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OPTICAL PHYSICS

Production of ultrashort pulses in fiber lasers

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The review is focused on finding an answer to the question of what is the minimum pulse duration of radiation possible in an "all-PM-fiber" cavity configuration of a fiber laser (including a fiber compressor if it is in use), not using short-lived or quickly failing components. Such configurations of fiber lasers are in highest demand since all the advantages that set apart fiber lasers are realized in them. Fiber-volume configurations and those very similar to the desired ones, but not meeting all the requirements, are analyzed. It is concluded that in the desired configuration of a fiber laser, the generation of picosecond pulses and longer is possible. Examples of resonator layouts for such lasers are given.

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1. INTRODUCTION

Ultrashort light pulses, with durations of tens of femtoseconds or even single femtoseconds [1–5], are no longer exotic, as they can be generated by a variety of methods [6–11]. It is natural that in recent years, researchers and developers have focused their efforts on producing ultrashort pulses in fiber lasers [12–14], which have several advantages over traditional laser types [15,16]. Studies have begun to emerge that demonstrate pulses with durations ranging from ∼4 fs [17] to about fifty femtoseconds [18–46], generated in fiber laser systems. However, as a more detailed examination reveals, all these solutions have significant drawbacks that prevent their widespread adoption: they are either irreproducible (the laser systems contain fiber polarization controllers, whose tuning procedure is essentially chaotic), or they are not implemented in an "all-fiber" format, which is one of the main advantages of fiber lasers, or the output radiation is unpolarized, or they use a material-based saturable absorber with a relatively short operational lifetime [47]. It is important to note that the duration of the pulses in a number of applications is considered alongside the pulse energy (or average output power). In this work, we will primarily focus on the duration of the output pulses, independent of their energy characteristics. The aim of this study is to analyze what are the shortest polarized pulses that can be obtained in all-fiber lasers, whose resonators can be reproducible and contain a long-living artificial saturable absorber.

We do not plan to analyze all works dealing with the generation of short pulses in fiber lasers, as their number being very large). We will primarily focus on works demonstrating lasers with the potential for realization/desirability in user/commercial implementation.

2. DIFFERENCE BETWEEN FIBER AND OTHER TYPES OF LASER CAVITIES

In many conventional solid-state non-fiber lasers, the radiation propagates within the cavity predominantly through air, whose refractive index is weakly dependent on the wavelength of radiation in the visible and infrared regions of the spectrum [48]. As a result, in the case of short-pulse radiation, the pulses do not significantly expand or compress while passing through the air, but their duration can change when interacting with the elements of the resonator (active medium, mirrors, saturable absorbers, and so forth) due to their chromatic dispersion [49]. Consequently, in conventional (non-super-compact) solid-state non-fiber laser cavities, elements with significant chromatic dispersion constitute a relatively small part of the resonator.

A fundamentally different situation exists in "all-fiber" fiber lasers. Here, the radiation within the cavity always propagates in an extended medium that exhibits chromatic dispersion (except for wavelengths near 1.3 μm, where the chromatic dispersion of quartz fiber is close to zero [50]). Depending on the radiation wavelength, the dispersion of the most commonly used single-mode quartz fiber can be normal ($\lambda <\sim 1.3$ μm) or anomalous ($\lambda >\sim 1.3$ μm) (see Fig. 1). Because of this, different materials/components are required to compensate for the dispersion of standard quartz fiber in different spectral regions (e.g., in Yb-doped fiber lasers emitting in the ∼1 μm range, in Er-doped lasers emitting in the ∼1.5 μm range, or in Tm-doped lasers emitting in the ∼2 μm range). Furthermore, the relatively small mode area in single-mode fibers contributes to the earlier manifestation of non-linear effects as the output power increases, complicating dispersion compensation at different output powers.

The production of short radiation pulses in fiber lasers while maintaining all the advantages of these lasers (long-living

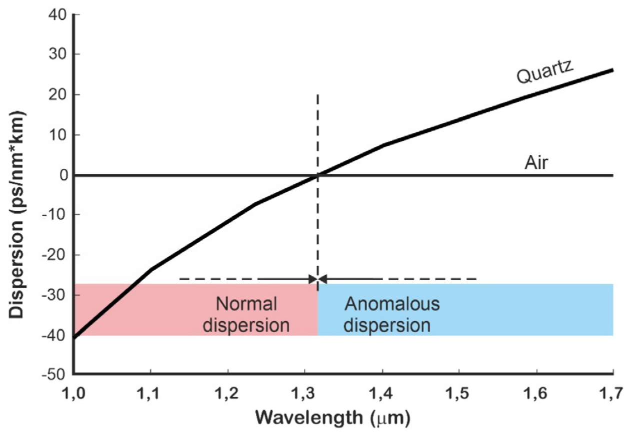

Fig. 1. Chromatic dispersion of quartz fiber and air as a function of the radiation wavelength.

all-fiber configurations, etc.) has proven challenging. Let us consider configurations for generating pulses of varying durations using fiber components.

3. FIBER LASERS/SYSTEMS WITH OUTPUT PULSES IN THE DURATION RANGE OF 4–50 fs

Ultrashort-pulsed fiber laser systems typically include a fiber laser, where passive mode locking is achieved through the effect of non-linear polarization evolution [45] or by using a material-based saturable absorber. Both solutions are primarily for laboratory use, with the first solution being virtually absent in commercial lasers. Pulse shortening is performed in a compressor, which can be constructed using fiber [17,20,25,28,29,33,34,39,42,43], two prisms [22,23,27], diffraction gratings [19,21,26,35,40], or through a combination of some of these elements, as well as chirped mirrors [15,16,32,37,38,41]. The successful use of fiber for pulse compression confirms the potential for creating an ultrashort-pulsed all-fiber laser system. Temporal compression of pulses can be either intra-cavity or extra-cavity. The shortest pulses have been obtained using a compressor; however, even without a compressor, the pulse duration directly at the laser output can be around 45 fs [31]. However, the resonator configuration demonstrated in [31] contains bulk elements and, therefore, cannot be considered optimal.

It should be noted that often in this range of output pulse durations, compressors (frequently including several stages) are significantly more complex to manufacture and have a greater number of components than master oscillators [17]. Therefore, it becomes less important what type of master oscillator was used—whether it was fiber-based or not. The compressor (which may partially consist of fiber elements) is, in these cases, essentially the main part of the laser system for generating ultrashort pulses. The system itself may be referred to as fiber-based, although, in fact, it may contain a relatively small number of fiber components.

Overall, it can be stated that there are currently no optimal solutions in ultrashort-pulsed fiber laser systems that clearly demonstrate the advantages of fiber platforms. Figures 2, 3, and 4 present typical diagrams of ultrashort-pulsed fiber laser

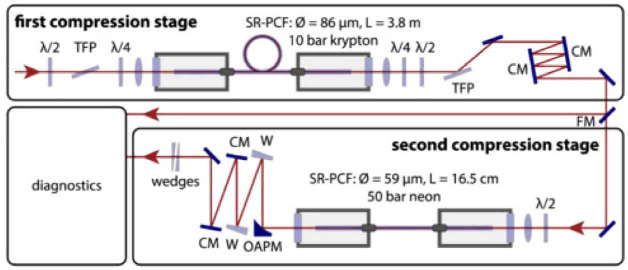

Fig. 2. Compression scheme of input pulses with a duration of 320 fs@1030 nm@9.6 MHz to a duration of 3.8 fs [17].

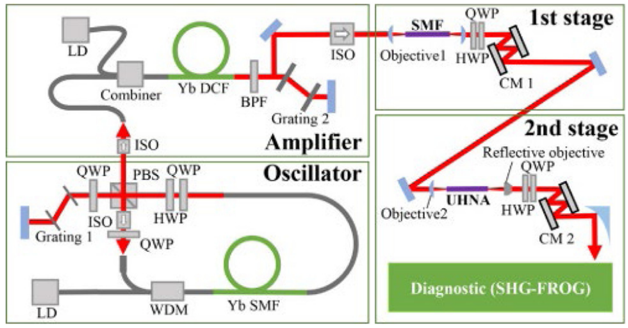

Fig. 3. Schematic diagram of the Yb fiber laser system for receiving pulses with a duration of 9.1 fs@1030 nm@90 MHz [19].

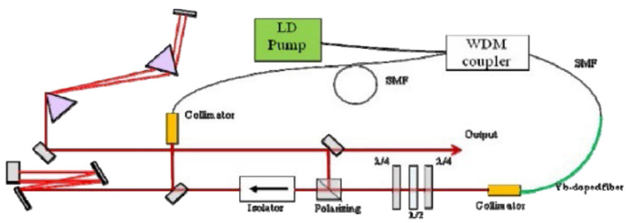

Fig. 4. Schematic diagram of the Yb fiber laser system for receiving pulses with a duration of 28 fs@1040 nm@80 MHz [21].

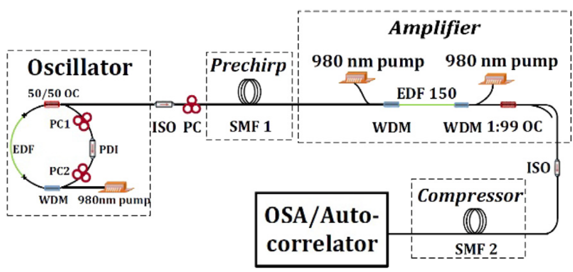

Fig. 5. Schematic diagram of the Er fiber laser system for receiving pulses with a duration of 22.7 fs@1550 nm@44.6 MHz [33].

systems, showing that these systems contain a relatively large number of bulk elements that do not conform to the "all-fiber" format. The system of Fig. 5 is the closest to the "all-fiber" format. However, this system contains three fiber polarization controllers, the adjustment of which is non-trivial and requires expensive equipment to monitor pulse characteristics.

Moreover, the combination of fiber and non-fiber components in a single optical layout complicates these systems due to the need to adjust the elements for guiding radiation into the fiber, which, if improperly adjusted, can introduce significant losses. Consequently, fiber-volume schemes are predominantly used in laboratory conditions by experienced researchers.

4. FIBER LASERS/SYSTEMS WITH OUTPUT PULSES IN THE DURATION RANGE OF 50–100 fs

Let us consider fiber systems providing output pulse durations in the range of 50–100 fs. We will try to understand at what pulse durations a fiber system can still maintain its major advantages (absence of non-fiber elements, etc.).

Most configurations for generating ultrashort radiation pulses in the range of 50–100 fs conceptually replicate the specifics of the schemes described above, i.e., combining fiber and bulk components. In such hybrid configurations, pulse durations of 89 fs [49] and sub-100 fs [50,51] have been reported. The number of examples may be significantly greater, but fundamentally different configurations are also, for the most part, hybrid, combining fiber and non-fiber components. We have not been able to find a study demonstrating the achievement of sub-100 fs in an "all-fiber" configuration without the use of radiation polarization controllers. The closest to the desired scheme is a solid-fiber 75 fs laser [52], but due to the use of radiation polarization controllers, the results are practically irreproducible, and when randomly reproduced (as a result of prolonged chaotic adjustment of the polarization controllers), the obtained results do not hold for long due to the well-known parameter creep of these controllers (due to changes in mechanical stress and plastic deformation of the fiber). A similar approach has been demonstrated, e.g., in works [53–68]. Accordingly, configurations relying on polarization controllers are doomed to be limited in most cases to laboratories provided it is possible to additionally use control and measurement equipment such as a radiation spectrum analyzer and an auto-correlator for measuring the duration of radiation pulses.

Attempts to apply algorithms for automatic tuning of polarization controllers [69] also result in the need to use a set of control and measuring equipment to characterize the pulse parameters [70].

It should be kept in mind that as pulse durations increase, the configurations for their production become simpler. The configurations of fiber lasers for generating pulses in the range of 50–100 fs do not yet meet the criteria specified at the beginning of the paper. There is, however, a well-defined trend of approaching the desired configuration as the generated pulses become longer.

5. FIBER LASERS/SYSTEMS WITH OUTPUT PULSES IN THE DURATION RANGE OF 100 fs–1 ps

Radiation pulses in the duration range of 100 fs–1 ps can be obtained from hybrid laser systems with mostly fiber components. For example, 100–200 fs long pulses can be generated in a fiber laser whose configuration includes only one bulk element (a saturable mirror), but also a special photonic crystal fiber, feeding radiation into which and its connection with a standard single-mode fiber are associated with significant radiation losses [71]. The configurations of fiber lasers/systems presented in the review [72] are also far from the preferred one. Most of the configurations discussed in the review [73] do not meet the criteria outlined in the Introduction either. Some configurations may seem to satisfy the criteria at first glance, although these generate relatively long stretched pulses (>100 ps), which are compressed outside the cavity, typically using bulk optics, and these compressors are not always shown. Such solutions cannot be considered optimal precisely because of the need to use a bulk compressor, which falls outside the concept of an "all-fiber" laser.

The problem of short-pulse generation in fiber lasers is studied from various perspectives, including conceptually [74], regardless of whether this can be realized in end-user lasers. The methods under analysis are interesting (Mamyshev oscillator [75], compressing pulses from non-mode-locked sources [76], spatio-temporal mode-locking [77]), and the subsequent implementation of some of them is close to optimal. For instance, the implementation of the Mamyshev oscillator in an "all-fiber" format has been demonstrated (albeit with a bulk compressor) [78,79] and in an "all-PM-fiber" format (though in the form of a compressor/amplifier for the seed laser) [80,81].

It should be noted that in works [80,81], only a radiation compressor/amplifier is shown, implemented in an "all-PM-fiber" format, and it is indicated that a pair of diffraction gratings is used for the final compression of the pulses, viz., bulk elements. Furthermore, the configurations of the seed lasers are not shown, which leads to the assumption that these configurations do not meet the "all-PM-fiber" format. Therefore, the solutions demonstrated in [80,81] do not meet the desired requirements.

Pulses with a duration of 139 fs [82], 165 fs [83], and 220 fs [26] can be obtained in the "all-fiber" format without using extra-cavity volume compressors. However, the disadvantages of these layouts are unpolarized output radiation and short-lived (material-based saturable absorbers) or quickly re-adjustable (fiber polarization controllers) components.

However, the combination of the "all-PM-fiber" format with long-lived artificial saturable absorbers and fiber compressors is already encountered for pulse generation with durations of less than 1 ps. For example, pulses with a duration of 688 fs (compressed in a fiber with anomalous dispersion) have been obtained from a Tm-doped fiber laser [84]. Approximately the same pulse duration (700 fs) has been achieved in a Yb-doped fiber laser with an all-PM fiber pulse compressor [85]. A shorter pulse duration (∼530 fs) was achieved in an all-PM Er-doped fiber laser without external compression [86].

In the next range of pulse durations (1–100 ps), there should be more examples of pulse generation of such durations in the preferred resonator format of fiber lasers.

6. FIBER LASERS/SYSTEMS WITH OUTPUT PULSES IN THE DURATION RANGE OF 1 ps–100 ps

Laser pulses in this duration range can already be obtained in the desired "all-PM-fiber" format (Figs. 6 and 7). Several works

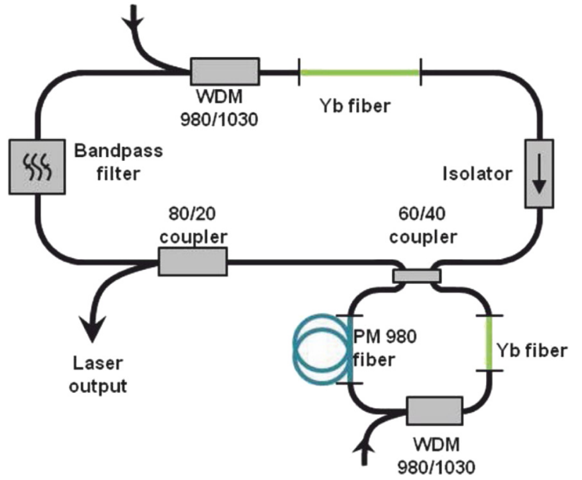

Fig. 6. Yb-doped "all-PM-fiber" laser with an artificial saturable absorber generates pulses with a duration of 1.6 ps [87].

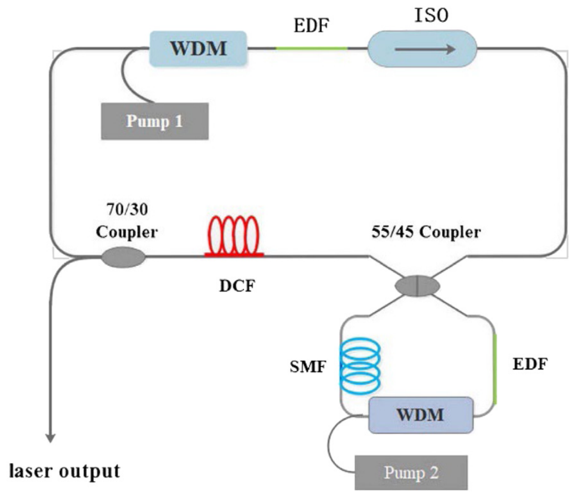

Fig. 7. Er-doped "all-PM-fiber" laser with an artificial saturable absorber generates pulses with a duration of 7.6 ps [88].

(see, for instance, [87,88]) have demonstrated Yb and Er-doped fiber laser schemes that most closely meet the target requirements. In works [87,88], the pulse duration is further reduced by adding bulk elements, but without them, the proposed lasers provide picosecond pulsed output using the desired resonator configuration types.

In fact, this is the answer to the question posed at the beginning of the paper: What is the shortest pulse duration obtainable from a fiber laser made in the "all-PM-fiber" format without the use of short-lived or rapidly destabilizing components is around one picosecond (slightly less than one picosecond, as it was demonstrated in the previous section, or several picoseconds).

7. CONCLUSION

The generation of short radiation pulses in fiber laser systems is possible, but extremely short pulses, with durations of units or tens of femtoseconds, require either bulk elements (gratings or prisms) to compensate for fiber dispersion or polarization controllers to adjust the polarization of the radiation in non-polarization-maintaining fiber configurations (the tuning procedure for these controllers is generally not described). Starting from sub-picosecond pulses (closer to a picosecond), their generation is possible in fully fiber layouts with polarization-maintaining fiber using long-lived artificial absorbers (NALM [87,88] or NOLM [84,89]) without polarization controllers. Picosecond, a little less and longer-duration pulses can be obtained in configurations that take full advantage of fiber technology: an all-PM-fiber format with a long-lasting artificial saturable absorber.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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