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Brillouin optical reflectometer with a Brillouin active filter

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***Abstract.* A new scheme of a fibre-optic Brillouin reflectometer is experimentally studied, in which the spectral line of spontaneous Brillouin scattering is selected by an active Brillouin filter represented by the tested fibre itself. To improve the reflectometer characteristics, a cyclic code and Raman amplification of the scattering signal are applied. With an averaging time of 5 min, scanning of 25 km of fibre with a spatial resolution of 4 m and a sampling resolution of 1 m are provided. The root-mean-square deviation in determining the Brillouin frequency is less than 1.1 MHz. The reflectometer sensitivity is evaluated with respect to the temperature changes and mechanical deformation.**

Keywords: *distributed sensor, Brillouin reflectometer, fibre optics.*

1. Introduction

After the discovery of a strong dependence of the Brillouin frequency shift on the mechanical deformation of the optical element, and also a noticeable temperature dependence of this shift [1], the idea of a Brillouin reflectometer was first proposed [2, 3]. The design of such a distributed sensor of mechanical deformations has opened up new opportunities for monitoring the state of infrastructure objects (pipelines, bridges, etc.). However, the engineering implementation of the Brillouin reflectometer is still a difficult task, since the intensity of spontaneous Brillouin scattering (BS) is approximately 20 dB lower than the Rayleigh scattering, and besides, a small frequency shift (about 10.5 GHz for a wavelength of 1550 nm) relative to the Rayleigh scattering frequency makes it difficult to isolate the Brillouin line and accurately determine its frequency.

The heterodyne scheme [4] may be regarded as the most successful engineering solution, in which the scattered radiation is mixed with the heterodyne radiation with the formation of beats at the Brillouin shift frequency. However, such a scheme assumes the use of microwave technology and other expensive components; as a result, the reflectometer turns out technically complex and expensive.

There are known works in which optical instruments are used to isolate the Brillouin component of scattered radiation, in particular, Mach – Zehnder [5] and Fabry – Perot [6] interferometers. The problem is to ensure the thermal stability and system stability to mechanical impacts. An ingenious method for isolating Brillouin radiation was proposed in [7]. It consists in using a Brillouin amplifier with a gain bandwidth comparable to the BS line width (about 40 MHz for a wavelength of 1550 nm). So far, to the best of our knowledge, this scheme has not been implemented as applied to Brillouin reflectometry. However, in itself, the idea of using stimulated BS for spectrometry purposes finds application [8].

The aim of this work is an experimental verification of the possibility of designing a Brillouin reflectometer based on a Brillouin amplifier performing the function of an active optical filter, and also a search for an optimal configuration of the Brillouin reflectometer with at least 25 km range.

2. Experimental setup

The scheme of the setup for our experiments is shown in Fig. 1.

Probe radiation was formed as follows. A distributed feedback (DFB) master laser diode LD1 (JDS Uniphase CQF975/5827) with a wavelength of 1550.65 nm operated in the cw regime with temperature stabilisation by means of a built-in Peltier element and injection current stabilisation at a level of 80 mA. The output power was 10 mW. The output pulses were formed by using a semiconductor optical amplifier (SOA), and then were amplified to a peak power of the order of a few watts by an erbium-doped fibre amplifier pumped at a wavelength of 980 nm. The semiconductor amplifier was controlled by a digital-to-analogue converter DAC1 with a clock rate of 200 MHz, which made it possible to produce both single pulses and arbitrary pulse trains. Through a polarisation scrambler (PS) and a directional optical coupler, probe radiation was launched into the investigated fibre wound on coils 1 and 2.

An active Brillouin filter was formed on the basis of the same fibre under test (FUT), into which cw radiation from the second DFB laser diode LD2, analogous to LD1 and operating at a close frequency, was delivered. Through the circulator and coupler, its radiation was launched into the FUT at a power level of 2 – 4 mW, providing amplification at the Brillouin line's maximum to 5 dB for the remote end of fibre with a total length of 25 km. To obtain the Brillouin line profile, the radiation frequency of this laser diode was scanned according to a linear law by changing the injection current in

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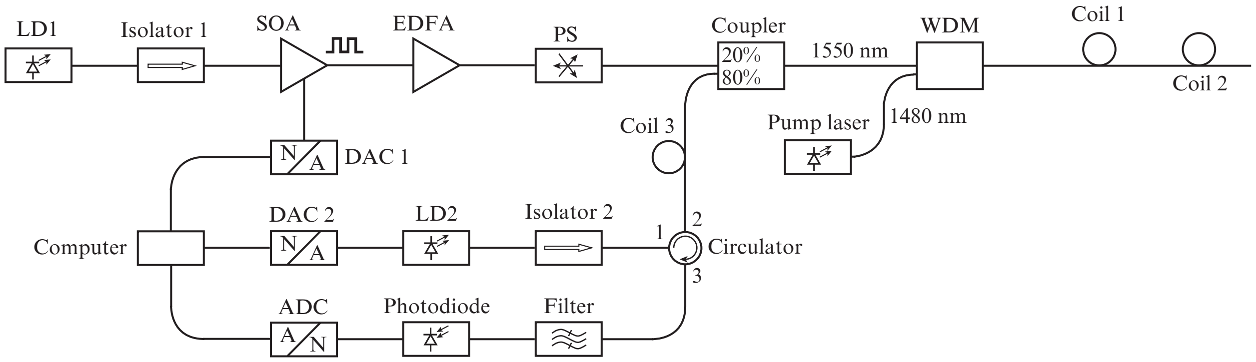

Figure 1. Scheme of the experimental setup: (LD1) and (LD2) coherent distributed feedback lasers; (SOA) semiconductor optical amplifier; (EDFA) erbium-doped fibre amplifier; (WDM) wavelength division multiplexer; (PS) polarisation scrambler. The lengths of fibres (Fujikura FutureGuide-LWP) in coils 1, 2, and 3 are 25 km, 200 m and 2 km, respectively.

small limits that are necessary for obtaining the Brillouin spectra. In particular, when obtaining the Corning LEAF fibre spectrum (Fig. 2), the scanning range was 1000 MHz. The scanning was performed slowly, with each scan taking up to 5 min. Linearity was provided solely at the expense of accurate setting of the laser diode's injection current (discretely through 2 μA; as many as 65536 positions in total).

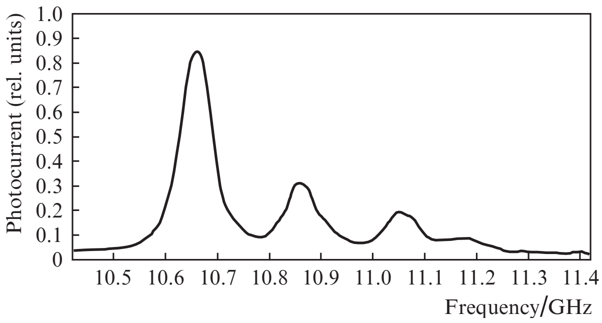

Figure 2. Brillouin spectrum of Corning LEAF fibre.

The radiation backscattered and amplified due to the Brillouin effect was delivered through the coupler and circulator to the photodetector based on a pin-photodiode with a transimpedance amplifier having a bandwidth of 50 MHz.

Coil 3 is included into the scheme to ensure the Brillouin amplification of radiation scattered by the near region of the FUT, since the scattered radiation in the absence of the coil does not undergo Brillouin amplification, and, consequently, its selection does not occur. This coil also contains Fujikura FutureGuide-LWP fibre having a single Brillouin peak. The fibre length is 2000 m.

Since the Brillouin amplification is a polarisation-dependent process, to exclude polarisation fading (signal 'fading'), a polarisation scrambler of our own design, randomly changing the radiation polarisation state, is included into the scheme. It is based on the induced birefringence in the fibre formed by a piezoelectric element and operates at a frequency of 20 kHz. The residual polarisation is 10%, which is enough to equalise the amplitude of the spectra over all channels of the range, each of which corresponds to a certain coordinate along the length of the FUT.

In this configuration, the spectral line width obtained in the experiment is determined by the convolution of the spectra of the radiation scattered by the fibre, pulsed laser source and active filter. In turn, the Brillouin filter spectrum represents a convolution of the Brillouin spectrum of the fibre and the radiation spectrum of a cw LD2 laser. This implies the need to control the width of the spectral lines of master laser diodes LD1 and LD2. According to the manufacturer data, the width of the radiation lines of these diodes is less than 20 MHz. To estimate the widths of the lines of cw lasers, the homodyne method with the use of a considerably unequal-arm Mach-Zehnder interferometer (25 km) was applied, similar to that described in [9]. It was found that the widths of the spectra of our laser diodes constituted 5 MHz at a half-maximum level.

An obligatory condition for the operation is the suppression of the Rayleigh scattering component. For this purpose, a filter consisting of series-connected thin-film filters with a bandwidth of 100 GHz was used.

To assess the spectral resolution of the setup, a segment of Corning LEAF fibre (not shown in Fig. 1) was used as a test object having a characteristic BS spectrum in the form of four lines. Since our setup does not produce absolute values of the Brillouin shift, the same segment was investigated for the purpose of binding to the true frequencies using an Ando AQ8602 reflectometer. The spectrum we have obtained is shown in Fig. 2. It can be seen that all four spectral lines are reproduced, the main peak width at half-maximum being 70 MHz. Due to the reasons described, this width exceeds the true width of the BS spectral lines, but does not prevent the measurement of the positions of these lines.

Originally, a single-pulse method was used, and 40-, 80- and 160-ns single pulses were employed as probes. In this case, due to the limitations caused by modulation instability, it was not possible to obtain acceptable BS spectra at a range of more than 3–5 km. However, the scheme used, in contrast to the heterodyne one, allows complex encoding of the probing package using cyclic code sequences [10]. Thus, in this work, by using a cyclic code of 512 bits in length, a gain in the signal-to-noise ratio is more than 10 dB in the situation close to ours (in the Brillouin analyser scheme). However, one must keep in mind that the simultaneous existence of tens and hundreds of pulses in the FUT multiply increases the interaction length; as a result of Brillouin amplification, the BS radiation from distant fibre regions turns out substantially enhanced by these probe pulses. The effect known to the designers of

Brillouin analysers [11], consisting in the ‘pulling’ effect of an amplifying medium on the recorded frequency of the spontaneous BS in these regions, arises. Therefore, in this case a restriction on the power of the probe pulses also appears, aggravated by an increase in their number and duration. It was found that at the pulse duration of 40 ns providing a spatial resolution of 4 m, the cyclic code’s optimal length for a 25-km-long fibre in question constitutes 50–70 bits. The results below correspond to a 59-bit code package (Fig. 3).

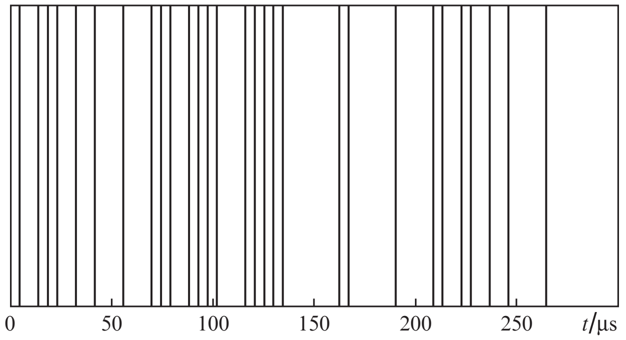

Figure 3. Code package at the DAC1 output.

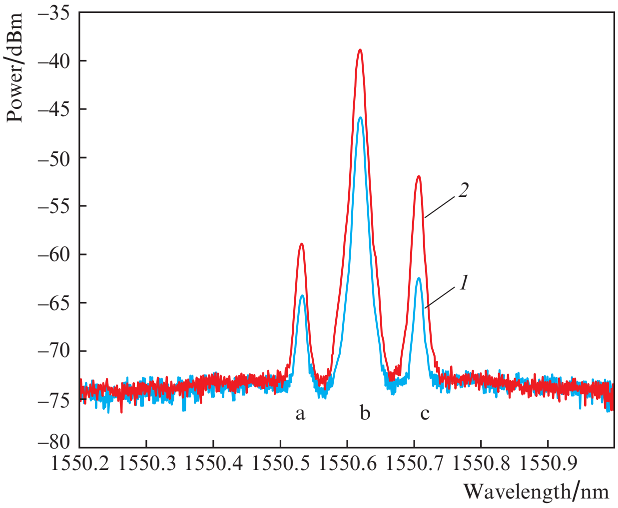

Figure 4. Backscattered radiation spectra in the fibre under investigation: (a, c) anti-Stokes and Stokes components of the BS; (b) Rayleigh scattering; (*1*) scattering from the probe sequence of pulses only; (*2*) same after Brillouin amplification by the active filter.

In work [11], as applied to the Brillouin analyser, a so-called colour cyclic code has been implemented, in which individual pulses in the probe sequence differ in frequency at least by the width of the Brillouin amplification line. This makes it possible, virtually without restrictions, to increase the code package length and to avoid the effect of frequency pulling. Unfortunately, it is impossible to implement such an idea in the proposed scheme. However, the frequency pulling effect can be partly diminished in another way – by forming a fibre line consisting of at least two fibres with different BS frequency shift values. In our case, this technique has not been used.

The effect of frequency pulling can be completely eliminated if the anti-Stokes component of the BS, but not the Stokes one, would be selected and amplified. However, in this case it would be necessary to filter out two lines of Rayleigh scattering – from the probe package and from the radiation of the active Brillouin filter, which seems challenging. Moreover, the constraint due to the stimulated BS does not completely disappear – as a result of stimulated scattering, with an increase in the product of the probe radiation power by the total duration of pulses in the code package, the Stokes component grows in such a way that the useful probe radiation turns out saturated.

The use of the cyclic code has significantly improved the characteristics of the scheme under study. However, in order to reach the prescribed action range of the reflectometer, we had to employ Raman amplification in the FUT, which was ensured by launching into the fibre radiation from a Fitel FOL-1402 semiconductor laser diode with a wavelength near 1480 nm and a power of up to 150 mW.

Figure 4 shows the backscatter spectra measured at point 3 of the circulator. The spectra were obtained with an Ando AQ6319 analyser having a spectral resolution of 12 pm. Curve (*1*) represents a spectrum corresponding to the propagation of only a pulsed probe code package in the tested fibre. It follows from the proximity of the powers of the Stokes and anti-Stokes components (the difference is 2 dB) that spontaneous BS predominates. After switching on the laser diode LD2, the Stokes component power increases substantially [curve (*2*)], which is required for the selection of spontaneous BS (the spectra were obtained in the absence of scanning at the maximum BS reflectogram amplitude).

Figure 5 shows the Brillouin shift distribution in the investigated 25-km-long Fujikura FutureGuide-LWP fibre and also within the fibre segment of 24760–24950 m in length (inset). The signal accumulation time was 5 min, and the scanning range was 200 MHz. The root-mean-square deviation in Brillouin shift determination at the fibre near end was approximately 0.45 MHz, and at the far end it constituted 1.05 MHz. An increase in the noise indicates that the frequency pulling effect is not dominant (in the presence of the pulling, the noises do not increase when approaching the far end of the fibre). The spatial resolution in accordance with the pulse duration is 4 m.

The inset in Fig. 5 illustrates the reflectometer response to the temperature changes and mechanical deformations in the range of about 25 km. Region 1 corresponds to a fibre segment that has been heated. The coil with a 30-m-long fibre was immersed into a container with water at a temperature of ~60 °C. The temperature in the room at the time of the experiment was 27 °C. Thus, the temperature change constituted about 33 °C. As can be seen from Fig. 5, the Brillouin frequency shift was 40 MHz. The temperature shift of the frequency in this case is 1.2 MHz $^{\circ}C^{-1}$. This value is typical for telecommunication fibres [12, 13].

Region 2 in Fig. 5 corresponds to a fibre length of 9 m, subjected to tensile deformations. The fibre segment was rigidly fixed from two sides, and preliminary tension was applied to eliminate sagging. Then, the fibre was stretched by 1.5 mm, so that its elongation amounted to 0.167 %. At this point of the optical path, the Brillouin line shift was 82 MHz, while the relative frequency change constituted 490 MHz $(\%)^{-1}$. This value is close enough to the results published in [12, 13].

In general, the characteristics we have obtained are close to those for the Ando AQ8602 reflectometer, in which the heterodyne scheme is used.

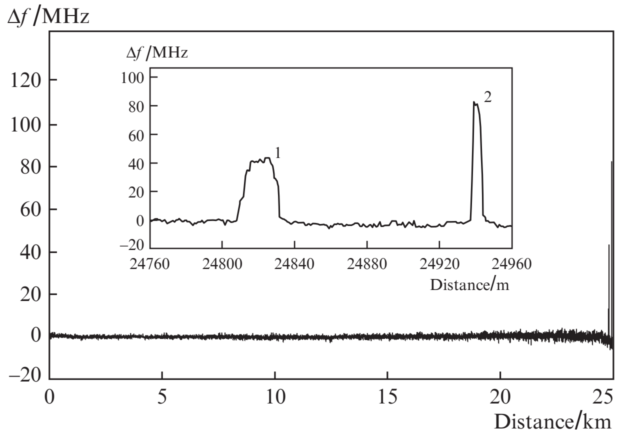

Figure 5. Brillouin frequency shift along the fibre length (the inset shows the shift within the fibre segment of 24760–24950 m in length).

3. Conclusions

We have experimentally shown the possibility of designing a fibre Brillouin reflectometer employing the Brillouin amplification effect for isolation of spontaneous Brillouin scattering in the fibre under test (without heterodyning). A range of 25 km is reached with a spatial resolution of 4 m, and the sensitivity to temperature changes and mechanical tensile deformations is shown. The achievement of these results has been facilitated by the use of cyclic codes and additional Raman amplification.

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