An important milestone of distributed fiber optical sensing technology: separate temperature and strain in single SM fiber

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Abstract
In the paper, the principle and performance tests of hybrid Brillouin-Rayleigh system are presented. The system allows one to independently measure strain and temperature using single SM optical fiber over long distances.

Introduction
Stimulated Brillouin Scattering (SBS) systems are considered to be capable of determining the strain and temperature distribution of monitored object and, as a consequence, are frequently called the Distributed Temperature and Strain Sensing (DTSS) systems. However, since both temperature and strain changes produce the shift of SBS frequency, the SBS-based instruments actually cannot separate strain and temperature contributions from the measured (total) shift. The amplitude based separation algorithm [1], reported for BOTDR only, considerably reduces precision of measurement results. The actual separation is possible only if an additional, independent relation between strain, temperature and shift is available.

The required relation can be provided by frequency shift of time domain Rayleigh backscattering [2]. The principle of Rayleigh backscattering is well known for several decades. It states that random inhomogeneities of density, arising during solidification process, manifest themselves as refractive index fluctuations, appearing as irregular vibration in the Coherent OTDR (C-OTDR) trace [3]. While the laser frequency is scanned to obtain the Rayleigh Scattering Spectrum (RSS) of specific portion of fiber, it shows a shift due to change of, again, both temperature and strain. However, with BOTDA and time domain Rayleigh backscattering, the frequency shifts obtained using two completely different phenomena (i.e. Brillouin shift is due to the change of phonon, while Rayleigh to the movement of *natural marks* printed inside the fiber) are available. These shifts can be used to determine and separate the strain and temperature, with very high accuracy and high spatial resolution.

In this paper, the performance tests of the hybrid Brillouin-Rayleigh scattering are reported. We provide the theoretical background and results of two experiments demonstrating the capability of the system to measure and separate strain and temperature with spatial resolution higher than 10 cm over several kilometers.

Principles of hybrid system design
The hybrid Brillouin-Rayleigh system is schematically presented in Fig. 1. It consists of high-precision Pulse-Pre-Pump (PPP)-BOTDA [4], high-resolution RSS sub-systems and two optical switches (OS1 and OS2), allowing one to selectively switch the signal from one sub-system to the other.

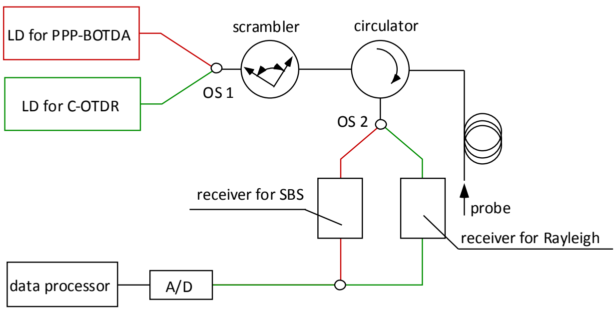

Fig. 1. Hybrid Brillouin-Rayleigh system scheme

The system provides for the SM fiber the measured shifts for Brillouin and Rayleigh scattering, denoted by $\Delta\upsilon_B$ and $\Delta\upsilon_R$, respectively. These values are used to separate the strain and temperature by means of the following set of equations:

$$\Delta\varepsilon = d_{11}\Delta\upsilon_B + d_{12}\Delta\upsilon_R \quad (1)$$
$$\Delta T = d_{21}\Delta\upsilon_B + d_{22}\Delta\upsilon_R \quad (2)$$

The obtained coefficient values and their units are listed in Table 1 below.

Table 1. Coefficients in equations (1) and (2)

coefficient	value	unit
d_{11}	- 12,755.10	με/GHz
d_{12}	- 10.92	με/GHz
d_{21}	1,530.61	°C/GHz
d_{22}	0.51	°C/GHz

The system underwent a series of rigorous tests, in an attempt to validate the design, and determine various performance factors. The SBS component is based on commercially available, cm-order spatial resolution PPP-BOTDA system. It found numerous industrial applications, providing highly reliable, high-accuracy measurements results, e.g. [5]. The RSS sub-system was thoroughly validated on experimental stands at Neubrex Co., Ltd. The selected results, demonstrating the sensitivity of spectrum shift within range of strain values from 0 to 200 με, are shown in Fig. 2.

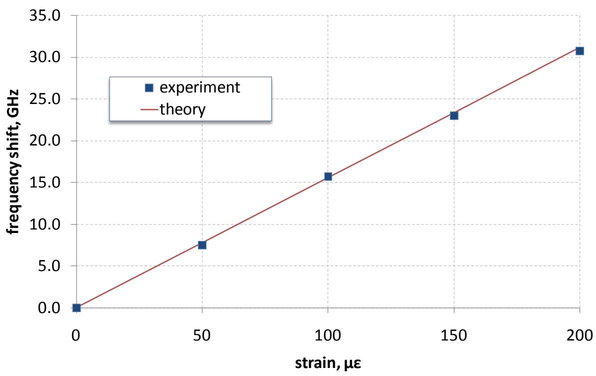

Fig. 2. Comparison of theoretical and experimental results

Technically, the Rayleigh scattering has the same sensitivity as fiber Bragg grating (FBG), that is, is three orders of magnitude higher than that of Brillouin. The high precision of PPP-BOTDA is able to match the requirements of hybrid measurement method.

Experimental verification

The capability of separating strain and temperature was tested on the experimental stand schematically depicted in Fig. 3. Inside the box, the constant temperature was maintained and controlled, while the (varying) strain was applied by pulling the fiber wound on the bobbin. All dimensions in Fig. 3 are given in millimeters.

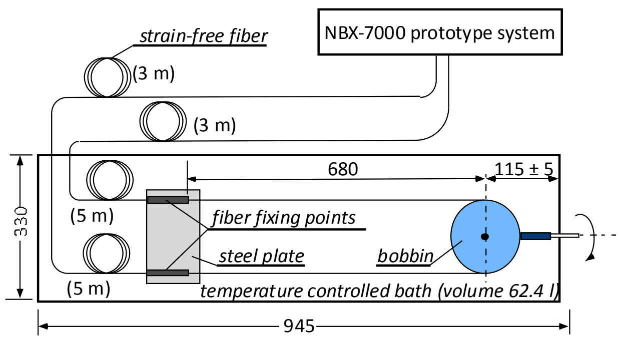

Fig. 3. Experimental stand for strain-temperature separation

The following conditions were applied during the experiment at initial (reference) state: temperature inside box: 0.0 ± 0.6 °C; strain-free (0 με) and at the changed state the strain value of 220 ± 5 με. In both states, the room temperature was 23.5 ± 0.5 °C and the same hardware settings applied.

The shift for RSS along the fiber is shown in Fig. 4, where appropriate portions of the fiber are also indicated. The absolute temperature distribution is presented in Fig. 5. The standalone SBS system is, naturally, unable to detect the strained region, while the hybrid system correctly *recognizes* that the temperature remained constant. The observed peaks in temperature distribution correspond to points on the bobbin where fiber started to stretch.

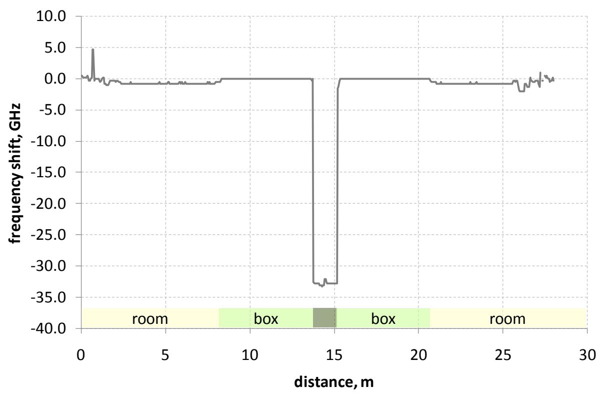

Fig. 4. Shift of Rayleigh scattering

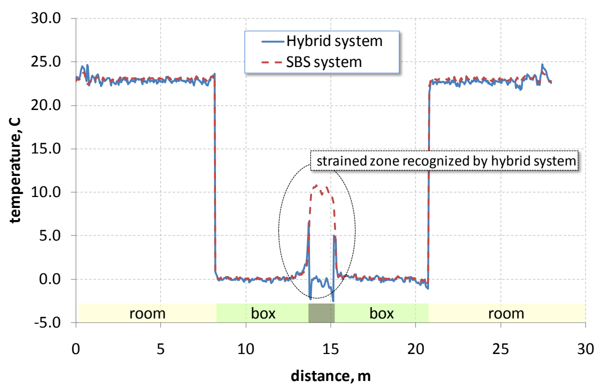

Fig. 5. Absolute temperature distribution

Conclusions

In the paper, the hybrid Brillouin-Rayleigh system is presented. The system is capable of separating strain and temperature in single SM fiber. The tests proved that high precision PPP-BOTDA is able to match the requirements of hybrid measurement method. Brillouin and Rayleigh scatterings are also the best match for commercial product, as both allow measurements over long distances, and both have stable signal as long as fiber optics works as a waveguide.

References

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