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Czech Technical University in Prague
Faculty of Nuclear Sciences and Physical Engineering

Ing. Pavel Peterka, Ph.D.

Vláknové lasery se samovolným rozmítáním vlnové délky v širším kontextu laserové fyziky

Self-sweeping of laser wavelength in fiber lasers

Summary

This lecture summarizes results of investigation of a special mode of self-pulsing, longitudinal-mode-instability regime, so-called self-induced laser line sweeping. This description reflects the fact that the self-pulsing (in the form of self-sustained relaxation oscillations) coexists with a spectacular laser line drift over broad spectral interval of several nanometers followed by quick bounce backward. The sweeping rate is relatively slow, of the order of nanometers per second. Thanks to narrow linewidth and simple construction, the SLLS fiber lasers are attractive sources for testing of photonics components, interrogation of optical fiber sensor arrays and for laser spectroscopy.

Despite the long-history of laser physics, the effect of laser wavelength self-sweeping was discovered in fiber lasers relatively recently. This lecture is focused on our contributions to the discovery: from the first note about the effect in fiber lasers (firstly in ytterbium fiber laser, then in erbium fiber laser and in holmium fiber laser); explanation of the self-sweeping effect in ring lasers; discovery of the sweeping in reverse direction; to the first evaluation of reflectance of the dynamic Bragg gratings created in fiber lasers with longitudinal mode instabilities, like it is the case of the self-swept fiber lasers. Analogies with transverse-mode instabilities and laser mode-locking are discussed in order to put the self-sweeping effect into broader context of laser physics.

Souhrn

Tato přednáška shrnuje výsledky zkoumání zvláštního režimu módových nestabilit laseru se samovolnou generací impulzů, tzv. jevu spontánního rozmítání vlnové délky vláknového laseru. Tento popis odráží skutečnost, že samovolná generace impulzů (ve formě ustálených relaxačních oscilací) je doprovázena pozoruhodným jevem přelaďování vlnové délky laseru ve spektrálním intervalu širokém několika nanometrů s následným rychlým návratem na začátek spektrálního intervalu. Rychlost rozmítání vlnové délky laseru je relativně pomalá, řádově nanometry za sekundu. Díky úzké šířce čáry a jednoduché konstrukci jsou vláknové lasery se samovolným rozmítáním vlnové délky atraktivními zdroji pro testování fotonických komponent, pro optické vláknové senzory nebo pro laserovou spektroskopii.

Navzdory dlouhé historii laserové fyziky byl jev samovolného rozmítání vlnové délky objeven ve vláknových laserech relativně nedávno. Tato přednáška je zaměřena na naše příspěvky k tomuto objevu: od první zmínky o daném jevu ve vláknových laserech (nejprve u ytterbiového vláknového laseru, později u erbiového vláknového laseru a holmiového vláknového laseru); přes vysvětlení vzniku jevu v kruhových rezonátorech laseru; objev rozmítání v opačném směru; až k prvnímu odhadu odrazivosti dynamických braggovských mřížek vytvořených ve vláknových laserech s podélnými módovými nestabilitami, jako je například právě laser se samovolným rozmítáním vlnové délky. Za účelem zasazení jevu rozmítání vlnové délky laseru do širšího kontextu laserové fyziky jsou diskutovány jeho analogie s příčnými módovými nestabilitami vláknových zesilovačů a s režimem generace krátkých impulzů metodou synchronizace módů laseru.

Keywords

Fiber lasers, wavelength tunable lasers, narrow-linewidth lasers, cladding pumping, mode instability, fiber Bragg gratings.

Klíčová slova

Vláknové lasery, přeladitelné lasery, lasery s úzkou šířkou čáry, optické čerpání přes plášť, módová nestabilita, vláknové braggovské mřížky.

Contents

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 [1-3]. The first fiber laser was proposed in 1960 by Elias Snitzer [4], even before the first ruby laser of Ted Maiman [5], and before the first single-mode optical fiber of Erich Spitz [6, 7]. 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 [8, 9]. 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.

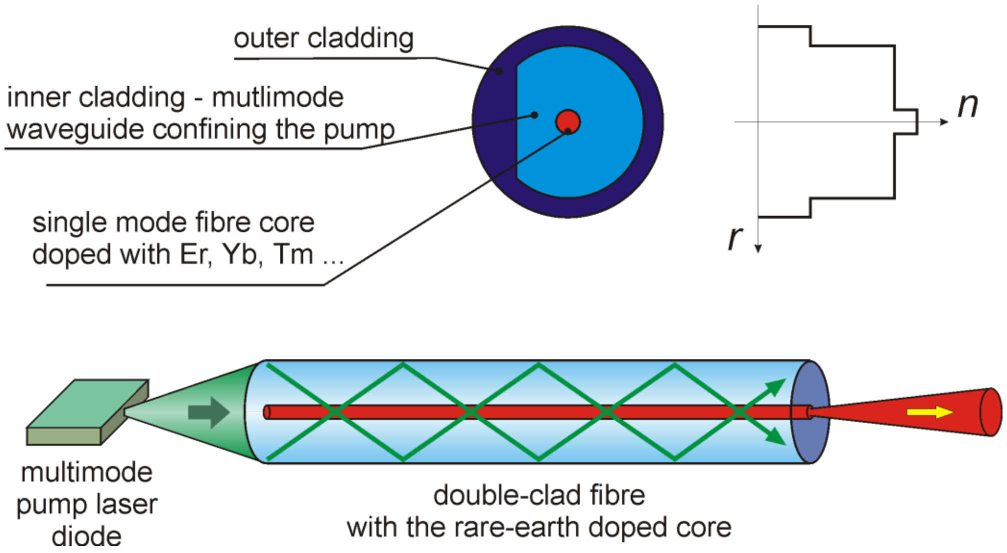
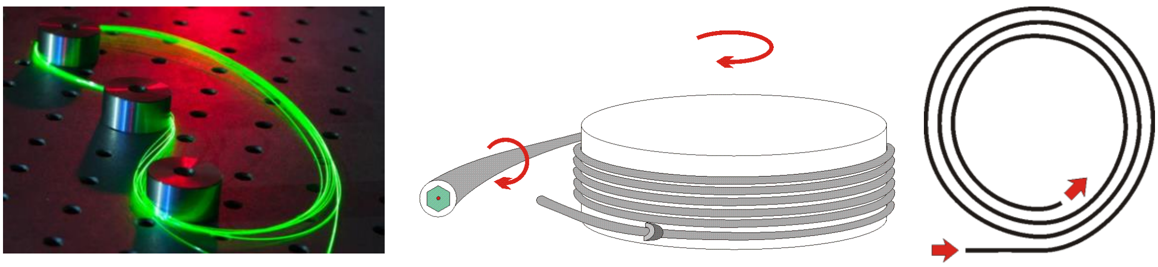


Figure 1. The principle of the cladding pumping of the DC active fiber: cross section of the DC active fiber, transversal refractive index profile and transformation of the high-power, low-quality (highly divergent) pump beam into high-power high quality (low divergent) laser signal.

The high-power operation of fiber lasers was enabled mainly by the invention of cladding pumping within a double-clad (DC) fiber structure [2]. 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. 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 multimode-pump. These shapes include a D-shaped, hexagon, octagon, flower, stadium, air-clad, stress-elements inclusion, spiral-cladding, air-hole inclusion and several other shapes having broken-circular symmetry. The beneficial effect of mode mixing of the pump radiation by unconventional coiling was also observed experimentally [10, 11], see Fig. 3(a). With the recently reported rigorous theoretical description of the mode mixing [12, 13], the new research direction of optimization of the double-clad active fibers was opened and the very first promising designs have been already published [14], see Fig. 3(b), and [15], see Fig. 3(c).



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

Figure 2. 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.

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 [16], modulational-instability-based ultrafast fiber lasers [17], preparation of twin-core fibers [18] and long-period fiber gratings [19] for fiber lasers; and range of active fibers doped with Er/Yb [20], Ho [21], and Tm [22]. They have pioneered the research of ceramic nanoparticle doping of rare-earth-doped silica fibers using Modified Chemical Vapor Deposition (MCVD) method [23, 24]. 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 [12, 13, 25, 26] as well as new solutions for pump and signal combining [20, 27]. Last but not least they contributed to the discovery of laser wavelength self-sweeping in fiber lasers [19, 28] that is subject of this theses.

2 Self-sweeping of fiber laser wavelength

Physical origin of the self-sweeping effect

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. 3 and 4, 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 [19]. 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. Our measurements of the year 2008 we published in more detail only in 2012 [28, 29] together with new measurements in Fabry-Perot fiber laser cavity. The first detailed journal papers on this subject were published in 2011 [30, 31].

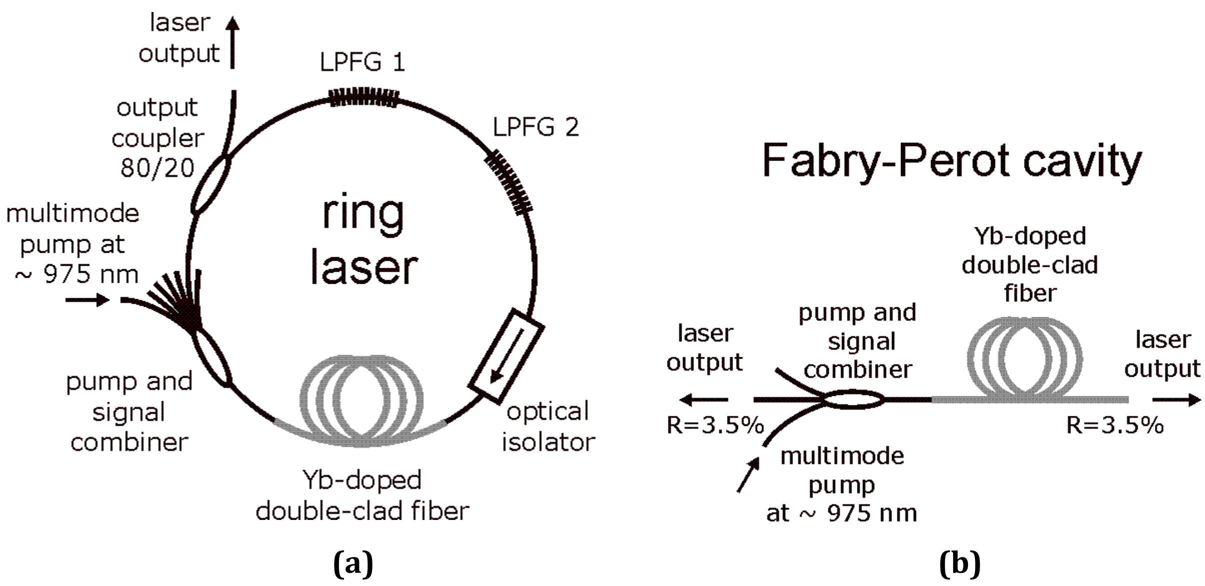
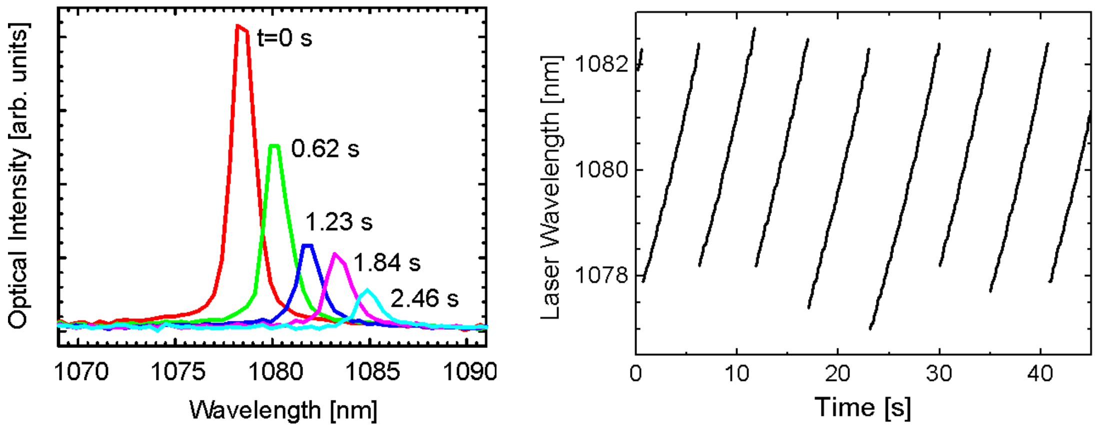


Figure 3. Examples of fiber laser setups in which the wavelength self-sweeping was observed: (a) Fiber ring laser with optional long-period fiber gratings for selection of spectral region of sweeping; (b) fiber laser in Fabry-Perot configuration.

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 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. 3(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. 4(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. 4(a) is also influenced by rapidly falling sensitivity of the silicon-based CCD photodetector of the used spectrometer. The laser emitted at around 1080 nm, 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.



(a) **(b)**

Figure 4. (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.

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 [32]. Spectral properties can be controlled to some extent by pump wavelength [33, 34], length of the active fiber [35] and, in particular, by different types of additional wavelength selective elements, such as wavelength division multiplexer [32], band pass filter [36] and combination of band-stop filters based on long-period fiber gratings [19, 28]. 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 [29, 33]. 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 [37]. Their laser was core-pumped by a single mode erbium fiber laser at 1570 nm.

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 [36]. 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. The SLLS phenomenon is not limited to rare-earth doped active media as it was observed also in a fiber laser doped with bismuth [38]. Apart from fiber lasers, reports of self-sweeping in ruby and dye lasers should be mentioned [39, 40].

We achieved self-sweeping also around 2100 nm thanks to stimulated emission of radiation in holmium where blueshift sweeping in 4 nm wide interval was observed [41]. The laser was pumped by in-house built thulium-doped fiber laser emitting at around 2020 - 2030 nm.

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 [42]. The refractive index change with light-induced change of inversion population was studied for ytterbium doped fibers in detail [43, 44]. However, despite the relatively long history of laser physics, the first evaluation of reflectivity of the FBGs spontaneously created in the active media itself [45, 46], see Fig. 5, as well as the inscription of phase gratings [47] 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.

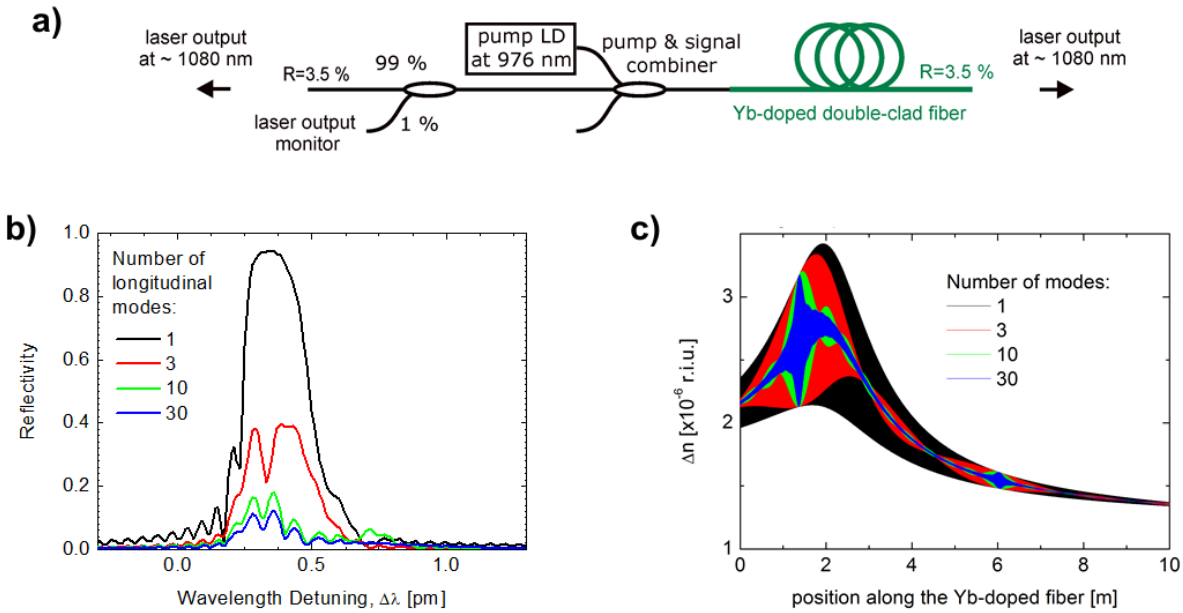


Figure 5. (a) Setup of fiber laser with self-sweeping of laser wavelength, (b) Evaluated reflectivity of the dynamic FBGs depending on number of longitudinal modes involved (c) The shape of refractive index grating along the active fiber. Note that the grating pitch is about 0.36 μm and therefore the refractive index modulation is not resolved in the figure and only the envelope of the refractive index change is shown. Used with permission from ref. [49] (©[2018] IEEE).

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. Firstly, 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. 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 [48]. 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 [50]. In the case of superimposed Bragg gratings we have developed new theoretical model for estimation of the reflective based on coupled mode theory [49]. 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.

3 Analogies between the self-sweeping effect and the transverse mode instabilities and mode locked lasers

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 [51, 52]. 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 [53].

4 Conclusions

A decade 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.

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 [32] and for testing high-speed spectrum analyzers were demonstrated [54]. SLLS fiber laser was used for coherent Brillouin optical spectrum analyzer [55]. 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 [56]. 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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6 Curriculum Vitae

Pavel Peterka (*1970)

Work experience:

1993-	Institute of Photonics and Electronics (ÚFE), Academy of Sciences of the Czech Republic, Chaberská 57, 182 51 Prague, senior research scientist (since 2013)
2001-2003	Postdoctoral fellow (13 months in total) in Laboratoire de Physique de la Matière Condensée (LPMC), CNRS - Université de Nice – Sophia Antipolis, 06108, Nice, France
2009	*Professeur invité* at LPMC CNRS - Université de Nice – Sophia Antipolis (6 weeks)

Education

Ph.D.:	2000 Faculty of Electrical Engineering, Czech Technical University (CTU) in Prague, Thesis title: "Twin-core optical fibers for fiber lasers"
Ing. (MSc):	1993, Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague

Research activities and teaching

- Research in the field of specialty optical fibers and fiber lasers and amplifiers
- External lecturer of the subject „Fiber lasers and amplifiers“ in the CTU in Prague (since 2007)
- Supervisor of PhD thesis: currently superving of 1 PhD student; 3 PhD theses defended
- Supervisor of undergraduate students: currently supervising of 2 undergraduate students; 8 MSc and 1 Bachelor degree theses defended
- Chairman of the summer school "International Training School on Fibre Lasers & Optical Fibre Technology," of the European Action COST MP1401 (2016)

Professional activities

2019- , and 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“

2017:	Chairman of the conference Micro-structured and Specialty Optical Fibres, part of SPIE Optics+Optoelectronics
2016:	Co-chairman of the photonics section of interdisciplinary symposium EU-US Frontiers of Engineering, Oct 17-19, 2016, Aalto University, Espoo, Finland.
2014-	Member of the Management Committee of the European Action COST MP1401 "Advanced Fibre Lasers"
2014-	Member of the Academy Assembly of the Czech Academy of Sciences

2013- Deputy leader of the research team of Fiber lasers and non-linear optics (ÚFE)

2013-2017 Member of the Council for popularisation of science of the Academy of Sciences CR

2012- Vice-chairman of the Supervisory board of the ÚFE

2012-2019 Board member of the Alpha sub-programme 1 of the Technological Agency of the Czech Republic

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

2000- 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

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

Memberships: Senior member of The Optical Society (OSA), senior member of The International Society for Optics and Photonics (SPIE), the Czech and Slovak Society for Photonics (ČSSF) and the European Optical Society (EOS)

SPIE Senior Member

Bibliographic data

P. Peterka is author or co-author of 58 scientific journal papers, more than 70 conference papers, 4 patents and one book chapter. These works were 568 times cited according to the database Web of Science (without self-citations); *h*-index is 16.

More details about the applicant can be found here:
http://www.ufe.cz/en/pavel-peterka

In Prague, 20 January 2020

7 Selected publications

1. O. Podrazký, P. Peterka, I. Kašík, S. Vytykáčová, J. Proboštová, J. Mrázek, M. Kuneš, V. Závalová, V. Radochová, O. Lyutakov, E. Ceci-Ginistrelli, D. Pugliese, N. G. Boetti, D. Janner, and D. Milanese, "In-vivo testing of a bioresorbable phosphate-based optical fiber," *J. Biophotonics* **12**, e201800397 (2019). DOI: 10.1002/jbio.201800397
2. P. Peterka, P. Koška, and J. Čtyroký, "Reflectivity of superimposed Bragg gratings induced by longitudinal mode instabilities in fiber lasers," IEEE J. Sel. Topics Quantum Electron. **24**, 0902608 (2018). DOI: 10.1109/JSTQE.2018.2806084
3. P. Navratil, P. Peterka, P. Honzatko, and V. Kubecek, "Reverse spontaneous laser line sweeping in ytterbium fiber laser," Laser Physics Lett. **14**, 035102, (2017). DOI:10.1088/1612-202X/aa548d
4. Jan Aubrecht, Pavel Peterka, Pavel Koška, Ondřej Podrazký, Filip Todorov, Pavel Honzátko, and Ivan Kašík, "Self-swept holmium fiber laser near 2100 nm," Opt. Express 25, 4120-4125 (2017). DOI:10.1364/OE.25.004120
5. M. Písarik, P. Peterka, J. Aubrecht, J. Cajzl, A. Benda, D. Mares, F. Todorov, O. Podrazky, P. Honzatko, I. Kasik, "Thulium-doped fibre broadband source for spectral region near 2 micrometers," Opto-Electron. Rev. 24, 223-231 (2016). DOI:10.1515/oere-2016-0022
6. 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. DOI:10.1109/JSTQE.2015.2490100
7. Pavel Koška, Pavel Peterka, Jan Aubrecht, Ondřej Podrazký, Filip Todorov, Martin Becker, Yauhen Baravets, Pavel Honzátko, and Ivan Kašík, "Enhanced pump absorption efficiency in coiled and twisted double-clad thulium-doped fibers," Opt. Express **24**, 102-107 (2016). DOI:10.1364/OE.24.000102
8. P. Peterka a J. Zavadil: "60 let světla v Ústavu fotoniky a elektroniky AV ČR, v.v.i.," Jemná mechanika a optika, **60**(5-6):200-203 (2015).
9. P. Peterka, P. Honzatko, M. Becker, F. Todorov, M. Pisarik, O. Podrazky, and I. Kasik, "Monolithic Tm-doped fiber laser at 1951 nm with deep-UV femtosecond-induced FBG pair," IEEE Photonics Technol. Lett., **25**, 1623-1625, (2013). DOI:10.1109/LPT.2013.2272880
10. 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). DOI:10.1364/OE.19.002773
11. P. Peterka, I. Kasik, V. Matejec, V. Kubecek, and P. Dvoracek, "Experimental demonstration of novel end-pumping method for double-clad fiber devices", Opt. Lett., **31,** 3240-3242 (2006). DOI:10.1364/OL.31.003240
    Excerpts of this article appeared also in the following journals: Photonics Spectra, January 2007, p. 105-106, "End-pumping fiber amplifiers made easy", Laser Focus World, December, p. 11, 2006, "End-pumping scheme improves fiber-based devices."