Fiber Lasers of Prof. Okhotnikov: Review of the Main Achievements and Breakthrough Technologies

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(Invited Paper)

Abstract—**This review is dedicated to the scientific work of Professor Oleg G. Okhotnikov (April 8, 1951 to April 8, 2016), an inspired scientist who has made a significant contribution to the development of fiber lasers. Prof. Okhotnikov published more than 280 journal articles, 100 conference papers, and numerous patents, many of which represented pioneering work in the area of fiber lasers. This article highlights the most valuable scientific and technological breakthroughs in fiber lasers achieved by Prof. Okhotnikov and his research groups.**

Index Terms—**Couplers, modeling, optical fiber dispersion, optical fiber lasers, optical pulses, optical pulse compression, optical pulse generation, power lasers, pulse amplifiers.**

I. Introduction

PROFESSOR Oleg G. Okhotnikov was born in the Moscow region on the 8th of April 1951, to Gennady Okhotnikov and Nina Okhotnikova, a technician and a kindergarten teacher, respectively. The greater part of his childhood was spent near Yurmala, in Latvia, where his grandmother, aunt and cousins lived.

A talented student with a curious mind, he decided to focus on Physics and Mathematics early on, completing a specialized high-school education in 1968. In the same year, he started his degree at the Moscow Institute of Electronic Technology in Zelenograd and graduated with a specialization in Automatics and Electronics in 1974. After that, he worked at the Lebedev Physical Institute Soviet Academy of Science (FIAN) as a graduate student, where he received his first professional award in a science competition for young researchers, for the "Study of optical characteristics of the active region of diode lasers and tunable single-frequency generation" in 1980.

In 1981 he was awarded his PhD in Physical and Mathematical Sciences and later, in 1992, he was awarded a D.Sc. at the Lebedev Physical Institute.

In 1985, Oleg married Elena Okhotnikova and was a loving father to their two children, Andrey and Evgenia.

In 1993, he started working at INESC, Porto, where he pursued a successful career as a professor and researcher. He also worked as a visiting professor abroad, the most extended stay being in Austria. Porto became a second home to Oleg; he grew extremely fond of the Portuguese language and culture.

He moved to Tampere, Finland, in 2000 animated by the opportunity to link semiconductor and fiber laser technologies, the two areas he cherished throughout his career. At the Optoelectronics Research Centre of Tampere University of Technology he established the Ultrafast and Intense Optics group, which he continued to lead for the rest of his life.

Through an outstanding dedication to his work, he had many achievements, yet the most important thing to him was always his students. Altogether, 22 PhD students obtained their doctorates under Prof. Okhotnikov's guidance.

His outstanding professional output was recognized around the world. His list of achievements includes more than 400 publications, two influential books, which he edited in the field of Semiconductor Disk Lasers [1] and Fiber Lasers [2], and several patents. In the catalogue of Finnish Professors published in 2007, he was introduced as a specialist in lasers, ultrafast optics, nonlinear optics, semiconductors, optical fibers and photonics.

Professor Oleg Okhotnikov passed away on the 8th of April 2016, following a critical illness. He has left a remarkable legacy that will be cherished by colleagues, friends and family.

This article is structured as a review of the most valuable achievements of Prof. Okhotnikov's work in the fiber lasers field. Chapter 2 describes the development of fused fiber couplers and multiplexers, as well as the invention of new resonator schemes based on these components. Chapter 3 is devoted to his simple yet exact method of laser material diagnostics based on spectrally resolved relaxation oscillations. This method was used to study the gain properties in novel active fibers. Chapter 4 is dedicated to the mode-locked laser,

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including the development of semiconductor saturable absorber mirrors tailored for fiber lasers, dispersion management, expanding the wavelength range using new gain materials, dissipative solitons lasers, and nonlinear frequency conversion. Chapter 5 reviews the main concepts and development steps for tapered double-clad fiber lasers and amplifiers. Chapter 6 summarizes his development of theoretical models for the effective amplification and generation of high-energy laser pulses.

II. Novel Laser Schemes and Principle Components

Prof. Okhotnikov began working with optical fibers in the middle of the 80s. His initial work was devoted to the development of fiber components such as biconical fused multiplexers and couplers. He developed the technology for biconical coupler fabrication by tapering and fusing two fibers together. In contrast to the methods existing at the time, these couplers were welded using high-frequency electric discharge [3]. Their distinctive features were the long fused area and highly reproducible parameters. This technology led to the demonstration of the first multiplexer-demultiplexer formed from two single-mode fibers with a spectral separation of the optical carrier channels equal to 1.5 nm, channel isolation of 20 dB and low losses of 0.2 dB. This device was first demonstrated in 1987 [3]. It was also shown that the characteristics of such a fused multiplexer could be varied by bending, which led to a change of the transfer coefficient. The initial result was further improved by the demonstration of a fused 2×2 single-mode coupler with 0.07 nm and 0.6 nm of spectral spacing and a decoupling value of better than 20 dB [4], [5].

Broadly speaking, the biconical fused coupler consisted of 2 single-mode fibers, which were tapered at several cm length and fused at the same time. The tapered part was significant and determined certain properties of the fiber coupler, such as its spectral and polarization selectivity. These properties were evaluated analytically and confirmed experimentally by manufacturing couplers and tapered filters with characteristics which were close to the theoretical limit [4]–[6].

One of the main applications of the 4-port biconical coupler, developed at the end of the 80s and the early 90s, was the fiber loop reflector (FLR) [7], [8], shown in Fig. 1(a), and the fiber interferometer shown in Fig. 1(b). These were utilized in different configurations as external dispersive elements. The FLR was proposed for intermode selection and ensured single-mode operation at the output of an external dispersive cavity with multimode-laser diode [6], [8]. The multimode laser diode coupled light into one end of the fiber loop reflector. As soon as the fiber loop reflector selectivity equaled the intermodal spacing of the diode, a single-mode regime occurred.

The FLR was also used for the line narrowing of a CW diode laser [9], [10]. The small portion of light ($\leq 1\%$) emitted by the diode laser was coupled into a high finesse fiber ring resonator via a fiber coupler. The Rayleigh backscattering which accumulated in the ring cavity was coupled back into the laser, which resulting in its line narrowing.

Another practical application of FLR was the realization of mode-locked operation [11]. In an active mode-locking scheme, the modulation of a laser diode light with the frequency coincided with the resonance frequency of the FLR or equaled the harmonics, which resulted in the appearance of a stable pulse train. In this case, the duration of the pulses was measured as 100 ps, and specified as detector-limited. By introducing a phase modulator into the loop it was possible to obtain a 100% power coupling out of the cavity. This enforced power dumping of all the stored energy in one pulse, enabling the generation of high repetition-rate, high-peak power pulses [12], [13]. The optical spectrum at the output was very similar to a CW regime.

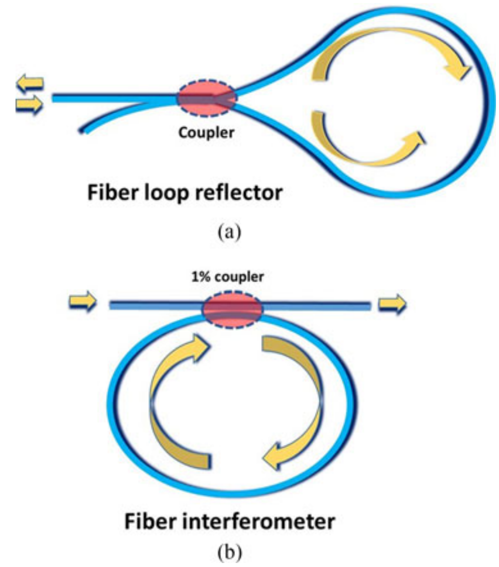


Fig. 1. The optical fiber element based on biconical fiber coupler. (a) Fiber loop reflector. (b) Fiber interferometer.

One of the most appealing applications at that time was the use of FLR as an artificial ultrafast saturable absorber for passive mode-locking. In this case, the FLR was used in the form of a non-reciprocal element [14], [15] and was called a nonlinear fiber-loop reflector (NFLR) with unbalanced directional coupler. The imbalance arose from the asymmetry between the beams propagating in the clockwise and counterclockwise directions. Due to the high non-linearity caused by the effect of self-phase modulation, the counter-propagating beams of different intensities underwent different phase retardations. Thus, when the power changed, the NFLR reflection was also changed. This intensity-dependent reflection allowed the intensities of the pulse peak and the pulse wings to be distinguished through the proper choice of the phase difference. Therefore, the NFLR operated as an artificial saturable absorber. This was one of the historic steps leading towards the "figure-of-eight laser" scheme.

Prof. Okhotnikov was not alone in working towards the investigation of new passive mode-locking laser setups. Several other research groups were working in a similar direction. At almost the same time, 2 months earlier than the results published in [10], Fermann *et al*. had submitted a manuscript describing the results of the nonlinear amplifying loop mirror (NALM) [16]. In NALM, the short piece of active fiber was spliced to one shoulder of a long fiber loop, and thus, this asymmetry

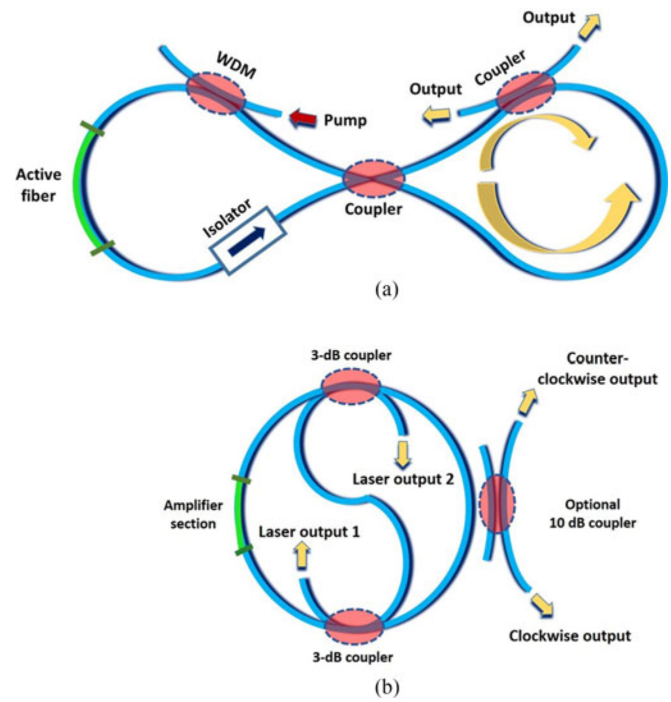


Fig. 2. The passive mode-locked fiber laser schemes. (a) Figure-of-eight-laser. (b) S-shape laser.

introduced even stronger intensity discrimination for the signal if the phase shift between the counter-propagating beams was properly adjusted. That article was published on July 1st, 1990, while on the 19th of July 1990, Prof. Okhotnikov submitted his manuscript [17], in which the combination of NOLM and NALM was considered as a unified laser resonator to achieve a self-starting mode-locked regime. The proposed scheme is shown in Fig. 2(a). This work also introduced a theoretical framework and found a steady-state solution for self-starting mode-locking without adjustment of the optical phase mismatch between two cavities (NOLM and NALM). The advantage of the proposed set-#up was that it did not require any additional active stabilization in order to withstand interferometric instabilities. This has made the "figure-of-eight laser" very attractive as a resonator for a mode-locked fiber laser, which is still a relatively popular scheme in current research. Duling III reached the same conclusions several months later using experimental observations [18].

A more sophisticated form of a non-reciprocal ring was proposed as an alternative option for a classical unidirectional ring configuration two years later in [19]. A schematic representation of the S-ring setup is shown in Fig. 2(b). The scheme comprises two 3 dB-fused couplers, one port from each coupler being used as the laser output, while three others were spliced together to form two loops. One loop contained an active fiber section and the opposite loop had optionally one more coupler with a 10 dB ratio, which allowed the light to be coupled out from both directions. The investigation of the S-shape scheme revealed unidirectional behavior over a wide range of the pumping power due to the presence of the S-shape fiber. The intensity ratio between the two counter-propagating waves amounted to 150. At the time of publication in [19], this value was greater than in the unidirectional ring configuration without a bulk Faraday isolator. Therefore, the concept of the S-shape was an elegant, compact and reliable solution for mode-locked fiber lasers.

III. Use of Relaxation Oscillations to Study Gain Properties

When optimizing lasers or amplifiers, it is very important to know the process that governs the transient emission build-up, particularly the energy transition scheme. For example, lasers demonstrate better results in four-level systems, characterized by a low threshold and the absence of reabsorption on one transition. The amplifiers are distinguished by higher ASE noise in quasi-three-level energy transition under backward pumping. However, three-level transition is undesirable for a gain medium with a low quantum defect. Such a laser transition system is characterized by small energy spacing between the principal energy levels and by high thermal population of the lower laser level. Moreover, the active medium has a broad spectrum of efficient gain, covering several tens of nanometers, or it has several emission bands depending on the pump wavelength. This is a result of Stark levels depletion, and, in consequence, different levels of one manifold can be involved in the operation that determines the change of the energy level scheme of the active medium for different wavelengths.

The study of laser transition is quite complicated and typically relies on optical spectroscopy, employing fluorescence and absorption processes [20], [21]. These methods are reliable and informative, but there are some difficulties in characterizing the active medium over the entire gain spectrum. In 1994, Prof. Okhotnikov proposed a simple and robust method for laser transition evaluation based on spectrally resolved transient oscillations [22]–[25]. Relaxation oscillations were exponential damped oscillations of small-amplitude and nearly sinusoidal form, which occurred when the laser was on. They had a transient nature which was manifested as a sinusoidal variation of the photon number and, thereby, the output power. When the laser was on, the continuous pumping resulted in an increase in the number of photons. When their number exceeded the steady-state level, the laser began to burn up excited states at a much faster rate than the pump could supply them, resulting in a decrease in the photon number. This process appeared as an oscillation around the steady-state level, which was eventually damped in a quasi-sinusoidal behavior [26]. As it was proposed, and theoretically and experimentally investigated [22]–[25], relaxation oscillations offered a useful tool for the analysis of emission build-up, the dynamics of population inversion and the nature of laser transition [26].

The typical setup of relaxation oscillation measurements in fiber lasers is shown in Fig. 3. It had a linear cavity terminated by a loop mirror from one side and a diffraction grating from the other side. The loop mirror also served as an output coupler, while the diffraction grating in the Littrow configuration operated as a wavelength selective element. The active fiber medium was pumped via a dichroic coupler. The beam from the active fiber was collimated by an anti-reflection coated lens onto the

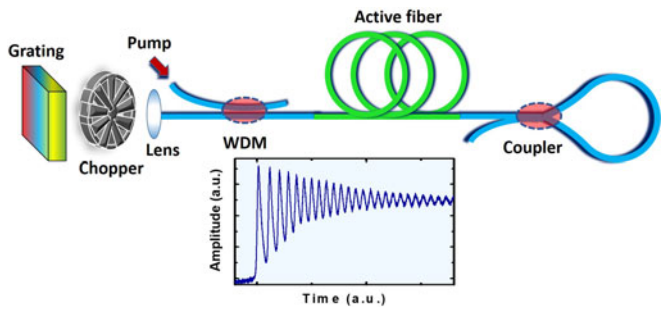


Fig. 3. The typical setup for the measurement of spectrally resolved relaxation oscillations.

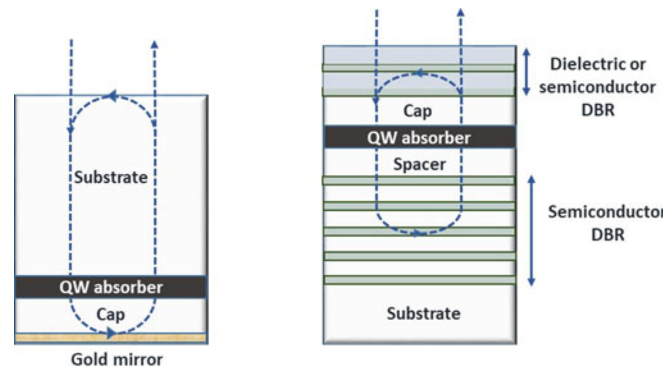


Fig. 4. General schematics of SESAMs developed at ORC. Left: SESAMs based on QWs with metal reflector and thinned substrate. Right: SESAM with monolithic DBR.

TABLE I
RESULTS OF RELAXATION OSCILLATION MEASUREMENTS IN RARE- AND NON-RARE-EARTH DOPED FIBERS

Active fiber type	Wavelength range, nm	T, K	Laser transition	Ref.
Nd^{3+}	888–914	297	Three-level	[22]
Nd^{3+}	1060–1080	297	Four-level	[22]
Er^{3+}	1530–1555	297	Three-level	[24], [25]
Er^{3+}	1530–1555	77	Four-level	[24], [25]
Er^{3+}	1555–1600	297	Quasi-three-level	[25], [27]
Er^{3+}	1555–1600	77	Four-level	[25], [27]
Yb^{3+}	1020–1050	297	Three-level	[28]
Yb^{3+}	1050–1105	297	Four-level	[28]
Tm-Ho	1860–1960	297	Three-level	[29]
Tm-Ho	1960–2020	297	Four-level	[29]
Bi	1160–1170	297	Three-level	[30]
Bi	1170–1180	297	Quasi-three-level	[30]
Bi	1160–1180	77	Four-level	[30]
Bi	1320–1340	297	Four-level	[30]
Bi	1320–1340	297	Four-level	[30]
Bi	1435–1465	297	Three-level	[31]
Bi	1710–1760	297	Three-level	[31]

reflection grating. The chopper, placed in a free-space part of the cavity and operating at a certain frequency, was used to observe the transient evolution of the laser emission towards its steady-state condition. The results of the laser transition evaluation in rare-earth- and Bi-doped fibers at different emission wavelengths obtained from relaxation oscillation measurements are summarized in Table I.

IV. Mode-Locked Fiber Lasers

This chapter is dedicated to the development of several technologies that have been instrumental in establishing mode-locked fiber lasers as practical systems for a broad range of applications in, for example, micromachining, biophotonics, or spectroscopy.

A. Semiconductor Saturable Absorber Mirrors

At the end of the 90's, semiconductor saturable absorber mirrors (SESAMs) emerged as a practical and flexible approach to self-start mode-locking in solid state lasers [32]. The benefits of using SESAMs, arising from their excellent versatility in engineering their nonlinearity and ultrafast response, were immediately leveraged for fiber lasers [33], [34]. Having a basic education in semiconductor physics and laser science, Prof. Okhotnikov recognized these benefits and embarked on a series of long developments of SESAM technology customized for the mode-locking of a large variety of fiber lasers (see summary of results in Fig. 6). In fact, his decision to move to Tampere at the end of the millenium was triggered by the opportunity to have access to semiconductor technology, and to link this to fiber laser developments. At the same time, he established a strong collaboration in the area of mode-locked fiber lasers between the ORC in Tampere and prof. Anatoly Grudinin, a former colleague and life-long friend (then with ORC in Southampton, UK). This collaboration led to several major project initiatives and pioneering developments aiming at commercializing mode-locked fiber lasers.

His initial work in the area of SESAMs was focused on developing InP-based SESAMs for mode-locking Er-doped fiber lasers aimed at telecom applications. Prof Okhotnikov exhibited outstanding creativity and the ability to solve scientific problems by adopting unconventional approaches. One example is his early work on InP SESAMs, for which he used simple quantum-wells (QWs) heterostructures (originally developed for telecom laser diodes) and combined these with metal reflectors followed by a process for substrate thinning [35]. Because they retained a thick remaining substrate, and hence a thick micro-cavity, such SESAMs exhibited a resonance behavior which led to important observations concerning the ability to engineer nonlinear behavior and its influence on mode-locking. A natural transition from this work was the development of SESAMs incorporating monolithic distributed Bragg reflectors (DBRs), for which the micro-cavity could be accurately engineered via epitaxy. To this end, the use of the Burstein-Moss shift method for fabricated InP DBRs was successfully implemented [36]. This development led to an improved ability to engineer the resonant operation, and hence the nonlinear response. At a general level, Fig. 4 shows the schematics of the SESAMs developed at ORC, while Fig. 5 exemplifies the general reflectivity behavior of anti-resonant and resonant SESAMs, developed for operation at 1.55 μm. The ability to engineer the resonant behavior was also applied to dispersion control (see the following section)

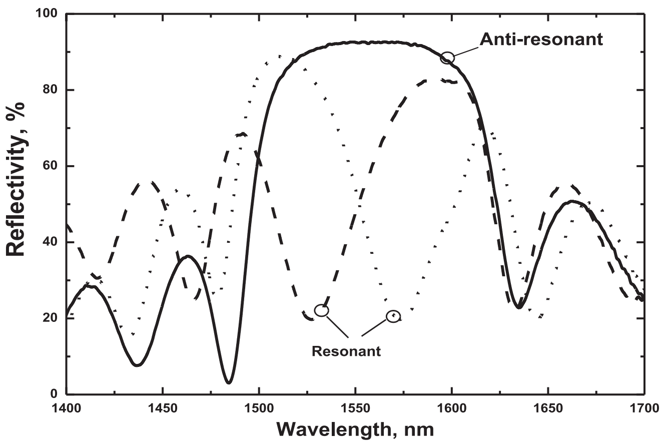


Fig. 5. Low-intensity reflectivity curves for InP SESAMs showing the difference between resonant and anti-resonant behavior.

and proved to be an essential distinction between mode-locking requirements in solid-state lasers and fiber-lasers.

Following the "telecomm-bubble" and the emergence of high-gain Yb-doped fibers, the SESAM work focused on developing GaAs-based structures, primarily for the 1-μm wavelength range [37], [38], with the major emphasis on engineering the nonlinear properties [39] and ultrafast response (see for example [40], [41]). A particularly important development concerned the use of GaInNAs QWs, enabling the deployment of GaAs/AlAs DBRs for SESAMs in the broad wavelength range, i.e., from 900 nm [42] to 1.5 μm [43]. GaInNAs/GaAs SESAMs proved instrumental in mode-locking a broad range of fiber lasers, most recently by exploiting Bi-doped fibers. In connection with expanding the benefits of SESAM-mode-locked fiber lasers to new wavelengths, the demonstration of GaSb-based SESAMs for the 2-μm wavelength range deserves a mention [44].

To this day, the SESAM technology initiated by prof. Okhotnikov remains a strong competence of the ORC at Tampere University of Technology and has been continuously expanded to encompass a broad range of solid-state and semiconductor lasers, from visible wavelengths [45] to beyond 2 μm [46], [47].

B. *Internal and External Cavity Dispersion Management*

Dispersion management is a crucial aspect of short pulse generation through intra-cavity dispersion compensation and/or external pulse chirping/compensation. For mode-locked fiber lasers operated at a 1 μm wavelength, all the fiber components exhibit normal dispersion. In some applications it can be beneficial to compensate for the normal chromatic dispersion to obtain a stretched-pulse regime with high peak power pulses, or to overcompensate in order to force the laser to work in a conservative soliton regime with ultrashort pulses of several tens of fs, to couple directly out from the cavity. From the other side, the fibers are characterized by strong anomalous dispersion at the 2 μm wavelength, and mode-locked fiber lasers in this wavelength range require a normal dispersion compensator to obtain a dispersion-managed soliton regime. To date, the methods applied for dispersion governance can be divided into two groups: bulk components, such as prism pairs, grating pairs, dispersive mirrors and etalons; and fiber elements, such as chirped fiber Bragg grating and fibers with tailored dispersion. Pioneering work led by Prof. Okhotnikov's group described the implementation of some dispersive elements for intra- and external-cavity dispersion management.

Photonic crystal fibers were examined for intra-cavity dispersion compensation in a series of publications following the first demonstration performed by H. Lim *et al*. in [48]. These fiber types exhibited anomalous dispersion in the 1 μm wavelength range, and they were implemented into the cavity of Yb-doped fiber lasers [49]–[52]. Solid-core photonic bandgap fiber (SC-PBG) was chosen as the dispersive element due to the obvious advantage of the ease with which it can be spliced to a standard fiber [49]. Moreover, the fiber structure exhibited no surface mode, and allowed for high anomalous dispersion with a relatively small critical nonlinear threshold. The SC-PBG was inserted into a linear Yb-doped fiber laser cavity. It was characterized by its 9 μm mode-filed diameter and 200 μm diameter fiber. The core indexes of a standard single-mode fiber and the SC-PBG were close enough to avoid the Fresnel reflection at the interface. As a result, with appropriate control of the pump power, self-starting mode-locked operation was achieved. The shortest pulse duration obtained in the cavity was 460 fs with 4.6 nm of spectrum bandwidth. Despite the good performance demonstrated by the SC-PBG as intra-cavity dispersion compensation, it was concluded that a major limitation to the pulse width originated from the third-order dispersion (TOD) exhibited by the SC-PBG. The extraordinarily high value of third-order dispersion also affected the shape of the optical spectrum [53]. The position of the Kelly sidebands showed notable asymmetry. As was investigated experimentally and confirmed theoretically, at a low value of TOD the spectrum shape was determined by second-order dispersion and characterized by the distribution of the symmetry sidebands. When the TOD exceeded a certain value, the sidebands concentrated mostly from the long-wavelength side were demonstrated to be highly asymmetric.

The combination of the dispersion compensation element and the active medium in one optical component provided a unique opportunity to achieve ultrashort pulses. At a high repetition rate, these exceeded 100 MHz in the short fiber laser cavity [51]. Yb-doped photonic band-gap (Yb-PBG) fiber was implemented in the linear cavity, mode-locked by SESAM. 27 cm of Yb-PBG was sufficient to provide enough gain and compensated for 0.5 m of a passive single-mode fiber. The specific feature of this type of PCF fiber was the spectral position of the zero-GVD wavelength. The waveguide dispersion determined by the resonance-like photonic bandgap (PBG) structure had anomalous behavior and shifted the zero-GVD wavelength towards the short-wavelength edge of the transmission band. From the other side, the strong normal material dispersion due to the all-solid PBG nature shifted the zero-GVD in the opposite direction. In the case of Yb-PBG fiber, the waveguide dispersion was dominated at the laser's operational wavelength of 1040 nm. This was attributed to the fact that the cut-off wavelength of the fundamental mode was located at the band edge, at 1094 nm. This caused a rapid increase in the dispersion at the edge of the long-wavelength, and also shifted the zero-GVD to the short-wavelength side of the transmission band. As a result, the laser delivered a 335-fs pulse at 117.5 MHz at the fundamental repetition rate. A similar idea of a combination dispersion compensator and gain medium was implemented in the set-up with a suspended core Yb-doped fiber. In this case, the laser operated in the ring cavity, and delivered 95 fs pulses [54].

The index-guided PCF generated sufficient anomalous dispersion around 1 μm with the mode-size and nonlinearity close to that of ordinary fiber. This was proposed as an alternative dispersion compensator in [50]. This fiber exhibited strong polarization dependence, which was compensated for with a Faraday rotator in the Yb-doped fiber laser cavity. This enabled self-starting environmentally stable mode-locked operation, which was independent of the fiber bending to within a few centimeters of the bending radius. The laser operated in a single-pulse regime, and delivered 200 fs transform-limited pulses without any sign of Raman scattering.

The first demonstration of a thin-film Fabry-Perot etalon operating as a dispersion compensator in a mode-locked fiber laser cavity was in 2007 [55]. The in-house-made thin-film etalon (TFE) was able to overcompensate the normal dispersion generated by 80 cm of standard fiber at 1 μm in a bandwidth sufficient to support sub-picosecond pulses. The pulse duration obtained in this case varied from 0.77 ps to 4 ps, depending on the length of the passive fiber. This study showed that there was a trade-off between the amount of dispersion and the optical bandwidth provided by the TFE to maintain the sub-picosecond regime in the fiber laser.

Promising results in short pulse generation through intra-cavity dispersion compensation were achieved through the utilization of tapered fiber [56]. The fiber taper was manufacturing from a standard single-mode fiber using a flame brush technique. It had a waist diameter of 1.8 μm and insertion losses of 0.3 dB. It exhibited anomalous dispersion of 50 fs/nm, which was capable of overcompensating normal dispersion from 1.6 m of conventional fiber length. The spectrum bandwidth of 10 nm and 3 ps of the pulse width were obtained directly from the cavity.

The combination of taper fiber and chirped fiber Bragg grating (FBG) were proposed as an alternative approach to the internal dispersion compensator [57]. The tapered FBGs (T-FBG) were obtained by imprinting a uniform and chirped FBG into the linear part of the taper transition section using the phase-mask technique. With uniform FBG, phase-mask T-FBG exhibited linear dispersion depending on the wavelength. The use of the chirped phase-mask meant that a T-FBG with nonlinear dispersion behavior could be achieved. Moreover, the grating demonstrated different dispersion-vs.-wavelength dependence for short- and long-wavelength side connections. By introducing T-FBG into the cavity, the soliton pulse-mode-locking resulted in stable, slightly chirped pulses of several picoseconds width.

Another example of a sophisticated dispersion compensator was the 170 nm/cm chirped FBG [58]. A specially designed phase-mask was used to imprint the grating into the standard single-mode fiber. This high chirp enabled the generation of enough dispersion to fully compensate for a 4 m cavity length. This resulted in a broad spectrum of 125 fs pulse operation near zero net-cavity dispersion. A similar chirped FBG was used for external pulse compression supporting 174 fs pulse duration.

Sometimes the pulses delivered directly from the laser were chirped, where the chirp sign (up or down chirp) depended on the position of the pulse extraction from the cavity of the dispersion-managed soliton laser [59]. In such cases, external dispersion tailoring was needed to obtain the transform-limited pulses. Microstructured fibers, such as passive suspended core fiber or hollow-core PBG, were demonstrated as the external pulse compressor. The passive suspended core fiber was used to fully de-chirp the pulses, which resulted in 150 fs of pure Gaussian shaped pulse duration [58] Hollow-core PBG was implemented for pre-chirping in anomalous dispersion, and subsequent nonlinear spectral compression was realized in an optical amplifier which provided nearly-transform-limited picosecond pulses [60].

C. Novel Gain Materials and Wavelengths of Mode-Locked Fiber Laser

Fiber lasers with ultrashort pulse operation are very attractive candidates for a variety of applications because they have a number of distinguishing characteristics. The fiber lasers feature compact-footprint, maintenance-free, power efficient systems, which provide pure Gaussian-shape beam quality, and are relatively inexpensive. Although some applications are wavelength-independent, most applications require the laser to operate at a specific wavelength in order to implement the technology successfully. Therefore, much scientific effort is aimed at satisfying this requirement through the continuous search for effective solutions for the operation of new laser wavelengths.

The first picosecond mode-locked operation of a Yb-doped fiber laser which was widely tunable over a 90-nm range (from 980 to 1070 nm) was demonstrated by Prof. Okhotnikov's group in 2003 [61]. This laser was based on 35–50 cm of Yb-doped alumo-silicate single-mode, single-clad fiber with a cut-off wavelength of 910 nm. Since the cut-off wavelength lay below the 915 nm pump source, the Yb-doped fiber was single mode at the pump's wavelength, which had a positive effect on the pump-to-signal wavelength conversion. The cut-off wavelength of the passive fiber was $\sim$920 nm. The laser cavity had a linear scheme, in which one end was terminated by a highly reflective mirror, and the other end by a SESAM, which enabled self-starting mode-locked operation. A pair of diffraction gratings were used as the intra-cavity dispersion compensator and the wavelength discriminator. This allowed the laser to be tuned by a slight adjustment of the grating position. To obtain a broad tuning range, special attention was paid to the design of the multiple-quantum-well saturable-absorber mirror in order to achieve optical matching of the reflection characteristics and the bandgap energy. This laser delivered picosecond pulses, whose widths varied slightly from 1.6 to 2 ps over the entire tuning range. The tuning range of this laser was close to that of Ti:sapphire lasers.

An in-depth investigation of the laser's operation at 980 nm was shown in [62]. Since the Yb-doped laser was in general characterized by poor noise parameters, which limited its applications, particular attention was paid to measuring the relative intensity noise (RIN). A RIN value of as much as −140 dB/Hz was achieved. The slope efficiency of the free-running laser was equal to 91%, which was close to the theoretical limit. The slope efficiency of the mode-locked laser was 40%, which can be regarded as a reasonable result considering the high reabsorption characteristics of Yb-doped fiber at the signal wavelength.

The shortest wavelength operation of a mode-locked fiber laser was achieved with a Neodymium-doped fiber laser [43]. A 1m-long Nd^{3+}-doped fiber with a cut-off wavelength of 800 nm was pumped by an 808 nm pump diode via a dichroic coupler. The linear cavity scheme was terminated by a loop mirror on one side, which simultaneously served as an output coupler delivering 8% of power out of the resonator, while the other side was terminated by a SESAM. All the passive components were made from fiber with a cut-off wavelength of around 735 nm, which ensured single-mode operation of the laser. Clean transform-limited pulses of 360 fs were obtained directly from the cavity at a 35.2 MHz repetition rate, which were quickly broadened by an output pigtail until they reached 620 fs. Moreover, the laser exhibited steady-state operation over the entire three-level transition band (894–909 nm).

The first passively mode-locked holmium-doped fiber laser was achieved in 2012 [63], [64]. The laser configuration incorporated 80 cm of purpose-built Ho^{3+}-doped silica fiber, which was pumped by a semiconductor disk laser illuminated at 1100 nm via a multiplexer. The dichroic mirror had high reflectivity for the signal wavelength, and high transmittance at the pump wavelength, which ensured the elimination of the residual pump in the cavity. Specially designed SESAM or carbon nanotubes (CNT) were utilized for the mode-locker. The shortest pulse operation was 890 fs at 2085 nm, which was the longest mode-locked wavelength for a fiber system ever reported at the date of publication [64]. By using CNT as a mode-locker, it was possible to achieve 70 nm tunability of the pulse operation with output power of up to 60 mW [65].

Prof. Okhotnikov's work on Bi-doped fiber lasers was particularly significant. He published a series of articles over several years (2007–2015) describing the details of the pulse dynamics and different operation regimes of resonators which utilized alumo-silicate or phosphor-silicate bismuth-doped fibers as their gain medium. The first mode-locked operation in Bi-doped fiber was detected in 2007 [66]. The laser delivered 50 ps pulses at 1161 nm. Later, these results were improved by the demonstration of 940 fs pulses and stable operation in a wavelength range of 1153–1170 nm [67], [68]. The pulse dynamics in this laser were investigated both experimentally and theoretically [69]. This research showed the detrimental effect of certain parameters on the pulse generation and the shaping, among which were the gain pumping level, the absorption saturation, and the average cavity dispersion. The first Bi-doped mode-locked laser with a central wavelength of 1.32 μm was described in [70]. This laser operated in both conservative and dissipative soliton regimes, where the switching between the regimes was achieved by introducing CFBG into the cavity. The shortest pulse duration at 1.32 μm was 580 fs. The effect of the absorption recovery

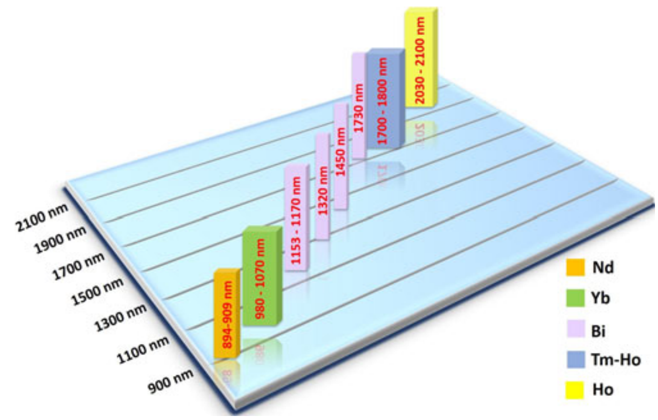


Fig. 6. The illustrative summary of new wavelengths pulse generation from mode-locked fiber laser demonstrated by Prof. Okhotnikov's group.

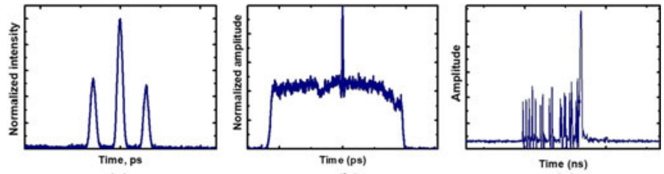
in bismuth-doped fiber was shown in the first Bi-doped mode-locked fiber laser operating at 1450 nm [71]. It was discovered that the gain saturation and the bleachable absorption of the bismuth fiber introduced a mechanism for pulse group formation. Later, a compact all-fiber MOPA system which incorporated a master oscillator and an amplifier operated at 1450 nm was demonstrated [72]. This system delivered 240 fs pulses with peak power of 3.1 kW. The first passive mode-locked fiber laser operating at 1700 nm was achieved with Bi-doped fiber [73]. The short–pulse operation of slightly over 1 ps duration was obtained in both conservative and dissipative soliton regimes. Moreover, the laser exhibited harmonic mode-locking with a maximum observed repetition rate frequency of 600 MHz.

There was one more notable study of a 1700–1800 nm tunable laser source based on a Tm-Ho-fiber mode-locked laser [74]. This work was inspired by Prof. Okhotnikov, but actually finished and published later by some of his students.

An illustrative summary of the work achieved by Prof. Okhotnikov during this period of his career is shown in Fig. 6.

D. *Dissipative Solitons Fiber Laser*

Traditionally, the counter-balance between dispersion and nonlinearity had always been assumed to be an essential requirement for pulse shaping in mode-locked fiber lasers. The fiber laser-system had always been determined as conservative, but this neglected the effect of energy exchange in the resonator. A balance between loss and gain had always been regarded as a general requirement for starting a laser. Therefore, the steady-pulse regime in a mode-locked fiber laser had been attributed to anomalous net cavity dispersion, in which the dispersion and nonlinearity were characterized by opposite signs and thus balanced each other. A turning point was reached at the beginning of the 1990s, when research showed that solitons in non-conservative systems can actually be obtained for any dispersion sign, so solitons were henceforth classified as dissipative [75]. The main principles of the theoretical considerations of dissipative solitons were unified and summarized in 2005 [76]. Prior to that, only one experimental work had described stable pulsed operation in a mode-locked fiber laser with net-normal



(a) (b) (c)

Fig. 7. Soliton complexes demonstrated in mode-locked fiber lasers: (a) autocorrelation trace of bound solitons (soliton molecules); (b) autocorrelation trace of bunch of solitons; (c) oscilloscope picture of soliton rain.

dispersion regime, which was that of Prof. Okhotnikov's group [77]. Although this study did not use the now common terms of dissipative solitons or all-normal dispersion fiber laser (ANDi) [2], [78]–[80], the regime was investigated experimentally and theoretically in this work. Yb-doped fiber laser was classified as dispersion compensation-free. This study of the laser included the initiation of mode-locking, stable operation, the dependence of the pulse width on the net-cavity dispersion, and the role of the SESAM parameters. The mode-locked operation was ensured with a high-contrast SESAM. The cavity incorporated a few fiber components: 15–35 cm of Yb-doped fiber, a dichroic coupler and a loop mirror. All the fibers were characterized by normal dispersion at the operational wavelength. The short resonator length allowed the overall intra-cavity dispersion to be minimized. A single pulse regime was achieved in the resonator, where the optical spectrum had a rectangular shape with sharp edges and the pulses were highly chirped. The shortest pulse duration, obtained in the cavity, was 3 ps, which was determined by high nonlinearity and speed of the SESAM.

Many years later, when ANDi lasers and dissipative solitons had become common place, plenty of publications described the characteristics of Yb- and Er-doped fiber lasers with dissipative soliton operation, and record values had been achieved for the pulse energy. The new challenge now facing the scientific community was how to achieve dissipative solitons operating at a wavelength at which the silica fiber dispersion was highly anomalous. The answer came in 2011 [81]. The Tm-Ho-doped fiber laser described in this study exploited strong dispersion-management through the anomalous dispersion of active and passive fiber samples and normal dispersion from the highly-chirped fiber Bragg grating. The laser operated in a dissipative-solitons regime with all the characteristic attributes, such as the rectangular shape of the spectrum with steep edges, highly-chirped pulses, and single pulse operation with enhanced pulse energy as compared to the conservative solitons operation.

In contrast to a laser working in normal net-cavity dispersion, the dissipative-solitons laser operated in anomalous dispersion is characterized by a multiple-pulse regime when accumulative nonlinear phase shift cannot be compensated for by dispersion. In addition, the energy dissipation, which exists in any mode-locked fiber laser led to pulse interactions through a variety of mechanisms. These interactions resulted in stable pulse group formations, such as bound solitons, bunches of solitons and soliton rain (Fig. 7). Detailed investigations of the pulse interactions in mode-locked fiber lasers, concentrating on the effects of the laser parameters on the pulse-dynamics and soliton group formation, were presented in a series of publications [82]–[89]. Different lasers, such as Yb-, Er- and Bi-doped fiber lasers, were used as the medium for revealing the major principles and dependency relations. The slow component of the SESAM's relaxation dependence served as a soliton attractor in the resonator, which pushed the pulses towards to each other [82], [83]. When the pulses reached the point at which the direct soliton-soliton interaction became significant, the repulsive force pushed the pulses away from each other. The combination of two counter-acting forces led to a continuous oscillation of the solitons within a certain time-frame, which was specified as a bunch of solitons. Excessive nonlinearity and anomalous dispersion destroyed the stable, bound soliton state (or soliton molecule). Nonlinearity resulted in bunch formation with chaotic motion of the pulses within the group, while dispersion pushed the pulses apart [84]. The dispersion sign of the gain medium also played an essential role in the soliton interaction [85]. Amplification in the active medium with normal dispersion in the cavity supported a stable bound-soliton state, while with anomalous dispersion there was a strong tendency for bunch formation [86]. When the gain-relaxation parameters were comparable to the cavity round-trip time, the formation of stationary soliton groups occurred, whose widths took up the whole length of the cavity [71].

E. Systems With Nonlinear Frequency Conversion

A good deal of Prof. Okhotnikov's work focused on systems with nonlinear frequency conversion, such as visible light generation by second or third harmonics, Raman lasers, the supercontinuum source, high harmonic generation or synchronized mode-locked operation by means of an external clock.

The all-visible-continuum generation was demonstrated in taper fiber seeded by a 532 nm picosecond signal [90]. The 532 nm seed was obtained by frequency doubling of the 1065 nm signal from the Yb-doped fiber MOPA system in periodically-polled lithium niobate (PPLN) crystal. The conversion efficiency was 14%. The taper was specifically designed to match the zero-wavelength dispersion to the wavelength of second-harmonic generation. The power of the visible-continuum source reached 55 mW, which corresponds to a spectral brightness of 0.17 mW/nm.

The simultaneous generation of second and third harmonics was obtained in periodically-polled KTP (PPKTP) crystal having a predesigned waveguide structure with precisely phase-matched frequency doubling and non-phase-matched sum-frequency mixing [91]. Frequency-doubling of the 1065 nm signal from the MOPA Yb-doped fiber system was achieved with a conversion efficiency of up to 33%. The emission at 532 nm reached a power level of 50 mW. The power of third-harmonic generation at 355 nm was 3 mW, which amounted to 2% of conversion efficiency.

Supercontinuum generation was achieved through various approaches using highly nonlinear photonic crystal fiber [92], [93] or suspended-core fiber [94]. The spectrum of the source with the suspended core fiber covered the region from 1.35 to 2 μm at a level of several watts of output power. The supercontinuum source obtained with the PCF fiber was used as a platform to investigate the temporal evolution of optical pulses within the spectrum, in order to understand the mechanism of supercontinuum formation. This study was performed by slicing the supercontinuum spectrum and measuring the temporal shape and width of the pulses. The results of the experiments confirmed the soliton-fission theory by observing the red-shifted fundamental solitons and blue-shifted non-solitonic radiation [92].

Raman lasers and amplifiers were implemented by employing a semiconductor disk laser (SDL) as a pump source [95]–[100]. The SDL lasers were low noise (−150 dB/Hz), high power (several watts) sources, which allowed Raman gain to be obtained at virtually any wavelength of interest. By using highly nonlinear Ge-doped fiber in the resonator along with nonlinear polarization rotation or SESAM mode-locked techniques, these experiments produced pedestal–free pulses in the order of a few picoseconds at wavelengths of 1.38 μm [97] and 1.6 μm [96], and dual wavelength operation (1.1 + 1.3 μm) by multiwave pumping [98]. The same concept was applied to a Raman amplifier. This resulted in a 1.3 μm Raman amplifier with nearly shot-noise limited operation [97] and a hybrid Raman-bismuth amplifier [99]. The dual-gain amplifier scheme improved the overall efficiency owing to its more complete pump consumption, and also exhibited a small-signal gain up to the 18 dB level at 1.3 W. Yet one more Raman shifter realization was performed based on a Tm-Ho fiber oscillator and amplifier [47]. This produced 150 fs soliton pulses at a wavelength of 2150 nm with average power of up to 250 mW and Raman conversion efficiency of up to 62%.

The external clock was a good technique to obtain stabilized mode-locked operation. 210 MHz harmonic mode-locking with dropout-free operation was shown in [101]. An intensity modulator was used to stabilize the pulse train while the pulse characteristics were solely determined by the passive mode-locking mechanism provided by the SESAM. Yb-doped and Tm-Ho fiber lasers were synchronized to the optical clock implemented by a 1.56 μm laser diode with applied modulation [102]–[105]. In the case of the Yb-doped fiber laser, the amplified seed pulses were launched into the resonator and the seed pulses synchronized the mode-locked pulses through the cross-phase modulation taking place in the highly nonlinear fiber [102]–[104]. Since the clock signal was electronically generated, and thus benefited from inherent stability and repeatability, this unique concept provided the ultimate pulse stabilization. Tm-Ho mode-locked fiber laser synchronization was based on a SESAM optically-triggered by a 1.56 μm diode laser [105]. This method allowed the fundamental repetition rate of the cavity to be raised to the third harmonic frequency, exclusively controlled by the frequency synthesizer.

V. Active Tapered Double-Clad Fibers, and the Lasers and Amplifiers Based on Them

In 1999 Prof. Okhotnikov proposed the concept of the so-called "flared amplifier" [106], [107], where a sequence of erbium-doped core-pumped fibers with increasing diameters were used as an amplifier. Later, this idea was further developed in a series of studies devoted to active tapered double clad

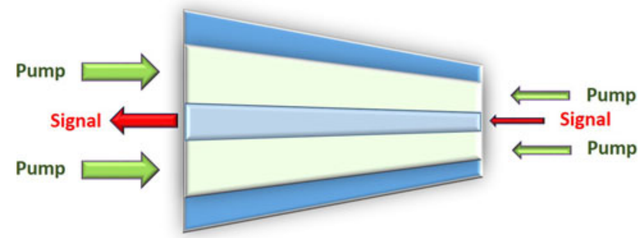


Fig. 8. An illustration of active tapered double-clad fiber.

fibers (T-DCF) and devices based on them. This research was carried out jointly by a team of scientists at TUT led by Prof. Okhotnikov, and another team at the Kotel'nikov Institute of Radio Engineering and Electronics Russian Academy of Sciences (IRE RAS, Moscow) led by Dr. Chamorovskii and Prof. Golant.

The technology of T-DCF manufacturing and production was developed at IRE RAS, while the group of scientists at TUT focused mainly on the study of the physical effects that occur in T-DCF, and the study of various T-DCF-based fiber lasers and amplifiers [108]–[125].

T-DCF is a fiber whose outer and inner claddings and core diameters vary smoothly with its length (Fig. 8).

The core at the narrow side of the T-DCF only supported propagation of the fundamental mode, whereas at its wide side the core was able to guide many modes. However, it was shown experimentally [126], [127], that the light launched into the narrow side of a T-DCF propagated in a wide core without any changes to the mode content. As a result, at the wide (essentially multimode) side of the T-DCF, the light coupling out contained a fundamental mode but with excellent beam quality. Thus, tapered fiber was a unique and easy way to implement fundamental mode regime propagation (and amplification) in the multimode fiber.

Experimentally, single-mode propagation in a fiber with a 120 μm core diameter [126] and even 200 μm [121] with a core NA equalling 0.11 was achieved. The large core diameter of the T-DCF allowed record values of peak power and energy to be reached without any significant non-linear distortions. Moreover, there seemed to be no practical limitations to the use of T-DCF as it could span a 30 cm size coil without any negative affect on its performance.

Due to its specific geometric configuration, T-DCF has a number of advantages, which make it very competitive with other types of fibers used for high power lasers and amplifiers. It is characterized by:

1) an extremely large core (up to 200 μm) and cladding (up to 1.6 mm) diameters;
2) more efficient double-clad pump absorption per unit length compared with the regular (cylindrical) active double-clad fiber;
3) built-in mechanisms for the suppression of stimulated Brillouin scattering (SBS) and amplified spontaneous emission (ASE);
4) immunity to mode instability;
5) record-high ratio of pump brightness enhancement.

A. Extremely Large Core (up to 200 μm) and Cladding (up to 1.6 mm) Diameters

The large active core diameter allows a high stored energy/power ratio to be reached and, simultaneously, it significantly increases the non-linear effects thresholds (SBS, SRS, SPM). The fortunate combination of these two characteristics helped Prof. Okhotnikov's team to achieve efficient amplification of short pulses. Using T-DCF, 60 ps pulses with 300 μJ energy [124] were demonstrated - the best result so far for all-fiber MOPAs.

B. High Absorption Per Unit Length

T-DCF is characterized by better double-clad pump absorption than regular double-clad fibers with similar levels of core doping. There are two main reasons for this. On the one hand, the absorption of the T-DCF was always better due to its superior clad mode mixing [108], [114]. On the other hand, the absorption per unit length in the wide side of the T-DCF was substantially higher because of its geometry. Indeed, rare earth ions were preferably located in the wide part of the T-DCF (proportional to the square of the core diameter). This feature allows the use of preforms with relatively low concentrations of dopants (absorption in the core 300–400 dB/m only), which helps to avoid the photo-darkening effect. The high absorption also made it possible to create a really short-amplifier (a few tens of cm), which was important for the amplification of ultrashort pulses.

C. SBS and Amplified Spontaneous Emission (ASE) Suppression

T-DCFs have embedded mechanisms for the suppression of SBS and ASE. It was already well-known from the literature that diameter modulation leads to an increase in the SBS threshold [115]. This important feature was very useful for the amplification of very narrow-band signals (MHz or kHz FWHM), such as the pulsed sources for LIDARs. ASE was suppressed in the T-DCF during propagation towards the narrow end due to the violation of the total internal reflection law. This allowed a T-DCF to be exploited for the amplification of pulses with a very low duty cycle (up to "on demand" mode).

D. Immunity to Mode Instability

It had earlier been shown that spatial modulation of the core diameter along a fiber length led to an increase in the mode instability threshold [124]. This meant that T-DCF could be exploited to build lasers/amplifiers with higher output power than that of devices containing a regular DCF.

E. High Brightness Magnification Factor

A laser (or optical amplifier) is a device which improves the brightness of a powerful pump source. More specifically, the low-brightness light from a pump source is, through the absorption process, converted into an output radiation with a longer wavelength and, simultaneously, with better brightness. The maximum launched pump power is determined by the clad diameter of the DCF. Since the diameter of a T-DCF's cladding was extremely high (up to 1.6 mm [124]), it was possible to achieve a better brightness enhancement factor than could be achieved with the regular DCFs.

Thus, the fact that this fiber was relatively cheap to produce, but had a number of special properties, meant that T-DCF could be used to create a wide range of high-power devices with unique properties:

1) Ultrafast (ps and sub-ns) powerful (tens of watts) amplifiers [108], [115];
2) SBS-free amplifiers for high coherent radiation [115];
3) Powerful, actively Q-switched pulsed lasers [111];
4) Brightness converters, i.e., lasers or amplifiers pumped by inexpensive powerful pumps with low brightness (laser bar stuck, VECSELs, etc.) [108]–[110], [112].

VI. Effective Amplification and Generation of High Power Pulses in Fiber Amplifiers

It is important to note that although Prof. Okhotnikov received recognition as an outstanding experimenter, he also engaged in a lot of theoretical work. In this section we present the models proposed by him, and developed with his participation, which were aimed at the effective amplification and generation of high-energy laser pulses.

It is well-known that the maximum energy of laser pulses after their passage through the fiber amplifier is limited due to nonlinear effects, mainly phase self-modulation (SPM). The effects of solitons also limited the pulse energy in the amplifier through anomalous group velocity dispersion (GVD). Thus, to amplify the laser pulses up to higher energies, fiber amplifiers with normal GVD were widely used [127]. When a pulse propagates in an amplifier of this type, the resulting chirp at the output due to the SPM leads to the broadening of the pulse spectrum beyond the amplification band and the development of nonlinear distortions. One known way to overcome these limitations is the chirped pulse amplification (CPA) technique. [128]. The development of the technology for active fibers with low nonlinearity and a large mode area, and their implementation in multi-cascade CPA systems, allows pulses with peak power of over a GW and energy of several mJ to be obtained [129].

An alternative method actively developed in recent years is the similariton amplification of pulses with an envelope in the asymptotic form of a parabolic type [130], [131]. The generation of parabolic similaritons was also possible in fibers with a decreasing normal GVD along the length of the fiber [132]–[134]. In this case, the dispersion-decreasing increment played the role of additional gain.

An original approach proposed by Prof. Okhotnikov was to use fibers with longitudinally increasing normal GVD in the amplifying cascade scheme. The results of these theoretical investigations were presented in [135], [136]. When the pulse was amplified in sections with a rapid growth of normal dispersion along the length, the growth of the chirp was actually suppressed, which promoted efficient energy transfer from the amplification band. The use of segments with decreasing normal

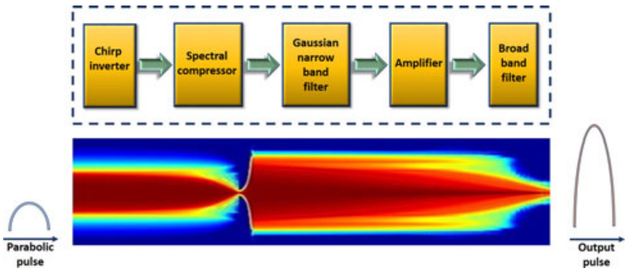


Fig. 9. An illustration of the cascade preamplifier system with spectral compression elements, and the expected evolution of the pulse spectrum.

dispersion also allowed the possibility to control the shape of the envelope and the width of the pulse spectrum, and therefore, to obtain a wide-range pulse with a linear chirp. Thus, the result of the passage of the fully fiber-amplifying cascade system was a powerful output pulse, which could be effectively compressed to powers of the order of several MW.

Another mechanism used for the reduction of SPM-induced pulse spectrum broadening was spectral compression (SC) [137]. A model of a laser pulse generator based on spectral compression and employed as a preamplifier was proposed by Prof. Okhotnikov in [138]. The essence of the theory was that the pulse spectrum can be compressed before amplification, which naturally increases the efficiency of the amplification and reduces the distortion. Technically, this method could be carried out by inversion of the pulse chirp and its subsequent propagation in a nonlinear fiber with normal dispersion. The use of the cascade scheme not only allows the spectrum to be narrowed, but also increases the energy of the initial pulse, i.e., this model could be considered as a preamplifier. One variant of this scheme is shown in Fig. 9. The presence of several filter elements was essential for smoothing out the distortions.

The main advantage of the model was that it offered a method of effectively amplifying chirped pulses with an initially wide spectrum, for example, parabolic laser pulses with a high normal dispersion of the resonator. Additionally, the possibility of obtaining pulses with a high spectral energy density should also be noted, since this could be used to tackle the problems of nonlinear frequency conversion and the generation of high harmonics, etc.

VII. Conclusion

This paper has summarized the major achievements of Prof. Okhotnikov in the field of fiber lasers and amplifiers. The material covered the results of both his experimental and theoretical work. The main focus has been on the technology and architecture of fiber components, SESAMs, innovative lasers and amplifiers for different laser operational regimes. Prof. Okhotnikov's legacy in laser technology lives on at TUT and elsewhere in industry and academia and is highly valued by his many former students and collaborators. His work has had a considerable impact on the emergence of the mode-locked fiber laser industry. In 2005, Prof. Okhotnikov co-funded RefleKron Oy., a spin-off from TUT which focused on customizing SESAMs in a wavelength range from 600 nm to 3 μm. In the same vein, he had collaborated closely with leading fiber-laser industry players, in particular with Fianium Ltd. Most recently, he was instrumental in the creation of Amliconyx Oy, a TUT spin-off focusing on developing products based on tapered-fiber amplifier technology.

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