

Long-Distance FBG Sensor System Using a Linear-Cavity Fiber Raman Laser Scheme

Peng-Chun Peng, Hong-Yih Tseng, and Sien Chi

Abstract—We propose a novel fiber Bragg grating (FBG) sensor system using a linear-cavity fiber laser scheme with a distributed Raman amplifier as a gain medium. The inhomogeneous broadening property of the distributed Raman amplifier is used for multiwavelength operation. The experiment shows that such a linear-cavity fiber Raman laser can provide a stable output with an optical signal-to-noise ratio over 50 dB even if the FBG is located at a 25-km remote sensing position. The feature of our proposed fiber laser can facilitate a long-distance or a large-scale fiber sensor system and can be easily extended for multipoint sensing applications.

Index Terms—Distributed Raman amplifier, fiber Bragg grating (FBG), fiber laser, fiber sensor.

I. INTRODUCTION

THE fiber Bragg grating (FBG) sensor systems using a fiber laser scheme have been the focus of a great deal of research. In contrast with the FBG sensor system based on a broad-band light source, the advantages of an FBG laser sensor includes its high resolution for wavelength shift and high optical signal-to-noise ratio (SNR) against the noisy environments in practical applications [1]. The simplest in-fiber cavity mirrors of an FBG laser can be constructed either by two FBGs with identical Bragg wavelength or by one FBG in conjunction with a broad-band reflector. In general, the erbium-doped fiber (EDF) is adopted as the gain medium between two mirrors for a linear-cavity fiber laser. With a sufficient gain provided by a 980-nm pumping laser diode (LD), the fiber laser lases and its lasing wavelength is determined by the Bragg wavelength of the FBG. When a strain or a temperature variation is imposed on the FBG, the Bragg wavelength drifts and the lasing wavelength shifts simultaneously. Another simple type of a fiber laser is the fiber ring laser, and its lasing wavelength also can be determined by an FBG. By inserting a tunable Fabry-Pérot filter within the cavity, we can simply implement a tunable fiber laser for the application of an FBG sensor system [2], [3]. However, the scanning rate of the tunable filter always limits the dynamic range of a fiber laser sensor.

Although the EDF laser has been widely discussed, a multiwavelength fiber laser is still an ongoing challenge since the dense wavelength-division-multiplexing (WDM) technique is

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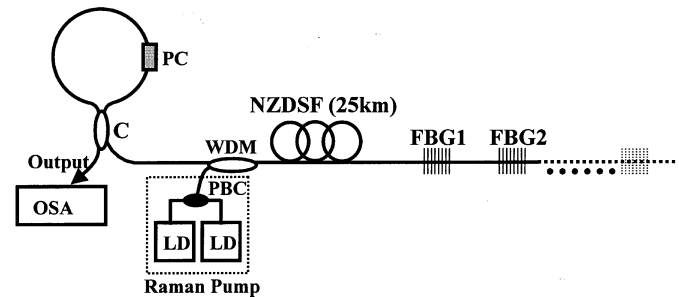


Fig. 1. Schematic diagram of the long-distance FBG sensor system. (C: 2×2 coupler. LD: 1450-nm laser diode. WDM: 1450/1550-nm WDM coupler.)

the most important solution for high-capacity fiber communication or fiber sensor systems. However, because the homogeneous broadening of an EDF is dominant at room temperature, it is difficult to obtain stable simultaneous lasing with close wavelength spacing. Therefore, much attention is devoted on multiwavelength fiber laser at room temperature. For example, the technique by inserting variable attenuators into the EDF laser cavity for multiwavelength oscillations has been reported [4], [5]. The cavity loss corresponding to each wavelength has to be balanced carefully in such arrangements. In recent year, the inhomogeneous broadened gain of the distributed Raman amplifier is used for a room-temperature wavelength-division-multiplexing (WDM) source [6]. Over 58 WDM channels have been demonstrated previously by using a fiber Raman ring laser with a Fabry-Pérot filter in the cavity [7].

In this letter, we propose an FBG sensor on the basis of a linear-cavity fiber Raman laser. The linear cavity is constructed by two FBGs combined with a fiber loop mirror, and a section of 25-km nonzero dispersion-shifted fiber (NZDSF) is used for the Raman gain. In our experiment, such a dual-wavelength fiber Raman laser sensor provided a high optical SNR up to 50 dB even if two FBGs were located at 25-km remote sensing points. In addition, each peak power was stable even if a strain was imposed on one of the FBGs. These features can facilitate a long-haul or a large-scale fiber sensor system and can be easily extended for multipoint sensing applications. Furthermore, we can directly construct a dynamic FBG sensor system by using our proposed FBG Raman sensor incorporated with a fixed filter as a fast wavelength interrogator [8]. The dynamic range of such a large-scale sensor system, therefore, would not be restricted by a tunable filter.

II. EXPERIMENT

The schematic diagram of the proposed long-distance FBG sensor system is shown in Fig. 1. The fiber Raman laser com-

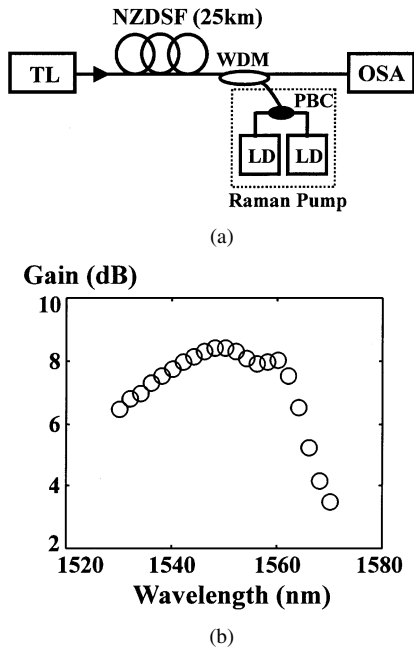


Fig. 2. (a) Schematic diagram of the Raman gain measurement. (b) Raman gain at different signal wavelength.

prises a fiber loop mirror acting as one of the cavity mirror with a fixed reflectivity, a section of 25-km NZDSF pumped by the 1450-nm Raman pump, and a series of FBGs simultaneously acting as another cavity mirror and sensing element. The lasing multiwavelength is determined by the sensing FBG chain and the lasing output leaks from the fiber loop mirror. Here, the fiber loop mirror is constructed by a piece of 2-m single-mode fiber, a polarization controller (PC), and a 2×2 optical coupler (C). Both the polarized direction of PC and the coupling ratio of C can be used to adjust a suitable reflectivity for the loop mirror. Furthermore, the Raman pump for this fiber laser consists of two 1450-nm LDs. The outputs from the two lasers at the pump wavelength are combined by using a polarization beam combiner (PBC) to result in a depolarized output. The output combined from two LDs is launched into the laser cavity via the WDM coupler multiplexing 1550-nm band signals and 1450-nm band pumps. This pump light is then absorbed by the 25-km NZDSF, which has a mode field area $A_{\text{eff}} = 73.7 \text{ m}^2$, 1497-nm zero-dispersion wavelength, and 5-dB loss at 1550-nm wavelength. Fig. 2(a) shows the experimental setup for the Raman gain measurement. The tunable laser (TL) with a tunable wavelength range of 1530–1570 nm at a power of -10 dBm was fed into the 25-km NZDSF. The Raman pump launched into NZDSF was 330 mW at 1450 nm. Fig. 2(b) shows the Raman gain at different signal wavelength. The maximum Raman gain is 8.45 dB at 1548 nm. The Raman gain spectrum depends on the index profile of the fiber [9]. Furthermore, the Raman amplifier is the inhomogeneous broadened gain. Therefore, the Raman gain spectrum is similar even if we increase the number of input signal wavelength. The saturation power of the Raman amplifier is much larger compared with that of other optical amplifiers. In [10], the Raman pump launched into 10-km dispersion-shifted fiber was 2.8 W at 1455 nm. The Raman gain decreased when the input signal power increased. Finally, the saturated output power was 1.4 W [10].

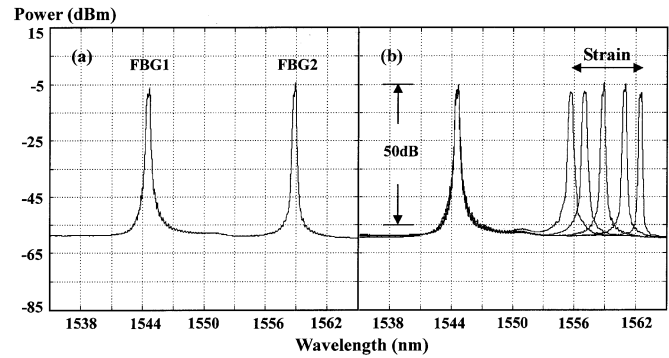


Fig. 3. Output spectra of the linear-cavity fiber laser with 330-mW pump power (a) when no strain was applied and (b) when strain was applied to FBG2.

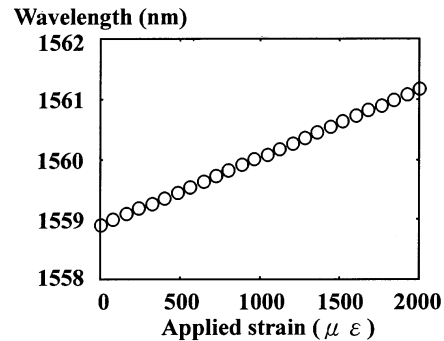


Fig. 4. Strain measurement of the FBG2.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In our experiment, we examined two sensing FBGs and achieved a dual-wavelength fiber Raman laser for the proposed long-distance sensor system. The Bragg wavelengths of FBG1 and FBG2 were 1544.69 and 1558.91 nm. Both the peak reflectivities of the FBGs were approximately 99% and their average 3-dB bandwidth were 0.45 nm. The Raman pump with 330-mW output power pumped the NZDSF via a 1450/1550-nm WDM coupler. The coupling ratio of the 2×2 coupler (C) for the laser output was 30:70 leading to its reflectivity 84%. Under these conditions, the linear-cavity Raman laser lased a continuous wave with dual-wavelength at 1544.69 and 1558.91 nm, simultaneously. Fig. 3(a) shows the output spectrum of this linear-cavity Raman laser. The optical SNRs provided by FBG1 and FBG2 for the sensor system were over 50 dB even if the two sensing points were located 25-km far from the optical spectrum analyzer (OSA). Fig. 3(b) shows the wavelength shifts of FBG2 when a strain was imposed on it. There was no influence on the lasing wavelength of FBG1 when the wavelength of FBG2 drifted. Fig. 4 shows the strain measurement of the FBG2. The FBG2 was strained in steps of 80 up to 2000 $\mu\epsilon$, which is equivalent to 2.27 nm of the wavelength shift. Resolution of the sensor system was determined by the OSA resolution of 0.01 nm. The peak power variation of the Raman laser as a function of time is shown in Fig. 5. The fluctuations of the dual-wavelength peaks were both smaller than 0.35 dB. Such a lasing output is stable and intense enough for the long-distance fiber sensor system. Moreover, to present the lasing mechanism for the dual-wavelength operation, in Fig. 6, we illustrate the peak power of the Raman

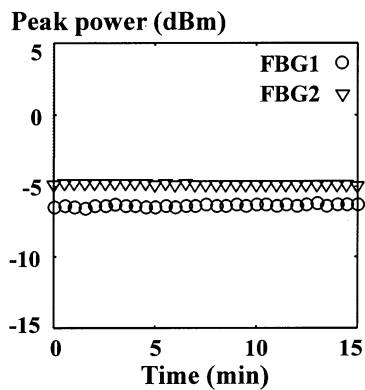


Fig. 5. Variation of peak power as a function time for each lasing line.

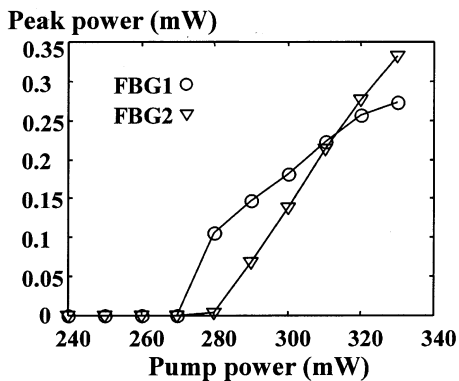


Fig. 6. Relationship between the peak power and the Raman pump power.

laser as a function of the pump power. The pumping threshold of FBG1 and FBG2 were 270 and 280 mW, approximately. After the pump power was larger than this threshold, the two wavelength outputs lased stably and were suitable for our proposed sensor system. The wavelength action range for this Raman laser depends on the cavity loss and the Raman gain at different wavelengths. In the previous study [11], when the Raman pump, launched into 9-km dispersion-shifted fiber, was 1.1 W, the Raman laser action range was up to 18 nm.

In this letter, we concentrate our study on the FBG sensor system using a linear-cavity fiber Raman laser scheme. Thus, we only used an OSA to measure the lasing wavelength. The dynamic strain measurement could be improved by using a better wavelength interrogator [8]. In addition, the main limitation on the maximum distance and number for the sensors would be the gain medium. The Raman gain can be improved by using the dispersion-compensating fiber to increase the Raman gain efficiency [9], [12] and by increasing the Raman pump power.

Moreover, we can use multiwavelength Raman pump to increase the gain bandwidth. The 100-nm flat gain bandwidth has been reported [12].

IV. CONCLUSION

A long-distance FBG sensor system using a linear-cavity fiber Raman laser scheme has been proposed. Because of the inhomogeneous broadening of the Raman gain, the proposed fiber laser can generate multiwavelength lasing output for multipoint sensing at a long distance. Experimental results showed a dual-wavelength fiber Raman laser with stable and intense peak power even if the FBGs were located at a 25-km far sensing position. The proposed fiber laser sensor system can be used for large-scale or long-haul smart structures.

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