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Raman-converter-diode-pumped continuous-wave femtosecond Er-doped fibre laser

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***Abstract*. An Er-doped fibre laser pumped at 1480 nm by a Raman converter of radiation from a diode-pumped ytterbium-doped fibre laser is built and investigated. The laser can operate in the soliton and stretched pulse regimes. The laser emits 1550-nm, < 100-fs pulses with a pulse repetition rate of 25 MHz and has an average power of 10 mW.**

Keywords: *erbium-doped fibre, continuous-wave femtosecond laser, Raman fibre converter.*

1. Introduction

At present continuous-wave (cw) femtosecond lasers attract great attention. It is explained, in particular, by the fact that such lasers emitting a repetitive train of pulses are also a source of equidistantly spaced narrow spectral lines separated by the interval equal to the pulse repetition rate in the train. The total extension of the spectrum is determined by the pulse duration, while the width of an individual line is determined by the stability of a continuous regime. In other words, the cw femtosecond laser is not only a source of ultrashort pulses but also a comb generator of highly monochromatic optical frequencies. Therefore, the time coherence of radiation from such a laser is characterised by two times: an ultimately short one, which is determined by the ultrashort-pulse duration, and an ultimately long one, which is determined by the stability of a continuous regime [1]. These times can differ by 15 orders of magnitudes in modern femtosecond lasers.

This unique feature – a combination of the properties of a narrow-band laser and an ultrashort-pulse laser, provides the basis for two extremely important applications of cw femtosecond lasers. The first of them is a precision metrology of optical frequencies. The use of cw femtosecond lasers in this field has led to a real revolution [2 – 4]. The optical frequency comb is in fact a ruler with divisions equal to the femtosecond pulse repetition rate. The interval between equidistantly spaced optical frequencies can be locked to the microwave frequency standard to perform the absolute measurement of an optical frequency lying between the UV and IR boundaries of the visible spectrum. Such measurements were performed with the help of a femtosecond Ti : sapphire laser without the use of a complex chain of intermediate frequencies.

Another important application of cw femtosecond lasers is their use in fibreoptic communication systems, where a comb generator of carrier frequencies is naturally employed for wavelength-division multiplexing (WDM). In WDM systems, information is transferred simultaneously along many wavelength-divided channels using an individual transmitter laser for each wavelength. In addition, optical time-division multiplexing (OTDM) can be applied. Because cw femtosecond lasers emit both a continuous sequence of equidistantly spaced carrier frequencies and a repetitive train of ultrashort pulses, the high-bit-rate hybrid OTDM/WDM systems with the bit rate above 1 Tbit s^{-1} can be developed in principle [5].

Figure 1a shows the separation of individual modes of a cw femtosecond laser with the help of an appropriate monochromator. If one mode is separated, the carrier frequency in the corresponding channel has the constant amplitude (Fig. 1b). If several modes are separated, a continuos train of pulses appears. The pulse duration is determined by the width of the spectrum of separated modes and the pulse repetition period is determined by the inter-

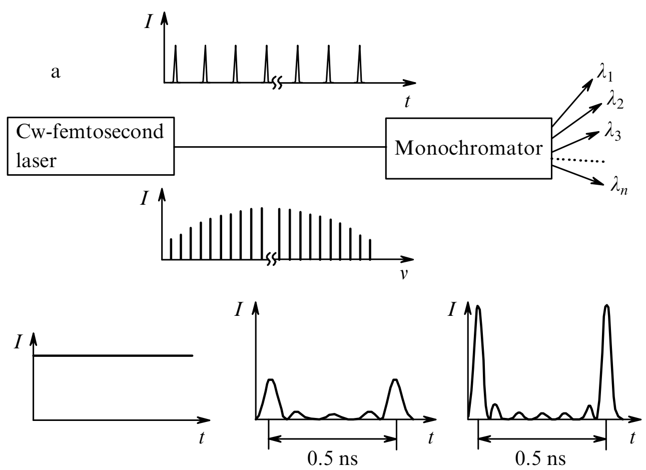

Figure 1. Principle of the use of a cw femtosecond laser in WDM fibreoptic communication systems.

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mode interval (Figs 1c, d). To realise WDM in practice, the frequency interval between the channels should be no less than 10 GHz. Modern mode-locked cw diode and fibre lasers can generate ultrashort-pulse trains with the repetition rate up to 30 GHz [6]. Thus, such ultrashort pulses can be used in WDM communication systems.

Although femtosecond Ti : sapphire lasers are widely used to generate optical frequency combs, they have a number of disadvantages. The main disadvantage is the necessity to use a rather costly pump laser. Therefore, it is desirable to develop femtosecond lasers of other types. Fibre lasers are especially attractive because of their small size and a relatively low cost. In addition, they emit in the other spectral region. Mode-locked fibre lasers were studied in Refs [7, 8].

In this paper, we study a laser we built using an Er^{3+}-doped single-mode fibre pumped by Raman-converted radiation from a diode-pumped ytterbium-doped fibre laser. The laser emits a continuous train of 1550-nm, < 100-fs pulses with an average power of 10 mW upon pumping at 1480 nm.

2. Features of the mode-locking regime

Ultrashort pulses are generated in modern lasers due to self-mode locking. This regime of multimode lasing is achieved because of the amplitude self-modulation of radiation circulating in the resonator. A cw femtosecond laser contains three basic elements placed in its resonator (Fig. 2).

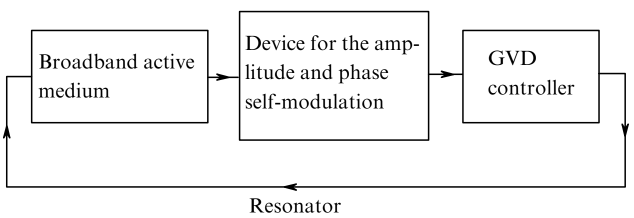

Figure 2. Scheme of a cw femtosecond laser.

The first element is an active medium having a sufficiently broad gain band pumped by stable radiation.

The second element is a device providing the amplitude self-modulation of radiation circulating in the resonator. Self-modulation means that modulation occurs automatically at the round-trip transit frequency for radiation circulating in the resonator, i.e., at the frequency of the axial mode interval. Such self-modulation in modern lasers is based on the dependence of the refractive index on the radiation intensity. If the Kerr nonlinearity (the third-order susceptibility $\chi^{(3)}$ related to bound electrons) is used, a high-frequency self-modulation required for the generation of pulses of duration as short as a few femtoseconds can be achieved. Note that the dependence of the refractive index on the radiation intensity leads to the self-phase modulation (SPM), i.e., to a change in the radiation phase and, hence, in the radiation frequency. Therefore, this effect can provide the generation of new frequencies, which is very important because amplification is accompanied by the regenerative narrowing of the emission spectrum, whereas, to generate ultrashort pulses, this narrowing should be not only compensated but the spectrum should be even broadened.

The third element is a group-velocity dispersion (GVD) controller. Any material, including an active element, has dispersion. Therefore, pulses circulating in the resonator are subjected to dispersion, resulting, in particular, in an increase in the pulse duration (pulse spread), which is called a chirp. To compensate for this chirp, it is necessary to introduce an element with the opposite-sign dispersion into the resonator. In addition, due to the broadening of the spectrum caused by the SPM, the pulse duration can be reduced by selecting the appropriate GVD. This principle is used for the efficient amplification of chirped pulses.

Unlike femtosecond vibronic crystal lasers, in which optical elements are located at certain places in the resonator, which are separated by air gaps, these elements in fibre lasers are distributed over the length of fibres forming the resonator. The mechanisms of the amplitude self-modulation required for mode locking in lasers of these two types are also different. This mechanism in solid-state lasers is based on self-focusing (Kerr lens), while the amplitude self-modulation in fibre lasers is caused by nonlinear birefringence. Figure 3 demonstrates the principle of amplitude self-modulation [9] based on nonlinear optical rotation. Any fibre always has a certain birefringence, resulting in the elliptic polarisation of radiation. A nonlinear relation between the transverse components E_x and E_y of the electric field leads, due to the phase cross-modulation (PCM), to the rotation of the polarisation ellipse, which depends on the radiation intensity. In combination with a polariser, this rotation provides the dependence of transmission on the radiation intensity.

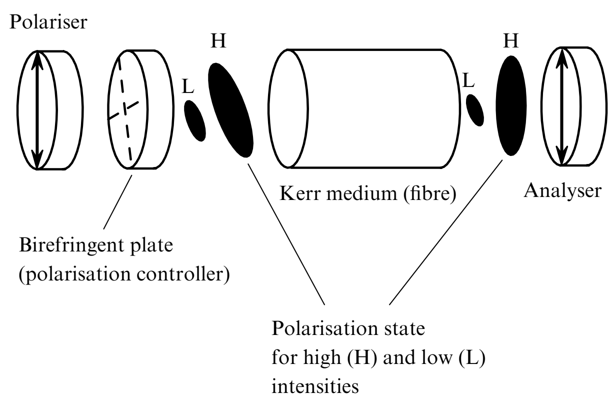

Figure 3. Principle of obtaining the amplitude self-modulation in an optical fibre [9].

3. Two operating regimes of the ultrashort-pulse fibre laser

Consider a general scheme of the laser shown in Fig. 4. The active medium, representing an Er^{3+}-doped single-mode fibre of length 4.94 m, has the GVD coefficient $\beta_2 = +0.0195$ ps^2 m^{-1}. The diameter of the mode field and the absorption coefficient at 1.55 μm are equal to 3.1 μm and 15 dB m^{-1}, respectively. The laser was pumped at 1480 nm by a Raman converter [10] of radiation from a cw ytterbium-doped fibre laser, which was pumped through its cladding by laser diodes at 980 nm. The 8-W output power from laser diodes provided 2 W of the pump power at 1480 nm, which was coupled into the active fibre through a 1480/1550 WDM multiplexer.

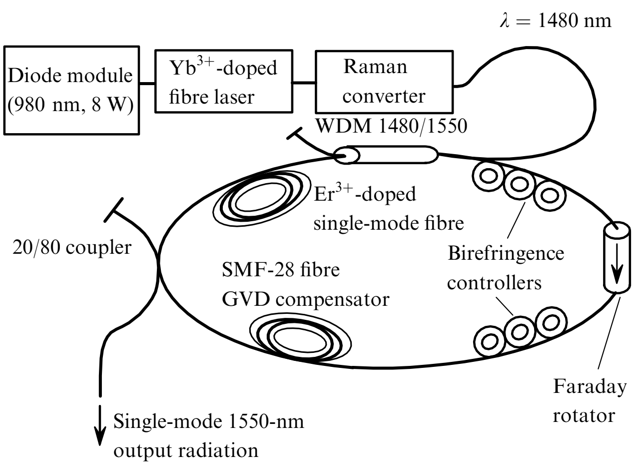

Figure 4. Scheme of a self-mode-locked fibre laser.

A Faraday rotator was used as a polariser, which also provided the unidirectional propagation of a beam in the ring laser cavity.

To obtain the total GVD required for the generation of ultrashort pulses, we added into the resonator a single-mode SMF-28 fibre of length 3 – 6 m with the fibre core diameter of ~ 10 μm, which had a negative GVD ($\beta_2 = -0.022$ ps^2 m^{-1} at a wavelength of 1550 nm).

The required degree of birefringence was obtained using polarisation controllers consisting of several coils of an SMF-28 fibre, whose number and the radius of curvature determine the degree of birefringence produced. These several coils are equivalent in fact to a birefringent plate. To achieve self-mode locking, two $\lambda/4$ plates should be placed in front of the polariser and the $\lambda/2$ and $\lambda/4$ plates behind it. The 1550-nm radiation is coupled out of the ring by means of a 20/80 coupler.

In such schemes, two self-mode-locking regimes can exist [11]. In the first regime, an optical soliton is formed. It appears when the negative GVD in the fibre is compensated by the SPM. The energy of a fundamental soliton propagating in the fibre is

$$E_{\text{sol}} = \frac{|\beta_2|}{\gamma\tau}, \quad (1)$$

where β_2 is the GVD coefficient; γ is the SPM coefficient depending on the nonlinear refractive index n_2; and τ is the duration of a pulse with the sech^2 shape. The soliton regime in the fibre-laser resonator was observed in Refs [12 – 14].

The main disadvantage of this regime is that, when an attempt is made to generate high-energy ultrashort pulses, several pulses are generated instead of a single pulse over a period. This is explained by the fact that, for specified parameters of the resonator, a soliton has a certain shape (amplitude and duration), while its energy is quantised. The pulse energy does not increase with pump power, but new uncontrollable pulses of a lower intensity appear over the pulse repetition period, thereby destroying the single-pulse regime.

There also exists another disadvantage. Figure 5 shows the typical laser emission spectrum in the soliton regime. The peaks in the spectrum are explained as follows. A soliton propagating in the resonator is subject to periodic variation due to amplification, filtration, and losses at splicings and the output coupler. When the pulse again acquires the soliton shape, it loses a part of radiation. The part of radiation lost by the soliton forms an extended pedestal of the pulse and represents a narrow spectral peak. These narrow peaks are distributed over the entire emission spectrum of the laser, their distribution being dependent on the resonator length, pulse duration, and fibre dispersion. As the resonator length increases or the pulse duration decreases, the peaks shift toward the central wavelength, resulting in a resonance instability, which is explained by the coherent interaction of the soliton with radiation concentrated in the pedestal.

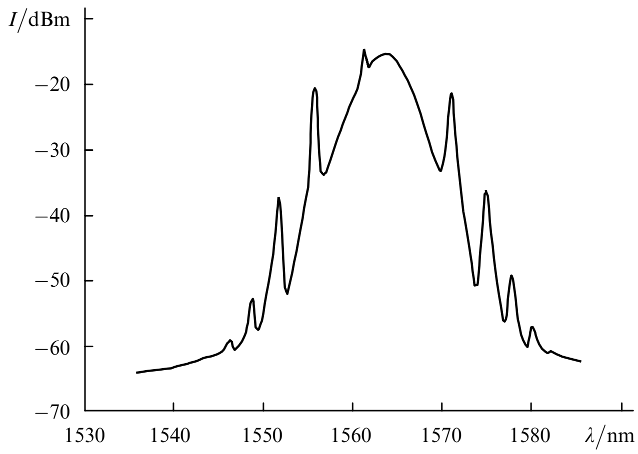

Figure 5. Laser emission spectrum in the soliton regime.

To obtain a single pulse with a higher energy and shorter duration, it is desirable to avoid such effects. For this purpose, another regime can be used, which is based on the employment of a large GVD, resulting in a strong chirping of the pulse propagating in the resonator fibre. The pulse propagation in the resonator is shown in Fig. 6. First a pulse is generated, which is strongly stretched due to a chirp, and then the pulse is compressed in the fibre with the negative GVD. This procedure is successfully used to amplify chirped ultrashort pulses (stretch – amplification of chirped pulses – compression). The pulse energy can be substantially increased this way, because the intensity of the stretched pulse remains below the level required for the soliton regime. In addition, to obtain this regime, an active fibre with a small core diameter is used, which allows the nonlinear rotation of the polarisation ellipse to be concentrated in the active fibre with the positive dispersion, reducing simultaneously nonlinear effects in the fibre with the negative dispersion. This also favours the suppression of the soliton regime. Also, no less important is that a high nonlinearity in combination with a positive dispersion allows a substantial broadening of the emission spectrum. All this provides an increase in the pulse energy and ensures its short duration due to the pulse compression in a fibre with the appropriate GVD. As a result, the peak power of a generated single pulse is approximately an order of magnitude higher than that in the soliton regime.

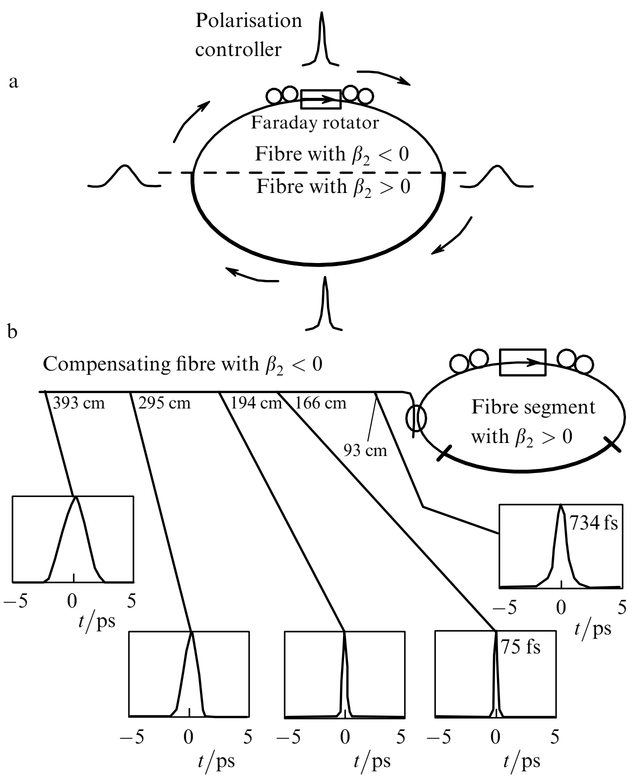

Figure 6. Scheme of a femtosecond fibre laser operating in the stretched-pulse regime (a) and regime of chirp compensation at the laser output with the help of a fibre piece with the negative GVD (b). The ACF profiles are shown for fibres of different lengths [11].

4. Study of the laser

The study of the laser involved the selection of the parameters of parts of the fibre resonator and pump parameters, as well as the detection of the oscillograms of radiation intensity, the emission spectrum, and the profile of the intensity autocorrelation function (ACF). The oscillograms were detected using a pin-photodiode with the fibre input and the 0.5-ns rise (decay) time, as well as an oscilloscope with the appropriate time resolution. Figure 7 shows a typical oscillogram of a repetitive train of ultrashort pulses. The emission spectrum was detected with a Hewlett-Packard spectrum analyser. The ACF was measured by the standard method of noncollinear phase matching of second-harmonic radiation in a nonlinear crystal.

To obtain pulsed lasing, it was necessary to select a proper total dispersion of the resonator $\beta_2 L = \sum \beta_{2i} l_i$. For this purpose, we calculated the dispersions of individual fibres ($\beta_{2i} l_i$) in the resonator by selecting the fibre lengths l_i so that the total dispersion was negative. By selecting the total dispersion in the resonator, we measured the dependence of the width of the emission spectrum on the dispersion in the range of $\beta_2 L$ from -0.08 to -0.01 ps^2 (Fig. 8). This allowed us to find the change in the width of the spectrum near the zero-dispersion point ($\beta_2 = 0$). The dependence $\Delta\lambda(\beta_2 L)$ was measured using the 10/90 output coupler. As we approached the zero-dispersion point, single-pulse lasing became unstable due to the increasing peak intensity. The unstable regime was characterised by multipulse lasing and the appearance of the pedestal of the ACF. To find the presence of multipulse lasing, we used, along with the

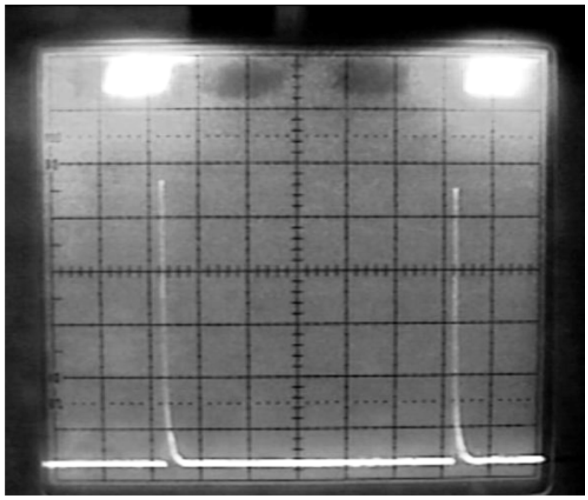

Figure 7. Typical oscillogram of a train of femtosecond pulses (pulse repetition rate is 25 MHz).

oscillogram recording, a broad scan range of the autocorrelator, which overlapped the time resolution of the photodetector. To avoid instability, we reduced the intracavity power by using the 20/80 output coupler and changed the total dispersion of the resonator to $+0.007$ ps^2. This resulted in the stable generation of 110-fs pulses.

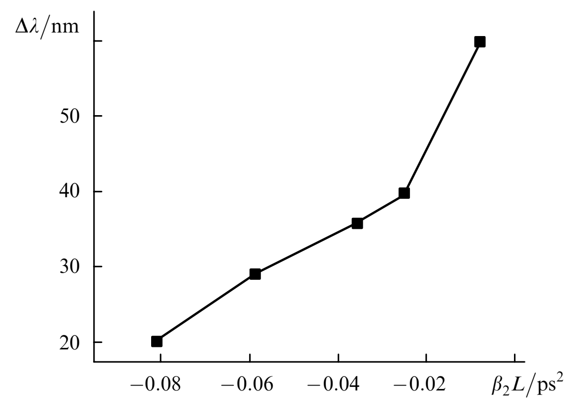

Figure 8. Dependence of the width of the laser emission spectrum on the total GVD.

The pulse duration can be reduced by compressing a chirped pulse in the fibre with the appropriate dispersion at the laser output. The experimental dependence of the pulse duration on the length of this fibre (Fig. 9) gives the fibre length at which the pulse has the maximum compression. The minimum pulse duration was 97 fs for the spectral width of the pulse equal to 53 nm. The spectrum and ACF of the pulse obtained are shown in Fig. 10. For the pump power equal to 270 mW at 1480 nm, the average output power was 10 mW at a pulse repetition rate of 25 MHz. The diode power used for pumping the ytterbium-doped fibre laser was 2.7 W.

5. Conclusions

We have built a 1550-nm femtosecond Er^{3+}-doped fibre laser. The laser is pumped by radiation at 1480 nm obtained with the help of a Raman converter of radiation

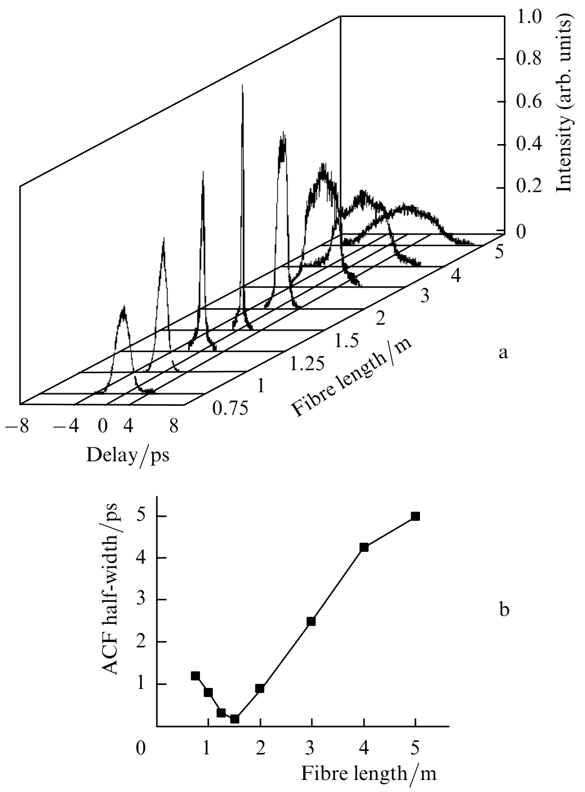

Figure 9. ACF profiles for different lengths of a compensating-fibre length (a) and the dependence of the ACF half-width on the compensating-fibre length (b).

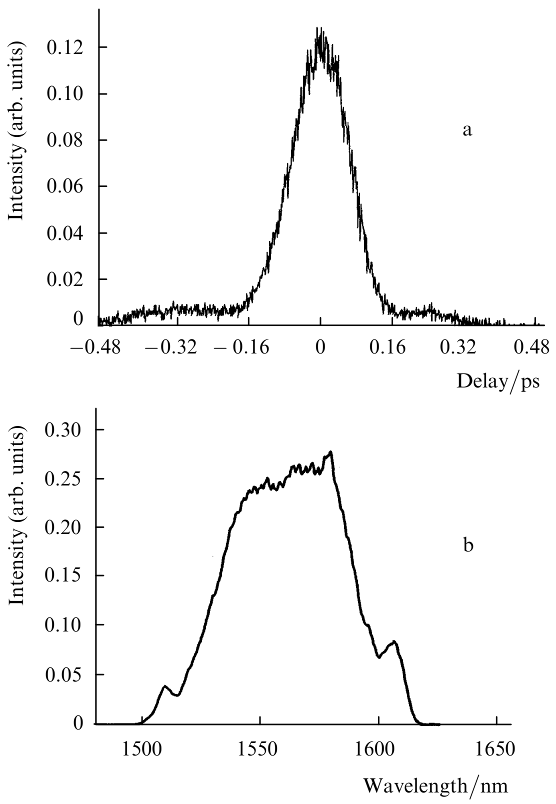

Figure 10. ACF profile (a) and the spectrum of the pulse of minimum duration (b).

from a diode-pumped ytterbium-doped fibre laser. We have shown that femtosecond pulses can be generated in the soliton or stretched-pulse regimes. The minimum pulse duration in the second regime was 97 fs for the spectral width of the pulse equal to 53 nm. The average power of a repetitive train of femtosecond pulses with a repetition rate of 25 MHz was 10 mW for the 270-mW pump power. Cw lasing means in our case that $\sim 10^6$ narrow emission lines are emitted.

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