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Research Article

Fiber Strain Measurement for Wide Region Quasidistributed Sensing by Optical Correlation Sensor with Region Separation Techniques

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The useful application of optical pulse correlation sensor for wide region quasidistributed fiber strain measurement is investigated. Using region separation techniques of wavelength multiplexing with FBGs and time multiplexing with intensity partial reflectors, the sensor measures the correlations between reference pulses and monitoring pulses from several cascadable selected sensing regions. This novel sensing system can select the regions and obtain the distributed strain information in any desired sensing region.

1. Introduction

To monitor the damage and environmental condition on civil structures is becoming an important research field for civil engineers. It is very important to know the structural health and the degradation of these structures during their lifetime. Nowadays, there are many types of electrical sensors (like strain gauges or thermocouplers) and also optical sensors. In the optical field, many sensing techniques have been developed. These techniques can be sorted into two types depending on the way to measure the physical magnitude: the point and the distributed sensing techniques. The point sensing technique consists in the point measurement of a physical magnitude in a large number of locations with a large number of sensors, while distributed sensing technique consists in the measurement along a fiber link that can be as long as several meters. The most popular point sensing techniques are the Fibre Bragg Grating-s (FBG-s) based techniques [1]. Their main drawback is the missing of the degradation measurement between sensors. Also, most of the point sensors used to have a limited maximum range to detect strain. On the other hand, the most common distributed sensing techniques are based on Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), and Optical Time/Frequency Domain Reflectometer and interferometers [2]. However, they require more complex information handling, have slower response time, and usually need higher input optical power requirement. Thus, measurement regions are strongly limited by the length due to the signal-to-noise ratio of backscattering intensity. Optical pulse correlation sensing system can inquire the total strain value of the monitoring fiber but cannot identify in which region the strain is located [3–6].

Therefore, we propose and demonstrate a compact and simple cascadable multiregion distributed sensing system for wide region sensing [7, 8]. It is based on optical pulse correlation measurement with region separation techniques. The system uses inline-multiple monitoring fibers connected by wavelength partial reflectors or intensity partial reflectors for cascadable multiregion measurement. Then, using wavelength scanning with wavelength selective reflectors (WSRs) by employing FBG or using time-position scanning with intensity partial reflectors (IPRs) by employing reflective index gap in fiber connectors, the system can successfully detect very short-length changes in multiple regional monitoring fibers for temperature or strain measurement. In this paper, firstly we will show the principle of pulse correlation sensing system and region separation and the identification techniques. Then, we will show the experimental setups for two different region measurements with no crosstalk using two region separation techniques. Later, we will discuss the comparison of the two methods of wavelength and intensity separation and their applications. Finally, we will give some conclusions about the presented techniques.

2. Principle

2.1. Optical Pulse Correlation Sensor. A schematic of the optical pulse correlation sensor with a monitoring fiber is shown in Figure 1. An optical pulse is split into a reference pulse and a monitoring pulse by a coupler. The monitoring pulse passes through an optical circulator and then enters in an optical fiber link. After that, the pulse is reflected by a mirror and guided through the monitoring fiber and a circulator and then input to an optical pulse correlation unit. The reference pulse is connected to a different input port of the optical correlation unit. There is a time drift Δt between the reference and monitoring pulses because of their different propagation paths. When the temperature or strain of the monitoring fiber changes, the propagation path of the monitoring pulse is modified due to the length expansion and contraction of the monitoring fiber. Therefore, the change in time drift Δt is proportional to the temperature and strain changes in the monitoring fiber.

The time drift Δt due to the environmental change in fiber-sensing region can be measured by the optical pulse correlation unit [3–6]. As shown in Figure 2, in the pulse correlation unit, the reference pulse is split into two pulses, A and B, polarized orthogonally with a fixed timing separation ô of 20 ps. The monitoring pulse has 45° polarization; so it is combined with doubled reference pulses (polarizations 0° and 90°). This yields Channel 1, the pair of forward pulse A and the monitoring pulse with a time drift (Δt), and Channel 2, the pair of backward pulse B and the monitoring pulse with a time drift ($\tau - \Delta t$). In each channel, the second harmonic generation (SHG) signals from the correlation region of the reference and monitoring pulses are observed by the SHG & APD module. The nonliner correlation signals yielded from the two channels by SHG crystals are proportional to their corresponding time drift. Therefore, the differential signal of Ch1-Ch2 is also proportional to $(2\Delta t - \tau)$ which can increase measurement sensitivity by double and isolate the power influence of optical pulse source. However, this optical pulse correlation sensor can monitor the temperature or strain change in only one region; so it is limited in real applications because multiple region measurement is required. Therefore, region separation techniques based on partial wavelength reflectors and partial power reflectors are employed.

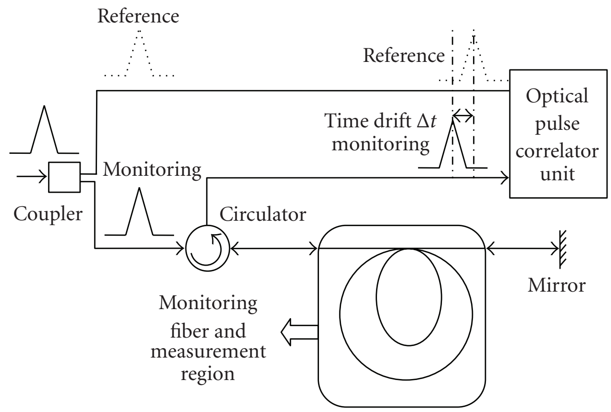

Figure 1: Schematic of temperature and strain measurement with monitoring fiber based on optical pulse time drift.

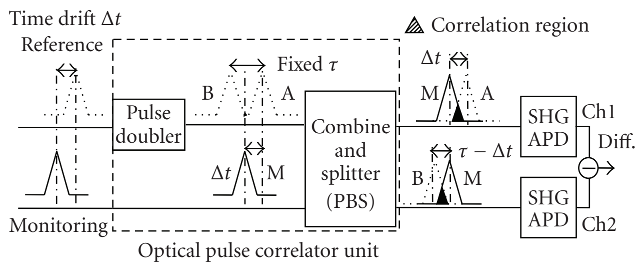

Figure 2: Schematic of fiber-optic pulse correlation sensing mechanism. PBS: polarization beam splitter; SHG: second harmonic generation; APD: avalanche photo diode.

2.2. Region Separation Technique Based on WSRs. The interrogation system scheme for point temperature sensors and multi-region distributed strain measurements based on the pulse correlation technique [7] is shown in Figure 3. The light source is a wavelength tunable laser that generates a pulse train. The pulse repetition rate is determined by the modulation frequency. The pulse train is coupled into two different ports named "*reference port*" and "*measuring port*". In the measuring port, the pulses pass through an optical circulator and then enter in a cascade of Strain Sensing Regions (SSRs) separated by the Wavelength Selective Reflectors (WSRs). The SSRs are fixed along the structure to monitor the strain changes induced in the structure. The WSRs are released free from the structure. The WSRs change their resonance with variations in temperature acting as a point temperature sensor. The scanning of the wavelength of the pulse source allows the temperature point sensors to be interrogated, also to monitor the different SSRs. In essence, the pulse in the WSR1, the pulse round-trip, reaches until the region SSR1 and it only contains information about the strain changes in this region, whereas the reflected pulse in the WSR2 crosses both SSR1 and SSR2 regions. Using the reflected signals from WSR1 and WSR2, the information of the strain changes in SSR2 can be retrieved. This scheme can be easily upgraded to the SSR*n* region.

The reflected pulses return to reach one input port of the pulse correlator unit. The other input of the correlator unit is fed with the pulses coming from the reference port. The reference pulses and the measuring pulses arrive at different time position due to the different lengths of the optical paths. A tunable delay line is placed in the reference arm to allow a partial overlap of both train pulses. The tunability range of

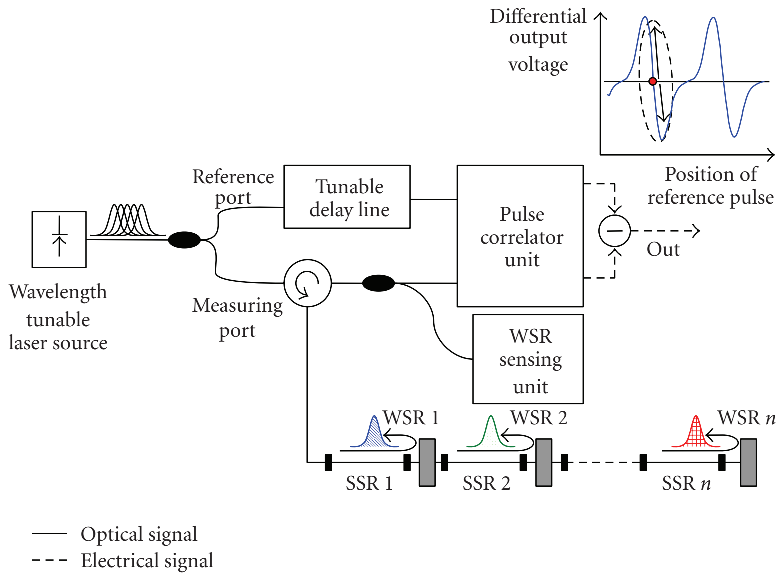

FIGURE 3: Scheme of point temperature and distributed strain measurement. WSR: wavelength selective reflector; SSR: Strain Sensing Region.

the tunable delay line has to be at least half of the inverse of the frequency repetition rate. If the strain in a sensing region is changed, the optical path in the measuring branch produces a time drift between reference and measuring pulse trains and there is a change in the overlapped energy between both train pulses. This change can be monitored by the optical pulse correlation unit. Differential detection technique is used after the pulse correlation unit.

The relationship of the typical differential output voltage is shown in an inset graph in Figure 3. It has the same speed of the pulse train from the laser source. The most important area of the differential output voltage curve, which is used for sensing, is highlighted inside a dashed oval (inset graph in Figure 3). The dot indicates the central position (also known as "decision point") in order to perform the highest excursion and to detect fiber compression and elongation. It is very important to mention that the output relationship is linear in this region and it is very useful for sensing applications. Each SSR is adjusted to have its initial value at the central position. This is done by adjusting the tunable delay line for each region response. The initial values of the tunable delay lines are recorded and used as references. Then, any strain applied is transformed in a change of the output voltage value.

2.3. Regions Separation Technique Based on IPRs. The schematic of a cascadable regional distributed sensor based on optical pulse correlation measurement and intensity partial reflectors (IPRs) [8] is shown in Figure 4. IPRs are made with thin-file of metal and are coated with the metal gold on the end of optical fiber by magnetron sputter method. A mode-locked laser diode (ML-LD) modulated by a synchronized source with frequency f_m produces a short optical pulse-train. The optical pulse-train is split into a reference (Ref.) pulse and a monitoring (Mon.) pulse by a coupler. The monitoring pulse accesses monitoring fibers in regions 1 and 2 (which are used to measure the strain change) through a circulator. Then, the monitoring pulse is reflected back by intensity partial reflectors 1 and 2 (IPR1 and IPR2), respectively, which become two region monitoring pulses M1 and M2. (There are multiple reflections (back and forth) between the two reflectors, which are attenuated quickly because of the low reflectivity of the first reflector and the absorption of optical pulse power in the long sensing fiber). The reflected back pulses M1 and M2 access to the monitoring fibers again and then they reach the input port of an optical pulse correlation unit whereas the reference pulse is connected at a different port.

Thus, M1 passes only through region 1 while M2 passes through both regions 1 and 2. Using the optical pulse correlation unit to detect the time drifts between the reflected pulses M1, M2, and the reference pulse, the information on the strain changes in regions 1 and 2 can be obtained. This scheme can be easily upgraded to the region N. Therefore, the time drifts between the monitoring pulses reflected by partial reflector $1, 2, \ldots, N$ (PR1, PR2,...,PRN) and their adjacent reference pulses are given by

$$\Delta t_i = \frac{n}{c}\Delta L_i + T_{\text{delay}} - k_i T_m, \tag{1}$$

where subscript $i = 1, 2, \ldots, N$, which indicate PR1, PR2, ..., PRN, T_m is the period of modulated signal equal to $1/f_m$, ΔL_i $(i = 1, 2, \ldots, N)$ are the differential propagation lengths between the reflected monitoring pulses and the reference pulses, k_i $(i = 1, 2, \ldots, N)$ are the constant integers standing for Δt_i less than T_m, and T_{delay} is the time position of the optical delay line device. Equation (1) indicates that ΔL_i is proportional to the T_{delay} and T_m when other parameters remain constant. Therefore, we can use a scanning of time position method to monitor temperature and strain changes of different sensing regions. As Figure 5 shows, when moving the time position of the time delay line device in

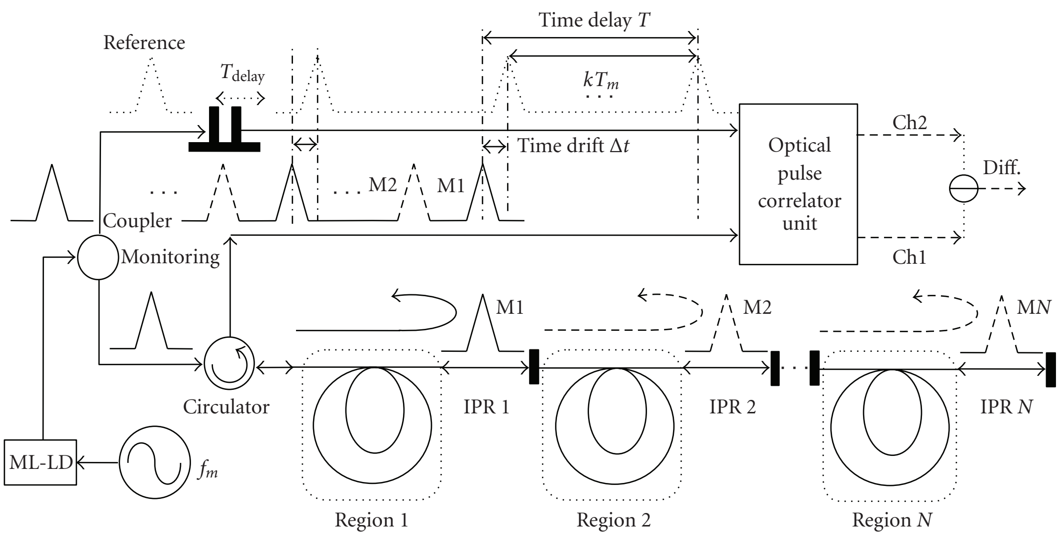

Figure 4: Schematic of selectable region distributed sensor based on reflected optical pulse correlation measurement. ML-LD: Mode-Locked Laser Diode, IPR: Intensity Partial Reflector.

the reference propagation path, the time position of the reference pulse will change, and the time drift between the reference and monitoring pulses will change, and so the correlations of each channel as well. While the differential correlation value is located at the peak point, the monitoring pulse completely overlaps with the reference pulse. In other words, the peak points of differential correlation indicate the monitoring pulse positions of each region, as shown in Figure 5. Therefore, by scanning the time position of the reference pulse we can detect the change in the monitoring fiber length in each region.

The experimental setup is shown in Figure 6. A Mode-Locked Fiber Laser (ML-FL) has been used as a laser source. The laser source is wavelength tunable and its pulse width can be adjusted between 10 ps and 20 ps. In this experimental setup, a pulse width of 12.9 ps has been used, 3.4 dBm of output power and a frequency of 9.956104 GHz, that implies a 100.4-picosecond pulse repetition rate. To divide the train pulses into reference and measuring ports, a 90/10 ratio optical coupler has been employed.

In the reference port, a delay line has been placed that can be manually adjusted. On the other port, an optical circulator is used to route the pulses to the sensing region and to the correlation unit. Two Fiber Bragg Gratings (FBGs) have been used as a demonstration of WSRs. FBGs central wavelengths are 1548.86 nm for FBG 1 and 1545.81 nm for FBG 2, with 0.26 nm of Full Width at Half Maximum (FWHM) and 80% of reflectivity in both FBGs. The SSRs have been implemented with two standard single mode optical fibers of 48.5 cm and 54.8 cm length, respectively. The pulse correlation unit and the dual SH Receivers (SHRs) have been connected to a 12-bit Analogy to Digital Converter (ADC) to obtain the voltage values of the two single channels. Finally, the output differential signal of these channels is stored in a personal computer. The temperature variations

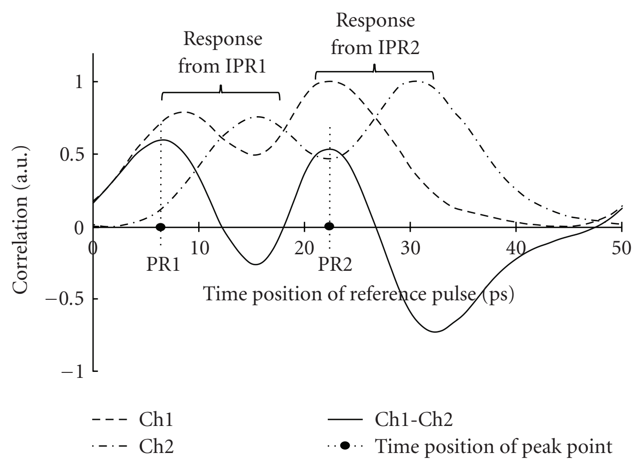

Figure 5: Correlation versus Time position of reference pulse.

have been sensed by the FBGs using an Optical Spectrum Analyzer (OSA).

3. Experimental Results

3.1. Using Wavelength Scanning with WSRs. The interrogation system has been characterized by checking its linearity, stability and resolution. In the first experiment, the laser source has been tuned at 1545.8 nm. Then, some strain has been applied to SSR2 in 0.1 mm steps (182.5 microstrains for a fiber of 54.8 centimetres length) and the differential output voltage values have been obtained. To calculate the strain applied, the first step is to adjust the decision point when SSR2 is relaxed (central point in the solid curve of inset graph in Figure 3). Then, any change in the applied strain (elongation or compression) is converted automatically in

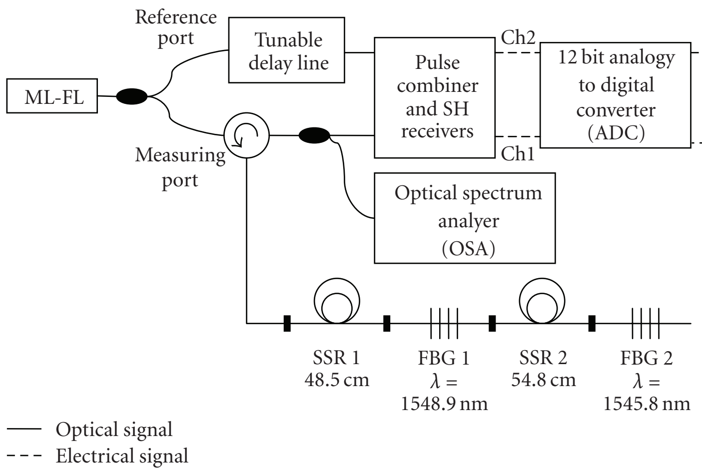

FIGURE 6: Experimental setup of pulse correlation and differential technique with wavelength sensing region separation. ML-FL: Mode-Locked Fiber Laser; SH: Second Harmonic; SSR: Strain Sensing Region.

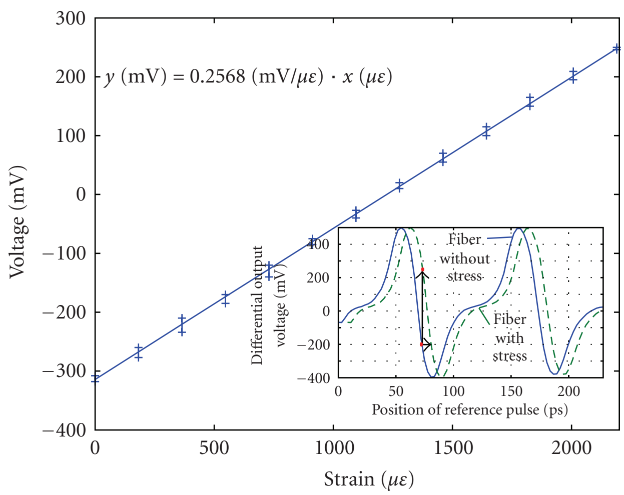

FIGURE 7: Differential output voltage when stress is applied to SSR2 with laser source tuned at 1545.8 nm. Subplot shows differential curves of relaxed fiber and 1.2 mm stressed fiber so that a time shift is observed.

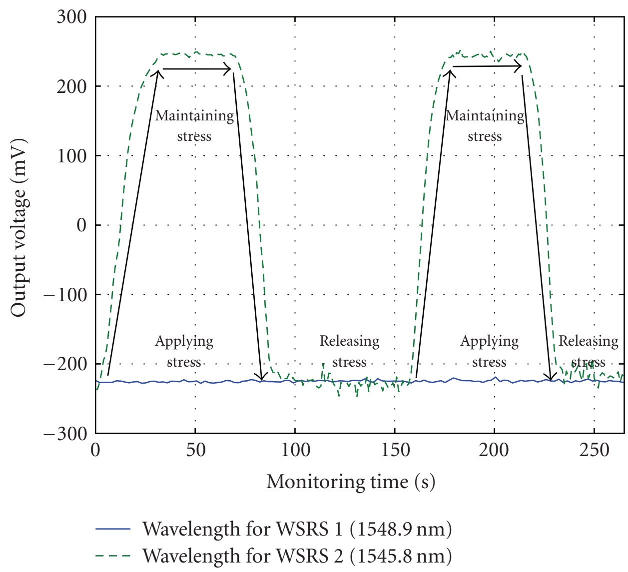

FIGURE 8: Output differential voltage with stress applied to the SSR2 using different central wavelengths from the laser source.

a change of the output differential voltage. The results are shown in Figure 7. It can be seen that the sensor has a linear response. The vertical error-bars at each strain measurement point show the maximum range of deviations after dozens of cycles. The stability in the measurements is quite high, and fluctuations of less than 0.2% have been observed even in the worst case.

To demonstrate the absence of crosstalk between the two strain sensing regions, the laser source has been tuned to 1545.8 nm to select WSR 2. Then, a stress has been applied in the SSR2. The dashed line of Figure 8 shows the changes in the output voltage. Later, the laser has been tuned to 1548.9 nm to select WSRS 1 and a similar stress has been applied to the same sensing region (SSR2). No change in the differential output voltage has been detected (solid line) showing the absence of crosstalk. At the same time, the temperatures of FBG 1 and 2 with free strain can be sensed by measuring the central wavelength shifting with an OSA. Then the strains of SSR 1&2 can be corrected by using the measured temperature value of FBGs.

3.2. Using Time-Position Scanning with IPRs. We used the experimental setup shown in Figure 9. The mode-locked laser diode (ML-LD) optical pulse source with 1555 nm centre wavelength is modulated with a frequency of 20 GHz. The generated pulse width and repetition period are 8.7 ps and 50 ps, respectively. (The pulse width can be extended to 10 ps in the monitoring fiber.) In this study, two partial reflectors are used to connect multi-region monitoring

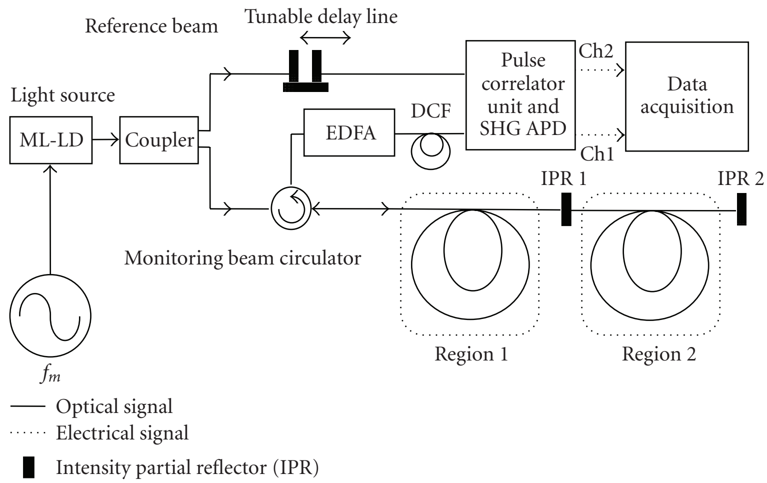

Figure 9: Experimental setup of quasi-distributed optical pulse correlation sensing system. ML-LD: Mode-Locked Laser Diode; DCF: Dispersion Compensated Fiber.

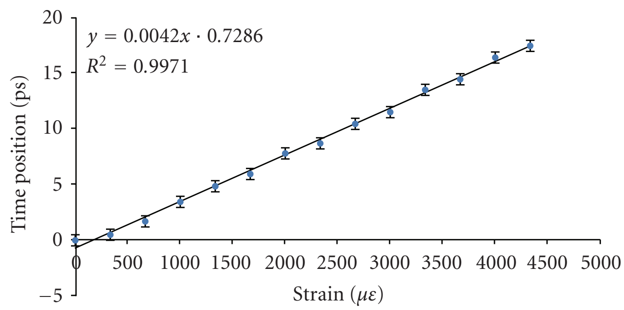

Figure 10: Strain calibration result for a fiber with a 600 mm gauge.

fibers. Two 600 mm single mode fibers are connected, acting as sensing regions. Then the correlation is detected by a data acquisition device whose output signal is uploaded to computer interfaced using Labview software. For well-connected fiber ends, the air gap is smaller than the wavelength of the pulse source, in which case the typical reflectivity of each IPR is nearly equal to 1%.

In order to demonstrate the applicability of the system in real multi-region distributed deformation measurement, strain calibration experiments were first carried out by deforming a 600 mm long fiber segment of region 1 in 0.2 mm steps (333.3 $\mu\varepsilon$ for a fiber of 600 mm length) and measuring the time shift in the peak point of differential correlation by scanning the time position of the optical delay line device in the reference propagation path. The linear relationship between the peak shift of correlation and strain over the range from 0 to 4300 $\mu\varepsilon$ is plotted in Figure 10. It can be seen that the sensor has a linear response. The stability in the measurement is quite high; the fluctuation in the measurement is less than 1%. The calibration coefficient can be calculated as 238 $\mu\varepsilon$/ps. The time resolution of the system is less than 0.02 ps, and therefore the strain resolution of the system is less than 5 $\mu\varepsilon$.

Then, multi-region strain experiments were carried out in sensing region 1 (R1) and region 2 (R2). For investigating the two regions' strain measuring, there were four cases for the stress of sensing regions, which included case 1: R1 and R2 without stress, case 2: R1 without stress and R2 with stress, case 3: R1 with stress and R2 with stress; and case 4: R1 with stress and R2 without stress. The sensing fibers of R1 and R2 applied, maintained, or released stress according to cases 1, 2, 3, and 4, orderly. Every case remained 5 minutes. The experiment results are shown in below part of Figure 11. The four different cases can be identified correctly. For the detail of experiment data, a comparison between case 1 and case 2 is shown in the upper left of Figure 11. R1 has no stress and R2 applied stress from case 1 to case 2. Therefore, the peak point of the response from R1 remained in a constant time position, while the peak point of response from R1 + R2 shifted forward. The other comparison between case 3 and case 4 is also shown in upper right of Figure 11. R1 remained stressed and R2 was released from stress. The peak point of response from R1 + R2 shifted backward and R1 showed no shifting. It can be seen that the multi-region sensor can measure the variations in the strain distribution without crosstalk.

4. Discussion

4.1. Time Resolution and Stability. The actual time resolution is not limited by SHG crystal length (pulse walk-off) because the combined double pulses have the same wavelength [3]. It is limited by the peak power and the dispersion of the monitoring pulse. The correlation time resolution of SHG is less than 0.02 ps [3–5]. Other more, in the time multiplexing with IPRs, the time resolution is also limited by the time resolution of optical delay line device. The optical delay line consists in beam collimators, a moving stage and a high accuracy step-motor controlled by computer from OZ Company, and is an ODL300 with 0.005 ps min step and 0

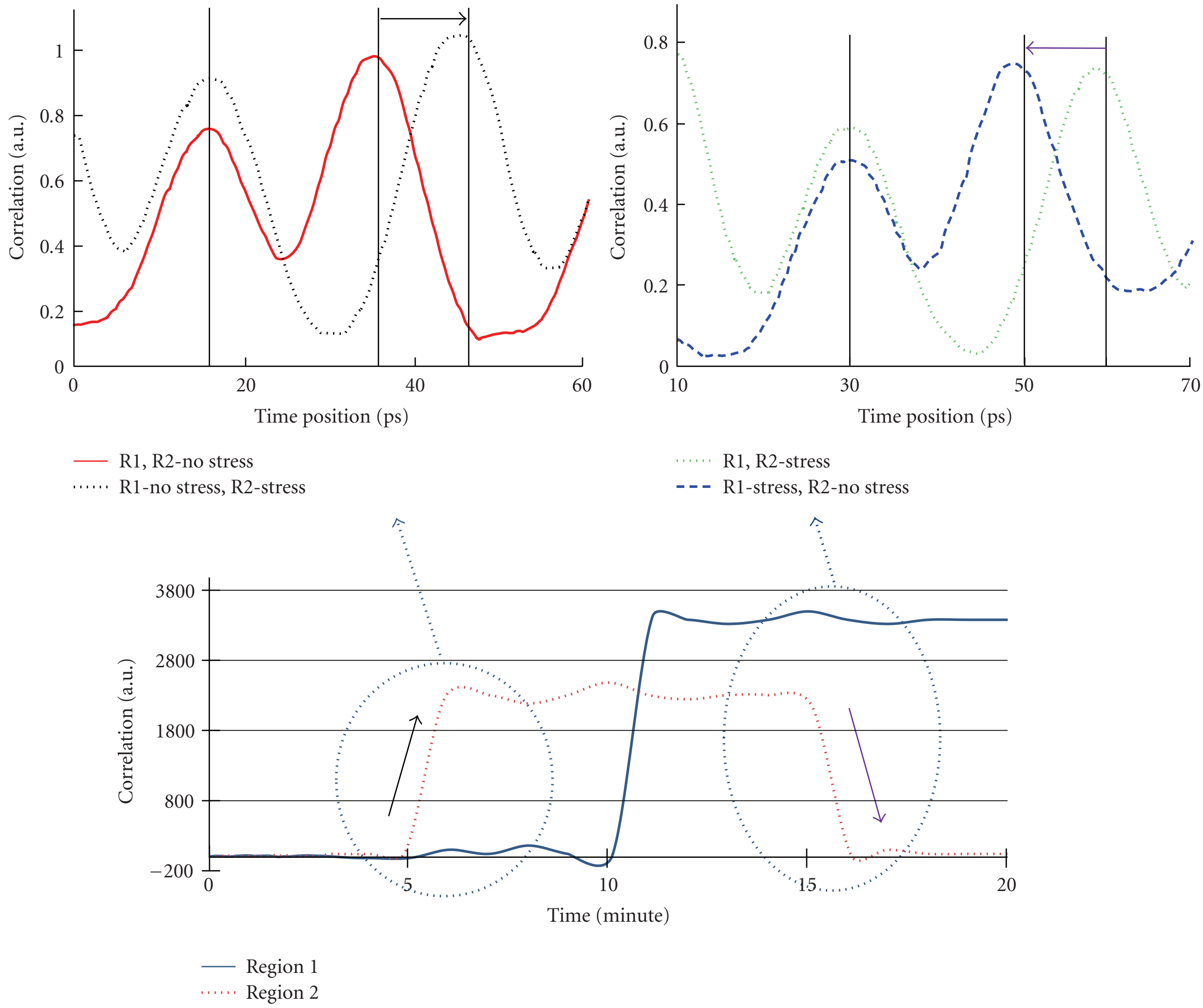

FIGURE 11: Results of the strain distribution measurement of Region 1 (R1) and Region 2 (R2).

to 350 ps range. In other words, the time resolution of the optical delay line device is very high and reaches to 0.005 ps. Therefore, the time resolution of both systems can reach to 0.02 ps.

The time drift stability is estimated from time jitter of the pulse source. In the two proposed systems, mode-locked pulse sources were used with a very low time jitter (less than 1 ps). The time stability also concerns to the polarization of the pulses. In the wavelength multiplexing system with WSRs (FBGs), the time stability depended completely on the polarization fluctuation of the pulse, so that a polarization controller was used in this system [5]. In the time multiplexing system with IPRs, the time stability is isolated from the fluctuation of pulse polarization. Because this system only detects the time shifting of the peak point of the optical pulse, a standard single mode fiber was used, which has a much smaller polarization mode dispersion (PMD) and much lower differential group delay (DGD). Moreover, the differential correlation method was used in both the two sensing systems. This method can isolate the pulse power fluctuation completely and the pulse time jitter fluctuation partially. Furthermore, the timing stability concerns the stability of transmission path. The two systems proposed are based on the pulse correlation measurement. The stability of the systems mainly depended on the differential transmission path between the reference pulse and the monitoring pulse. When the transmission fibers (except the fiber in the sensing region) are maintained in a temperature and strain stable environment, the sensing system can maintain stability for a very long time. For these reasons, the timing stability of both systems is less than 1 ps.

4.2. Estimation of the Number of Cascadable Regions. For the wavelength multiplexing system with WSRs (FBGs), the maximum number of cascadable sensing regions mainly depends on the number of wavelengths in the pulse source. The key point is to use a multiwavelength mode-locked pulse source. In this experiment, a tunable wavelength mode-locked fiber laser source was used. If the pulse power can be amplified enough, the maximum number of sensing regions can be very high.

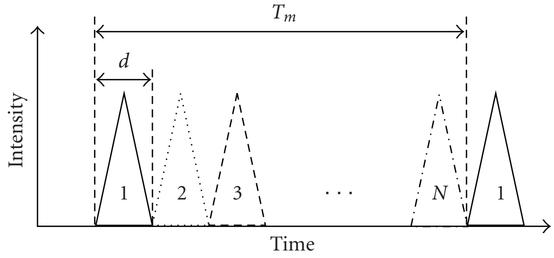

Figure 12: Schematic of the maximum number of cascadable regions using optical pulse source.

For the time multiplexing system with IPRs, the number of cascadable regions is limited by the combination of the repetition frequency of the pulse source, the width of the pulse source and the detection sensitivity limit of the back reflected optical signal. Then, the maximum number of cascadable regions can be calculated by separating several different cases as follows.

Case 1. The number of cascadable regions depends on the repetition period of the optical pulse and inversion of pulse width as shown in Figure 12. When 20 GHz repetition rate ML-LD (50 ps period, 10 ps pulse width) pulse source was used, the number of cascadable regions can be calculated as $T_m/d = 5$ (where T_m is the repetition period, 10 ns, and d is the pulse width, 2 ps) as shown in Table 1. Moreover, the maximum range of the optical delay line is 350 ps much larger than the period (50 ps) from the 20 GHz ML-LD pulse source. In this system, the range of scanning of optical delay line just needs 50 ps.

Case 2. The number of cascadable regions also depends on whether the reflected power I_R(i) is more than $I_{\min}$, the detection limit of the reflected back optical signal, as (2) shows:

$$I_R(i) \geq I_{\min}, \quad i = 1, 2, \ldots, N. \tag{2}$$

In this experiment with 10 ps pulse width, our reflected back light detection system has a detection sensitivity limit power of 0.01 mW and S/N larger than 20 dB. It means that the $I_{\min}$ is 0.01 mW in this study. As Figure 13 shows, at each region fiber's end surface, the optical pulse partly reflects and partly transmits due to the air gap in the connector. For well-connected fiber ends, the air gap is smaller than the wavelength of the pulse source, in which case the typical reflectivity R is nearly equal to 1%. The transmission coefficient T can be calculated as $T = 0.89$, and the typical fiber optic connection insertion losses (except reflective losses) coefficient β can be calculated as $\beta = 0.9$ [9]. The insertion losses coefficients of the circulator are $\alpha_1 \approx 0.84$ from port A to port B and $\alpha_2 \approx 0.85$ from port B to port C. Therefore, the received optical pulse reflected from the partial reflector i, $I_R(i)$, can be given by

$$I_R(i) = I_0 \alpha_1 \alpha_2 R T^{2(i-1)} \beta^{2(i-1)}, \quad i = 1, 2, \ldots, N, \tag{3}$$

where I_0 is the input power to the circulator. Then, the normalized optical signal power versus the fiber optic sensor

Table 1: The number of cascadable regions limited by different cases (with 1% reflectivity IPRs).

Conditions	Light source	20 GHz ML-LD
	Pulse width d	10 ps
	Period of Pulse T_m	50 ps
	Range of optical delay line T_d	350 ps
	Input Power I_0	10.7 mW
	Detection limit $I_{\min}$	10 μW
Number of cascadable sensing regions	Number of Case 1	5
	Number of Case 2	6
	Minimum number	5
	Dynamic measurable time range of each region	10 ps

number i is plotted in Figure 14. When we use the 20 GHz ML-LD pulse source, the input power is 10.7 mW in this study. According to (2) and (3) and taking into account of the above data, the number of cascadable regions can be calculated as $N = 6$.

It is very important to mention that the number of cascadable regions is estimated to 5 depending on the minimum value of the number of sensing regions in the above two cases as Table 1 shows when using the 20 GHz ML-LD.

To obtain a greater maximum number of cascadable regions, one approach is to increase the detection limit of this sensing system. Additional improvement is the usage of different designed reflectivity to control the power of each reflected signal equal to the detection limit ($I_R(i) = I_{\min}$, $i = 1, 2, \ldots, N$). Moreover, to decrease the pulse width by using a pulse compression technique and to increase the pulse peak power, the number of sensing regions can be easily upgraded. To correctly operate the sensing system, the dynamic delay range of the optical delay line device should be longer than the pulse repetition period. And to fulfill the system requirements of each user, repetitions rate flexible pulse source is desirable key components.

4.3. Comparison. Using the region separation and identification techniques, these sensing systems can successfully achieve the multiple region distributed strain sensing. Compared with other fiber-optic sensors, such as FBG sensors, the region separation pulse correlation sensing systems have a number of distinguishing advantages. (1) They can give hybrid intelligent sensing combination of the distributed and point sensors for WSRs. (2) They can use a cascadable standard single mode fiber as the sensing gauge for WSRs. (3) They can supply real-time measurement, high-resolution and high-speed measurement. (4) The position resolution is not so high, but wide region monitoring does not require very high spatial resolution; thus they can apply in a very wide region infrastructure monitoring. One of the most important applications of these sensors that have been demonstrated is the so-called fiber optic smart structure

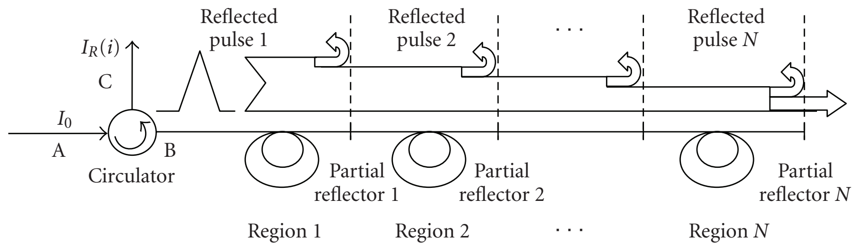

Figure 13: Schematic of power fluxes of transmissive and reflective optical pulse in the cascadable fiber sensors.

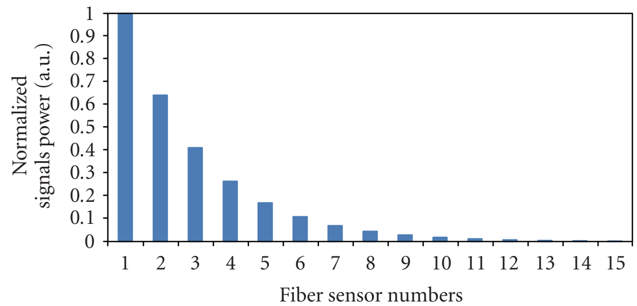

Figure 14: Normalized optical signal power versus Fiber-optic sensor number.

health monitoring, where multiplexed optical fiber sensors are embedded into the structure to monitor its strain distribution.

In order to see the characteristics of region separated pulse correlation sensors, a comparison between the two region separation technologies would be as follows. The WSRs have the advantages of high-resolution and high-speed measurement, making it ideal for short distance and high speed measurement in fiber optic for smart structures, such as an intelligent building. Meanwhile, the IPRs have the advantages of low cost, large sensing region and low-speed measurement, making it ideal for long distance, medium precision measurement situations, such as large build, long oil/gas pipeline, and power supply cable/line. However, temperature compensation of the strain error caused by thermal fluctuation is essential for practical applications.

5. Conclusion

We successfully proposed and demonstrated the optical pulse correlation sensing system for multiple region-distributed fiber strain measurement with two kinds of region separation techniques, WSRs and IPRs. Using these regions separation techniques, the sensor measures the correlations between the reference pulse and the monitoring pulse from cascadable selected sensing regions. The system uses inline-multiple monitoring fibers connected by FBG or air gap for cascadable multi-region measurement. Then, using wavelength scanning with WSRs (FBG) or time position scanning with IPRs (air gap), the system can successfully detect the length change of multiple regional monitoring fibers for strain measurement. With WSRs, the system can be used for short distance, high precision, and high speed for distributed strain measurement. With IPRs, the system can be used for long distance, large sensing regions and low speed for distributed strain measurement. This novel sensing system with WSRs and IPRs can select the regions, and know the distributed strain information in any different sensing regions.

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