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Measurement Improvement of Distributed Optical Fiber Sensor via Lorenz Local Single Peak Fitting Algorithm

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Abstract: Brillouin frequency shift (BFS) of distributed optical fiber sensor is extracted from the Brillouin gain spectrum (BGS), which is often characterized by Lorenz type. However, in the case of complex stress and optical fiber self damage, the BGS will deviate from Lorenz type and be asymmetric, which leads to the extraction error of BFS. In order to enhance the extraction accuracy of BFS, the Lorenz local single peak fitting algorithm was developed to fit the Brillouin gain spectrum curve, which can make the BSG symmetrical with respect to the Brillouin center frequency shift. One temperature test of a fiber-reinforced polymer (FRP) packaged sensor whose BSG curve is asymmetric was conducted to verify the idea. The results show that the local region curve of BSG processed by the developed algorithm has good symmetry, and the temperature measurement accuracy obtained by the developed algorithm is higher than that directly measured by demodulation equipment. Comparison with the reference temperature, the relative measurement error measured by the developed algorithm and BOTDA are within 4% and 8%, respectively.

Keywords: optical fiber sensor; Brillouin gain spectrum; Brillouin frequency shift; Lorenz local single peak fitting algorithm; signal symmetry

1. Introduction

Distributed optical fiber sensing technology based on Brillouin scattering technique has realized fully distributed strain and temperature measurement along one single-mode opticalfiber and been widely used for the structural monitoring of railways, pipelines, and bridges [1–8]. Strain and temperature information loaded on the optical fiber sensor are linear with the Brillouin frequency shift (BFS). The Brillouin frequency shift of optical fiber (OF) can be obtained theoretically by calculation on a range of optical fiber physical parameters, but the physical parameters dispersion and the damage of optical fiber itself often lead to large calculation errors. Therefore, the experimental measurement method was conducted to obtain the BFS directly. The Brillouin scattering signal intensity is very weak, which is smaller by about two orders of magnitude than the Rayleigh scattering signals intensity, so that it is very difficult to measure it. The research and development of high-quality Brillouin sensing demodulation equipment is an important research focus, and the BFS is usually obtained from the coherent detection method or direct detection method. The traditional direct detection method is to separate the Brillouin scattering light from the Rayleigh scattering light using the F-P interferometer. The BFS measured by this method is not accurate enough; the interferometer is unstable and the insertion loss is large. A coherent self-heterodyne detection system was proposed, which enables one-end measurement of the Brillouin frequency shift distribution in optical fibers with a single-way dynamic range (SWDR) of 16 dB and a frequency resolution of 5 MHz for a spatial resolution of 100 m [9]. Based on this method, a commercial BODTR (Brillouin Optical

Time Domain Reflectometry) system, named AQ8603, was produced by Japan NTT with the characteristics of the longest measuring distance of 80 km, a strain accuracy of $\pm 30 \mu\varepsilon$ and the smallest spatial resolution of 1000 mm. Strain and temperature are correlated with Brillouin frequency shift simultaneously, which limits its engineering applications. In order to decouple strain and temperature, the methods of the Landau–Placzek ratio and cascaded Mach–Zehnder interferometric filters were proposed and the accuracy of 4 °C and $290 \mu\varepsilon$ were realized [10]. In order to obtain higher measuring accuracy, Brillouin optical time domain analysis (BOTDA) was proposed, which needs to form a sensing loop [11,12]. Now, the commercial BOTDA system, named DiTeSt produced by Omnisens, reached the measuring distance of 30 km, the measuring accuracy of $\pm 20 \mu\varepsilon$ and the spatial resolution of 500 mm. The Neubrex Company in Japan produced PPP-BOTDA (pulse-pre-pump optical time domain analysis); the measuring accuracy and spatial resolution of the instrument reached $10 \mu\varepsilon$ and 100 mm, respectively, which has been used for [13–15].

With the improvement of the high-sensitivity and high-bandwidth photoelectric detectors, the system stability and the measuring accuracy of the BOTDA and BOTDR systemshave also been greatly improved, which satisfy the test requirements for most engineering structures. In practical applications, the Brillouin gain spectrum of the Brillouin optical sensors often become complex Lorenzand asymmetry due to the complex stress state or large optical loss, which lead to the failure or large error for strain or temperature measurement. In order to solve this problem, some fitting algorithm to calculate BFS should be chosen, but the BFS fitting algorithm in the commercial BOTDA or BOTDR equipment is immobilization. One method of area-dividing and the least square nonlinear analysis to fit the Brillouin spectrum data was proposed, and then enhance the strain measurement accuracy [16]. A peak location method was proposed to extract the Brillouin frequency shift of the Brillouin gain spectrum, which can reduce processing complexity by omitting Lorenz fitting [17]. Furthermore, an artificial neural network (ANN) was used to obtain temperature information extracted directly from the local Brillouin gain spectra and not from the Brillouin frequency shift, which shows that ANN has higher accuracy and larger tolerance to measurement error [18].

In this paper, in order to enhance the measuringaccuracy of distributed optical fiber sensors, we present the Lorenz local single peak fitting algorithm for Brillouin gain spectrum to extract Brillouin frequency shift, and one temperature test for one optical fiber sensor packaged by fiber-reinforced polymer (FRP) was conducted to verify the idea, the Brillouin gain spectrum of which is complex and deviates from Lorenz shape.

2. The Introduction of the Lorenz Local Single Peak Fitting Algorithm

The spectrum of Brillouin scattering light is not a single spectrum line, which is spread over a range of frequency shifts centered about v_B. In fact, the decay process of light is assumed to be exponential in time, and the corresponding spectrum is a Lorenzian shape in the frequency domain, expressed as follows:

$$g_B(v) = \frac{g_0}{1 + 4\left[\frac{v - v_B}{\Delta v_B}\right]} \tag{1}$$

where v_B is the central frequency of Brillouin gain spectrum; g_0 is the peak gain; v the central frequency shift; Δv_B is the linewidth [19,20].

Figure 1 shows the shapeof Brillouin gain spectrum of common coning optical fiber under some uniform stress, and the BFS is about 10.855 GHz fitted by the Lorenz algorithm. Figure 2 is the Brillouin gain spectrum of FRP packaged Brillouin OF sensor; it can be seen that the shape of Brillouin gain spectrum does not match Lorenzian shape, the reason being that the optical fiber is subjected to uneven stress in the process of sensor packaging. It can also be found that the Lorenz–Brillouin gain spectrum is symmetrical in Figure 1 and asymmetric in Figure 2. If the Brillouin gain shape of the FRP packaged sensor is directly fitted by Lorenz algorithm, the BFS is about 10.94 GHz, which greatly deviates from the actual BFS of 10.86 GHz and then causes large measurement error. Here, the complex

Brillouin gain spectrum of the FRP packaged sensor is caused by the complex local stress during the fabrication process. In fact, the center wavelength of FBG is close to the work wavelength of the BOTDA system (1550 nm), the Brillouin gain spectrum will deviate from the Lorenz shape seriously [21].
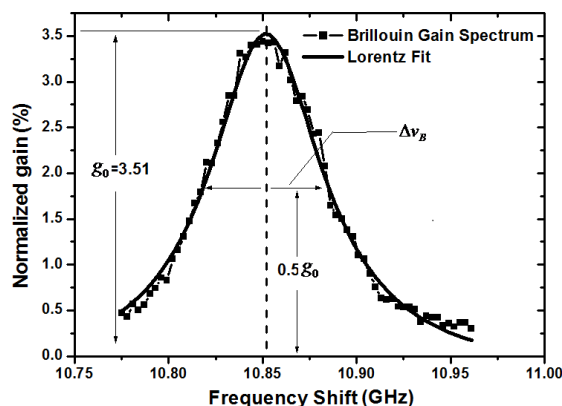

Figure 1. Brillouin gain spectrum of coningunder some uniform stress.
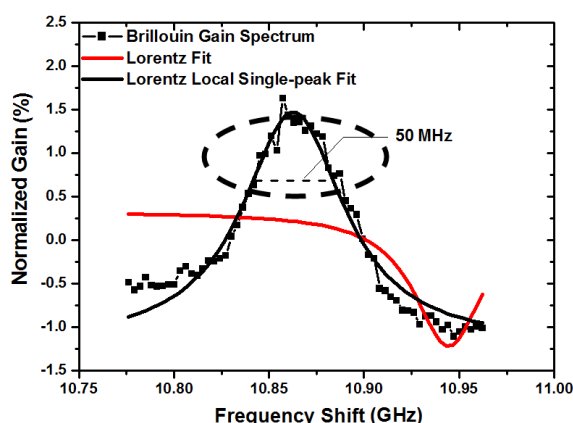

Figure 2. Brillouin gain spectrum of FRP packaged optical fiber sensor under complex stress.

In order to void the failure of the Lorenz fitting algorithm for the complex Brillouin gain spectrum with local multi-peak or local mutation depicted in Figure 2, the complex Brillouin gain spectrum is assumed to be locally Lorenz-type at some linewidth which will be used to calculate or fit the BFS, and this method is named the Lorenz local single peak fitting method. The fitting procedure of the Lorenz local single peak fitting algorithm is as follows: firstly, an appropriate linewidth is chosen, and the shape inside the linewidth is assumed Lorenz shape, which can ensure the symmetry of the Lorenz curve in the selected area; secondly, some abnormal data which deviates from the Lorenz curve is deleted directly; finally, the chosen data is fit by the Lorenz algorithm, and the corresponding BFS is obtained.

In Figure 2, the Brillouin gain spectrum is a far deviation from the Lorenz shape, so the result of the Lorenz fitting is wrong, while the data in the region of 50 MHz linewidth close to the peak is chosen to fit the Brillouin gain spectrum and the corresponding BFS is corrected.

3. Investigation of Lorenz Local Single Peak Fitting Algorithm to Enhance Bfs Accuracy

3.1. ValidityTest of Lorenz Local Single Peak Fitting Algorithm Based on FRP Packaged Optical Fiber Sensor

Figure 3 shows the structure of the FRP packaged optical fiber sensor with a FBG sensor, where the FBG sensor with the initial center wavelength of 1535.580 nm is used

as a local high-precision strain or temperature sensor and the OF is used as a distributed optical fiber sensor. In order to validate the Lorenz local single peak fitting algorithm, one temperature cycling test was conducted, and the Brillouin gain spectrum of the FRP packaged optical fiber sensor under temperature loading varying was given. The FBG sensor measured the temperature with a highprecision of 0.1 °C.
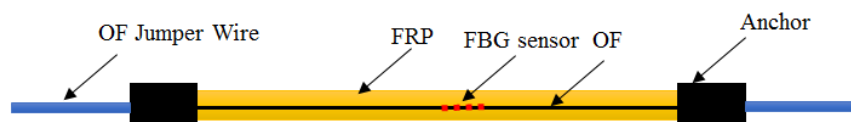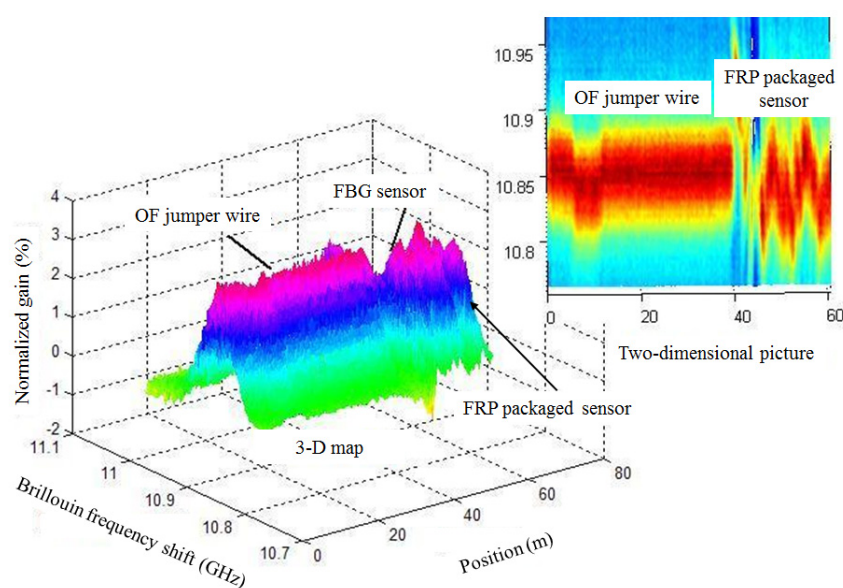

Figure 3. The FRP packaged optical fiber sensor with a FBG sensor.

In the test, the FRP-packaged optical fiber sensor was placedin one temperature box, and the loading rule applied to the optical fiber sensor is listed in Table 1. Figure 4 depicts the Brillouin gain spectrum of the packaged sensor under some temperature. It can be seen that the three-dimensional Brillouin gain spectrum of the optical fiber jumper wireis Lorenz shaped, while that of the FRP packaged optical fiber sensor (especially the FBG sensor) is complex and deviatesfrom the Lorenz shape. The reason for the complex Brillouin gain spectrum is that the optical fiber suffers from complex stress during the fabrication procedure. Furthermore, the FBG sensing unit can be taken as some damage model of optical fiber, which also further causes the complex of Brillouin gain spectrum. In this test, the Brillouin gain spectrum of the FRP packaged optical fiber sensor was measured by the BOTDA produced by Ominisens Company with the spatial resolution of 500 mm and the temperature accuracy of ±0.2 °C; the diameter and length of the FRP packaged optical fiber sensor are 5 mm and 2000 mm, respectively, and each temperature step requiresfive minutes to reserve enough test time for the optical fiber sensor (see Table 1).

Table 1. Temperature loading rule of the temperature test for the FRP packaged sensor.

| Loading Rule	Temperature (°C)				
Heatingup	23	34	52	58	64
Coolingdown	64	48	37	27	23

Figure 4. Brillouin gain spectrum of the FRP packaged optical fiber sensor under some temperature.

3.2. Test Results and Analysis

The Brillouin gain spectrum of the FRP packaged Brillouin OF sensor with a FBG sensorwas chosen to validate the Lorenz local single peak fitting algorithm. Figure 5 shows the Brillouin gain spectrum curve at the FBG point in the FRP packaged optical fiber sensor before and after fitting with linewidth of 50 MHz. In Figure 5a, it can be seen thatthe Brillouin gain spectrum curve deviates from the Lorenz shape at some temperature and the Lorenz curve is asymmetrical. The Brillouin gain spectrum curve has two peaks at 52 °C. the BFS fitted by the Lorenz local single peak fitting algorithm is about 10.893 GHz and the corresponding temperature calculated by the fitted BFS is 52.8 °C, while the BFS measured by BOTDA directly is 10.894 GHz, and the corresponding temperaturecalculated by the BFS is 53.04 °C. The Brillouin gain spectrum curve of the packaged sensor has one mutation data at 27 °C, as shown in Figure 5b. The BFS fitted by the developed algorithm is 10.863 GHz after deleting the mutation data, and the corresponding temperature is 28 °C, while the BFS measured by BOTDA is 10.864 GHz, and the corresponding temperature is 28.8 °C.
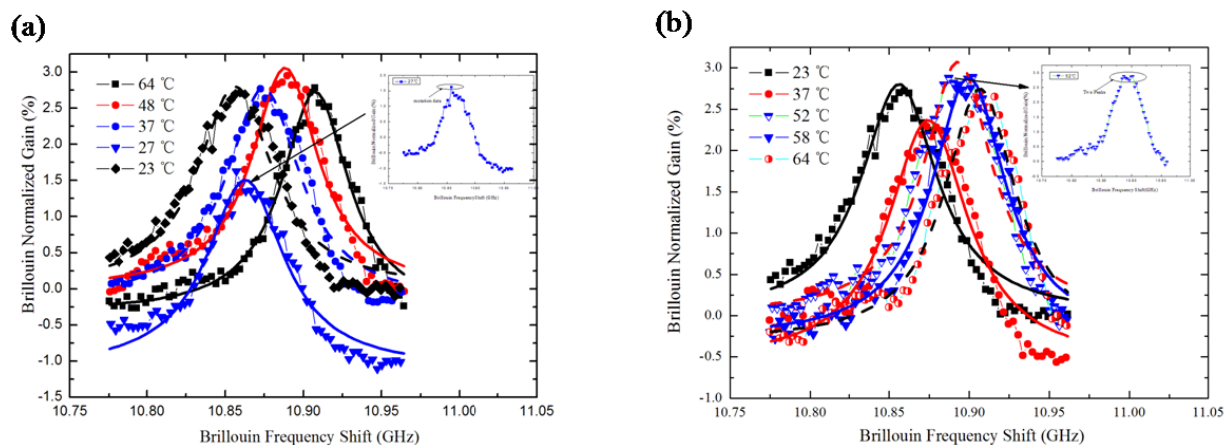
Figure 5. The results of Lorenz local single-peak fitting of Brillouin gain spectrum with 50 dB linewidth. (**a**) Temperature rise process and (**b**) temperature reduction process.

Figure 6a shows the comparison of the reference temperature (T_0), the temperature (T_1) fitted by the developed algorithm and the temperature (T_2) measured by BOTDA at each level of temperature. Here, the reference temperature (T_0) is measured by FBG sensor, Abs ($T_0 - T_1$) denotes the relative error between the reference temperature (T_0) and the fitting temperature (T_1), and Abs ($T_0 - T_2$) denotes the relative error between the reference temperature (T_0) and the temperature measured by BOTDA (T_2). Figure 6b illustrates the measuring errors at different temperature. It can be found that the maximum error of the temperature calculated by the BFS fitted by the developed algorithm is about 4% and that of the temperature measured by BOTDA is about 8% in comparison with the reference temperature. The reason for the two biggest errors occurring in step 1 and 8 is that the Brillouin gain spectrum at 23 °C and 37 °C are larger deviations from Lorenz shape compared with those at other temperatures. On the whole, the measuring accuracy by the Lorenz local single peak fitting algorithm is better than that by the BOTDA equipment.

(a) **(b)**
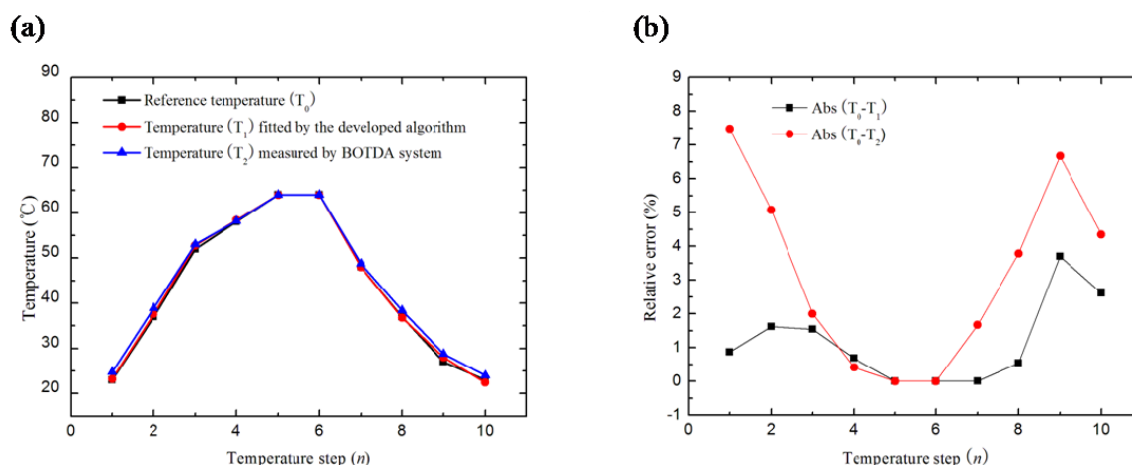
Figure 6. The temperature measurement comparison between reference values and the values calculated by BOTDA and developed algorithm. (**a**) Temperature measurement by different methods and (**b**) temperature error.

4. Conclusions

In this paper, to enhance the Brillouin frequency shift extracting accuracy, a Lorenz local single peak fitting algorithm was developed for complex Brillouin gain spectrum which deviates from the Lorenz shape. One temperature measurement test based on a FRP packaged optical fiber sensor was conducted, and the Brillouin frequency shifts at different temperature levels were calculated by the developed algorithm and BOTDA system. The test results show that the Brillouin gain spectrum of the FRP packaged sensor deviates from Lorenz shape and is asymmetrical, and the Brillouin gain spectrum curve in the selected region can be modified to be symmetric or Lorenz shape by using the developed algorithm. Comparing with the reference temperature, the maximum measuring errors of temperature measured by the developed algorithm and BOTDA system are 4% and 8%, respectively. In field application, the service environment of the distributed optical fiber sensor is harsh and changeable, and the sensor itself is damaged or the force is complex. Its sensing performance will inevitably decline, which is reflected in the deviation of Brillouin gain spectrum from Lorenz form; the method proposed in this paper is an ideal fitting algorithm.

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