Analysis of the Applicability of Singlemode Optical Fibers for Measurement of Deformation with Distributed Systems BOTDR

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Abstract. *Distributed optical fiber sensors allow monitoring physical effects across the whole cable. The paper presents results obtained from the performed tests and shows that single mode fibers can provide analyses of the deformation changes, when distributed optical systems BOTDR used. We used standard optical fiber G.652.D with primary and secondary protected layers and specialized cable SMC-V4 designed for this purpose. The aim was to compare the deformation sensitivity and determine which fiber types are the best to use. We deformed the fiber in the longitudinal and transverse directions and mechanically stressed in orthogonal directions to find how to localize optical fibers. They could be deployed in real use. For achieving optimal results of mechanical changes and acting forces, sensor fibers have to be located carefully.*

Keywords

Deformation, distributed system, sensor, special cable, standard telecommunication fiber.

1. Introduction

Distributed fiber optic sensors is a group of fiber-optic sensors. Distributed sensors enable the measurement of quantity along the entire length of optical fiber. The general principle of these systems is the phenomenon called light scattering. Based on the light scattering analysis, we distinguish several types of such systems. Rayleigh scattering is used for the measurement of attenuation profile of the optical fiber [1]. Raman scattering is possible to use for monitoring the temperature along the optical fiber [2] and Brillouin scattering can be used for measuring the temperature and deformation [3] and [4]. This article is focused on the measurement of deformation utilizing Brillouin Time Domain Reflectometry (BOTDR). The principle is based on the measurement of the stimulated Brillouin scattering. The frequency shift of Brillouin scattering is linearly dependent on the temperature and deformation. Distributed sensors are used in many areas of measurement, for example, for monitoring of the condition of building structures, the temperature distribution along the electrical cables, etc. Special optical cable SMC-V4 is designed for measurement of deformation with BOTDR system. However, this cable is more expensive, and implementation of the cable is considerably expensive for the measurement of long distance. The alternative possibility is the use of standard telecommunications optical fiber, which is not recommended for these purposes. The disadvantage of standard optical fiber is a non-tight bond between the optical fiber itself and the secondary protection in the case of measurement of the deformation. For this reason, it is considered that the applied deformation is weakly transmitted to the optical fiber itself. Standard telecommunications optical fibers G.652.D can be used for the measurement of deformation, where there is not a big emphasis on accuracy of measurement, for example, in security systems. This combination offers less accuracy, but the main requirement is knowledge about a disruption of perimeter system. This solution represents a possible low-cost alternative solution of perimeter systems using BOTDR systems. The aim of this article is the comparison of sensitivity to deformation of these types of optical fiber and determining the suitability of these standard optical fibers for the measurement of deformation with distributed systems.

2. Distributed System BOTDR

In practical applications, optical fiber is sticked on the surface of an analyzed structure. The optical fiber is mounted directly inside of the building structure for the analysis of construction. In this paper, we use of a special cable SMC-V4, because the emphasis is placed on the accuracy of measurement. Special cables, with higher tensile strength and better protection, are also more suitable for measurement of the terrain and soil layers [5]. The authors [6] and [7] show that it is possible to use different types of cables for measurement of deformation.

BOTDR (Brillouin Optical Time Domain Reflectometry) operates on the principle of measurement of stimulated Brillouin scattering. Brillouin scattering arises due to the interaction of acoustic waves and pump of the light beam, under the condition of supercritical power of light passing through the optical fiber. The transmitted light is diffused according to the changes in the refractive index. The scattered light is shifted due to Doppler effect on frequency by an amount υ_B. This value is given by:

$$\upsilon_B = \frac{2nV_a}{\lambda_0}, \tag{1}$$

where λ_0 is the wavelength of transmitted light, n represents the refractive index of the core of the optical fiber and V_a denotes the propagation velocity of acoustic waves within the optical fiber. The resultant value is given by:

$$V_a = \sqrt{\frac{K}{\sigma}}, \tag{2}$$

where σ is the density of the material and K express module of volume compressibility. The value σ is determined by the magnitude of deformation and temperature on the optical fiber itself.

The strain response is defined as follows:

$$\upsilon_B(\varepsilon, n) = C_{\varepsilon 1}\varepsilon + C_{\varepsilon 0}, \tag{3}$$

where coefficient $C_{\varepsilon 1}$ is 0.5 GHz/% and coefficient $C_{\varepsilon 0}$ is 10.87 GHz [8] for standard ITU-G.652 optical fiber at wavelength 1550 nm.

Figure 1 shows a Brillouin frequency shift, which is linearly dependent on the applied deformation and temperature. The value of the magnitude of applied deformation and temperature is obtained by scan Brillouin frequency shift using the probing of light. The light is directed into the optical fiber from the opposite end.

Experimental measurements were performed using a distributed system for the measurement of deformation and temperature DiTEST STA-R from Omnisens, which exploits the sensitivity of the Brillouin frequency shift for sensing of temperature and strain. This technique uses standard low-loss single mode optical fiber. The optical fiber offers the longest distance range with unrivaled performances and a compatibility with standard telecommunication components. The functionality principle consists of the frequency measurement of the Brillouin scattered light. The spatial resolution of 1 m is a distance of 20 km in the optical fiber, resolution 2 m is a distance 30 km, and value of resolution 3 m is a maximum length of optical fiber 50 km. The system contains two independent channels with a reach of 50 km. A step of measurement of 10 cm can be set for short segments of optical fibers in hundreds of meters. A maximum of measuring steps is limited to a value of 100 000 measurement points across the length of optical fiber.

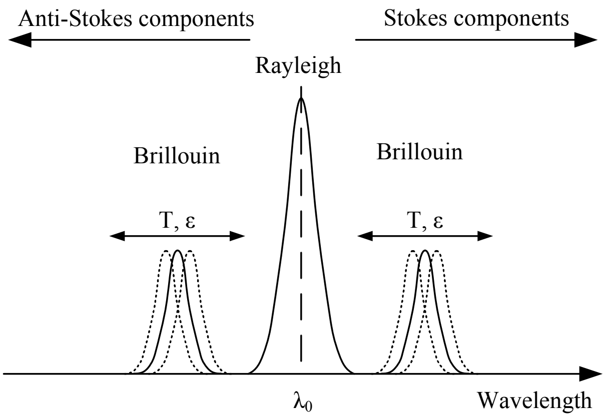


Fig. 1: Rayleigh and Brillouin scattering.

In Fig. 2, we can see how to measure the Brillouin frequency shift with a BOTDR. Pulsed light is introduced into the optical fiber (from one end of the optical fiber), and the power of spontaneous Brillouin backscattered light is then measured in the time domain using heterodyne detection. The frequency of the incident light slightly changes. Therefore, the same measurements

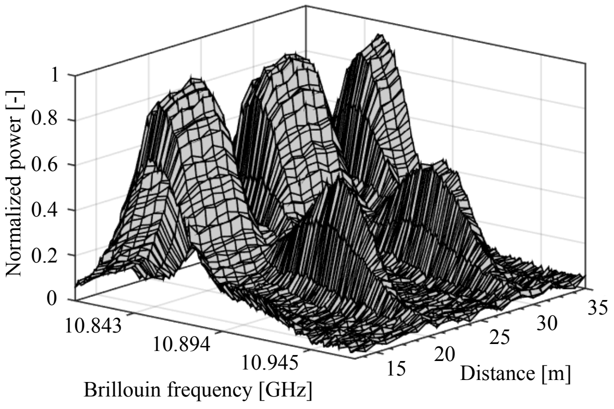


Fig. 2: Principle of BOTDR strain measurement.

are carried out to obtain the Brillouin spectrum repeatedly at many frequencies. The specific frequency, which indicates the peak power, is calculated by fitting the spectrum to a Lorentzian curve. It must be calculated at each point of the optical fiber. The strain is obtained from this frequency. The distance D defines a place, where the pulsed light is released into the position, where the scattered light is generated.

$$D = \frac{cT}{2n}, \tag{4}$$

where n is the refractive index, c is the light velocity in a vacuum and T is the time interval between receiving the scattered light and launching the pulsed light.

3. Experimental Setup

The constructed preparation was used to deform of the optical fiber for experimental measurement (Fig. 3). The preparation consists of galvanized sheet with dimensions 100 × 100 cm. Sheet with glued optical fiber is affixed to the wooden frame. Subsequently, this sheet is bending from the unloaded state ’0’ (0°) to the maximum bend ’10’ (180°).

Fig. 3: Equipment for deformation measurement.

Bragg grating was used for the deformation assessment of glued optical fiber at preparation in Fig. 3 for various size of radius bending in the individual positions ’1’–’10’. Deformation was zero in position ’0’. Figure 4 shows the size of deformation at each position.

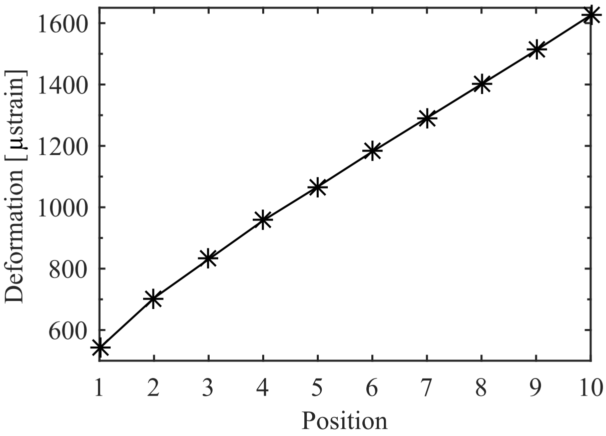


Fig. 4: Deformation of optical fiber with the Fiber Bragg grating glued on preparation for various size of radius bending in the individual positions ’1’–’10’.

Two types of standard telecommunications fibers G.652.D (in primary protection and in a tight secondary protection) were used for experimental measurements, and special optical cable SMC-V4 was also used. This cable is designed for the deformation measurement. It provides the maximum sensitivity on deformation and the ability to detect very small deformations. Individual types of optical fibers were glued on the test sheet in the longitudinal and the transverse direction (Fig. 5) along its entire length. The directions were chosen based on previous research [9]. Polymer adhesive MAMUT Glue was used for gluing. Then measurements were carried out for each arrangement and each condition and each fiber, thus a total 600 repetitions.

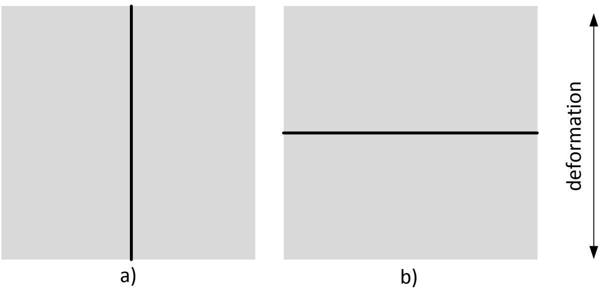
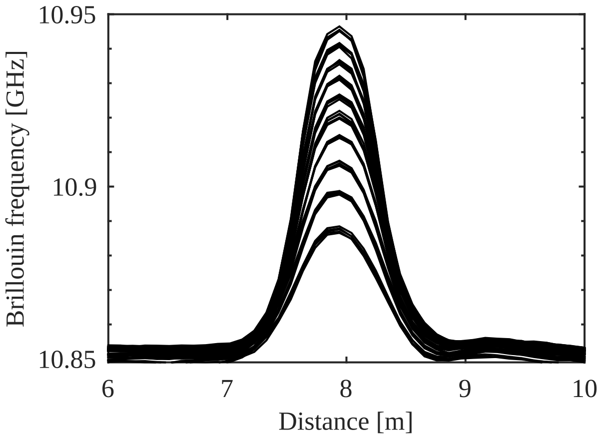
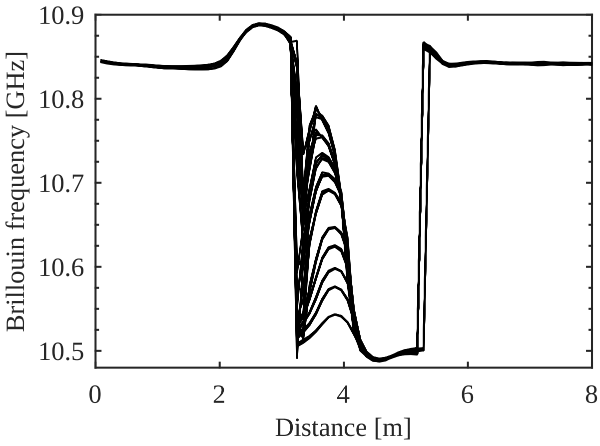


Fig. 5: Arrangement of optical fiber.

Distributed system BOTDR is based on measurement of Brillouin scattering, whose frequency is dependent on applied deformation. Figure 6 shows individual waveforms of Brillouin frequency depending on the distance of optical fiber for deformation at positions ’1’ to ’10’. Figure 6(a) shows the waveforms of Brillouin frequency for longitudinally mounted optical fiber G.652.D in the primary protection. Figure 6(b) shows the waveforms of Brillouin frequency for longitudinally mounted optical cable SMC-V4. In this cable, the optical fiber is characterized by the shifted Brillouin frequency towards lower frequencies (see waveform between 3 and 5 m in Fig. 6(b)).



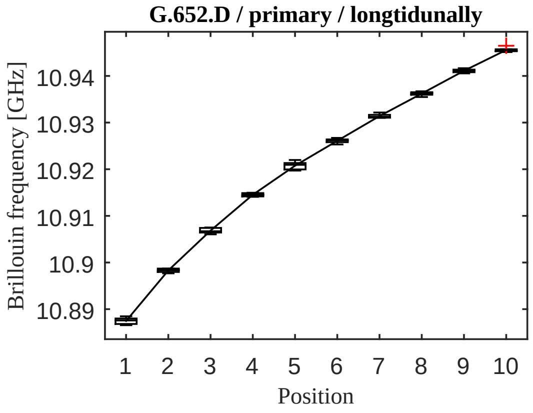
(a) G.652.D in primary protection.

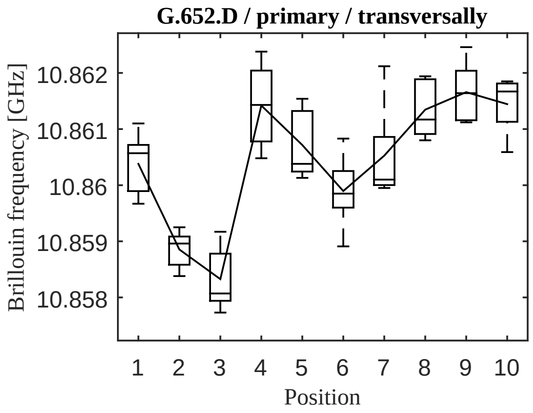


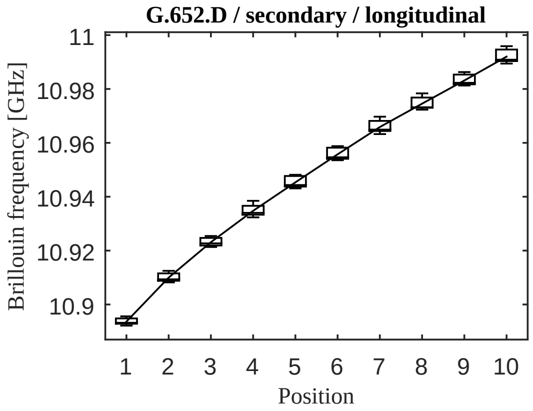
(b) SMC-V4.

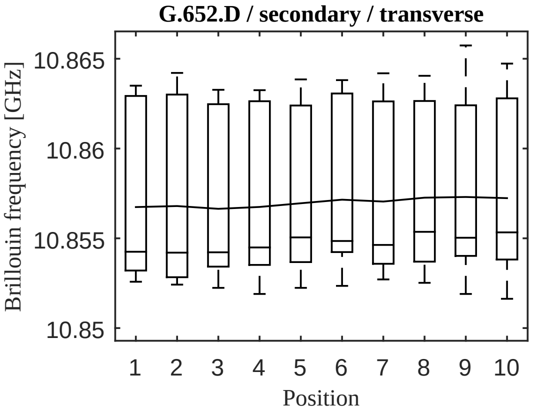
Fig. 6: Dependence of Brillouin frequency on applied deformation.

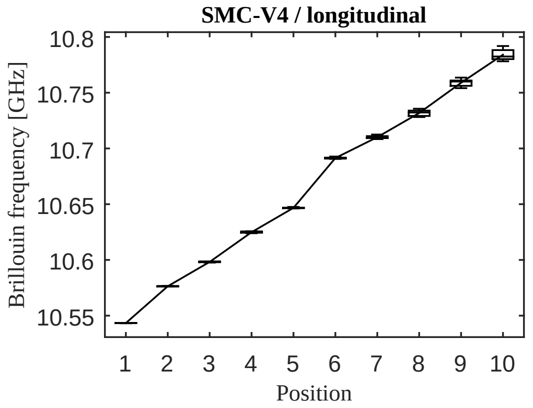
Following Fig. 7 (sef of 6 images) displays dependencies of the Brillouin frequency on deformation in positions '1'–'10' for all three types of optical fibers in the longitudinal and transverse configuration.











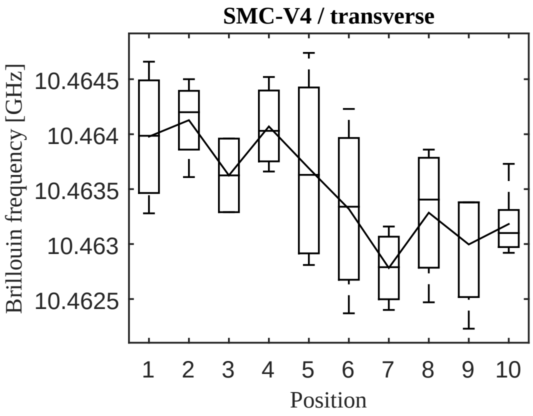


Fig. 7: The dependence of Brillouin frequency on deformation in positions ’1’ to ’10’ for all types of optical fibers and the arrangement.

Figure 8 shows the comparison of different configurations. The individual curves represent the average value of the measured data for each configuration and the type of optical fibers.

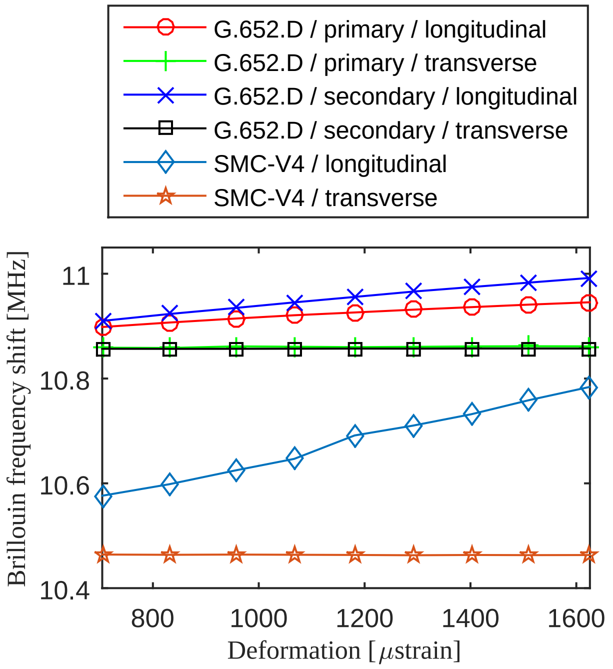


Fig. 8: Comparison of individual configuration and types of optical fibers.

A sensitivity of Brillouin frequency on deformation and the maximum change of deformation were calculated for shown arrangement (Tab. 1).

Tab. 1: The sensitivity of Brillouin frequency on the type of arrangement of the optical fiber during measurement of deformation and the maximum change of deformation.

Configuration	**Sensitivity**	**Max Brillouin change frequency**
	(kHz/μstrain)	(MHz)
G.652.D/ primary/ longitudinal	53.561	58.09
G.652.D/ primary/ transverse	0.981	1.064
G.652.D/ secondary/ longitudinal	90.688	98.356
G.652.D/ secondary/ transverse	0.459	0.497
SMC-V4/ longitudinal	221.952	240.72
SMC-V4/ transverse	-0.733	-0.7995

4. Conclusion

The presented results show that the tested optical fibers have a small sensitivity to transverse deformation. This sensitivity reaches lower values than 1 kHz/μstrain. It can be stated that the tested types of optical fibers are not suitable for measurement of transverse deformations. The sensitivity of SMC-V4 is 4.15 times greater than the sensitivity of G.652.D in the primary protection, and 2.45 times greater than the sensitivity of G.652.D in tightly secondary protection in the case of longitudinal deformation. The ratio of sensitivity is 1.69:1 between the optical fiber G.652.D with tight secondary protection and primary protection. An optical cable SMC-V4 is characterized by shifted of typical Brillouin frequency to lower frequencies about 350 MHz.

This article confirms further the possibility of using standard single-mode fiber for the measurement of deformation using apparatus DiTEST STA-R, which is based on measurement of the Brillouin frequency. However, there is the significant difference in sensitivity between the longitudinal and transverse effect of deformation, which is a hundred times larger in a longitudinal action than in a transverse action. The article confirms further the use of standard telecommunication fibers in security systems, where there is not a big emphasis on the measurement accuracy of deformation. According to the results, this combination offers less accuracy, but the primary requirement is knowledge about a disruption of perimeter system. This solution represents a possible low-cost alternative solution of perimeter systems using BOTDR systems.

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