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Simultaneous Temperature and Strain Measurement Using Deep Neural Networks for BOTDA Sensing System

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Abstract: DNN is used for the first time in simultaneous measurement of temperature and strain along a large-effective-area fiber (LEAF) in a BOTDA system with short processing time.
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1. Introduction

Normally, it is difficult to measure temperature and strain simultaneously in conventional Brillouin optical time domain analyzer (BOTDA) sensing systems because the cross-sensitivity of temperature and strain [1]. One solution to solve this problem is to use fibers with multiple Brillouin peaks instead of standard single mode fiber (SSMF), such as photonic crystal fiber (PCF) [2], large effective-area fiber (LEAF) [3], and few-mode fiber [4]. However, the solution requires time-consuming iterative curve fitting to determine Brillouin frequency shift (BFS) of multiple peaks and then calculation of two BFS equations to obtain the temperature and strain.

Recently we have demonstrated that the use of deep neural networks (DNN) to extract the temperature distribution from measured Brillouin gain spectrum (BGS) along the SSMF in a BOTDA system [5]. It is expected that DNN can be used to extract both the temperature and strain distribution from spectra of multiple Brillouin peaks directly without the need of curve fitting and calculation of two BFS equations, which can greatly shorten the processing time. In this paper, we achieve this purpose by using DNN in a BOTDA system with LEAF as the sensing fiber. There is no need to fit the BGS using conventional curve fitting methods to obtain the BFSs of different peaks and solve the two BFS equations to obtain the temperature and strain. Thus without algorithm iteration like curve fitting, the processing speed is very fast. Note that in [6] the authors use ANN to classify the effect of strain and temperature in SMF but without the capability of measuring their values. So this is the first report to use DNN for simultaneous measurement of temperature and strain distribution and we believe it is a practical method with short processing time, acceptable accuracy, and low system cost.

2. DNN training and simulation results

The structure of DNN used for simultaneous temperature and strain measurement in BOTDA is shown in Fig. 1. It consists of one input layer, two hidden layers and one output layer. In this case, the input vector X (x_1, x_2, …, x_N) represents the multi-peak Brillouin spectra with N as the number of data points on the spectra. The two output y_1 and y_2 in the output layer extract the temperature and strain information, respectively. The number of neurons in the two hidden layers are determined based on performance.

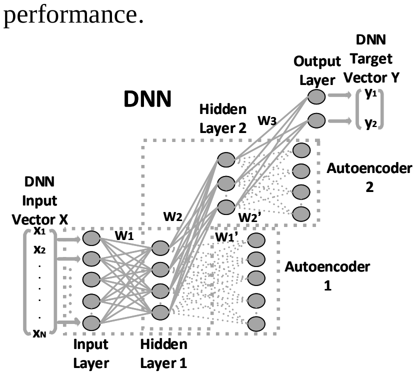

Fig. 1. The structure of DNN with 2 autoencoder hidden layers and 2 output for simultaneous temperature and strain measurement.

Before using the DNN to measure temperature and strain, we first calibrate the characteristics of our LEAF using the same BOTDA setup as that in [5]. Fig. 2 (a) shows the measured Brillouin spectra at room temperature when the LEAF is free from strain, where two peaks are observed from a frequency range of 10.550GHz to 11.000GHz. The frequency scanning step is 2MHz, which means that there are 226 data points on the two Brillouin peaks as the input vector of DNN. In addition, the BFS temperature and strain coefficients of these two peaks have also been obtained as shown in Fig. 2 (b) and Fig. 2 (c). The temperature and strain coefficients of Peak1 are measured to be 1.0118MHz/ºC and 0.0424MHz/με, while those of Peak2 are 1.0429MHz/ºC and 0.0408MHz/με, respectively.

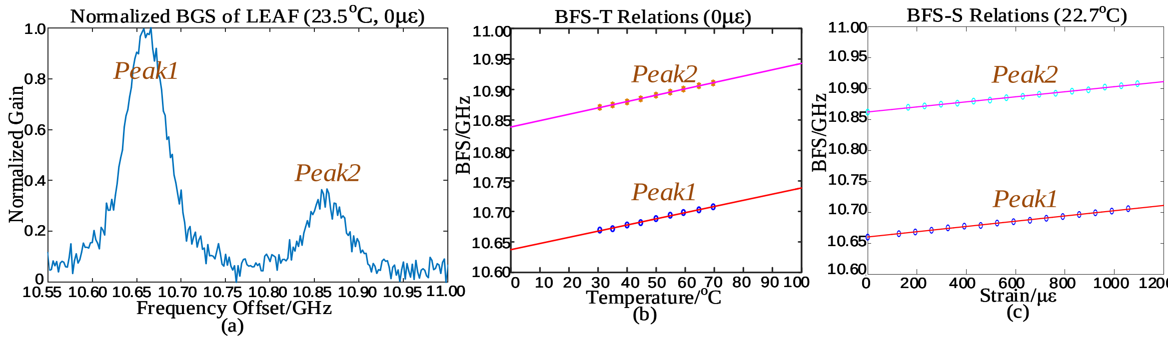

Fig. 2. (a) The normalized BGS of LEAF in the 23.5ºC and 0με condition; (b) The BFS-temperature relation curves of the Peak1 and Peak2 of the LEAF; (c) The BFS-strain relation curves of the peak1 and peak2 of the LEAF.

Then these coefficients and theoretical Lorentzian curves are used to simulate ideal two-peak Brillouin spectra as input data for training and validation of DNN, while the corresponding temperature and strain values are used as target output. To demonstrate the proof of concept, in this work the range of target temperature is set to be 20 to 40ºC at an interval of 1ºC, while the range of target strain is from 0 to 200με at an interval of 20με for fast DNN training. The simulated BGSs are normalized with the peak value of Peak2 set to include three values of 0.25, 0.30, 0.35, which is observed from experiment. In addition, the bandwidth of the Peak1 is set to include three values of 44, 47 and 50MHz, while that of the Peak2 is set to include three values of 37, 43 and 49MHz, respectively. The value of these parameters are combined in all cases to generate the simulated ideal BGSs. In addition, a group of simulated BGSs with white Gaussian noise (AWGN) added are also generated for training and validation, where the signal to noise ratio (SNR) is set to be the same as experimental data, i.e. 12.788dB at the center of Peak1. Therefore, there are 12474 X-Y data pairs for training and validation in total. The training process is similar to that in [5]. After several trials, the number of neurons in the first and second hidden layers are determined to be 40 and 10, respectively. After the DNN training, 1000 simulated noisy two-peak Brillouin spectra under two combinations of temperature and strain values are used to test the DNN. The simultaneously extracted temperature and strain are shown in Fig. 3, which indicates excellent performance.

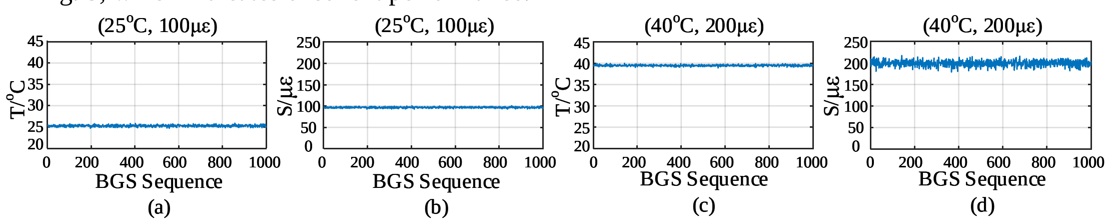

Fig. 3. The extracted temperature and strain by DNN from 1000 simulated noisy two-peak Brillouin spectra under (a) & (b) temperature and strain combination of 25ºC and 100με; (c) & (d) temperature and strain combination of 40ºC and 200με.

3. Experiment

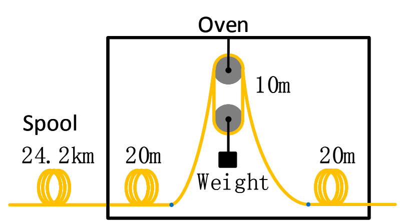

Fig. 4. The experiment setup of the FUT section.

In this section we perform experiment using the setup in [5] to verify the proposed approach. The pump pulse is 20ns and sampling rate is 1.25GS/s. The 24.3km LEAF serves as the fiber under test (FUT), whose last 50m section is put inside the oven with the middle 10m section coiled on the pulley for adding strain, and remaining section is free from strain at room temperature, as shown in Fig. 4. Thus different temperature and strain can be applied to the middle 10m section by setting the temperature of the oven and hanging different weights on the pulley. The BFS distribution of Peak1 along the last 50m FUT at 35ºC is shown in Fig. 5, where different weights (i.e. different strain) are applied to the middle 10m section. It is found that the strain is only applied successfully within a small section of about 2.5m rather than the whole 10m section on the pulley.

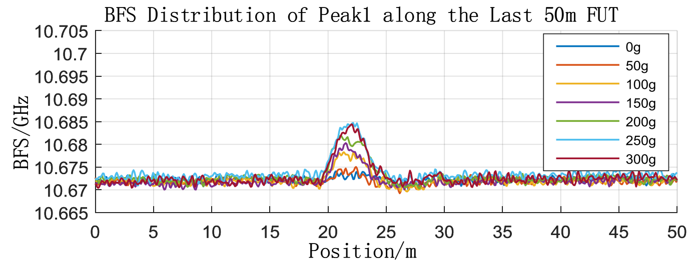

Fig. 5. The BFS distribution of PEAK1 along the last 50m FUT.

A group of temperature and weights/strain combinations are applied during experiment to test the DNN which has been trained in Section 2. Table 1 summarizes the error performance along the 2.5m FUT section, including the root-mean-square error (RMSE) and the standard deviation (SD). The weight is converted to strain by using the linear BFS-strain relation and the linear BFS-weight relation obtained from experiment. Both the temperature and strain have been successfully extracted from the two output of DNN. In these preliminary results for demonstration of the concept, there are some fluctuations of the RMSE and SD for different combinations of temperature and strain values. This may be due to the fact that best optimization for DNN models is not reached and the strain applied is not that uniformly distributed, which can be expected to improve accordingly.

Table 1. The Error Performance along the 2.5m FUT Section

			RMSE		SD	
Temperature/ºC	Weight/g	Strain/με	Strain/με	Temperature/ºC	Strain/με	Temperature/ºC
21.7	100	30.408	37.6599	1.2287	8.5112	0.3975
22.3	150	66.518	13.2854	1.6918	3.1610	0.2782
30.9	150	66.518	11.5468	0.6930	1.8603	0.6619
30.8	200	102.628	4.2024	3.0999	4.1796	0.8238
35.5	200	102.628	29.2930	2.0485	5.2642	0.4649
35.6	250	138.738	6.2220	2.0521	5.1119	0.3989
40.2	250	138.738	26.8295	0.5315	5.7017	0.3324
40.3	300	174.848	10.3419	0.5584	4.9227	0.2374

4. Conclusions

We have demonstrated the use of DNN to measure temperature and strain simultaneously along LEAF in a BOTDA system. To the best of our knowledge, this is the first report on using DNN for simultaneous temperature and strain measurement without the need of curve fitting and calculation of the two BFS equations. Results of using simulated and experimental data to test the DNN show the feasibility of using this method with acceptable accuracy. No need to do iterative curve fitting and solve the BFS equations makes this method have fast processing speed and a practical way of achieving simultaneous temperature and strain measurement for BOTDA sensing systems. The authors would like to thank the supports of grant HKPU 1-ZVHA.

5. References

[1] X. Bao and L. Chen, "Recent progress in Brillouin scattering based fiber sensors," *Sensors*, vol. 11, no. 12, pp. 4152-4187, 2011.

[2] L. Zou, X. Bao, S. Afshar, and L. Chen, "Dependence of the Brillouin frequency shift on strain and temperature in a photonic crystal fiber," *Opt. Lett.*, vol. 29, pp. 1485–1487, 2004.

[3] X. Liu and X. Bao, "Brillouin spectrum in LEAF and simultaneous temperature and strain measurement," *Journal of Lightwave Technology*, vol. 30, no. 8, pp. 1053-1059, 2012.

[4] A. Li, Y. Wang, J. Fang, M. Li, B. Y. Kim, and W. Shieh, "Few-mode fiber multi-parameter sensor with distributed temperature and strain discrimination," Optics Letters, vol. 40, no. 7, pp. 1488–1491, 2015.

[5] B. Wang, N. Guo, F. N. Khan, A. K. Azad, L. Wang, C. Yu, and C. Lu, "Extraction of temperature distribution using deep neural networks for BOTDA sensing system," *The 22nd Opto-Electronics and Communications Conference*, 2017.

[6] R. Ruiz-Lombera, A. Piccolo, L. Rodriguez-Cobo, J.M. Lopez-Higuera, J. Mirapeixa, "Feasibility study of strain and temperature discrimination in a BOTDA system via Artificial Neural Networks," 25th International Conference on Optical Fiber Sensors, Proc. of SPIE Vol. 10323, paper 103237Z, 2017.