High Time Resolution Fibre Optic Sensing System Based on Correlation and Differential Technique

Article *in* Measurement Science and Technology · February 2006

DOI: 10.1088/0957-0233/17/4/004

4 authors, including:

Hongbin Song
The Chinese University of Hong Kong (Shenzhen)

Koji Nonaka
Mitsubishi Minatomirai Industrial Museum

Meas. Sci. Technol. **17** (2006) 631–634 doi:10.1088/0957-0233/17/4/004

High time resolution fibre optic sensing system based on correlation and differential technique

H B Song, T Suzuki, M Sako and K Nonaka

Department of Electronic and Photonic Systems Engineering, Kochi University of Technology, 185 Miyanokuchi Tosayamada, Kochi-Pref, Japan

E-mail: 096405y@gs.kochi-tech.ac.jp

Received 18 July 2005, in final form 29 November 2005
Published 10 February 2006
Online at stacks.iop.org/MST/17/631

Abstract

A novel fibre optic sensing system with a high time resolution of less than 0.04 ps based on an optical pulse correlation measurement mechanism and differential detection technique is investigated. The optical pulse correlation state corresponding to time drift in fibre optic transmission lines is detected by SHG. The results of temperature and strain sensing experiments demonstrate an excellent linear relationship between the differential signal and the measurands inducing time drift of the optical pulse through a fibre optic. Based on the sensing system, a temperature resolution of 0.04 m °C and a strain resolution of 0.2 $\mu\varepsilon$ are obtained, respectively, which indicate that the sensing system can be successfully applied to monitor the environment conditions around fibre optic transmission lines with high resolution.

Keywords: correlation measurement, fibre optic sensor, optical pulse, temperature sensor, strain sensor, differential detection

(Some figures in this article are in colour only in the electronic version)

1. Introduction

As a typical sensor with small size, light weight, high strength, flexibility and independence of electromagnetic interference, the fibre optic sensor has been widely applied to fields of industry, environment, biology, health monitoring of civil engineering and inertial navigation [1–6]. Since the appearance of the fibre optic sensor in early 1970s, various sensing techniques have been developed, such as sensing based on the wavelength shift of fibre Bragg grating, coherence mechanism, Brillouin scattering and Faraday effect [7–10]. Much more attention of researchers has been focused on the fibre Bragg grating sensor due to its superiority in multi-point measurement and high resolution [11–13]. However, in the fibre Bragg grating sensing system, a broadband light source is indispensable, which increases the cost dramatically. Moreover, various interrogators are required to substitute the high resolution optical spectrum analyser due to the high cost and low scanning speed. Some interrogators are simple but are more limited in measurement resolution, dynamic range or multiplexing; others provide better resolution but are more complicated, expensive or unstable [14]. As far as sensors based on the coherent technique are concerned, the monitoring length of coherent detection is strongly limited by the coherent length of the light source and the mechanical scanning. Therefore, a simple, real-time fibre optic sensor with high resolution is required. Pulse measurement is an alternative method [15]. In this paper, a novel simple, high resolution fibre optic sensor free of mechanical scanning is proposed.

Time drift in fibre optic devices such as pulse compression fibre, nonlinear optical loop mirrors and erbium-doped fibre amplifiers resulting from the optical power and environmental condition change limits the performance of all-optical fibre modulation multiplexing/demultiplexing in the fibre optic communication system [16]. Therefore, it is necessary to monitor time drift in fibre optics. The sensing system presented in this paper offers a solution. With the optical

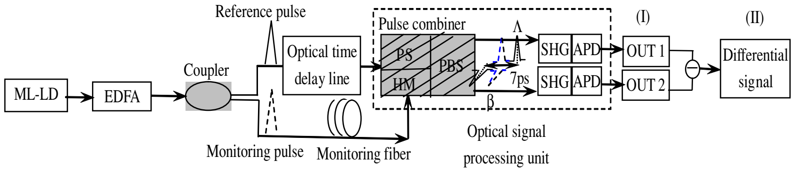

Figure 1. Scheme of an optical pulse correlation sensing system. PS: pulse splitter, HM: half mirror and PBS: polarization beam splitter.

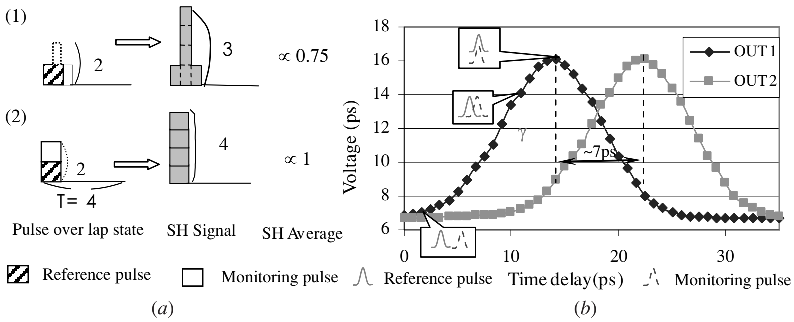

Figure 2. (*a*) Relationship between pulse overlaps and SH signals of pulse pair Λ: (1) half overlap and (2) full overlap. (*b*) SH average versus pulse position in each channel (part I in figure 1).

pulse correlation and differential detection technique, both the value and direction of the time drift can be detected easily. In addition, time drift contains abundant information such as the temperature, strain and pressure around fibre optic transmission lines. Therefore, by detecting time drift in an optical pulse, the environmental conditions around fibre optic transmission lines can be monitored. The sensing system has excellent sub-picosecond time resolution due to the stable distance between reference pulses polarizing in orthogonal planes. The timing monitor circuit is bit-rate flexible and does not need high-speed optical detectors or high-speed IC circuits. By using this sensing system, sub-picosecond time drift value and direction are both easily detected [17].

2. Principle

The novel simple, real-time fibre optical sensing system is based on the cross-correlation characteristics of two pulses realized by SHG and the differential detection technique [17]. SHG is a second-order nonlinear effect, in which the output power of the second harmonic wave is proportional to the square of the fundamental wave power under the condition of phase matching. An average of the SH signal denotes the overlap state of two pulses. The combination of optical pulse correlation measurement and differential detection constitutes a real-time sensing system with high time resolution and excellent linearity.

To acquire the correlation and differential signals containing monitoring information, a special optical pulse processing technique which doubles the reference pulse, combines the signal pulse with double reference pulses and separates two pairs of overlap signals with perpendicular polarization states, is required. As is shown in figure 1, we designed an optical pulse processing unit consisting of a PS (pulse splitter), a HM (half mirror) and a PBS (polarization beam splitter).

An amplified optical pulse train from a ML-LD (mode-locked laser diode) modulated by a RF (radio frequency) signal with a frequency of approximately 20 GHz is divided into a reference pulse train and a monitoring pulse train by an optical coupler. By tuning an optical time delay line, the overlap state of the reference pulse train and monitoring pulse train is initialized. The pulse splitter, composed of a birefringent crystal in the optical signal processing unit, separates the reference pulse train into two orthogonally polarized pulse trains with a time delay of approximately 7 ps (determined by the length of the birefringent crystal). By tuning the polarization of the monitoring pulse, an offset polarization angle is controlled so that the monitoring pulse train projects equally in orthogonal polarizing directions. Then the monitoring pulse is combined with each polarization reference pulse, yielding pulse pairs Λ and β, where Λ is composed of a monitoring pulse and a forward reference pulse, and β is composed of a monitoring pulse and a backward reference pulse. The combined pulses are split by the PBS and turned into cross-correlation SH signals, which were detected by two APDs (avalanche photodiodes).

The relationship between input pulses and SH signal, the output characteristic of each channel (which corresponds to part I in figure 1) and the corresponding correlation state of the pulse pair are illustrated in figure 2. It can be seen that around point γ the intensity of the SH signal varied linearly with the time delay. A resolution of less than 0.1 ps was obtained. In order to improve the resolution of the system, we introduced a differential detection technique. The differential signal between OUT1 and OUT2 is monitored. The resolution in differential detection depended on the balance of the OUT1 peak and the OUT2 peak, which was determined by the offset polarization angle of the monitoring pulse and detector sensitivity. Therefore, the offset polarization angle is controlled as 45° to obtain equal components of monitoring pulse in orthogonal polarization directions. On the other hand, if there is a little difference between the sensitivities of the two detectors, the offset polarization angle used to eliminate the asymmetry is monitored by the output voltages of OUT1 and OUT2 with only the monitoring pulse input.

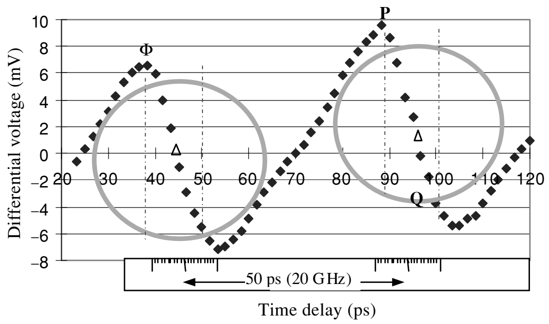

Figure 3. Differential signal versus pulse time position (part II in figure 1). Φ: peak of OUT1, Ω: peak of OUT2 and Δ: decision point.

If the monitoring pulse drifts forward, the intensity of OUT1 increases, while that of OUT2 decreases. Then the sign of the differential signal between OUT1 and OUT2 becomes positive. If the monitoring pulse drifts backward, the intensity of OUT1 reduces, while that of OUT2 rises. And the sign of the differential signal becomes negative. The change of the differential signal with pulse time delay is illustrated in figure 3. It indicates that the differential signal varies periodically with pulse time delay. The period is approximately 50 ps due to the repetition rate of the optical pulse train from the ML-LD, i.e., when the monitoring pulse N has a small time drift it overlaps with pulse M in the reference pulse train (pulse $(N+1)$ in the monitoring pulse train overlaps with pulse $(M+1)$ in the reference pulse train). The sensing region is between the points ϕ and Ω in figure 3 corresponding to peaks of OUT1 and OUT2, respectively. When the time drift of the monitoring pulse is beyond this region, monitor pulse N will overlap with reference pulse $(M+1)$. Then the region PQ is available. The time resolution of the differential detection system is less than 0.04 ps, which is twice that of single channel measurement. Therefore, the measuring range of the system can be 'zoomed out' with rough resolution and 'zoomed in' with high resolution. Compared with single channel measurement, the differential signal detection has unique advantages:

1. It indicates not only the time drift value, but also the drift direction;
2. Its resolution is nearly double that of single channel detection.

Based on this sensing system, temperature and strain experiments were conducted.

In the sensing system, the overlap state of pluses is indicated by the SH signal detected by the APD module instead of pulse scanning. The SHG signal nearly has no response limit in time. Hence, the response time of the sensing system is determined by that of the detector module. The response time of the detector module to a stepped pulse is several micro-seconds, which allows the measurement to be immune to fluctuations resulting from external perturbations. Therefore real-time sensing can be realized with this sensing system.

3. Experiments and results

According to the relationship between the differential signal and pulse time position in figure 3, the pulse time drift indicated the change of environment conditions of the pulse train in fibre optic transmission lines. Therefore, we can use the system to measure physical quantities such as temperature, strain and pressure around a fibre optic. A typical temperature measurement setup is shown in figure 4.

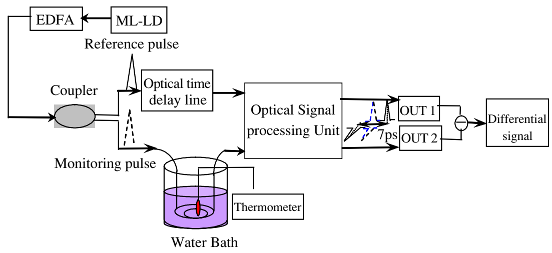

Figure 4. Experimental setup for temperature measurement.

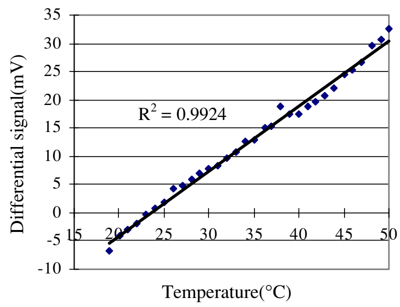

Figure 5. Differential signal of correlation pulse versus water bath temperature.

Before heating the water bath, we located the pulse positions around the decision point by tuning the optical time delay line. When the temperature of water was increased, a timing delay was generated in the monitoring pulse train, which caused a change in the differential signal. A single mode fibre of length 1 m with polyamide sleeve was employed. By controlling the temperature of the water bath, the differential pulse correlation signal was monitored by a digital multimeter.

The variation of differential signal with the temperature of the water bath is shown in figure 5. An excellent linearity was observed, when the water bath temperature was increased from 19 °C to 50 °C within about 1 h. By fitting the experimental data with the least-squares method, a curve correlation coefficient of 99.24% was obtained. A resolution of about 0.04 m °C was obtained, which indicated that different temperature resolutions could be realized with different fibre lengths to satisfy the corresponding applications. Some fluctuations appeared when the temperature was higher. The main reasons are discussed in the next section.

In addition, an experiment for strain measurement with a single mode fibre of length 56 cm was carried out using a similar approach. Due to the strain, the fibre optic was extended, which yielded a timing delay for the optical pulse through it. The relationship between the differential signal and the manipulator position was shown to be extremely linear with a correlation coefficient rate of 99.78% as indicated in figure 6. A resolution of 0.2 $\mu\varepsilon$ was obtained.

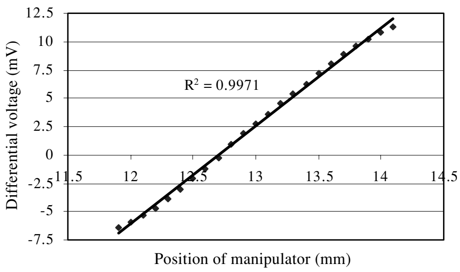

Figure 6. Differential signal correlation pulse versus tensile strain position.

4. Discussion

The resolution of the optical pulse correlation system is up to the pulse width of the light source, time jitter and SHG intensity [17]. Basic SH signal resolution has a potential around the femtosecond range. If these factors are optimized, the time resolution can be improved further. In addition, the difference of OUT1 peak and OUT2 peak has a dramatic effect on the time resolution. By equalizing the input optical powers of the optical signal process unit, the time resolution is enhanced to less than 0.04 ps from 0.06 ps.

According to the periodical characteristic between time drift and differential signal as shown in figure 3, the measurement range of the sensing system based on correlation and differential detection techniques can be selected corresponding to specific applications. Moreover, the result of temperature experiment indicated a selective temperature resolution with different fibre optic lengths. This flexible design in measurement resolution and range provides the correlation sensing system with great potential for applications.

During the temperature experiment, the output voltage of OUT1 is very stable, while that of OUT2 briefly fluctuates. Hence, a fluctuation in the differential signal is yielded. The possible reasons for this instability are from two aspects: one is the phase mismatch in SHG due to the expansion coefficient difference between the fibre optic core and the sleeve; the other is the change of polarization due to birefringence resulting from uneven thermal distribution in the water bath. To obtain higher resolution and stability for pure time drift detection, the polarization fluctuation should be eliminated. A possible solution is to use the polarization-maintaining fibre, or to introduce an active polarization controller at the output end of the monitoring fibre.

5. Conclusions

A simple, real-time fibre optic sensing system with an excellent time resolution of less than 0.04 ps is proposed. The results of temperature and strain experiments demonstrated good linear relationships between the optical pulse correlation signal and the measurands. Resolutions of 0.04 m °C and 0.2 $\mu\varepsilon$ were obtained in temperature and strain experiments, respectively. The temperature resolution and measurement range are related to the length of fibre optic employed in the experiment. Therefore, we can 'zoom out' to satisfy a large range measurement with a short fibre optic, or 'zoom in' to acquire a high resolution with a long fibre optic. The periodical characteristic between the differential signal and time drift also offers the possibility of long range measurement.

Acknowledgment

The authors would like to thank Professors Kanbe and Iwashita of Kochi University of Technology for helpful discussions on technique, and Professor Lawrie Hunter for help in writing in English. This research was partly supported by High Tech Research Center and RSP Projects.

References

[1] Osaka K *et al* 2001 Effects of pressure on measurement of strains in EFPI optical fiber sensors embedded in FRP laminates *Adv. Compos. Mater.* **10** 169–76
[2] Zak E A and Kravchenko N P 1991 Industrial applications of amplitude-type fiber-optic sensors *Meas. Tech.* **34** 1211–4
[3] Wolfbeis O S, Kovács B, Goswami K and Klainer S M 1998 Fiber-optic fluorescence carbon dioxide sensor for environmental monitoring *Microchem. Acta* **129** 181–8
[4] Preejith P V, Lim C S, Kishen A, John M S and Asundi A 2003 Total protein measurement using a fiber optic evanescent wave-based biosensor *Biotechnol. Lett.* **25** 105–10
[5] Murayama H, Kageyama K, Kamita T and Igawa H 2003 Structural health monitoring of a full-scale composite structure with fiber-optic *Adv. Compos. Mater.* **11** 287–97
[6] Hotate K 1993 Fiber-optic gyros *Opt. Laser Technol.* **25** 262
[7] Botsis J, Humbert L, Colpo F and Giaccari P 2005 Embedded fiber Bragg grating sensor for internal strain measurements in polymeric materials *Opt. Lasers Eng.* **43** 491–510
[8] Tsuda H 2000 Response of Michelson interferometric fiber-optic sensors to impact loading *J. Mater. Sci. Lett.* **19** 1–2
[9] Bernini R, Minardo A and Zeni L 2005 Distributed fiber-optic frequency-domain Brillouin sensing *Sensors Actuators* A **123–124** 337–42
[10] Rastogi P K 1997 *Optical Measurement Techniques and Applications* (Boston, MA: Artech House) pp 226–48
[11] Chen X F, Zhou K M, Zhang L and Bennion I 2005 High sensitivity biosensor based on dual-peak LPG sensitized by light cladding etching *OFS-17 Conf. (Bruges, Belgium)* pp 383–6
[12] Igawa H, Murayama H, Kasai T, Yamaguchi I, Kageyama K and Ohta K 2005 Measurement of strain distribution with a long gauge FBG sensor using optical frequency domain reflectometry *OFS-17 Conf. (Bruges, Belgium)* pp 547–9
[13] Yokosuka H, Tanaka S and Takahashi N 2005 High-sensitive fiber Bragg grating vibration sensor using intensity-modulated laser source *OFS-17 Conf. (Bruges, Belgium)* pp 731–4
[14] Lee B 2003 Review of the presents status of optical fiber sensors *Opt. Fiber Technol.* **9** 57–79
[15] He Z and Hotate K 2002 Distributed fiber-optic stress-location measurement by arbitrary shaping of optical coherence function *J. Light. Technol.* **20** 1715–23
[16] Uchiyama K, Nonaka K and Takara H 2004 Subpicosecond timing control using optical double-pulse correlation measurement *IEEE Photon. Technol. Lett.* **16** 626–8
[17] Nonaka K, Sako M and Suzuki T 2005 Optical pulse time drift sensing for fiber delay monitoring using pulse correlation and differential detection *OFS-17 Conf. (Bruges, Belgium)* pp 76–9