Fiber Lasers for Optical Sensing Applications

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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 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 [3]. As it is know, 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.

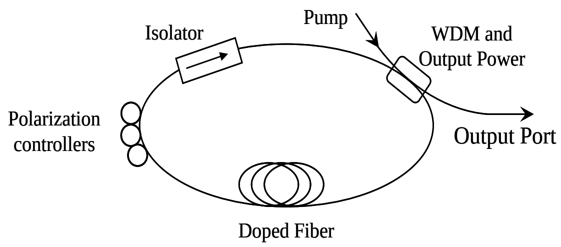

Fig.1. Schematic of a unidirectional ring cavity used for fiber lasers.

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 multiwavelength 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 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. 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 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.

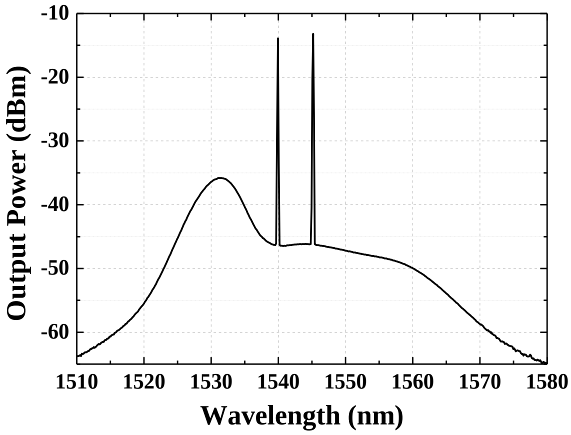

Fig.2. Output power spectral density (res=0.1nm) of a single-stage EDFA with λ_1=1540nm, λ_2=1545nm, P_p=90mW, L= 32 m, and λ_p=980nm.

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 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 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.

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) multiwavelength 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^{3+} 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.

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