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Efficient source of femtosecond pulses and its use for broadband supercontinuum generation

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Abstract. **A femtosecond Er^{3+}-doped fibre laser system is developed and studied. The system contains a master oscillator operating in the pulse stretching regime, an amplifier of chirped pulses, and a device for pulse compression. The laser emits 1.55-μm, 100-fs, 90-mW pulses with a pulse repetition rate of 25 MHz. The setup was used for supercontinuum generation in an optical fibre heavily doped with GeO_2. The width of the generated supercontinuum was close to an octave.**

Keywords: *femtosecond pulses, supercontinuum, optical chirp.*

1. Introduction

Modern femtosecond lasers operate in the cw mode, which alleviates the fine adjustment of their parameters determining the properties of output radiation. Especially important is the possibility to control the group velocity dispersion (GVD), which allows the generation of few-cycle radiation pulses. The cw lasing mode makes it possible to obtain a comb of extremely narrow equidistant spectral lines whose frequencies are coherently coupled with each other. The interval between the lines in the comb is equal to the repetition rate of ultrashort pulses, which is determined by the optical length of the laser resonator and can be continuously varied. This rate is a few fractions of gigahertz, i.e., lies in the region of well developed radiofrequency measurements and can be locked to the microwave cesium frequency standard.

2. Formulation of the problem

The use of cw femtosecond lasers produced a real revolution in the precision metrology of optical frequencies [1 – 4]. The extension of the frequency comb spectrum is inversely proportional to the ultrashort pulse duration and can achieve for a femtosecond pulse a few hundreds of terahertz, i.e., the comb spectrum can cover a significant part of the optical spectrum. Therefore, this comb represents an extended optical frequency ruler with divisions locked to the cesium frequency standard.

Such frequency locking can be performed only if the comb is not displaced in the frequency scale as a whole. At the same time, it is known that although the frequency interval and the total width of the comb can be controlled by measuring the pulse repetition rate and the width of the comb spectrum, the control of the comb position on the frequency scale is not a simple problem. The matter is that, although the comb frequencies are equidistant, they are not multiples of each other. One can see from Fig. 1 that neither of the comb frequencies coincides with the zero on the frequency scale, but all the frequencies are offset from it by some frequency f_{CEO} (carrier-envelope offset), which is equal to a fraction of the frequency interval of the comb [3].

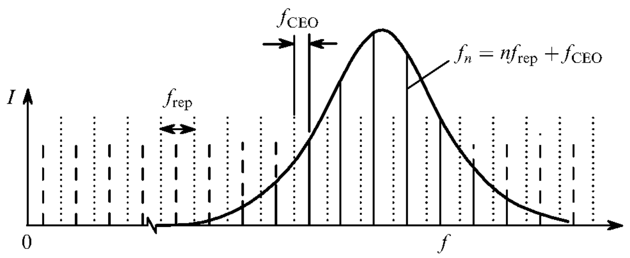

Figure 1. Scheme of the frequencies of a cw femtosecond laser (solid straight lines), the same frequencies attached to the coordinate origin (dashed straight line), and equidistant frequencies with the same period (dotted straight lines); f_{rep} is the intermode interval, f_{CEO} is the carrier frequency-envelope maximum offset, and f_n is the frequency of the nth mode.

This frequency offset is caused by the operation mechanism of a cw femtosecond laser. The resonator of such a laser contains three components required for its operation: a broadband active medium, a device for the self-amplitude modulation, and a device for the GVD control. When the condition for generation of ultrashort pulses is fulfilled, the laser generates a continuous train of light pulses. The electric field of the electromagnetic wave of each of the pulses has the form

$$E(t) = A(t)\sin\omega_0 t + \varphi_{CEO}, \quad (1)$$

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where $A(t)$ is the pulse shape envelope; ω_0 is the carrier frequency of the centre of the laser emission spectrum; and $\varphi_{\rm CEO}$ is the phase offset between the envelope maximum and the nearest maximum of the carrier frequency (Fig. 2). The pulse described by expression (1) circulates in the resonator. In this case, the envelope moves at the group velocity, while the carrier frequency moves at the phase velocity. Because of dispersion in the resonator, these velocities are different, which results in the appearance of the phase offset $\varphi_{\rm CEO}$. The spectral analysis of radiation shows that the comb frequency offset $f_{\rm CEO}$ is determined by the phase offset $\varphi_{\rm CEO}$, which depends on dispersion in the resonator.

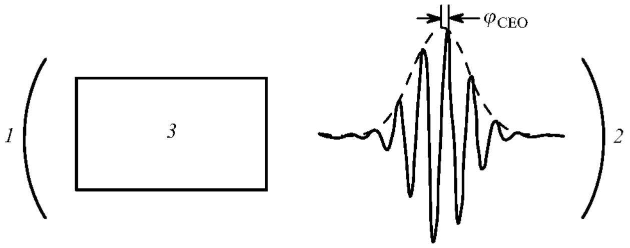

Figure 2. Shape of the pulse circulating in the resonator: (*1, 2*) resonator mirrors; (*3*) intracavity elements: an active medium, a self-amplitude modulation device, and a GVD controller.

Thus, the nth frequency f_n of the comb is completely determined by the ultrashort pulse repetition rate $f_{\rm rep}$ and the comb frequency offset $f_{\rm CEO}$:

$$f_n = nf_{\rm rep} + f_{\rm CEO}. \tag{2}$$

Such a 'frequency ruler' can be used to determine the optical frequencies lying within the comb spectrum by measuring beats – the difference between the frequency being determined and the nearest comb frequency. The frequency $f_{\rm rep}$ can be easily measured and controlled because it is determined by the optical length of the resonator. It is much more difficult to measure and control $f_{\rm CEO}$. Of course, since $f_{\rm CEO}$ depends on dispersion in the resonator, it can be controlled by changing the dispersion. But to control $f_{\rm CEO}$, it is necessary to measure the value of $f_{\rm CEO}$ itself. For this purpose, the so-called 'f to $2f$' interferometer was proposed, which allows the measurement of the required frequency by comparing the doubled frequency of the red edge of the comb with the frequency of the blue edge [3]. However, in this case the width of the comb spectrum should exceed an octave, i.e., the doubled frequency of the red edge should be lower than the frequency of the blue edge.

Femtosecond lasers cannot usually provide the required width of the comb spectrum even in the case of shortest pulses. To increase the width of the comb spectrum, the supercontinuum generation in optical fibres is employed. It is important to note that supercontinuum pulses should have the same repetition rate as comb pulses. In this case, the supercontinuum spectrum will be also a comb of spectral lines separated by the same interval. This means that the required width of the supercontinuum spectrum (above an octave) should be produced by a continuous train of pulses with a comparatively low energy and peak power. They cannot be amplified by usual methods (for example, by amplifying chirped pulses) because this reduces the pulse repetition rate.

For this reason, special optical fibres are used for supercontinuum generation. In this case, the efficient generation is achieved due to two factors: first, due to a small cross section of the radiation mode propagating in the fibre core, which provides the high radiation intensity; and, second, because, when the fibre has properly selected parameters, a pulse can propagate in the fibre over large distances (tens of centimetres) without significant attenuation, thereby providing a substantial increase in the nonlinear interaction length. The required dispersion parameters are obtained in microstructure optical fibres (of the photonic crystal type) [5–7] and single-mode fibres heavily doped with GeO_2.

The results demonstrating outstanding achievements in the precision metrology of optical frequencies [1–4] were first obtained by using Kerr lens passively mode-locked femtosecond Ti:sapphire lasers. Due to the high output power and extremely short pulses, these lasers made possible supercontinuum generation in microstructure fibres with a small-diameter core and the GVD zero shifted to the maximum of the femtosecond laser wavelength [7]. In this case, the supercontinuum width exceeded an octave, which provided the possibility to measure and control the value of $f_{\rm CEO}$. The high requirements to a pump laser necessitate the use of expensive lasers such a Millenia, Spectra-Physics or Verdi, Coherent. However, it is still difficult to provide a continuous operation of a femtosecond laser for several weeks or even days, which is one of the main requirements to modern metrological devices such as an optical clock.

In this connection the possibility of using femtosecond erbium-doped fibre lasers instead of Ti:sapphire lasers is being extensively studied in the last years [8–11]. Although these lasers still have a significantly more intense high-frequency noise and a lower output power than Ti:sapphire lasers, they may become more preferable due to a number of advantages. First, they can continuously generate femtosecond pulses for several weeks, which makes them attractive for applications in routine permanent metrology devices and a continuously operating optical clock. Second, erbium-doped fibre lasers are comparatively low-cost, compact, and efficient. In addition, they emit at a wavelength of 1.55 μm, which lies in the telecommunication spectral range, so that the accurate time signals can be transmitted through fibreoptic communication links.

In this paper, we studied a femtosecond erbium-doped laser and a supercontinuum generator based on this laser. We used in our setup the optical fibres developed at the Fiber Optics Research Center, A.M. Prokhorov General Physics Institute, RAS and the Institute of Chemistry of High-Purity Substances, RAS. We believe that the developed generator of femtosecond pulses can compete with its foreign analogues.

3. Master oscillator – amplifier system

3.1 Master oscillator

Figure 3 shows the scheme of the experimental setup consisting of a master oscillator and an amplifier. We used a laser that was similar to that described in [12] and consisted of an Er^{3+}-doped active fibre with the positive GVD ($\beta_2 = +0.0195$ ps^2 m^{-1}) and an SMF-28 fibre with the negative GVD ($\beta_2 = -0.022$ ps^2 m^{-1}). The total length of the resonator was 8 m, corresponding to a pulse

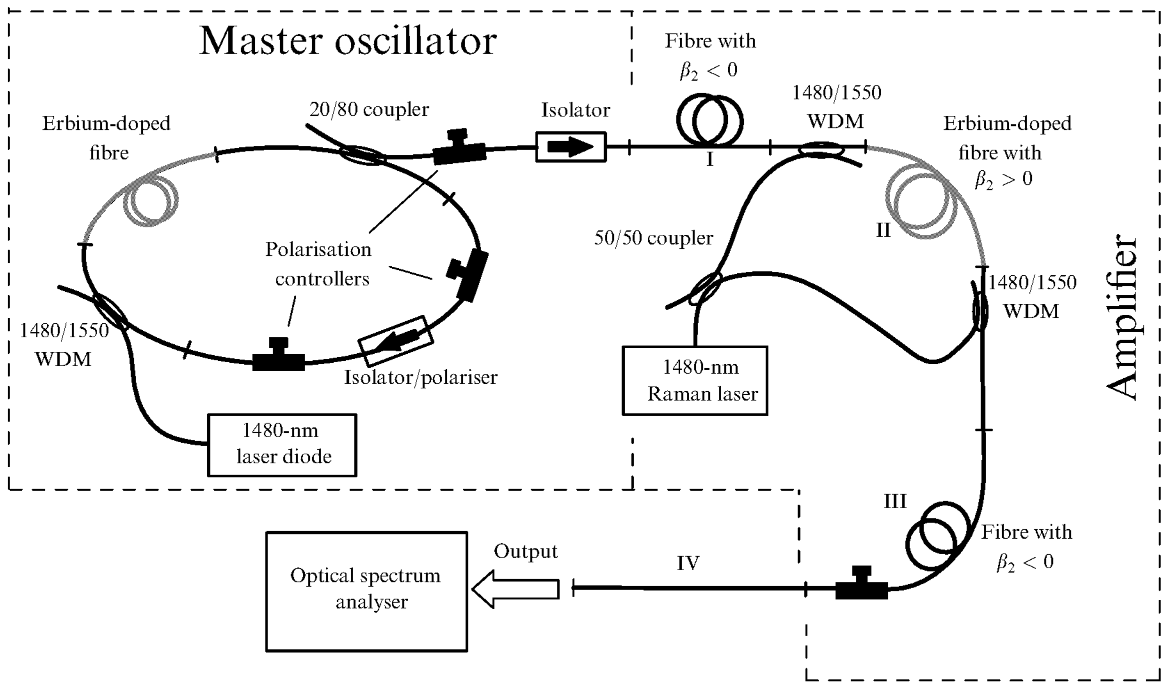

Figure 3. Scheme of the master oscillator – amplifier setup.

repetition rate of 25 MHz. The laser was pumped by a 360-mW laser diode at 1480 nm. The pump radiation was coupled into the active fibre by using a spectrally selective (1480/1550 WDM) fibre coupler in the direction of propagation of optical pulses in the resonator. One-directional lasing was provided with a polarisation-sensitive Faraday isolator, which together with two polarisation controllers ensured generation of ultrashort pulses in the self-mode-locking regime due to nonlinear birefringence in optical fibres.

Pulsed lasing self-started when the pump power achieved 150 mW. As the pump power was increased up to 223 mW, pulsed lasing was observed with an averaged power of 24 mW. Because the laser operated in the 'stretched pulse' regime (a pulse was stretched and compressed during each round trip in the resonator), the output pulse should be compressed to obtain the transform-limited pulse (to compensate the chirp). The pulse chirp in the output fibre piece is mainly determined by the GVD. This allows one to select easily the length of the output fibre piece. We compensated the pulse chirp by using an SMF-28 fibre of length 85 cm. The autocorrelation function corresponding to the maximally compressed pulse is shown in Fig. 4. The half-width of the autocorrelation function was 113 fs, which, assuming a Gaussian shape of the pulse envelope, corresponds to the pulse duration of 80 fs. The autocorrelation intensity function was obtained using an autocorrelator based on a silicon photodiode operating in the two-photon absorption regime. The spectrum of the compressed pulse is shown in Fig. 5.

To prevent the entry of stray light reflected from amplifier elements into the laser, which inevitably quench pulsed lasing, a fibre Faraday isolator was mounted at the laser output.

3.2 Amplifier

The amplifier (Fig. 3) consists of an Er^{3+}-doped active fibre with the positive GVD and of two fibres with the negative GVD. The length and dispersion of these fibres were selected by the method similar to that used for laser

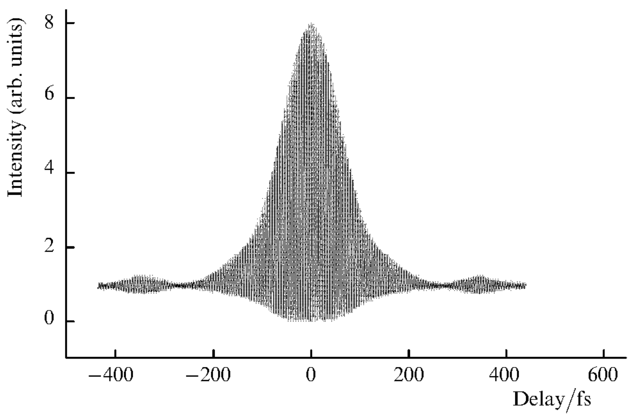

Figure 4. Autocorrelation function of the pulse intensity of the master oscillator.

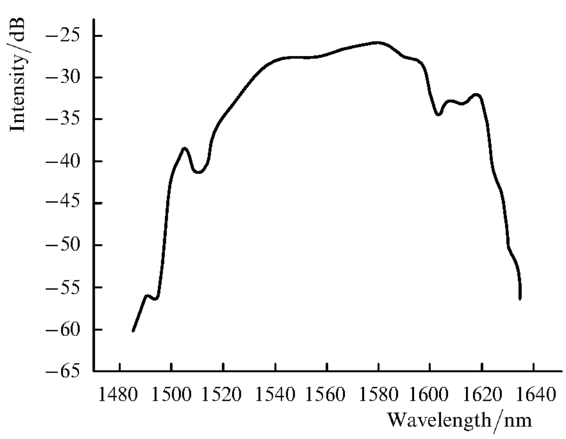

Figure 5. Emission spectrum of the master osciallator.

optimisation. The laser pulse propagating in the fibre amplifier was first stretched and then compressed. The fibre length was optimised to minimise the second-order GVD for obtaining the output pulse with the minimal linear chirp. The third-order GVD and nonlinear effects were neglected, and the amplifier length was minimised to avoid the irreversible increase in the pulse duration caused by these effects.

The length of input single-mode fibre I determined the preliminary stretching of the pulse before its entry to the amplifier. The pulse was amplified in Er^{3+}-doped fibre II, stretched under the action of the positive GVD, and the pulse spectrum broadened due to nonlinear effects. The pulse acquired a positive frequency modulation (positive chirp). In optical fibre III, the pulse was compressed under the action of the negative GVD.

The active fibre length (2.5 m) was selected to provide the absorption of $\sim$95 % of the pump power of the amplifier. The active fibre had the dispersion $\beta_2 = 0.035$ ps^2 m^{-1}, absorption at the laser wavelength of 1530 nm was 55 dB m^{-1}, and the mode field diameter at a wavelength of 1550 nm was 3.5 μm. The active fibre was pumped by a 0.4-W, 1480-nm Raman fibre laser [13]. The Raman laser radiation was divided by a 50/50 fibre coupler into two equal parts and was coupled into the active fibre from two sides by using two spectrally selective couplers.

The spectrum of the amplified pulse is shown in Fig. 6. The length of fibre I used for the preliminary stretching of the pulse was 2 m. For the pump power equal to 0.4 W, we obtained the average output power of 90 mW.

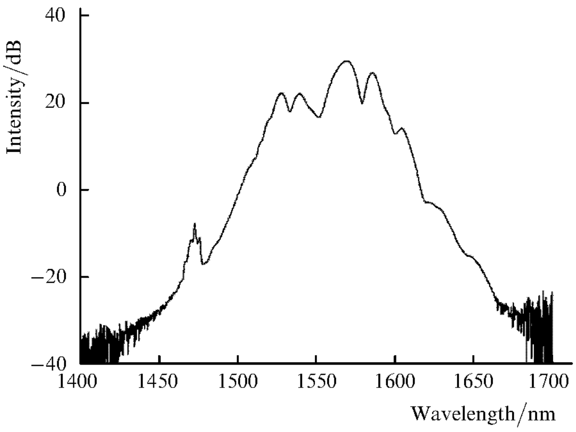

Figure 6. Output emission spectrum of the amplifier with the average output power of 73 mW.

The pulse was compressed at the amplifier output in a single-mode SMF-28 fibre with the GVD $\beta_2 = -0.022$ ps^2 m^{-1}.

4. Supercontinuum generation

The amplified radiation from the femtosecond fibre laser was coupled into fibre IV with a high nonlinearity and shifted dispersion. The emission spectrum at the output of this fibre was measured with an ANDO 6317B fibre spectrum analyser.

Optical fibre IV had the following parameters: the molar concentration of germanium oxide in the fibre core was $\sim$25 %, the mode field diameter was 4.3 μm, the cut-off

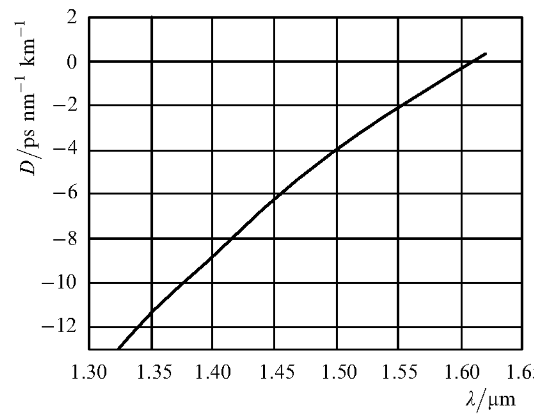

Figure 7. Dispersion of the highly nonlinear fibre with a shifted dispersion.

wavelength was 1480 nm, and the zero-dispersion wavelength was 1.65 μm. Figure 7 shows the dispersion of this fibre as a function of the lasing wavelength. Dispersion at a wavelength of 1.55 μm was −2.4 ps nm^{-1} km^{-1}.

Figure 8 shows emission spectra at the output of fibre IV for different input powers. Because the spectral range of the ANDO spectrum analyser is 600 – 1750 nm, one of the supercontinuum spectra was recorded in a broader spectral range by using a standard monochromator with a PbS photoresistance (Fig. 9).

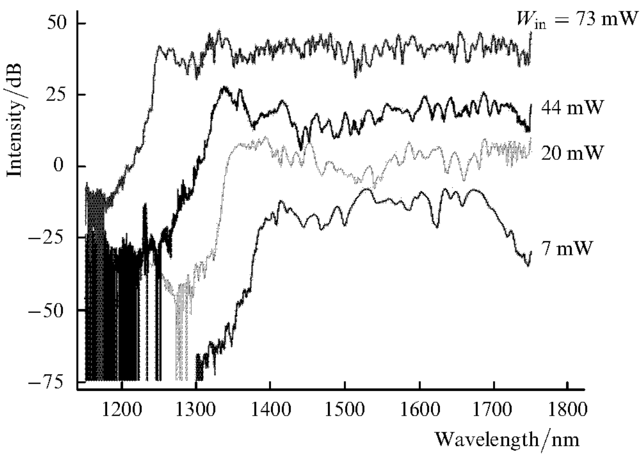

Figure 8. Dependence of the supercontinuum spectrum on the average radiation power W_{in} coupled into fibre IV with a high nonlinearity and shifted dispersion.

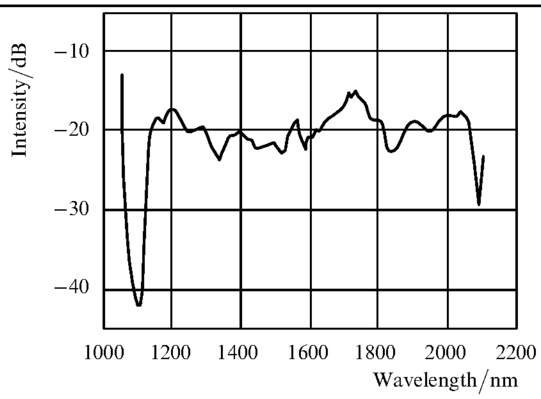

Figure 9. Long-wavelength part of the supercontinuum spectrum.

5. Conclusions

We have developed and studied the femtosecond Er^{3+}-doped fibre laser setup. The setup consists of the master oscillator operating in the stretched pulse regime and the amplifier. The maximum average output power of the amplifier achieves 90 mW at a wavelength of 1.55 μm, a pulse duration of 100 fs, and a pulse repetition rate of 25 MHz. The master oscillator was pumped by a 360-mW laser diode, while the amplifier was pumped by a 400-mW Raman fibre laser.

The setup has been used to generate a supercontinuum in a fibre with high nonlinearity and shifted dispersion. For the pump power at the fibre input equal to 70 mW, the maximum width of the supercontinuum achieved 980 nm, i.e., it was close to an octave.

The results of the study allow a further optimisation of the generator of a supercontinuum excited by a femtosecond fibre laser to obtain even broader spectrum.

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