This work presents the results of research on the possibilities of automating the processing of measurement data obtained from the Brillouin optical time domain reflectometer. Analyzing the parameters of the Mandelstam -Brillouin scattering obtained by processing data from Brillouin reflectograms, it is possible to identify the type of fibers in optical cables of telecommunication systems, as well as to evaluate the change in the Brillouin frequency shift and determine the degree of longitudinal strain of optical fibers. The initial values of the Brillouin frequency shift and the Mandelstam - Brillouin scattering spectrum differ for each kind of optical fibers. The developed programs for processing of Brillouin reflectogram data are presented. Conclusions are drawn about the accuracy of the estimates obtained by various algorithms, based on the accumulated experience in working with the presented programs. Estimates of the work of programs using various algorithms are given. The presented programs make it possible to classify the optic fibers according to the Brillouin reflectograms, calculate the characteristics of the Brillouin frequency shift and the degree of longitudinal strain, as well as identify the impact factor on the fiber and compensate for the influence of temperature influences. By analyzing the level of the back-reflected signal, it is possible to obtain distributions of longitudinal strain along the optical fiber caused only by mechanical influences on the optical fiber. For a more complete and accurate analysis of the Mandelstam-Brillouin scattering spectrum and classification of the type of optic fibers, full Brillouin reflectogram measurement data files should be used. Further improvement of programs for automated processing of Brillouin reflectograms is associated with additional assessments related to the combination of the studied graphs according to the positions of the Mandelstam - Brillouin scattering spectrum maxima.
Introduction

High competition among communication operators causes the necessity of automated monitoring of transmission parameters of optical fibers (OFs). For reliable functioning of communication fiber optical systems, it is necessary to carry out early diagnostics of the physical condition of optical fibers in optical cables (OC) [1-3]. Brillouin reflectometers (BOTDR – Brillouin optical time domain reflectometer) are used to identify the areas of OF with altered tension and temperature in the OC [4-6]. A functioning of the BOTDR is based on the analysis of the characteristics of the Mandelstam – Brillouin scattering (MBS).

Due to the properties of the distributed sensing of communication lines using Brillouin scattering system based on the Brillouin scattering principle, low-power lasers are used, it has a high dynamic range for non-destructive measurement of the attenuation. This ensures portability compared to traditional reflectometry using lasers with high power. In addition, they are not critical to Fresnel reflections.

Research methods and results

Currently, many varieties of OF have been developed for various purposes [4, 7-10]. The composition of suppliers of materials used for the production of OF and the manufacture of OC (as well as manufacturers of OF and OC themselves) in Russia has changed significantly in recent years. The assessment of the optical characteristics of the OF in the laid OC, as well as the classification of varieties of OF in OC (including OF of similar types, but different manufacturers) are urgent tasks [7-10].

To solve them, it is advisable to obtain and analyze Brillouin reflectograms. With the help of data obtained using BOTDR, it is possible to determine the kind of the fiber in the OC, because the frequency parameters of the MBS are different [7-12].

In the structure of modern OF, there may be several layers, the optical and acoustic properties of which are different, which affects the formation of the MBS spectrum [4, 9-12].

To study the parameters of the MBS (MBSS and calculate the frequency of the main maximum of the MBSS – Brillouin frequency shift – BFS) for all tested varieties of fibers, data from BOTDR reflectograms are required [9, 13, 14]. Having a set of MBS parameters (MBSS profiles) of various types of OF, it is possible to classify OF in OC, as well as to speed up the identification of potentially unreliable fiber sections of the FOCL by automating the processing of research results [13-15].

Figure 1 shows the BOTDR reflectogram (MBSS distribution along the length of the light guide obtained after processing the measurement results in the BOTDR “Ando AQ 8603”). The light guide consists of a normalizing coil (OF1 (ITU-T G.652 recommendation). The length of the OF1 is approximately 1 km) and of two types of the OF with an offset cut-off wavelength (G.654 ITU-T. This is OF with an offset cut-off wavelength equal to 1530 nm): OF2 is the OF-G.654E “Fujikura” and OF3 is the OF-G.654 “Corning”.

In the lower right corner, the MBSS profile is shown in the selected cross-section of the light guide (at a distance of 1103.72 m, where the section of the light guide consists of OF2 – OF-G.654E “Fujikura”). There are also indicated the BFS (fB = 11.0032 GHz), the bandwidth of the MBSS (fB = 179.5 MHz) and the level of the back-reflected signal at the maximum (Am = A(fB) = 82.380 dB).

Fig. 1. Example of the initial Brillouin reflectogram of the light guide

In the lower left corner there are data on the maximum measurement distance (2 km), refractive index (1.46810), duration of the probing pulse (10 ns), the number of averaging (214), the resolution presented after processing along the length of the light guide (0.1 m), as well as data on the frequency characteristics of scanning (F1, F2, n, N and h), which are required to obtain values at grid points along the frequency axis [13-15].

Since the BSS profile in the maximum region has a parabolic shape, it is convenient to apply second-order interpolation. To reduce calculations when processing arrays of the following templates, you should save the results of additional calculations for the array under study. This will avoid repeated calculations, as well as make possible subsequent interpolations more accurate.

To form the BOTDR reflectogram (obtaining the MBSS, and then calculating the BFS and longitudinal tension), a frequency scan is performed, which in this case begins with the frequency F1 (for example, in Fig. 1 F1 = 10.8 GHz = fB) in increments h (h = 20 MHz).

The frequency F2 (F2 = 11.6 GHz in Fig. 1) is achieved only when the scanning process passes through all points of the frequency grid (n = N = 41). Since the scanning process during BOTDR operation can be stopped at any step n (in Fig. 1 n = 30), the frequency of scanning completion in this case is equal to:

\[ f_2 = f_1 + h(n-1) \]  

For example, for the reflectogram in Fig. 1 fB = 11.5 GHz. The highest value of the level of the back-reflected signal (Am) will be observed at BFS (fB).

Figure 2 shows an example of a profile with MBSS taken at the same measurement on another section of the same light guide. But on this site (OF3) OF was used a different manufacturer (“Corning”) was used, although of the same variety (OF-G.654).

At the same time, the BFS is equal to 11.0513 GHz. Figure 3 shows the MBSS profile for a similar variety of G.654E JSC “Optical Fiber Systems” (Saransk) under normal conditions [8]. The BFS in this case is equal to 11.0289 GHz (“0” ... “250” along the frequency axes are the numbers of scan samples).
Comparing the MBSS profiles shown in Figures 1-3, you can notice their differences, which can be used to identify the types of OF.

Let’s analyze the algorithms used to determine the type of OF in the presence of samples of Brillouin reflectograms (templates) of previously studied OF. Earlier in the works [4, 9, 13-15], some algorithms have already been considered, which, based on the correlation assessment of the coincidence of the uploaded MBSS image with templates from the database of reflectograms.

The analysis showed that, taking into account the specifics of the data processing of measurement results in BOTDR (Brillouin reflectograms), it is convenient to rewrite the correlation estimate (Kc) according to the r-Pearson criterion in the following form:

\[ K_c = \frac{\sum_{i=1}^{N} (a_i - \bar{a}_i)(a'_i - \bar{a}'_i)}{\sqrt{\sum_{i=1}^{N} (a_i - \bar{a}_i)^2} \sqrt{\sum_{i=1}^{N} (a'_i - \bar{a}'_i)^2}}, \]  

(2)

where \( a_i \) is the ordinate value in the \( i \) node of the frequency grid (abscissa) of the loaded array, \( a_{i} \) is the arithmetic mean of the ordinates of the loaded array, \( a'_{i} \) is the ordinate value in the \( i \) node of the frequency grid of the evaluated template, \( a'_{i} \) is the arithmetic mean of the ordinates of the evaluated template, \( N \) is the number of coordinates of the frequency range for analysis [14-17].

The process of calculating the \( K_c \) is carried out for all samples from the database of reflectograms of OF, and as a result, a “sample” with the maximum value of \( K_c \) is selected.

If the frequency ranges coincide (or after matching the frequency graphs), the evaluation of the coincidence of the reflectograms should be carried out according to the following formula:

\[ K_c = \frac{\sum_{i=1}^{N} (a_i - \bar{a}_i)^2 \cdot k_i (A_i)}{N}, \]  

(3)

where \( k_i \) is the coefficient of “importance” of the “i” reference.

A “sample” with a minimum value of \( K_c \) according to formula (3) will be considered as the template having the best match with the analyzed profile of the MBSS [14].

If the data on the ordinate axis (the \( v \) value in the frequency \( f \) array) differs from the ordinate grid of the template, then it is necessary to interpolate by neighboring values. Since the MBSS profile in the maximum region has a parabolic shape, it is convenient to apply second-order interpolation. To reduce calculations when processing arrays of the following templates, you should save the results of additional calculations for the array under study. This will avoid repeated calculations, as well as make possible subsequent interpolations more accurate.

Since the significance of the counts (ordinate values) decreases with distance from the maximum value, it is possible to increase the efficiency of estimates by choosing the adaptive value of \( k \) (depending on the magnitude of the decrease in the level relative to the value in the maximum). For example, take in (3) \( k = 0.95 \) for \( A_i \) values that differ from the maximum by \(-3...-5 \) dB, and for values with a level of \(-5...-9 \) dB from the maximum level \( k = 0.9 \) and so on.

For a more accurate classification of the type of OF, the similarity estimation algorithm should be improved. When assessing the degree of coincidence of reflectograms, it is necessary to make a single scale of graphs along the abscissa and ordinate axes. Since the tension and temperature of the investigated OF may differ from similar characteristics of the “model” OF, in this case, an erroneous classification is possible (the wrong template will be selected).

For example, when the OF–G.652 is heated to a temperature of \( +60 \) °C, the profile of the MBSS (and the BFS) shifts, and in this case \( f_{B} \approx 10.90 \) GHz (at room temperature – \( f_{B} \approx 10.84 \) GHz).

In this case, it would be advisable to align the position of the main maxima and bring the axes to a single scale before comparing the data arrays. To do this, you will need to recalculate the scale and coordinates along the abscissa axis for the template. It is also possible to shift all points along the ordinate axis by the amount of the difference in values in maxima, which will lead to their identical values.

After analyzing the data of the loaded array, it is possible to determine the magnitude of the offset of the BFS (the difference between \( f_{B} \) and \( f_{B0} \)) and the change in the level of the back reflection signal in the region of the maximum MBSS. This makes it possible to determine changes in the tension of the OF under the influence of various external factors [16-17].

To process the data of BOTDR reflectograms, automate calculations and classify the factors that caused changes in the BFS and longitudinal tension, programs were created at OmSTU [16, 17], the work of which is briefly described below.

An example of the screen of the program used to classify a variety of the fiber (OF–G.655 – NZDSF) is shown in Figure 4. After starting the program, you need to download the BOTDR output reflectogram file. Figure 4 in the upper left corner shows a loaded multireflectogram indicating the characteristic areas and BFS. It shows the dependence of the tension, the width of the MBSS, the signal level and the profile of the MBSS. (Any other type of BOTDR reflectograms can be used, which contains the characteristics of the MBSS.) After that, the process of allocating data corresponding to the MBSS schedule is started. This MBSS graph is displayed to the right of the multireflectogram image (Fig. 4), and after it follows the graph of the normalized array, which will be compared with the template database.

After the analysis (in this example, based on formula (2), the “sample” (template), which, according to the final estimates, received the best match with the analyzed image (the maximum value of the estimate according to formula (2)), is highlighted by the program in green (in Fig. 4, marked with an arrow, as well as the original graph MBSS). “Samples” with a smaller (but close) degree of similarity are highlighted in yellow (shown in Fig. 4).
In subsequent versions of the program, the functions of determining the tension of the OF and additional corrective actions were added. At the first stage, the program automatically determines data on the frequency range, maximum amplitude, etc. The user can access graphical images of all “samples” from the database of reflectograms.

In the improved version of the program [17], after determining the MBSS, the parameters of the MBS are also determined and the value of the longitudinal tension along the OF is estimated.

When analyzing multireflectograms of BOTDR, it is possible to identify areas with a changed temperature and to correct the values of BFS and longitudinal tension based on the isolation and compensation of changes that were caused only by temperature and to correct the values of BFS and longitudinal tension based on the isolation and compensation of changes that were caused only by temperature influences. As a result, the value of the longitudinal tension of the OF is calculated, which was caused by longitudinal force loads [1].

With an increase in the longitudinal tension or an increase in temperature, the value of the BFS increases, but with an increase in temperature, the level of the back-reflected signal also increases [1].

Figure 5 shows a copy of the screen (an example of the program working in the “Multi” mode) when calculating the BFS, temperature and tension, on which a graph of changes in the BFS due to temperature influences is displayed in the lower right corner.

In addition to determining the BFS (and its possible change relative to the initial value), the value of the tension of the OF is calculated, and the temperature of the analyzed OF and its changes (“∆T”) relative to the initial (“T0”) is also found.

According to the reflectogram of the level of the reverse signal (“Loss”), using the algorithm described in detail in [1, 15], it is possible to determine the change in the BFS, which is caused solely by temperature influences.

After pressing the “Compensate” button in the lower right corner of the screen, the corresponding compensation of changes
in the degree of longitudinal tension due to temperature changes will be made [17].

To compare the results of similarity assessments obtained by various methods, a special version of the presented programs was developed, in which all the obtained estimates were brought together into single tables (Fig. 6).

In the lower left corner (area “1” in the Fig. 6) there is a correlation table between the data from each template from the database and the original image, according to the selected formula and mode. The data in the table are sorted in descending order for estimates by the first two methods, or for the third method (formula (3)) – in ascending order.

Fig. 6. Screenshot of comparisons of estimates of BOTDR data obtained by various variants

The modes are located in the “Mode” section (area “2”):

1. “Default” – no changes are made, all coordinate values are transferred to the selected formula in order from each of the images.

2. “Mutual freqs” – a common frequency range is selected from both images (as well as linear interpolation is performed). This is necessary in order to get the template coordinate values from the database using the same frequency values as in the original image. Then these coordinate values – from the original image and the interpolated from the template from the database are transferred to the selected formula.

3. “Mutual fB” – the same process is performed as in the “Mutual freqs” mode, except that before transferring data to the formula, the positions of the maxima are “aligned” and “cut off” extra coordinates that do not match.

The value “ΔfB” is calculated as the difference between the BFS module (fB) of the source image and the BFS of the template having the best value of the correlation estimate in accordance with the selected mode and formula. The value of “Stretching/Compression” is calculated as the modulus of the ratio of the BFS of the source image to the BFS of the template having the best correlation value, with conversion to a percentage.

By clicking on any row of the table, two graphs are displayed side by side on the same plane – from the original image and from the selected template (area “3”). When displaying, the selected mode is taken into account in the “Mode” section. (For “Mutual freqs” – the general frequency range is used, for “Mutual fB” – the maxima are additionally aligned). Examples are shown in Figure 7.

The analysis showed that the first [6] and the third (3) of the algorithms considered give similar estimates.

Fig. 7. Screenshots of similarity estimates obtained by various variants

One of the problems that was identified as a result of the analysis of a large number of experimental BOTDR reflectograms is the classification of OF for varieties with a single “peak” having similar values of BFS. Since MBSS shifts can be caused by mechanical and temperature influences, this can cause classification errors in such cases.

To increase the accuracy of estimates of the degree of similarity of the MBSS graphs, it is necessary to combine these graphs in the region of maxima before calculations. When assessing the degree of similarity of the graphs of the MBSS OF with a single “peak” having similar values of the BFS, fewer classification errors were found when evaluating the second algorithm (2). Correction of the importance coefficients in (3) improves the accuracy of the third algorithm.

Conclusion

Thus, the presented programs make it possible to classify the OF according to the BOTDR reflectograms, calculate the characteristics of the BFS and the degree of longitudinal tension, as well as identify the impact factor on the fiber and compensate for the influence of temperature influences.

By analyzing the level of the back-reflected signal, it is possible to obtain distributions of longitudinal strain along the optical fiber caused only by mechanical influences on the optical fiber. Differences in the frequency dependencies of the MBSS allow us to identify the type of the OF.

For a more complete and accurate analysis of the MBSS and classification of the type of the OF, full BOTDR measurement data files should be used.

Further improvement of programs for automated processing of BOTDR reflectograms is associated with additional assessments related to the combination of the studied graphs according to the positions of the MBSS maxima.
ВЫЯВЛЕНИЕ РАЗНОВИДНОСТЕЙ ОДНОМОДОВЫХ ОПТИЧЕСКИХ ВОЛОКОН И ОПРЕДЕЛЕНИЕ ХАРАКТЕРИСТИК ИХ ПРОДОЛЬНОГО НАТЯЖЕНИЯ

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Аннотация
В этой работе представлены результаты исследований по автоматизации обработки данных измерений бриллюэновских рефлектограмм, содержащих различные виды одномодовых оптических волокон (ОВ). Анализируя параметры рассеяния Мандельштама – Бриллюэна (РМБ), возможно различить разновидности оптических волокон в исследуемых оптических кабелях (ОК), а также оценивать изменение бриллюэновского частотного сдвига (БЧС) и определять степень продольного натяжения. Начальные значения БЧС и спектр РМБ (СРМБ) для каждой разновидности ОВ отличаются, и эти различия позволяют выявлять тип ОВ. Для выявления участков ОВ с измененными характеристиками и температурой в ОК применяются бриллюэновские оптические импульсные рефлектометры (БИРМ). В настоящее время для различных типов ОВ разработаны многочисленные алгоритмы обработки бриллюэновских рефлектограмм, которые позволяют определить характеристики ОВ. Приведены разработанные программы для обработки бриллюэновских рефлектограмм, которые позволяют определить характеристики ОВ, а также оценивать влияние температуры на ОВ.

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