15 September 2002

Optics Communications 210 (2002) 313–318

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Wideband wavelength tunable fiber ring laser with flattened output power spectrum

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Received 19 November 2001; received in revised form 27 March 2002; accepted 11 July 2002

Abstract

A wavelength tunable erbium-doped fiber ring laser with flattened output power spectrum over a broadband is proposed and demonstrated. The power flattening is achieved using a high-birefringence fiber loop mirror, in which a number of high-birefringence fiber sections and polarization controllers are used to get a reflection spectrum that can compensate for the output power spectrum. The wavelength tuning is realized by compressing or stretching the FBGs in the laser cavity. A 1×3 switchable fiber Bragg grating array is incorporated into the fiber ring to get a wideband tuning range of 38 nm, from 1527 to 1565 nm. Within this range, the output power uniformity is controlled within ± 0.8 dB. The total output power is about 4 dBm, the 3-dB linewidth is 0.01 nm, and the side mode suppression ratio is more than 48 dB. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Fiber Bragg grating; Fiber ring laser; Tunable laser; High-birefringence fiber loop mirror; Power flattening

1. Introduction

Wavelength tunable erbium-doped fiber lasers operating at the 1550-nm window have important applications in telecommunications, sensors and photonic true-time-delay (TTD) beamforming systems [1–7]. Among different types of fiber lasers, unidirectional traveling-wave ring laser has the advantages of eliminating backscattering and spatial hole-burning effects, and therefore has been intensively investigated recently. For applications such as wavelength division multiplexing, TTD beamforming, wideband tunable laser source with uniform output power over a broadband is required. However, for lasers based on erbium-doped fiber (EDF), the power spectrum uniformity is usually limited by the gain profile of the EDF. To improve the output power uniformity, the EDF gain profile should be properly compensated. Yamada et al. [8] demonstrated that an inherent flat gain could be obtained by using fluoride-based erbium-doped fiber as the gain medium in the amplifier design. For amplifiers using EDF, Pandit et al. [9] proposed to use tunable long-period gratings for EDFA gain equalization. Recently, Li et al. [10] suggested that the gain of an EDFA

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PII: S0030-4018(02)01767-4

could be flattened by employing a high-birefringence fiber loop mirror. All these approaches, however, concentrated on the gain flattening of fiber amplifiers. For fiber lasers, uniform power spectrum over a broadband is usually desirable, and the technique to flatten the power spectrum also needs to be investigated. In this paper, we demonstrate a wideband tunable fiber ring laser with uniform output power spectrum over a bandwidth of more than 38 nm. The power uniformity is controlled using a high-birefringence fiber loop mirror (HiBi-FLM) [10], in which a number of high-birefringence fiber sections and polarization controllers are employed. By tuning the polarization controllers, the reflection spectrum of the loop mirror can be adjusted to compensate for the variations in the gain profile of the EDF, and hence a flattened output power spectrum is achieved.

In order to get a very large tunable range, in the proposed laser system the wavelength tuning is implemented by tuning the center wavelengths of the incorporated FBGs. A single FBG can normally be tuned with a tunable range of about 16 nm. To realize wavelength tuning over a broader band, an array of FBGs with different center reflection wavelengths are used. In the laser system, the switchable FBG array consists of a 1×3 optical switch and three parallel discrete FBGs with center reflection wavelengths of 1534, 1549.15 and 1559.4 nm. Each FBG can be continuously tuned in a range of over 16 nm by stretching (7 nm) and compressing (8 nm) the FBG. Therefore, a fiber ring laser with a broad wavelength tuning range of about 38 nm can be demonstrated. In the experiment, a two-section HiBi-FLM and three-section HiBi-FLM are constructed and experimented. With two-section HiBi-FLM and three-section HiBi-FLM, the flattened output power spectrum can be controlled within ± 1.1 and ± 0.8 dB over a bandwidth of 38 nm, respectively.

2. Configuration of the fiber ring laser

The schematic diagram of the unidirectional tunable fiber ring laser [3,4] used in our experiment is shown in Fig. 1. It is constructed using 15-m long silica optical fiber doped with approximately 200 ppm of erbium. The numerical aperture (NA) of the erbium-doped fiber is 0.21 and the cutoff wavelength is 920 nm. The erbium-doped fiber has an absorption coefficient of 12 dB/m at 980 nm. To increase the optical pump efficiency, the erbium-doped fiber is pumped at 980 nm in dual directions by a diode laser through two 980/1550-nm wavelength division multiplexers (WDMs). A polarization-independent fiber isolator is used to achieve the unidirectional ring oscillation so as to avoid spatial hole burning in the gain medium. A polarization controller (PC) is used in the cavity to adjust the polarization state. The 10:90 coupler acts as the port to direct the lightwave to the switchable FBG array and also the output coupler for the fiber laser. The switchable FBG array, which is employed as a wavelength selector, consists of a 1×3 optical switch and three parallel discrete FBGs with central reflection wavelengths of 1534, 1549.15 and 1559.4 nm. The lasing wavelength is determined by the reflection peak of the FBG and can be tuned by compressing or stretching the FBG.

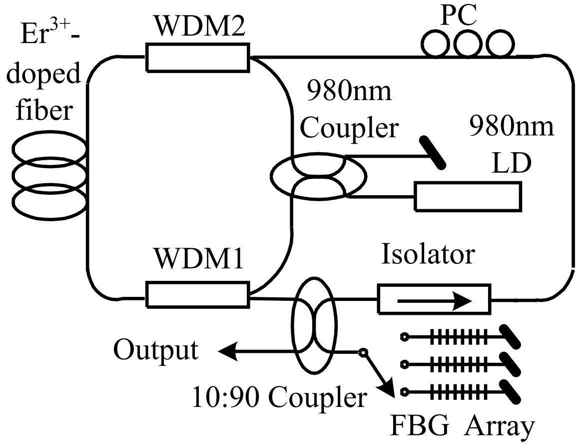

Fig. 1. Wideband tunable fiber ring laser using an array of switchable fiber Bragg gratings.

The tuning method is schematically illustrated in Fig. 2. The gratings are glued onto a piece of organic glass. When a force is applied to the fiber via compressing one side of the organic glass, the gratings will experience a tensile or compressive strain depending on the applying direction of the

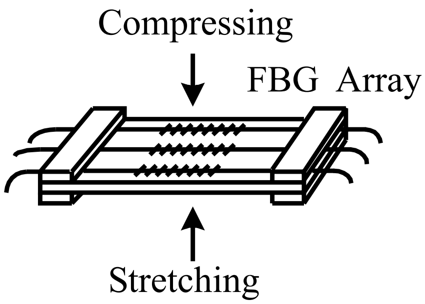

Fig. 2. Wavelength tuning by applying strain.

force, which will results in a period change of the FBGs. The overall effect is a shift of the reflection peak of the FBGs. In the tensile case, the wavelength will be shifted towards a longer wavelength. On the contrary, if a force is applied in the opposite direction, the reflection wavelength will be shifted to a shorter wavelength. Thus, tuning towards both shorter and longer wavelengths could be achieved. Usually, compression-tuning can results in a large tuning range since the silica fiber is much stronger in compression than in expansion.

3. Power flattening

The gain profile of the EDF is inherently uneven in its gain bandwidth, which leads to an output power profile similar to the gain profile of the EDF for a tunable fiber laser using EDF as the gain medium. For applications such as WDM and TTD beamforming systems, it is desirable that the output power uniformity can be controlled within an acceptable range. To solve this problem, we propose to use an HiBi-FLM to compensate for the power spectrum of the fiber ring laser. The use of HiBi-FLM was first proposed by Fang et al. [11] for polarization-independent wavelength division multiplexer. Recently, Li et al. [10] proposed to use the HiBi-FLM to flatten the gain profile of an EDFA. In the experiment reported by Li et al. [10], the HiBi-FLM with one HiBi fiber section and two HiBi fiber sections have been incorporated to achieve a flattened gain profile. A gain equalization within ±0.9 dB over 33 nm using a two-section HiBi fiber has been demonstrated.

A HiBi-FLM consists of a number of high-birefringence fiber sections and polarization controllers. We show that, by setting the polarization controllers properly, the reflection spectrum of the loop mirror can be adjusted to compensate for the variations in the gain profile of the EDF, and hence to flatten the output power of the erbium-doped fiber laser. Fig. 3 shows the schematic setup for power flattening using HiBi-FLM. The uncompensated lasing coming from the fiber ring laser is directed to the HiBi-FLM through an optical circulator. The power-flattened light is reflected to the optical circulator and then extracted from the output-port of the circulator. The HiBi-FLM loop is constructed by connecting alternately n polarization controllers ($PC_1, PC_2, \ldots, PC_n$) and n sections of HiBi fiber (HiBi fiber 1, HiBi fiber $2, \ldots,$ HiBi fiber n). Controlling the n polarization controllers can adjust the reflection spectrum and therefore compensate for the output power spectrum of the fiber ring laser.

The HiBi-FLM filter can be considered as n polarimetric interferometers and n polarization controllers alternately connected in series [10]. The input light into the HiBi-FLM filter is split into two counter-propagating beams at the 3-dB coupler. Each of the two counter-propagating beams is then disassembled into 2^n beams after traveling through n polarimetric interferometers constructed using n HiBi fiber sections. These counter-propagating 2^{n+1} lasing beams interfere with each other when they propagate in the loop and are reflected to the circulator. Controlling the lengths of the HiBi fiber sections to adjust the phase differences among the interfering beams and controlling the polarization controllers to adjust polarization states of light entering the n interferometers, we

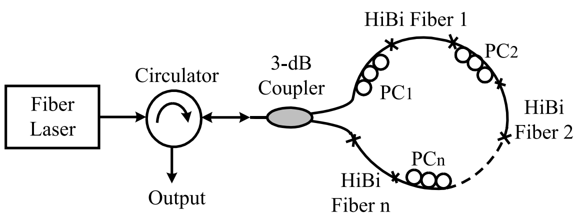

Fig. 3. High-birefringence fiber loop mirror for fiber laser power spectrum flattening.

can control the intensity of the output light reflected from the loop mirror at various wavelengths. In other words, we can control the reflection spectrum of the HiBi-FLM. In general, when the lengths of the HiBi fiber sections are determined properly, the reflection spectrum of the HiBi-FLM can be made to match the power spectrum of the fiber laser by controlling the polarization controllers.

4. Experimental results

In the experiment, a three-section HiBi-FLM is used to flatten the power spectrum of the fiber laser. The beat length of the HiBi fiber we used is 1.5 mm at the wavelength of 633 nm. For the output spectrum of the HiBi-FLM to cover the bandwidth of about 38 nm, the HiBi fiber should have a length of approximately 10 cm. The actual lengths of the three HiBi fiber sections are 12.5, 11.6 and 13.0 cm, respectively. The HiBi-FLM filter has an insertion loss of about 7 dB, which is mainly induced by the fiber splices between the HiBi fibers and single-mode fibers, and the loss of the 3-dB coupler. Fig. 4 illustrates the measured reflection spectrum of the three-section HiBi-FLM by adjusting the polarization controllers. It can be seen that the reflection spectrum in general consists of two asymmetric notches, which can be used to flatten the two peaks in the gain profile of the EDF if the three polarization controllers could be set properly. As shown in Fig. 4(a), the notch depths can be adjusted by more than 15 dB without changing the notch wavelength. On the other hand, the entire reflection spectrum can be shifted in wavelength without changing the shape, as shown in Fig. 4(b). Such flexibility in the control of the HiBi-FLM filter response offers a wide dynamic range for the flattening of the gain profile of the EDF, and therefore gives a flat output power spectrum of the fiber laser.

Fig. 5 shows the gain profiles of the EDF with and without gain equalization at a pump power of 75 mW. Curve 1 shows the gain profile without compensation while curve 2 shows the flattened gain profile with the three-section HiBi-FLM. From Fig. 5, it can be seen that, by setting the three polarization controllers properly, the gain profile of the EDF with the unevenness less than ±0.8 dB over a bandwidth of 38 nm at the center wavelength of 1546 nm is achieved. Without compensation, however, the unevenness is more than 7 dB over the same bandwidth. Due to the insertion loss of the HiBi-FLM filter, the compensated gain is about 7 dB lower than that without compensation.

Fig. 6 shows the output optical power of the tunable fiber ring laser with and without power spectrum compensation. In order to get a tunable range of about 38 nm, a 1×3 optical switch and three parallel discrete FBGs are incorporated into the fiber laser, as shown in Fig. 1. The peak reflection wavelengths of the three discrete FBGs are

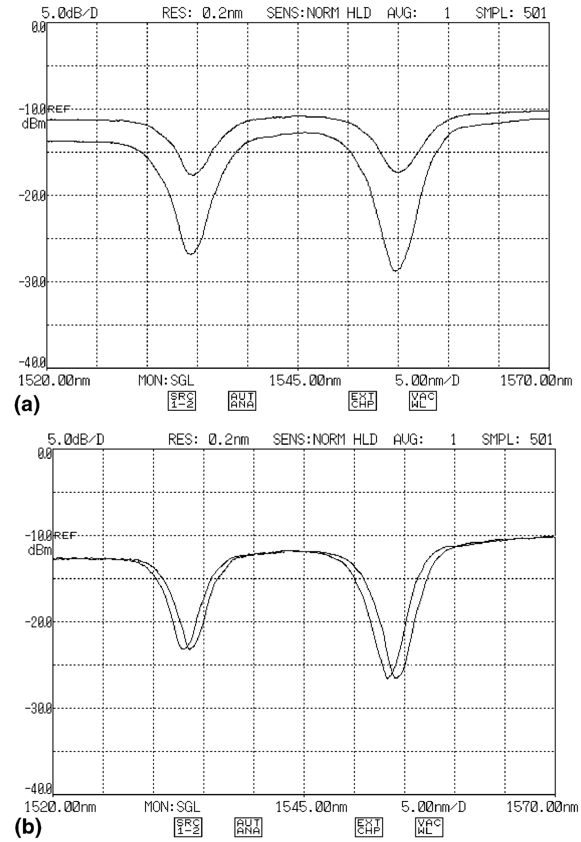

Fig. 4. Measured optical reflection spectrum of the HiBi-FLM by adjusting the polarization controllers. (a) Change of the notch depths. (b) Shift of the notch positions.

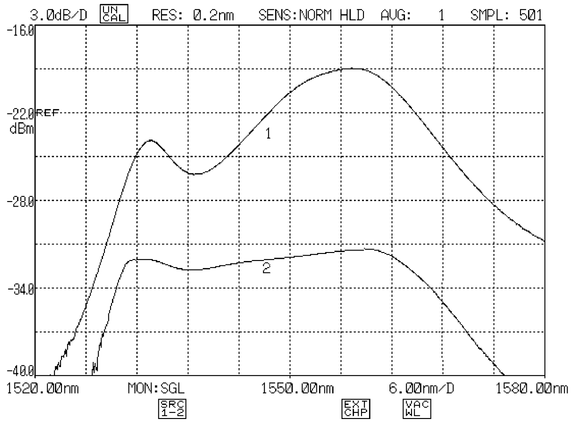

Fig. 5. Gain profile of the EDF used in the ring laser at a pump power of 75 mW: curve 1 – gain profile without compensation; curve 2 – flattened gain profile with a three-section HiBi-FLM.

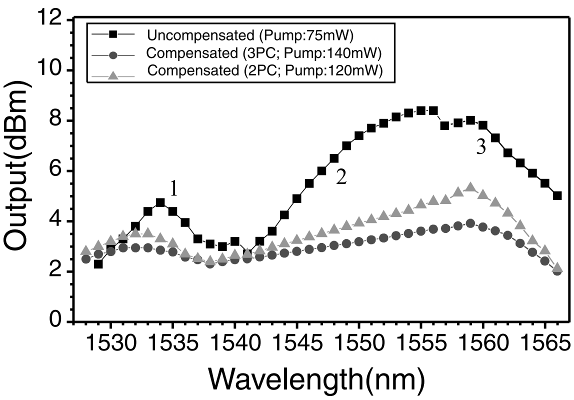

Fig. 6. Output power spectrum of the tunable fiber laser with and without power spectrum compensation.

1534, 1549.15 and 1559.4 nm. Each FBG can be continuously tuned in a range of over 16 nm. Therefore, a fiber ring laser with a very large tunable range is realized. Without compensation, in order to reduce the power spectrum unevenness, the three FBGs are fabricated with reflectivities selected to be 99%, 96% and 95%, respectively. With compensation, all the three FBGs are produced with the same reflectivities of 99%. It can be seen in Fig. 6 that, with a two-section HiBi-FLM, the compensated output power spectrum is controlled within ± 1.1 dB over a bandwidth of 38 nm at the center wavelength of 1546 nm. With a three-section HiBi-FLM, the compensated output power spectrum is further improved to be within ± 0.8 dB. While without compensation, the power unevenness is more than 7 dB over the same bandwidth, as shown in Fig. 6. We also note that, after compensation with a three-section HiBi-FLM, the total output power is about 4 dBm, the 3-dB linewidth is 0.01 nm, and the side mode suppression ratio is more than 48 dB.

5. Discussions

In general, the output polarization state of the ring laser is elliptic. The polarization axis orientation or ellipticity of polarization can be adjusted using the polarization controller in the laser cavity. The output polarization state has little impact on the flatness of the output power spectrum. Since the proposed fiber ring laser would be used in communication or TTD beamforming systems as optical carrier, signals are modulated onto this carrier using an external modulator, which is usually polarization-dependent. To get maximum output from the external modulator, one may adjust the polarization controller. The experiment results have also shown that the polarization dependent loss of the HiBi-FLM is less than 0.14 dB, which is close to the value given in [10].

We should note that for wideband TTD beamforming applications, the time delay performance is greatly affected by the wavelength stability of the tunable laser, especially for systems working at high microwave frequencies. For the proposed laser system, the wavelength tuning is implemented by applying strain to the gratings, so the wavelength stability will be affected by the variation of force applied. To make the laser system suitable for TTD applications, the tuning method should be improved. One way to achieve accurate wavelength tuning is to use piezo-electric actuator method [12,13], which can give accurate and fast tuning. It is reported that the tuning speed with piezo-electric actuator method can be in the range of tens of nanometers per milliseconds [13], which corresponds to a beamsteering speed of several milliseconds per scan.

We should also note that the HiBi-FLM technique employed in the proposed laser for spectrum flattening is essentially an interferemetric technique, which is sensitive to small fluctuations such temperature and vibrations. These changes will affect the stability of the laser output. For TTD application, such as beamforming networks using a fiber Bragg grating prism [14,15], the amplitude variation will not affect the time delays, and the amplitude variations can be compensated at the amplification stage after photo-detection with automatic gain control.

6. Conclusion

A wavelength tunable erbium-doped fiber ring laser with a broadband wavelength tuning over a bandwidth of 38 nm with an output power spectrum uniformity better than ±0.8 dB has been constructed and demonstrated. The output power spectrum uniformity was controlled in the fiber laser by using a HiBi-FLM. By properly controlling the reflection spectrum of the HiBi-FLM, a compensated output power spectrum with improved power uniformity was achieved. The wavelength tuning was implemented by compressing or stretching the FBGs to change their center reflection wavelengths. To achieve a wavelength tuning over a broadband, a switchable FBG array was employed. The wavelength tuning range of the fiber ring laser was 38 nm, from 1527 to 1565 nm. Within this tunable range, the output power spectrum was controlled into within ±1.1 dB with a two-section HiBi-FLM, and ±0.8 dB with a three-section HiBi-FLM.

Acknowledgements

Kejiang Zhou would like to acknowledge the partial support from Pao Chaolung and Pao Yukong Scholarship, Zhejiang University.

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