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New design of a high-power femtosecond 800-nm laser

E.A. Khazanov

***Abstract*. A new simple design of a femtosecond laser is proposed, which consists of a 1550-nm erbium-doped fibre laser, a fibre stretcher, a BBO crystal parametric amplifier converting the input radiation to the 800-nm radiation, a Ti : sapphire or a BBO amplifier, and a diffraction grating compressor.**

Keywords: *optical parametric amplifier, chirped pulse, stretcher, femtosecond laser.*

The majority of high-power femtosecond lasers emitting pulses shorter than 50 fs are based on amplification of chirped pulses in a Ti : sapphire crystal. The general scheme of such lasers is shown in Fig. 1a. Many elements of this scheme [master oscillator (MO), stretcher, regenerative amplifier, multipass wide-aperture Ti : sapphire amplifiers] are rather bulky and are difficult to align and operate. In this paper, a laser design free from these disadvantages is proposed (Fig. 1b), which consists of a fibre laser, a fibre stretcher, and synchronously pumped optical parametric amplifiers (OPAs) of chirped pulses.

The replacement of a conventional femtosecond MO by a fibre MO is attractive because fibre lasers are simple, reliable, compact, and inexpensive, especially erbium-doped fibre lasers emitting at 1550 nm [1, 2]. In [2], a pulse energy of 9 nJ was achieved for a 35-fs pulse, while a substantially lower pulse energy of ~ 1 nJ is sufficient for the efficient operation of the laser proposed in our work. Note that fibre lasers emitting at 800 nm have not been developed so far. Although frequency doubling of the erbium laser pulses permits the amplification of these pulses in Ti : sapphire crystals, this results in large energy losses (the frequency doubling efficiency is about 10 %). At the same time, the wavelengths of Er and Ti : sapphire lasers permit realising the phase matching conditions in the parametric amplification upon pumping by the second harmonic of a neodymium laser: $\omega_1 + \omega_2 = \omega_3$, where $\omega_{1,2}$ are the Er ($\lambda = 1550$ nm) and Ti : sapphire ($\lambda = 800$ or 810 nm) laser frequencies, respectively, and ω_3 is the second harmonic frequency of a neodymium laser ($\lambda = 527$ or 532 nm).

In recent years, OPAs were widely used instead of laser amplifiers (see, for instance, [3 – 7] and references therein). The BBO crystals upon the ooe interaction have a parametric amplification width of about 3000 cm^{-1} near 800 nm, allowing the generation of 8-fs pulses even taking into account the amplitude and phase distortions of the spectrum [4]. In addition, unlike the KDP and DKDP crystals, the BBO crystals are transparent at 1550 nm and may be employed instead of Ti : sapphire amplifiers [7]. Until recently, a considerable limitation in this case was the absence of a method for synchronising the femtosecond MO with the pump laser with an uncertainty much shorter than the chirped-pulse duration. For this reason, the pump pulse of duration much longer than that of the chirped pulses were used [7], which considerably reduced the efficiency. This disadvantage was removed in the synchronisation technique proposed and described in detail in Refs [6, 8, 9].

The 1550-nm wave in the BBO-crystal OPA is an idler wave, i.e., a wave whose wave-vector direction is frequency-dependent. That is why to obtain collimated radiation at the output of the first OPA requires placing an ordinary prism in front of the BBO crystal to introduce the appropriate angular dispersion [6]. Into the second OPA it is better to inject the 800-nm signal wave. An electooptical shutter is not required in this case, because the OPA itself will perfectly select out of the pulse sequence a single pulse which is incident on it simultaneously with the pump pulse.

Generally speaking, after the second OPA it is possible to compress both the 800-nm signal and 1550-nm idler wave pulses, but the former version appears to hold greater promise. This is because, first, the 800-nm pulse energy is twice as large as that of the idler pulse and, second, the signal pulse can be further amplified not only in a BBO crystal, but in a Ti : sapphire amplifier as well. If the stretcher uses one wave (for example, the idler wave) and the compressor uses another (for example, the signal wave), the pulse phase $\Phi(\Omega)$ after the compressor will be described, instead of the conventional expression, by the relation

$$\Phi(\Omega) = \Phi_{\rm com}(\omega_{10} + \Omega) - \Phi_{\rm str}(\omega_{20} - \Omega), \qquad (1)$$

where ω_{10} and ω_{20} are the central frequencies of the signal and idler waves; Ω is the detuning from the central frequency; $\Phi_{\rm com}$ and $\Phi_{\rm str}$ are the phases introduced by the compressor and the stretcher. To satisfy expression (1) for the 1250-nm idler and 910-nm signal waves, a

E.A. Khazanov Institute of Applied Physics, Russian Academy of Sciences, ul. Ul'yanova 46, 603950 Nizhnii Novgorod, Russia; e-mail: khazanov@appl.sci-nnov.ru

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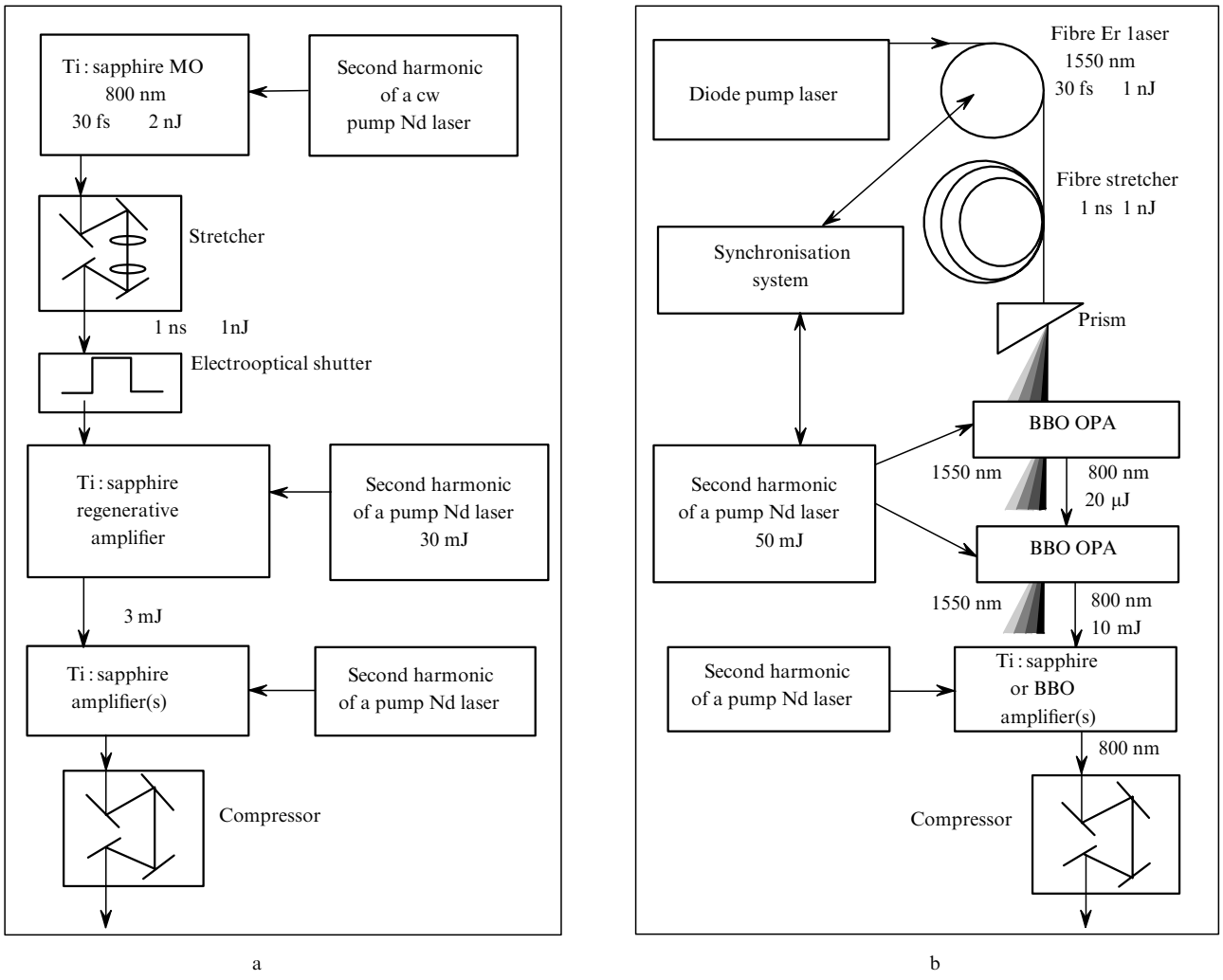

Figure 1. Conventional (a) and proposed (b) schemes of a high-power femtosecond laser.

compressor with two prisms was used as a stretcher [6]. For the 1550-nm and 800-nm waves, it is also possible to make a fibre stretcher by using the broad possibilities to control dispersion in fibres at 1550 nm (see, for instance, Ref. [10]). It follows from relation (1) that the stretcher should possess the anomalous second-order dispersion, which is fulfilled for the majority of fibres. The exact values of dispersion of second, third, an higher orders may be obtained by selecting the fibre with the optimal dispersion or by choosing the lengths of sequentially arranged fibres of different type. Note that nonlinear effects in the fibre stretcher will be insignificant due to the low pulse energy (1 nJ).

The estimate of the small-signal OPA gain for a 12-mm long BBO crystal pumped by 1.5-ns, 50-mJ pulses (the pump intensity is 1 GW cm^{-2} and the laser beam diameter is 2 mm) gives the value 2×10^4. The amplification in the second OPA will therefore proceed in the strong saturation regime. For a photon efficiency of 25 % – 30 % typical for this regime (the record-high values are ~60 % [11]), the output energy at 800 nm will be 8 – 10 mJ.

Further amplification can be performed both in Ti : sapphire crystal amplifiers and BBO-crystal OPAs. In the latter case, the pump laser should be synchronised with the femtosecond MO. Among the disadvantages of OPAs also are their lower efficiency and smaller (than in the case of Ti : sapphire crystals) aperture. The advantages of OPAs are a substantially lower heating and a higher gain. Therefore, to decide between the BBO and Ti : sapphire crystals in high-power amplification stages and to choose the number of these stages one has to take into account the specific parameters of output radiation.

We summarise the advantages and disadvantages of the new design (Fig. 1b) compared to the traditional one (Fig. 1a). Among the advantages are a substantially simpler, reliable, compact, and inexpensive MO; a simple stretcher which does not necessitate adjustment; the use of an OPA instead of a regenerative amplifier; the absence of an electrooptical shutter for lowering the pulse repetition rate; and the possibility of employing OPAs in high-power amplification stages. The disadvantages, namely, the existence of a synchronisation system and a chirp-modulation prism are quite insignificant owing to the simplicity and reliability of these devices [6, 8, 9].

The new design features all the advantages of fibreoptic elements intended for the operation at 1550 nm and of broadband parametric amplification in the BBO crystals and broadband laser amplification in Ti : sapphire crystals at 800 nm. The design can be employed for developing new Ti : sapphire laser systems and upgrading the existing ones.

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