We are IntechOpen,
the world's leading publisher of
Open Access books
Built by scientists, for scientists

6,900
Open access books available

186,000
International authors and editors

200M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Multi-Wavelength Fiber Lasers

Rosa Ana Perez-Herrera and Manuel Lopez-Amo

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/53398

1. Introduction

A fiber amplifier can be converted into a laser by placing it inside a cavity designed to provide optical feedback. Such lasers are called fiber lasers. In this kind of lasers there are optical fibers that act as gain media such as erbium or ytterbium doped fibers among other, although some lasers with a semiconductor gain medium and a fiber resonator have also been called fiber lasers.

Nowadays, multiwavelength lasers are of great interest for telecommunications and sensors multiplexing. These lasers also have a great potential in the fiber-optic test and measurement of WDM components. The requirements for such optical sources are: a high number of channels over large wavelength span, moderate output powers (of the order of 100μW per channel) with good optical signal to noise ratio (OSNR) and spectral flatness, single longitudinal mode operation of each laser line, tunability and accurate positioning on the ITU frequency grid. Reaching all these requirements simultaneously is a difficult task, and many different approaches using semiconductor or erbium-doped fiber technology have been proposed and experimented in order to obtain multiwavelength laser oscillation.

Fiber lasers also offer great possibilities as multiwavelength sources. Their ease of fabrication has yielded many ingenious designs. The main challenge in producing a multiline output with and erbium doped fiber laser (EDFL) is the fact that the erbium ion saturates mostly homogeneously at room temperature, preventing stable multiwavelength operation.

Single longitudinal mode operation of fiber lasers is desirable for many potential applications where coherence is necessary. These include coherent communications, interferometric fiber sensors and coherent light techniques in bulk or micro-optics, such as holography or spatial filtering. [1]. However, these lasers normally operate in multiple longitudinal modes because of a large gain bandwidth (>30 nm) and a relatively small longitudinal-mode spacing (< 100 MHz). The spectral bandwidth of laser output can ex-

ceed 10 nm under CW operation [2]. Many applications of continuous wave (CW) lasers require operation in a narrow-linewidth single mode whose wavelength can be tuned over the gain bandwidth. Numerous methods have been used to realize narrow-line-width fiber lasers, however fiber Bragg gratings (FBGs) are preferred for this purpose since they can be fabricated with a reflectivity spectrum of less than 0.1 nm.

It is also worth noting that the large gain bandwidth of fiber lasers is useful for tuning them over a wavelength range exceeding 50 nm [2]. Several other methods have been used to achieve single longitudinal mode operation of fiber lasers and these include unidirectional ring resonators [3], intracavity wave-mixing in a saturable absorber [4], fiber Fox-Smith resonators [5] and injection locking using the line narrowed output form a separate source [6]. Nevertheless, no technique is free from operating difficulties due to the problems of isolating the fiber laser resonator from environmental influences, such as vibrations and temperature drift among other factors. Most of these problems can be addressed by using some clever schemes, as will be presented in this work.

2. Fiber lasers design

Fiber lasers can be designed with a variety of choices for the laser cavity [2]. One of the most common type of laser cavity is known as the Fabry-Perot cavity, which is made by placing the gain medium between two high-reflecting mirrors. In the case of fiber lasers, mirror often butt-coupled to the fiber ends to avoid diffraction losses.

Several alternatives exist to avoid passing the pump light through dielectric mirrors. For example, one can take advantage of fiber couplers. It is possible to design a fiber couple such that most of the pump power comes out of the port that is a part of the laser cavity. Such couplers are called wavelength-division-multiplexing (WDM) couplers. Another solution is to use fiber gratings as mirrors. As it is known, a FBG can acts as a high-reflectivity mirror for the laser wavelength while being transparent to pump radiation. The use of two such gratings results in an all-fiber Fabry-Perot cavity. An added advantage of Bragg gratings is that the laser can be forced to operate in a single longitudinal mode. A third approach makes use of fiber–loop mirrors that can be designed to reflect the laser light but transmit pump radiation.

Ring cavities are often used to force unidirectional operation of a laser. In the case of fiber lasers, an additional advantage is that a ring cavity can be made without using mirrors, resulting in an all-fiber cavity. In the simplest design, two ports of a WDM coupler are connected tighter to form a ring cavity containing the doped fiber, as shown in Figure 1.

An isolator is inserted within the loop for unidirectional operation. However, some alternative fiber laser configurations have been shown, where these kinds of devices can be suppressed from the cavity rings by using optical circulators [7]. Theoretically, a polarization controller is also needed for conventional doped fiber that does not preserve polarization. However, some works [7] have demonstrated that this device has little influence on the multiwavelength regime.
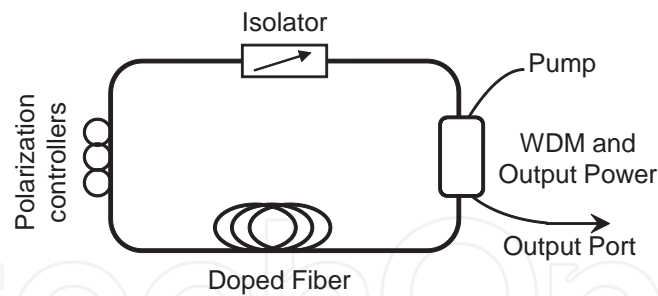
Figure 1. Schematic of a unidirectional ring cavity used for fiber lasers.

Ring fiber lasers are also known to be susceptible to power fluctuations. These instabilities can significantly degrade the characteristics of a sensor array based on a tunable ring laser interrogation scheme [8]. Although the laser output power stability usually depends on many parameters like the EDF lengths, the coupling ratio on the output and the total cavity length [9], [10]-[15], it can be improved through an appropriate choice of laser parameters.

For sensor applications, a tunable narrow-band laser source is very attractive since it significantly simplifies the detection scheme. However, the interaction of laser relaxation oscillations with external perturbations induces self-pulsation and output power variations. In addition, the long coherence length of the radiation emitted by a single-mode laser may result in Fabry-Perot type unwanted interference within the sensing arm. In a few-mode regime, mode-hopping results in power fluctuations. To avoid these fluctuations the laser must operate in a many-mode regime, in which the power carried by each mode is sufficiently small. Specifically, the spacing between longitudinal modes is defined by the length of the cavity which is usually a few tens of meters. The number of modes (N) and modes spacing ($\Delta\lambda$) in a fiber ring laser are given by:

$$\Delta\lambda = \frac{\lambda^2}{nL} \tag{1}$$

$$N = \frac{nL}{\lambda} \tag{2}$$

where n: is the refractive index of the Er fiber, L: the ring length, and λ: the centered mode wavelength.

Some experimental studies have been carried out with the purpose of enabling an erbium doped fiber ring laser (EDFRL) design to be optimized, by using highly Er-doped fiber instead of conventional one [16], in order to meet the required performance by analyzing several configurations. In that way, the optimal EDF length [17] required to generate both the highest possible gain for a given signal and output power oscillations as low as possible under certain constraints can be found.

Thus, several EDFL hybrid cavity configurations, combining both EDFR and short cavity fiber laser, have been designed and experimentally analyzed [18], [19]. Figure 2 shows the experimental setup of a short-cavity fiber laser. These studies were focused on the optimization of laser parameters, which include EDF lengths, pump power and diverse configurations, without changing the basic scheme, which was kept as simple as possible.

Figure 2. Experimental setup of a short-cavity fiber laser

Regarding to the spectral characterization of these kind of EDFLs, Figure 3 shows the exit amplified spontaneous emission (ASE) measured in the amplifier configuration, i.e., when the free end of the EDF was connected to an optical spectrum analyzer (OSA). It may be useful to note that the steady-state ASE spectra can be accurately simulated with the standard static model [20] based on the doped fiber parameters provided by the fiber manufacturer.
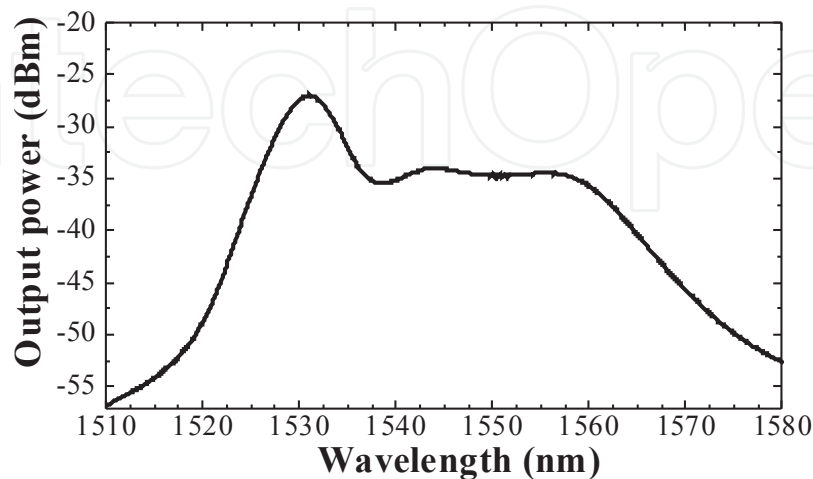

Figure 3. ASE obtained from a 1 m length of Er-80 when it is pumped by a 980nm light source.

Spectrally resolved measurements of the laser (i.e., closed cavity) output with different EDF lengths as the gain medium (and 500mW of input power) show a multiple-wavelength operation. The position of the comb depends on the fiber length. For a 25cm-long fiber, the generation occurs at shorter wavelengths values, while already for a 1m-long fiber the generation shifts to longer wavelengths (Figure 4). This shift is due to an increase of the effective fiber length when the cavity is closed and it corresponds to the L-band operation of an EDFA with an increased fiber length.

Frequency hopping to other longitudinal cavity modes is possible since neighboring modes may have a higher (unsaturated) gain. Usually, when no cavity filters are used, linear cavity lasers are less stable in power and frequency than ring cavity lasers. Ring cavity EDFLs use the gain provided by the EDF more efficiently and have a cavity free spectral range (FSR) that is twice as large for the same cavity length compared to linear cavity lasers [16].

On the other hand, the linear, or Fabry–Perot cavity, is the most common laser cavities, and the first EDFL cavity that was explored. Its main advantages are its simplicity and the possibility to make very short cavities. It is thus well suited for robust single longitudinal mode operation. They are also suitable for master oscillator power amplifier (MO-PA) [21] applications since it is usually easy to recover unabsorbed pump power at the output coupler.
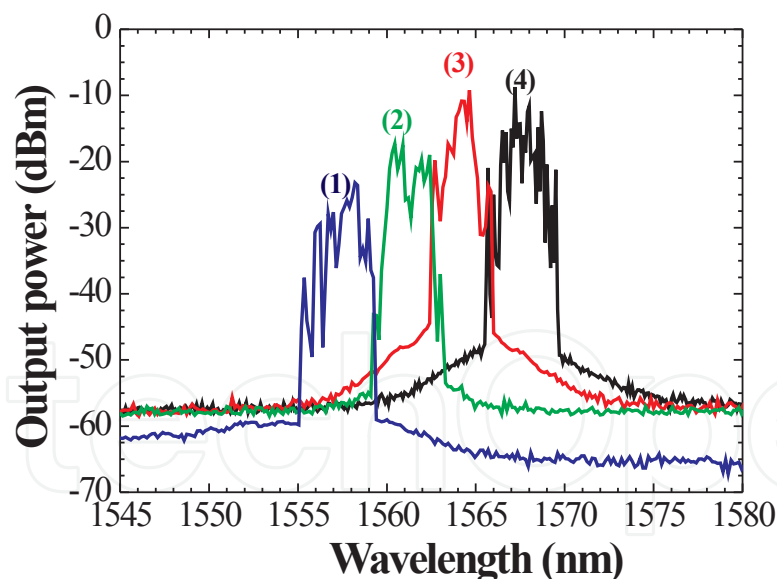
Figure 4. Output power spectra for closed cavity configuration with different EDF lengths. (1) 25, (2) 50, (3) 75 and (4) 100 cm length of the erbium-doped fiber. 500mW pump power.

An example of a linear cavity is presented in Figure 5. In a forward pumped linear cavity EDFL, the pump light is injected through a wavelength-dependent reflector (WDR) which is, ideally, perfectly transparent at the pump wavelength and perfectly reflective at the signal wavelength. The output coupler completes the linear cavity. It is preferable that the output coupler be highly

reflective at the pump wavelength to recycle unused pump power thus providing optimized pumping and no residual pump at the output.

The output coupler must also have a reflectivity at the signal wavelength that optimizes the output power [22]. The output coupler reflectivity in the signal band can either be broadband, leading to a lasing wavelength determined by the erbium-doped fiber gain curve, or wavelength-selective, leading to a lasing wavelength selected, and possibly tuned, by the output coupler. Linear cavities are also ideal for compact single-longitudinal mode lasers and for high power applications.

Many other cavity designs are possible. For example, one can use two coupled Fabry-Perot cavities. In the simplest scheme, one mirror is separated from the fiber end by a controlled amount. The 4% reflectivity of the fiber-air interface acts as a low-reflectivity mirror that couples the fiber cavity with the empty air-filled cavity. Because of that, all the free terminations on the systems have to be immersed in refractive-index-matching gel to avoid undesired reflections. Such compound resonator has been used to reduce the line width of an Er-doped fiber laser [23]. Three fiber gratings in series also produce two coupled Fabry-Perot cavities. Still another design makes use of a Fox-Smith resonator [5].
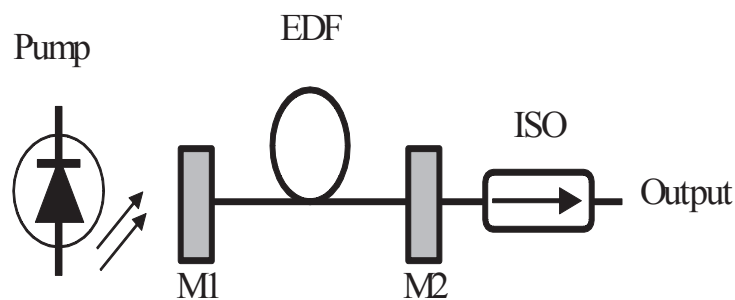

Figure 5. General schematic diagram of a linear cavity EDFL. M1: pump WDR mirror, M2: output coupler, EDF: erbium-doped fiber, ISO: optical isolator.

As it was previously pointed out, multiwavelength lasers are of great interest for telecommunications and sensors multiplexing. These lasers also have a great potential in the fiber-optic test and measurement of WDM components. The requirements for such optical sources are: a high number of channels over large wavelength span, moderate output powers (of the order of $100\mu W$ per channel) with good OSNR and spectral flatness, single longitudinal mode operation of each laser line, tunability and accurate positioning on the ITU frequency grid [25].

2.1. Laser output fluctuations

Many lasers, exhibit fluctuations in their output intensity that appear as either a sequence of sharp, narrow pulses (spikes) or a small oscillation "ripple" superimposed upon the steady-state laser output signal. The lasers that experience these fluctuations are lasers in which the

recovery time of the excited-state population inversion is significantly longer that the laser cavity decay time.

It has been recognized that such instabilities can significantly degrade the performance characteristics of a sensor array based on a tunable ring laser interrogation scheme. Most of the factors influencing stability of the output power of fiber laser have been analyzed theoretically in detail [23]. A systematically effort to study these causes has been carried out. Based on previous experience these studies have been focused on optimization of some the following parameters: pump power [19], doped fiber length and ions concentration [26], output coupling ratio [7], total cavity length [26], spectral hole-burning effect [27] or the cavity losses [28]. However, polarization control seems not very important for the multimode regime [7].

2.2. Room temperature operation of fiber lasers

Multiple gain medium: In a manner similar to semiconductor laser arrays, it is possible to create multifrequency EDFLs that use a single gain medium per wavelength. In 1994, Takahashi et al. [29] demonstrated a multifrequency ring EDFL oscillating simultaneously over four wavelengths spaced 1.6 nm apart by using an 8 x 8 AWG and four EDFAs. Later, Miyazaki and his co-worker [30] showed a ring EDFL that lases on 15 lines separated by 1.6nm. Again, the laser consisted of 15 EDFAs placed between two 16 x 16 AWGs. The light from a 1480 nm pump laser was evenly distributed to N fiber segments by a 1 x N broadband coupler. Each segment was composed of a piece of EDF followed by an optical isolator, a tunable optical filter and variable attenuator. By adjusting each attenuator it was possible to establish multifrequency oscillation in this ring cavity. Independent wavelength tuning of each laser line was the main feature of this structure.

Various schemes have been demonstrated to show both SLM and tunability simultaneously, for example, using such schemes as a multi-ring cavity with a band pass filter [31], a tunable fiber Bragg grating (FBG) Fabry-Perot etalon [32] and a saturable absorber with a tunable FBG [33]. It has been shown in prior works that a section of unpumped EDF in a Sagnac loop can be used as a saturable absorber in which two counter-propagating waves form a standing wave and induce spatial-hole-burning (SHB). The refraction index of the unpumped EDF changes spatially due to SHB and this results in an ultra-narrow bandwidth self-induced FBG [34], [35].

By means of optimized length of unpumped EDF, the beat frequencies corresponding to the multimode lasing disappeared when a saturable absorber is introduced [36] so, lasers that can be wavelength-swept over the entire C-band (1520nm-1570nm) window with linewidth less than 0.7 kHz [37], laser that can also achieve switching modes among several wavelengths by simple adjustment of two polarization controllers in the cavities [38], C- plus L-band fiber ring laser with wide wavelength tunability and single-longitudinal-mode oscillation [39], generation of terahertz (THz) electromagnetic waves by photomixing two wavelengths in a high speed photodetector [40] can be obtained among others.

In 2008, Tianshu Wang [41] reported a novel high power tunable single-frequency erbium-doped fiber laser. The single-frequency operation was realized by using the FBG as a narrow

band filter and a section of unpumped EDF as a saturable absorber in the cavity. The obtained slope efficiency was more than 20%, the stability was less than 0.005 dB and the modes adjacent to the lasing mode were completely suppressed.

Single gain medium: The very first attempts [42], [43] at room temperature operation of single gain stage multifrequency EDFLs showed, notwithstanding their inefficiency, the great potential of these sources. Later, Hübner et al. [44] proved that a multifrequency EDFL could be obtained through writing a series of DFB (distributed feedback laser) fiber Bragg gratings in a single erbium-doped fiber. Their laser produced five lines over a 4.2 nm range. The use of specialty doped fiber has also led to very elegant designs. A twincore EDF was used by Graydon et al. [45] as an inhomogeneous gain medium in a multifrequency ring EDFL. In that fiber, wavelength-dependent periodic coupling between the two cores partially decouples the available gain for each wavelength, since they interact with a different subset of erbium ions. Poustie et al. [46] used a multimode fiber to create a frequency periodic filter based on spatial mode beating and showed multi-wavelength operation over four lines spaced by 2.1 nm. In 1992, Abraham et al. [47] conceived a multifrequency hybrid laser composed of a 980 nm pump laser diode with antireflection coating coupled to an EDF with a fiber mirror. That laser produced an output spectrum with six lines spaced by 0.44 nm. In 1997, Zhao et al. [48] demonstrated that the control of optical feedback in a modified S-type cavity allowed stable multifrequency operation. In addition to this, a very interesting scheme to realize room temperature operation of a multifrequency EDFL was demonstrated by Sasamori et al. [49]. They used an acousto-optic modulator to prevent the laser from reaching steady-state operation. Initially, the authors believed that the repeated frequency shifting of the circulating ASE by the acousto-optic modulator prevented laser oscillation and yielded an incoherent source. Recently, it was shown that this source is in fact a laser and its potential as a frequency reference was demonstrated [9], [50], [51].

X.S. Liu et al. [52] experimentally demonstrated a simple-structure but efficient multiwavelength EDFL based on dual effects of nonlinear polarization rotation (NPR) and four-wave-mixing (FWM). With this structure, a maximum of 38-lines output in C-band and 28-wavelength flattened output within 3 dB bandwidth in L-band, both with the same spacing of about 0.4 nm, was obtained. Through the comparative experiments, it was demonstrated that introducing hybrid nonlinear effects by using a length of DSF is more efficient to generate multiwavelength lasing than using SMF.

2.3. Liquid nitrogen cooled multifrequency fiber lasers

The most obvious way to force multifrequency operation in a single gain medium EDFL is to cool the EDF by immersion in a bath of liquid nitrogen (77 K). At these temperatures the erbium ions become inhomogeneous, and multifrequency operation is much easier. It must be noted that this complex and unreliable approach is not recommended for field applications. Nonetheless, many potent experimental results have been published using this method and it is worthwhile to review them. In 1996, Chow et al. [53] published results concerning a multifrequency ring EDFL using two different types of frequency periodic filters. They obtained eleven laser peaks spaced by 0.65nm using a Fabry–Perot filter based on chirped fiber Bragg gratings

[54], and five laser peaks spaced by 1.8 nm with a sampled fiber Bragg grating. An example of these kind of structures can be seen in Figure 6.

That same year, Yamashita et al. [55] proposed a single-polarization linear cavity multi-frequency EDFL. This laser does not use polarization-maintaining fiber and operates in a travelling-wave mode, thus preventing spatial hole burning, since cavity feedback is provided by Faraday mirrors. A Fabry–Perot etalon is used as the frequency periodic filter. A polarizer and a Faraday rotator are placed on each side of the etalon to prevent parasitic reflections. With this setup, the authors obtained simultaneous oscillation over 17 wavelength spaced by 0.8 nm. Simultaneous lasing of up to 24 wavelengths has been demonstrated by Park et al. [56] using controlled polarization evolution in a ring cavity and liquid nitrogen cooling to enhance spectral hole burning, polarization hole burning, and polarization selectivity. A polarizer and a polarization controller were placed before a piece of polarization maintaining fiber to form a Lyot filter with a free spectral range of 1.1 nm. Finally, Yamashita et al. [57] realized a multiwavelength Er:Yb Fabry–Perot micro-laser with 29 0.4 nm-spaced lines.
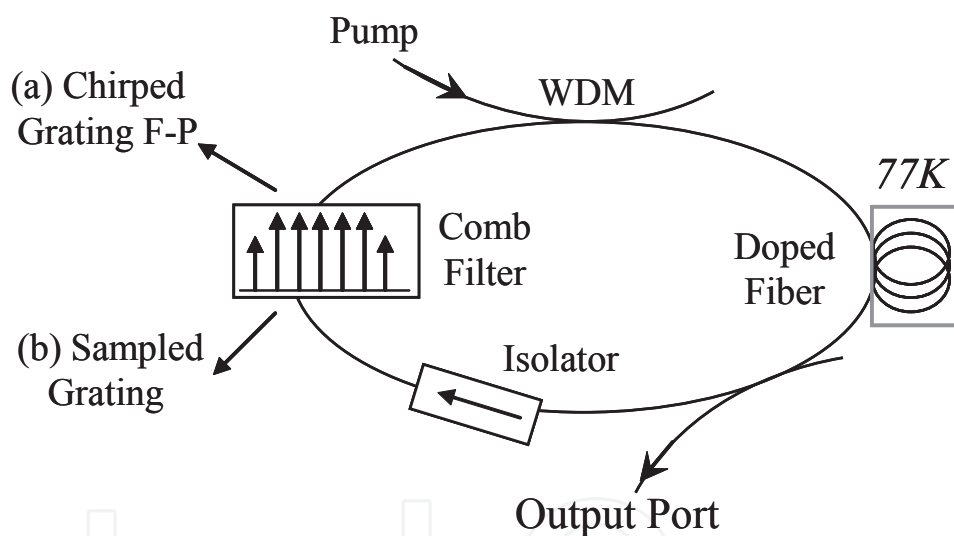

Figure 6. Schematic diagram of a nitrogen-cooled multifrequency EDFL.

2.4. Multiwavelength fiber laser-based multiplexing systems

One of the major difficulties to detect the sensing signals when broadband light sources are more than 50 km long is the Rayleigh scattering-induced optical noise as well as loss of background signal in the transmission fiber [58]. To increase the performance of sensing systems, a fiber laser-based sensing probe with a narrow bandwidth and a high extinction ratio should be considered.

As it was said, FBGs are suitable for use as spectrally narrowband reflectors for creating cavities for fiber lasers. Multisensor fiber Bragg grating lasers utilizes several FBGs nor-

mally at different wavelengths, an amplification section and a mirror (or structure acting as a mirror) to create an in-fiber cavity [59]. The utilization of an amplifying medium between the gratings and the mirror pumped inside or outside the cavity provides gain and thus lasing. The cavity may show single mode or multimode performance depending on the gratings and the cavity length. This multimode performance can be seen in Figure 7, where the output optical spectrum measured by a BOSA (Brillouin optical spectrum analyzer) for a multiwavelength erbium doped fiber ring laser tested by heating one FBG on a climatic chamber in the range of 30°C to 100°C is shown. In addition to this, a linear relation between each lasing wavelength with the temperature can be observed. For single mode operation using typical FBG bandwidth, the cavity required to be on the order of a few cm, thus most part of remote sensing system are multimode. Numerous configurations to multiplex a number of FBGs have been carried out. These new sensing configurations offer a much improved SNR than the non-lasing ones. Initially Er-doped fiber amplifiers were utilized, being nowadays utilized Raman amplification, EDFAs and SOAs depending on the application and distance to be achieved [7].
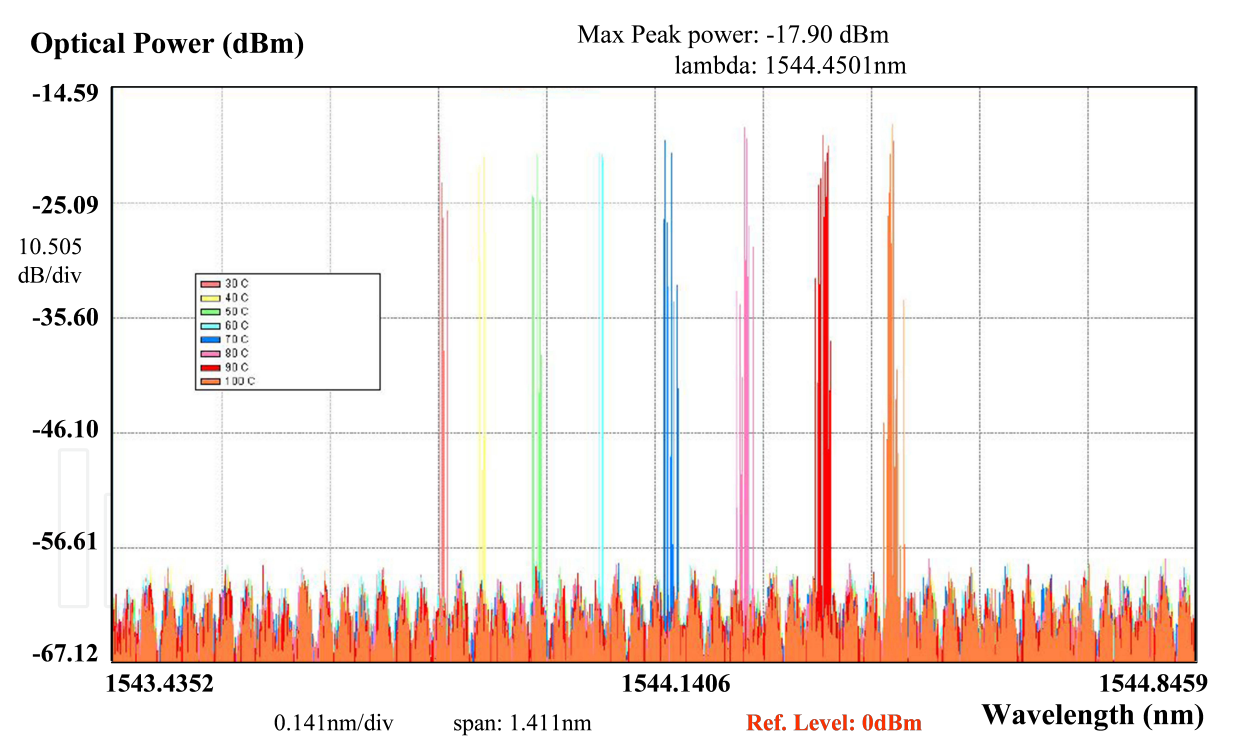

Figure 7. Output optical spectrum measured by the BOSA for the MEDFRL (with 1.5m of highly doped Er-fiber (Er-80) from Liekki) tested by heating one FBG on a climatic chamber in the range of 30˚C to 100˚C.

Several approaches based on fiber lasers have been reported in order to realize long-distance and remote sensing. Peng et al. [60] proposed an advanced configuration based on the use of

a linear cavity Raman laser configuration formed by FBGs and a fiber loop mirror to achieve a high optical signal-to-noise ratio (50 dB), but in such a system the number of FBG sensors was limited by the relatively low Raman gain, which is difficult to improve even by using a high Raman pump power and multiwavelength lasing characteristics.

Another approach, also proposed by Peng et al., [61] was a multiwavelength fiber ring laser configuration with an erbium doped waveguide amplifier and a semiconductor optical amplifier (SOA), but only six or so FBG sensors can be used in such a system with its narrow effective bandwidth of 20 nm, which depends on the overlap of the spectrum between the EDFA and the SOA. Moreover, its sensing distance is limited by the SOA, which cannot be pumped remotely.

Recently, numerous multiwavelength switchable erbium-doped fiber lasers have been developed [62]. These topologies offer a stable operation without the necessity of passive multi-ring cavities [63] or polarization maintaining fiber [64], are suitable for the selection of all the possible output combinations of several different lasing wavelengths and they have been used for remote sensing up to 50 km [65]. In addition to this, in [66], an approach using a tunable fiber ring laser with hybrid Raman–Erbium-doped fiber amplification was demonstrated, obtaining an optical SNR of 60 dB for 50 km. However, ultra-long distance FBG multiplexing systems have been demonstrated [67] without using optical amplification, obtaining acceptable signal to noise ratios (20 dB) after 120 km. Besides, a 200 km long fiber ring laser for multiplexing FBG arrays was recently developed [68] and it was also able to detect four multiplexed FBGs placed 250 km away, offering a signal to noise ratio of 6–8 dB [69].

As can be seen in [70] backward Raman amplification approach is an effective way to realize ultra-long distance FBG sensing systems. Because of that, a 300km transmission distance has been recently achieved with an optical SNR of 4 dB [71], which is the longest FBG sensing distance, to the best of our knowledge.

3. Laser cavity resonance modes

In a typical laser, the number of cavity resonances that can fit within the gain bandwidth is often plotted as a function of laser output power versus wavelength. This subsection deals with how varying the appropriate frequencies can alter curves describing the number of cavity modes and gain bandwidth of a laser.

One can suppress all but one lasing mode by increasing the spacing between adjacent modes such that other modes lie outside the width of the laser gain curve. This is usually achieved by designing very short cavity lasers. In fiber lasers, this can be achieved by designing a very short (few centimeters long) standing-wave cavity combined with one or two narrow band Bragg gratings that select a single longitudinal mode.

A common misconception about lasers results from the idea that all of the emitted light is reflected back and forth within the cavity until a critical intensity is reached, whereupon some "escapes" through the output mirror as a beam [72]. In reality, the output mirror always

transmits a constant fraction of the light as the beam, reflecting the rest back into the cavity. This function is important in allowing the laser to reach an equilibrium state, with the power levels both inside and outside the laser becoming constant.

Due to the fact that the light oscillates back and forth in a laser cavity, the phenomenon of resonance becomes a factor in the amplification of laser intensity. Depending upon the wavelength of stimulated emission and cavity length, the waves reflected from the end mirrors will either interfere constructively and be strongly amplified, or interfere destructively and cancel laser activity. Because the waves within the cavity are all coherent and in phase, they will remain in phase when reflected from a cavity mirror. The waves will also be in phase upon reaching the opposite mirror, provided the cavity length equals an integral number of wavelengths. Thus, after making one complete oscillation in the cavity, light waves have traveled a path length equal to twice the cavity length. If that distance is an integral multiple of the wavelength, the waves will all add in amplitude by constructive interference. When the cavity is not an exact multiple of the lasing wavelength, destructive interference will occur, destroying laser action. The following equation defines the resonance condition that must be met for strong amplification to occur in the laser cavity:

$$N \cdot \lambda = 2 \cdot (Cavity\ length) \tag{3}$$

where N is an integer, and λ is the wavelength. The condition for resonance is not as critical as it might appear because actual laser transitions in the cavity are distributed over a range of wavelengths, termed the gain bandwidth [72]. Wavelengths of light are extremely small compared to the length of a typical laser cavity, and in general, a complete roundtrip path through the cavity will be equivalent to several hundred thousand wavelengths of the light being amplified.

Resonance is possible at each integral wavelength increment and because the corresponding wavelengths are very close, they fall within the gain bandwidth of the laser. Figure 8 illustrates a typical example in which several resonance values of N, referred to as longitudinal modes of the laser, fit within the gain bandwidth.

Laser beams have certain common characteristics, but also vary to a wide degree with respect to size, divergence, and light distribution across the beam diameter. These characteristics depend strongly upon the design of the laser cavity (resonator), and the optical system controlling the beam, both within the cavity and upon output. Although a laser may appear to produce a uniform bright spot of light when projected onto a surface, if the light intensity is measured at different points within a cross section of the beam, it will be found to vary in intensity. Resonator design also affects beam divergence, a measure of beam spreading as distance from the laser increases. The beam divergence angle is an important factor in calculating the beam diameter at a given distance.
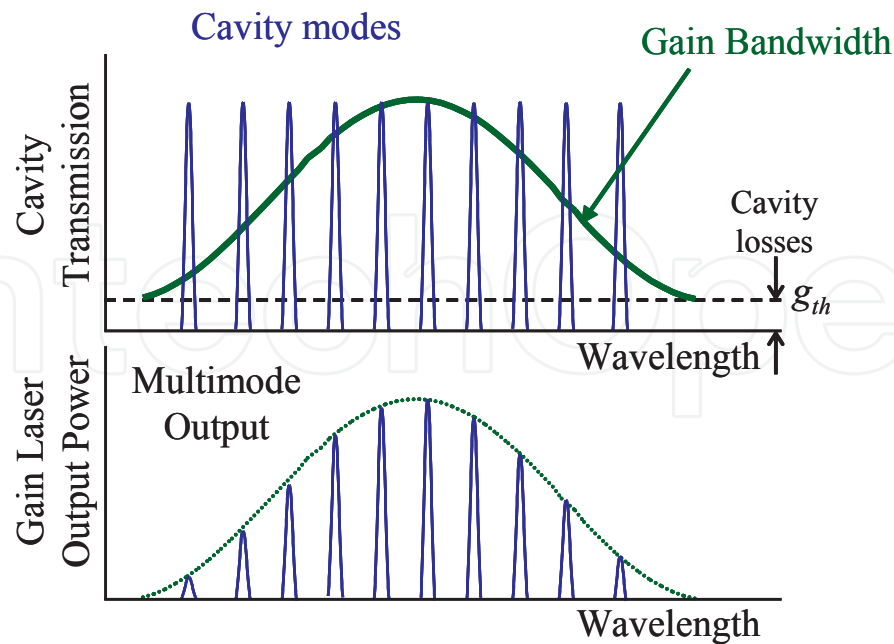
Figure 8. Cavity resonance modes and gain bandwidth.

In order to obtain monochromatic or single-mode laser radiation, it is usually necessary to insert a frequency dependent loss element (a filter) to insure that gain exceeds loss for only a single longitudinal mode.

4. Fiber lasers

4.1. Rare earth doped optical fiber lasers

Rare earth doped optical fibers are now a well-established class of gain media with many diverse applications that extend far from the original conceived application; namely, in-line amplifiers [73], [74]. Erbium-doped silica fiber lasers have been use, for example, for distributed sensing applications [75], remote sensing of magnetic fields [76], and as sources of optical solitons for all-optical fiber-based communications networks [77]. Many of these applications have evolved because of the advantages accrued from placing the rare earth ion in the optical fiber host lattice. The interaction between the rare earth ion and the intrinsic electric field associated with the host results in a broadening of the absorption and emission lineshapes associated with the rare earth ion. It is fortuitous that the absorption bands associated with many of the rare earth ions occur at wavelengths that are common to well-established laser diodes. The broadening of the absorption bands removes some of the wavelength-tailoring problems encountered with rare earth doped crystalline materials [78]. In fact, the ability to convert the output radiation from low-cost laser diodes, which generally occurs in a low-quality output mode with a poor frequency definition, into a high-brightness coherent source, is beneficial to applications, such as remote sensing and fiber-based communication systems,

because it results in compact systems with low power requirements. The broadband emission of trivalent rare earth ions allows the development of sources emitting either broad continuous-wave (CW) spectra or ultrashort pulses, as well as widely tunable narrow-linewidth operation [73].

A fiber laser using a trivalent rare earth as the active element has the potential for very narrow linewidth operation compared with other sources that oscillate in the same spectral regions, such as semiconductor lasers [73]. The output radiation from a single-frequency laser is not monochromatic, but has a finite bandwidth. The theoretical limit for the bandwidth is known as the Schalow-Townes limit and depends on both the linewidth of an individual longitudinal mode of the cavity and the amount of amplified spontaneous emission coupled to the oscillating longitudinal mode [22]. The cavity linewidth scales inversely with the cavity length of the laser, and the waveguiding nature of a fiber allows cavity lengths of many meters to be established. In comparison, the cavity length of semiconductor lasers is typically a fraction of a centimeter. Also, the optimum linewidth that can be expected from a fiber laser is significantly smaller than that of a semiconductor laser, making the fiber a suitable tool for narrow-linewidth applications [22].

Because of potential applications of multiwavelength fiber lasers, such as the fields of optical communication, optical fiber sensing, optical component testing and microwave photonics among other, erbium-doped fiber lasers emitting in multiple wavelengths simultaneously have attacked much interest recently [79],[80]. The multiwavelength fiber lasers used have various advantages such as the wavelength multiplexing operation, simple and compact structure, low cost, and small insertion loss, etc. It is worth mentioning than another important application of these multiwavelength fiber lasers is their use as light sources themselves in WDM systems.

Erbium-doped fiber is rarely employed to implement a stable multiwavelength lasing at room temperature owing to the homogeneous line-broadening property of the EDF. Over the last decade, various approaches have been proposed to address the above issue, for example, as it was previously pointed out in section 2.3, the EDF cooling the frequency shifting [9], the spatial and polarization hole-burning-effect-based [81], the nonlinear effects, and the nonlinear polarization rotation-based methods [82]. Most of these aspects have the following drawback: they use to offer few lasing wavelengths or they use to show a rather broad linewidth.

Moreover, EDFLs can operate in several wavelength regions, ranging from visible to far infrared. The 1.55 μm region has attracted the most attention because it coincides with the low-loss region of silica fibers used for optical communications.

The performance of EDFLs improves considerably when they are pumped at the 0.98 or 1.48 μm wavelength because of the absence of excited-state absorption. Indeed, semiconductor lasers operating at these wavelengths have been developed solely for the purpose of pumping Er-doped fibers. Their use has resulted in commercial 1.55-μm fiber lasers.

EDFLs pumped at 1.48 μm also exhibit good performance. In fact, the choice between 0.98 and 1.48 μm is not always clear since each pumping wavelength has its own merits. Both have been used for developing practical EDFLs with excellent performance characteristics [83], [84].

An important property of continuously operating EDFLs from a practical standpoint is their ability to provide output that is tunable over a wide range and many techniques can be used to reduce the spectral bandwidth of tunable EDFLs [2]. Ring cavities can also be used to make tunable or switchable EDFLs [62], [65], [85].

Besides, fiber gratings can also be used to improve the performance of EDFLs. Since 1990, when a Bragg grating was used to realize a line width of about 1 GHz [86], fiber gratings have been used in EDFAs for a variety of reasons [87]. The simplest configuration splices a Bragg grating at each end of an erbium-doped fiber, forming a Fabry–Perot cavity. Such devices are called distributed Bragg reflector (DBR) lasers. These fiber lasers can be tuned continuously while exhibiting a narrow line width. They can also be made to oscillate in a single longitudinal mode by decreasing the fiber length. Multiple fiber gratings can be also used to make coupled-cavity fiber lasers. Figure 9 shows an example of the output power spectral density of a single-stage EDFA (with two FBGs centered at 1540 and 1545nm and pump power of 90mW at 980nm. This EDFA (Photonetics, model BT 1300) provides 13 dBm output saturation power and a maximum 35 dB small signal gain.
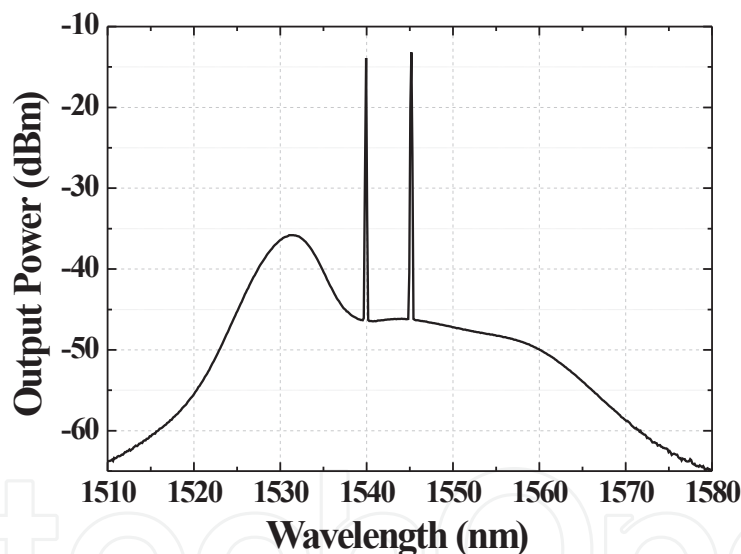

Figure 9. Output power spectral density (res=0.1nm) of a single-stage EDFA with λ_1=1540nm, λ_2=1545nm, P_p=90mW, L= 32 m, and λ_p=980nm.

Multiwavelength optical sources, capable of simultaneously emitting light at several well defined wavelengths, are useful for WDM lightwave systems. Fiber lasers can be used for this purpose, and numerous schemes have been developed [88]. The cavity length is made quite small (~ 1 mm or so) since spacing between the lasing wavelengths is governed by the longitudinal-mode spacing. A 1mm cavity length corresponds to a 100 GHz wavelength spacing. Such fiber lasers operate as standard multimode lasers. Cooling of the doped fiber helps to reduce the homogeneous broadening of the gain spectrum to below 0.5 nm. The gain spectrum is then predominantly inhomogeneously broadened, resulting in multimode

operation through spectral hole burning. Long cavities with several meters of doped fibers can also be used. Wavelength selection is then made using an intracavity comb filter such as a Fabry–Perot interferometer.

Many other rare-earth ions can be used to make fiber lasers. Holmium, samarium, thulium, and ytterbium have been used in nearly simultaneous experiments to make fiber lasers emitting at wavelengths ranging from visible to infrared. Attention later shifted to Pr3+ ions in an attempt to realize fiber lasers and amplifiers operating at 1.3 μm. Pr-doped fiber lasers can also operate at 1.05 μm. Thulium-doped fiber lasers have attracted considerable attention because of their potential applications. Operation at several other important wavelengths can be realized by using fluoride fibers as a host in place of silica fibers.

Holmium-doped fiber lasers have attracted attention because they operate near 2 μm, a wavelength useful for medical and other eye-safe applications. Thulium codoping permits these lasers to be pumped with GaAs lasers operating near 0.8 μm. Ytterbium-doped fiber lasers, operating near 1.01 μm and tunable over 60 nm, were first made in 1988 [89]. In 1992, the use of fluoride fibers as the host medium provided output powers of up to 100 mW. In a later experiment, more than 200-mW power with a quantum efficiency of 80% was obtained from a silica-based Yb-doped fiber laser pumped at 869 nm [90].

4.1.1. Single longitudinal mode operation

A number of schemes have also been demonstrated to show single-longitudinal mode (SLM), using such schemes as a multi-ring cavity with a band pass filter [31], a tunable fiber Bragg grating (FBG) Fabry-Perot etalon [32] and a saturable absorber with a tunable FBG [33]. In addition to this, it has been experimentally demonstrated [36] that the beat frequencies corresponding to the multimode lasing disappeared when saturable absorber (an optimized length of unpumped EDF) is introduced.

Even when single-mode regime is achieved, these lasers suffer from multi-gigahertz mode hopping. However these rings are at least several meters long so thermally induced hops to adjacent cavity modes still occur. An alternative approach is to use gratings, or distributed Bragg reflectors (DBR), in a linear cavity. These can be fabricated directly into an optical fiber through refractive index changes induced by short wavelength radiation to provide both optical feedback and wavelength selectivity [91]. Such a linear laser must possess better wavelength selectivity than a ring to overcome spatial hole burning. However, because the cavity losses can be so low, the resonator can potentially be made much shorter and with greater finesse. Singlemode operation has been reported in erbium-doped fiber DBR lasers with cavity lengths of 50cm [91] and 10cm [87]. To assure that the singlemode operation is robust, the cavity should be sufficiently short such that the mode spacing is comparable to the grating bandwidth.

On the other hand, and as reported in [92], a SLM fiber ring laser can be made to annihilate the mode competition with an auxiliary lasing. Owing to the interaction of the seed light produced from one channel to the other one and vice versa, multiple-longitudinal-mode oscillation can be suppressed, and thus the mode competition and mode hopping is not

produced. Therefore, the laser oscillation is rather stable. In a single-wavelength operation of these lasers, has been experimentally demonstrated that multiple longitudinal modes are supported by the cavity. However, for similar pumping levels, a single-mode operation of the laser when we emit simultaneously several wavelengths using a special ring cavity configuration has been achieved [85]. The stable SLM operation is guaranteed if the output power of both channels is similar. This implies that it is possible to avoid the utilization of additional optical filtering techniques (that reduce the optical efficiency) to achieve the SLM operation.

4.1.2. Applications of single frequency fiber lasers

The narrow linewidhs and excellent frequency noise characteristics of single-frequency fiber lasers make them ideal form many applications. One key area for which the fiber geometry is attractive is remote sensing. The advent of fiber lasers based on Bragg reflectors has triggered a revolution in sensing applications, making possible, for example, the ustrasensitive detection of strain and magnetic fields. The narrowband reflection of the Bragg reflector meant that only a small precentage of the incident signal was reflected by the device, resulting in difficulties in extracting the optical signal from the background noise. The ability to incorporate Bragg gratings into fiber lasers has allowed the development of high-power (> 1mW) sensitive optical sensors and alleviated these signal to noise problems [73].

Several approaches have been investigated to developed fiber laser based strain sensors [93]. Also, cavities for narrow-linewidth fiber lasers can be made with matched pairs of fiber Bragg reflectors. These lasers have been employed to produce both single point and multipoint sensors [94]. Instead of using the Bragg reflector to sense the environmental change, the actual laser acts as the sensor. As it is well known, a change in the optical path length induces a change in the frequency, so by monitoring the wavelength change the environmental perturbation can be monitored. The multipoint sensor consists of a series of fiber lasers made from Bragg reflectors peaking at different wavelengths. In addition to this, magnetic fields can be detected using an active fiber laser sensor [76]. A single frequency fiber laser was attached to a magnetostrictive element. This element exhibits a quadratic dependence to the applied field, and it can be used to detect either AC or DC magnetic fields [73].

The foregoing sensors rely on changes in laser wavelength to provide information on the perturbation applied to the active sensor. The polarization properties of fiber lasers can be also be exploited to produce a sensor. Dual-frequency operation can be obtained in narrow-linewidth fiber lasers by exiting the orthogonal polarization axes of the weakly birefringent laser cavity. Because the refractive indices associated with polarization axes are different, the oscillating frequencies of the two modes are also different. Detection of these two frequencies result in a beat note at the detector. By applying to the cavity a perturbation that alters its birefringence, the beat frequency changes, and by monitoring this frequency change the applied perturbation can be quantified.

The need for a suitable standard close to 1.5 μm is driven by the use of narrow-linewidth lasers for wavelength multiplexed communication systems. In general, the light sources used for these systems have been distributed feedback semiconductor lasers. However, it has been demonstrated that narrow-linewidth fiber lasers are a potentially suitable replacement [73].

5. Raman lasers

Raman fiber lasers (RFLs) are attractive light sources for generating laser light at wavelengths which are difficult to obtain with other lasers. One of the most significant characteristics of these lasers is versatility in terms of wavelength, since Raman gain is achievable throughout the complete window of transparency of silica (300-2200nm). Providing that a suitable high power pump is provided, the Raman amplification process can be cascaded several times [95] allowing lasing in a broad wavelength range. Such wavelength versatility cannot be achieved using traditional lasers based on rare-earth-doping that have limited emission bands not broader than a few tens of nanometers. The nonuniform nature of the Raman gain spectrum is of concern for wavelength-division-multiplexed (WDM) lightwave systems because different channels will be amplified by different amounts. This problem is solved in practice by using multiple pumps at slightly different wavelengths. Each pump provides nonuniform gain but the gain spectra associated with different pumps overlap partially. With a suitable choice of wavelengths and powers for each pump laser, it is possible to realize nearly flat gain profile over a considerably wide wavelength range.
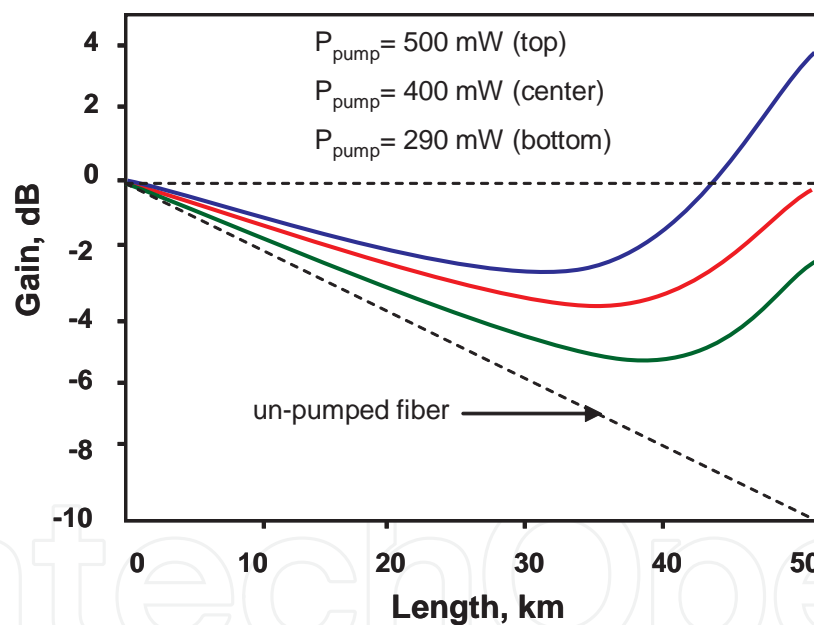

Figure 10. Measured gain evolution observed within a 50 km standard fiber transmission span for different pump powers.

In addition to this, and besides the advantages due to distributed amplification, another merit of the Raman amplifier is that any gain band can be tailored by proper choice of pump wavelength. One of the main purposes of discrete Raman amplifiers is to realize an amplifier operating in different windows than EDFA. There have been many efforts to develop discrete Raman amplifiers operating in 1.3 [96], 1.52 [97], and 1.65 μm [98] bands. Because the interaction length of the Raman amplifier is typically orders of magnitude longer than that of EDFA, nonlinearity, saturation, and double Rayleigh backscattering may become serious issues.

However, by optimizing the length of the gain fiber (see Figure 10) and using a two-stage structure, one may be able to design discrete Raman amplifiers that are good for signal transmissions. Raman fiber lasers have been used in several of the pioneering experiments in distributed Raman amplification. For example, the first demonstrations of (a) capacity upgrades using Raman amplification by Hansen et al. [99], (b) multiwavelength pumping for large bandwidth by Rottwitt and Kidorf [100], and (c) higher order pumping by Rottwitt et al. [101] all used single wavelength Raman fiber lasers. Many other systems' results have also established an RFL as a viable Raman pump source.

In long-distance FBG systems, the most important problem is Rayleigh scattering in the transmission fiber connecting the FBGs and interrogator. The noise floor of the FBG re‐flection spectrum is caused by Rayleigh-scattered light. The FBG reflection spectrum de‐tected by the interrogator decreases and the power of the Rayleigh-scattered light increases as the length of the transmission fiber increases. When the length is about 70 km, the signal to noise ratio (OSNR) of the FBG reflection spectrum becomes very low, limiting the practical length of the transmission fiber for FBG sensor systems of about this length (70 Km). A number of long-distance remote sensing systems using multiwa‐velength Raman lasers have been also proposed [102].

There were several methods used to improving the sensing distance of FBG-based sensor systems [103]. Based on a tunable laser and optical amplification, a sensing distance of 100km was achieved with a SNR of about 57 dB [104]. Takanori Saitoh et al. developed a FBG sensor system based on EDFA, whose performance was highly dependent on the quality of the light source and sensing distance of 230 km was obtained with a SNR of 4dB [70]. On the other hand, Fernandez-Vallejo et al. developed an ultra-long range fiber Bragg grating sensor interrogation system able to detect four multiplexed FBGs placed 250 km away, offering a signal to noise ratio of 6–8 dB [104]. Due to in many applications, such as railway, oil or gas pipelines, FBG sensor systems with even longer sensing distance are needed. Recently, a novel tunable fiber ring laser configuration with combination of hybrid Raman amplification and EDFA has been presented [105] to improve the sensing characteristics of the FBG-based ultra-long sensor system. A maximum sensing distance of 300 km with an SNR of about 4 dB has been obtained.

6. Random lasers

Random lasers are miniature sources of stimulated emission in which the feedback is provided by scattering in a gain medium [107]. Random lasers have currently evolved into a large research field. The recent review of random lasers can be found in [108]. Since scattering provides the feedback in random lasers, they do not require any external cavity or mirrors. However, external mirrors enhance the performance of random laser if they are positioned close enough to the gain medium and help to increase the feedback of stimulated emission or the efficiency of utilization of pumping. The random laser with one mirror, which had high transmission at the pumping wavelength and high reflection at the stimulated emission wavelength, was demonstrated in [109]. It has been shown that the mirror helps to reduce the

threshold by~25% and increase the slope efficiency by~30%. The relatively moderate improvement was explained by the fact that the mirror and the laser powder in [109] were separated by a1 mm thick wall of the cuvette.

An intrinsic fundamental loss mechanism of an optical fiber is Rayleigh scattering (RS) [110]. When using Raman amplification besides losses due to RS there will also be losses due to double Rayleigh scattering (DRS). The long lengths of fiber used for Raman amplification make the Rayleigh scattering associated noise an issue. As the gain in Raman amplifiers increases so will RS and DRS, which eventually limit the achievable gain [111]. An interesting approach in order to diminish these losses is using this Rayleigh associated noise as an active part of the laser. It can be used as a distributed random mirror transforming what were losses in gain in the output signal [112], [113]. Lasers taking advantage of cooperative Rayleigh scattering as a self-feedback mechanism of Brillouin-Rayleigh scattering have been reported [114]-[116]. Schemes have been implemented by using four-wave mixing method through the use of reduced high nonlinear Bismuth-erbium doped fiber for Brillouin-Raman multiwavelength lasing with comb generation [117], or high-reflectivity mirror in the linear cavity for distributed feedback [118], [119]. Different multiwavelength Raman fiber lasers based in these same structural setups have been recently developed: a multiwavelength Raman fiber laser based in highly birefringent photonic crystal fiber loop mirrors combined with random mirrors [110] or based in Sagnac structures [120], [121].

7. Other fiber lasers

Besides the fiber lasers previously pointed out, there are other fiber lasers that it is worth taking into consideration. This subsection is devoted to show some of the most common types.

Different techniques have been used to Q-switch a fiber laser. Q-switching can be achieved actively through the action of an electrically controlled loss modulator. It can also be carried out passively [73]. For example, a saturable absorber placed in the cavity acts as a loss modulator, with an intensity-dependent transmission controlled by the laser field itself. Active Q-switching has been used preferentially with fiber lasers. Ideally, in its low-transmission state the loss modulator should introduce a loss high as possible, to maintain the laser below threshold while gain is built-up to high values. On the other hand, it should be as transparent as possible in its high-transmission state, to minimize the loss it adds to the laser field. Finally, the switching time of the loss modulator should be short enough to accommodate the rapidly expanding laser field. A slow-opening modulator is a source of loss and can also result in multiple pulsing [22], [122].

Mode-locked fiber lasers are capable of producing pulses with widths from close to 30 fs to 1ns at repetition rates, ranging from less than 1 MHz to 100 GHz. This versatility, as well as the compact size of optical fibers, is quite unique in laser technology, and thus open up fiber lasers to a large range of applications. Indeed, mode-locked fiber lasers have been established as a premier source of short optical pulses, ranking equally with semiconductor and solid-state lasers. As mode-locked fiber laser technology matured and

these lasers became commercially available, they have been used in many different fields, such as laser radar, all-optical scanning delay lines, nonlinear frequency conversion, injection-seeding, two-photon microscopes, THz generation, and optical telecommunications, just to mention the most widely publicized areas [73].

Separately, stimulated Brillouin scattering (SBS) is a nonlinear process that can occur in optical fibers at input power levels much lower than those needed for stimulated Raman scattering (SRS). It manifests through the generation of a backward-propagating Stokes wave that carries most of the input power, once the Brillouin threshold is reached. For this reason, SBS limits the channel power in optical communication systems. At the same time, it can be useful for making fiber-based Brillouin amplifiers and lasers.

Brillouin fiber lasers consisting of a Fabry–Perot cavity exhibit features that are qualitatively different from those making use of a ring cavity. The difference arises from the simultaneous presence of the forward and backward propagating components associated with the pump and Stokes waves. Higher-order Stokes waves are generated through cascaded SBS, a process in which each successive Stokes component pumps the next-order Stokes component after its power becomes large enough to reach the Brillouin threshold. At the same time, anti-Stokes components are generated through four-wave mixing between copropagating pump and Stokes waves. The number of Stokes and anti-Stokes lines depends on the pump power. Most Brillouin fiber lasers use a ring cavity to avoid generation of multiple Stokes lines through cascaded SBS. The performance of a Brillouin ring laser depends on the fiber length used to make the cavity.

Considerable attention was paid during the 1990s to developing hybrid Brillouin erbium fiber lasers capable of operating either at several wavelengths simultaneously or in a single mode, whose wavelength is tunable over a wide range [106]. Besides the foregoing fiber lasers, some novel FBG interrogation techniques for remote sensing using a hybrid Brillouin-Raman fiber laser (100 km) [123] or combining Raman, Brillouin and erbium gain in a fiber laser (155 km) [124] have experimentally demonstrated.

8. Conclusions

This work dealt with various aspects of the multiwavelength fiber lasers. These kinds of lasers can be designed with a variety of choices for the laser cavity, because of that a brief explanation about the suitable configuration design has been shown.

There are a number of fiber lasers with different configurations and amplification methods; however this work has been centered on the erbium doped and Raman fiber lasers. The importance of the multiwavelength fiber lasers has been pointed out. Some of their problems, such as the laser output fluctuations, have been explained just as several reported stabilization techniques.

Finally, it is worth highlighting that multiwavelength fiber lasers are the hot topic in industrial-laser circles. They promise to revolutionize the laser industry through a disruptive combina-

tion of high reliability, high efficiency, low cost, and excellent beam quality. Fiber lasers are merely the most prominent example of these technologies' proliferation in industrial lasers.

Acknowledgements

Author details

Rosa Ana Perez-Herrera[*] and Manuel Lopez-Amo

*Address all correspondence to: rosa.perez@unavarra.es

Department of Electric and Electronic Engineering, Universidad Pública de Navarra, Campus Arrosadia S/N, Pamplona, Spain

References

[1] López Higuera JM. Advanced Photonic Topics. Universidad de Cantabria; 1997

[2] Liu K. et al. Broadband diode-pumped fibre laser. Electronics Letters 1988; 24(14) 838-840.

[3] Fernandez-Vallejo M, Diaz S, Perez-Herrera RA, et al. Comparison of the stability of ring resonator structures for multiwavelength fiber lasers using Raman or Er-doped fiber amplification. IEEE Journal of Quantum Electronics 2009; 45(12) 1551-1557

[4] Horowitz M, et al. Narrow-linewidth, singlemode erbium-doped fibre laser with intracavity wave mixing in saturable absorber. Electronics Letters 1994; 30(8) 648-649

[5] Barnsley P, et al. Fiber Fox-Smith resonators: application to single-longitudinal-mode operation of fiber lasers. Journal of the Optical Society of America 1988; 5(8) 1339-1346

[6] Jones JDC, et al. An injection-locked erbium fibre laser. Optics Communications 1990; 76(1) 42-46

[7] Perez-Herrera RA, et al. Stability comparison of two ring resonator structures for multiwavelength fiber lasers using highly doped Er-fibers. IEEE Journal of Lightwave Technology 2009; 27(14) 2563-2569

[8]   Chan CC, Jin W, Ho HL, Demokan MS. Performance analysis of a time-division-multiplexed fiber Bragg grating sensor array by use of a tunable laser source. IEEE J. Selected Topics Quantum Electronics 2000; 6(5) 741–749

[9]   Bellemare A, Karasek M, Rochette M, LaRochelle S, Tetu M. Room temperature multifrequency erbium-doped fiber lasers anchored on the ITU frequency grid. Journal of Lightwave Technology 2000; 18(6) 825–831

[10]   Gusarov A, Liegeois F. Experimental study of a tunable fiber ring laser stability. Optics Communications 2004; 234(1-6) 391-397

[11]   Chen X, Yao J, Zeng F, Deng Z. Single-longitudinal-mode fiber ring laser employing an equivalent phase-shifted fiber Bragg grating. IEEE Photonics Technology Letters 2005; 17(7) 1390-1392

[12]   Bellemare A, Karásek M, Riviere C, Babin F, He G, Roy V Schinn GW. A Broadly Tunable Erbium-Doped Fiber Ring Laser: Experimentation and Modeling. IEEE Journal on Selected Topics in Quantum Electronics 2001; 7(1) 22-29

[13]   Liu CK, Jou JJ, Liaw SK, Lee HC. Computer-aided analysis of transients in fiber lasers and gain-clamped fiber amplifiers in ring and line configurations through a circuit simulator. Optics Communications 2002; 209(4-6) 427–436

[14]   Yeh CH, Chi S. A broadband fiber ring laser technique with stable and tunable signal-frequency operation. Optics Express 2005; 13(14) 5240-5244

[15]   Yeh CH, Shih FY, Chow CW, Chi S. Dual-Wavelength S-Band Erbium-Doped Fiber Double-Ring Laser. Laser Physics 2008; 18(12) 1553-1556

[16]   Talaverano L, Abad S, Jarabo S, López-Amo M. Multiwavelength Fiber Laser Sources with Bragg-Grating Sensor Multiplexing Capability. Journal of Lightwave Technology 2001; 19(4) 553-558

[17]   Bellemare A. Continuous-wave silica-based erbium-doped fibre lasers. Progress in Quantum Electronics 2003; 27(4) 211-266

[18]   Perez-Herrera RA, Chen S, Zhao W, Sun T, Grattan KTV, Lopez-Amo M. Stability performance of short cavity Er-doped fiber lasers. Optics Communications 2010; 283(6) 1067-1070.

[19]   Perez-Herrera RA, Chen S, Zhao W, Sun T, Grattan KTV, Lopez-Amo M. Experimental optimization in terms of power stability and output power of highly Er-doped fiber lasers with single and hybrid cavities. Fiber & Integrated Optics 2010; 29(2) 106-120

[20]   Giles CR, Desurvire E. Modeling erbium-doped fiber amplifiers. Journal of Lightwave Technology 1991; 9(2) 271-283

[21]   Ball GA, Holton CE, Hull-Allen G, Morey WW. 60mW 1.5μm single-frequency low-noise fiber laser MOPA. IEEE Photonics Technology Letters 1994; 6(2) 192–194

[22] Siegman AE., editor. Lasers. University Science Books: Mill Valley; 1986

[23] O'Sullivan MS, Chrostowski J, Desurvire E, Simpson JR. High-power narrow-line-width Er3+-doped fiber laser. Optics Letters 1989; 14(9) 438-440

[24] Pang H-W, Cui H-M, Lian H., Zhao R-M, Hu B-N, Wang Y-F. Design of erbium-doped fiber laser based on linear multi-cavity. In: Yang L, Chen Y, Kley E-B, Li R (eds.) 3rd International Symposium on Advanced Optical Manufacturing and Testing Technologies: Advanced Optical Manufacturing Technologies, AOMATT 2007, 8-12 July 2007, Chengdu, China

[25] International Telecommunication Union (ITU-T). Optical interfaces for multichannel systems with optical amplifiers. Recommendation G.692, 40pp, 1998

[26] Liegeois F, Gusarov AI. Mid-term stability of a fiber ring laser with a wavelength-tunable Fabry-Perot filter. In proceedings of SPIE - The International Society for Optical Engineering 2004; 5480(36) 36-45

[27] Liu Y, Dong X, Shum P, Yuan S, Kai G, Dong X. Stable room-temperature multi-wavelength lasing realization in ordinary erbium-doped fiber loop lasers. Optics Express 2006; 14(20) 9293-9298

[28] Deepa V, Vijaya R. Linewidth characteristics of a filterless tunable erbium doped fiber ring laser. Journal of Applied Physics 2007; 102(8), art. no. 083107-4

[29] Takahashi H, Toba H, Inoue Y. Multiwavelength ring laser composed of EDFAs and an arrayed waveguide wavelength multiplexer. Electronics Letters 1994; 30(1) 44–45

[30] Miyazaki T, et al. A multiwavelength fiber ring-laser employing a pair of silica-based arrayed-waveguide-gratings. IEEE Photonics Technology Letters 1997; 9(7) 910–912

[31] Yeh CH, Huang TT, Chien HC, Ko CH, Chi S. Tunable S-band erbium-doped triple-ring laser with single-longitudinal-mode operation. Optics Express 2007; 15(2) 382-386

[32] Cheng XP, Shum P, Tse CH, Zhou JL, Tang M, Tan WC, Wu RF, Zhang J. Single-longitudinal-mode erbium-doped fiber laser based on high finesse fiber Bragg grating Fabry-Perot Etalon. IEEE Photonics Technology Letters 2008; 20(12) 976-978

[33] Song YW, Havstad SA, Starodubov D, Xie Y, Willner AE Feinberg J. 40-nm-wide tunable fiber ring laser with single-mode operation using a highly stretchable FBG. IEEE Photonics Technology Letters 2001; 13(11) 1167-1169

[34] Fischer B, Zyskind JL, Sulhoff JW, DiGiovanni DJ. Nonlinear wave mixing and induced gratings in erbium-doped fiber amplifiers. Optics Letters 1993; 18(24) 2108-2110

[35] Frisken SJ. Transient Bragg reflection gratings in erbium-doped fiber amplifiers. Optics Letters 1992; 17(24) 1776-1778

[36] Sharma U, Kim CS, Kang JU. Highly Stable Tunable Dual-Wavelength Q-Switched Fiber Laser for DIAL Applications. IEEE Photonics Techn. Letters 2004; 16(5) 1277-1279

[37] Zhang K, Kang JU. C-band wavelength-swept single-longitudinal mode erbium-doped fiber ring laser. Optics Express 2008; 16(18) 14173-14179

[38] Liu Y, Feng X, Yuan S, Kai G, Dong X. Simultaneous four-wavelength lasing oscillations in an erbium-doped fiber laser with two high birefringence fiber Bragg gratings. Optics Express 2004; 12(10) 2056-2061

[39] Yeh C-H, Chi S. A broadband fiber ring laser technique with stable and tunable signal-frequency operation. Optics Express 2005; 13(14) 5240-5244

[40] Sun J, Yuan X, Zhang X, Huang D. Single-longitudinal-mode dual-wavelength fiber ring laser by incorporating variable saturable absorbers and feedback fiber loops. Optics Communications 2007; 273(1) 231–237

[41] Wang T. Study on high power single-frequency erbium doped fiber laser for long distance communications. Microwave and Optical Techn. Letters 2008; 50(6) 1660-1662

[42] Schmuck H, Pfeiffer T. Fibre-pigtailed Fabry-Perot filter used as tuning element and for comb generation in an erbium doped fibre ring laser. In proceedings of the Technical Digest of 17th European Conference on Optical Communication, ECOC'91, 9-12 Sept 1991, Paris, France.

[43] Park N, Dawson JW, Vahala KJ. Multiple wavelength operation of an erbium-doped fiber laser. IEEE Photonics Technology Letters 1992; 4(6) 540–542

[44] Hübner J, Varming P, Kristensen M. Five wavelength DFB fibre laser source for WDM systems. Electronics Letters 1997; 33(2) 139–140

[45] Graydon O, Loh WH, Laming RI, Dong L. Triple-frequency operation of an Er-doped twincore fiber loop laser. IEEE Photonics Technology Letters 1996; 8(1) 63–65

[46] Poustie AJ, Finlayson N, Harper P. Multiwavelength fiber laser using a spatial mode beating filter. Optics Letters 1994; 19(10) 716–718

[47] Abraham D, Nagar R, Ruberto MN, Eisenstein G, Zyskind JL, DiGiovanni D, Koren U Raybon G. Intracavity-diode-pumped erbium doped fibre laser. Electronics Letters 1992; 28(19) 1830–1832

[48] Zhao Y, et al. Multiple wavelength operation of a unidirectional Er-doped fiber ring laser with optical feedback. In proceedings of the Technical Digest of Lasers and Electro-Optics, CLEO'97, 18-23 May 1997, Baltimore, Maryland

[49] Sasamori H, Isshiki K, Watanabe H, Kasahara K. Multi-wavelength erbium-doped ring light source with fiber grating filter. Technical Digest of Optical Amplifiers and Their Applications, OAA'97, 1997, paper WC3, pp. 235–238

[50] Bellemare A, Rochette M et al. Multifrequency erbium-doped fiber ring lasers anchored on the ITU frequency grid. In proceedings of the Technical Digest of Conference on Optical Fiber Communication, OFC'99, 21-26 Feb 1999, San Diego, California.

[51] Karásek M, Bellemare A. Numerical analysis of multifrequency erbium-doped fiber ring laser employing a periodic filter and a frequency shifter. IEE Proceedings-Optoelectronics 2000; 147(2) 115–119

[52] Liu XS, Zhan L, Hu X, Li HG, Shen QS, Xia YX. Multiwavelength erbium-doped fiber laser based on nonlinear polarization rotation assisted by four-wave-mixing. Optics Communications 2009; 282(14) 2913–2916

[53] Chow J, Town G, Eggleton B, Ibsen M, Sugden K, Bennion I. Multiwavelength generation in an erbium-doped fiber laser using in-fiber comb filters. IEEE Photonics Technology Letters 1996; 8(1) 60–62

[54] Town GE, Sudgen K, Williams JAR, Bennion I, Poole SB. Wide-band Fabry-Perot-like filters in optical fibers. IEEE Photonics Technology Letters 1995; 7(1) 78–80

[55] Yamashita S, Hotate K. Multiwavelength erbium-doped fiber laser using intracavity etalon and cooled by liquid nitrogen. Electronics Letters 1996; 32(14) 1298–1299

[56] Park N, Wysocki PF. 24-line multiwavelength operation of erbium-doped fiber-ring laser. IEEE Photonics Technology Letters 1996; 8(11) 1459–1461

[57] Yamashita S, Hsu K, Loh WH. Miniature Erbium:Ytterbium fiber Fabry-Perot multiwavelength lasers. IEEE Journal of Selected Topics in Quantum Electronics 1997; 3(4) 1058–1064

[58] Lopez-Amo M, López-Higuera JM. Multiplexing Techniques for FBG Sensors. In: Cusano A, Cutolo A, and Albert J. (eds.) Fiber Bragg Grating Sensors: Research Advancements, Industrial Applications and Market Exploitation. Oak Park, Illinois: Ed. Bentham Science Publishers Ltd; 2010.

[59] Koo KP, Kersey AD. Bragg grating based laser sensor systems with interferometric interrogation and wavelength division multiplexing. Journal of Lightwave Technology 1995; 13(7) 1243-1249.

[60] Peng PC, Tseng HY, Chi S. Long-Distance FBG Sensor System Using a Linear-Cavity Fiber Raman Laser Scheme. IEEE Photonics Technology Letters 2004; 16(2) 575-577

[61] Peng PC, Feng KM, Peng WR, Chiou HY, Chang CC, Chi S. Long-distance fiber grating sensor system using a fiber ring laser with EDWA and SOA. Optics Communications 2005; 252(1-3) 127-131

[62] Perez-Herrera RA, Fernandez-Vallejo M, Diaz S, Quintela MA, Lopez-Amo M, López-Higuera JM. Stability comparison of two quadruple-wavelength switchable erbium-doped fiber lasers. Optical Fiber Technology 2010; 16(4) 205-211

[63] Liaw S-K, Lee C-C, Ho K-P, Chi S. Power equalized wavelength-selective fiber lasers using fiber Bragg gratings. Optics Communications1998; 155 (4-6) 255–259.

[64] Feng S, Xu O, Lu S, Ning T, Jian S. Switchable multi-wavelength erbium doped fiber ring laser based on cascaded polarization maintaining fiber Bragg gratings in a Sagnac loop interferometer. Optics Communications 2008; 281(24) 6006– 6010.

[65] Perez-Herrera RA, et al. Switchable multi-wavelength erbium-doped fiber laser for remote sensing. In proceedings of the SPIE 20th International Conference on Optical Fiber Sensors, OFS-20, 5-9 Oct 2009, Edinburgh, United Kingdom, 75031Y-1. 75031Y-4.

[66] Rao YJ, Ran ZL, Chen RR. Long-distance fiber Bragg grating sensor system with a high optical signal-to-noise ratio based on a tunable fiber ring laser configuration. Optics Letters 2006; 31(18) 2684-2686

[67] Saitoh T, Nakamura K, Takahashi Y, Iida H, Iki Y, Miyagi K. Ultra-Long-Distance Fiber Bragg Grating Sensor System. IEEE Photonics Technology Letters 2007; 19(20) 1616-1618

[68] Fernandez-Vallejo M, Bravo M, Lopez-Amo M 200-km long fiber ring laser for multiplexing fiber Bragg gratings arrays. In proceedings of the SPIE 22th International Conference on Optical Fibre sensors, OFS-22, 15-19 October 2012, Pekin, China, 84218J.

[69] Fernandez-Vallejo M, Rota-Rodrigo S, Lopez-Amo M. Remote (250 km) fiber Bragg grating multiplexing system. Sensors 2011; 11(9) 8711-8720

[70] Saitoh T, Nakamura K, Takahashi Y, Iida H, Iki Y, Miyagi K. Ultra-long-distance (230 km) FBG sensor system. In proceedings of the SPIE 19th International Conference on Optical Fiber Sensors, OFS-19, 14-18 April 2008, Perth, Western Australia, 70046C-70046C-4

[71] Rao YJ, Feng S, Jiang Q, Ran Z. Ultra-long distance (300km) fiber Bragg grating sensor system using hybrid EDF and Raman amplification. In proceedings of the SPIE 20th International Conference on Optical Fiber Sensors, OFS-20, 5-9 Oct 2009, Edinburgh, United Kingdom, 75031Q-75031Q-4

[72] http://www.olympusmicro.com/primer/java/lasers/gainbandwidth/index.html

[73] Digonnet MJF, editor. Rare-Earth-Doped Fiber Lasers and Amplifiers. Second Edition. Boca Ratón, EEUU: CRC Press, Taylor & Francis Group; 2001

[74] Snitzer, E. Optical Maser Action of Nd+3 in a Barium Crown Glass. Physical Review Letters 1961; 7(12) 444-446

[75] Kersey AD, Morey WW. Multi-element Bragg-grating based fibre-laser strain sensor. Electronics Letters 1993; 29(11) 964-966

[76] Koo K, Kersey A, Bucholtz F. Fiber Bragg grating laser magnetometer. In proceeding of the Conference on Lasers and Electro-Optics, postdeadline paper PD41, 1995, Baltimore, Maryland

[77] Taylor JR. Soliton fiber lasers. In proceedings of the Conference on Lasers and Electro-Optics, paper CWM3, 1995, Baltimore, Maryland

[78] Koechner W, editor. Solid State Laser Engineering. Berlin: Springer, 2006.

[79] Liu XS, Zhan L, Hu X, Li HG, Shen QS Xia YX. Multiwavelength erbium-doped fiber laser based on nonlinear polarization rotation assisted by four-wave-mixing. Optics Communications 2009; 282(14) 2913-2916

[80] Zhang K, Kang JU. C-band wavelength-swept single-longitudinal mode erbium-doped fiber ring laser. Optics Express 2008; 16(18) 14173-14179

[81] Ibsen M, Ronnekleiv E, Cowle GJ, Zervas MN, Laming RI. Multiple wavelength all-fibre DFB lasers. Electronics Letters 2000; 36(2) 143-144

[82] Yamashita S, et al. Multiwavelength Er-Doped Fiber Ring Laser Incorporating Highly Nonlinear Fiber. Japanese Journal of Applied Physics 2005; 44(33-36) L1080-L1081

[83] Humphrey PD, Bowers JE. Fiber-birefringence tuning technique for an erbium-doped fiber ring laser. IEEE Photonics Technology Letters 1993; 5(1) 32-34

[84] Chieng YT, Minasian RA. Tunable erbium-doped fiber laser with a reflection Mach-Zehnder interferometer. IEEE Photonics Technology Letters 1994; 6(2) 153-156

[85] Quintela MA, Perez-Herrera RA, Canales I, Fernandez-Vallejo M, Lopez-Amo M, Lopez Higuera JM. Stabilization of dual-wavelength erbium doped ring fiber lasers by single-mode operation. IEEE Photonics Technology Letters 2010; 22(6) 368-370

[86] Kashyap RP et al. All-fibre narrowband reflection gratings at 1500 nm. Electronics Letters 1990; 26(11) 730-732

[87] Ball GA, Morey WW. Continuously tunable single-mode erbium fiber laser. Optics Letters 1992; 17(6) 420-422

[88] Perez-Herrera RA, et al. L-Band Multiwavelength Single-Longitudinal Mode Fiber Laser for Sensing Applications. IEEE Journal of Lightwave Technology 2012; 30(8) 1173-1177, art. no. 6062627

[89] Hanna DC, et al. Continuous-wave oscillation of a monomode ytterbium-doped fibre laser. Electron. Letters 1988; 24(17) 1111-1113

[90] Allain JY, Bayon JF, Monerie M, Bernage P, Niay P. Ytterbium-doped silica fiber laser with intracore Bragg gratings operating at 1.02 μm. Electronics Lett. 1993; 29(3) 309-310

[91] Ball GA, Morey WW, Glenn WH. Standing-Wave Monomode Erbium Fiber Laser. IEEE Photonics Technology Letters 1991; 3(7) 613-615

[92] Sun J, Huang L. Single-longitudinal-mode fiber ring laser using internal lasing injection and self-injection feedback. Optical Engineering 2007; 46(7) 074201-1-6

[93] Kim HK, Kim SK, Kim BY. Polarimetric fibre laser sensors using Er-doped fibre. Optical and Quantum Electronics 1995; 27(5) 481-485

[94] Ball GA, Morey WW, Cheo PK. Singlepoint and multipoint fiber-laser sensors. IEEE Photonics Technology Letters 1993; 5(2) 267–270

[95] Lin C, Cohen LG, Stolen RH, Tasker GW, French WG. Near-infrared sources in the 1–1.3 μm region by efficient stimulated Raman emission in glass fibers. Optics Communications 1977; 20(3) 426–428

[96] Gapontsev DV, Chernikov SV, Taylor JR. Fibre Raman amplifiers for broadband operation at 1.3 μm. Optics Communications 1999; 166(1) 85-88

[97] Kani J, Jinno M, Oguchi K. Fibre Raman amplifier for 1520nm band WDM transmission. Electronics Letters 1998; 34(18) 1745-1747

[98] Masuda H, Kawai S, Suzuki K-I, Aida K. 1.65 μm band fibre Raman amplifier pumped by wavelength-tunable amplified spontaneous emission light source. Electronics Letters 1998; 34(24) 2339-2340

[99] Hansen PB, Eskildsen L, Grubb SG, et al. Capacity upgrades of transmission systems by Raman amplification. IEEE Photonics Technology Letters 1997; 9(2) 262–264

[100] Rottwitt K, Kidorf HD. A 92 nm bandwidth Raman amplifier. In proceedings of Optical Fiber Communication Conference, OFC, 22 Feb 1988, Postdeadline Paper PD6, San Jose, California.

[101] Rottwitt K, Stentz A, Nielson T, Hansen P, Feder K, Walker K. Transparent 80 km bidirectionally pumped distributed Raman amplifier with second order pumping. In proceedings of the European Conference on Optical Communication, ECOC´99, 26-30 Sept 1999, II-144–145, Nice, France.

[102] Fernandez-Vallejo et al. Resilient long-distance sensor system using a multiwavelength Raman laser. Measurement Science and Technology 2010; 21(9), art. no. 094017.

[103] Rao Y-J, Ran Z-L, Chen R-R. Long-distance fiber Bragg grating sensor system with a high optical signal-to-noise ratio based on a tunable fiber ring laser configuration. Optics Letters 2006; 31(18) 2684-2686

[104] Fernandez-Vallejo M et al. Remote (250 km) Fiber Bragg Grating Multiplexing System. Sensors 2011; 11(9) 8711-8720

[105] Rao Y-J, Feng S, Jiang Q, Ran Z-L. Ultra-long distance (300km) fiber Bragg grating sensor system using hybrid EDF and Raman amplification. In proceedings of the SPIE 20th International Conference on Optical Fiber Sensors, OFS-20, 5-9 Oct 2009, Edinburgh, United Kingdom, 75031Q-75031Q-4

[106] Al-Mansoori MH et al. Widely tunable linear cavity multi-wavelength Brillouin-Erbium fiber lasers. Optics Express 2005; 13(9) 3471-3476

[107] Noginov MA, Zhu G, Small C, Novak J. Neodymium random laser with external mirrors. Applied Physics B: Lasers and Optics 2006; 84(1-2) 269-273

[108] Noginov MA, editor. Solid-State Random Lasers. USA: Springer, 2005

[109] Noginov MA, Noginova N, Egarievwe SU, Wang JC, Caulfield HJ. Nonlinear Optical Phenomena and Coherent Optics in information Technologies. In: Chesnokov SS, Kandidov VP, Koroteev NI (Eds.) ICONO'98, 29 June-3 July 1998, Moscow, Russia

[110] Pinto AMR, Frazão O, Santos JL, Lopez-Amo M. Multiwavelength Raman Fiber Lasers Using Hi-Bi Photonic Crystal Fiber Loop Mirrors Combined With Random Cavities. Journal Of Lightwave Technology 2011; 29(10) 1482-1488

[111] Headley C, Agrawal GP, editor. Raman Amplification in Fiber Optical Communication Systems. London, U.K.: Elsevier Academic Press, 2005

[112] Pinto AMR, Frazao O, Santos JL, Lopez-Amo M. Multiwavelength fiber laser based on a photonic crystal fiber loop mirror with cooperative Rayleigh scattering. Appl. Phys. B. 2010; 99(3) 391–395

[113] Zamzuri AK, et al. Contribution of Rayleigh scattering on Brillouin comb line generation in Raman fiber laser. Appl. Opt. 2010; 49(18) 3506–3510

[114] Park KD, et al. Dynamics of cascaded Brillouin-Rayleigh scattering in a distributed fiber Raman amplifier. Optics Letters 2002; 27(3) 155–157

[115] Giraldi MTM, et al. Rayleigh assisted Brillouin effects in distributed Raman amplifiers under saturated conditions at 40Gb/S. Microw. Opt. Technol. Lett. 2010; 52(6) 1331–1335

[116] Min B, Kim P, Park N. Flat amplitude equal spacing 798-channel Rayleigh-assisted Brillouin/Raman multiwavelength comb generation in dispersion compensating fiber. IEEE Photon. Technol. Lett. 2001; 13(12) 1352–1354

[117] Shahi S, Harun SW, Norizan SF, Moghaddam MRA, Ahmad H. Brillouin-Raman multi-wavelength laser comb generation based on Bi-EDF by using dual-wavelength in dispersion compensating fiber. J. Nonlinear Opt. Phys. 2010; 19(1) 123–130

[118] Zamzuri AK, et al. Flat amplitude multiwavelength Brillouin-Raman comb fiber laser in Rayleigh-scattering-enhanced linear cavity. Opt. Exp. 2007; 15(6) 3000–3005

[119] Zamzuri AK, Ali MIM, et al. Brillouin-Raman comb fiber laser with cooperative Rayleigh scattering in a linear cavity. Opt. Lett. 2006; 31(7) 918–920

[120] Pinto AMR, Lopez-Amo M. Double random mirror Hi–Bi photonic crystal fiber Sagnac based multiwavelength fiber laser. Applied Physics B: Lasers and Optics 2011; 103(4) 771-775

[121] Pinto AMR, Bravo M, Fernandez-Vallejo M, Lopez-Amo M, Kobelke J, Schuster K. Suspended-core fiber Sagnac combined dual-random mirror Raman fiber laser. Optics Express 2011; 19(12) 11906-11915

[122] Midwinter, JE. The theory of Q-switching applied to slow switching and pulse shaping for solid state lasers. British Journal of Applied Physics 1965; 16(8) 1125-1133

[123] Fernández-Vallejo M, et al. Fiber Bragg Grating interrogation technique for remote sensing (100km) using a hybrid Brillouin-Raman fiber laser. In proceedings of the SPIE 21st International Conference on Optical Fiber Sensors, OFS-21, 15-19 May 2011, Ottawa, Canada, 77537I

[124] Leandro D. et al. Remote (155 km) Fiber Bragg Grating Interrogation Technique Combining Raman, Brillouin, and Erbium Gain in a Fiber Laser. IEEE photonics technology letters 2011; 23(10)