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Time Division Multiplexing of 106 Weak Fiber Bragg Gratings Using a Ring Cavity Configuration

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Abstract: A time division multiplexing of 106 weak fibers Bragg gratings (FBGs) based on a ring resonant-cavity is demonstrated. A semiconductor optical amplifier is connected in the cavity to function as an amplifier as well as a switch. The 106 weak FBGs are written along a SMF-28 fiber in serial with peak reflectivity of about −30 dB and equal separations of 5 m. The crosstalk and spectral distortion are investigated through both theoretical analysis and experiments.

Keywords: Fiber Bragg grating (FBG); semiconductor optical amplifier (SOA); time-division multiplexing (TDM)

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1. Introduction

Fiber Bragg grating (FBG) sensors network [1‒3] has attracted considerable interests for quasi-distributed sensing. Wavelength-division multiplexing (WDM) is a popular scheme because of its intuitionistic wavelength demodulation method. However, limited by the bandwidth of broadband light sources, often less than 100 nm, only tens of sensors can be multiplexed in one fiber. Time-division multiplexing (TDM), distinguishing the FBG sensors with an identical wavelength by detecting the different time delay between reflected pulses along the fiber, has substantial potential for increasing the number of the multiplexing sensors [4‒5]. Several TDM schemes with a resonant cavity were reported [6‒9]. The schemes have excellent advantages such as low component count, simple drive circuitry, and high extinction signal. However, the required interrogated sensors of these schemes are traditional FBGs with reflectivity ≥ −20 dB because of the restriction of amplification of a single semiconductor optical amplifier (SOA). As a consequence, the multiplexing capacity of those method is limited to a few tens of FBGs (generally within about 50) due to crosstalk induced by intrinsic multiple reflections. Although the multiplexing capacity can be improved to some extent by using hybrid schemes, such as WDM + TDM, these technologies are limited by the bandwidth and transmission loss.

In this paper, a TDM scheme based on an improved ring resonant configuration is proposed. An SOA is connected in the cavity to function as an

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amplifier and switch. An erbium-doped fiber amplifier (EDFA) is introduced to improve the amplification of the ring cavity. The proposed design is demonstrated to be capable of interrogating sensors with reflectivity as low as –30 dB which increase the multiplexing capacity to more than 500 FBGs. A serial TDM network with 106 weak FBGs is demonstrated experimentally. The crosstalk and spectral distortion are investigated through both theoretical analysis and experiments.

2. Theory

The interrogation system based on improved ring cavity configuration is illustrated in Fig. 1. An EDFA is connected in the cavity as an optical source. The light is modulated and amplified into nanosecond pulses when passing through SOA. A pulse generator drives the SOA functioning as a modulator as well as an optical amplifier. The pulses are split by a coupler where one of its output connects to an optical spectrum analyzer (OSA), which detect variation of FBG's central wavelength, while the other output is connected to Port 1 of a circulator. The pulses are launched into a weak FBGs array (G_1, G_2, ⋯, G_i, ⋯, G_N) via Port 2 of the circulator, where N is the number of the FBG sensors and $1 \le i \le N$. Each weak FBG sensor has the peak reflectivity of about –30 dB and equal separation of 5 m. The signals reflected by FBGs arrive the input port of EDFA via Port 3 of the circulator. The pulse is further amplified by EDFA and eventually returns to the input port of the SOA.

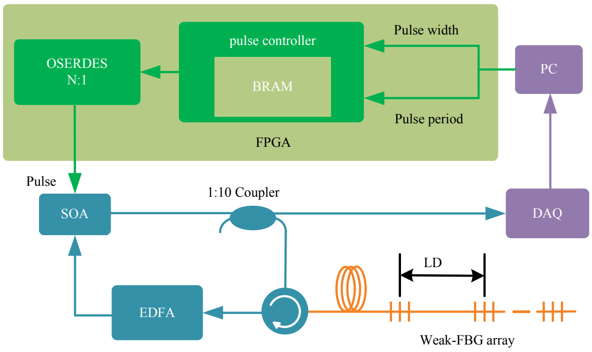

Fig. 1 Interrogation system of the serial TDM sensor array.

A field-programmable gate array (FPGA) serves as the pulse generator to drive SOA. The pulse waveform is realized by mapping it into block random-access memory (BRAM). The width of the pulse is expressed by the continuous digital "1" stored in the BRAM, and a low level of pulses corresponds to the continuous digital "0". Then, the pulse cycle is expressed by the read/write BRAM depth. Output parallel-to-serial logic resources (OSERDESE) is a dedicated parallel-to-serial converter with specific clocking and logic resources in the FPGA. By converting the parallel data into the serial bit signal of the I/O interface by OSERDESE after reading BRAM sequentially, a periodic pulse train will be generated. By using the serial port, PC communicates with FPGA to configure the parameter of the pulse (pulse width and pulse period).

When the SOA is ON, the pulse arriving at the SOA is amplified and passes through the SOA, while the other signals are isolated. Therefore, the signal reflected by the same grating will be amplified each time and collected through data acquisition (DAQ) module. When the SOA is driven by a periodic pulse train, each FBG in the array can be interrogated respectively by changing the period of the driving pulses. The period (τ_i) of the driving pulse corresponding to the ith FBG is

$$\tau_i = \frac{2nL_i}{c} \tag{1}$$

where c is the speed of light, n is the effective refractive index, and L_i is the fiber length from Port 2 of the circulator to the ith FBG, respectively. The multiplexing capacity of a TDM sensor networks is mainly limited by two kinds of crosstalk, namely, multiple-reflection crosstalk and spectral shadowing [10].

(1) Spectral shadowing

Assume N identical weak FBGs are written on a fiber serially. The reflective power from the ith (i = 1, 2, ⋯, N) FBG at wavelength λ can be approximated as [11]

$$I_{ri}(\lambda)=I_0(\lambda)R(\lambda)(1-R(\lambda))^{2(i-1)} \quad (2)$$

where $I_0(\lambda)$ is the source spectrum, and $R(\lambda)$ is the reflection spectrum of the FBG. The central wavelengths, full width at half maximum (FWHM), and reflectivity of the FBGs are assumed as 1552.2 nm, 0.2 nm, and −30 dB, respectively. The reflective power decreases gradually with an increase in the multiplexing number of weak FBG, as shown in Fig. 2, because the spectrums of front-end FBGs always shield the spectra of back-end FBGs.

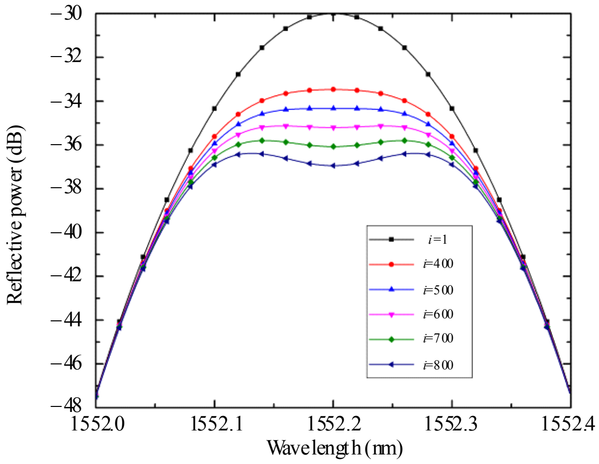

Fig. 2 Reflective spectrum of *i*th FBG with reflectivity of −30 dB (simulation result).

(2) Multiple-reflection crosstalk

Multiple-reflection crosstalk comes from the light reflected two more times by FBGs other than the target FBG but reaching the detector at the same time with the real signal. For weak FBG array with identical reflectivities, the first-order crosstalk is far more than higher-order crosstalk, which is negligible. The influence of first-order crosstalk on the reflective signal from the *i*th FBG can be expressed as [11]

$$C_i(\lambda)=\frac{(i-1)(i-2)}{2}\left(\frac{R}{1-R}\right)^2,\ i\geq 3. \quad (3)$$

Figure 3 illustrates the relationship between the first-order multiple-reflection and multiplexing number of weak-FBGs. The multiplexing number increases gradually with a decrease in the reflectivity of weak FBG.

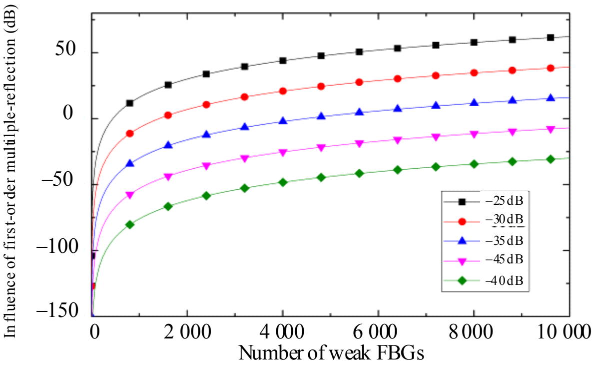

Fig. 3 Relationship between the first-order multiple-reflection and multiplexing number of weak-FBGs.

3. Experiment and analysis

In order to investigate the performance of the above-mentioned system, a group of weak FBGs are written to a single-mode optical fiber in series. The weak FBG array is fabricated by an on-line writing method [12]. All weak FBGs in the array are inscribed with a same phase mask, therefore, each FBG has almost the same central wavelength. The central wavelengths of those FBGs vary from 1552.17 nm to 1552.29 nm because of the fabrication error. Figure 4 shows the central wavelengths of those FBGs.

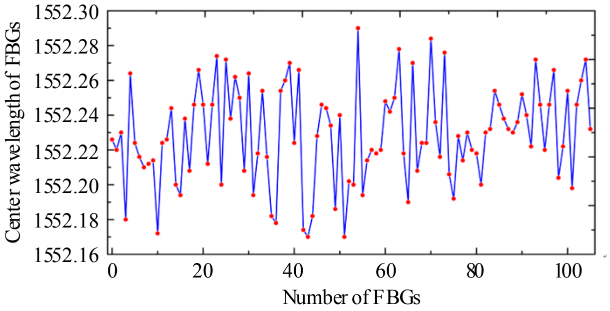

Fig. 4 Central wavelength of the weak FBGs array.

A roll of single-mode optical fiber with length of 1108 m severs as a fiber delay line to connect Port 2 and the first weak FBG. The distance between Port 2 of the circulator and each FBG is easily measured. The spectrum of each FBG can be displayed on optical spectrum analyzers (OSA, YOKOGAWA AQ6370B) through adjusting the period of the pulse. According to (1), the period of the driving pulse arriving at each FBG is approximated. When the pulse period is adjusted to 11.078 μs (T_1), the first FBG where L_1=1108 m is interrogated. The first 10 and the last 10 FBGs are interrogated accurately by adjusting the period of the pulse, respectively, as shown in Fig. 5. The experimental result is consistent with the theoretic analysis.

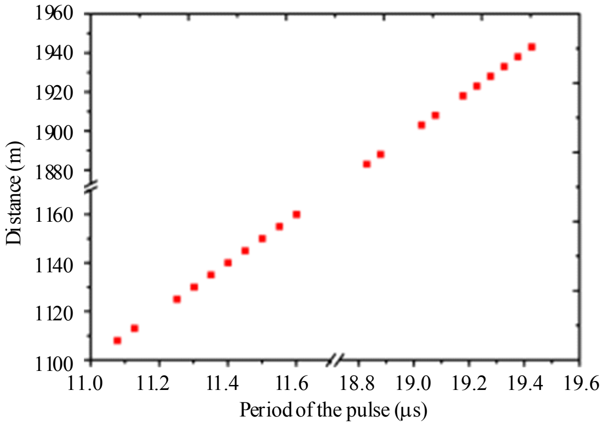

Fig. 5 Result of interrogating the first 10 and the last 10 FBGs.

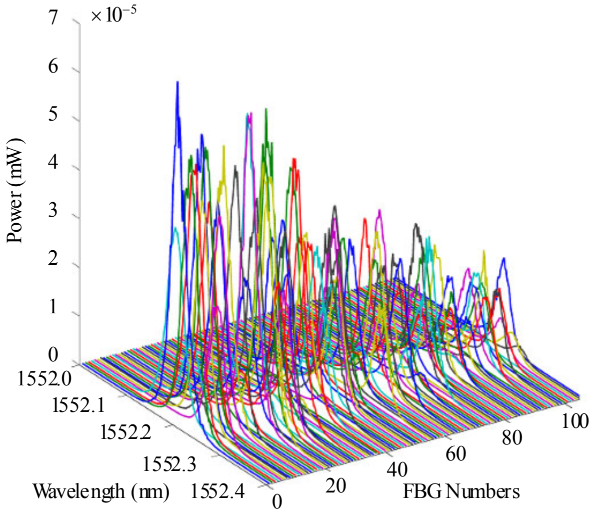

Fig. 6 Reflected spectrum of the FBG sensor array.

Figure 6 gives the reflected spectrum of all the FBGs detected by the interrogation system. The measured optical power reflected by the first FBG is about 5 dB larger than that reflected by the last FBG. This is because the optical pulses reflected by the first FBG have higher repeat frequency than that reflected by the last FBG. The reflective spectra of FBGs in the end of the array show a low transmission loss which can be further reduced by using even weaker FBGs, and this means the interrogation system has the ability to demodulate even larger number of sensors in serial.

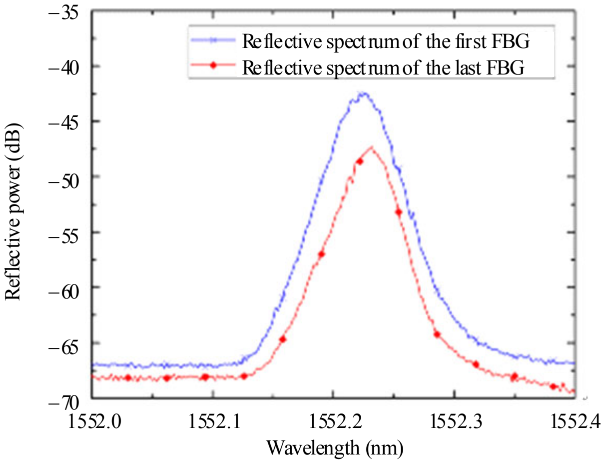

Fig. 7 Reflective spectrum of the first and the last FBG with reflectivity of −30 dB.

The reflective spectra of the first and the last FBGs are measured by the experimental setup to observe the crosstalk (see Fig. 7). Obviously, there is no distinct spectral distortion in the spectrum caused by crosstalk. Therefore, the proposed system is capable of multiplexing more than 500 FBGs even though the multiplexing capacity is limited by above two kinds of crosstalk.

In order to investigate the sensing preference of the sensor network, the last FBG is placed into a high-low temperature test chamber (SIDA TEMI300) with accuracy of 0.1℃. The chamber temperature is set from 25℃ to 90℃ with a step of 5℃. Figure 7 illustrates the perfect linearity of the TDM system.

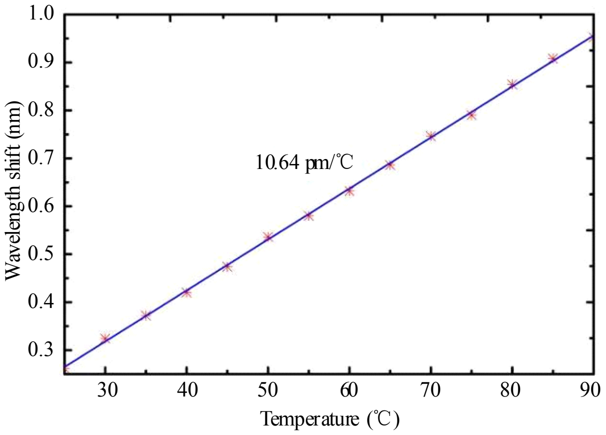

Fig. 7 Wavelength shift of the last weak FBG with temperature.

4. Conclusions

A novel interrogation system for a large scale sensing network with an identical weak FBGs system based on serial TDM is proposed and experimentally demonstrated in this paper. The experimental results show that the proposed sensor network can interrogate lower reflectivity FBGs (less than −30 dB) and multiplex more than 100 FBG sensors array. The simulation result, meanwhile, indicates that the multiplexing capability of the proposed system is about 500, theoretically. Supposing it is able to utilize charge-coupled device (CCD), whose response time can be as fast as tens of micro-seconds, to collect the spectrum of weak FBG, the propose system will realize automatic measurement, and the response frequency achieves more than 1 kHz. Therefore, the proposed system has a promising future for sensor application, in which large numbers of FBGs are needed.

Acknowledgement

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