Journal of the Optical Society of Korea, Vol. 8, No. 4, December 2004, pp. 168-173

Temperature Compensation of a Fiber Optic Strain Sensor Based on Brillouin Scattering

Seok-Beom Cho and Jung-Ju Lee*

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701, KOREA

Il-Bum Kwon

Center for Environment and Safety Measurement, Korea Research Institute of Standards and Science, P. O. Box 102, Yuseong-gu, Daejeon 305-600, KOREA

(Received July 20, 2004)

Brillouin scattering-based fiber optic sensors are useful to measure strain or temperature in a distributed manner. Since the Brillouin frequency of an optical fiber depends on both the strain and temperature, it is very important to know whether the Brillouin frequency shift is caused by the strain change or temperature change. This article presents a temperature compensation technique of a Brillouin scattering-based fiber optic strain sensor. Both the changes of the Brillouin frequency and the Brillouin gain power is observed for the temperature compensation using a BOTDA sensor system. Experimental results showed that the temperature compensated strain values were highly consistent with actual strain values.

OCIS codes : 060.2370, 290.5830

I. INTRODUCTION

Stimulated Brillouin scattering (SBS) has been extensively studied in recent years in optical fiber communications and in distributed optical fiber sensors [1,2]. Brillouin scattering refers to the scattering of a lightwave by an acoustic wave [3]. When this process occurs in an optical fiber, the backscattered light suffers a frequency shift known as a Brillouin frequency shift, which is dependant on the temperature and strain environment of the fiber. This process has been proven useful as a sensing mechanism for distributed optical fiber sensors [4]. Horiguchi and Tateda demonstrated a new technique when they used a counter-propagating pulsed lightwave and a continuous Stokes probe wave and estimated the fiber loss from the amplification of the Stokes wave by SBS. They also carried out a theoretical investigation of this method called Brillouin optical-fiber time-domain analysis (BOTDA) [5].

In a configuration of BOTDA, two counter-propagating lightwaves interact with an acoustic wave. The processes of interaction between these waves are characterized by the Brillouin gain factor $g_B(z, \nu)$, z is the location along the fiber and ν is the frequency difference between the two lightwaves. The gain is maximum for $\nu = \nu_B$, called the Brillouin frequency, and is determined by monitoring the dependence of the power transfer from one lightwave to the other on ν. Spatial resolution is achieved by using a pulsed and continuous-wave (CW) light source. The spatial resolution is equal to the interaction length between pulse and CW lights, which is half the pulse length. If the frequency of the CW lightwave is higher than that of the pulse, power is transferred from the CW light to the pulse. If the CW light has a lower frequency, the power transfer is from the pulse to the CW light. The first configuration is referred to as the loss process since the CW light loses power, the second as the gain process because of the CW power gain [6].

The measurement of temperature or strain change along an optical fiber is usually made by extracting the Brillouin gain/loss spectrum for each sensing section along the fiber. Each spectrum is produced by measuring the power of the transmitted CW light while the frequency difference between the two lightwaves is stepped. The Brillouin frequency shift, at a specified section, is evaluated as the pump-probe frequency difference at which the maximum amplification or depletion occurs.

A merit of linear dependence of Brillouin frequency shift on the strain and temperature change is that Brillouin-based sensor can be applied to both the strain sensor and temperature sensor. On the other hand, a disadvantage is that a Brillouin-based sensor can be affected by the change of temperature, and a temperature senor can be affected by the strain change. For a structural health monitoring by using a Brillouin-based fiber optic strain sensor, an optical fiber can be attached to the surface of a structure to measure a strain or a strain distribution of the structure. However, the Brillouin frequency shift caused by a temperature change of the structure can be misinterpreted as a strain change for the Brillouin-based strain sensor, and this is why the strain sensor needs a temperature compensation to measure the actual strain change of the structure. One of the simplest temperature compensation techniques of the Brillouin-based optical fiber strain sensor is to use a reference fiber as a temperature sensor [7]. The reference fiber is not attached to the structure to measure only the temperature change, and the temperature change measured through the reference temperature sensor can be considered for the temperature compensation of the strain sensor. However, because the temperature of the reference fiber which is not attached to the structure is, generally, not equal to the temperature of the structure, heat transfer between the structure and the reference fiber must be considered. So, the temperature compensation by using a reference temperature sensor may be rather complicated because the heat transfer is dependent on many parameters such as heat transfer medium, heat source and contact between the structure and the fiber.

In this paper, a temperature compensation technique of a Brillouin-based fiber optic strain sensor is presented. The maximum power of Brillouin gain spectrum (BGS) as well as Brillouin frequency was observed for the temperature compensation. Experiments were conducted with an optical fiber which is under both the strain and temperature changes.

II. THEORY

The solution of the steady state SBS can be described by the two simple differential equations for scattering light and pump light fields and is expressed as

$$\frac{dI_{CW}}{dz} = -g_B I_L I_{CW} + \alpha I_{CW} \quad (1)$$

$$\frac{dI_L}{dz} = -g_B I_L I_{CW} - \alpha I_L \quad (2)$$

where α is the fiber absorption coefficient, I_L is the intensity of the incident light, I_{CW} is the intensity of the scattering light [8,9]. The parameter g_B is called the Brillouin gain factor and is given by

$$g_B(\nu) = g_0^e \frac{(\Delta\nu_B/2)^2}{(\nu-\nu_B)^2 + (\Delta\nu_B/2)^2} + g_0^a \frac{\Delta\nu_B(\nu-\nu_B)}{(\nu-\nu_B)^2 + (\Delta\nu_B/2)^2} \quad (3)$$

where ν is the frequency difference between the incident light and scattering light, $\Delta\nu_B$ is the full width at half maximum (FWHM) Brillouin gain linewidth. The BGS peaks at the Brillouin frequency ν_B. The gain factor consists of two parts, an electrostrictive contribution and an absorptive contribution. The electrostrictive gain factor has a Lorentzian frequency dependency; the maximum value is given by the equation

$$g_0^e = \frac{2\pi(\nu_s)^2(\gamma^e)^2}{c^3 n\rho_0 V_a \Delta\nu_B} \quad (4)$$

where ν_s is the frequency of the scattered light, γ^e is the electrostrictive coupling coefficient, ρ_0 is the density, and c is the vacuum velocity of light [3].

The second contribution to the gain factor is caused by the linear absorption of light and by the resultant heating of the medium. The maximum gain is given by the equation

$$g_0^a = \frac{\pi(\nu_s)^2\gamma^e\gamma^a}{2c^3 n\rho_0 V_a \Delta\nu_B} \quad (5)$$

where γ^a is called the absorptive coupling coefficient [3].

The relation between ν_B and strain/temperature can be expressed as

$$\nu_B(\Delta\varepsilon, \Delta T) = \nu_{B0} + C_\varepsilon \Delta\varepsilon + C_T \Delta T \quad (6)$$

where, ν_{B0} is the Brillouin frequency for a fixed strain and temperature, $\Delta\varepsilon$ and ΔT are the changes in strain and temperature, and C_ε and C_T are the Brillouin frequency shift/strain and shift/temperature coefficients [10]. Note that temperature changes along an optical fiber also induce the Brillouin frequency shift due to thermal strain. However, the contribution of thermal strain to the coefficient C_ε can be neglected because the coefficient of thermal expansion is very small compared to the coefficient C_ε.

The C_ε and C_T depend on the wavelength of the incident light and on the optical fiber through which the incident light propagates, and they must be measured experimentally to measure the strain or temperature of the optical fiber for the given test fiber and sensor system. Because both of the strain and temperature change induce the Brillouin frequency shift, for a Brillouin-based strain sensor, the Brillouin frequency shift due to the temperature change can be misinterpreted as a strain change. However, fortunately, there is a difference between the changes of the BGS characteristics caused by the change of the two parameters. While the strain change of the fiber causes only the shift of the Brillouin frequency, the temperature change of the fiber induces not only the Brillouin frequency shift but also the change of the Brillouin gain power. So, the temperature compensation can be made through the monitoring of the variation of the Brillouin gain power.

The strain change $\Delta\varepsilon$ can be derived from the equation (6) and can be expressed as

$$\Delta\varepsilon = \frac{1}{C_\varepsilon}(\nu_B(\Delta\varepsilon,\Delta T)-\nu_{B0}) - \frac{C_T}{C_\varepsilon}\Delta T = \frac{1}{C_\varepsilon}(\nu_B(\Delta\varepsilon,\Delta T)-\nu_{B0}) - \frac{C_T}{C_\varepsilon}\frac{1}{C_{PT}}\Delta P \tag{7}$$

with

$$C_{PT} \equiv \frac{\Delta P}{\Delta T} \tag{8}$$

where, ΔP is the variation of the maximum Brillouin gain power, and C_{PT} represents the rate of increase of the Brillouin gain power per increase of the temperature. The value of C_{PT} can be obtained experimentally, and it is dependent on the width of the launched pulse.

III. EXPERIMENTAL SETUP

The pump and probe configuration shown in Fig. 1 was used to measure the Brillouin gain spectrum. The output of DFB LD at 1553 nm is first split by a coupler. One output of the coupler is amplitude-modulated by a 2.5 Gb/s electro-optic modulator (EOM) to generate pulses. This pump light is amplified by Erbium-doped fiber amplifier (EDFA) and is launched into a test fiber. The other output of the coupler is frequency-modulated by a 10 Gb/s EOM and is launched into an opposite end of the test fiber. When a single frequency lightwave is modulated at a fixed frequency f_m using an external modulator, the modulation creates new frequency lines in the optical spectrum, the so-called modulation sidebands. For pure intensity modulation, the obtained spectrum is symmetrical around the incident lightwave frequency ν_0, and the new lines are equally spaced in the frequency by f_m. When the modulation frequency f_m equals the Brillouin frequency $\nu_0 - f_m$, the lightwave at frequency ν_B, which is the sidebands, can interact with the incident pump lightwave at frequency ν_0 through the Brillouin gain process. On the contrary, the lightwave at frequency ν_0+f_m, the upper sideband, amplifies the pump light through the Brillouin loss process [11]. The BGS can be scanned by sweeping the frequency of a frequency sweeper. In-line isolators were inserted inside the loop to avoid interference, and polarization controllers were used to control the polarization states of the interacting waves.

The BGS was measured by sweeping the modulation frequency f_m in the vicinity of the Brillouin frequency ν_B and by detecting the optical power of the probe light using a photo receiver. The output voltage signals of the photo receiver were acquired by a data acquisition board at a 100 MHz sampling rate, which corresponds to a 1 m distance resolution.

The probe light signal detected by a photo detector is classified into two power signals such as the power detected before the launch of the pulse-top and the power detected after the launch of the pulse-top. Hence, the net Brillouin gain amplified by a contribution of the pulse-top can be obtained by subtracting the power detected before the launch of the pulse-top from the power detected after the launch of the pulse-top. Because the power of the frequency-modulated probe light showed some variation for the modulation frequency f_m, the net Brillouin gain obtained through the interaction with pulse-top was normalized through dividing by the probe light power at the given modulation frequency.

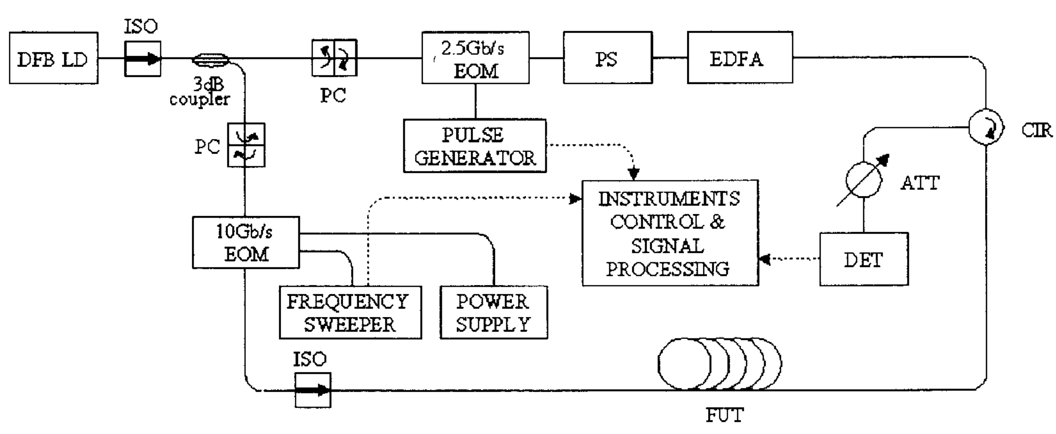

FIG. 1. Experimental setup for Brillouin gain spectrum measurements. (ISO = isolator, PC = polarization controller, PS = polarization scrambler, DET = detector, ATT = attenuator, CIR = circulator.)

IV. EXPERIMENTAL RESULTS

The Brillouin strain coefficient is needed to obtain the strain values from the measured Brillouin frequencies. For a measurement of the strain coefficient, the Brillouin frequency shift for different strain values was observed at fixed temperature. For a dispersion-shifted single mode fiber (DSF), the strain coefficient of 467 MHz/%, as shown in Fig. 2, was obtained.

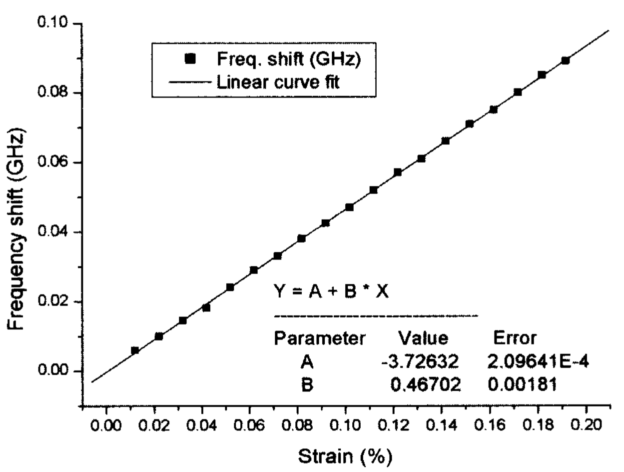

FIG. 2. Brillouin strain coefficient of a DSF.

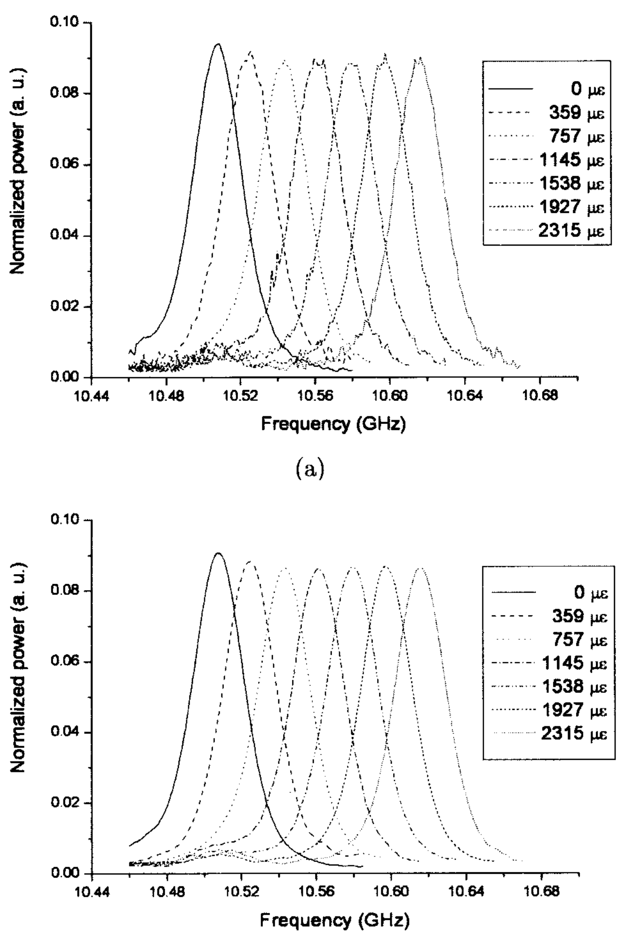

FIG. 3. BGS's with the applied strain change. (a) raw BGS's. (b) smoothed BGS's.

The BGS's for different strain values were measured to observe the change of the BGS characteristics due to the changes of the strain. A 200-meter-long DSF was used for the measurement, the strained section of the fiber was about 6 meters in length, the width of the launched pulse was 50 ns, and the pulse-top power was 500 mW. Figure 3 shows the BGS's for the different strain values of the fiber. The CW Brillouin threshold power for a 2-km-long DSF corresponds to about 0.2 mW. Because the power of pulse-base was under 0.1 mW, and because the length of the DSF was about 200 m, the pulse-base effect on the measured BGS can be neglected.

Generally, the signal to noise ratio (SNR) of the BGS depends on the width and the power of the launched pulse. Because the SNR of the Brillouin gain signal obtained by the injection of the 50 ns pulses was comparatively low, as shown in Fig. 3 (a), if the maximum Brillouin gain power and its corresponding frequency are taken as the maximum Brillouin gain power and Brillouin frequency there would be a relative big errors in their values. To avoid the errors caused by the low SNR, the raw BGS was smoothed by the signal processing and the Brillouin frequency and the maximum Brillouin gain power were obtained from the result of the second order polynomial curve fitting of the smoothed BGS. An example of the smoothed BGS is shown in Fig. 4.

As the strain of the fiber increases, as shown in Fig. 3, the Brillouin frequency increases without change of the peak power. However, the maximum Brillouin gain power gradually decreases in the region from the unperturbed state to the strain state which causes smaller frequency shift than Brillouin linewidth. The decrease of the gain power in that region is thought to be a characteristic that appears when an optical fiber is mechanically elongated, and it is thought that

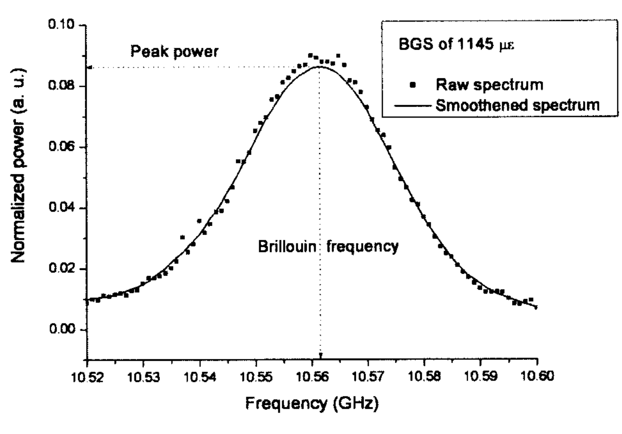

FIG. 4. Smoothing of BGS.

the variation of the power must be considered for the temperature compensation of the strain in that region.

A part of 200-meter-long DSF was installed into a thermal chamber and the BGS's for different temperature values were measured to observe the change of the BGS characteristics due to the change of the fiber temperature. The installed section was about 30 meters in length. Figure 5 and 6 show the results of the measurement. The Brillouin temperature coefficient of $C_T = 0.99$ MHz/℃ was obtained from the measurement, and the values of C_{PT} are shown in Fig. 6.

To verify the effectiveness of the temperature compensation technique presented in this paper, a section of a DSF was strained with and without heat, the BGS's were measured, and the values of the maximum Brillouin gain power as well as the Brillouin frequency for the temperature compensation. Figure 7 shows the translation device used to elongate the optical fiber. The strained fiber section was about 6 meters in length, and 50 ns pulses were launched for the measurement.

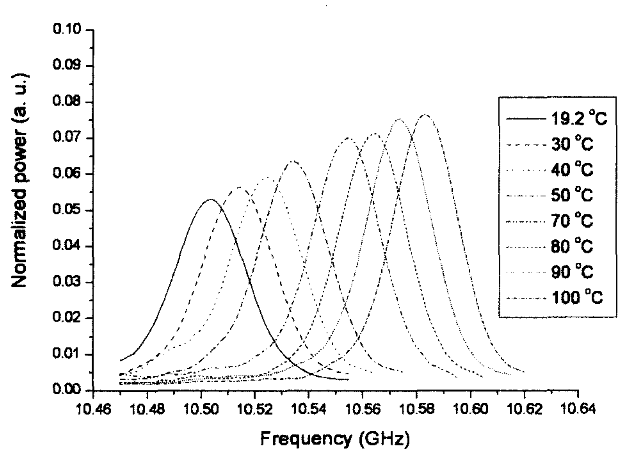

FIG. 5. Smoothed BGS's of 50 ns pulses for different temperature.

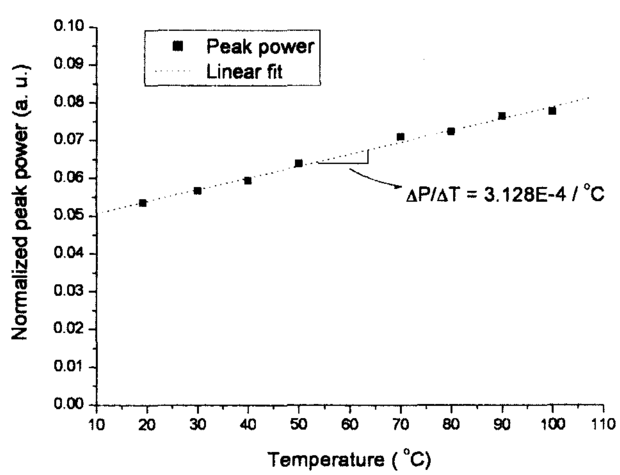

FIG. 6. Brillouin gain power increase due to the increase of fiber temperature.

Figure 8 shows the measured BGS's. The BGS's of unperturbed state (S 0) and three strain states, S 1, S 2 and S 3, were measured with fixed room temperature of 22℃. After the measurement with fixed temperature, the strained section was heated by 8 infrared ray heaters and the BGS's were measured for S 4 and S 5; the mechanical strain of S 4 equals that of S 2, and the mechanical strain of S 5 is equals to that of S 3.

The measured strain values of S 1, S 2 and S 3 were 764 $\mu\varepsilon$, 1158 $\mu\varepsilon$ and 1548 $\mu\varepsilon$ respectively. The increases of Brillouin frequency and Brillouin gain power due to the increase of temperature were observed at the state of S 4 (S 2 + heat) and S 5 (S 3 + heat). The values of the temperature change of the two strain states, S 4 and S 5, were 6.1℃ and 8.4℃, which were obtained by the Brillouin frequency shift and Brillouin temperature coefficient. The increments of the maximum Brillouin gain power of S 4 and S 5 correspond to 0.00155 and 0.00231 respectively. If the Brillouin frequencies of S 4 and S 5 were directly converted into the strain values without temperature compensation, the strain values of the two states correspond to 1290 $\mu\varepsilon$ and 1730 $\mu\varepsilon$ respectively, and there would be errors of 132 $\mu\varepsilon$ and 182 $\mu\varepsilon$, respectively, when compared to the actual strain values of S 4 and S 5. In this case, Equation (7) can be applied for the temperature compensation with consideration of the Brillouin gain increment, the temperature compensated strains of S 4 and S 5 correspond to 1186 $\mu\varepsilon$ and 1574 me respectively, and the errors between the actual

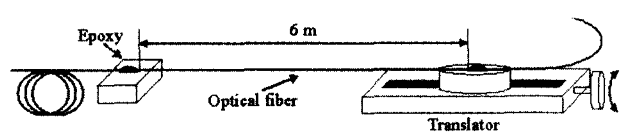

FIG. 7. Configuration of a fiber elongation device.

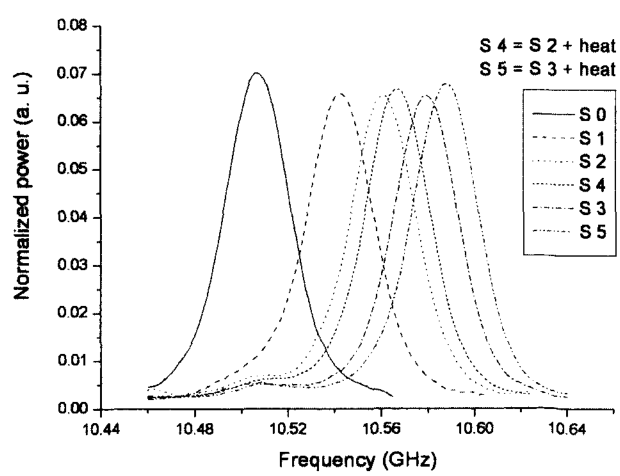

FIG. 8. Smoothed BGS's of 50 ns pulses for different strain values with and without heating.

TABLE 1. Strain values of 6-m-long strained fiber section.

	S 2	S 2 + heat	S 3	S 3 + heat
ν_B (GHz)	10.5612	10.5674	10.5794	10.5879
P_{max} (a. u.)	0.065962	0.067506	0.065954	0.068267
Strain without T.C ($\mu\varepsilon$)	1158	1290	1548	1730
	Error: 132		Error: 182	
Strain with T.C ($\mu\varepsilon$)	1158	1186	1548	1574
	Error: 28		Error: 26	

P_{max}: Brillouin gain peak power, T.C: Temperature Compensation.

strain and temperature compensated strain don't exceed 28 $\mu\varepsilon$. The summary of these data is shown in Table 1.

V. CONCLUSION

A temperature compensation technique of a Brillouin-based fiber optic strain sensor was demonstrated through the tension test of an optical fiber with temperature change. In the presented technique, not only the Brillouin frequency but also the maximum Brillouin gain power was observed for the temperature compensation. Since the Brillouin frequency of an optical fiber depends on both the strain and temperature of the optical fiber, the temperature compensation must be conducted for the fiber optic strain sensor to obtain an actual strain value of the fiber regardless of the temperature change. The strain errors between actual strain and temperature compensated strain were under 28 me. It is thought that the higher SNR of the BGS can decrease the strain errors. The presented technique which utilizes the variation of the maximum Brillouin gain power for the temperature compensation is a comparative simple technique, but it needs, as is the often case with a Brillouin-based optical fiber sensor, stable powers of launched lights because of the dependence of the compensation efficiency on the power and SNR of measured BGS. The advantage of the presented technique is that a reference fiber is not needed for the temperature compensation, and it is, especially, useful for strain monitoring of the structure which needs to embed the fiber into the structure.

ACKNOWLEDGEMENT

This study has been supported by the Korea Science and Engineering Foundation through the Human-friendly Welfare Robot System Engineering Research Center (HWRS-ERC) at KAIST in South Korea. One of the authors has been supported by the National Research Laboratory Program of Ministry of Science and Technology.

*Corresponding author : jjlee@mail.kaist.ac.kr

REFERENCES

[1] C. L. Tang, "Saturation and spectral characteristics of the Stokes emission in the stimulated Brillouin process," *J. Appl. Phys.*, vol. 37, no. 8, pp. 2945-2955, 1966.

[2] T. Horiguchi and M. Tateda, "Optical fiber attenuation investigation using stimulated Brillouin scattering between a pulse and a continuous wave," *Opt. Lett.*, vol. 14, no. 8, pp. 408-410, 1989.

[3] W. Kaiser, M. Maier, Laser Handbook, F. T. Arecchi, and E. O. Schulz-Dubois, Eds. (North-Holland, Amsterdam, 1972), vol. 2, pp. 1077-1150.

[4] T. Horiguchi, T. Kurashima, and M. Tateda, "Tensile strain dependence of Brillouin frequency shift in silica optical fibers," *IEEE Photon. Technol. Lett.*, vol. 1, no. 5, pp. 107-108, 1899.

[5] T. Horiguchi and M. Tateda, "BOTDA-Nondestructive measurement of single-mode optical fiber attenuation characteristics using Brillouin interaction: Theory," *J. Lightwave Technol*, vol. 7, no. 8, pp. 1170-1176, 1989.

[6] T. Horiguchi, K. Shimizu, T. Kurashima, M. Tateda, and Y. Koyamada, "Development of a distributed sensing technique using Brillouin scattering," *J. Lightwave Technol*, vol. 13, no. 7, pp. 1296-1302, 1995.

[7] I. B. Kwon, C. Y. Kim, S. B. Cho, and J. J. Lee, "Temperature compensation of a strain sensing signal from a fiber optic Brillouin optical time domain analysis sensor," *J. Opt. Soc. Korea*, vol. 7, no. 2, pp. 106-112, 2003.

[8] G. P. Agrawal, Nonlinear Fiber Optics, (Academic Press, Boston, 1989), pp. 370-403.

[9] L. Chen, X. Bao, "Analytical and numerical solutions for steady state stimulated Brillouin scattering in a single-mode fiber," *Optics Comm.* Vol. 152, pp. 65-70, 1998.

[10] R. Bernini, A. Minardo, and L. Zeni, "Reconstruction technique for stimulated Brillouin scattering distributed fiber-optic sensors," *Opt. Eng.*, vol. 41, no. 9, pp. 2186-2194, 2002.

[11] M. Niklès, L. Thévenaz, and P. A. Robert, "Brillouin gain spectrim characterization in single-mode optical fibers," *J. lightwave Technol.*, vol. 15, no. 10, pp. 1842-1851, 1997.