



# Power equalized wavelength-selective fiber lasers using fiber Bragg gratings

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Received 21 April 1998; accepted 17 July 1998

## Abstract

A fiber Bragg grating (FBG) based multi-wavelength ring laser is experimentally investigated in this paper. The lasing wavelengths can be dynamically selected by using a  $1 \times N$  optical switch. Micro-bender between FBGs is used as variable attenuator to equalize the output power for each lasing wavelength. By using passive multi-ring cavities (MRC) method, single- or dual-wavelength laser of equal output power is demonstrated for a signal-to-noise ratio (SNR) of 63 dB and a narrow linewidth of 3 kHz. © 1998 Elsevier Science B.V. All rights reserved.

**Keywords:** Fiber ring laser; Fiber Bragg grating; Power equalization; Signal-to-noise ratio (SNR); WDM

## 1. Introduction

Fiber lasers have been extensively investigated for important applications in laser spectroscopy, optical fiber communication [1], fiber-optic sensors [2,3], optical signal processing and wavelength conversion, etc. The realization of stable, equal output power and multi-wavelength operation in the 1.55- $\mu\text{m}$  low-loss window has attracted a great attention recently because of its potential application in wavelength-division-multiplexed (WDM) optical communication systems [4]. Simultaneous dual-, trio- and multi-wavelength operations have been demonstrated by using a  $2 \times 2$  coupler, a section of erbium-doped twin-core fiber and comb filters, respectively, in some previous works [5–7]. In this paper, we propose a ring cavity configuration for single- and dual-wavelength operations and equal power output by using an  $1 \times N$  optical switch (OSW) and an optical circulator (OC), several micro-benders and several fiber Bragg gratings (FBGs) with different central wavelengths [8]. The lasing wavelength (or wavelengths) can be

dynamically selected by switching the OSW to the desired port. The measured signal-to-noise ratio (SNR) for both single- and dual-wavelength-laser is as high as 63 dB. To facilitate single-mode operation, the multiple-ring cavity (MRC) method [9] is used in the FBG-based ring cavity to stabilize the lasing wavelength and to achieve narrow linewidth.

## 2. Proposed configuration and experimental setup

The main cavity of the proposed wavelength-selective, power-equalized FBG ring laser is shown schematically in Fig. 1. The  $1 \times N$  OSW, with connection loss of less than 0.5 dB from the common port to port  $i$  ( $1 \leq i \leq N$ ), was used for wavelength-selective function. An appropriate length of alumino-germano-silicate erbium-doped fiber (EDF) was inserted and pumped by an 80 mW, 980-nm LD via a 980/1550-nm WDM coupler to provide the gain. The saturated power of the EDF is 13 dBm. Most of the connectors are angled to reduce the backward reflections and spectral instabilities. The interport isolation and insertion losses of the OC are 50 dB and 1.2 dB, respectively.

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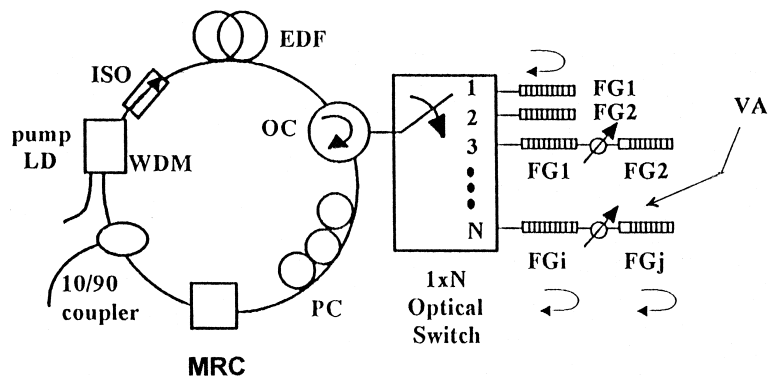


Fig. 1. Schematic configuration of the proposed equal-power, multiple wavelengths ring lasers. EDF: erbium-doped fiber; FG: fiber Bragg grating; ISO: optical isolator; OC: optical circulator; PC: polarization controller; MRC: multiple-ring cavities; VA: micro-bender as variable attenuator.

Conventionally, tunable bandpass filters are used as wavelength-selective elements. In this work, the apodized FBGs with peak reflectivity larger than 90%, 3-dB bandwidth of 0.25 nm at the wavelengths of 1534.0 and 1549.2 nm, respectively, were used as narrow-band reflective mirrors to reflect the desired wavelengths back into the ring cavity. An optical isolator was required in the ring cavity to ensure unidirectional operation. The evolution of amplified spontaneous emission (ASE) was monitored by dynamically inserting a 5/95 coupler at different connection points. The loop was completed with a fused fiber coupler, which provided 10% for the output and 90% for the feedback function.

We investigated single- and dual-wavelength operation of the fiber ring laser and demonstrated the power-equalization function in the dual-wavelength operation. For example, by switching the  $1 \times N$  OSW to port 1 where only a FBG is connected, single wavelength lasing can be realized. On the other hand, if the OSW is switched to port 3 where two cascading FBGs which reflect light at different wavelengths in the 1.55  $\mu\text{m}$  band, simultaneous lasing of two wavelengths is possible. Stable two laser operation with equal power outputs can be realized by inserting a micro-bender between the two neighboring FBGs to adjust the gains of different wavelengths. The FBG that reflects a certain wavelength with smaller cavity loop gain should be located closer to the OSW than the FBG for larger cavity loop gain. The micro-bender between the FBGs can be used to finely adjust loop gain between these two FBG wavelengths.

### 3. Results and discussion

#### 3.1. Single wavelength operation

When the OSW was switched to the port 1 where FG1 reflects 1534.0 nm light, the output optical spectrum is

shown in Fig. 2(a). It was observed from the 10% output port of the 10/90 coupler by using an optical spectrum analyzer (OSA). The lasing output power is  $-3.5$  dBm with SNR as high as 63 dB. Meanwhile, the majority part of the background amplified spontaneous emission (ASE) is several nanometers away from the 1534.0-nm lasing wavelength. The lasing light was passed through the FBG1 and come out from another end of the FBG1. Similar result was obtained by switching the OSW to port 2 where the FBG2 reflects 1549.2 nm light. Fig. 2(b) shows that the SNR was also as high as 63 dB. Because of long cavity length, the longitudinal mode spacing is small and the fiber ring laser is susceptible to have multiple lasing modes or mode hopping effects. To facilitate single-longitudinal mode operation, a technique called multiple-ring cavity (MRC) method was used. The MRC technique extends the effective free spectral range (FSR) by using multiple cavities which served as mode filters. The FSR is defined as the spectral distance between the adjacent maximum filtering peak. Each ring cavity, including a polarization controller (PC) and a section of single-mode fiber (SMF), is connected to the main ring cavity via a  $2 \times 2$  coupler. The PC in each sub-ring cavity must be tuned to the same state of polarization as that of the main cavity. These sub-ring paths provide external cavities for the ring laser. The FSR for each sub-ring cavity is defined as  $\text{FSR}_i = C/n_{\text{eff}} L_i$ . Where  $C$  is the speed of light in vacuum,  $L_i$  is the length of the  $i$ th ring cavity and  $n_{\text{eff}}$  is the effective refractive index of the ring cavity. The final FSR is the least common multiplier of all FSRs, longitudinal modes within the FSR are suppressed and modes separated more than the FSR are unlikely to be excited.

#### 3.2. Linewidth and side-mode suppression ratio (SMSR) measurements

The delay self-heterodyne technique [10,11], using 75-km SMF as delay line, was employed to measure the laser

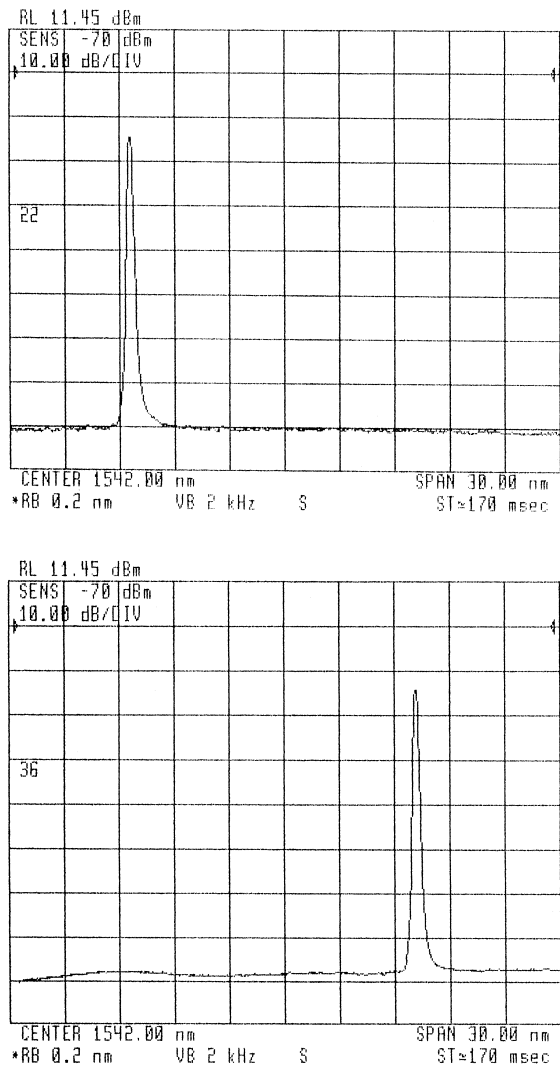


Fig. 2. Output spectra of the dynamically selective fiber grating ring lasers: When the  $1 \times N$  optical switch was switched to (a) the port 1 (FG1 reflects 1534.0 nm light), or (b) the port 2 (FG2 reflects 1549.2 nm light).

linewidth. If Gaussian broadening is assumed, the measured linewidth of the heterodyne spectrum turns out to be  $2^{1/2}$  times the actual linewidth [12]. Fig. 3 shows the heterodyne RF spectrum with an optical linewidth of 3 kHz, while the linewidth of a commercial single-longitudinal-mode distributed laser is 10 to 100 MHz.

The self-heterodyne method can also characterize the side-mode suppression ratio (SMSR) of the laser [13] if the side mode is less than 20 GHz (the upper limit of our electrical spectrum) away from the central wavelength. The SMSR is defined as the gain difference between the main mode and the second largest adjacent mode. However, no side mode larger than  $-50$  dB is observed in our self-heterodyne measurement and the equipment cannot

effectively measure side modes less than  $-50$  dB due to the equipment noise floor. For side mode larger than 20 GHz away, a conventional OSA with 0.1 nm (about 12.5 GHz) resolution can be used to measure the SMSR. The OSA also shows no side mode having a power range larger than  $-50$  dB. Combining these two measurements, we conclude that the SMSR is larger than 50 dB as limited by the noise floor of the measuring equipment.

Because of the fiber birefringence, there exist usually two cavity modes with different polarization states. The PC was inserted in our experiment for single-mode operation. Thus, the linewidth can be reduced when using a RF spectrum analyzer for linewidth measurement. However, the phenomena cannot be observed easily because the resolution is limited by the OSA resolution.

### 3.3. Dual-wavelength operation

To demonstrate the equal-power operation, the OSW was switched to the port 3 having two cascaded FBGs with over 90% reflectivities at wavelengths of 1534.0 and 1549.2 nm. Because the gain is often clamped by the cavity loss of only one lasing wavelength, the gain provided by the EDF at 1549.2 nm would uniquely determine the gain of the EDF at 1534.0 nm. The optical spectrum is shown in Fig. 4(a) for dual-wavelength operation. To equalize the power level of the two wavelengths, a variable micro-bender is used to adjust the cavity loss and to equalize the effective loop gain of the two lasing wavelengths of 1534.0 and 1549.2 nm and the output spectrum is shown in Fig. 4(b). The power variation of each wavelength is less than 1.5 dB at room temperature for two hours operation. In our experiment, the FBG1 which reflects 1534.0 nm

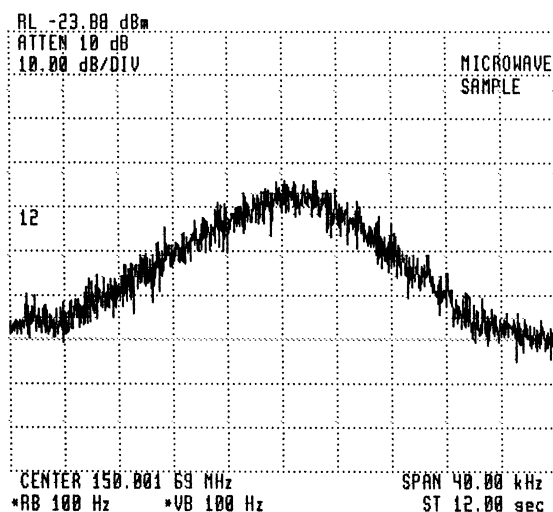


Fig. 3. Measured linewidth of the FBGs based ring laser by using the self-heterodyne method with 75-km single-mode fiber as the delay line.

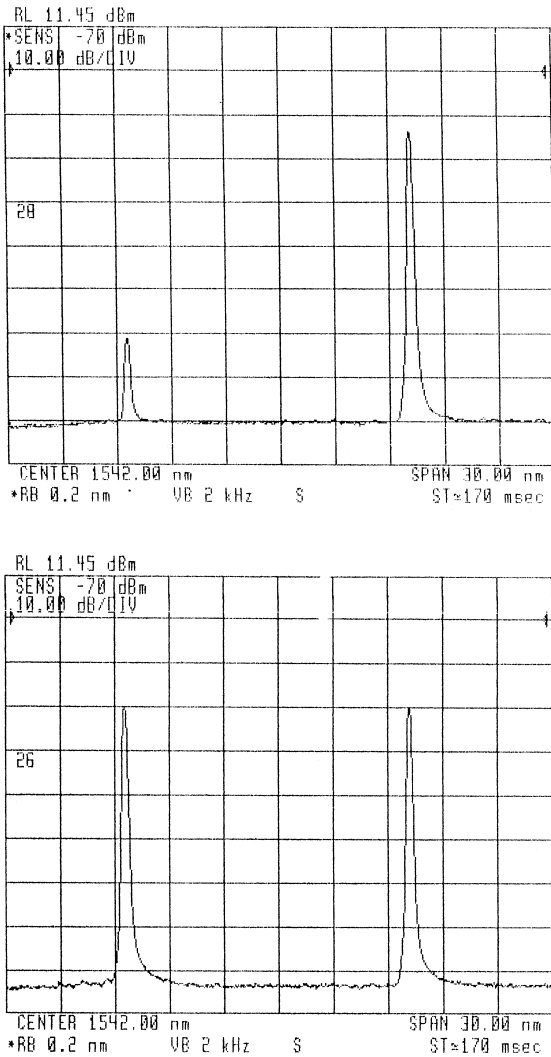


Fig. 4. Output spectra of the dynamically selective FBGs ring lasers: When the  $1 \times N$  optical switch was switched to the port 3 (a) without, or (b) inserting a micro-bender as variable attenuator for the gain-equal control.

light was located closer to the port 3 of OSW because of the smaller lasing power at 1534.0 nm when the micro-bender is not used. The attenuation value can be dynamically adjusted to match the FBGs with various reflective wavelengths and reflectivities. Both the laser output power ( $-8.5$  dBm each wavelength) and the ASE noise level of the dual-wavelength operation are about 5 dB lower than those of single wavelength operation, as shown in Fig. 2(a). The additional 5 dB loss is due to a 3 dB power loss from the power sharing of the two wavelengths and extra cavity loss of about 2 dB included by the micro-bending method (micro-bender) for power equalization. However, the SNRs were still maintained as high as 63 dB.

The experiment showed the dual- or potentially multi-wavelength lasing in the whole range of 1534.0 to 1549.2, which even can be extended to 1560.0 nm. When the loop gains of the different lasing wavelengths differ substantially and the micro-bender is used to ensure equal-power operation, the equalized output power may suffer a large loss. An intuitive reasoning may derive that a gain flatten EDF may extend the operation wavelength.

#### 3.4. Proposed multi-wavelength operation

We proposed a FBG-cascaded-chain with  $N$  pieces of FBGs of different central wavelengths for multi-wavelength operation. The equal-power operation of the multi-wavelength laser can be achieved as follows: Firstly, the  $N$  pieces of FBGs are randomly cascaded one-by-one to one certain port of the OSW. Secondly, the lasing output wavelengths could be observed from an OSA with unequalized power levels. Thirdly, the  $N$  pieces of FBGs are rearranged and connected to the OSW in power level sequentially from the lowest to the highest. In other words, the FBG of the corresponding wavelength with less loop gain should be located more closely to the OSW than the others having higher loop gain. Finally,  $N - 1$  pieces of micro-benders are inserted one-by-one between the FBG-chain to adjust the differential loop gain between them. Thus, multi-wavelength ring lasers with equalized power are possible when the OSA is switched to a certain port. This proposed multi-wavelength ring laser configuration is more cost-effective than in the previous work [14].

#### 4. Conclusion

In summary, we have demonstrated both single wavelength and power-equalized, dual-wavelength operation with SNRs as high as 63 dB. By using the MRC technique, single-longitudinal mode operation was achieved with measured linewidth of less than 3 kHz. A configuration for power-equalized, multi-wavelength ring laser is also proposed. The wavelengths can be dynamically and precisely selected by using a  $1 \times N$  OSW combining several FBGs with high reflectivities at different wavelengths. Equalization of the lasing powers can be achieved by inserting a micro-bender as variable attenuator in-between every cascaded FBG to adjust the differential cavity loss between the lasing wavelengths. The proposed power equalized, multiwavelength FBGs based ring lasers should prove highly attractive for a wide variety of applications such as in WDM transmissions and sensor applications.

#### Acknowledgements

The authors would like to thank Dr. Y.-K. Tu and J.-W. Liaw of Chung-Hwa Telecommunication Laboratories in

Taiwan for encouragement. K.-Y. Hsu of Chyn-Optics Communication Inc., Taiwan for fruitful discussions. The work was partially supported by Grant NSC-87-2215-E-009-012 from the National Science Council, Taiwan, Republic of China.

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