Research of the influence of optical fibers structure on the spectral characteristics of Mandelstam – Brillouin scattering

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Abstract. Influences of structures of optic fibers, fiber types and the dopant concentration, composition, number and thickness of layers on the characteristics of Mandelstam – Brillouin backscattering are discussed. Results of modeling and experimental tests for different types of optic fibers are presented. The comparative analysis of the obtained results is carried out.

Index Terms. Optic fiber, Mandelstam – Brillouin backscattering, acoustic modes, Brillouin frequency shift, Brillouin reflectometry.

1. Introduction

A forecasting of the physical state of optical fibers (OFs) which are part of the operated optical cables (OCs) is required for evaluation the operational characteristics of fiber-optic channels of infocommunication systems [1, 2]. “Potentially dangerous” fiber segments (OF sections with increased longitudinal mechanical strain, areas with significant temperature changes, etc.) must be identified in advance. Such sections may cause damage to the fibers on the sections of fiber-optic communication lines (FOCLs) over time due to the gradual degradation of the infocommunication network. Therefore in fiber monitoring systems it is necessary to monitor the fiber states, since significant mechanical tensile forces affect the durability of fibers [1–4].

To assess the physical state of fibers that are located in the laid OCs, it is desirable to use Brillouin optical time domain reflectometers (BOTDRs) which analyze the reflected signal of Mandelstam – Brillouin scatter (MBS) [3–5].

After getting a trace of the MBS spectrum (MBSS) distribution along the light-guide, we need to determine the frequency of the MBSS “peak” which is called the Brillouin frequency shift (BFS – $f_B$). Further, a strain distribution along the light-pipe is determined [1–3].

Optical time domain reflectometers (OTDRs) using in monitoring systems of FOCLs are not designed for such tasks. They analyze Rayleigh backscatter signal. To analyze only temperature changes in OF are used Raman reflectometers [1–4].
2. Theory. Statement of the problem

It is possible to distinguish several layers with different physical characteristics in actual varieties of single-mode fibers [5–12]. In this case, the BFS is defined by formula

\[ f_B = 2v_{\text{eff}}(E_e, T)n_{\text{eff}}/\lambda , \]  
(1)

where \( v_{\text{eff}}(E_e, T) \) is the hyper-acoustic wave effective velocity, \( \lambda \) is the laser wavelength, \( n_{\text{eff}} \) is the averaged (effective) refractive factor of the medium. For cases with homogeneous fiber core structure, the formula (1) uses the usual values \( n \) and \( v_A \) [1 – 6]. \( v_A(v_{\text{eff}}) \) depends on the longitudinal tensile loads \( (E_e) \), the fiber temperature \( (T) \), and the fiber core structure.

The relation of BFS to changes in the longitudinal strain or the fiber temperature is calculated by the expression

\[ f_B = f_{B0} + C_{\text{f}}^L \cdot (E_e - E_{e0}) + C_{\text{f}}^T \cdot (T - T_0) , \]  
(2)

where the “zero” indexes \( (f_{B0}, E_{e0}, T_0) \) correspond to conditions when fibers have room temperature and have no any longitudinal strain), \( C_{\text{f}}^L \) and \( C_{\text{f}}^T \) are coefficients for parameters of BSF dependences on the fiber temperature and strain [1 – 6]. At the wavelength of the emitting laser 1.55 microns, MBSS usually occupies the frequency band 9 GHz – 12 GHz.

The values of \( f_{B0} \) for different OF types are given in works [3–5].

In order to determine the characteristics of MBS in well-known types of fibers, it is necessary to analyze the OF structure and features of acoustical modes of this OF [5 – 15].

3. An analysis of the effect of the composition of doping additives on the shape of the MBS spectrum in OFs

The MBS frequency profile (and the MBS parameters consequently in general) forms on the basis of the dependence of the acoustic modes distributing in OFs, the transverse structure in the OF cross-section, and the longitudinal orientation of acoustic modes. Parameters depend on the layers OF structure, as well as on the varieties and concentrations of different doping additives in fibers.

A structure of the OF layers, an adding of alloying supplements and changes in concentration values of alloying substances – all of this affects on \( v_{\text{eff}} \) in the OF core and \( n_{\text{eff}} \) of the fiber core. This in turn modifies both the \( f_{B0} \) value and the frequency profile of MBSS as a whole [4–16].

Graphs of the dependence of \( f_{B0} \) on the GeO\(_2\) concentration and F (fluorine) concentration are given in [3–5, 12]. With changes in GeO\(_2\) concentrations (from 0 to 20 %) and F (from 0 to 10 %), we can vary the values of the initial BFS level \( (f_{B0}) \) from 11.2 GHz to 8.0 GHz [3, 6, 8, 10, 12].

The influence of the P\(_2\)O\(_5\) doping on the OF parameters is considered in works [11, 16].

Researches of the impact of common alloying substances on the optical and acoustic parameters of fibers related to the characteristics of MBS showed the following.

There are additives that increase both the acoustic refractive factor and the optic refractive factor with increasing concentration (while the wave propagation speeds decrease). These are GeO\(_2\), P\(_2\)O\(_5\), TiO\(_2\), and so on [4–7, 10–16].

Other alloying additives increase the optic refractive factor, but reduce the acoustic one. These include Y\(_2\)O\(_3\) and Al\(_2\)O\(_3\) [7, 12, 16].

Another alloying additives lower the optic refractive factor, but increase the acoustic one. These are B\(_2\)O\(_3\) and F [5, 7, 8, 14, 16].

By combining the core layers of different thickness and different composition, you can change the characteristics of the MBS within a wide range.
Fig. 1 shows an example of the MBSS frequency profile for OF-G.653 (DSF – dispersion shifted fiber) obtained in experimental studies [1, 2, 9]. The lower-left corner shows the initial scan frequency the final scan frequency demonstrates in the lower-right corner. BFS is presented in the right upper corner. BFS width is shown in the left upper corner.

The MBBS frequency graph of the ECDF (a fiber with erbium and cerium additives – fiber with radiation resistant effect) is shown in Fig. 2 [12].

4. An estimation of the impact of fiber acoustic modes on the parameters of MBS different kinds of fibers

Researches of different forms of MBS frequency profiles initially were aimed at giving special properties to OFs. For example, by changing the OF structure, the researchers sought to solve the problem of “mitigation of MBS” (raising the emergence threshold of stimulated MBS). As a result, higher intensity of the optic radiation can be input into the OFs without undesirable nonlinear phenomena [4, 8–12].

The effective optic area ($A_{\text{eff}}$) and acousto-optic effective area (the acousto-optic area of the interaction) of the acoustic mode ($A_{\text{Am}}$) with $m$-order the defined by formulas [3, 9]:

$$A_{\text{Am}} = \left( \frac{\langle F^2(r) \rangle}{\langle F^2(r) \cdot \xi_m(r, \varphi) \rangle} \right)^2 \langle \xi_m^2(r, \varphi) \rangle, \quad A_{\text{eff}} = \frac{\langle F^2(r) \rangle}{\langle F^4(r) \rangle},$$

(3)

where $F(r)$ is the allocation of the amplitude of single optic mode fashion on the fiber radius, $\xi_m(r, \varphi)$ – amplitude distribution of the acoustic mode $m$-th order at the OF cross section (the OF radius $r$ and angle $\varphi$, for OF commonly used cylindrical coordinate system). The “corner”-parenthesizes denote that all quantities over the fiber transverse section are averaging [3, 13, 16].

The allocation of the $A_{\text{eff}}(r, \varphi)$ and $A_{\text{Am}}(r, \varphi)$ over the fiber cross-section determines characteristics of MBS. The structures of acoustic modes and the areas of acoustic-optic effective interactions
corresponding to their allocation differ significantly for various structures. There are many acoustic modes that propagate in OFs along the light guide [5–16]. An only single optic mode (HE11 or LP01) propagates in single-mode OFs. The back-reflected signal of MBS is generated when this main optic mode is scattered by all acoustic modes.

Since an ordinary fiber has axial symmetry, all important modes will also be axially symmetric, and the dependence of the acoustic mode distribution on \( \phi (\xi_m(r, \phi) \to \xi_m(r)) \) can be excluded from the analysis [4, 8, 12]. Of the fibers researched, this approval does not apply to OFs that do not have axial symmetry (such as “Panda” – a fiber that preserves the state of polarization [4, 5]. When the fiber is bent, the axial symmetry can also be broken, since the light beam and the field distribution as a whole are shifted relative to the axis of the OF core.

To determine characteristics of the acoustic field (\( \xi_m(r) \)) of the m-th order mode with a known dependence of \( n(r) \), we need to solve the following wave equation:

\[
\frac{\partial^2 \xi_m(r)}{\partial r^2} + \frac{\partial \xi_m(r)}{r \partial r} + \left( \frac{\omega_A^2}{v_A^2(r)} - k_A^2 \right) \xi_m(r) = 0. \tag{4}
\]

where \( \omega_A \approx k_A \sqrt{\frac{v_A^2}{v_A^2 - i\omega_A \Gamma}} \) is the acoustical wave frequency (cyclic), \( k_A \approx \frac{\omega_A}{v_A} + \frac{i \Gamma}{2v_A k_A^2} \) is the wave acoustical factor, \( \Gamma \) is the factor of the acoustic wave damping [3, 8–13].

The capabilities of the fiber internal reflection those are obligatory for the optic mode at the boundary “core-cladding”, do not apply to acoustic modes. Therefore acoustic modes can penetrate into the cladding [3–5, 8–16].

A scattering factor \( (g_{Bm}) \) for the each acoustical m-th mode is calculated by the expression [14]

\[
g_{Bm} = p_{12} \omega_L \beta_m \int_0^b \xi_m(r) F^2(r) rdr, \tag{5}
\]

where \( p_{12} \) is a longitudinal acousto-optic coefficient \( (p_{12} \approx 0.27) \) [3, 8, 9], \( \omega_L = 2\pi f_L = 2\pi c / \lambda_L \) is an input laser frequency (cyclic), \( \beta_m \) is a phase factor for acoustic mode of the m-th order, \( b \) is the OF cladding radius (is taken into consideration that acoustic modes can penetrate from the OF core in the cladding).

The distribution of acoustical modes in the transverse section and the properties of these modes generally depend on the OF structure (the thickness and parameters of the physical layers, the presence of alloying substances and their concentration, etc.). At first glance, differences in the parameters of acoustic modes of near orders are inessential, but these distinctions in acoustic-optical mutual influences can considerably affect to the frequency dependences of MBS, including “peaks” numbers and their relative levels.

Acoustic modes as stated in work [9] can be considered statistically independent. Therefore, a MBS spectrum in the fiber \( (A(f)) \) calculated by simply summing the frequency characteristics of all the acoustic modes \( (A_{Am}(f)) \) under consideration.

\[
A(f) = \sum_{m=1}^{M} A_{Am}(f), \tag{6}
\]

in which the every m-order mode contribution is estimated by the following formula:

\[
A_{Am}(\omega) = \frac{0.5 g_{Bm}^2 \Gamma_m}{(\omega - \omega_{Lm} - \omega_m)^2 + (\Gamma_m)^2}, \tag{7}
\]

and \( M \) is a quantity of acoustical modes taken into account in the analysis.
Knowing the structure (types of alloying substances, physical parameters of layers and their distribution over layers in general, etc.), based on the formulas discussed above, it is possible to determine the functional depending on the parameters of the required number of acoustic modes. This, after analyzing their interaction with the field of the single fiber optical mode, allows us to finally calculate the MBS characteristics [4–14].

A graph of the refractive index profile characteristic for G.655 ITU–T recommendation is shown in Fig. 3. The mode distribution over the OF radius in this case is presented in Fig. 4.

![Figure 3](image)

**Figure 3.** A graph of the refractive index distribution along the OF radius (NZDSF)

Fig. 4 shows graph of the distribution of the main optical (“O”) and the first \((m = 1, 2, 3 – “1”, “2”, “3”)\) acoustical modes over the OF radius in this case.

![Figure 4](image)

**Figure 4.** Graph of the dependences of the mode distribution over the radius OF-G.655 (NZDSF)

As can be seen from the dependence graphs shown in Fig. 4, most of the intensity of acoustical modes is concentrated in the core region, and therefore, acoustic modes effectively dissipate the optical mode. At the core boundary, the acoustic mode field decreases exponentially and disappears in the cladding. The obtained dependences were calculated based on acoustic-optical areas of the interaction using expressions (3) – (7).

For example, Fig. 5 shows the forming of final MBSS for G.653 (DSF) by \(m\)-th order acoustical modes \((A_{lm})\).
Figure 5. Forming MBSS for DSF (G.653)

Modes of the 2-nd and 3-rd orders are comparable in level with the 1-st mode, so MBSS has side maximums with levels commensurable to the main “peak”.

Below are similar graphs for G.652 fiber, which have a conventional two-layer structure (core radius is 4.3 microns, shell radius is 62.5 microns).

Fig. 6 presents the results of modeling the mode distribution over the radius of the SMF-28 (“Corning”) OF with the GeO₂-doped core and the silicon shell. This OF has a GeO₂ concentration of 6%, which leads to an increase in refractive factors by 0.6% and decrease in the longitudinal velocity by 4.3%.

Figure 6. Dependences of the mode distribution over radius of SMF-28 (G.652)

Fig. 6 shows that the fields of acoustic modes is concentrated in the fiber core, therefore, acoustic modes scatter the optical mode quite effectively.

Fig. 7 presents the corresponding simulated spectrum MBS of SMF-28 fiber.
The MBSS in the graph in the Fig. 7 contains two peaks. The contribution of the first-order acoustic mode \( f = 10.8 \text{ GHz} = f_B \) to the MBSS will be predominant. The contribution of the third acoustical mode leads to the small “side peak” (10.95 GHz). The second-order acoustic mode (10.86 GHz) did not make a significant contribution to the MBSS. Fig. 8 shows a graph of the refractive index profile that is typical for a conventional standard single-mode OF (G.652).

As is known, in this case there is one pronounced maximum \( f = 10.86 \text{ GHz} = f_B \). The contribution of the second and third acoustic modes can cause to a very small “peak” in the frequency range 11.05 – 11.15 GHz [3–5].

5. Conclusion
The OF structure (the number and thickness of physical layers, the composition of alloying additives, the dopant concentration, etc.) considerably effects on MBSS parameters. Modelling of optical signal propagation processes in OFs, taking into account the given formulas, allows determining the MBSS profile for various OF types.
The behaviour of acoustic modes makes it possible to estimate the composition of OFs. For each of the fiber varieties we should get the form of the MBSS graphs, define “initial level” $f_{B0}$ and MBS parameters. By selecting the MBSS profile and other MBS characteristics, we can create the OF database of different kinds and various manufacturers. This database may be useful for classification of fiber kinds which increases performances of the operating parameters predicting of optical channels of infocommunication systems.

For most ordinary fibers that have axial symmetry, the analysis is simplified because all accounting acoustical modes also have axially symmetry, and acoustical modes with asymmetrical distribution can be excluded from the processing.

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