Analysis of Brillouin Frequency Shift in Distributed Optical Fiber Sensor System for Strain and Temperature Monitoring

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Abstract: In this paper, we have analyzed Brillouin frequency shift (BFS) in single mode silica optical fiber. The BFS is analyzed in conventional Brillouin optical time domain analysis (BOTDA) at operating wavelength of 1550 nm by a pump-probe technique. The effects of strain and temperature on BFS are fully characterized. We found that, the BFS change of 0.06 MHz/μ-strain and 1.26 MHz/ºC, respectively. The BFS changes in Brillouin gain and Brillouin loss mechanism have been analyzed. In addition, we also presented Brillouin linewidth and peak gain variations of Brillouin gain spectrum with various temperature and strain values. The results demonstrate, the BFS have a strong linear relationship with strain and temperature along the sensing fiber.

1 INTRODUCTION

In Brillouin based distributed optical fiber sensors, the basic principle for measuring strain and temperature is based on the frequency difference between the incident light and the backscattered Brillouin light at every point along the fiber. The distributed optical fiber sensor [DOFS] based on Brillouin scattering is an attractive technique to monitor the strain and temperature simultaneously and independently. Compared to conventional optical sensors such as fiber Bragg grating (FBG) and Raman scattering based sensors, the Brillouin based DOFS offers, capability of monitoring both strain and temperature with high spatial resolution and sensing range over tens of kilometers. As FBG sensors are point type sensors, they are just good at monitoring a specific location of interest. Raman based distributed sensors are intensity based sensors and only sensitive to the temperature, and also its receiver has most complex structure compared to the other fiber sensor techniques (Bao and Chen, 2011). DOFS based on Brillouin scattering techniques offers cost-effective and structural health monitoring applications such as rail-track monitoring, pipeline, bridge, dam, power line, slopes and boarder security monitoring in real-time. Brillouin sensors are also an excellent for corrosion and micro-crack detection in large scale structures (Agarwal, 2000).

For simultaneous monitoring of strain and temperature, the Brillouin optical time domain reflectometry (BOTDR) (Kurashima et al., 1990) based on spontaneous Brillouin scattering and the Brillouin optical time domain analysis (BOTDA) (Horiguchi et al., 1993) based on stimulated Brillouin scattering (SBS) are introduced. The BOTDR features with simple implementation schemes (Maughan et al., 2001), while BOTDA allows higher sensing range and high resolution in the measurement, but requires access to the both ends of the same fiber (Minardo et al., 2003). The BOTDA is more dominant technique as it uses SBS method through pump beam and counter propagating probe beam. Due to the strong backscattered signal strength, BOTDA system has an accurate strain and temperature measurements and longer sensing range compared to BOTDR technology (Kurashima et al., 1993). Distributed strain and temperature monitoring both in BOTDR and BOTDA systems are based on Brillouin frequency shift (BFS), the BFS changes linearly with both strain and temperature along the sensing fiber.

In this paper, we focus on BFS in Brillouin based DOFS system. In particular, the BFS is investigated in conventional BOTDA. In section 2, a short description of Brillouin sensing principle in BOTDR and BOTDA is discussed, and the BFS is described in Brillouin gain/loss mechanism in section 3. In section 4, the BFS, Brillouin linewidth and peak gain

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variations for different strain and temperature values are analyzed and demonstrated. Finally, the BFS dependence on micro-strain has been investigated and reported in section 5.

2 BRILLOUIN SENSING PRINCIPLE IN DISTRIBUTED OPTICAL FIBER SENSOR

When a light beam injected into the optical fiber, a small part of the light is backscattered due to the Brillouin interaction between input pump photons and acoustic phonons within the fiber. Because of this interaction, the injected pump beam frequency is down shifted (stokes) and up shifted (anti-stokes). The down shifted frequency linearly changes with an acoustic wave frequency within the sensing fiber. During this inelastic scattering process, the energy is shifted or converted. This affiliated frequency shift is known as BFS. The BOTDR system has a simple implementation setup, as it requires access to the only at one end of the fiber, as shown in Figure 1(a). BOTDR system has a weak backscattered Brillouin signal, thus the sensing range is limited compared to the BOTDA.

The simplified BOTDA measurement setup is shown in Figure 1(b), where the pulse light (also known as pump) is propagate through one end of the fiber, while a counter propagating continuous wave (also known as probe) is injected at the other end of the fiber. The BOTDA system utilizes the amplified Brillouin scattering within the fiber, when the spontaneous Brillouin scattering light interacts with the counter propagating continues wave probe beam. The frequency difference between the pump beam and probe beam modulates the refractive index of the fiber via electrostriction process, and then excites an acoustic wave (phonons), which moves same direction as pump beam (Agarwal, 2008). As a result, small fraction of pump light is backscattered into the SBS light. The SBS light frequency is downshifted by the stokes frequency, this frequency shift is BFS, and described as,

$$v_B = \frac{2nv_a}{\lambda_p} \tag{1}$$

where n is the refractive index, v_a is the acoustic velocity and λ_p is the pump wavelength of the fiber. The relationship between the strain change $(\Delta\varepsilon)$, temperature change (ΔT) and BFS change (Δv_B) is described as (Bao and Chen, 2012),

$$\Delta v_B(\varepsilon / T) = C_T \Delta T + C_\varepsilon \Delta\varepsilon \tag{2}$$

where $C_T = (1.26\ \text{MHz}/^o\text{C})$ and $C_\varepsilon = (0.06\ \text{MHz}/\mu\text{-strain})$ are the temperature and strain coefficients at 1550 nm for a single mode silica fiber (Thévenaz, 2010). These coefficients changes slightly for different types of single mode fibers. Whenever the temperature and strain changes, the Brillouin peak frequency will shift linearly. As stated before, BOTDA is the most preferred technique compared to BOTDR, therefore, in this paper all measurements has done in conventional BOTDA system. Figure 2 is a measured Brillouin gain spectrum (BGS) with a central frequency of 12.90 GHz. The BGS in standard single mode silica fiber is perfectly fit with Lorentz profile shape. The fitted Lorentz curve reveals the spectrum peak frequency, gain and linewidth at full width at half maximum The BGS spectrum varies from Lorentz shape to Gaussian shape, if the input power greater than the threshold value (Bao and Chen, 2012). From the BGS

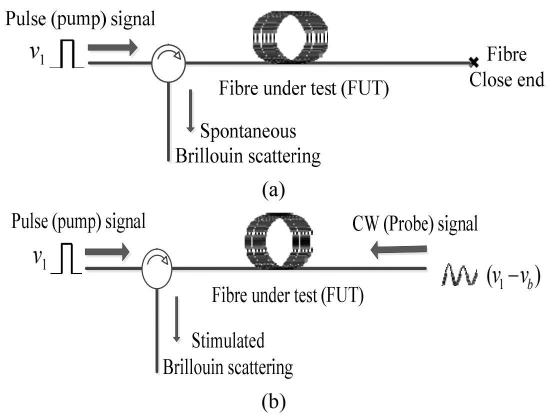

Figure 1: A simplified measurement setup of (a) BOTDR and (b) BOTDA.

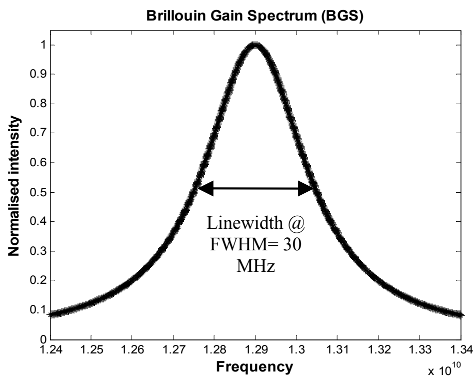

Figure 2: Brillouin gain spectrum (BGS) of single mode fiber with Brillouin frequency (v_B) = 12.90 GHz and spectral linewidth (FWHM) = 30 MHz at room temperature and strain free.

spectrum for each point along the fiber, we can calculate strain/temperature along the sensing fiber based on the time resolved measurement.

3 BFS CHANGES IN BRILLOUIN GAIN AND BRILLOUIN LOSS MECHANISM

In BOTDA system, a short pump pulse (≥10 ns) is injected into one end of the fiber, while a continuous wave (CW) probe beam is injected at another end of the same fiber. From the quantum mechanism in optical fiber, the pump wave and acoustic phonon creates a Brillouin scattering at the same time. If the CW probe beam set at Brillouin stokes frequency $(v_o - f_m)$, the energy transferred from the pump wave to stokes wave, then the CW stokes beam experiences Brillouin gain. If the CW probe beam set at anti-stokes frequency $(v_o + f_m)$, then the energy transferred from the probe wave to pump wave, then CW anti-stokes wave experiences Brillouin loss, respectively (Smith, 1999). In this mechanism the pump wave acts as a donor and receiver for both Brillouin gain and Brillouin loss mechanism. The schematic representation of the energy transfer process between pump wave and probe stokes and anti-stokes wave is illustrated in Figure 3.

The BGS of single mode silica fiber has a BFS of 12.90 GHz, at strain free and ambient room temperature. The 0.2% (2000 με) tensile strain is applied on sensing fiber; then the BFS is shifted to 13.02 GHz as shown in Figure 4. In this mechanism, the CW signal is in stokes frequency $(v_o - f_m)$ than anti-stokes frequency $(v_o + f_m)$, so that the CW signal experiences gain, while the BFS is shifted with applied 0.2% strain. The strain induced BFS is equivalent to 120 MHz (Lalam et al., 2015). In this process, the energy transferred from pump to probe beam, therefore, the pump acts as a donor while probe stokes wave acts as a receiver in energy flow mechanism. The pump and stokes beam, which are propagating in opposite direction is assumed to be linearly polarized along their propagation directions. If we use polarization maintaining fiber, the states of polarization (SOP) of the two beams will coincide, otherwise, polarization noise will distort the backscattered traces. This noise significantly leads to BFS measurement error. Therefore, SOP plays an important role in DOFS system, therefore polarization scrambler (PS) is employed to maintain

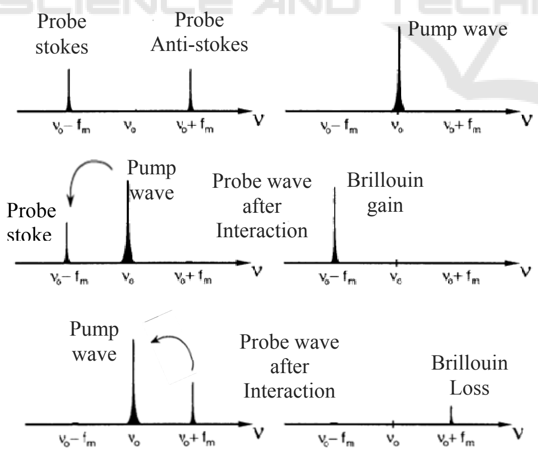

Figure 3: Schematic diagram of Brillouin gain and Brillouin loss mechanism (a) Probe wave with stokes $(v_o - f_m)$, anti-stokes $(v_o + f_m)$ and pump wave with frequency (v_o) before interaction. (b) Stokes wave set as probe wave (Brillouin gain), probe wave experiences gain after interaction with pump wave. (c) Anti-stokes wave set as probe wave (Brillouin loss), probe wave experiences loss after interaction with pump wave.

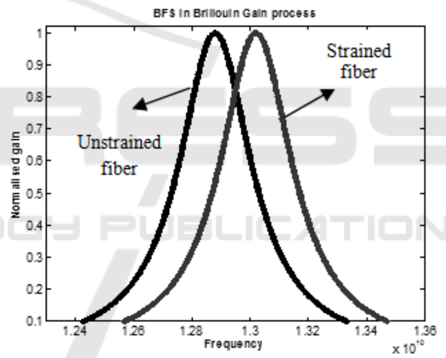

Figure 4: Brillouin frequency shift obtained for 0.2% tensile strain to the fiber in Brillouin gain mechanism.

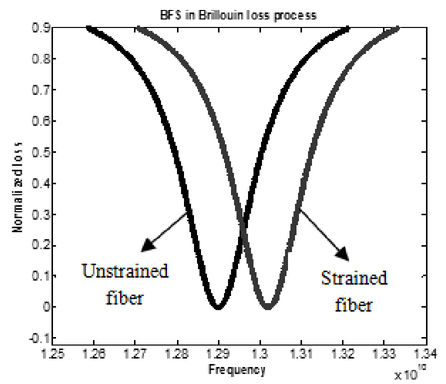

Figure 5: Brillouin frequency shift obtained for 0.2% applied tensile strain to the fiber in Brillouin loss mechanism.

the SOP, as shown in system block diagram. Figure 5, shows a Brillouin loss spectrum and BFS changes with a 0.2% applied strain. In this case, the probe signal is set at anti-stokes frequency, so that probe beam experiences energy loss. The energy transferred from probe to pump, therefore, the pump wave switches from donor to receiver, while probe beam acts as a donor in energy flow process. For 0.2% applied strain in Brillouin loss mechanism the frequency shift is found as 120 MHz. Therefore, the amount of frequency shift is same in both Brillouin gain and Brillouin loss mechanism.

4 TEMPERATURE AND STRAIN EFFECTS ON BRILLOUIN FREQUENCY SHIFT AND BRILLOUIN GAIN

As described in equation (1), the BFS depends on the refractive index n, pump wavelength λ_p and acoustic velocity v_a of the fiber. The group velocity of an acoustic wave is given by,

$$v_a = \sqrt{\frac{k}{\rho}} \tag{3}$$

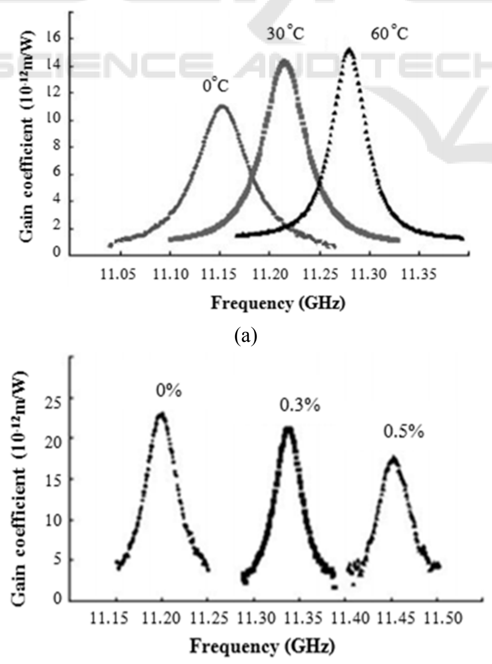

Figure 6: Brillouin frequency shift, linewidth and peak gain variations of single mode silica sensing fiber for (a) different temperatures (b) different strains.

change, hence result in a shift in Brillouin frequency material density of sensing fiber. The material where k is the bulk modules, ρ is the average density changes when strain and temperature By analyzing the back scattered BGS consists of BFS and Brillouin gain coefficient, it is possible to measure the distributed strain and/or temperature along the sensing fiber.

Figure 6 shows, the BFS, Brillouin gain and linewidth changes with different strain and temperature applied on sensing fiber (Nikles et al., 1997). By measuring Brillouin gain coefficient and BFS changes, the strain/ temperature information along the fiber can be determined. The performance of BOTDA system certainly depends on three parameters namely, the spatial resolution, measurement accuracy, and the sensing range. The spatial resolution is determined as, the smallest fiber length which measurement can be detected. The measurement accuracy is difference between the measured value and expected value of strain/temperature along the fiber. The sensing range indicates the longest length of the fiber, which we can extract the information from the received BGS. Three fundamental parameters that characterize the BGS, which are the Brillouin linewidth, measured at full width at half maximum, the BFS and the Brillouin gain coefficient. An interesting feature from Figure 6(a) is the Brillouin spectrum linewidth is decreases when the temperature increases. The linewidth dependence is not linear with the temperature and tends to meet at a constant value at higher temperature for all different fibers (Pine, 1969). The Brillouin gain increases according to the temperature increase due to its spectral narrowing and thus phonon absorption. The two parameters; Brillouin gain and BFS linearly changes with applied different temperatures. Another important feature observed from Figure 6(b) is the Brillouin gain decreases with increase strain values up to the fiber breaking point (~1% elongation), while the linewidth remains unchanged. An important observation from Figure 6(b), the BFS linearly varies with applied strain values, while the Brillouin linewidth is invariant. From Figure 6, we can conclude that, the Brillouin linewidth decreases when the temperature increases, and unchanged with applied strain. Therefore, the changes of two fundamental parameters; namely BFS and Brillouin gain were considered in BGS for measuring the strain and temperature along the sensing fiber. The BFS determines the strain/temperature range, while Brillouin gain discriminates, which is strain and temperature, simultaneously.

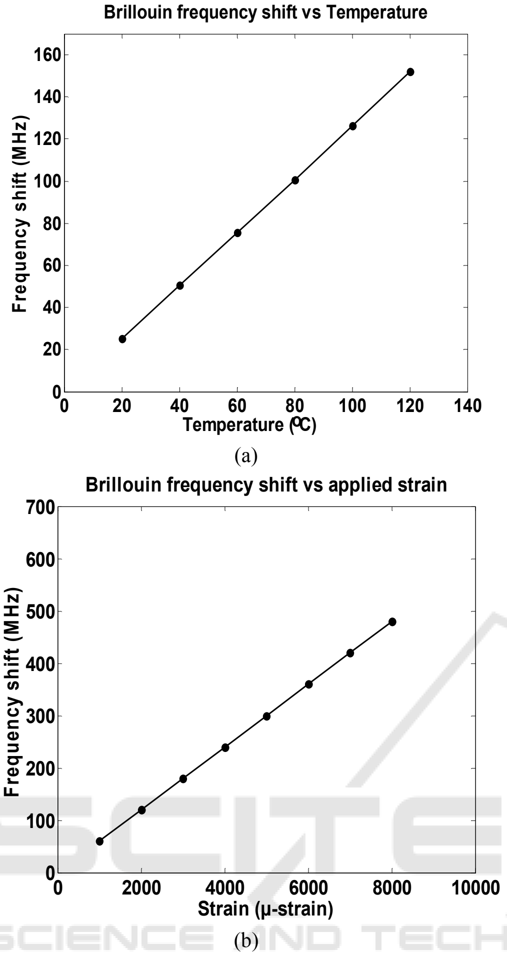

Figure 7: Brillouin frequency shift changes with (a) temperature (^{o}C) and (b) strain (µε).

Table 1: Measured coefficient values of BFS and gain for temperature and strain.

Description	Measured value
Change in Brillouin frequency versus strain	0.06 MHz/(µ-strain)
Change in Brillouin frequency versus temperature	1.26 MHz/^{o}C
change in Brillouin gain versus strain	-9×10^{-4} %/(µ-strain)
change in Brillouin gain versus temperature	0.416 %/K

The summary graph of different strain and temperature vs BFS is depicted in Figure 7. It shows a linear relationship between the applied strain and temperature with Brillouin frequency shift. The Brillouin gain $g_B(v)$ is expressed as (Robert and Norcia-Molin, 2006),

$$g_B(v) = g_o \frac{(v_{BW}/2)^2}{(v - v_B)^2 + (v_{BW}/2)^2} \qquad (3)$$

where g_o is the Brillouin gain coefficient, v_{BW} is the Brillouin linewidth at full width at half maximum v is the pump frequency and v_B is the Brillouin center frequency. The Brillouin gain factor g_o is expressed as follows (Lanticq et al., 2009),

$$g_o = \frac{2\pi n^2 p_{12}^2 \gamma}{c\lambda_P^2 \rho \, v_a v_{BW}} \qquad (4)$$

the gain coefficient g_o depends on many structural parameters as shown in equation (5). The value of peak Brillouin gain coefficient changes between 5×10^{-11} m/w to 7×10^{-14} m/w at 1550 nm wavelength. The parameters used for Brillouin gain coefficient calculation are shown in Table 2 (Benassi, 1993),

Table 2: Parameters used for calculation of Brillouin gain coefficient.

Parameter	Symbol	Value
Refractive index	n	1.44
Electro-optic constant	p_{12}	0.29
Polarization factor	γ	0.5
Pump wavelength	λ_P (nm)	1550
Fiber density	ρ (kg/m^3)	2330
Acoustic velocity	v_a (m/s)	5996
Brillouin linewidth at FWHM	v_{BW} (MHz)	30

5 MICRO-STRAIN DETECTION USING BFS TECHNIQUE IN BOTDA SYSTEM

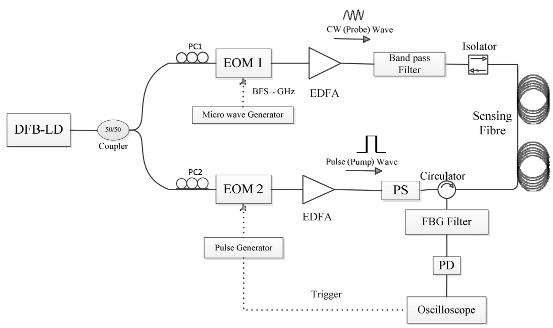

Figure 8: BOTDA system setup for measuring Brillouin frequency shift (BFS).

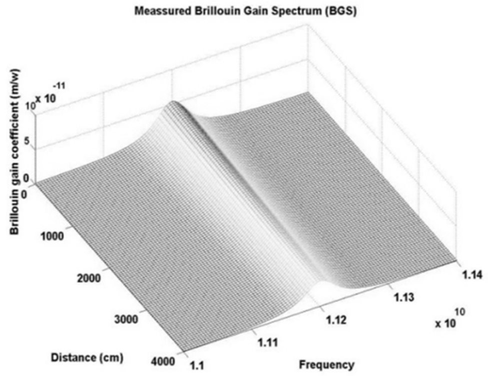

Figure 9: Three-dimensional Brillouin gain spectrum of 40 m long SMF at room temperature and strain free.

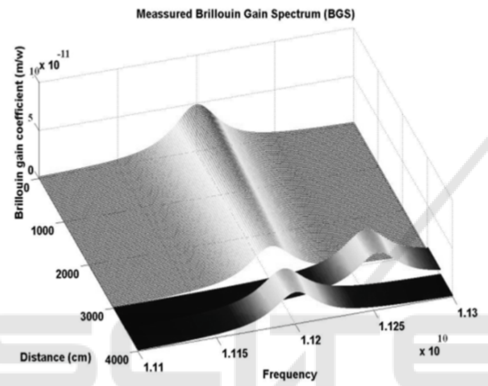

Figure 10: The 0.1% strain applied induced BFS on 5 m section of the fibre.

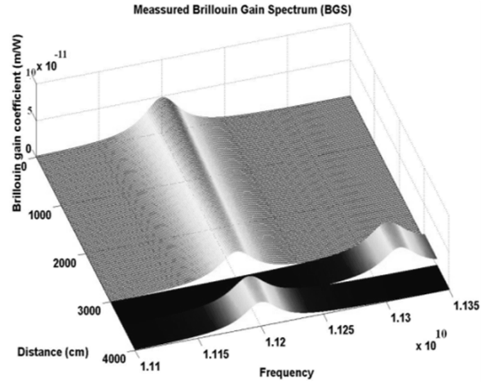

Figure 11: The 0.2% strain applied induced BFS on 5 m section of the fibre.

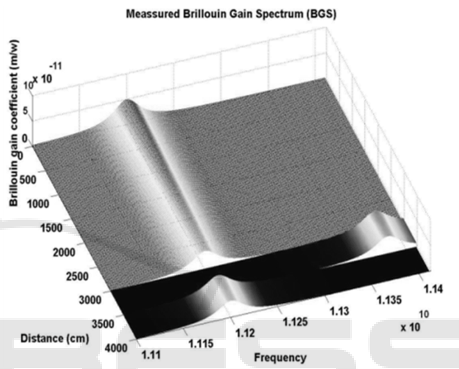

Figure 12: The 0.3% strain applied induced BFS on 5 m section of the fibre.

The system block diagram for BFS based micro-strain measurement is shown in Figure 8. A distributed feedback laser diode (DFB-LD) is used as a laser source at 1550 nm. The laser output is split into two beams, the pump and probe beam using a 50/50, 3 dB coupler. The polarization controller (PC) controls the state of polarization of the injected beam, in order to control the polarization sate of input beam. An electro- optic modulator (denoted as EOM2 in Figure 8), which convert the electrical pulses into optical and to set high extinsion ratio. EOM1 modulates the input signal around the fiber BFS (~ 11 GHz), driven by an external microwave signal generator. The output signal consists of two sidebands, the upper sideband and fundamental frequency is filtered out using an optical filter, while the lower sideband set as probe wave. After that, the probe signal is amplified by erbium doped fiber amplifier (EDFA). In this paper, we consider a Brillouin gain process, as lower sideband set as CW probe beam. In general, the lower sideband represents as a stoke beam with respect to the pulse signal and amplifies during propagation. The upper sideband acts as an anti-stokes wave experiences depletion. The upper sideband and fundamental frequency introduces negative effect to the SBS gain process. Using the EOM2, we can set high extinction ratio and the electrical pulses generated from a pulse generator will convert into optical pulses. The pulse width in conventional BOTDA is limited to 10 ns, because of an acoustic wave life time (decay time) is ~10 ns, below this time no more information about BFS can be obtained. Brillouin scattering is a polarization sensitive process; therefore we employ a polarization scrambler (PS) in setup. The received backscattered signal is sent to the optical filter, which eliminates the Raleigh and Raman components. Then the Brillouin stokes signal is sent to photo detector (PD) and analyzed by oscilloscope.

Figure 9, shows the Brillouin gain spectrum detected at room temperature without any applied strain. Therefore, no frequency shift is found along the sensing fiber. As described before, the BGS spectrum shape is well fitted by a Lorentz curve profile shape. However, the BGS profile gradually changes from a Lorentz shape to a Gaussian shape, when the pulse width approaches near to the phonon lifetime. As described in section 4, the Brillouin linewidth does not vary with applied strain and experiences a very small dependence on temperature, ~-0.1 MHz/ºC. Therefore, the Brillouin linewidth would be a limited use for distributed strain/temperature measurements. This is the reason why we consider the two fundamental parameters; the Brillouin gain and BFS for measuring distributed strain and temperature, simultaneously.

Figure 10, shows a BGS corresponding to a 5 m section of fiber under 0.1% tensile strain. The frequency is shifted away from the spectrum to 60 MHz. The strain is increases to 0.2%, 0.3% respectively, and then the strained section frequency is shifted to 120 MHz and 180 MHz far away from the spectrum, respectively, as shown in Figure 11 and Figure 12. Therefore, we observe that, for 0.1% (1000μ-strain), the frequency shift is 60 MHz. For 0.2% (2000μ-strain), the frequency shift is 120 MHz, for 0.3% (3000μ-strain), the frequency shift is 180 MHz. As a result, for each μ-strain, the frequency shift is found as 0.06 MHz, as perfectly matched with strain coefficient C_{ε} (0.06 MHz/μ-strain) as given by equation (2). The pump pulse width is set at 10 ns in measurement, corresponding to a 1 m spatial resolution.

6 CONCLUSIONS

In conclusion, we have analyzed Brillouin frequency shift in distributed optical fiber sensor system. The measurements performed for different strain and temperature values. The results demonstrate that, the BFS has a strong linear relationship with strain and temperature along the sensing fiber. Brillouin gain/loss measurements performed based on stokes and anti-stokes of the probe wave. BOTDA is a frequency based technique system as compared to Raman systems, which are intensity based technique. Brillouin frequency technique is more accurate, since intensity based techniques suffer from sensitivity to frequency drifts. Therefore, distributed fiber sensor systems based on Brillouin scattering is a better technique for structural health monitoring utilizing BFS.

Brillouin peak gain and linewidth variations under different temperature and strain conditions are characterized. We can conclude that, the Brillouin linewidth does not vary linearly with temperature and unchanged with applied strain. The Brillouin gain increases with increased temperature due to phonon absorption and very small gain decrement with applied strain. Therefore, we found BFS have a strong linear relationship with both applied strain and temperature along the fiber. As a result, the BFS change is used for strain and temperature measurements, while the Brillouin gain changes discriminate that, which is temperature and which is strain simultaneously. From the measurement results, it is evident that, for each μ-strain and temperature on sensing fiber, the BFS found as 0.06 MHz/μ-strain and 1.26 MHz/ºC, respectively. Therefore, the BOTDA sensing system based on BFS technique is a promising technique for structural health monitoring in real-time.

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