a broadband optical amplifier, and propagates along a fibreoptic communication system. After an additional amplification, the radiation is separated over wavelengths at the output of this system with the help of a demultiplexer. An increase in the bit rate is achieved by increasing the number of spectral channels, which can exceed 100. Thus, researchers at NEC (Japan) reported the bit rate of 6.4 Tbit s^{-1} achieved in a 186-km fibreoptic cable using 160 channels [15]. As radiation sources, a set of wavelength-stabilised semiconductor lasers with a distributed feedback is commonly used.

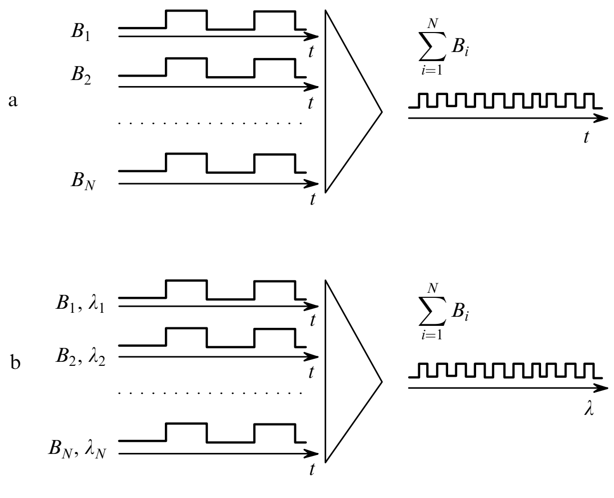

Figure 7. Multiplexing in fibreoptic communication systems: time-division multiplexing (a) and wavelength-division multiplexing (b); B_i is the information capacity of a channel.

The ability of ultrashort-pulse lasers to emit a continuous, strictly equidistant train of pulses with the spectrum representing a comb of equidistantly spaced lines can provide in principle both TDM and WDM. In this case, only one laser can be used for multiplexing instead of a set of lasers.

Recently, the data transmission was reported over 106 channels at a bit rate of 10 GHz s^{-1} over a distance of 640 km using a continuous mode-locked diode laser and a fibreoptic supercontinuum generator [16].

4.2 Precision optical frequency metrology

Laser frequency standards are one of the most important achievements of quantum electronics [17]. Their development requires the measurement of frequencies of extremely narrow resonances in the optical range with respect to the frequency of the international cesium standard, which lies in the microwave range (about 9.2 GHz). This means that optical frequencies (about 500 THz) should be transferred to the microwave range without the loss of accuracy.

For this purpose, radio-optical bridges are used [18]. They represent rather complicated and bulky setups consisting of a chain of specially selected phase-matched near-, mid-IR, and submillimetre lasers, microwave oscillators (klystrons and Gunn oscillators), and fast frequency converters. An optical clock and a unified length and time standard are based on this scheme [17]. The method for measuring optical frequencies based on radio-optical bridges was used until recently, but it was available only for few national scientific centres.

The problem of comparison of optical and microwave frequencies can be alternatively solved using a source of many optical frequencies separated by a constant interval lying in the radio-frequency range, i.e., if a stable comb generator of optical frequencies is available. A continuous ultrashort-pulse laser is such a source.

The idea of using cw ultrashort-pulse lasers in optical frequency standards and ultrahigh-resolution laser spectroscopy was first proposed by Chebotaev in papers [19, 20]. It has been shown in these papers that the method of separated resonators proposed in paper [21] for obtaining narrow resonances in the radio-frequency range can be in principle used in the optical range. Of course, the difference in the wavelengths by four-five orders of magnitude requires a sophisticated modification of this method.

It has been shown that the pulses separated in time can be equivalent to resonators separated in space. In paper [22], this idea was experimentally realised using a synchronously pumped picosecond cw dye laser.

When the spectrum of an optical comb generator covers more than an octave (i.e., when $f_{max} > 2f_{min}$), it is possible to compare directly the optical frequency lying within the spectrum of the comb generator with a microwave frequency. The principle of such measurements of optical frequencies is explained in Fig. 8. Having measured the beat frequency Δf_1 between the optical frequency f_{op} being measured and its second harmonic $2f_{op}$ and the beat frequency Δf_2 between the nearest frequencies of the comb

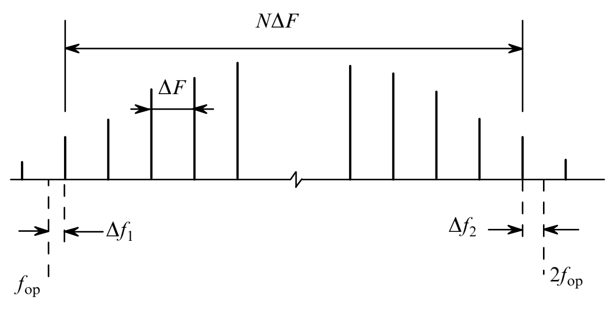

Figure 8. Principle of measuring optical frequency f using a comb of equidistantly spaced frequencies with the interval ΔF in the radio-frequency range.

generator at the long-wavelength and short-wavelength ends of the comb, one can determine the exact value of $f_{op} = 2f_{op} - f_{op} = N\Delta F + \Delta f_1 + \Delta f_2$, by counting the number N of lines in the comb. Therefore, an optical comb generator with the spectrum covering more than an octave can be used instead of a radio-optical bridge.

It follows from the above that the same cw ultrashort-pulse laser in combination with a fibreoptic supercontinuum generator can be used in principle in both applications instead of rather complicated systems involving many lasers.

5. Cr : forsterite supercontinuum generator

All the results on the generation of supercontinuum reported in the literature were obtained using Ti : sapphire femtosecond lasers. We studied tapered fibres using a 1.25-μm Cr : forsterite femtosecond laser. The parameters of this laser are:

Pump power/W	7.5
Self-mode-locking threshold/W	6.2
Average power/mW	320
Pulse repetition rate/MHz	100
Minimum pulse duration/fs	67
Wavelength/μm	1.25
Spectral width/nm	25

The tapered fibre had dimensions shown in Fig. 9. We studied two samples with waist diameters 6 (sample 1) and 2 μm (sample 2). Upon launching a beam from a femtosecond laser into a fibre with the help of a microscope objective, the radiation that was reflected from the fibre back to the laser destroyed self-mode-locking. Therefore, a Faraday isolator should be used. Unfortunately, because only a Faraday isolator at 1.3 μm was available to us, the maximum average power coupled to the fibre did not exceed 150 mW.

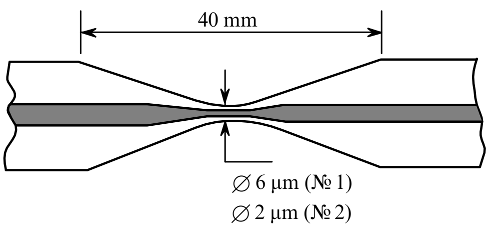

Figure 9. Tapered fibre with the waist of diameter 6 (sample 1) and 2 μm (sample 2).

The emission spectra obtained before and after propagation of radiation through samples 1 and 2 are shown in Fig. 10, which demonstrates the broadening of the spectrum. Note that, unlike the results presented in Fig. 8, the detection was performed at a level of several decibels. It seems that the waist length, as follows from Fig. 10, is insufficient for the maximum broadening of the supercontinuum spectrum.

6. Conclusions

The development of femtosecond lasers opened up their new possibilities. They are not only sources of extremely short pulses but also allow one to obtain, in conjunction with fibreoptic devices, a comb of a vast number of strictly equidistantly spaced frequencies. This remarkable feature resulted in two extremely important applications of femtosecond lasers in the precision frequency metrology and fibreoptic WDM communications. Note, by the way, that both these applications are closely related because the modern communications cannot be imagined without accurate measurements of frequencies and time intervals.

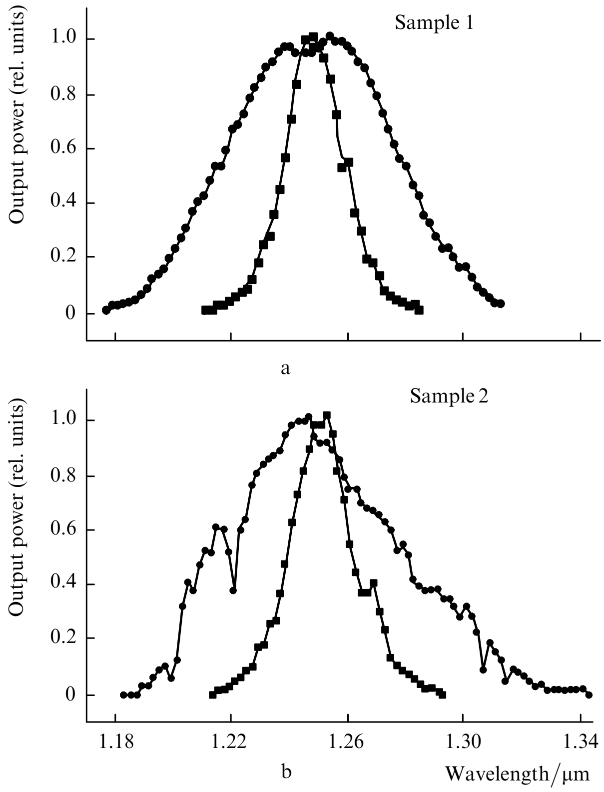

Figure 10. Emission spectra at the input (■) and output (●) for samples 1 (a) and 2 (b).

In both applications, fibreoptic elements play a crucial role. First, they are used in supercontinuum generators without which no outstanding advances would have been achieved. Second, there is reason to believe that the development of femtosecond fibre lasers will result in the creation of systems of a new generation, which will be more compact, more efficient, and broadly available. It is obvious that studies in this field are very urgent and promising.

References

1. Kryukov P G *Kvantovaya Elektron.* **31** 95 (2001) [*Quantum Electron.* **31** 95 (2001)]
2. Dianov E M *Kvantovaya Elektron.* **30** 659 (2000) [*Quantum Electron.* **30** 659 (2000)]
3. Drexler W, Morger U, Kartner F X, Pitris C, Boppart S A, Li X D, Ippen E P, Fujimoto J C *Opt. Lett.* **24** 1221 (1999)
4. Udem T, Reichert J, Holzwarth R, Hansch T W *Phys. Rev Lett.* **82** 3568 (1999)
5. Diddams S A, Jones D J, Ye J, Cundiff S T, Hall J L, Ranka J K, Windler R S, Holzwarth R, Udem T, Hansch T W *Phys. Rev Lett.* **84** 5102 (2000)
6. Morioka T, Mori K, Saruwatari M *Electron. Lett.* **29** 862 (1993)
7. Morioka T, Kawanishi S, Mori K, Saruwatari M *Electron. Lett.* **30** 790 (1994)
8. Morioka T, Takara H, Kawanishi S, Kitoh T, Saruwatari M *Electron. Lett.* **32** 833 (1996)

9. Alfano R R, Shapiro S L *Phys. Rev Lett.* **24** 584 (1970)
10. Bellini M, Hansch T W *Opt. Lett.* **25** 1049 (2000)
11. Knight J C, Birks T A, Russell P St J, Atkin D M *Opt. Lett.* **21** 1547 (1996)
12. Zheltikov A M *Usp. Fiz. Nauk* **170** 1203 (2000)
13. Ranka J K, Windeler R S, Stentz A J *Opt. Lett.* **25** 25 (2000)
14. Birks T A, Wadsworth W J, Russell P St *J Opt. Lett.* **25** 1415 (2000)
15. *Proc. Europ, Conf. ECOCS-2000* (Munich, Germany, 2000)
16. Takara H, Yamada E, Ohara T, Sato K, Jinguji K, Inoue Y, Shibata T, Morioka T *Proc. CLEO QELS-2001* (Baltimore, MD, USA, 2001), CPD11-1
17. Bagaev S N, Chebotaev V P *Usp. Fiz. Nauk* **148** 143 (1986)
18. Chebotaev V P, Goldort V G, Klementyev V M, Nikitin M V, Timchenko B A, Zakharyash V F *Appl. Phys. B* **29** 63 (1982)
19. Baklanov Y V, Chebotaev V P *Kvantovaya Elektron.* **4** 2189 (1977) [*Sov. J. Quantum Electron.* **7** 1252 (1977)]
20. Baklanov Y V, Chebotaev V P *Appl. Phys.* **12** 97 (1977)
21. Ramsey N *Molecular Beams* (Moscow: Inostrannaya Literatura, 1960)
22. Eckstein J N, Ferguson A I, Hansch T W *Phys. Rev Lett.* **40** 847 (1978)