WORKS IN THE NSC KIPT ON THE CREATION AND APPLICATION OF THE CPA LASER SYSTEM

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A CPA laser system with an output power of 10^{10} W is presented, which at the final stage will be brought to a power close to 10 TW. The areas of its application are described, the results of the supercontinuum investigation on photonic crystal fibers and other samples are presented. A technique and device for manufacturing biconical fibers for the purpose of obtaining a supercontinuum on them has been developed. Different schemes of accelerators, including those on chips and surface electromagnetic waves, have been proposed.

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Approximately, since 2000, high-power femtosecond laser systems that exceed the TW level have received the widest distribution in solving both research and applied problems. These laser systems have already been given a well-known name – CPA (ie the abbreviation "chirp pulse amplification") of laser systems in accordance with the CPA method, which underlies their creation.

There is no point in enumerating all fields of science, including the fundamental, and techniques in which laser-based systems are used [1]. It will be advisable to point out the unique features that determine this diversity. Let's note two principal aspects. First, these are primarily applications associated with the use of Fs pulses in the study of superfast processes, for which they are practically a delta function. It is also important to note the possibility of obtaining a relative frequency stability, up to 10^{-18}, which is closely related to this feature of the laser, for the generation of a supercontinuum of longitudinal oscillation types [2]. And second, the applications associated with the use of ultrahigh-intensity pulses, for example, in areas close to our NSC, such as particle acceleration for basic research, research in the field of thermonuclear fusion and plasma generation, generation of x-rays and attosecond pulses, etc.

In the NSC KIPT an intermediate laser stage with an output power of 10^{10} W in pulse was created at the intermediate stage of the work. It operates at a wavelength of 0.8 μm and generates 30 fs pulses.

In order to understand the merits and features of a laser installation – very briefly – the principle of its operation. Fig. 1 shows the functional scheme of the CPA laser system. As you can see, it consists of four main blocks. The Masteroscillator is a 30 fs Ti-Sa laser.

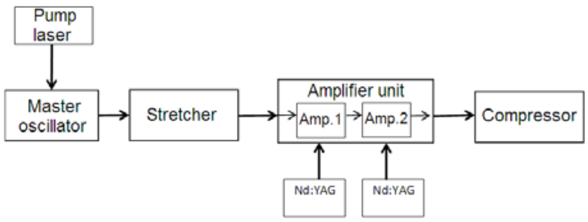

Fig. 1. Functional scheme of CPA laser system

Further, these 30 fs impulses are not simply amplified, as in the traditional schemes, but are expanded in the Stratcher. Then, the extended pulses are amplified in the two amplification amplifier amplifiers stages: in the weak optical amplifier (Amp. 1) and the power amplifier (Amp. 2). And in the Compressor, their compression occurs. So, the output pulse of 3 W from 10^5 W increased 10^7 times to 10^{12} W at the compressor output.

Fig. 2 shows a general view of the CPA laser installation and further in Fig. 3 its fragment – the master oscillator [3]. Here is a plant with dimensions of 300×130×40 cm.

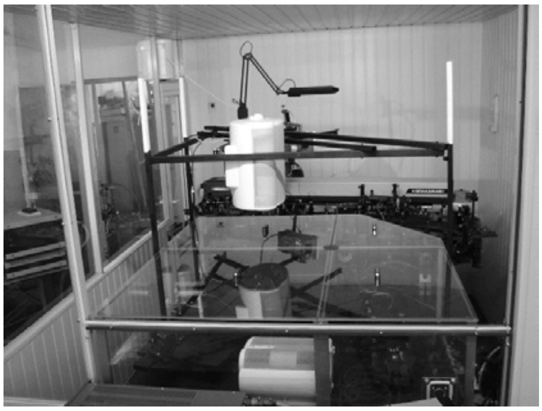

Fig. 2. A general view of the CPA laser installation

At the final stage, we are planning to create a compact version of a CPA laser system with dimensions of 140×60×60 cm and a pulse duration of less than 20 fs, and the pulse power will be brought to a level close to 10 TW.

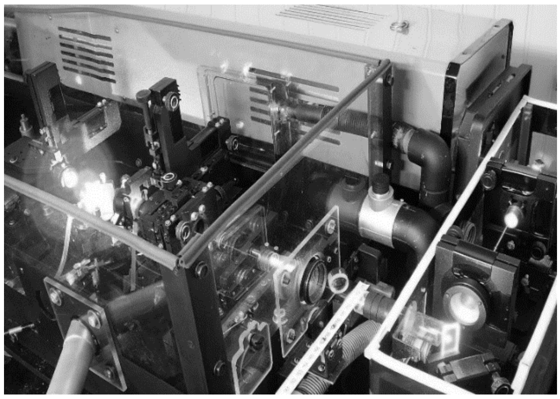

Fig. 3. The setting generator CPA laser installation

Next we will touch on the application of CPA laser systems within the NSC KIPT. These applications follow from the structure of the construction of the CPA system:

- applications related to the use of the CPA master generator of a laser system generating pulses of less than 20 fs;

- applications related to the use of anCPA laser system with an output power level of 10^{10} W to about 1 TW;

- applications related to the use of CPA laser system with a level of output power from several TW and above.

For practical implementation of the master oscillator, we carried out a sufficiently large volume of research aimed at improving the quality of its output characteristics, such as: pulse duration and emission spectrum, relative frequency stability. In the laser system originally designed by the CPA, the pulse duration was 30 fs. Fig. 4 shows the autocorrelation functions obtained by the correlator we have created, with the help of which, according to the formula $\tau_p = N\lambda / 1.55$ c, where N is the number of interference bands at the half level; λ is the wavelength of the radiation; 1.55 – coefficient for the shape of the pulse sech2; c – is the speed of light, durations of 30 fs and 17 fs of pulses were determined. Fig. 5 shows their spectra measured by the SP-1 spectrometer from Thorlabs.

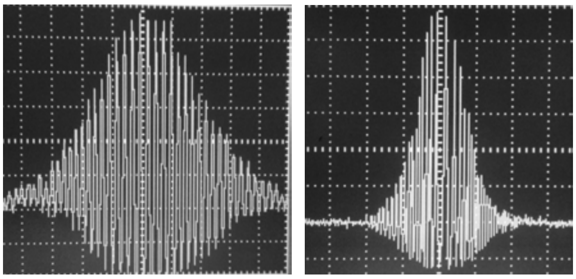

Fig. 4. Correlation functions of 30 fs Ti-Sa laser (left) and 17 fs Ti-Sa laser (right)

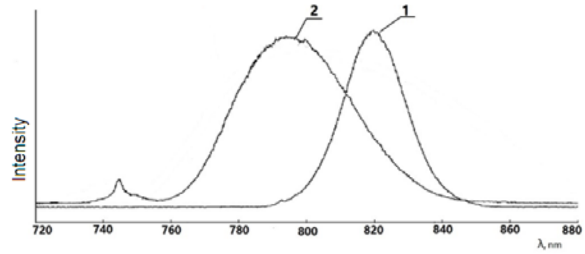

Fig. 5. 1 – emission spectrum of 30 fs Ti-Sa laser, spectral width 22.6 nm; 2 – radiation spectrum of 17 fs Ti-Sa laser, spectral width 58.4 nm

Calculations show that in this case for the shape of the pulse sech2 the width of the emission spectrum should correspond to a value of approximately 45 nm. Consequently, the spectrum shown in Fig. 5, having a width of 58.4 nm, indicates that the pulse at the output of the Ti-Sa laser undergoes dispersion expansion when a glass substrate of the output mirror of the M1 laser passes through a 6 mm (see Fig. 1). In accordance with formula (1) for the theoretical limit, the pulse duration τ and sech2 type should be equal to about 12 fs:

$$\tau_p = 0.315\ \lambda 2/c\ \Delta\lambda,$$

where λ is the wavelength of the laser radiation, Δλ is the width of the laser emission spectrum, and c is the speed of light.

Pulses with a duration of 12 fs of the output of the master oscillator can be obtained with a prism external compressor.

In the conditions of our laboratory, taking measures on passive frequency stabilization made it possible to obtain a relative stability of 100 Hz/80 THz = 1.25×10^{-12} Hz. Which is an order of magnitude greater than the stability that metrologists sought at the dawn of laser technology.

To expand the scope of the master oscillator, a number of experiments were carried out using nonlinear fibers. This made it possible to obtain ultra-wide output spectra. The experiments were carried out on two types of photonic crystal fibers (PCF): Thorlabs for λ = 1060 nm, fiber length 60 cm and Newport for λ = 800 nm, fiber length 20 cm.

In Fig. 7 shows the results of measurements of the emission spectra at the output of photonic crystal fibers for λ = 1060 nm, 60 cm and for λ = 800 nm, 20 cm, depending on the wavelength and power of the laser pump radiation.

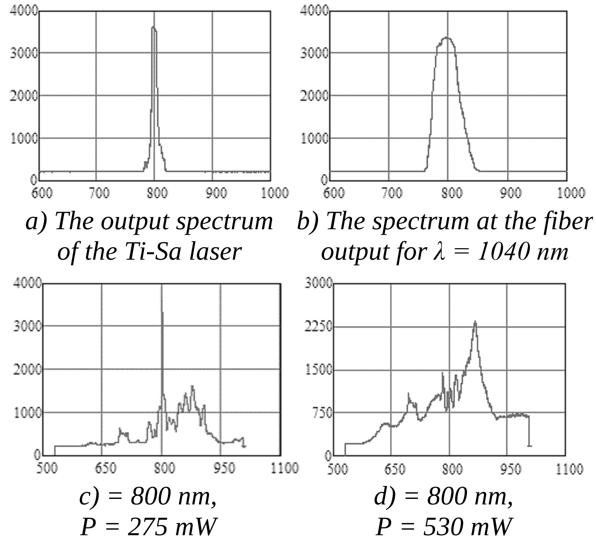

Fig. 6. Measured emission spectra at the output of photonic crystal fibers

From Fig. 6, the spectrum at the output of the fiber is shown to be up to 500 nm, which indicates the promise of using PCF for expanding the emission spectrum of the master oscillator.

However, obtaining the same wide spectra is possible with the help of biconical fibers [4], which have the advantage over PCF, namely – small dimensions of the equipment, easy manufacturing, no critical focus, no rigid requirements for the adjusted devices.

The attractiveness of this method predetermined its practical application in the conditions of the NSC KIPT.

The diameter of the waist for a biconical fiber for a wavelength of 800 nm should not exceed 2.5 μm. Biconical fibers are obtained by drawing from a conventional single-mode optical fiber SMF-28.

Fig. 7 schematically shows the image of a biconical fiber.

The fiber structure includes a constriction about 2.5 μm in diameter, connected by conical junctions with 120 μm fiber parts.

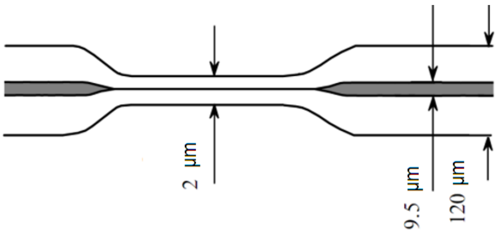

Fig. 7. Schematic representation of a biconical fiber

Thus, using this technique, based on the published data [4], it is possible to obtain a broadening of the spectrum to a width equal to two optical octaves (Fig. 8).

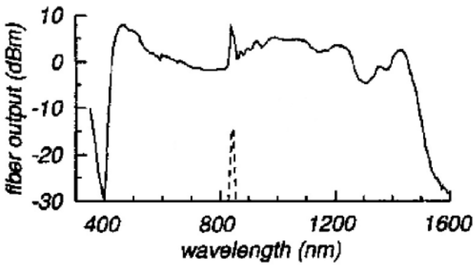

Fig. 8. The radiation spectrum at the output of a biconical fiber

The device for drawing biconical fibers provides the production of fibers with a total length of up to 20 cm. Fig. 9 shows a general view of the device for drawing biconical fibers created at the NSC KIPT.

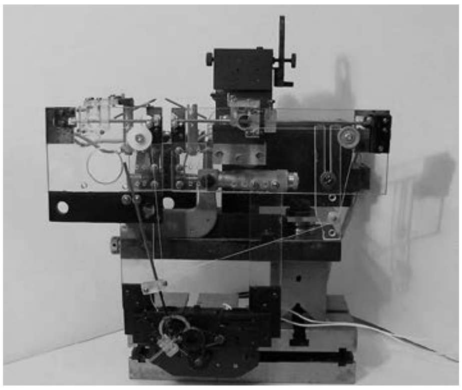

Fig. 9. General view of the device for drawing biconical fibers

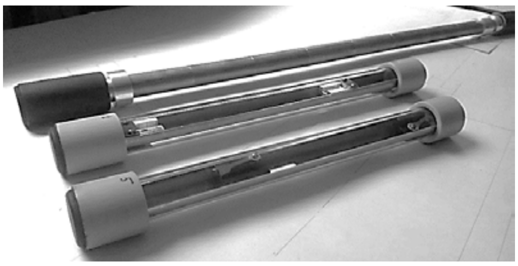

Fig. 10. A photo of a protective casing of a biconical fiber

To protect the fiber from dust, mechanical damage and other undesirable effects affecting them, a protective casing design was developed and manufactured, the photo of which is presented in Fig. 10.

It was of interest to find out the possibility of obtaining supercontinuum on other, more compact samples. As samples, quartz and window glass plates having the same thickness of 2 mm were tested and the breakdown in air was investigated. Fig. 11 shows the spectra of supercontinuums for various samples.

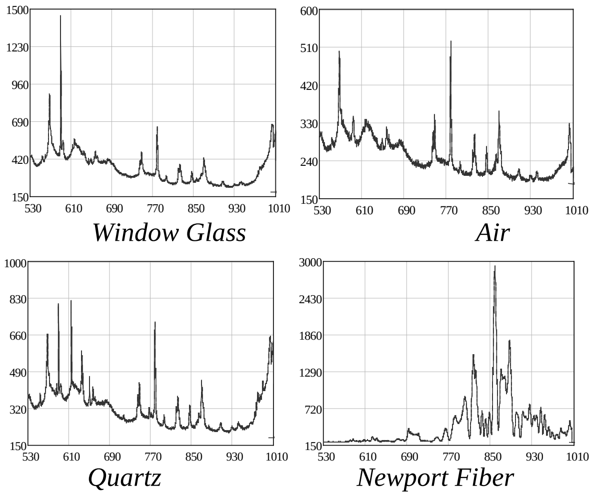

Fig. 11. Spectra of supercontinuums for various samples

The acquisition of such ultra-wideband spectra finds its application in metrology, space navigation, relativistic gravimetry [5].The next direction of applications is related to the CPA-installation, which provides an output power level from 10^{10} W to 1 TW. The level of input power of 10^{10} W, received to date at NSC KIPT, we plan to use to accelerate electrons using the latest technology associated with the use of chips [6]. Quartz chips have extremely small dimensions on the order of 25×150 μm with grooves applied on the surface, approximately 1400 per mm. Dimensions of accelerators based on them significantly decrease and can have dimensions from mm and more, depending on the required acceleration rates. Acceleration experiments on chips, described in the literature [6], indicate the possibility of obtaining an acceleration rate of 850 MeV/m. To this end, afs Ti-Sa laser with a pulse energy of 150 μJ, i.e., with the energy achievable at a laser facility created by the NSC KIPT, was used.

Fig. 12 shows the proposed scheme of a desktop accelerator based on the use of an accelerating structure on two chips. It will use the system created in the NSC KIPT CPA, which even with one amplifier gives an output energy of up to 1000 μJ. To generate electrons, a new method based on a tungsten nanotape [6] will be used, which will ensure compact longitudinal (several mm) and transverse (tens of nm) beam dimensions.

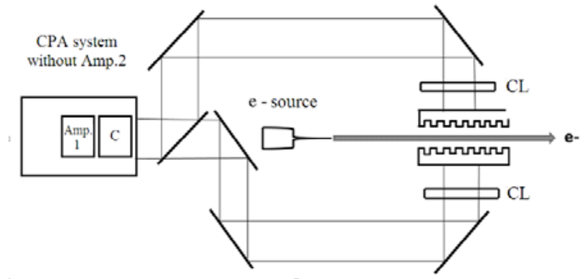

Fig. 12. Accelerator circuit on chips

The third direction of applications is associated with the application of the laser-based CPA system, providing an output power level of up to 10 TW and above.

When receiving a system of pulses with a power of 1 TW and higher at the output of the CPA, this system can be used to implement the method proposed and developed in the late 80 s of the last century in the KIPT by N.A. Khizhnyak and S.V. Zhilkov [7]. The essence of the method is the acceleration of charged particles by surface electromagnetic waves excited above the dielectric surface by a powerful laser beam, which is guided from the inside of the dielectric to the boundary of its separation from the external medium at an angle exceeding the limiting angle of total internal reflection (Fig. 13).

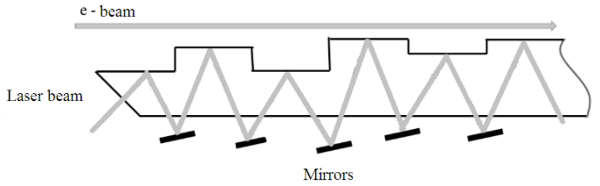

Fig. 13. Scheme of acceleration of an electron beam by surface electromagnetic waves

Such an accelerating structure for the performed calculations provides a rate of acceleration up to 1 GeV/m. If we apply a scheme similar to Fig. 13, it is possible to achieve large values of the rate of acceleration. Another planned application of the TW CPA system is the acceleration of electrons in the laser plasma [8], followed by acceleration on the chips (Fig. 14).

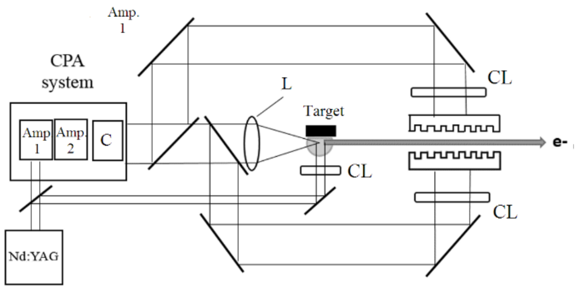

Fig. 14. Scheme of electron acceleration in a laser plasma with subsequent acceleration on chips

The universality of the laser system developed at our institute CPA provides the possibility of constructing various configurations of accelerator systems. One of the proposed schemes for electron acceleration in a laser plasma with subsequent acceleration on chips is shown in Fig. 14. At the first stage, relativistic electrons are obtained, and at the second stage, their further acceleration. The plasma is formed by an Nd-YAG laser, which is used to pump the first CPA amplifier of the laser system, part of the pump radiation, less than 50 mJ, is directed to the target. Nylon can be used as a target material. As an accelerator, a focused beam of a CPA system is used, with parameters such as a wavelength of 800 nm, a pulse duration of 30 fs, and an energy in the pulse of 210 mJ. That is, it is possible to obtain an output power of up to 7 TW. Part of the radiation is diverted directly to the chip-accelerator, thereby completing the integrated system of the desktop accelerator.

Thus, possible directions of application of various components of the laser system are shown. Possible methods for obtaining a supercontinuumare described, and a ready-made device for obtaining biconical fibers is presented. Also, possible schemes for the use of the CPA of a laser system for accelerating electrons are indicated.

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РАБОТЫ В ННЦ ХФТИ ПО СОЗДАНИЮ И ПРИМЕНЕНИЮ CPA-ЛАЗЕРНОЙ СИСТЕМЫ

А.В. Васильев, А.Н. Довбня, А.М. Егоров, В.П. Зайцев, В.П. Лещенко, И.Н. Онищенко, А.И. Поврозин, Г.В. Сотников

Представлена CPA-лазерная система с выходной мощностью 10^{10} Вт, которая на завершающем этапе будет доведена до мощности, близкой к 10 ТВт. Описаны области ее применения, представлены результаты исследования суперконтинуума на фотонно-кристаллических волокнах и на других образцах. Разработана методика и устройство для изготовления биконических волокон с целью получения на них суперконтинуума. Предложены различные варианты возможного применения CPA-лазерных систем для исследования схем перспективных ускорителей, в том числе на чипах и на поверхностных электромагнитных волнах.

РОБОТИ В ННЦ ХФТІ ПО СТВОРЕННЮ І ЗАСТОСУВАННЮ CPA-ЛАЗЕРНОЇ СИСТЕМИ

А.В. Васильєв, А.Н. Довбня, А.М. Єгоров, В.П. Зайцев, В.П. Лещенко, І.М. Онищенко, А.І. Поврозін, Г.В. Сотников

Представлена CPA-лазерна система з вихідною потужністю 10^{10} Вт, яка на завершальному етапі буде доведена до потужності, близької до 10 ТВт. Описано області її застосування, представлені результати дослідження суперконтинуума на фотонно-кристалічних волокнах і на інших зразках. Розроблено методику та пристрій для виготовлення біконічних волокон з метою отримання на них суперконтинуума. Запропоновано різні варіанти можливого застосування CPA-

лазерних систем для дослідження схем перспективних прискорювачів, в тому числі на чіпах і на поверхневих електромагнітних хвилях.