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DEMONSTRATION OF TEMPERATURE MEASUREMENT DISTRIBUTED ON A BUILDING USING FIBER OPTIC SENSOR

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Abstrac: We have demonstrated a feasibility study of the fiber optic sensor to monitor the distributed temperature on a building construction. A fiber optic BOTDA sensor system, which has a capability of measuring the temperature distribution, attempted over several kilometers of long fiber paths. This simple fiber optic sensor system employs a laser diode and two electro-optic modulators. The optical fiber of the length of 1400 m was installed on the surfaces of the building. The change of the distributed temperature on the building construction was well measured by this fiber optic sensor. The temperature changed normally up to 4 °C through one day. Also, The temperature distribution of spring season was compared with that of early winter season.

Keywords: fiber optic BOTDA sensor, temperature

1. INTRODUCTION

Fiber optic sensors for the application of smart structures have many advantages in that they are easy to be embedded in large structures, very sensitive, and can give some distributed information of structures[1]. Especially, large structures are necessary to monitor the distributed temperature not only to compensate the temperature effects on the strain measurement but also to evaluate the structural integrity. Many researchers have been researched on the development of fiber optic distributed sensors. Sensor utilizing stimulated Brillouin scattering has the capability of measuring the absolute physical properties such as strain and temperature. Stimulated Brillouin scattering fiber optic sensor employs a pumping pulse and a CW probe beam running along a single mode optical fiber in opposite direction and detects the stimulated Brillouin back scattering signal amplified by two light beam and acoustic wave mixing [3,4]. In this method the frequency of CW probe beam differs from the pump beam by the amount of Brillouin frequency of optical fiber to enable the amplification and high intensity Brillouin scattering signal can be obtained [5].

In this study, we investigated the feasibility of the continuous measurement of the distributed temperature on a building. The fiber optic BOTDA sensor system was developed with one laser diode and two electro-optic modulators. The optical fiber of 1400 m was installed on the surfaces of the building. The surface temperature was measured continuously on the time interval of 1 hour.

2. OPERATION PRINCIPLE

When the power of optical signal, which propagates along the single-mode optical fiber, is larger than the Brillouin threshold power, the backward stimulated Brillouin scattering (SBS) signal is generated. SBS can be described as a parametric interaction among the incident light, the Stokes light, and an acoustic wave. The Brillouin frequency shift ν_B of the backward scattering light of the propagating light in an optical fiber is given by [7].

$$\nu_B = \frac{2n\nu_A}{\lambda_P} \tag{1}$$

where ν_A is the acoustic velocity, n is the effective refractive index, and λ_P is the pump wavelength. The spectral width $\Delta\nu_B$ of the Brillouin gain spectrum is related to the phonon lifetime by the following expression.

$$\Delta\nu_B = (\pi T_B)^{-1} \tag{2}$$

where T_B is the damping time of acoustic waves or the phonon lifetime.

A sensor using this stimulated Brillouin scattering of optical fiber is shown in Fig. 1. The pumping pulse light is launched at $Z = 0$ and propagates in the +Z direction, while the CW light is launched at the opposite fiber end ($Z = L$) and propagates in the –Z direction. In this configuration, the pump pulse generates backward Brillouin gain in a single-mode fiber [8]. The center frequency in the Brillouin gain bandwidth is downshifted from the pump frequency ν to the Stokes frequency $\nu - \nu_B$. When the CW light frequency is in resonance with the Stokes frequency, the CW light is amplified through Brillouin interaction with the pump pulse. The amplified CW light is passed through the 2×2 coupler and is detected by the time-resolved measurement.

The detected power P_d of the CW light that arrives at $Z = 0$ is time dependent. The CW light amplified at $Z = z$ in the fiber arrives at the fiber end ($Z = 0$) at time $t = 2z/\upsilon$ after the injection of the pumping pulse into the fiber. Here, υ is light velocity in the fiber. Therefore, the amplified CW light spreads over a period of $2L/\upsilon$ for a fiber of length L as shown in Fig. 2. The increment of the power of the CW light due to Brillouin interaction is approximately independent of the interaction point in the fiber. However, the CW light amplified at $Z = z$ is attenuated by the fiber between $Z = 0$ and $Z = z$. Therefore, the detected signal decays with time. The decay rate with fiber length yields the fiber attenuation coefficient at the CW light frequency α_{cw}.

Assuming that the pump pulse has a narrow pulse width W and peak power $P_p(0)$ the power detected at $Z = 0$ at time $t = 2z/\upsilon$ can be expressed as

$$P_d(z) = P_{cw}(L)\exp(-\alpha_{cw}L) + (g/A)(\upsilon W/2)P_{cw}(L)\exp(-\alpha_{cw}L)P_p(0)\exp(-\alpha_p z) \quad (3)$$

which is valid for a sufficiently low CW power $P_{cw}(L)$ [8]. In the above expression, g is the Brillouin gain factor, A is the effective cross section of the fiber, and α_p is optical fiber loss coefficient at the pump pulse wavelength. The Brillouin gain factor g has a well-known expression,

$$g = 2\pi n^2 p_{12}^2 \gamma / c\lambda^2 \rho \upsilon_a \Delta\nu_B \quad (4)$$

where n is refractive index of optical fiber, is photoelastic constant of the fiber, □ is wavelength of the optical source, ρ is the fiber density, υ_a is the acoustic velocity, $\Delta\nu_B$ is Brillouin gain bandwidth, and γ is coefficient of polarization. Table 1 summarizes the values of parameters used in the present calculation of Brillouin gain factor and the wavelength of optical source used in the present study is 1550 nm.

Brillouin frequency shift of an optical fiber increases linearly with temperature or strain,

$$\nu_B(T) = \nu_B(0)(1 + C_T T) \quad (5)$$

where T is temperature and CT is the coefficient of temperature, which is known to be 1 MHz/°C for conventional single mode optical fibers used at the 1.5 μm wavelength range of the optical communication. Based on the above discussions we calculated a simulation of a temperature effect as shown in Fig. 2.

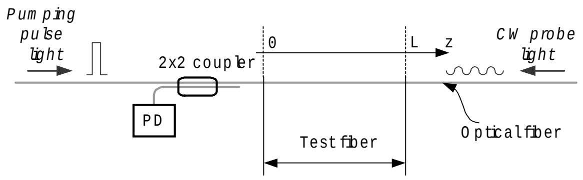


Fig. 1. Schematic diagram for the fiber optic BOTDA sensor operation.

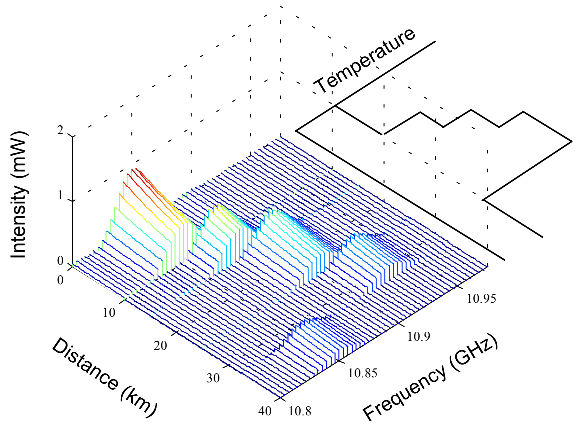


Fig. 2. Simulated signals for backward Brillouin scattering and strain effects.

In this figure, if the temperature effect is assumed to induce constant values along three sections of the fiber, then Brillouin frequency is shifted. The temperature effect is shown as a stepwise change of Brillouin frequency in this figure so that both the location and quantities of the temperature can be determined clearly.

3. FIBER INSTALLATION

The experimental setup for the pretest using the fiber optic BOTDA sensor is shown in Fig. 3. The system consists of an optical source assembly, two modulators, and the detector part. Optical source is composed of a DFB diode laser of its maximum output of 30 mW and normal bandwidth of 3 MHz, and an optical amplifier of its maximum output of 18 dBm. Pump pulse is generated at the electro-optic modulator 1 (EOM1, 2.5 Gb/sec modulation), which is driven by a pulse generator. Pump pulses of width, 50 ns, have been used in this experiment, which is corresponding the spatial resolution of 5 m. CW probe light is modulated at about 10 GHz by using EOM2 (20 Gb/sec) driven by a signal generator. Two 50:50 bidirectional fiber couplers were used as shown in Fig. 3. An optical detector was used to receive the backward Brillouin signal and its output data was transferred to PC by using high speed A/D converter. When CW pump light was launched into the fiber with no modulation and the frequency of CW probe light is swept over near the resonance, we obtained the Brillouin gain spectrum as shown in Fig. 4. From this measurement, we were able to deduce the fact that the Brillouin frequency shift of the present optical fiber is about 10.823 GHz and the bandwidth of spectrum at FWHM is about 13.4 MHz. The optical fiber was installed on the building as shown in Fig.

5. The total length of fiber was about 1400 m. The fiber status was verified by mini-OTDR as shown in Fig. 6.

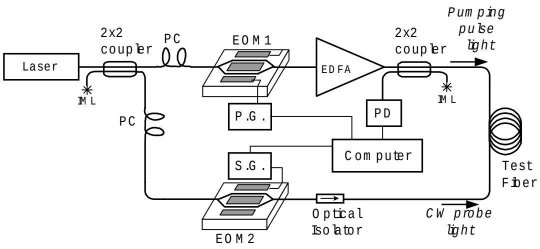
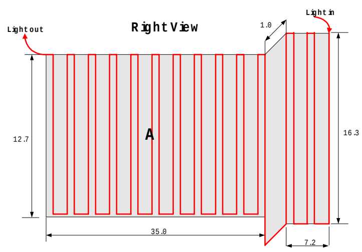
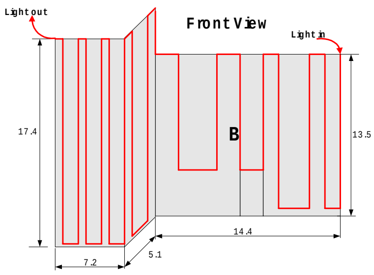


Fig. 3. A diagram of the fiber optic BOTDA sensor.

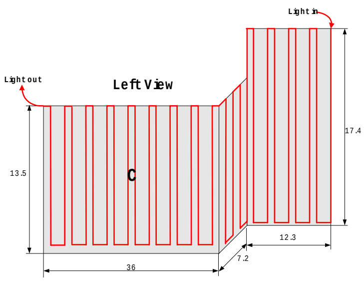
(a) Building with an optical fiber



(b) south surface



(c) west surface

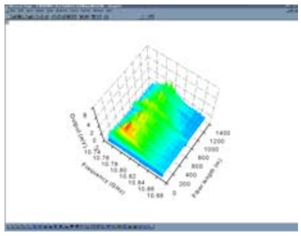


(d) north surface

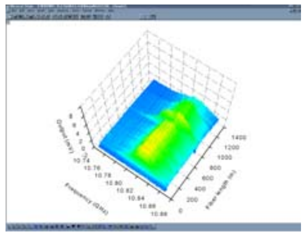
Fig. 5. Location of fiber installed on the building.

4. TEMPERATURE MEASUREMENT

The temperature was measured by the fiber optic BOTDA sensor with the data averages of 10000 times. The frequency of the CW probe beam was modulated between 10.75 GHz to 10.87 GHz as the 1 MHz step. So, the measuring time is about 25 minutes. The temperature was measured at the time interval of 1 hour. Brillouin gain spectra, which are acquired for one day, were shown in Fig. 7. The frequency at maximum gain is correlated with the temperature by Eq. 5. In this figure, we can show the temperature changes of about 10 °C.



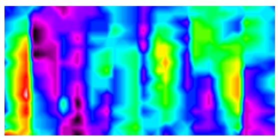
(a) At night



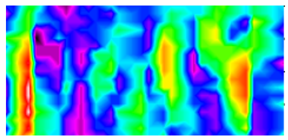
(b) At noon

Fig. 7. Brillouin gain spectra at one day.

Also, Fig. 8, Fig. 9, and Fig. 10 show the distribution of temperature on the surfaces of the building at spring. In these figures, the temperature distributions at night were less fluctuated than that at noon. So, we can calculate the temperature differences between the reference distribution (temperature distribution at night) and the temporary distribution (temperature distribution at noon). It can be expected that the abnormal change of the temperature distribution is to be found to determine the abnormal status of the building from these difference distributions.

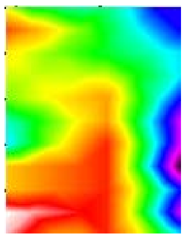


(a) At noon
(Min: 18 Max: 29 Avr: 22)

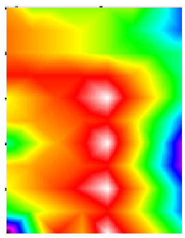


(b) At night
(Min: 13 Max: 24 Avr: 17)

Fig. 8. South surface (A surface in Fig. 5).

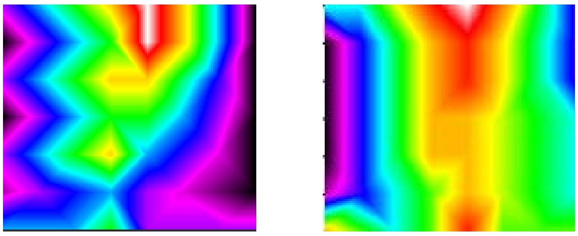


(a) At noon
(Min: 19 Max: 27 Avr: 23)



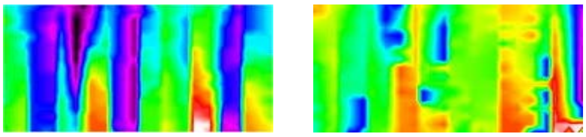
(b) At night
(Min: 15 Max: 21 Avr: 18)

Fig. 9. west surface (B surface in Fig. 5).



(a) At noon (b) At night
(Min: 19 Max: 25 Avr: 21) (Min: 13 Max: 18 Avr: 15)
Fig. 10. North surface (C surface in Fig. 5).

The temperature at was distributed on the surfaces at the time of early winter as shown in Fig. 11. In these figures, the temperature at night was less fluctuated than that at noon as same as the distribution at spring. However, the average temperature has some differences between spring distribution and winter distribution.



(a) At noon (b) At night
(Min: 9 Max: 18 Avr: 12) (Min: -16 Max: 9 Avr: -2)
Fig. 11. South surface (A surface in Fig. 5).

5. CONCLUSIONS

The feasibility of the continuous measurement of the distributed temperature on a building was investigated. The fiber optic BOTDA sensor system was developed with one laser diode and two electro-optic modulators. The optical fiber of 1400 m was installed on the surfaces of the building. The surface temperature was measured continuously on the time interval of 1 hour. The temperature differences can give the useful information to determine the structural status of a building. The temperature changed normally up to 4 °C through one day. According to the change of season, the averaged temperature had changed about some tens of degree.

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