Automated determination of types and characteristics of the optical fibers state located in the laid cables

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Abstract. The classification of the optical fiber types and influencing factors by using the Brillouin reflectograms are considered. The programs for automated data processing of Brillouin reflectograms are presented. The types of the optical fibers are determined by the characteristics of the frequency profile of the Mandelstam – Brillouin scattering spectrum. Based on the analysis of Brillouin multi-reflectograms, we can detect the factors that effect on the characteristics of the back-reflected Mandelstam – Brillouin scattering signal in the tested segments of the optical fibers.

Index Terms. Single-mode optical fiber, strain, Mandelstam – Brillouin scatter, backscattered signal, Brillouin frequency shift, frequency profile of scattering spectrum.

1. Introduction
Early diagnostics of the state of optical fibers (OFs) is necessary for prediction of operating parameters of physical channels of optical telecommunication systems. This is necessary for early detection of segments of OFs located in the laid optical cables (OCs), which over time lead to a destruction of the OFs and disruption of the normal operation of the fiber optical communication lines (FOCLs) [1 – 3]. Therefore, the control of the physical state of OF is needed in the FOCL monitoring system [3 – 5], since increased longitudinal mechanical loads on the OF affect its durability. Temperature changes in OF in the FOCL can indicate the problem segments on the cable routing (heat main pipeline breakout, unauthorized access, damages to the protective elements, etc.) [6, 7].
The Brillouin optical time domain reflectometers (BOTDRs) are applied for early diagnostics and prediction of states of OFs located in the laid OCs. A backscattered signal of the Mandelstam – Brillouin spontaneous scattering (MBS) is analyzed in the BOTDR [1 – 4]. The Brillouin frequency shift (BFS – $f_B$) is determined in the process of obtaining the graphics of the Mandelstam – Brillouin backscatter spectrum (MBBS) along the optical waveguide. After that the graphics of strain along the light-guide is constructed [5 – 7].
After determining the BFS and elongation (strain) of OF an uncertainty takes place in identifying the factors that caused the BFS change in study segment, since the BFS depends on both the longitudinal strain and temperature of the OF [4 – 7]. Therefore, the factor identification (longitudinal mechanical load or temperature change) that leads to the BFS in tested OF segment in FOCL is useful for early diagnostics and prediction of the optical fiber state in the FOCL. This ensures the real risk of factor (short-term and long-term) for the OF in the FOCL.
The ability to analyze a structure and layer composition, forming an OF core, using the obtained MBBS profiles and specifications of MBS is of practical value [1, 3, 6, 8 – 12]. The database of MBS characteristics, MBBS traces of OFs of various kinds and manufacturers enables us to classify the fiber types in the FOCL and detect potentially unreliable segments [1, 3, 13 – 15].

2. Statement of the problem. Identification of the impact factor on the characteristics of MBS

The BFS ($f_b$) is related to the characteristics of propagation medium by equation:

$$f_b(E, T) = 2 f_{\alpha} v_{\alpha e f f,\alpha}(E, T) n_{e f f} / c = 2 v_{\alpha e f f,\alpha}(E, T) n_{e f f} / \lambda_c.$$  

(1)

where $v_{\alpha e f f,\alpha}(E, T)$ is the speed of hypersonic wave, which depends on the temperature ($T$), longitudinal strain ($E$), and the fiber core structure, $n_{e f f}$ is the effective refractive index of the core, $f_{\alpha}$ is the frequency of the emitting laser ($\lambda_c$ is the wavelength), $c$ is the light speed in vacuum [3 – 7].

The relationship of the BFS to changes in the core and temperature ($E$) and $T$ is determined by:

$$f_b(E, T) = f_{b 0} + C^e_f (E - E_{0}) + C^T_f (T - T_0).$$  

(2)

where “0” are components corresponding to normal conditions (at room temperature ($T_0$) and in loose state ($E_{0}$)). $C^e_f$ and $C^T_f$ are coupling coefficients for the corresponding parameters ($f_b(E), f_b(T)$ [1, 7, 10]. $C^T_f (T - T_0) = f_{at}$ is the offset of the BFS relative to $f_{b 0}$ due to temperature changes [2, 7].

After the analysis of the MBBS-traces in light-guides the $f_b(E, T)$ (values of MBBS peaks) is estimated along the optical waveguide, which is aimed to find the strain degree of all fiber segments and to troubleshoot the irregularities.

The longitudinal strain of about 0.3% and above is a suspicious event that requires further analysis. The offset of BFS caused only by temperature changes, allows strain changes to be highlighted made solely by the temperature. As a result, a graphics of the strain in the light-guide caused only by longitudinal tensile loads is depicted [7].

To do this, besides the determination of BFS (MBBS analysis) and estimation its offset relative to $f_{b 0}$, it is necessary to register the distribution of the level of backscattered MBS signal along the waveguide. After excluding the explicit reflective events such as the joints of different OFs, etc., the OF segments with a linear increase (increase in OF temperature) or decrease (OF cooling) of the intensity ($I$) of the backscattered MBS signal along the waveguide are determined [4 – 7].

The temperature change is calculated as follows:

$$\Delta T = T - T_0 = \frac{I(T) - I(T_0)}{1.0033 \frac{[\text{dB}]}{[\text{dB} / \% C]}}.$$  

(3)

This provides an opportunity to determine the BFS and OF strain change at a fixed temperature $f_b(E)$ and to select the strain due to the longitudinal tensile forces:

$$f_b(E) = f_{b 0} + C^e_f (E - E_{0}) + f_{at}. \quad E = E_{at} + (f_b - f_{at} - f_{b 0}) / C^e_f.$$  

(4)

Special programs were developed at the OmSTU in order to automate and accelerate the process of type determination of potentially dangerous factors for OF by using the Brillouin reflectograms, and to evaluate BFS and strain changes [13 – 15].

3. The analysis of profiles of the MBS spectrum by the Brillouin reflectograms

The doping materials and changes in their concentration, the structure of OF layers influence on the velocity of hypersound in the OF and the effective refractive index [3, 8 – 13]. Depending on the types and concentration of doping, it is possible to modify characteristics of the fiber core within certain limits, which in turn lead to the change of the BFS and MBBS profile [8 – 10, 13? 16].

Fig. 1 illustrates the dependences of $f_{b 0}$ on the concentration of germanium oxide (GeO$_2$ in %) at fixed fluorine (F in %) concentration.
Figure 1. Dependences of $f_{B0}$ on the concentration of germanium oxide (GeO$_2$ in %) at fixed fluorine concentration (F in %)

The fiber structure with concentration of doping significantly influence on characteristics of the acoustic modes of the OFs. Although the differences in the distribution characteristics of lower order optical modes in the fiber are insignificant, these differences in the interaction between optical and hyperacoustic waves lead to the changes of the structure of MBBS traces, amount of “humps” and their levels [7 – 10].

Figures 2 – 4 illustrate the examples of frequency profiles of MBBS for some single-mode OF types obtained in experimental researches [1, 3, 13].

Fig. 2 shows the MBBS graph of the G.652 fiber.

Figure 2. MBBS graph of the G.652 OF

The MBBS graph of G.653 OF (dispersion-shifted single mode fiber – DSF) is presented in Fig. 3.

Figure 3. MBBS graph of the G.653 fiber (DSF)
Fig. 4 illustrates the profile of the G.657 fiber (OF with high resistance to bends).

Figure 4. MBBS profile of the G.657 OF

The start frequency (F1) in the lower left corner and stop frequency (F2) in the lower right corner are shown in Fig. 2 – Fig. 4, position (f_B) and the intensity of the MBBS peak are shown in the upper right corner, MBBS linewidth (at level of 3 dB) and the grid step on intensity axis (5 dB) are depicted in the left corner. Grid step along the frequency axis: on “lines” – (F2 – F1)/5, on “points” – (F2 – F1)/25.

A slight rise in the profile graphs of all OF in the range of 11.0 – 11.5 GHz is observed due to the presence of the core-cladding interface.

Experimental tests of the characteristics of the MBBS in different types of OFs and manufacturers performed by BOTDR allowed to determine the start level of BFS (f_B0) for each tested variety of OF and to create a database with characteristics of MBBS of the different OF types and manufacturers [1, 3, 13? 16]. It is used to classify the type of the OFs.

Special programs were developed in the OmSTU to automate and speed up the process of forming the database with characteristics of MBBS of the OFs, changing the samples based on Brillouin reflectograms [13, 14].

4. Programs for automatized determination of types and characteristics of the optical fiber state and influence factors

The concept of the programs [1, 13, 14] is based on the analysis of the image uploaded by user from a BOTDR, and the selection of the image element used to highlight the MBBS profile and to classify the OF type [14].

The correlation score of matching the uploaded file with the template is expressed by:

$$ C_r = \sum_{i=1}^{N} (k_0^i \cdot k_g^i), $$

where $C_r$ is the correlation score of matching, $k_0^i$ are the coordinates of the template, and $k_g^i$ are the coordinates of the uploaded graph. Summation occurs over the entire array of graph coordinates [1, 13].

Another modification of the program [14] uses a classification algorithm using the r-Pearson correlation, which works as described below.

First, the sum of all coordinates on the ordinate axis is calculated for both uploaded image and sample. Second, the average value of the coordinates (for both graphs) is evaluated.

Third, the deviation from the average value is found for each one; then these deviations for each coordinate are squared and added together to get the dispersion values for both graphs. Subsequently, the deviations for each pair of coordinates are calculated, and the results are summed.

The correlation score [13, 14] in programs is estimated using the next equation:

$$ C_r = \frac{\sum_{i=1}^{N} (k_0^i - M_0^i) \times (k_g^i - M_g^i)}{(N-1) \times \sigma_0^2 \times \sigma_g^2}. $$

where $k_0^i$ is the coordinate of the uploaded image, $M_0^i$ is the mathematical expectation of the coordinates of the uploaded image, $k_g^i$ is the sample coordinate, $M_g^i$ is the mathematical expectation.
of the sample coordinates from the database, \( N \) is the number of coordinates (in our case \( N = 250 \)), \( \sigma^2 \) is the dispersion of the coordinates of the uploaded image, \( \sigma \) is the dispersion of the sample coordinates [1, 13].

Images of all uploaded templates can be presented to the user. As a result, the program displays the sample that has the best match with the uploaded image.

The improved version of the program [13, 14] permits user not only to select the MBBS profile from the BOTDR reflectogram, but also to determine the MBS characteristics and estimate the strain along the waveguide.

The uploaded image of the MBBS distribution along the waveguide is depicted in the upper left corner in Fig. 5 and Fig. 6. The required region for analysis is automatically “cut out” by the program, then the profile of the MBBS of OF is formed and displayed on the screen (the middle upper image), and the data is analyzed. In addition, the data needed to determine the MBBS characteristics is highlighted.

Fig. 5 depicts the screen after selecting the MBBS profile.

![Figure 5. Copy of the screen with reflectograms and profile selection](image)

At this stage, the program also determines and presents the start and stop frequency (in GHz), as well as the intensity (in dB) of the backscattered MBS signal at the maximum (upper right corner).

Note that the user can modify the characteristics in this version of the program [14].

The “Approximate” button means that the obtained OF MBBS profile is compared with sample graphs from the program database based on a special algorithm described earlier. For convenience of study reflectograms, the sample that has the best match with the uploaded image is highlighted in green.

Fig. 6 illustrates the screen copy after selecting the MBBS profile. We also observe the obtained values of the BFS (in MHz) and strain (in %) change. (In this example, the “LEAF” OF heated to +90 °C is analyzed).

To detect the influence factor and compensate the influence of temperature on the BFS and OF strain, the “Multi” tab should be activated, and then the file with the image of the BOTDR multi-reflectogram should be downloaded [7, 15].

Each BOTDR multi-reflectogram (an image of which is shown in Fig. 7 – Fig. 10 in the upper left corner) presents the corresponding dependences of the strain along the waveguide (“Strain”), MBBS profile for the selected longitudinal coordinate (“B.S.”), MBBS linewidth (B.S.W) and the intensity of the backscattered light wave (“Loss”) [7, 13].
The data required for analysis is automatically selected by the program, and then a frequency graph of the MBBS of the OF is generated, as well as graphs of the strain and level of the backscattered signal, which are displayed on the screen and used for further analysis.

![Figure 6. Determination of the OF type, BFS and strain level](image1)

The temperature (“T0”) selected as the start temperature (Fig. 7) is also displayed.

![Figure 7. Screen shot after downloading the file with multi-reflectogram](image2)
The “Calculate” button for the OF segment means that the BFS changes relative to the initial one are calculated, and then the OF strain is estimated (elongation or compression - negative elongation), as well as the temperature of the tested OF and its changes (“∆T”) relative to the initial one (“T0”) are determined (see Fig. 8).

If the “T0” changes after clicking the “Calculate” button, the difference between the temperature and strain of the OF can be corrected [15].

The BFS change (caused only by a temperature change) is determined by the graph of the level of the backscattered signal (“Loss”) based on the algorithm described earlier, and the corresponding compensation in the longitudinal strain dependencies is made [13, 15].

Fig. 9 shows the screen copy with the calculation of BFS, temperature and strain. The graph of BFS changes due to temperature influences is displayed in the lower right corner (Fig. 9) [15].

The “Compensate” button (on the strain graph in the lower right corner) means that the corresponding compensation of changes in the BFS and strain dependencies (caused only by temperature influences) will be made (Fig. 10) [15].
5. Conclusion
The results presented in this study show how to automatically identify the factor having a predominant influence on the BFS and the OF strain in the studied segments of fibers by using the Brillouin multi-reflectograms.

This feature increases an efficiency of the prediction of operating parameters of physical channels in optical telecommunication systems.

Selection of the MBBS profile and other characteristics of the MBS allows user to create the database of the OFs of various types and manufacturers, which can be used for classification of the OF type.

If both the power change of the backscattered MBS signal and BFS displacement are observed, user can automatically estimate the temperature variation and modify the longitudinal strain graphs, which results in the detection of longitudinal tensile effects in the OF.

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