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HABILITAČNÍ PRÁCE

Samovolné rozmítání vlnové délky vláknových laserů

Self-sweeping of laser wavelength in fiber lasers

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Poděkování

Tato habilitační práce shrnuje poznatky ze studia samovolného rozmítání vlnové délky vláknových laserů, jakožto speciálního případu nestability podélných módů rezonátoru. Práce je pojata jako komentovaný soubor časopiseckých prací na dané téma. Časově zahrnuje období posledních deseti let, od prvních našich pozorování tohoto jevu až po nejčerstvější práce z roku 2018 zabývající se studiem odrazivosti vláknových mřížek samovolně vytvářených v rezonátoru laseru. Práce mohla vzniknout díky podpoře několika projekty, zejména projektem Ministerstva školství, mládeže a tělovýchovy "FILA-Kompaktní celovláknové lasery s pasivním Q-spínáním a vysokým výkonem" (program Kontakt) a projektem Grantové agentury České republiky "Samovolné rozmítání vlnové délky a související nestability vláknových laserů". V posledních deseti letech jsem se věnoval i dalším tématům jako je studium šíření čerpání v dvouplášťových vláknech, komponenty a aktivní vlákna pro lasery generující záření ve spektrální oblasti v okolí 2 μm nebo spektroskopie vláken dopovaných prvky vzácných zemin. Výsledky z těchto oblastí výzkumu nejsou přímo součástí habilitační práce, proto jsou alespoň zmíněny v úvodní části.

Výsledků shrnutých v habilitační práci nebylo možné dosáhnout bez pomoci řady kolegů z výzkumných laboratoří v České republice i v zahraničí. Na prvním místě chci poděkovat kolegům Pavlovi Honzátkovi a Ivanovi Kašíkovi za každodenní nezištnou a obětavou podporu a rady. Dále Pavlovi Koškovi a Petru Navrátilovi, které jsem měl možnost doprovázet při jejich doktorském studiu, Janu Aubrechtovi, Filipu Todorovovi, Ondřeji Podrazkému a všem ostatním kolegům z týmu "Vláknové lasery a nelineární optika" Ústavu fotoniky a elektroniky (ÚFE) Akademie věd ČR. Velký přínos zejména k prvotním experimentálním pracím měli Radan Slavík, dlouholetý kolega z ÚFE, který od roku 2009 působí v Optoelectronic Research Centre při Univerzitě v Southamptonu v Anglii, a prof. Václav Kubeček s kolegy z katedry fyzikální elektroniky FJFI ČVUT v Praze. Prof. Kubečkovi, prof. Jiřímu Čtyrokému a Mirkovi Karáskovi rovněž vděčím za to, že mi dali možnost se věnovat vedle výzkumu i výuce a vedení studentů.

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Za velkou trpělivost a uvolnění od napětí v práci děkuji své manželce Veronice, dcerám a mamince.

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1 Scope of this thesis

The theses offer a review of author's investigation of laser wavelength self-sweeping in fiber lasers since the first notice of the effect almost ten years ago. The theses begin with introduction about the fiber lasers; the fields closely related to the authors' actual research interests, others than the main topic of thesis, are also mentioned. The introduction is followed by comments to the collection of research papers starting from explanation of the self-sweeping effect and the first observations of the self-sweeping in ring and Fabry-Perot cavities of ytterbium fiber laser, to description of the associated self-pulsing, observation of self-sweeping in fiber lasers with other active media and, finally, to investigation of the reflectivity of fiber Bragg gratings that are spontaneously created along with the self-sweeping effect. The first section is concluded with remarks concerning mainly the research prospects in the field and, finally, with references.

1.1 Introduction

Fiber lasers are generally considered as one of the youngest and most rapidly developing branch of lasers. In fact, we may observe waves of increased interest in fiber lasers in time driven by various motivations and societal conditions [1-5]. The first fiber laser was proposed in 1960 by Elias Snitzer [6], even before the first ruby laser of Ted Maiman [7], and before the first single-mode optical fiber of Erich Spitz [8, 9]. Indeed, the neodymium-doped fiber laser was experimentally demonstrated soon after the fiber laser proposal [10]. However, the research of fiber lasers was then interrupted for about a decade. New interest came with laser diode pumps [11]. Due to low power of the laser diodes the research become silent until the fiber lasers devices were re-invented in mid-80's as the erbium-doped fiber amplifiers (EDFA) become almost ideal amplifiers for the telecom systems operating around 1550 nm [12, 13].[1] The EDFA revolutionized the world of telecommunications and fueled the global boom of the internet in 90's. A second revolution started just at the beginning of the third millennium. With the availability of high-power, high brightness diode lasers to pump rare-earth-doped double-clad fibers, the race for high power from ytterbium-doped single mode fiber lasers began.

The high-power operation of fiber lasers was enabled mainly by the invention of cladding pumping within a double-clad (DC) fiber structure. Such a fiber serves as an efficient transformer of the low-brightness, high-power radiation of the laser diodes (coupled into the large area inner cladding of the double-clad fiber) into a high-brightness, high-power laser beam coming out from the rare-earth-doped, narrow fiber core, see Fig. 1. This form of cladding pumping was first proposed by Robert Maurer in the seventies [16] and later demonstrated by Elias Snitzer [17]. Independently, the cladding pumping was investigated by research group of Valentin P. Gapontsev in the Institute of Radio Engineering and Electronics (IRE) of the Academy of Sciences in Frjazino near Moscow and they proposed an elegant and efficient all-fiber pump and signal combiner based on side-pumping scheme [18-20].[2] Since the most common circular shape of optical fibers provides poor effective absorption of the pump, various cross-sectional shapes of double-clad fibers have been investigated both experimentally and theoretically in order to enhance the absorption of the

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[1] In the region of the Czech Republic, the first working rare-earth-doped fiber was fabricated 18 July 1990 in the Czechoslovak Academy of Sciences by Vlastimil Matějec and coworkers and the laser action was demonstrated soon after by Jiří Kaňka and coworkers in the fiber sample no. P321 [14, 15].

[2] The first Czech cladding-pumped fiber laser was demonstrated in 2003 by Václav Kubeček and Alena Zavadilová and coworkers in the Czech Technical University using the erbium- and ytterbium-doped double-clad fiber made by the group of Vlastimil Matějec and Ivan Kašík in the Institute of Radio Engineering and Electronics (ÚRE), now Institute of Photonics and Electronics (ÚFE) of the Czech Academy of Sciences [21-23].

multimode-pump. These shapes include a D-shaped (shown in Fig. 1), hexagon, octagon, flower, stadium, air-clad, stress-elements inclusion, spiral-cladding, air-hole inclusion and several other shapes having broken-circular symmetry, see examples in Fig. 2. The beneficial effect of mode mixing of the pump radiation by unconventional coiling was also observed experimentally [24, 25], see Fig. 3(a). With the recently reported rigorous theoretical description of the mode mixing [26, 27], the new research direction of optimization of the double-clad active fibers was opened and the very first promising designs have been already published [28], see Fig. 3(b), and [29], see Fig. 3(c).

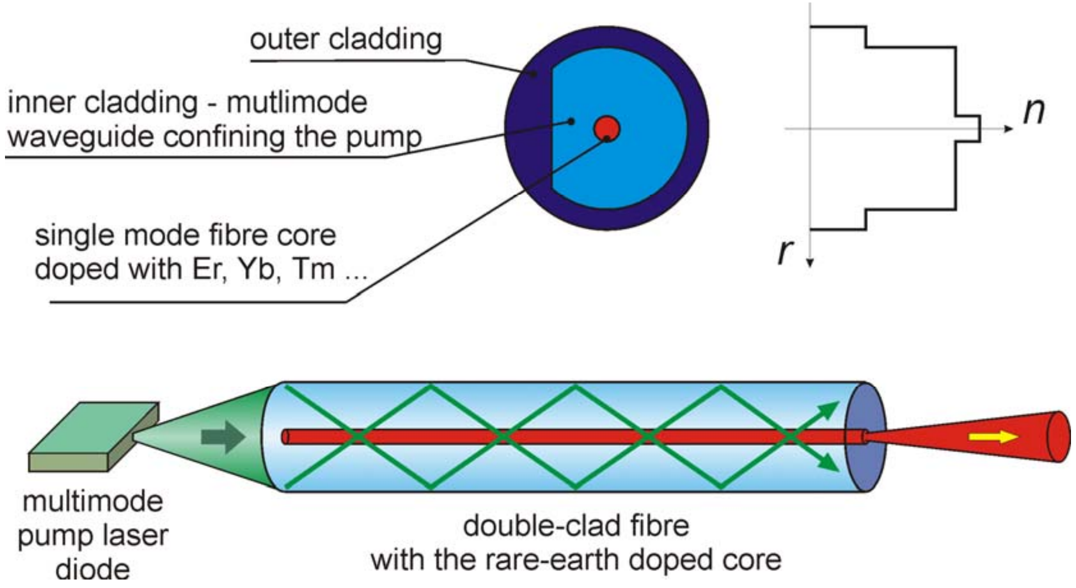


Figure 1. The principle of the cladding pumping of the DC active fiber: cross section of the DC active fiber, transversal refractive index profile and transformation of the high-power, low-quality (highly divergent) pump beam into high-power high quality (low divergent) laser signal.

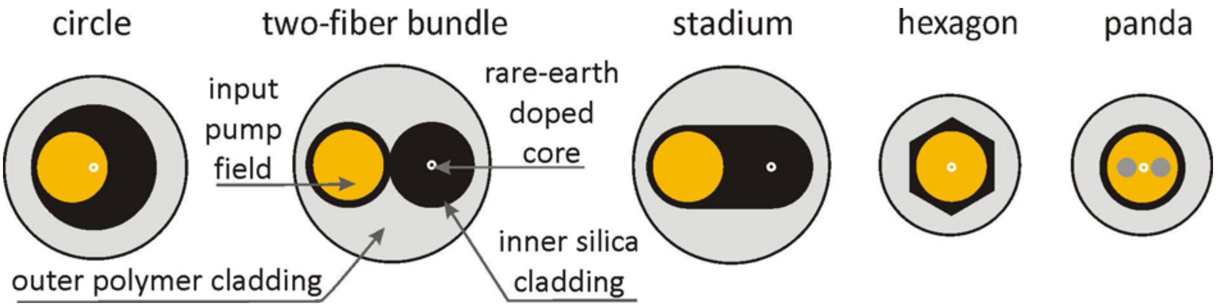
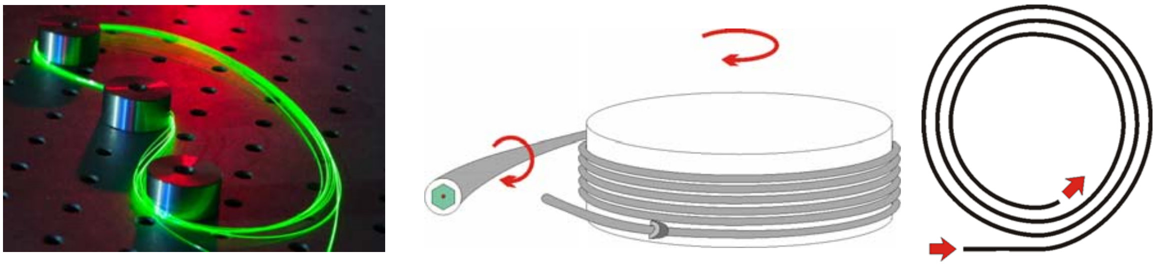


Figure 2. Examples of DC fiber cross sections of the inner cladding; yellow part schematically represent possible input pump distribution.

Main research effort was initially devoted to ytterbium-doped fiber lasers at wavelength at around 1 µm, with the dominant industrial applications in material processing. Ytterbium-doped fibers exhibit low quantum defect (the difference between the laser wavelength and the optical pump wavelength is very small) that helps to solve the active fiber cooling because the excess heat is relatively small. Other advantages are simple energy level structure (and correspondingly small effect of harmful energy upconversion processes) and almost 100 % radiative transition from the upper laser level of ytterbium near 1 µm even in the silica glass with high phonon energy. Similarly, erbium still exhibits almost 100 % radiative transition at 1.5 µm. However, the laser transitions at longer wavelengths at around 2 µm in holmium and thulium-doped fibers are strongly affected by the non-radiative, phonon assisted transitions that decrease the emission quantum efficiency to much lower levels, e. g., only about 10 % in the case of 2 µm laser transition in silica-based thulium-doped fibers [30].



(a) **(b)** **(c)**

Figure 3. Examples of fiber layout for improvement of pump absorption efficiency: (a) kidney-shaped spool, (b) twisted fiber on a standard circular spool, and (c) spiral spool. Spiral spool offers slowly varying effective absorption cross section through change of coiling diameter.

Even in the favorable case of ytterbium-doped fibers, great number of fiber design and material issues has to be solved to allow the increase of the output power and to mitigate number of limiting effects like stimulated Raman and Brillouin scattering (SRS, SBS), cooling capabilities of the fibers, launched pump power, background losses, low effective pump absorption, transverse mode-instabilities, optical damage and photodarkening [3]. It is well known that mitigation of an unwanted effect has to be done taking into account other effects. For example, the low effective absorption of the pump in double-clad active fibers can be solved by using longer fiber but it is in contradiction with the effect of background losses and especially with the detrimental nonlinear effects that scale proportionally with the fiber length. The major breakthroughs in novel fiber designs involve the invention of large mode area (LMA) fibers, typically achieved by making large cores with lower numerical aperture, and methods to maintain single mode operation of LMA fibers [31], invention of various kinds of components and fiber designs for efficient coupling and combination of the optical pump and laser signal into the double-clad active fiber [3, 18, 19], microstructure and air-clad designs of the double clad fiber and very large mode area rod-type fibers for high pulse energy amplification. The output power levels emitted out of single ytterbium-doped fiber laser source reached the theoretical level of about 20 kW [3]. Such high average power was achieved thanks to the so called tandem pumping where the last stage of the laser amplifiers is not pumped directly by multimode laser diode as shown in Fig. 1 but it is pumped by multiple of high brightness fiber lasers.

This is the early millennia boom of fiber laser research that gives the general notion of fiber laser being the youngest branch of lasers. Nowadays, we are witnessing new wave of interest in fiber lasers that coincide with emerging new applications in many areas of human activities, including new fast manufacturing processes (e. g., for the so called factories of the future), robot-based processing, processing of new materials/organic electronic, solar cell mass production, healthcare, light sources in biophotonics, environmental control and security applications. For the new applications of fiber lasers, the race for the highest power is usually not the priority, but the fiber laser devices with tailored performance, e. g., unconventional wavelengths, tailored beam shape, small footprint, high efficiency, are often required.

The author and his coworkers contributed in many aspects to the research of fiber lasers, e. g., in the study of coherent combination of Tm fiber lasers [32], modulational-instability-based ultrafast fiber lasers [33], preparation of twin-core fibers [34] and long-period fiber gratings [35] for fiber lasers; and range of active fibers doped with Er/Yb [36], Ho [37], and Tm [38]. They have pioneered the research of ceramic nanoparticle doping of rare-earth-doped silica fibers using Modified Chemical Vapor Deposition (MCVD) method [39, 40]. They developed rigorous theoretical description of the mode mixing in DC fibers that opened new way to design and optimization of high-power fiber lasers [26, 27, 41, 42] as well as new solutions for pump and signal combining [36, 43]. Last but not least they contributed to the discovery of laser wavelength self-sweeping in fiber lasers [35, 44] that is subject of this theses.

1.2 Self-sweeping of fiber laser wavelength and its physical origin

Spontaneous or self-induced laser line sweeping (SLLS) is a special case of self-pulsing, longitudinal-mode instability of a laser cavity. The designation of the effect reflects the fact that the self-pulsing coexists with spectacular laser line drift with time. Examples of the laser cavities where the self-sweeping effect was observed and examples of the laser line drift are shown in Fig. 4 and 5, respectively. Most of the SLLS fiber lasers described in the literature were configured in a Fabry-Perot resonator although other cavity arrangements are possible. In fact, it was the ring cavity in Fig 3(b), where such laser wavelength drift in the range of 1076-1084 nm was for the first time briefly mentioned [35]. This observation was taken in November 2008 while we were investigating applications of band-stop filters based on long-period fiber grating (LPFG) for stabilization of laser output and determination of laser wavelength.[3] We studied the effect in various cavity setup and pump powers but we had not found suitable explanation for the effect. The slow dynamics of the sweeping led us to attribute the effect to temperature dependence. On the other hand almost perfect periodicity and long term stability of the wavelength drift was in contradiction with the temperature origin. Since the paper [35] was aimed at improving stability of a continuous-wave operation of fiber ring laser and since we were not sure about correct explanation of the self-sweeping, we mentioned the wavelength drift only shortly in the paper. Our measurements of the year 2008 we published in more detail only in 2012 [44, 46] together with new measurements in Fabry-Perot fiber laser cavity. The first detailed journal papers on this subject were published in 2011 [47, 48]. Kir'yanov and Il'ichev [47] introduced the abbreviation SLLS for the observed phenomenon and it is often adopted since then. As an active medium, they used Yb-doped double clad fiber in a two-fiber bundle configuration, so called GT Wave. The cross section of the GT Wave waveguide structure can be seen Fig. 2. Ivan Lobach et al. [48] used similar fiber as it was used in [35]. They found notably excellent explanation of the spectacular self-sweeping effect. Their explanation were inspired by Victor Sergeyevich Pivtsov who recall his earlier observation of the self-sweeping in Ruby laser, though in limited range of about 20 pm only [49]; self-sweeping was also observed in unidirectional ring dye laser that swept in the interval of about 100 pm [50].

The SLLS can be explained by a spatial-hole burning (SHB) in the active fiber. At laser threshold, the laser may radiate at single longitudinal mode that create standing wave in the cavity. The population inversion is less depleted at nodes, where the laser intensity is minimal, than at anti-nodes of the standing-wave, where the laser signal intensity is high. Therefore, the initially lasing longitudinal mode quickly becomes less preferred than the neighboring longitudinal modes as its gain decreased. The laser wavelength hops to the next

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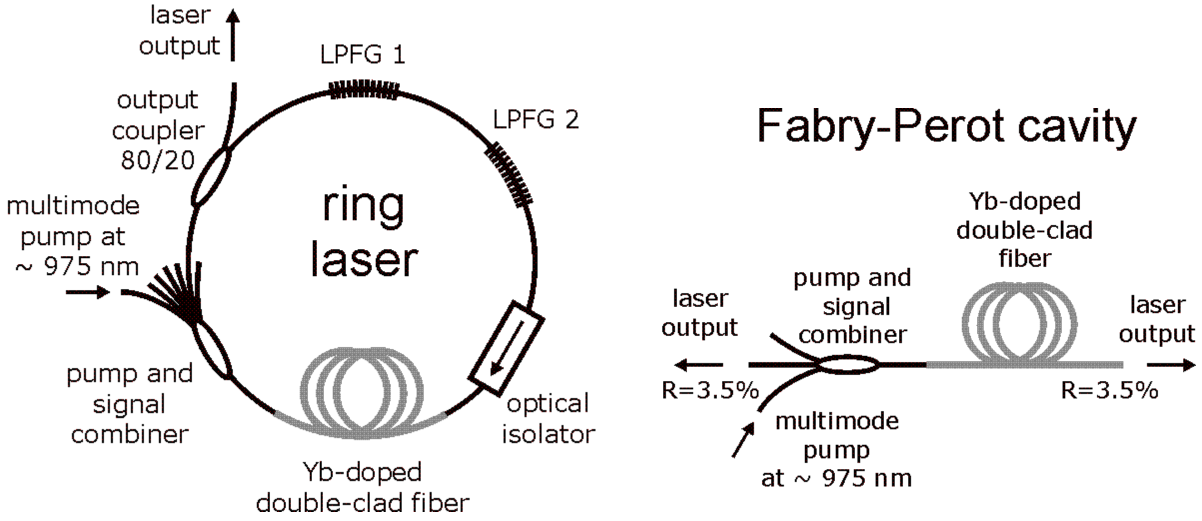
[3] Earlier observation was taken in Yb-fiber laser in Fabry-Perot setup in the Czech Technical University in spring 2008 [45]. However, the sweeping was not recorded and studied in details as it was in the case of the ring laser.

longitudinal mode and the situation repeats as long as the spectral gain exceeds the cavity losses. Then the longitudinal mode jumps back approximately to the position of the initial laser wavelength. Note that in the case of fiber ring laser, the standing wave was created by interference of the laser signal with parasitic reflection from unintentionally left perpendicular cleave of the output coupler, see Fig. 4(a). The wavelength sweeping is quasi-continuous because it respects the longitudinal mode-instability of consequential mode hopping. Since the fiber laser cavity is typically couple of meters long, the spectral hops are rather small, e. g., about 10 MHz for 10 m long Fabry-Perot cavity or 20 m long ring laser cavity. It should be noted that the width of the detected spectral line in Fig. 5(a) does not correspond to the actual line width but reflect the spectral resolution of the spectrometer used, which was about 1 nm. Typically, the laser output is composed of single-longitudinal mode or few-longitudinal modes and the linewidth is below 10 MHz. Spectral recording in Fig. 5(a) is also influenced by rapidly falling sensitivity of the silicon-based CCD photodetector of the used spectrometer. The laser emitted at around 1080 n, it means it emits on the near-infrared edge of the photodetector sensitivity. In fact, the amplitude of the laser output decreases much less from the beginning of the sweeping interval towards its end.



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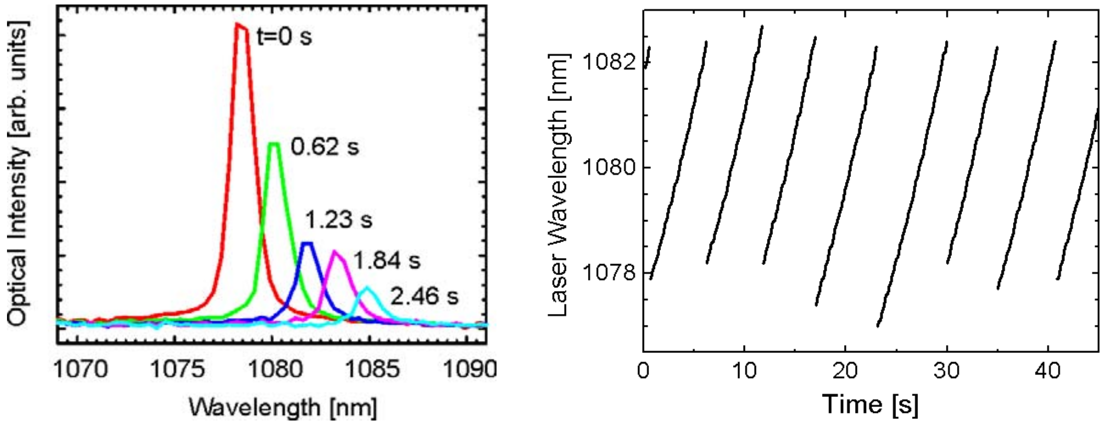
(a) **(b)**

Figure 4. Examples of fiber laser setups in which the wavelength self-sweeping was observed: (a) Fiber ring laser with optional long-period fiber gratings for selection of spectral region of sweeping; (b) fiber laser in Fabry-Perot configuration.

From the spectral point of view the self-written grating exhibit itself as an inhomogeneous gain broadening. The gain/loss spectrum is then modulated by a function proportional to $sinc(C(\lambda-\lambda_0))$ where the constant C depends primarily on the grating length and λ_0 is the wavelength of the narrow-bandwidth, high-power beam, see Fig. 6. Such a spectral modulation is known from applications in erbium doped fiber lasers, e.g., narrowing and stabilization of the linewidth of erbium doped fiber laser can be achieved by SHB in twin-core fiber with cores doped with erbium [51]. Modulation of the laser cavity spectral loss by the function $sinc(C(\lambda-\lambda_0))$ is apparent, e. g., from results of detailed numerical modeling of the laser with erbium-doped twin-core fiber tracking filter in [51]. Lobach et al. assumed in their explanation of the SLLS that the integral inversion population along the fiber change significantly in time. Typically, the population inversion is higher before the threshold and correspondingly the spectral gain curve, see the blue curve in Fig 5(a). As the spectral peak of the gain shifts towards longer wavelength with decreasing excited level population, such explanation implicates that only sweeping towards longer wavelengths is possible. However, we reported later also sweeping in reverse direction, i. e., from longer towards shorter wavelengths [52-54]. Therefore, the theoretical description in [48] became no longer valid in regard to the initiation of sweeping and setting the direction of the wavelength drift. The explanation of the self-sweeping had to be modified.

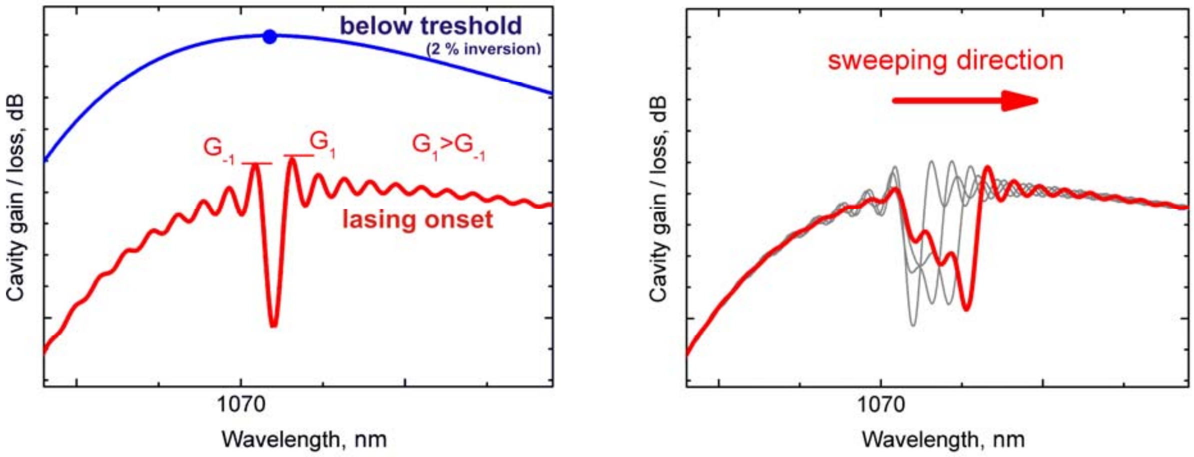


(a) **(b)**

Figure 5. (a) Spectra of the SLLS laser output radiation at several time instants during one sweep period. The resolution of the spectrometer was 1 nm. (b) Example of the recording of the laser wavelength in time.

One possible explanation of the SLLS is based on an assumption that the temporal variation of the spectral gain (without taking into account the SHB) is significantly lower than the modulation of spectral gain by $sinc(C(\lambda-\lambda_0))$ because of the SHB and the associated gain grating. Under this assumption, the direction of sweeping is given by the slope of the gain around the peak gain at the beginning of the sweeping interval. The laser wavelength is shifted in the direction where the slope is lower, i. e., where the side peak of the gain grating is higher, see Fig. 6(a). Such a theoretical hypothesis can explain the reverse (blue-shift) sweeping direction as well as the red-shift observed in the first self-sweeping reports. However, the difference between the sidelobes of the spectral gain caused by the gain grating is very low and it is expected that other effect might be involved in the process of determination of the sweeping direction.

Another possible explanation is based on refractive index grating discussed in sections 1.4. Briefly, the longitudinal grating in inversion population (due to the SHB) causes not only spectral modulation of gain, i. e., the gain grating, but also weak modulation of refractive index through Kramers-Kronig relations, i. e., the reflective fiber Bragg grating (FBG). Such narrowband reflection can modulate the spectral losses of the cavity. In such way the actual direction of the sweeping would be determined by combination of effects of the reflective and the gain gratings. In some SLLS laser cavities the effect of the gain grating could dominate over the refractive index grating, e. g., in short cavities like the Ruby laser, while in long cavities of fiber lasers could dominate the effect of the dynamic FBG. In conclusion, the question of origin of the self-sweeping has not been answered yet fully and it is a topic of ongoing research.



(a) (b)

Figure 6. (a) Yb-fiber gain spectrum just before laser threshold and at the onset of lasing. Narrow-line laser signal creates a standing-wave that result in periodically changed population inversion along the fiber. Such a grating leads to modulation of the gain spectrum. (b) The gain spectra after four successive wavelength-mode hops. Figures are only illustrative, not in real scale.

1.3 Self-pulsing associated with the laser wavelength self-sweeping

Each longitudinal mode radiates in limited time only, it does not reach the continuous wave regime and it emits only in its temporal stage of relaxation oscillations. Therefore, the temporal output of SLLS fiber laser is a pulse train of sustained relaxation oscillations. Indeed, the sweeping rate scales with square root of an average lasing power [48, 55]. This tendency coincides with the well-known dependency of the frequency of relaxation oscillations on the average laser output power [56]. It supports the idea that the self-sweeping effect exists only along with the self-pulsing mode of sustained relaxation oscillations. Self-sweeping appears just above the threshold and it operates up to pump power levels of multiple of the laser threshold pump power.

Further increases of the pump power may lead to a self-Q-switched regime. The peak power of the giant pulses is limited by the onset of SRS. It can be of the order of several kW as it was reported for the similar setup and pump-power levels [57]. It should be noted that the transition from SLLS to self-Q-switched regime is not abrupt, but it is rather a gradual process. The sweeping regime become less regular and it is transformed into a continuous wave operation of the laser or giant pulses start to appear. Typical temporal characteristics of the output power for different pump power levels are shown in Fig. 7. It refers to the ytterbium fiber laser in Fabry-Perot configuration shown in Fig. 4(b) [58, 59]. A train of ~µs long narrow-linewidth pulses was generated in the SLLS regime. The laser in SLLS regime oscillates either in a single or only a few longitudinal modes [48] and [44]. Indeed, a sinusoidal beat signal corresponding to the interference of neighboring longitudinal modes was often detected under the pulse envelope, see details of selected pulses in Fig. 7(b). While increasing the pump power, a gradual transition of the sinusoidal signal to giant pulses shorter than 10 ns could be observed.

Such self-pulsing instability with giant pulses generation may appear unexpectedly and may have catastrophic consequences as it is well known among experimental researchers in the field of fiber lasers; "ytterbium fiber lasers are particularly notorious in this regard" wrote David Richardson et al. in [1]. For example, improperly designed rare-earth doped fiber high-power amplifier chain may inder some conditions generate intense pulses that may destroy inline components as well as the pump lasers. Despite the apparent importance of the effect of self-Q-switched instability, only little information and investigations have been reported in an open literature. Indeed, the researchers and engineers have been often satisfied when they succeeded to avoid such instability; without revealing its cause and physical principles [60]. The self-pulsation regimes have been attributed, e. g., to reabsorption in an unpumped part of the active fiber [61, 62], Raman and Brillouin scattering processes [57, 63] and ion pairs formation [64, 65]. Thanks to the stable periodic sweeping, SLLS lasers can advantageously serve as a research platform for the investigation of self-pulsing, longitudinal-mode instabilities in general. Although question about the physical origin of the self-Q-switching mode has not been fully answered yet, the investigation of the SLLS effect has already brought some important indications. The narrow-band feature of the SLLS favors the stimulated Brillouin scattering (SBS) and the distributed mirror may increase the Q-factor of the resonator. It is the longitudinal-mode instability, including SLLS as its special case, that may trigger the self-Q-switched regime, either through the SBS or due to enhanced Q-factor of the cavity by creation of highly reflective FBGs that are described in section 1.4.

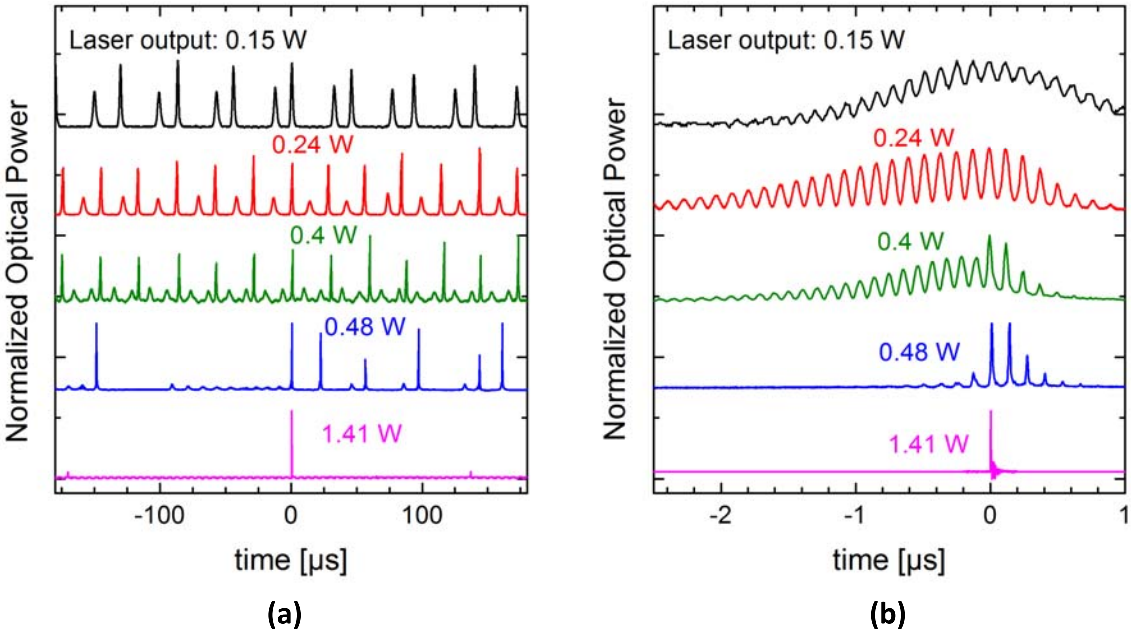


Figure 7. Temporal trace for various output powers of the fiber laser that gradually transit from the SLLS regime (laser output power 0.15 W– 0.4 W) to the self-Q-switched regime (>0.5 W). Pulse train (a) and detail of selected pulse (b). Note the beating between the neighboring longitudinal modes below the pulse envelope.

1.3 Self-sweeping in different active media

The first self-swept fiber lasers were demonstrated with ytterbium doped fibers as an active medium as it was reviewed in previous chapters. Sweeping interval of more than 20 nm was reported [66]. Spectral properties can be controlled to some extent by pump wavelength [53, 55], length of the active fiber [67] and, in particular, by different types of additional wavelength selective elements, such as wavelength division multiplexer [66], band pass filter [52] and combination of band-stop filters based on long-period fiber gratings [35, 44]. The control of the sweeping direction by the pump wavelength and pump power (and correspondingly the population inversion) was demonstrated in the case of self-swept ytterbium fiber laser, see Fig. 8-10 [46, 53]. The laser was built in Fabry-Perot configuration according to Fig. 4(b).

So far, most of the research works were about self-swept ytterbium fiber lasers. Nevertheless, the self-sweeping effect has been demonstrated in lasers with number of other active media. Xiong Wang et al. built a self-swept laser using thulium- and holmium-doped fiber that reached maximum sweeping interval of 17 nm in the emission band of thulium between 1900 and 1930 nm; spectral position and sweeping range and rate were dependent on the pump power [68]. Their laser was core-pumped by a single mode erbium fiber laser at 1570 nm.

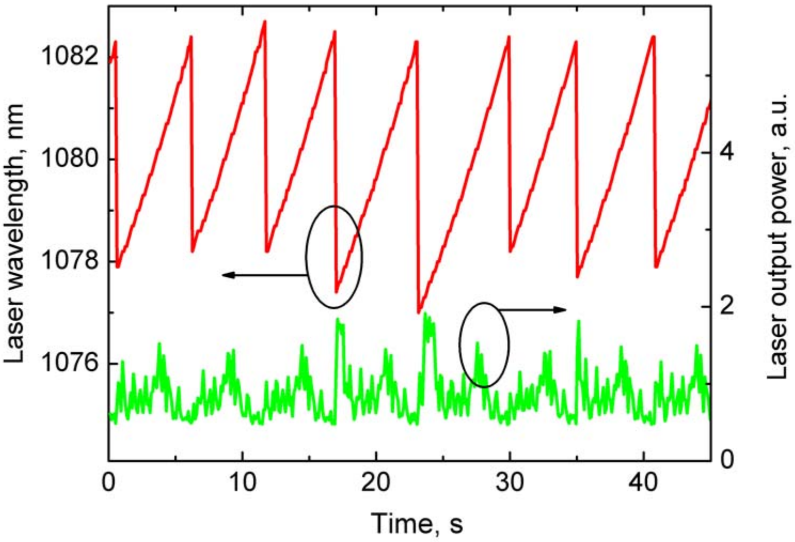


Figure 8. Typical temporal dynamics of the laser wavelength and the peak power for the regime of sweeping towards longer wavelengths, the so-called normal or redshift regime. Pump power and laser diode case temperature was 0.38 W and 40 °C, respectively. The data were collected using spectra measurements by the CCD-type spectrometer.

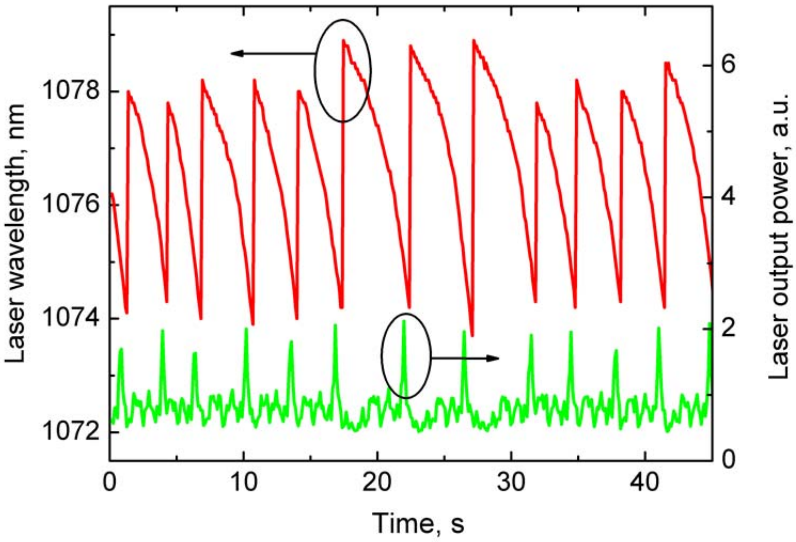


Figure 4. Temporal dynamics of the laser wavelength and the peak power for the regime of sweeping towards shorter wavelengths, the so-called reverse or blueshift regime. Pump power and laser diode case temperature was 0.28 W and 40 °C, respectively. The data were collected using spectra measurements by the CCD-type spectrometer.

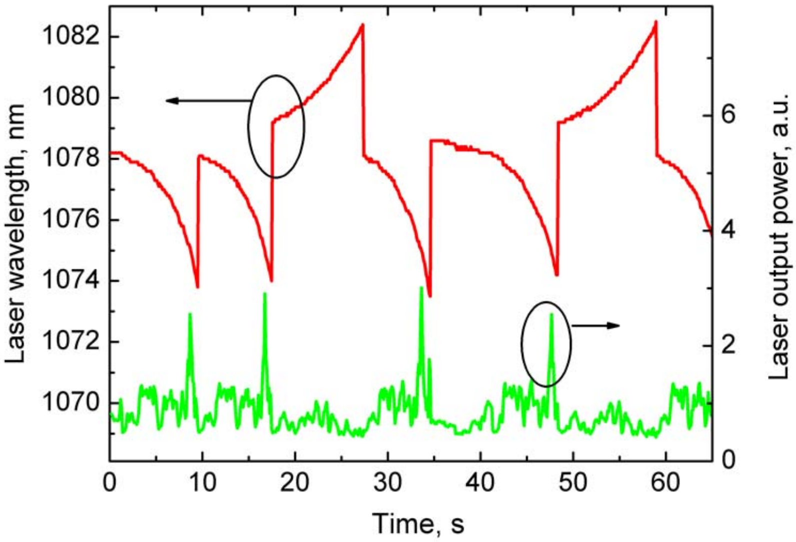


Figure 5. Temporal dynamics of the laser wavelength and the peak power for transition regime between the two sweeping directions: sweeping towards longer wavelengths and sweeping towards shorter wavelengths. Pump power and laser diode case temperature was 0.31 W and 40 °C, respectively. The data were collected using spectra measurements by the CCD-type spectrometer.

Concerning the most commonly used active fibers, i. e., erbium-doped fibers, it is not possible currently to assemble the SLLS fiber laser as easily as it is in the case of ytterbium fiber lasers. Erbium fiber laser with the SLLS effect was reported only by our team [52]. The laser operated in the SLLS mode within in the range 1541 – 1565 nm set by the tunable band-pass filter of 3 nm bandwidth. The sweeping interval was only about 0.5 nm as it was limited by the bandpass filter. Both redshift and blueshift sweeping directions were observed. Although we tested many different configurations and fibers, we achieved self-sweeping only with a tunable band pass filter. The SLLS phenomenon is not limited to rare-earth doped active media as it was observed also in a fiber laser doped with bismuth [69].

The bismuth fiber laser was pumped at 1310 nm by Raman fiber laser and operated in about 10 nm wide self-sweeping regime around 1460 nm. Thanks to long-length of the fiber laser (90 m), the small frequency separation of about 1 MHz between the longitudinal modes gives almost quasi-continuous wavelength tuning. In addition, the output was described as quasi-continuous as it consisted of densely spaced long pulses (~3 µs) that almost overlapped in time with each other. Apart from fiber lasers, reports of self-sweeping in ruby and dye lasers should be mentioned [49, 50].

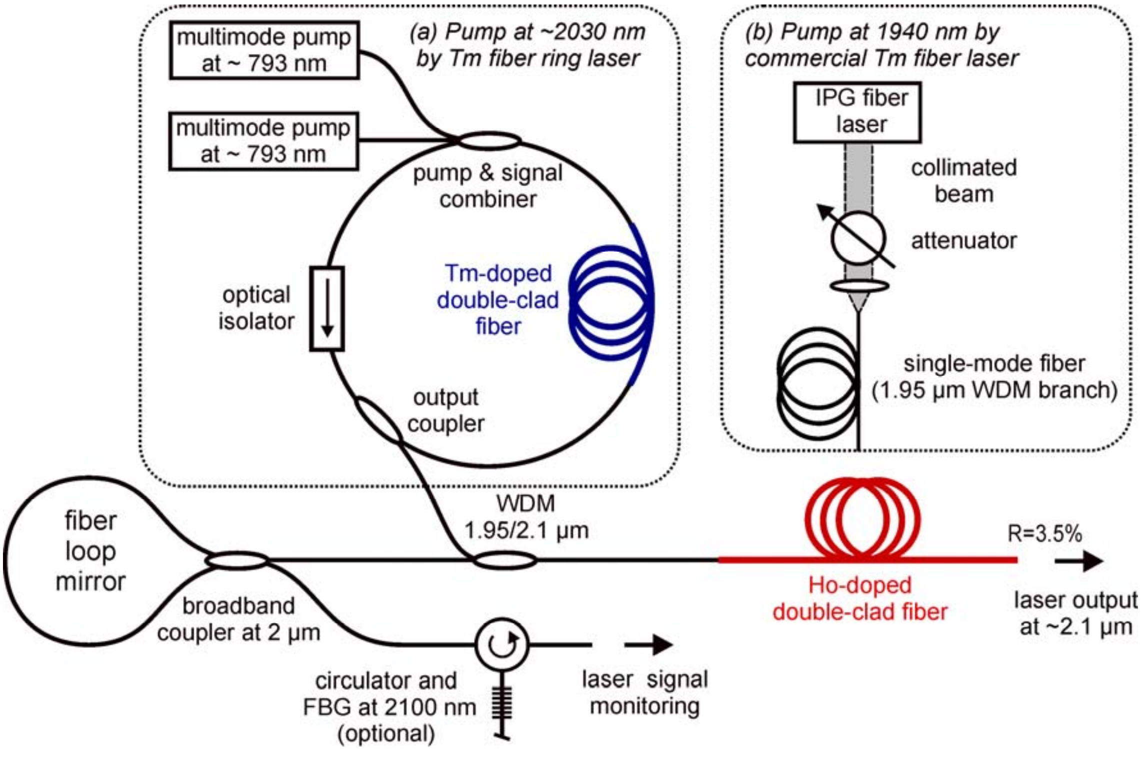


Figure 9. Experimental setup of the holmium-doped fiber laser pumped by Tm-doped fiber ring laser at around 2030 nm (a) and by a commercial fiber laser at 1940 nm (b).

The latest successful SLLS demonstration was achieved around 2100 nm thanks to stimulated emission of radiation in holmium where blueshift sweeping in 4 nm wide interval was observed [54]. However, the sweeping was not that stable in time as it was the case in ytterbium fiber lasers; it lasted only for couple of minutes and then it transferred into irregular longitudinal-mode instability self-pulsing. After cooling down the holmium-doped fiber, the SLLS could be again set into operation. The laser was pumped by in-house built thulium-doped fiber laser emitting at around 2020 - 2030 nm. We tested the same holmium fiber in the Czech Technical University by using commercial thulium fiber laser emitting at 1940 nm but only self-pulsing, longitudinal-mode instability regime was established and we did not see the regular self-sweeping regime; both types of pumping were compared in reference [70].

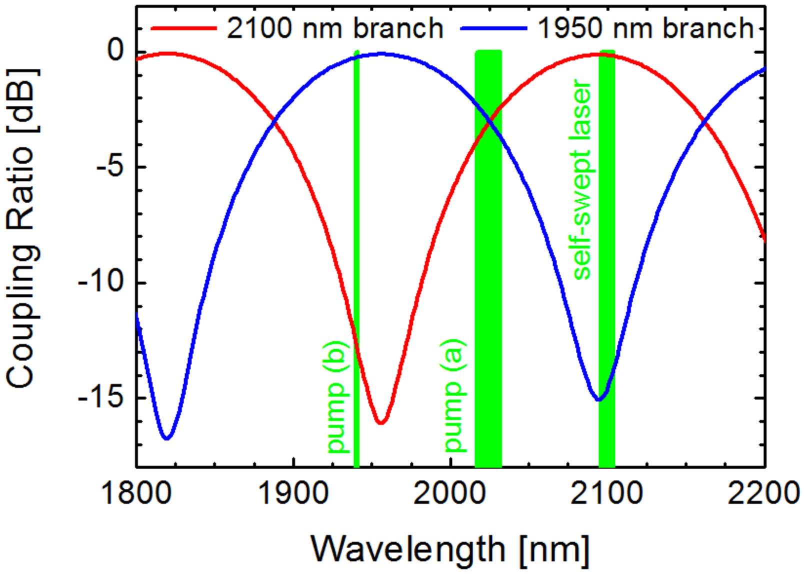
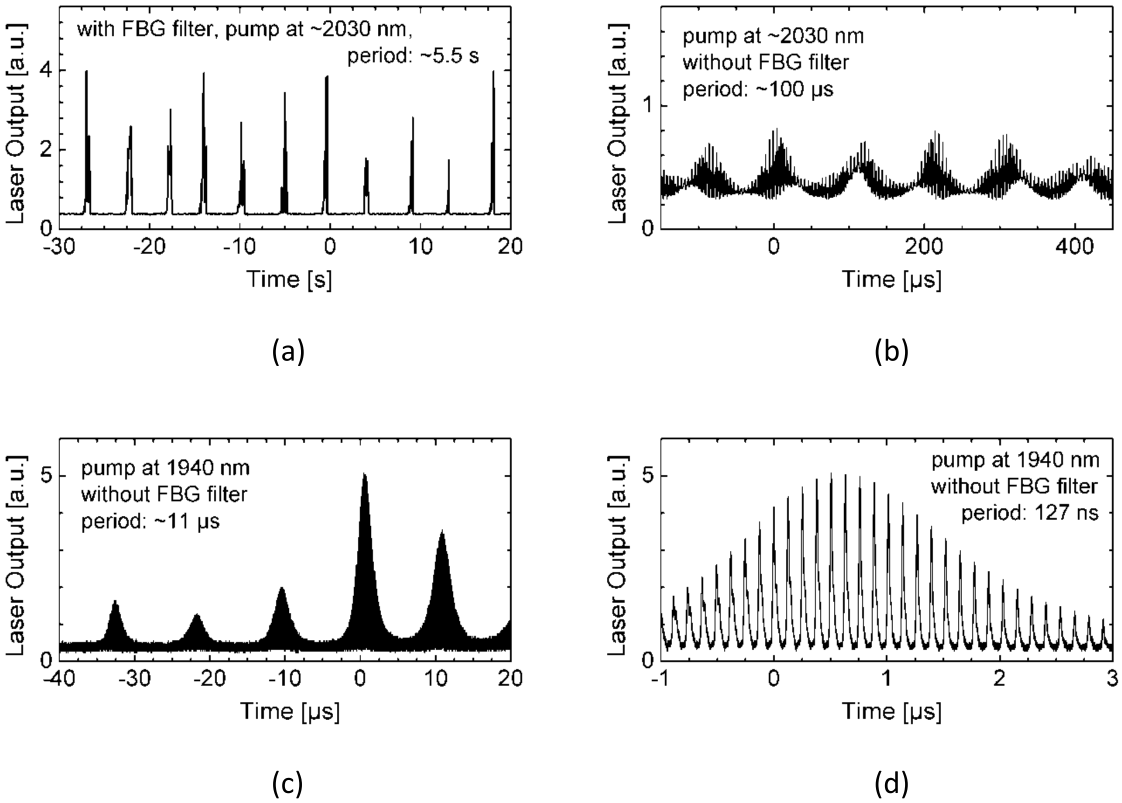


Figure 10. Transmission of the wavelength division multiplexer. Wavelengths of the pump lasers and signal are illustrated in the figure. Note that the resolution of FTIR spectrometer was set to 16 nm. Therefore, the water vapor absorption around 1950 nm as well as the minima of the coupling ratios are not resolved.

The experiments with holmium fiber laser are described here in more detail in order to show an example of self-swept fiber leaser other than ytterbium-doped fiber laser. The SLLS regime was observed in Fabry-Perot cavity configuration with low reflectivity of the output mirror of 3.5 %, see Fig. 9. The other mirror was formed by the highly-reflective fiber-loop mirror made of 3 dB coupler with broad and flat spectra transmission characteristics around 2 micrometers. Residual part of the laser radiation in the fiber-loop mirror was coupled out from the cavity through the other branch of the coupler. Then, this branch was used for monitoring of the laser signal and correspondingly for monitoring of the laser output temporal behavior. The InGaAs photodiode with oscilloscope were connected either through a circulator and FBG written into standard single mode fiber at 2100 nm, so that only laser signal in close proximity to 2100 nm was detected, or directly using that branch of the coupler. The fused fiber couplers were fabricated from G.652 fiber [37, 71]; measured coupling ratio of the wavelength division multiplexer 1.95/2.1 µm is shown in Fig. 10. Temporal traces of the laser output when the laser was pumped at ~2030 nm are shown in Fig. 11 (a,b). The self-sweeping operation can be clearly identified from the temporal output behavior recorded using the FBG and the circulator, see Fig. 11 (a). The SLLS period is ~ 5.5 s. Without the circulator and the FBG, we detected the typical train of sustained relaxation oscillations, see example in Fig. 11(b). Individual pulses may contain fine substructure of mode beating of neighboring longitudinal modes. The period of the mode beating corresponds to the roundtrip time or its integer multiple. In the case of pumping at 1940 nm, we tested various fiber lengths from 8 m down to 5 m.



(a)

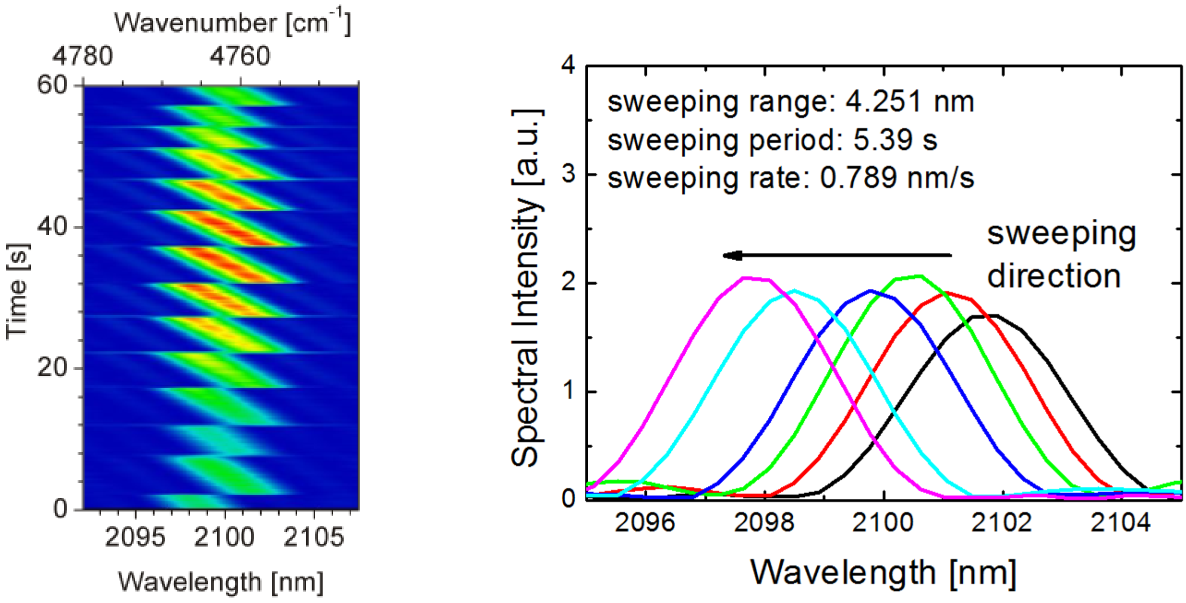
(b)

(c)

(d)

Figure 11. Temporal characteristics of the laser output traces beyond the FBG filter at 2100 nm and the circulator recorded by the oscilloscope for the case of pumping at ~2030 nm (a). Temporal characteristics (b,c,d) were recorded without the FBG filter and the circulator. The pump wavelength is shown in the respective figures. Longitudinal mode-instability and mode beating was observed also for the case of pumping at 1940 nm (c,d).

The time evolution of the spectra was recorded by the Fourier-transform infra-red spectrometer Nicolet 8700. We used the so-called time series mode of the spectrometer, in which fast spectrum recording was performed consecutively within a specified time interval, e. g., 60 seconds. Example of such a time series recording is shown in Fig. 12. The spectrometer linear scan velocity of 2.53 cm/s and low resolution of about 3 nm (8 cm^{-1}) were set in order to allow fast scanning and in order to obtain more spectra within one sweep. We observed SLLS with 3-6 nm span of laser wavelength sweeping at around 2100 nm and the sweeping rate was typically 0.7-0.9 nm/s.



(a) (b)

Figure 12. Sweeping of the laser wavelength recorded by the FTIR spectrometer in color contour plot just after the laser was switched on (a) and selected spectra slices of the time series recorded within one sweep (b). Note that the resolution was set to 3 nm in order to allow fast recording of the time series spectra.

1.4 Reflectivity of dynamic gratings in self-swept fiber lasers

Longitudinal mode instabilities in fiber lasers may induce periodic modulation of inversion population in the active medium through the SHB effect. Since the spectral absorption and emission of the gain media and its refractive index dispersion are related through the Kramers-Kronig relations, it means that the periodic modulation of inversion population creates also a grating in refractive index. Such gratings have pitch of less than a micrometer, defined by half of the wavelength of the laser mode responsible for the grating build-up. The effect of standing waves on the refractive index along the fiber is known for a long time; it was even used for the creation of the first ever FBG by Ken O. Hill [72]. The refractive index change with light-induced change of inversion population was studied for ytterbium doped fibers in detail [73, 74]. However, despite the relatively long history of laser physics, the first evaluation of reflectivity of the FBGs spontaneously created in the active media itself [58, 59] as well as the inscription of phase gratings [75] has been reported only very recently. Since the reflectivity is significant in a wavelength range just around the lasing wavelength, it is not easy to measure the reflectivity of these FBGs experimentally. Finally, the reflection of about 5 % of such FBGs was successfully measured in a self-swept Yb fiber laser with a polarization-maintaining fiber cavity laser. For the reflectivity measurement, the probe beam was perpendicularly polarized with respect to the self-swept laser radiation [76, 77]. The fiber laser was sweeping in wavelength interval from 1047 to 1070 nm and the external probe laser was a single-frequency, linearly polarized Nd:YAG laser with about 1 kHz linewidth at 1064 nm. When the self-swept laser wavelength crossed the wavelength of the external probe beam, the dynamic fiber-Bragg gratings (associated with the instantaneous wavelengths of the self-swept laser) reflected the probe beam. Since several other effects affected the reflected probe signal and also the reflectivity of the dynamic fiber Bragg grating can be polarization-dependent, the measured ~5 % reflectivity is only rough estimation and more detailed study is needed to determine the reflectivity of the dynamic gratings experimentally. Nevertheless, the existence of theoretically predicted significant reflection was proved already experimentally.

The author of the theses developed a theoretical model of FBGs in a self-swept fiber laser that allows for estimation of spectral reflectivity of the FBGs. The model consists of several steps, as it is schematically shown in Fig. 13. Firstly, the refractive index change is evaluated without taking into account interference effects. For given laser setup and active fiber parameters one can evaluate the distribution of inversion population along the active fiber by using a comprehensive numerical model of the active medium. The model is based on simultaneous solution of laser rate equations and set of differential equations describing propagation of the radiation. An efficient algorithm and computer code was developed in house [78]. The paper [78] is about thulium fiber laser but the algorithm is easily transferrable to another active media and the transient FBGs in self-swept ytterbium fiber lasers were studied.

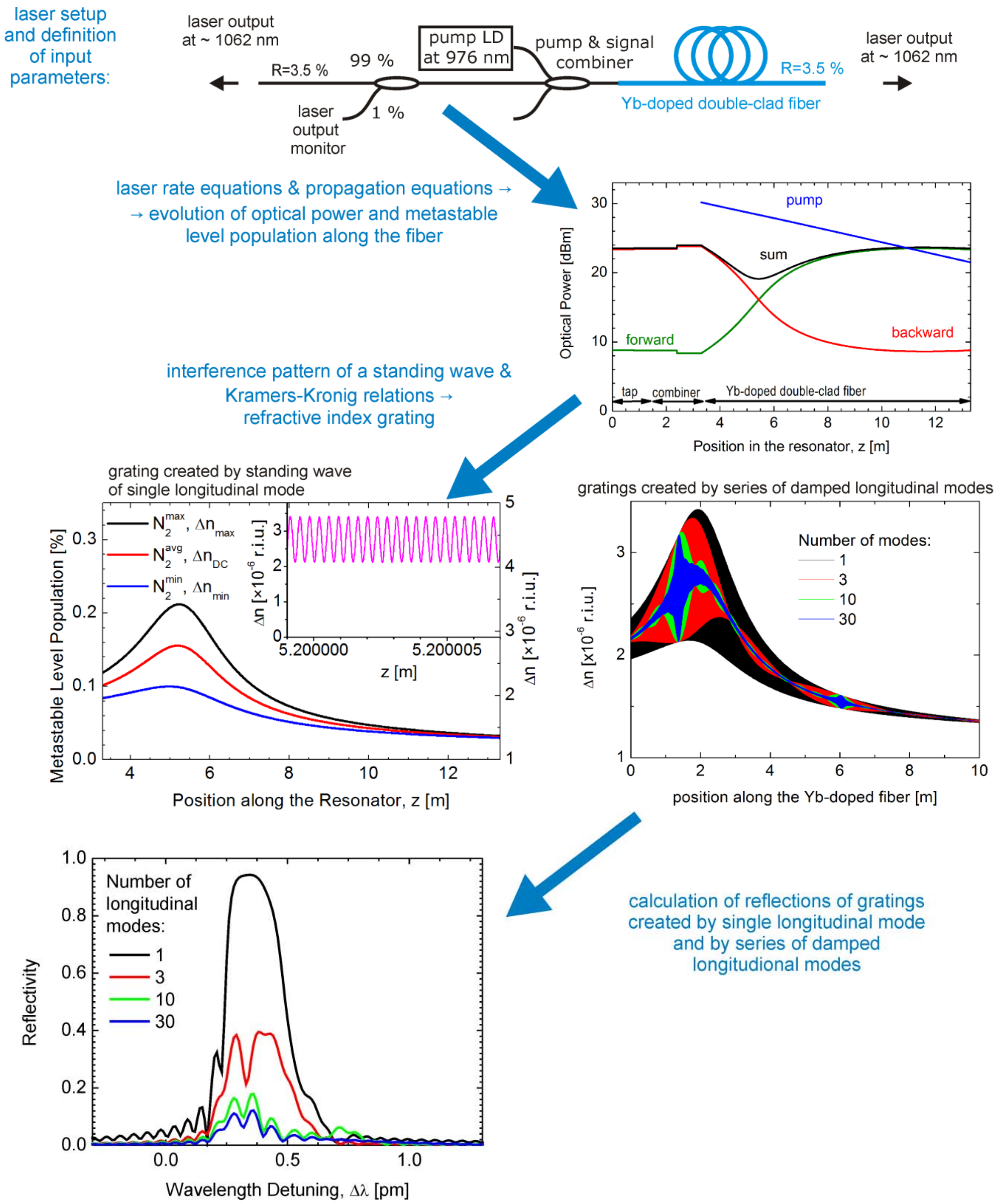


Figure 13. Steps of evaluation of reflectivity of the dynamic gratings created inside the fiber laser with longitudinal mode-instability, e. g., the laser wavelength self-sweeping. The procedure is shown on an example of Yb-doped fiber laser in Fabry-Perot cavity. Since the period of spatial modulation of the refractive index is very small comparing to the resonator length, only the envelopes of refractive index modulation between Δn_{min} and Δn_{max} is shown; Δn_{DC} is the average of the refractive index change. Sinusoidal modulation of the refractive index is assumed (shown in the inset graph).

Secondly, the interference pattern was considered in the model. Initially, only one standing wave was considered, but the model was recently modified and extended so that it can estimate reflection of more realistic case of several superimposed gratings with damped modulation depths. Such superimposed damped Bragg gratings would be created by number of successive lasing of neighboring longitudinal modes. It should be noted that sinusoidal refractive index modulation is assumed, but in fact, the modulation can be different as shown for an analogical case of spatial hole burning in the erbium-doped twin-core fiber [51]. However, the models of fiber-Bragg gratings used in the next step are based on the assumption of sinusoidal refractive index modulation.

Thirdly, the reflectivity is evaluated for the calculated refractive index grating. In the simplest case of single Bragg grating, the reflectivity of the fiber grating of the whole Yb doped fiber was evaluated by the transfer matrix method, described in detail by Erdogan [79]. In the case of superimposed Bragg gratings we have developed new theoretical model for estimation of the reflective based on coupled mode theory [80]. The model allows treating complex refractive index in order to account for gain and loss along the fiber.

The resulted spectra of FBG reflectivity show that the overall reflectivity of the series of superimposed gratings decreases with increasing number of modes involved. However, for realistic values of temporal damping of the transient gratings they can still reach significant values on the orders of units or tens of percent. The reflectivity depends on the mutual position of the interference pattern and in the ratio of the optical power of the forward and backward propagating laser signal. Therefore, the reflectivity can be to some extent controlled by parameters of the laser. We have shown the influence of the resonator length. The calculated reflection spectra correspond qualitatively to the recently reported reflectivity measurement of spontaneously created distributed Bragg mirror in a fiber laser with a similar setup.

1.5 Concluding remarks

Almost ten years of investigation of the wavelength self-sweeping in fiber lasers have brought important contributions to laser physics and technology. Significance of the results has two aspects: contribution to laser physics fundamentals and practical applications.

From the point of view of laser physics fundamentals, the SLLS fiber lasers offer unique test bed for investigation of longitudinal mode instability thanks to regular periodic nature of the effect. Significant reflection of spontaneously created FBG in the active medium of the laser was predicted for the first time. Research of SLLS helps to understand fiber laser instabilities and to find ways how to avoid them. For example, SLLS or longitudinal-mode instability in general are undesired effects in fiber lasers that are intended for cw mode of operation. In the case of self-pulsing instability like self-Q-switching it is even more important as the peak power may damage components of the laser device itself or measurement devices.

There are interesting analogies between the SLLS effect and transverse mode instabilities and mode locked lasers. Therefore, thorough understanding of the self-sweeping effect can be useful for research of other effects in fiber laser devices. The transversal-mode instability can occur in high-power fiber amplifiers, namely those formed by LMA fibers [81, 82]. The transversal mode instability is caused by creating a fiber grating with grating pitch orders of magnitude longer than the laser wavelength responsible for the grating build-up; the grating enables coupling between different transversal modes of the fiber core propagating in the same direction. On the contrary, the longitudinal-mode instability is accompanied by creating a fiber grating with grating pitch close to the half of the laser wavelength responsible for the creation of the grating; the grating enables coupling between different longitudinal modes of the fiber core propagating in the opposite direction (it works in reflection). Despite differences between the transversal and longitudinal mode instabilities, both types of instabilities are analogical in terms of creating the refractive index grating along the fiber. Therefore, the knowledge acquired in the description of transient FBG may also be useful for understanding the transversal mode instabilities.

The longitudinal-mode instability (or longitudinal-mode sweeping) is kind of unique special case of the free running regime of the laser, analogical to some extent with another unique special case of the free running regime, the well-known regime of mode-locking. In the regime of mode-locking, the longitudinal modes oscillate all together and they are locked in phase. The spectrum is broad and the pulses are ultra-short. In the regime of mode-(or self-) sweeping, the longitudinal modes do not oscillates together but they are ordered in such a way that they are hopping from one longitudinal mode to the next one. The spectrum is ultra-short (mostly single-frequency) and the pulses are broad. Since self-swept lasers emit many longitudinal modes, arbitrary-waveform, short-pulses can be synthesized in the Fourier domain [83].

From the point of view of applications, the self-swept fiber lasers may find similar use as other swept sources. Although the self-swept fiber lasers have drawbacks of slow scanning frequency and narrower sweeping interval, they are attractive for their relatively high power, simple design and inherently narrow linewidths. It makes these swept sources interesting for applications in interrogation of optical fiber sensor arrays, component testing and in laser spectroscopy. Indeed, SLLS applications in spectral testing of components with narrow spectral features [66] and for testing high-speed spectrum analyzers were demonstrated [84]. SLLS fiber laser was used for coherent Brillouin optical spectrum analyzer [85]. Slight variations of the sweeping interval start and end, see for example Fig. 5(b), can be mitigated by Michelson interferometer in the laser cavity as shown recently [86]. The stabilizing effect of the Michelson interferometer is also an indirect evidence of dynamic grating reflectivity. Another field of practical exploitation is all-fiber self-Q-switched fiber lasers because understanding of triggering mechanisms should lead to substantial improvement of all-fiber Q-switched laser sources and/or to development of stable and cost-effective self-Q-switched fiber lasers.

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2 Relevant journal papers published by the author

[1] P. Peterka, P. Navratil, J. Maria, B. Dussardier, R. Slavik, P. Honzatko, and V. Kubecek, "Self-induced laser line sweeping in double-clad Yb-doped fiber-ring lasers," *Laser Phys. Lett.* **9**, 445-450 (2012).

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2.1 Self-induced laser line sweeping in double-clad Yb-doped fiber-ring lasers

Citation:

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2.4 Self-swept erbium fiber laser around 1.56 µm

Citation:

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Appendices

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Patents

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Curriculum Vitae

Personal information

First name, Surname, titles	***Pavel Peterka, Ing., Ph.D.***
E-mail	*peterka@ufe.cz*
Nationality	*Czech*
Year of birth	*1970*

Work experience

Dates	*1993 onwards*
Occupation or position held	*senior research scientist (since 2013)*
Activities and responsibilities	*basic and applied research, project management, vice-chairman of the Supervisory board*
Name and address of employer	*Institute of Photonics and Electronics of The Czech Academy of Sciences, v.v.i., (ÚFE)* *Chaberská 57, 182 51 Prague*
Type of business or sector	*photonics, optoelectronics, optical fibers and components, optical fiber communications, lasers*
Dates	*2001-2003 (13 months in total), 2009 (6 weeks)*
Occupation or position held	*postdoctoral fellow (2001-2003), professeur invité (2009)*
Activities and responsibilities	*research in the field of optical fibers and fiber amplifiers*
Name and address of employer	*Laboratoire de Physique de la Matière Condensée, CNRS - Université de Nice - Sophia Antipolis, Nice, France*
Type of business or sector	*photonics, optical fiber communications*

Education and training

Dates	*1995-2000*
Title of qualification awarded	*Ph.D.*
Principal subjects/ skills covered	*Thesis title: "Twin-core optical fibers for fiber lasers"; teaching undergraduate courses*
University	*Faculty of Electrical Engineering, Czech Technical University in Prague (CTU)*
Level	*doctoral*
Dates	*1988-1993*
Title of qualification awarded	*Ing.*
Principal subjects/ skills covered	*Lasers and optical fibers, optics communications, photonics, physical engineering*
University	*Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague*
Level	*master*

Personal skills & competences

Management skills and competences

2014 - today: member of the Academy Assembly of the Czech Academy of Sciences (CAS)
2013 - today: Deputy head of the team of Fiber lasers and non-linear optics (ÚFE)
2013 - 2017: Member of the Council for popularization of science of the CAS
2012 - today: Vice-chairman of the Supervisory board of the ÚFE
2007-2012 secretary of the Supervisory board of the ÚFE
2000 onwards: principal or co-principal investigator of research projects of various programs and providers: National: Czech Science Foundation, Grant Agency of the CAS, Ministry of Education, Youth and Sports, Ministry of Industry and Trade;
European: Micro-and Nano Technologies (mnt-era.net), part of the 7th Framework Program.
List of current and recently completed projects is available on my employer web page www.ufe.cz

Teaching

2007 - today: Lecturer of the subject „Fiber lasers and amplifiers“ in the CTU in Prague
Supervision of master degree theses (1999 onwards) and doctoral theses (2010 onwards)

Award

2010: Special achievement award of the chairman the Czech Science Foundation for the project "Tunable active fiber components based on long-period fiber gratings" (member of the project team)

Volunteer and Professional Society Activities

2016: Co-chairman of the photonics session of the interdisciplinary symposium EU-US Frontiers of Engineering, 17 - 19 October 2016, Aalto University near Helsinki, Finland. Organizers: National Academy of Engineering (NAE) in partnership with the European Council of Academies of Applied Sciences, Technologies, and Engineering (EuroCASE)

2016: Chairman of the International Training School on Fiber Lasers & Optical Fiber Technology, https://its.ufe.cz/

2016 - today: Chairman of the conference Micro-structured and Specialty Optical Fibers, part of the symposium SPIE Optics+Optoelectronics

2014 - today: Management committee member of the European Action COST MP1401 "AFLASER"

2012 - today: Board member of the Alpha sub-program 1 of the Technological Agency of the Czech Republic

*2011 - 2015**:** Vice-chairman of the evaluation panel P102 „Electrical Engineering and Electronics“ of the Czech Science Foundation and member of its Discipline committee OK1 „Technical sciences“*

2005-2008: lecturer and local organizer of the "Open Science" project aiming at talented students and summer courses for high-school teachers

2004 - 2011: organization of "Open Doors Days" in the ÚFE

2002 onwards: reviewer of scientific papers for Applied Optics, Optics Letters, Optics Express, IEEE Photonics Technology Letters, Optics Communications, Electronics Letters and other journals

Membership

Senior Member of The Optical Society (OSA), Senior Member of The International Society for Optics and Photonics (SPIE), Czech and Slovak Society for Photonics (ČSSF) and European Optical Society (EOS)

Foreign languages

English (excellent, State language exam), Russian (good), German and French (basic)

Selected achievements since 2000

Contribution to discovery of laser-wavelength self-sweeping in fiber lasers.
This phenomenon may lead to improved fiber laser designs and cost effective pulsed fiber lasers or self-swept lasers. It can also help to reveal physical origins of several types of fiber laser instabilities, namely the triggering of self-Q-switching and longitudinal mode-instabilities. Our contribution to the discovery: first short note of the effect in fiber lasers (1076-1084 nm in Yb-fiber ring laser), explanation of the effect in ring lasers, sweeping in reverse direction, self-sweeping in erbium (~1560 nm) and holmium (~2100 nm) fiber lasers, evaluation of the reflectance of the transient fiber Bragg gratings created in fiber lasers with longitudinal mode instabilities.

Selected achievements since 2000

(continued from the previous page)

- *P. Peterka, P. Navrátil, J. Maria, B. Dussardier, R. Slavík, P. Honzátko, V. Kubeček, "Self-induced laser line sweeping in double-clad Yb-doped fiber-ring lasers", Laser Phys. Lett. 9, 445-450 (2012); and Laser Phys. Lett. Vol. 6, 732-736. (2009).*
- *J. Aubrecht, P. Peterka, P. Koška, O. Podrazký, F. Todorov, P. Honzátko, and I. Kašík, "Self-swept holmium fiber laser near 2100 nm," Opt. Express 25, 4120-4125 (2017).*

New method of coiling of double-clad fibers for fiber lasers.

The method reduces detrimental nonlinear effects and improves fiber laser efficiency. The rigorous explanation of the pump absorption in double-clad fibers for high-power fiber lasers was given for the first time. It opened new way to optimize the double-clad fiber design.

- *P. Peterka, P. Koška, O. Podrazký, V. Matějec, I. Kašík, "Optical fiber gain module, method for its fabrication and double-clad fiber laser device," CZ Pat. 305888, 9 March 2016.*
- *P. Koska, P. Peterka and V. Doya, "Numerical modeling of pump absorption in coiled and twisted double-clad fibers," IEEE J. Sel. Top. Quantum Electron. 22(2):55-62, 2016.*

Comprehensive numerical model of rare-earth doped fibers and devices.

The developed numerical model was used, e.g., for optimization of thulium doped fiber laser devices and for spectroscopic characterization of rare-earth doped fibers.

- *P. Peterka, B. Faure, W. Blanc, M. Karasek and B. Dussardier, "Theoretical modelling of S-band thulium-doped silica fiber amplifiers", Optical and Quant. Electronics, 36:201 (2004). 76 citations without self-citations.*
- *D. A. Simpson, W. E. K Gibbs, S. F. Collins, W. Blanc, B. Dussardier, G. Monnom, P. Peterka, and G. W. Baxter, "Visible and near infra-red up-conversion in Tm3+/Yb3+ co-doped silica fibers under 980 nm excitation," Opt. Express 16, 13781 (2008).*
- *P. Peterka, I. Kasik, A. Dhar, B. Dussardier, and W. Blanc, "Theoretical modeling of fiber laser at 810 nm based on thulium-doped silica fibers with enhanced 3H4 level lifetime," Opt. Express 19, 2773-2781 (2011).*

New method for pumping of fiber lasers and amplifiers.

The method is based on direct splicing of the signal and pump fibers onto asymmetric double-clad fiber od specially designed cross section. No intermediate pump and signal combiner is needed. The patented method was tested in ytterbium and ytterbium/erbium doped fiber laser devices**.**

- *P. Peterka, I. Kašík, V. Matějec, V. Kubeček, and P. Dvořáček, "Experimental demonstration of novel end-pumping method for double-clad fiber devices," Opt. Lett. 31, 3240 (2006).*
- *P. Peterka, I. Kašík, V. Matějec: "Method and device for coupling the signal and pump into double-clad optical fiber for fiber amplifiers and lasers", CZ Pat. 301215, 9 December 2009.*

Twin-core fibers for fiber lasers.

Novel designs, fabrication, measurement, numerical modelling and applications in fiber lasers, e.g., in modulational- instability-based ultrashort-pulse fiber lasers

- *P. Peterka, I. Kasik, J. Kanka, P. Honzatko, V. Matejec, and M. Hayer. "Twin-core fiber design and preparation for easy splicing". IEEE Photonics Technology Lett. 12,1656 (2000).*
- *P. Peterka, P. Honzatko, J. Kanka, V. Matejec and I. Kasik. "Generation of high repetition rate pulse trains in a fiber laser through a twin-core fiber". in Proc. SPIE 5036, 376 (2003).*

I am author or co-author of 4 patents, 46 scientific journal papers, more than 100 conference papers, and one book chapter. These works were 421 cited according to the database Web of Science (without self-citations); publication h-factor is 14. List of most of the publications can be found there: http://www.ufe.cz/en/pavel-peterka

In Prague, 24 April 2018 ***Ing. Pavel Peterka, Ph.D.***