Fiber Lasers for Optical Sensing Applications

ROSA ANA PEREZ-HERRERA, MANUEL LOPEZ-AMO SAINZ
Department of Electric and Electronic Engineering
Public University of Navarra
Campus Arrosadia S/N E-31006 Pamplona
SPAIN
rosa.perez@unavarra.es

Abstract: All-fiber multiwavelength lasers have attracted much interest recently because of their potential applications in wavelength-division-multiplexing (WDM) communications, microwave generation, high-resolution spectroscopy, fiber optic sensing, etc. This paper is devoted to these lasers and several of their aspects, as the laser design, the output power fluctuations, or different kinds of lasers, have been shown.

Key-Words: fiber amplifier, fiber laser, fiber Bragg grating, laser cavity.

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. These lasers normally operate supporting 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 exceed 10 nm under continuous wave (CW) operation [1]. Many applications of CW lasers require operation in a single mode narrow-linewidth whose wavelength can be tuned over the gain bandwidth. Several methods have been used to realize narrow-linewidth fiber lasers [2]. 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].

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 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 EDFL is the fact that the erbium ion saturates mostly homogeneously at room temperature, preventing stable multiwavelength operation.

2 Fiber lasers design
Fiber lasers can be designed with a variety of choices for the laser cavity [2]. One of the most common types 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 coupler such that most of the pump power comes out of the port that is a part of the laser cavity. A third approach makes use of fiber gratings as mirrors [3]. As is known, a fiber Bragg grating can act 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 [4]. Another solution is to use fiber gratings as mirrors [3]. As is known, a fiber Bragg grating can act 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 [4]. 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 obtain a 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 Fig. 1.

An isolator is usually inserted within the loop for
unidirectional operation. However, some alternative
fiber laser configurations have been shown, where
these kind of devices can be suppressed from the
cavity rings by using optical circulators [5].

Theoretically, a polarization controller is also needed
for conventional doped fiber that does not preserve
polarization. However, some works [6] have
demonstrated that this device has little influence on
the multimode regime.

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 a compound resonator has been
used to reduce the line width of an Er-doped fiber
laser [7].

Three fiber gratings in series also produce
two coupled Fabry-Perot cavities. Still another design
makes use of a Fox-Smith resonator.

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 than 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. A systematically
effort to study these causes has been carried out.

Based on previous experiences these studies have
been focused on the optimization of some the
following parameters: pump power [8], doped fiber
length and ions concentration [9], output coupling
ratio [10], total cavity length [9], spectral hole-
burning effect [11] or the cavity losses [12].
However, polarization control seems not very
important in the multimode regime [9].

3 Erbium doped fiber lasers

Erbium doped fiber lasers (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 [13].

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 EDFLs [14].

Fiber gratings can also be used to improve the
performance of EDFLs. Since 1990, when a Bragg
grating was used to achieve a line width of about 1
GHz [15], fiber gratings have been used in EDFAs
for a variety of reasons [16]. 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. Fig. 2 shows an example
of the output power spectral density of a single-stage
EDFA (with two FBGs centered at 1540 and 1545 nm
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.
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 for this purpose [17]. 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 1 mm cavity length corresponds to a 100 GHz wavelength spacing. Such fiber lasers operate at 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.

4 Raman lasers
Stimulated Raman scattering (SRS) is an important nonlinear process that can turn optical fibers into broadband Raman amplifiers and tunable Raman lasers. It can also severely limit the performance of multichannel lightwave systems by transferring energy from one channel to the neighboring channels. The EDFA-based WDM transmission systems have begun to face their limit in terms of both bandwidth and noise. An optical amplifier besides EDFA is now sought in order to extend bandwidth and further reduce noise for higher capacity and longer distance transmissions. In this context, fiber Raman amplifiers are receiving much attention because of their adjustability of the gain band by choosing the proper pumping wavelength, and their low-noise nature due to an off-resonance amplification process that fits well in the distributed amplifier configuration. In fact, fiber Raman amplifiers were already extensively studied before EDFA was developed in the late 1980s. However, because fiber Raman amplifiers needed more than 100 mW output power from the pump laser for most useful applications, fiber Raman amplifiers were not employed in the real world due to lack of compact and robust pump lasers at that time. Instead, EDFA, operating at pump powers less than 100 mW, could be pumped by compact laser diodes, so they were deployed in the real world. However, extensive studies in the 1970s to 1980s showed that the Raman amplification process could be used for optical transmission systems. 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 carry out nearly flat gain profile over a considerably wide wavelength range.

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 carry out an amplifier operating in different windows than EDFA. There have been many efforts to develop discrete Raman amplifiers operating in 1.3 [18], 1.52 [19], and 1.65 µm [20] 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 [21] 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 (i) capacity upgrades using Raman amplification by Hansen et al. [22], (ii) multwavelength pumping for large bandwidth by Rottwitt and Kidorf [23], and (iii) higher order pumping by Rottwitt et al. [24] 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 reflection spectrum is caused by Rayleigh-scattered light. The FBG reflection spectrum detected 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).

There were several methods used to improving the sensing distance of FBG-based sensor systems [25]. Based on a tunable laser and optical amplification, a sensing distance of 100km was achieved with a SNR of about 57 dB [25]. 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 [26]. 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 [27] 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.

5 Other fiber lasers

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 Pr ions in an attempt to realize fiber lasers and amplifiers operating at 1.3μm. 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 achieved 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 [28]. 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 [29].

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 L 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 [30].

6 Conclusions

This paper dealt with various aspects of the 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 was 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.
References: