Delayed Transmission/Reflection Ratiomaric Reflectometry

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ABSTRUCT

A new Time Division Multiplexing (TDM) optical fiber interrogation system for distributed Fiber Bragg Gratings (FBGs), designated as Delayed Transmission/Reflection Ratiometric Reflectometry (DT3R), is presented. The Bragg wavelength shift of FBG, which varies according to temperature or strain, is estimated as the ratio of transmittance and reflectance of a slope filter, to which the reflected light from the FBGs is input. To obtain both simultaneously using a single detector, a definite propagation delay is given to either transmission or reflection path, both of which are added to each other and detected using a common photodiode. The reflection impulse response of the FBGs is analyzed using OTDR based on Pseudo-random Noise code (PN) correlation scheme. The hardware structure of an interrogator is simple, resulting in low cost. The FBG topology is a “bus”: multiple FBGs branch from the through line started from the interrogator. Each FBG is distinguished by its time of flight between the interrogator and the FBG. Because of these schemes, the FBGs can all be identical. A breakdown of any FBGs has no effect on the other sensors; moreover, “hot swapping” is possible. Experimental evaluation results are presented herein.

Keywords: Fiber optic sensors, distributed sensing, fiber Bragg grating, slope filter, PN code correlation, push-pull ratiometry, temperature sensing, dynamic strain sensing

1. Introduction

Wavelength multiplexing is useful for a multi-point FBG interrogation system[1], which usually consists of a wideband light source and a polychrometer. Time domain interrogation systems have also been proposed[1], one of which uses a tunable filter or tunable laser. It can be regarded as a tunable OTDR. Another one very uniquely utilizes a Semiconductor Optical Amplifier (SOA) within a resonating cavity consisting of FBGs and a rear reflector [2]. Existing systems mentioned above, however, require very expensive optical devices such as tunable devices or SOA. An inexpensive interrogator will be proposed for solving such problems. It will be shown that a novel time domain FBG interrogation system based on PN code correlation reflectometry is useful to this end, which will be called Delayed Transmission/Reflection Ratiometric Reflectomery (DT3R), hereafter.

2. Principle

Figure1 portrays the system configuration of DT3R. The interrogator consists of SLD, PD, circulators, a slope filter, and digital signal processing circuits, including PN code generator, A/D converter and correlator, none of which is expensive. The sensor network topology is of a “bus”, consisting of a through line and FBG sensor branches.

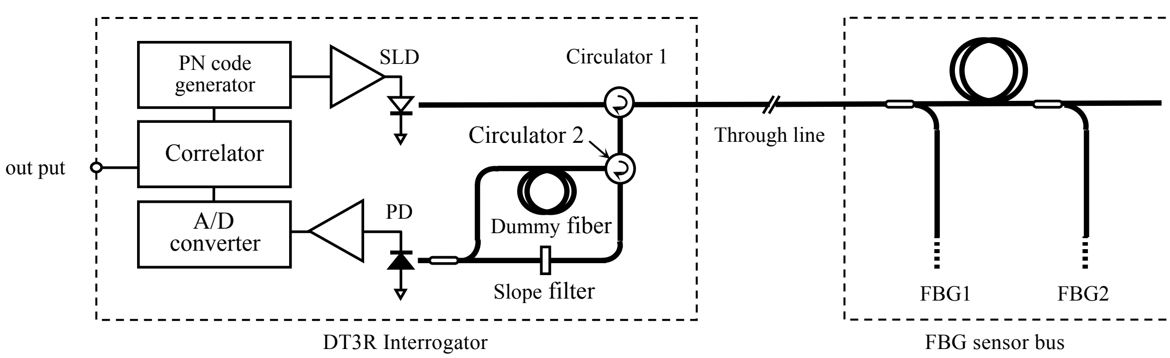

Figure 1. System configuration of DT3R

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An SLD is binary modulated by a PN code[3], whose output is launched into the through line that uses a single mode fiber. Reflected light from these FBGs is brought together to a slope filter via circulators 1 and 2. The transmitted light of the filter is input to the photodiode via a fiber coupler. The reflected light of the filter, on the other hand, returns to circulator 2 and is input to the above photodiode through a dummy fiber and the coupler. Consequently, the transmitted and reflected lights from the filter, of which levels vary complementarily according to the Bragg wavelength of FBG (see Figure 2), are jointly detected by the same photodiode with a propagation time difference. The photodiode output is converted to digital form at the A/D converter, of which cross correlation between the former modulating PN code is calculated at the correlator. The correlation output gives the reflective impulse responses of the FBGs, in which peak pairs of transmission and reflection of the filter appear at every point of FBGs, as distinguished by its time of flight [4,5]. The peak ratios of transmittance and reflectance of the slope filter correspond to the Bragg wavelength of each FBG, from which the temperature or strain at the FBG can be estimated.

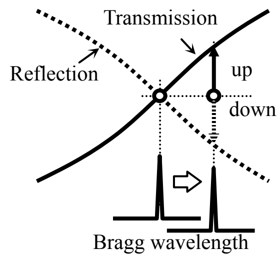

Figure 2. Slope filter

Table 1. Simulation conditions

FBG locations	500/800m
Chip rate	100MHz
Code length of PN	2^{16}-1
Dummy fiber	30m

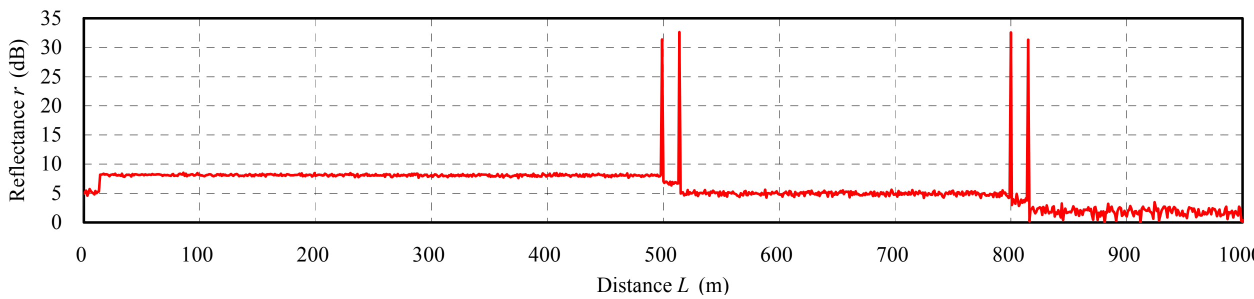

Figure 3. Simulated reflective impulse response of FBGs

Figure 3 depicts a simulated reflective impulse response of the FBGs branched from the through line. The interrogation condition is given in Table1. The base line of the waveform shows the Rayleigh backward scattering level. The bump at 15m, half of 30m, is attributable to the propagation delay through the dummy fiber in the reflection arm of the filter, because the Rayleigh scattering light from the reflection arm of the slope filter is added to that from transmission arm having the propagation delay at the coupler in front of the detector. The transmission and reflection peaks can be seen at 500m and 800m separately by 15m. Therefore, the ratio of transmission and reflection corresponding to each FBG can be found readily as a decibel difference between transmission and reflection.

3. Experimental Results

The experiments described below use a single FBG for simplicity. Spectra of light waves emitted from SLD are shown in Figure 4. It ranges over 40nm wide, covering a sufficient FBG spectrum shift. Figure 5 depicts transmission and reflection spectra of the slope filter. Their complementary characteristics are readily apparent.

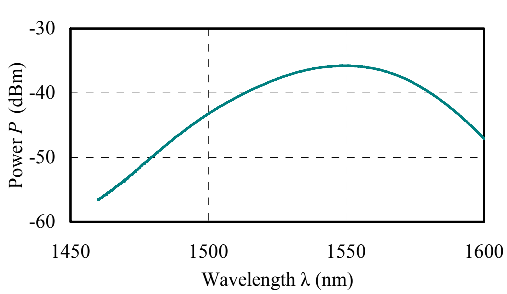

Figure 4. Emission spectrum of SLD

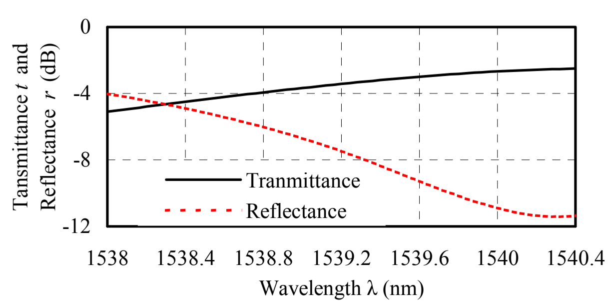

Figure 5. Transmission and reflection of slope filter

1) Temperature sensing

An FBG temperature probe is used, of which the Bragg wavelength shift is enhanced by its stainless steel tube's thermal expansion. Figure 6 presents its temperature characteristics. The temperature coefficient was 29pm/°C.

The main specification of the DT3R interrogator is portrayed in Table 2. The chip rate of the PN code (f_c) was 6.25MHz. The distance resolution, which is given by $10^8/f_c$ in meter, was 16m.

Figure 7 presents the measured temperature variation, in the case an FBG probe was put into hot water and cooled as it was. The measured and actual temperature values, as obtained using a platinum resistance thermometer, are shown for comparison in Figure 8. The standard deviation was estimated as 0.42°C. It is usually sufficient, however, it can be more improved by providing a temperature-controlled reference FBG in the interrogator.

Table 2. Main Specs of DT3R

Chip rate	6.25MHz
Sampling rate	12.5MHz
Code length of PN	2^{10}-1
Dummy fiber	30m

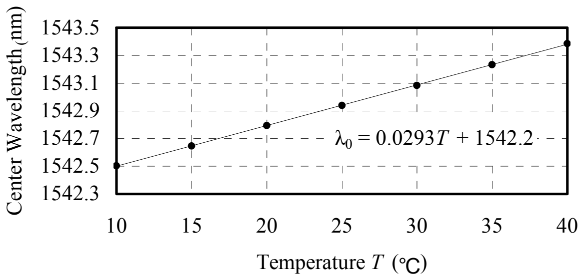

Figure 6. Temperature characteristics of FBG

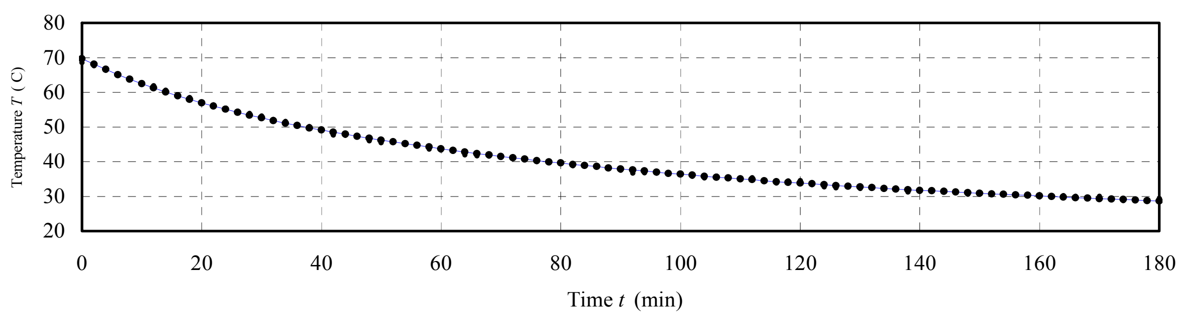

Figure 7. Measured temperature variation

2) Dynamic strain Sensing

Another FBG is fixed on a cantilever. Bending strain characteristics are presented in Figure 9, showing quite linear characteristics. The strain coefficient was 1.2pm/με.

Giving forced vibration to the cantilever and response waveforms of the transmittance and reflectance of another slope filter were obtained as presented in Figure 10(a).

As seen in the figure, the transmittance and reflectance move complementarily. The resultant dynamic strain waveform is found as a decibel difference, as presented in Figure 10(b).

Figure 11 portrays a comparison between the measured and actual strain values obtained by strain gauge fixed on the same position of the cantilever. The difference between them is estimated as 2.2με in standard deviation.

Vibration frequency was 5Hz this time. However, the sampling speed can greater than 3000 samples /sec.

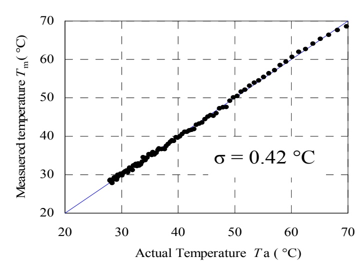

Figure 8. Accuracy of measured

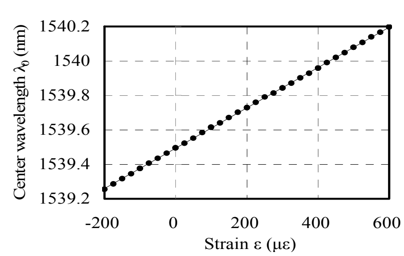

Figure 9. Strain characteristics of FBG

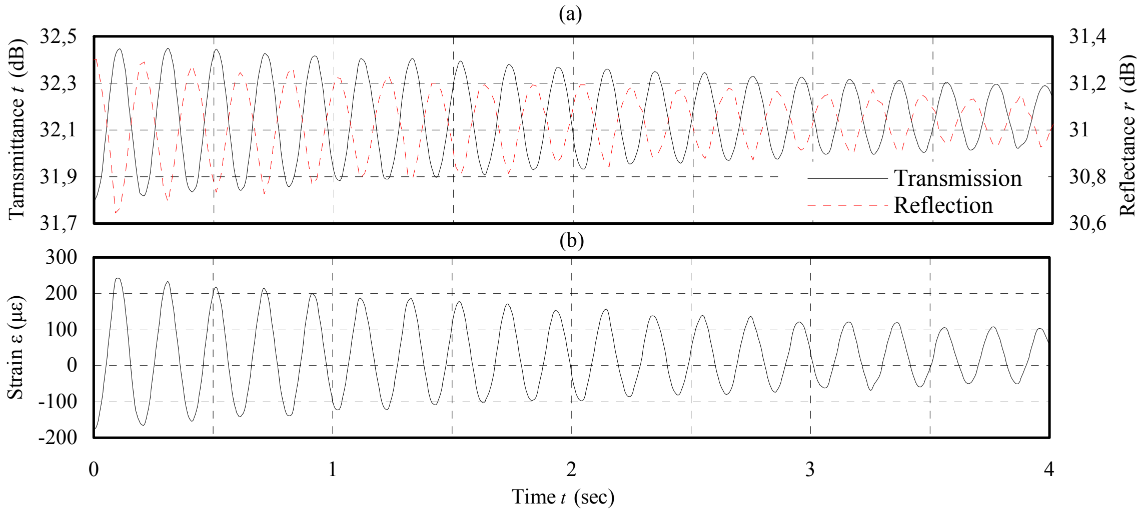

Figure 10. Response waveforms of strain

4. Summary and conclusions

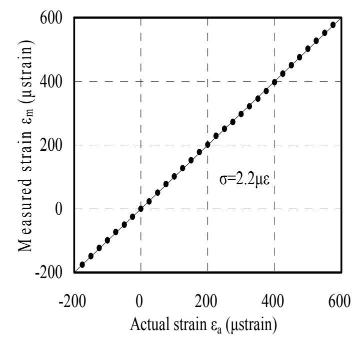

Figure 11. Accuracy of measured strain

A new time domain FBG interrogation system was proposed and then evaluated experimentally. The interrogation scheme is quite simple: the reflected light from FBGs on bus topology is led into a slope filter, of which transmitted and reflected lights are recombined with an amount of time difference. The impulse response is analyzed using a PN code correlation scheme. The ratio of the transmission and reflection peak levels, which can be estimated separately on a time axis, correspond to the Bragg wavelength shift of the FBG. This interrogation scheme is named DT3R, which has some remarkable features compared with existing schemes.

It can be produced at low-cost because its hardware configuration is quite simple: no expensive optical components are necessary.

Because of the push-pull ratiometric scheme between the transmittance and reflectance of a slope filter, the interrogation performance can be very robust and stable against any disturbance except for a spectrum shift of FBG reflections.

Bus topology is available: every FBG sensor can be identical. Moreover, a breakdown of any FBG branch has no effect on the other FBG's operations. For that reason, "hot swapping" of FBG sensors is possible, which makes the installation, maintenance, and operation of an interrogating system much more flexible.

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