Frequency-Difference Brillouin Reflectometry of Optical Fiber Parameters

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Abstract: The paper discusses the variety of the Brillouin reflectometry technique proposed by the authors. The distinctive feature of this technique is the isolation of the differential frequency of Brillouin scattering signals which come from the inhomogeneity and the fiber segment adjacent to it. First, a number of components are allocated from the entire signal spectrum, each of which occupies a narrow frequency band. Each of these narrow-band components is further subjected to amplitude detection and averaged with the data of several measurements. The proposed technique allows implement the simplest and most convenient principle of constructing a Brillouin reflectometer, and also it enables to obtain Brillouin reflectograms from conventional Rayleigh reflectometers. This technique can find wide applications both in the field of distributed fiber-optic sensors and for early troubleshooting of telecommunication optical cables.

1 INTRODUCTION

The well-known problem of the high cost of equipment which characterizes the current situation in the field of Brillouin reflectometry creates prerequisites to search for innovative technical solutions. Among the factors determining the complexity of measuring equipment [1], we should mention a sufficiently great significance of the Brillouin frequency shift with its relatively small change depending on the measured parameters (tension and temperature). The devices must contain a tunable frequency synthesizer with the necessary characteristics, as well as an optical modulator and a photodetector with the appropriate speed. We should also mention the high requirements for the radiation spectrum of the laser used.

2 THEORETICAL BACKGROUNDS

Works [2] and [3] describe the optical signal heterodyne oscillation generated by forced Mandelstam-Brillouin scattering (FMBS). Developing this idea we propose a technical solution based on the use for this purpose of a spontaneous Brillouin scattering signal received from an adjacent section of an optical fiber with relation to the measured one.

Figure 1 shows a part of the schematic diagram of the reflectometer working on the described principle of operation.

The scheme contains a laser and an optical modulator, two directional couplers, between which there is a fiber segment that creates the necessary time delay. Optical probing impulses are formed at the modulator output. Radiation from the couplers outputs enters the photodetectors, their spectrum of the output signals has components conditioned by Brillouin scattering. The frequency of one of these

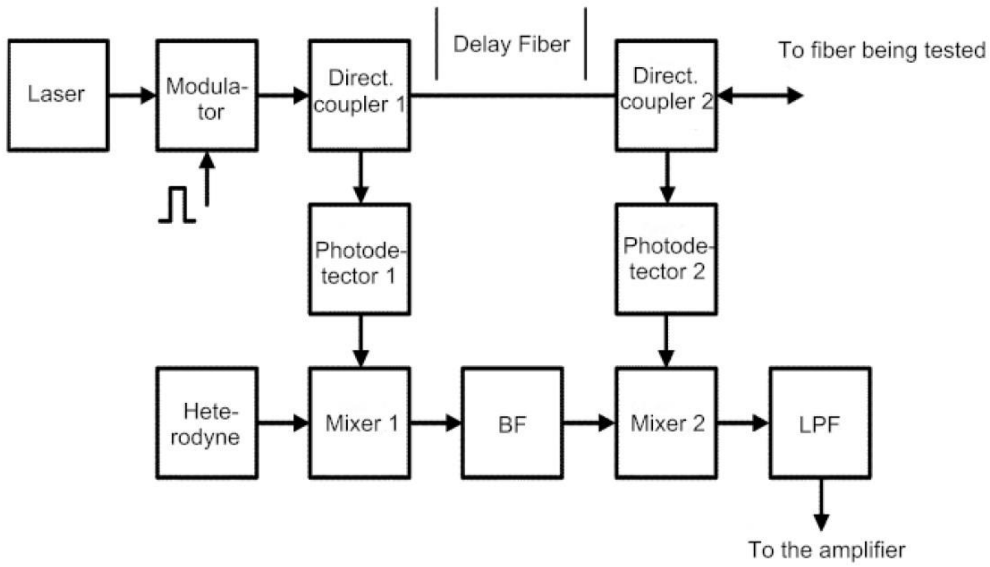

Figure 1: Schematic diagram of the frequency-difference Brillouin reflectometer.

signals is shifted by a mixer and a heterodyne oscillator. The received signal as well as the signal from the output of another photodetector are fed into the second mixer to form a differential frequency. After being filtered by means of a low-pass filter (LPF), the output signal from this mixer is amplified, digitized and processed using a microcomputer to obtain a reflectogram.

According to the scheme, the signal frequency at the output of the LPF placed after the second mixer is determined (at a fixed frequency of the heterodyne oscillator) by the frequency difference of the Brillouin scattering signals in neighboring fiber sections whose beginnings are located at a distance equal to the length of the delay fiber.

Additional frequency conversion is particularly necessary to enable the identification of the direction of change in the tension (or temperature) of the fiber as the wave path propagates along it. This inhomogeneity of the fiber state will be further referred to as Brillouin inhomogeneity. Let us consider the probing impulse and the inhomogeneity, the lengths of which do not exceed the length of the delay fiber l_d, (Figure 2). The figure shows how the frequency difference between the source and delayed signals changes when the packet passes through the inhomogeneity in the absence and the presence of additional frequency conversion.

In the first case, the frequency shift of the Brillouin signal due to the presence of inhomogeneity does not depend on which of the packets (the source one or the delayed one) is inside the inhomogeneity. In both cases, the frequency increment Δf_H is the same. It is also possible that the first inhomogeneity is followed by the second one, in which the frequency shift occurs in the same direction and by the same value. If the position of the source packet corresponds to this second inhomogeneity, and the position of the delayed one corresponds to the first inhomogeneity, then the frequency shift will also be equal to Δf_H and it will not be possible to distinguish this situation from the one shown on the right top in Figure 2.

The presence of additional frequency conversion makes it possible to solve this problem (Figure 2, lower graphs). Additional frequency shift Δf_{add} must satisfy the inequation [4].

$$\Delta f_{add} \geq |\Delta f_{H\,max}| + \frac{2}{t_{min}},$$

where $\Delta f_{H\,max}$ is the maximum frequency shift due to inhomogeneity;

t_{min} is the minimum duration of the signal element corresponding to the Brillouin inhomogeneity.

The second term takes into account the restriction imposed by Kotelnikov's theorem. It enables us to detect short inhomogeneities, which also have a small effect on the frequency of the scattered signal.

The upper graph corresponds to the absence of an additional frequency conversion, and the lower graph corresponds to the presence of this conversion.

To obtain a tension or temperature distribution curve along the fiber, it is necessary to integrate the dependence of the difference frequency on time (distance), taking as zero the value corresponding to the shift frequency Δf_{add}.

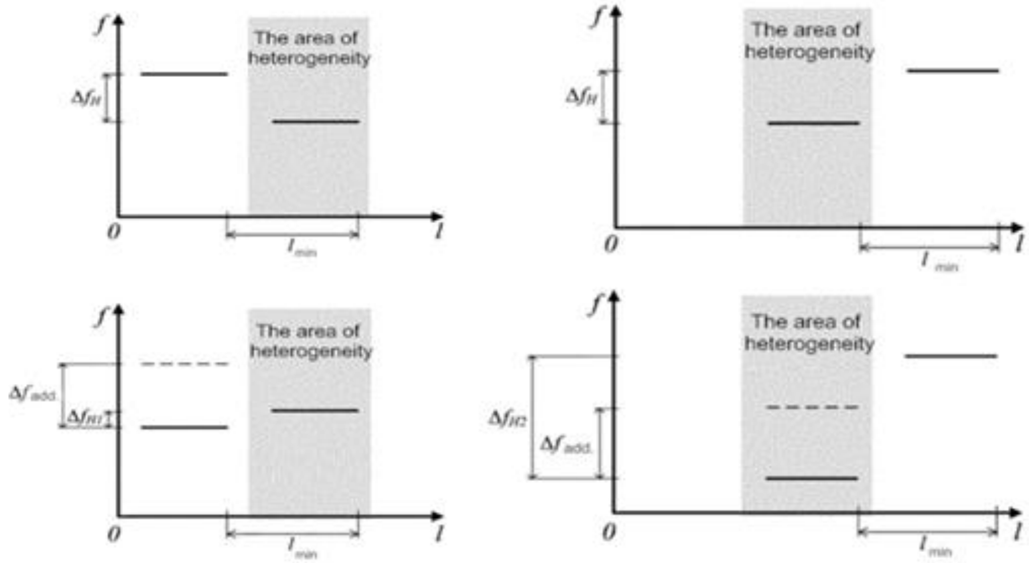

Figure 2: Frequencies of Brillouin scattered signals for a short-length probing impulse.

We should note a number of significant deficiencies of the scheme, which include high requirements for the speed of photodetectors, the presence of microwave mixers, as well as the fact that due to the use of an additional directional coupler, the power of the backscattering signal drops by 3 dB. Therefore, a technical solution providing for the presence of adirectional coupler and one photodetector at the input of which there are both outgoing and delayed optical signals is of considerable practical interest. At the output of such a detector, it is possible to distinguish difference spectral components and this significantly reduces the requirements for its performance. We have to find a method to determine the direction of change of the measured value in the path of propagation of the probing impulse [5].

Obviously, the longer the delay time, the longer inhomogeneities can be determined unambiguously. This trend also takes place concerning the increase in the length of the probing impulse (Figure 3).

Let us note that in the situation shown in Figure 3, with a probing impulse length exceeding the length of the Brillouin inhomogeneity, signals scattered by both this inhomogeneity and adjacent fiber sections will simultaneously occur at the photodetector input. This allows us to formulate a very important conclusion. The signal at the output of the photodetector of a conventional reflectometer can carry information about the presence of Brillouin inhomogeneities in the fiber and theoretically can be detected in digitized data stored in the device memory by special processing.

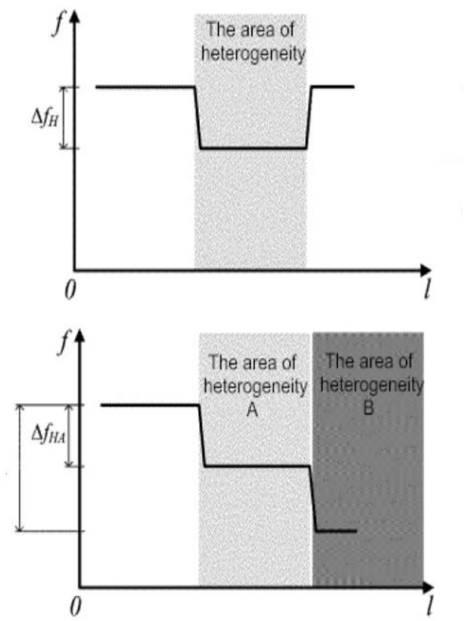

Figure 3: Frequencies of Brillouin scattered signals for a long-length probing impulse.

The increase in the wavelength of the probing impulse is known to decrease the resolution of the OTDR [6]. Therefore, each measurement cycle of this kind should include obtaining a number of reflectograms at different packet lengths. The data generated by the reflectometer and transmitted to further processing stages should not be the result of an averaged set of received reflectograms, since in this case the Brillouin component of the signal would be suppressed.

In order to extract data on Brillouin inhomogeneities, processing of the digital image of the fiber response stored in the memory of the reflectometer can be performed as follows. First, a number of components are allocated from the entire signal spectrum, each of which occupies a narrow frequency band. A set of such adjacent frequency bands should cover the entire spectrum region of the original signal, in which components due to Brillouin scattering may occur. Each of these narrow-band components is further subjected to amplitude detection. This is followed by averaging over the data of several measurements.

The data set formed at the detection stage and averaged carries information about both the frequency of the Brillouin scattering signal and its amplitude. The latter is determined by summing the amplitudes of all components and can be determined only in cases where there is at least one non–zero summand, i.e., in the fiber sections where the frequency of the Brillouin signal changes. For the remaining points the amplitude should be determined by interpolation and extrapolation methods.

Information about the value of the Brillouin frequency shift is contained in the distribution of amplitudes between the components and can be isolated in the manner described below. With each signal envelope obtained as a result of detection, an action is performed that can be called conditional or adaptive inversion. The next step is time integration. The data obtained as a result of it for each narrow frequency band should be multiplied by weight coefficients, and the products should be summed up element-by-element in order to obtain the dependence of the tension (or temperature) of the fiber on its length. The result together with the previously obtained data on the signal amplitude is used to form a three-dimensional Brillouin reflectogram.

The idea of adaptive inversion is that the signal is either inverted or not, depending on certain conditions. The need for inversion is due to the absence of an additional frequency shift Δf_{add}, considered in the first part of the paper (see Figure 1), and, accordingly, because of the fact that the signal directly received by the described technique does not contain information about the signs of change in the measured value as the probing impulse propagates along the fiber. As we have shown earlier, this information can be extracted from the data of several measurements in which packets of different lengths are used.

Thus, during the measurement process, a number of sets of digital data samples must first be obtained, representing the averaged results of the amplitude detection mentioned above. Sets are formed when different probing impulse lengths are specified. Then we make the tables of points in the inversion mode of signals for switching on and off o. Further processing is carried out taking into account these tables.

Let's note also that the absence of an additional frequency shift Δf_{add} excludes the possibility of detecting short inhomogeneities, which are characterized by a slight change in the frequency of the Brillouin scattered signal. This is a significant disadvantage of this variant of the technical implementation of the considered technique.

It should be assumed that not every reflectometer can be used for this kind of measurement. In addition to the ability to save raw data received from the ADC to a file and the possibility of external control from a computer, it is necessary to note the special requirements for its laser.

The requirements for Brillouin reflectometer lasers are significantly more stringent than for conventional ones. The laser should form one narrow spectral line [7]. A significant change in the oscillation frequency of the probing impulse throughout its length (chirp) is not allowed. This phenomenon is typical for the case of applying a modulating signal directly to the laser. Therefore, the reflectometer must have a separate optical modulator. We should emphasize that the considerable width of the spectral line makes it difficult or impossible to identify inhomogeneities characterized by a slow increase and decrease in the frequency of the Brillouin signal.

In addition, it follows from the abovesaid that the duration of the probing impulse should be several times longer than the maximum period of the difference frequency component of the signal involved in this measurement. This means that the bandwidth of the receiving path of the reflectometer should be wider than necessary for conventional reflectometry for a given packet duration. Since the signal-to-noise ratio increases when the bandwidth is narrowed, developers most likely strive to optimize it for each duration of the probing impulse, which is a significant obstacle to the proposed measurement technique [8].

The study of the available reflectometers for their suitability for the considered application has not been carried out. However, the authors consider it to be a very promising area of research, giving a chance to implement the simplest and most affordable installation for Brillouin reflectometry. Although this method cannot be considered a fully-functional replacement for the conventional one, it can be widely used both in the field of distributed fiber-optic sensors and for early diagnostics of telecommunications optical cable malfunctions [9].

3 RESEARCH AND DISCUSSIONS

The authors of the report conducted experimental studies using the Brillouin optical reflectometer of the Swiss company "Omnisens SA" DITEST Interrogator on a single-mode optical fiber of the G.652 standard according to the scheme in Figure 4.

The magnitude of the Brillouin frequency shift from the radius of curvature of the optical fiber winding was investigated. At the same time, two cylinders with diameters of 37.5 mm and 19.9 mm were used. In both cases, 2 meters of optical fiber were wound on the cylinders. The measurements were carried out at different spatial resolution capabilities of the device.

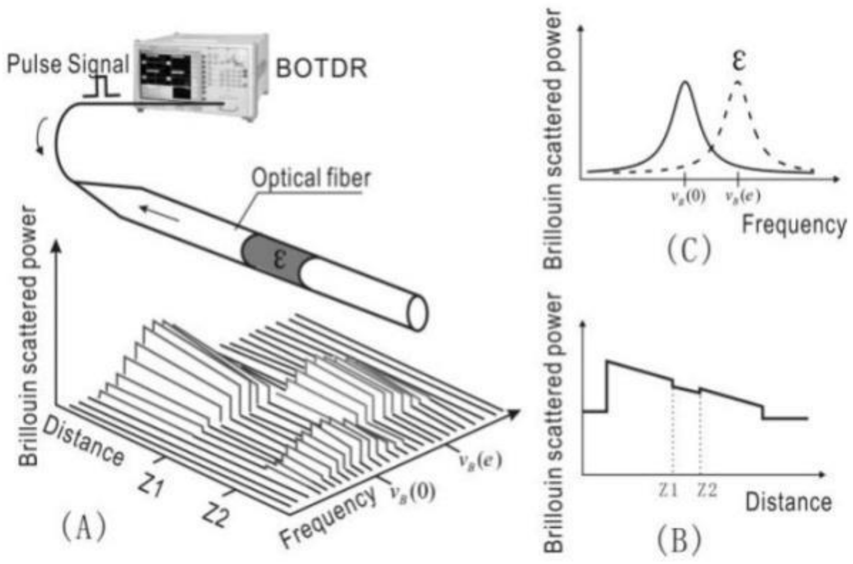

Figure 4: The scheme of experimental studies.

The spectrograms obtained during the experiment are shown in Figures 5-8, where 1 – 17 turns, diameter 37.5 mm, 2 – 32 turns, diameter 19.9 mm.

With an average Brillouin shift without deformation of 10.7802 GHz, the difference was 2.9 MHz.

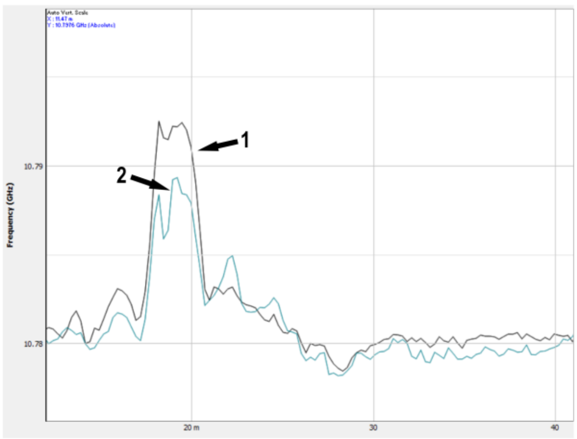

Figure 5: Spectrogram for an optical fiber of the G.652 standard at a resolution of (1-0.25) m.

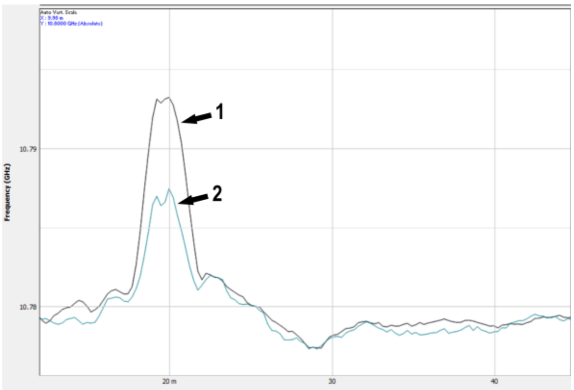

Figure 6: Spectrogram for an optical fiber of the G.652 standard at a resolution of (2-0.25) m.

The additional Brillouin shift was 5.7 Mhz.

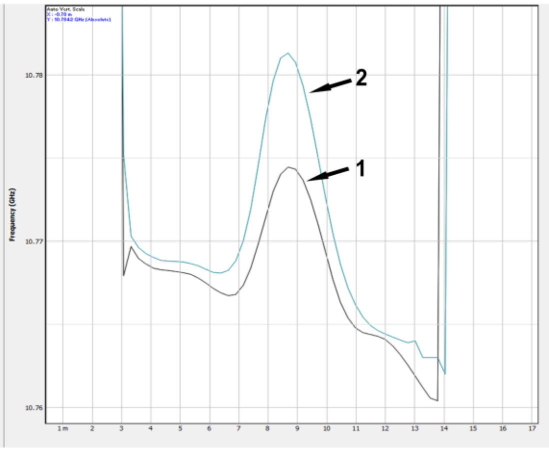

Figure 7: Spectrogram for an optical fiber of the G.657 standard at a resolution of (2-0.25) m.

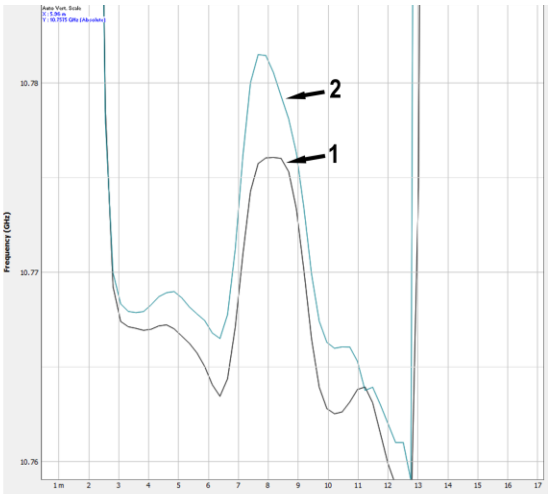

Figure 8: Spectrogram for an optical fiber of the G.657 standard at a resolution of (1-0.25) m.

The results obtained show that the value of the additional Brillouin frequency shift is inversely proportional to the bending radius of the optical fiber.

4 CONCLUSIONS

The proposed model of frequency-difference Brillouin reflectometry enables the improvement of the control quality of the main transfer parameters of optical fibers. In addition, the model is efficient for monitoring during the technical operation of fiber-optic communication lines.

Optical reflectometers based on the Brillouin scattering principle can be widely used in telecommunications systems, mechanical engineering, electric power, construction, aviation and space. They can take a special place in control and automation systems of technological processes and objects. They are widely used to prevent natural disasters. However, there are no generally accepted or well-developed standards for Brillouin reflectometer applications, which has led to the embarrassing fact that they cannot be adopted in some intelligent design and construction structures, especially for safety-related functions. This fact is pointed out in the works of researchers S. Delepine-Lesoille, J. Bertrand, L. Lablonde and X. Phéron [10]. The details of the application should be guided and limited by the relevant industry standards. Proposals and the development of standards or guidelines are necessary to promote the popularization of the use of Brillouin reflectometers.

The objectives of further research will be the metrological analysis of all stages of transformation of measuring information and replenishment of the database of Brillouin spectrograms of optical fibers of various types. Of particular importance is the improvement of algorithms for the automatic processing of spectra in order to expand the functionality of the sensors under study.

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