Time- and Wavelength-Division Multiplexing of FBG Sensors Using a Semiconductor Optical Amplifier in Ring Cavity Configuration

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***Abstract*—A fiber Bragg grating (FBG) sensor system based on a semiconductor optical amplifier connected in a ring cavity configuration is proposed. The proposed configuration produces high power signal with good extinction ratio for FBGs with ~1% reflectivity. A sensor system consists of four group of three FBGs of different wavelengths was constructed to demonstrate time- and wavelength-division multiplexing of FBG sensors.**

***Index Terms*—Fiber Bragg grating (FBG), semiconductor optical amplifier, sensors, time-division multiplexing (TDM), wavelength-division multiplexing (WDM).**

I. Introduction

FIBER Bragg grating (FBG) is being accepted as an important sensor technology because of its self-referencing capability, large-scale multiplexing capability, and immunity to electromagnetic interference. The wavelength-division-multiplexing (WDM) technique [1] can be easily employed to multiplex and interrogate FBG sensor array, and thus, it is commonly used in FBG sensor applications. The number of FBG sensors that can be accommodated in a WDM-FBG sensor array is determined by the usable spectral bandwidth of the system and the wavelength-shift of each FBG sensors. On the other hand, the time-division-multiplexing (TDM) technique identifies the sensing signal by gating the pulses reflected from FBGs, therefore, FBGs having identical resonant wavelengths can be deployed along the same fiber. Hence, the TDM-FBG technique relieves the spectral bandwidth issue and permits the interrogation of up to 100 FBGs along a fiber. However, the reflectivity of the FBGs employed in TDM sensor systems are generally less then 5%, and thus, the reflected signal power is fairly weak in comparison with WDM-FBG systems.

Various TDM systems have been reported during the last decade [2]–[7]; the main challenge of TDM system is to measure the sensing signal accurately because of the weak signal power reflected from low reflectivity sensors. Amplified spontaneous emission (ASE) generated by an erbium-doped fiber amplifier [3] and passively mode-locked fiber laser operating in square-pulse regime [4] have been employed as sources to illuminate low reflectivity FBGs array with the objective to increase the signal power reflected from the FBGs. Another approach utilized the active mode-locking technique [5] to selectively address individual FBG in a two-FBG array that act as reflectors of a linear cavity erbium-doped fiber laser. This active laser approach produces intense output power at the resonant wavelength of the selected FBG sensor. Recently, Lloyd *et al.* [6], [7] reported a resonant TDM configuration that uses a semiconductor optical amplifier (SOA), a broad-band reflector, and an array of ten FBGs to construct a linear resonant cavity sensor system, high power and high extinction ratio output signal were demonstrated by properly gating the SOA. In this letter, we propose a ring resonant configuration for simultaneous TDM+WDM of FBG sensors. The ring cavity comprises of an SOA, an output coupler, and an optical circulator that connects to an FBG array. The low component count, simple drive circuitry, and high extinction signal of the proposed system makes it an excellent candidate for dealing with large FBG sensing array.

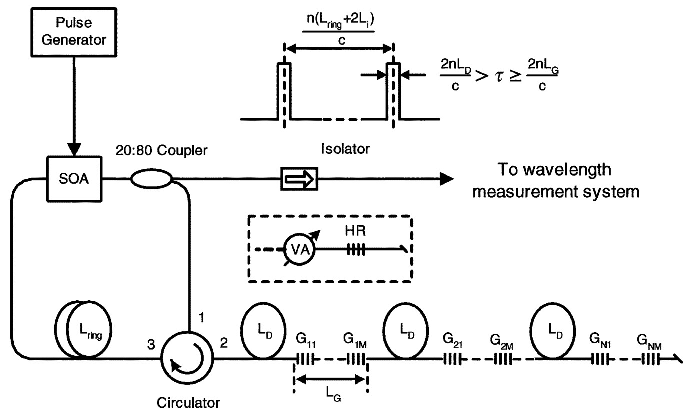

Fig. 1. Configuration of the proposed TDM+WDM FBG sensor system and the timing signal (ON–OFF signal) applied to the SOA for addressing different groups of FBGs $(G_{11},\ldots,G_{1M},\ldots,G_{N1},\ldots,G_{NM})$ in the sensor array. Inset shows the setup to evaluate the sensing signal produced by the system for FBG with different reflectivity. $L_{\rm ring}$: fiber length of the cavity; L_D: length of the fiber separating adjacent FBG groups; L_i: fiber length from Port 2 of circulator to middle of a group; VA: variable optical attenuator; HR: high reflectivity FBG.

II. Configuration and Operation Principle

Fig. 1 shows the configuration of the proposed TDM+WDM FBG sensor system; the ring cavity consists of an SOA driven by a pulse generator which can switch ON the SOA

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at different repetition rates. The output of the SOA is split by the coupler where one of its output acts as the output port of the system, while the other output is fed to Port 1 of the circulator which directs the signal to the FBG array $(G_{11}, \ldots, G_{1M}, \ldots, G_{ij}, \ldots, G_{N1}, \ldots, G_{NM})$ via Port 2, where $1 \leq i \leq N$ and $1 \leq j \leq M$. N is the number of group of FBGs in the array, and each group has M FBGs with different wavelengths. Therefore, the total number of FBGs in the array is $N \times M$. Each group of FBGs is separated by a delay line with $\text{length} \geq L_D$. The signal reflected by the FBGs return to the input port of the SOA through Port 3 of the circulator, hence forming the ring cavity, the circulator also ensures unidirectional operation of the cavity.

In this configuration, when the SOA is activated by an electrical pulse, a broad-band optical pulse is generated at the output of the SOA and part of the power is sent to the FBG array. Each FBG reflects part of the incident pulse at different time back to the input of the SOA. Those reflected pulses arrive at the SOA when it is switched ON are amplified while other pulses are absorbed. When the SOA is driven by a periodic pulse train having a period equals to the cavity's round-trip time formed by one group of the FBGs (having different wavelengths), the pulse reflected by this group of FBGs will be amplified each time they pass through the SOA. Hence, high power signal generated by this group of FBGs can be obtained at the output port of the coupler. A different group of FBGs in the array can be interrogated separately by changing the pulse frequency. The driving frequency (f_i) and pulsewidth (τ) of the signal to address the ith group of FBGs in the array are

$$f_i = \frac{c}{n(L_{\text{ring}} + 2L_i)} \tag{1}$$

and

$$\frac{2nL_D}{c} > \tau \geq \frac{2nL_G}{c} \tag{2}$$

respectively, where c is the speed of light, n is the refractive index of the fiber, L_{ring} is the fiber length of the ring cavity, L_i is the fiber length from Port 2 of the circulator to the middle of a group of FBG, and L_G is the fiber length that spanned a group of FBGs.

III. Experimental Results and Discussion

A. Sensing Signal Strength Versus FBG Reflectivity

The sensitivity of the proposed ring cavity was evaluated with a variable attenuator followed by a ~95% reflection FBG to simulate FBGs with different reflectivity, as shown in the inset of Fig. 1. The SOA used in this experiment has a small signal gain of 25 dB and saturated output power of +7 dBm at a driving current of 150 mA. The center wavelength and optical bandwidth are 1540 and 40 nm, respectively. The SOA was biased at 30 mA and modulated with 120 mA by a current driver (Analog Devices, AD9662) with pulse rate and pulsewidth controlled by the pulse generator (Standard Research Systems, DG535). The coupler feed back 80% of the power to the cavity. About 220 m of single-mode fiber was inserted in the cavity to allow for the 1-MHz maximum frequency of the pulse generator. Fifteen-nanosecond pulses (τ) were used to emulate a fiber delay line of >1.5 m as depicted in (2). The isolator was employed to prevent unwanted reflection to the cavity. The output signal is measured by an optical spectrum analyzer (OSA) with a resolution of 0.06 nm, Fig. 2 shows the optical power and extinction ratio of the output signal as the attenuation is increased. The average output power and extinction ratio of −17 dBm and 40 dB, respectively, were measured when no attenuation was inserted between the circulator and the high reflection FBG. The peak power of the output pulse is, thus, over +3 dBm (insertion loss of the variable optical attenuator (VOA) = 0.6 dB and the ON–OFF ratio ~1/70). Inset of Fig. 2 shows the output spectra at different attenuation settings. As the attenuation increases, the ASE power increases and the average power decreases. With 10-dB attenuation, which correspond to an FBG with <1% reflection, the noise floor is raised by ~8 dB. However, high quality signal with average power of −24 dBm and extinction ratio of 27 dB can still be obtained. These results demonstrate that the proposed configuration is capable of interrogating FBGs with very low reflectivity, and hence, large number of FBGs can be multiplexed in a single strand of fiber.

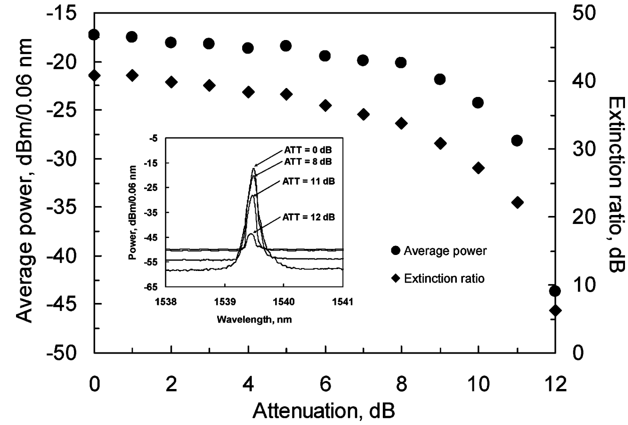

Fig. 2. Average power and extinction ratio of the output signal as a function of additional attenuation. Inset shows the spectra of the signal at four different attenuation (ATT) settings.

B. Single-Wavelength TDM System

The system was then tested by connecting an array of nine FBGs having nearly identical Bragg wavelengths of 1535~1536 nm and reflectivity of 1%~4%, and ~2-m-long fiber delay lines were used to separate each FBG. A high reflection (~90%) FBG with Bragg wavelength of 1540.5 nm was also connected at the end of the array to evaluate the crosstalk induced by the sensing signal when a strong reflection from different wavelength is introduced. The SOA was driven by the same current condition and pulsewidth as in the previous experiment. The output frequency of the pulse generator was tuned to address each FBG in the array sequentially and the output signal measured by the OSA. Fig. 3 shows the captured spectra of different FBGs where the frequency of the pulse generator varied from 896.7 to 804.2 kHz. The spectra produced by the low reflectivity FBGs show similar output characteristics and no crosstalk located at the wavelength of the high reflectivity FBG was observed. Variations of the output power and extinction ratio of these spectra are due to different reflectivity of the

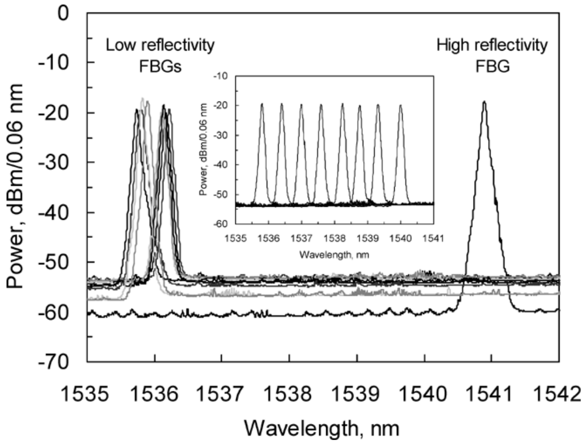

Fig. 3. Output spectra of the first to ninth low reflectivity FBGs, as well as the tenth high reflectivity FBG obtained at the output of the ring cavity by changing the driving frequency of the pulse generator. Inset shows the wavelength change of the eighth FBG as a function of applied strain.

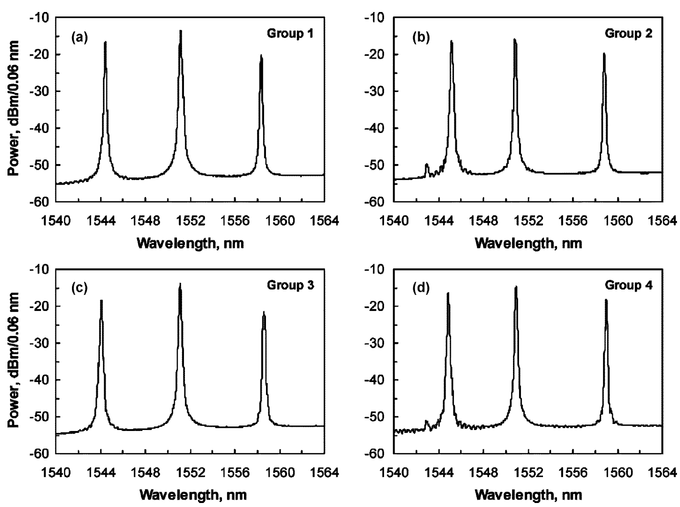

Fig. 4. Output spectra of four groups of three FBGs measured at the output port of the ring cavity, (a) at $f_i = 962.8$ kHz, (b) at $f_i = 920.1$ kHz, (c) at $f_i = 883.6$ kHz, and (d) at $f_i = 847.4$ kHz.

FBGs. The frequency was then fixed at 821.4 kHz that match the repetition rate of the eighth FBG while axial strain was applied to tune its wavelength. The inset in Fig. 3 shows the change of output spectra of the FBG as a function of applied strain, the peak wavelength change exhibits excellent linearity with a relationship of $\sim$ 1.1 pm/$\mu\varepsilon$ up to a level of 4000 $\mu\varepsilon$, and no significant changes in the output power, extinction ratio and spectral shape were observed.

C. Simultaneous Multiwavelength TDM and WDM System

To demonstrate simultaneous TDM+WDM operation, an FBG array comprises of four groups of three FBGs which have reflectivity of ~4% and Bragg wavelength of 1544, 1551, and 1559 nm was constructed. The length of fibers separating each group and that separating the FBGs within a group were ~6 and ~4 m, respectively. The 40-ns pulses were used to interrogate each group sequentially; Fig. 4(a)–(d) shows the measured spectra when the driving frequency of the pulse generator were 962.8, 920.1, 883.6, and 847.4 kHz, respectively. The spectra from each group show similar output characteristic. Higher signal power at the second FBG (1551 nm) within each group was observed. This is because the pulses reflected from FBGs located near the center of the group experiences longer period of amplification each time it passes through the SOA. A small spectral peak due to wave-mixing effects in the SOA appeared occasionally. However, its amplitude is very small (<40 dB compare to the sensor signals) and can be completely eliminated during the wavelength measurement process.

IV. Conclusion

We have demonstrated a TDM+WDM FBG sensor system using a pulsed SOA connected in a ring cavity configuration. The low component count and low loss features of the system improve the power and extinction ratio of the sensing signals significant. Excellent results were obtained from both TDM and TDM+WDM experiments. The proposed system would be very useful for sensor applications where large numbers of FBG are needed.

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