Investigation of Brillouin Reflectometry Method Application for Mechanical Stresses Diagnostics in Optical Fiber

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Abstract: The paper strength characteristics and data based on the theory of optic fiber strength. The possibility of application of Brillouin Reflectometry Method for mechanical stresses control in optical fiber is studied. A special attention is given to the analysis of displacement of spectral components in Brillouin scattering of light depending on tension value or fiber elongation. The proposed method makes it possible do detect potentially dangerous sections in optical cable during all production stages and to improve production technologies, used in the cable manufacturing process as well as in the process of building and technical operational support of optical fiber communication lines. Obviously, it is the only optical method which makes it possible to measure the absolute tension value in the optic fiber. In addition, by use of Brillouin scattering spectral allocation along the fiber it is possible to determine the allocation of tension along the fiber line. Determination of the tension value in cable optic fiber allows predicting the reliability of the line as well as timely detecting the risk sections in the communication line.

1 INTRODUCTION

To ensure the long-term operation of the physical channel in optical access networks, it is necessary to guarantee the absence of mechanical tension in the optical fiber (OF). Even a slight tension of an optical fiber can lead to a significant decrease in its service life; therefore, to evaluate the reliability, information is required about the tension of an optic fiber in a cable.

Three groups of linear deformations of optic fiber can be distinguished: safe – up to 0.3%, dangerous from 0.3% to 0.6% and unacceptable – more than 0.6%. Therefore, it is necessary to create a measuring basis to control the deformations of the optical fiber in order to ensure the reliable operation of the fiber-optic communication lines. The most urgent tasks are to study the deformation fields (mechanical stresses) and temperature [1]. The principles of optical fiber deformations measurement are based on a variety of physical effects. However, the greatest practical interest can be given to methods based on the use of Mandelshtam – Brillouin scattering (MBS – acoustic phonons scattering). The Brillouin reflectometry method has two main advantages.

Firstly, it is practically the only optical method that allows to measure the absolute tension of the fiber. To do this, it is necessary to measure only the frequency of the maximum signal in the MBS spectrum and there is no need to undertake additional stretching of the fiber. In other well-known optical methods, the magnitude of the fiber elongation that occurs under additional tension in the fiber is measured, which makes these methods unsuitable for determining the tension of the fiber laid in the transmission line.

Secondly, MBS leads to the formation of a back wave in the fiber. Therefore, by probing the fiber with short pulses and scanning the frequency of these pulses, it is possible to find the distribution along the fiber of the MBS spectrum and, accordingly, the frequency of the maximum signal in this spectrum. And since this frequency is proportional to the tension in the fiber, this shows how this tension along the fiber is propagated [2]. It is known that glass starts breaking from the surface. The degree of its destruction is determined by shell defects. At the same time, the majority of measuring instruments for fiber-optic communication lines are based on measurements of the parameters of optical radiation propagating through a fiber at a wavelength of an optical signal. More than 90% of the optical radiation power of this signal is concentrated in the core of the fiber [3]. Obviously, only the state of the core is controlled. To identify the defects of the shell and, accordingly, to assess the state of the optic fibers, instruments are used based on measurements of the Stimulated MBS parameters (SBS). It is known that SBS is scattering by acoustic phonons and its parameters such as capacity and frequency depend on the internal mechanical stresses in the fiber, and, consequently, on the degree of destruction of the shell [4 – 6].

2 METHODS

2.1 Measurements in Deformations

Various monitoring techniques are currently applied to control fiber condition. These techniques could be classified into several groups:

- Single wavelength Optical Time Domain Reflectometer (OTDR), including upstream OTDR measurements, active bypass, semi-passive bypass, reference reflector, switchable reflective element;
- Tunable OTDR, including wavelength routing and reference reflector;
- Brillouin OTDR (BOTDR);
- Embedded OTDR;
- Optical frequency domain reflectometer (OFDR);
- Optical coding;
- Self-injection locked reflective semiconductor optical amplifier (SL-RSOA);
- Reflective signal.

A detailed description of the monitoring techniques mentioned is given in the work [7]. The most efficient techniques to measure and evaluate deformations in OF are Brillouin reflectometry methods [4 – 6].

In recent few years, the Brillouin reflectometer has proven itself to be a very informative tool capable of detecting sections with loaded fiber in the laid communication lines during their operation. Analysis of the data obtained by using the Brillouin reflectometer allows operating organizations to determine with great accuracy the location of the cable line section with highly loaded fibers, estimate the level of their stresses and evaluate the reliability of the cable line. It is quite natural to use the device at the factory – manufacturer of optical cables during the tests, both in the process of developing the design of new products, and when conducting typical and periodic tests.

Regardless of the type and configuration, the cable is gradually stretched, controlling its stretching and tension. Essential differences in test methods are considered only when choosing the method for recording fiber elongation. The first method consists in measuring the attenuation gain of a fiber in a cable, and it is assumed that the fiber tension is accompanied by such an increase. This method of determining the beginning of the tension of the fiber is very inaccurate and depends on the design of the cable and the device used to stretch it. For example, when testing a cable with a central tube, it is not clear why a damping increase should occur, if you do not take into account edge effects. For a longitudinally stretched fiber that does not touch the cable walls, there are no direct mechanisms for generating attenuation gain. The second method, the phase shift method, or the method for detecting the propagation time of light pulses in a stretchable fiber, practically has no drawbacks. At the moment when the fiber begins to stretch in a stretchable cable, the optical path length for light pulses begins to grow, their propagation time increases, and the device registers it. But in a real situation, as the dimensions of the setup are limited, the device detects the accumulated effect along the length of both in the stretched fiber and in the transient region, where the tension smoothly increases. Moreover, in case when several fibers of the cable under test are welded into the cable, there is an additional uncertainty associated with the possible spread of excess lengths of different fibers. It is clear that the level of fiber elongation detected by this method is average with an unpredictable level of error.

2.2 Brillouin Reflectometry Method

The Brillouin reflectometer has at least one indisputable advantage – it makes it possible to measure the distribution of fiber tension level along the length. This removes all the uncertainties mentioned above. The result of measurements carried out by the Brillouin reflectometer is a well-localized distribution of tension, which makes it possible to isolate and take into account the edge effects and the variation of the tension in different fibers in case of their welding into a stub. MBS is the scattering of optical radiation by condensed media (solids and liquids) as a result of its interaction with own elastic oscillations of these media. It is accompanied by a change in the set of frequencies (wavelengths) characterizing the radiation – its spectral composition. In the spectrum of the backward wave in the fiber, in addition to the unbiased component due to Rayleigh light scattering, there are also spectral components caused by Brillouin (MBS) and Raman light scattering (RS) on Figure 1 [6, 8].

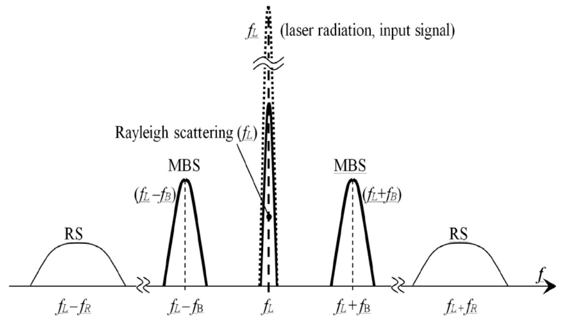

Figure 1: Spectrum of light scatterings in the fiber (f_B ~ 10 … 11 GHz, f_R ~ 13 THz).

The occurrence of these components can be explained as follows. In the case of Rayleigh scattering, the light is scattered on the fluctuations of the refractive index frozen in the fiber, and therefore the frequency of the scattered light does not change.

In MBS and Raman scattering, the frequency of scattered light changes, since scattering occurs on time-varying fluctuations of the refractive index (caused, respectively, by thermal fluctuations of the medium density and intramolecular vibrations) [6, 9].

When the power of light pulses is less than 25 ... 30 dBm, Rayleigh scattering makes the main contribution to the power of the reverse wave. For comparison, the spontaneous MBS (SPBS) coefficient $\alpha_B \cong 0.03/\lambda^4$ is approximately 14 dB less than the Rayleigh scattering coefficient $\alpha_0 \cong 0.75/\lambda^4$, where λ is the radiation wavelength in microns [1]. When the threshold value is reached (~ 5 dBm with continuous pumping), the dependence of the reflected power on the pumping power becomes nonlinear. At the threshold increase, the result from SBS scattering becomes comparable with Rayleigh scattering. With an increase in the pump power several times, almost all the power is reflected from the fiber [2 – 4].

Weaker spectral components due to SPBS can be distinguished using an optical filter, since they are different in frequency.

2.3 Determination of the Fiber Tension

The threshold power can be increased by reducing the effective length of the interaction of the light wave with the acoustic wave. For a single pulse, the effective length is equal to half the pulse length [8]:

$$L_{eff} = L_p = \frac{c \cdot \tau}{2 \cdot n}, \qquad (1)$$

where τ is the pulse duration;

c is the speed of light in vacuum;

n is the group index of refraction of the fiber (n = 1.5).

For a typical value of τ = 1 μs, we obtain L_{eff} = L_p = 0.1 km, which is approximately two orders less than the magnitude of the effective interaction length (L_{eff} = 20 km) for a narrow-band radiation source.

The spectral components due to MBS have such an important property for practical applications as their frequency which is shifted by an amount proportional to the tension (relative elongation ε) of the fiber. For a standard single-mode fiber (SMF – G.652), the measured value of the coefficient is [8 – 10]:

$$K = (f_B - f_{B0})/\varepsilon, \qquad (2)$$

where f_B is the frequency shift when registering the fiber tension (Brillouin frequency shift);

f_{B0} is frequency shift in the absence of fiber tension (strain);

ε is the relative elongation of optic fiber.

Thermal fluctuations in the medium density can be considered as a combination of elastic waves propagating in a medium in all possible directions and possessing all sorts of frequencies. Each flat sound wave is similar to a diffraction grating, since in places with the increased density, the refractive index of the medium is greater than in discharged locations.

For a light wave of length λ, there will always be a grating with a suitable period providing the maximum reflection of light in the opposite direction. The length of the corresponding sound wave is determined by the Bragg – Wulf condition: $\Lambda = \lambda/2$. In the fiber, MBS is observed only backward (the frequency shift between the pump and the wave scattered in the forward direction is zero). The wave reflected from such a moving diffraction grating, due to the Doppler effect, will be shifted in frequency by the value [9]:

$$f_B = \frac{2 \cdot n \cdot v_A}{\lambda}, \qquad (3)$$

where $v_A \approx 5.7$ km/s is the speed of the acoustic wave in the fiber core [6].

At the wavelength λ = 1550 nm, the frequency shift (f_B) is 10.8 … 10.9 GHz [6, 11].

The fiber tension affects the sound speed v_A and the refractive index n. In turn, the formula for the speed of sound in the OF has the form:

$$v_A = 1.05\sqrt{\frac{E_Y}{\rho}}, \quad (4)$$

where E_Y – Young's modulus, when stretched.

E_Y is equal to 72 GPa = $7.2 \cdot 10^{10}$ N/m^2 for quartz glass; ρ = 2201 kg/m^3 is the density of quartz glass [6, 9].

The most contribution to the change in the frequency of the scattered light results from a change in the Young's modulus [9 – 11].

3 RESULTS AND DISCUSSION OF THE EXPERIMENTAL RESEARCH

BOTDR-graphs of the "bad" (potentially dangerous) fiber place located in the laid optical cable (OC), some section of which was under the influence of a strong displacement force is shown on Figure 2 [12].

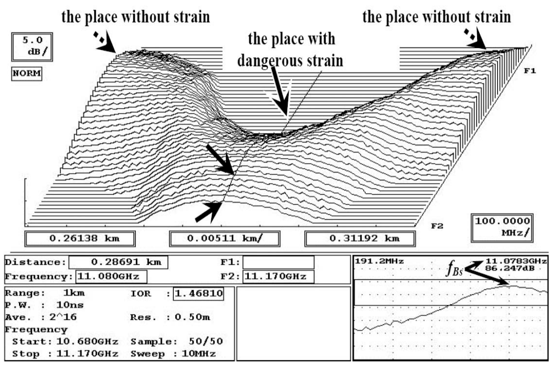

Figure 2: MBS graphs in "bad" OF section.

The significant shift of the maximum of MBS-spectrum (from 10.84 GHz (f_{B0}) up to the frequency 11.08 GHz (f_{Bs})) is observed in the place with dangerous strain [12].

Figure 3 shows the BOTDR multi-traces corresponding to MBS graphs presented in Fig. 2. It can be seen from the multi-traces that the strain in the place of mechanical action applied to the OC increased by more than 0.45 %, which is dangerous for the OF [12].

The analysis of BOTDR-traces for OF in OC under test showed that the sections of the route were localized which required a further investigation of factors that caused dangerous mechanical loads on the OC. After eliminating these factors and restoring the "bad" OF sections, the fiber optical communication line returned to its normal operation.

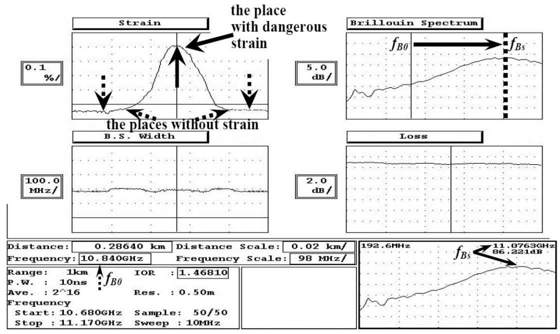

Figure 3: Multi-trace graphs in "bad" OF section.

In addition to fiber diagnostics in optic communication cables, the proposed Brillouin reflectometry method could be applied in large variety of fields, which involve mechanical deformation measurements and temperature measurements. For example, in avionics and auto electronics under conditions of low (up to –70°C) and high (up to +150°C) temperatures in electromagnetic interferences, as well as in power industry to test power electric cable under pressure, bending and stretching conditions. In oil and gas industry the proposed technique could be used to control temperature in a well up to 4 km deep with stretching load up to 520 kg. The technique could be applied in waste nuclear fuel storage.

4 CONCLUSIONS

It is recommended to include BOTDR in the control system to monitor the characteristics of the OF to detect locations of optical cable with increased mechanical stress and temperature changes. This will allow identifying potentially hazardous areas in the cable at different stages of manufacturing and improving the technologies used in the production process. In the process of optic fiber and cable production, it is easy to access both ends of the OF, which makes it possible to use phase methods or BOTDA. During the construction and operation of the cable, access is possible only to one end of the OF, and this makes it possible to use only reflectometric methods (BOTDR). Measurement of the tension value in the optical fiber of the cable will make it possible to predict the operating time before failure and timely identify areas of risk [6].

Information-measuring systems using in their operation MBS effect are very reliable in extreme operation conditions which result in their great demand in the market.

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