Improvement of devices for early diagnostics of the optical fibers state of telecommunications systems

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Abstract. A construction of the Brillouin reflectometers schemes is discusses in this work. The algorithms for processing measurement results are consider.

The results presented in the researches allow us to improve the algorithms for processing Brillouin reflectograms by introducing reference channels and a reference database.

The presented schemes of Brillouin reflectometers are of interest for improving optical fiber monitoring systems.

Index Terms. Optical fiber, strain, Mandelstam – Brillouin backscatter, back-reflected signal, Brillouin frequency shift, Brillouin reflectometer.

1. Introduction

Ensuring uninterrupted and high-quality operation of fiber-optic communication lines (FOCL) requires improvement of monitoring systems for timely detection of malfunctions in optical fibers (OFs), as well as early diagnostics of the state of fibers [1, 2].

Early diagnostics of the fiber state presupposes early detection of “precarious” sections of the OF located in the laid optical cables (OCs), which over time can lead to disruption of the normal operation of the fiber optic network [2, 3].

We shall call “precarious” sections of the fiber that have increased longitudinal mechanical strain, changed temperature, leakage channels, and so on. Increased fiber strain affects the durability of the OC [1 – 3]. The longitudinal strain of 0.2% and above is a suspicious event that requires further analysis. Temperature changes in the fiber optic telecommunication system also can indicate the problem segments on the OC laying route (damage in the protective structures of the OC, unauthorized access, etc.) [4].

Thus, it is necessary to control the physical state of the OF, in particular the mechanical strain of OFs in the fiber optic telecommunication systems.

Specialized devices such as Brillouin optical time domain reflectometers (BOTDRs) can be used for early diagnostics of fiber conditions located in laid OCs [1 – 5]. BOTDR allows detecting of OF sections with increased longitudinal tension and temperature changes.

Conventional reflectometers (optical time domain reflectometers – OTDR) widely used in monitoring systems of FOCLs are not designed for such tasks. They analyze Rayleigh backscattering signal [1, 2].
Raman reflectometers are used to analyze only temperature changes [1, 6, 13].

2. Theory. Statement of the problem
A back-reflected signal containing Mandelstam – Brillouin backscattering (MBS) components is analyzed in the BOTDR [1 – 4].
A Brillouin frequency shift (BFS – \( f_B \)) is defined in the process of obtaining of the distribution graphs of the Mandelstam – Brillouin scattering spectrum (MBSS) along the OF (MBSS distribution reflectogram). After that a distribution of the strain along the light-guide is determined [1 – 5].
In the classical structural scheme of the BOTDR, the receiving tract is tuned according to the frequency of the back reflected MBS signal, which allows the transmitting tract to do without tuning the frequency of the emitting source [2 – 4].
Fig. 1 shows a scheme with a non-tunable transmission part used in the “Ando AQ 8603” BOTDR [3].

![Simplify structural scheme of the BOTDR](image_url)

The radiation source is a laser (L) which frequency is \( f_L \) (usually \( \lambda_L \) (wave length) is 1.55 microns), pulse modulation is carried out by a pulse shaper (PS, an electro-absorption modulator – EOM). After changing the polarization, the optical signal is amplified in the erbium optical amplifier (EOA) and enters the testing fiber via the directional coupler (or circulator – C).
The back-reflected optical signal is sent to the input of the receiving device (photodetector – RD) via the coupler (or circulator). This signal contains a Rayleigh scattering component (whose frequency is \( f_L \)) and Stokes and anti-Stokes components of the MBS. The Stokes component displaced down in frequency \( (f_L - f_B) \), and the anti-Stokes component displaced up \( (f_L + f_B) \). Coherent receiving of the signal is used to select the Stokes component. A small part of the input laser signal power is fed to the RD, where this input signal part is mixed with the backscattered lightwave in the OF.
Using the coherent receiving increases the sensitivity of the RD. Compared to the direct detection scheme used in usual OTDR, the improvement is about 20 dB [1, 3]. More sensitive RD implementations (in comparison with OTDR) need to be applied in BOTDR, since the coefficient of MBS is significantly less than the Rayleigh scattering coefficient [1 – 4].
Before measuring, the scanning range is set from the specified initial (F1) and final frequency (F2) and the scanning step \( (\Delta f) \), which is uniform and depends on numbers of observation points \( (N) \) and averaging numbers [3, 10]. After scanning, the distribution of the spontaneous MBSS along the light
guide is detected, and after that the frequency of the MBSS “peak” is determined, which is BSF. After determining BSF, the strain distribution along OF is calculated. The profile of MBSS along the light guide is determined by selecting the difference between the frequency of the source (f_L) and the frequency spectrum of the backscattered signal in the receiving part. A frequency of the researched scanning range (the difference frequencies corresponding to the MBSS are in the band 9 – 12 GHz) in the frequency converter is lowered to values that allow a digitalization of the signal in the processing unit.

There are other types of BOTDR construction schemes [1, 3, 7 – 10, 14 – 16]. For example, in the transmitting tract, we can adjust the frequency of the input signal into the OF through the acoustic-optical modulator, which simplifies the receiving tract, since it will be configured to receive a back-reflected light-wave of the fixed frequency (“Ando AQ 8602”) [1, 9, 12]. It is also possible to use for analysis the Rayleigh reflectogram (as in the OTDR) [5], as well as the introduction of the benchmark channel containing either the fiber in the receiving reference channel [7, 9], or the benchmarking reflectogram from the database of various fiber types [8]. After probing the light guide with short pulses, the MBSS distribution is found along the fibers. After analyzing the MBSS distribution in the light guide, the BSF (values of the MBSS maxima) along the fibers is determined. This makes it possible to determine the strain degree (E_ε – Young’s modulus) of fiber based on the MBS dependence (f_B(E_ε)) and discover the distributed irregularity locations in the light guide:

\[
E_ε(z) = \frac{f_B(E_ε,z) - f_B(0)}{f_B(0) \cdot C_f^ε}, \quad \Delta E_ε(z) = \frac{\Delta f_B(z)}{f_B(0) \cdot C_f^ε},
\]  

where \(E_ε(z)\) is the strain dependence from the longitudinal coordinate \(z\) along the light guide; \(\Delta E_ε(z)\) is the change of fiber strain relative to the initial value; \(f(E_ε,z)\) is the frequency dependence offset from the strain and coordinates; \(f_B(0)\) is the initial value of BSF (f_B); \(\Delta f_B(z)\) is BSF change along OF, \(C_f^ε\) is a coupling coefficient of the corresponding parameters – \(E_ε\) and \(f_B\) (\(C_f^ε = 48 \text{ kHz/µε} = 480 \text{ MHz/}%\)) [2 – 4].

For a more accurate determination of BSF (f_B) is not just the frequency of the received signal with the maximum level, but near the “peak” approximation is performed on the neighboring samples (used to derive the Lorentz’s profile (quadratic parabola) of MBSS needed three dots) to determine the maximum MBS, is a quadratic parabola passing through these samples. In the simplest case, for this resulting parabola, the bandwidth is determined by the level –3 dB from the maximum value, and then BSF is calculated as the average frequency of this range [3, 4].

3. An improvement of devices for determining the Brillouin frequency shift

The measurement process at high resolution and a large number of averaging in the “Ando AQ 8603” BOTDR is very slow, which was confirmed by practical tests. For example, the process of obtaining reflectograms with 50 measurement points, the number of averagings in 216 and the representation accuracy in 0.1 m can take about thirty minutes. Although this time can be significantly reduced by modifying the specified values, it remains significant compared to conventional OTDR.

The process of finding the MBSS “peak” may be accelerated if the process of measurements is made adaptive. Researches of reflectograms detect that not all samples taken at the BOTDR reflectogram nodes with uniform frequency step are of interest to determine the final data.
After an initial scan with a uniform step in each cross-section, defined by the scanning step along the longitudinal coordinate, the intensity of the back-reflected signal is determined and the maximum value for the current samples is selected. After that, the frequency change step is reduced by half, but the next generation of reflectograms based on frequencies of the back-reflected signal will be performed only in areas with signal levels that have intensity comparable to the maximum level (less than 5 dB from the maximum) for each longitudinal coordinate.

Samples in the region of maxima are necessary for further analysis – determining BSF, but samples with intensity values less than 5 dB relative to the maximum level are excluded from further processing.

As a result, this algorithm significantly accelerates the process by decimation and ignoring counts that do not affect the final result.

If the “peak” is detected at a certain step of the process, then the process of determining the fiber tension along the light guide $E_\varepsilon(z)$ can be started in parallel with the main process [10]. The calculations will be refined in the next steps.

Another way to speed up the detection process is adaptive accumulation time of measurements (number of samples) [10]: from the start takes a small number of samples (e.g., $2^{11}$), in the following steps, it is increased (e.g., $2^{13}$), and only in the region of the maxima of the number of averages will be maximum for given conditions (e.g., $2^{16}$).

To speed up the operation of the BOTDR as a whole, you can also offer the organization of several parallel channels of processing. Several samples will be found at each step of the calculation process simultaneously in this case [10].

Typical values of the initial level (for normal conditions – at room temperature and in the absence of mechanical stresses) of the BFS were obtained for popular types of fibers [10, 11]. For a conventional single-mode OF (G.652), the BFS value is in the range from 10.83 GHz to 10.86 GHz. For known types of fibers, we can use the BFS values from the database [11] to determine the scanning range based on the frequency of the measured MBS signal.

Fig. 2 presents the BOTDR scheme [7], which is adapted for use in monitoring systems of FOCLs. The laser (L) radiation passes through the pulse shaper (PS), which generates pulses of the predetermined duration with predetermined repetition frequency, the input of the erbium amplifier (EOA), from which the amplified signal is fed to the input of the adjustable attenuator (AA), which sets the optimal power level of test signal (above the threshold of occurrence of the MBS, but lower threshold of the occurrence of other nonlinear effects) depending on the length of the fiber and its type, from the output AA of the signal supplied to the input of the first optical splitter (OS$_1$) and divided them into two parts [7].

The first (smaller) part of the radiation is input to the first circulator (C$_1$), and then through one of its outputs fed to the input of the reference fiber segment (RFS). This radiation leads to the MBS appearance in the RFS, which is circulated in the reverse direction and returns to the circulator C$_1$. The RFS has the fiber type with the same properties as the tested OF, which is not subject to mechanical tension and has a constant known temperature. Further, the backscattering components pass through the second output of the circulator C$_1$ through an optical filter (F$_1$), which passes only the MBSS band spectrum obtained in the absence of strain in the RFS (the frequency of the maximum of the MBSS is shifted by $f_{\text{B0}}$ relative to the frequency of the laser $f_L$), and then the filtered signal with the frequency $f_L - f_{\text{B0}}$ enters the input of the first photodetector (PD$_1$). As a result, a reference channel is formed that is necessary for further signal processing. The second (most) part of the radiation from the optical splitter OS$_1$ enters the input of the main circulator C$_2$, and from its output through the optical connector (OC) is inputted into the tested fiber.
Figure 2. The BOTDR scheme for using in monitoring systems of FOCLs

Back-reflected signal from the irregularities of the tested fiber, which contains Rayleigh scattering components (they have the same frequency as the laser radiation $f_L$) and MBS (the maximum frequency is shifted by $f_B$ relative to the laser frequency $f_L$), returns to the circulator $C_2$ through the optical connector OC and then enters the input of the second optical splitter (OS2) [7].

Radiation from the first output of the OS2 (a smaller part) is fed to the input of an additional optical filter $F_2$, which is tuned to the laser frequency ($f_L$) to highlight the Rayleigh backscattering signal.

Radiation from the second output of the OS2 (most of it) is fed to the optical filter $F_3$, the bandwidth of which is adjusted so as to pass the MBS components of the tested fiber to the input of the photodetector $PD_3$ to form the Lorentz profile and register the maximum of the MBSS.

When the strain changes, the MBS signal coming from the output of the PD3 photodetector will have less power than the same signal in the absence of mechanical tension. Since the power decrease can also be caused by other factors (temperature changes, defects in the fiber), it is necessary to measure the power of the reverse Rayleigh scattering signal from the output of the PD2. The value of the shift of MBSS and hence the fiber strain degree is determined by the measured power levels.

As practice has shown, even fiber the same type from the same manufacturer have a significant variation in the OF parameters, including the characteristics of MBSS, the analysis of which is used to calculate the degree of the OF strain. As a result, the reference channel formed using a reference OF segment a specific fiber type with a terminator at the end [7 – 10] will form the initial $f_{b0}$ level for a specific variety of fibers, which will differ significantly from the $f_{b0}$ values for other OF types and other manufacturers [9 – 12]. As a result, the efficiency of BFS and strain measurements various OF types and manufacturers is reduced.
To compensate for this drawback, instead of the reference channel that was formed in the prototype [7], a block for generating a database of Brillouin reflectogram templates (BGDBRT) [8] can be used, which has a two-way connection with the processing unit. The BGDBRT stores templates of MBS profiles of various types of OM and different manufacturers [8, 11], obtained as a result of experimental researches and formed by special programs were developed in the OmSTU [10, 11]. They are used in the processing unit to select the best template, set the initial $f_{BO}$ level (BFS at room temperature and without fiber strain), calculate the OF strain, classify OF type. MBS profiles and OF characteristics measured by BOTDR data can be entered into BGDBRT for further use [8, 11]. BFS depends not only on the strain, but also on the temperature [1, 4]. If you need to highlight each of these factors, in addition to determining the BFS value, you should take into account the change in the signal power level, which will allow you to adjust the strain values along the light-guide [7, 8, 10, 12].

Fig. 3 presents the improved BOTDR scheme [9] compared to BOTDR [1, 7, 8], which estimates the effect of temperature and also takes into account the Rayleigh reflectogram data.

Figure 3. BOTDR scheme of the device for early diagnostics of FOCLs
The BOTDR scheme [9] contains an additional (compared to BOTDR [8]) optical switch (K), the main entrance of which is connected to the first output of the optical splitter (OS), a main output connected to the input of the first photodetector (PD 1), the first optical filter (F 1) tuned to the frequency of Rayleigh scattering connected to the first pair of additional inlet and outlet, and the second pair of additional input and output switch connected to the second optical filter (F 2), with bandwidth tunable (and the third filter F 3) under control of the processing unit, which is connected with the control inputs of the pulse shaper (PS) and the adjustable attenuator (AA), with temperature sensor system (T).

After detecting the Rayleigh reflectogram based on the signal that passed F 1 (f L), the intensities of frequency fragments are analyzed (which is necessary for obtaining Brillouin reflectograms) based on the signals that passed through the tunable optical filters F 2 and F 3.

To detect the maximum MBSS, are selected the start and end frequencies of the scanning range and the scan step is set. For known OF types, we can use data from BGDBRT.

In the next step, after switching the filter switch (K) on output PD 1 removed values for the start frequency, and the output PD 2 – ending frequency of scanning range. After that, using the adaptive algorithm [9, 10] for determining the scanning step, the filters are adjusted to other frequencies in the scanning range, the MBSS profile and the frequency of MBSS maximum are determined, which is the BFS for a certain coordinate of the light-guide.

In many of the previously discussed schemes for building BOTDR and processing algorithms, to obtain the final results, you can suggest organizing several channels of the processing in the receiving path. Several samples will be determined simultaneously at each step of the calculations in this case [7 – 9].

4. Conclusion

Using a reference OF segment which is not subject to mechanical strain and has a fixed (or controlled) temperature, allows us to organize a reference receiving channel. In this case, the photodetector will process not the difference between the laser and MBS frequencies, but a much smaller difference between the MBSS frequencies of the researched OF and the reference fiber segment, which simplifies the requirements for digital devices necessary for final processing of measurement results.

In addition, in monitoring systems and early diagnostics of FOCL with known OF varieties in OCs the use of segments of these OF as a reference channel allows us to distinguish exactly the deviation of MBSS in the presence of tension in OF relative to OF, which is under normal conditions.

In the simplified version of BOTDR, as part of the monitoring system, it is possible to use MBS characteristics from the database of known OF types of data to form a reference channel.

Work continues to search for new processing algorithms and improve BOTDR schemes [9, 14 – 16].

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