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Brillouin backscattering analysis in recent generation of telecom optical fibers

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This paper reports on examination of the latest generation of telecom optical fibers for the Brillouin backscattering strain sensor application. Over 30 fibers from 5 different manufactures have been tested in terms of their ability to create a stable and accurate strain sensor. It has been proved that fibers that belong to the same standard, according to ITU-T (International Telecommunication Union), and even if provided by one manufacturer, demonstrate fundamentally different Brillouin backscattering response. It has been shown that unimodal Brillouin spectrum cannot be treated as the main parameter for fiber selection. In order to achieve accurate and reproducible results of strain measurement, it is necessary to perform initial examination of the fibers over the range of laser pulse width.

Keywords: Brillouin backscattering, optical fiber, optical fiber application, optical fiber sensors, strain measurement.

1. Introduction

Optical fiber strain sensing devices are widely used in the industry for strain and temperature monitoring [1]. Their applications include sensing in nondestructive health monitoring [2], aviation [3], marine [4] and geotechnical engineering [5–7]. Optical fiber sensors are build based on Bragg gratings [8], Fabry–Perot sensors (F-P) [9] or based on Brillouin or Raman scattering effects [10]. Brillouin scattering [11] is the most popular method as it is based on frequency shifting rather than intensity (as Raman scattering), thus providing good stability and incurring lower influence from any potential bias caused by step loss [12]. BOTDR (Brillouin optical time domain reflectometer) is a valuable tool for identifying strain and temperature distribution along the sensing fiber [13,14]. BOTDR is based on the coherent detection method that uses a pulsed light launched into the optical fiber to generate spontaneous Brillouin scattering. The sensor technology utilizing Brillouin backscattering is distinguished by the accuracy of the measurement and the possibility of using conventional, commercially available optical fibers as a sensing medium [15]. Moreover, the type of optical fiber cable is significant, due to the material strain transfer to sensor fiber issue [16]. Although sensing based on Brillouin effect has been reported for many other types of fibers as: polarization-maintaining fiber [17], large effective area fibers [18] or trench-assisted multimode fiber [19], regular single mode communication fibers are providing the most cost effective solution. Recently, using G. 652.D commercial fiber. HU *et al.* [20] presented distributed strain and temperature sensor based on spontaneous scattering. XING *et al.* [21] apply the G. 652.D fiber as a sensing element based on the SBS (stimulated Brillouin scattering) effect to eliminate the crosstalk caused by temperature and strain.

Brillouin frequency shift depends on the acoustic velocity and refractive index of the fiber and is affected by fiber design and environmental effects such as temperature and strain. Due to the fact that manufacturers constantly optimize fibers to improve their transmission parameters while reducing production cost, it is very difficult to obtain reproducible results for a specific fiber type, laser source and signal modulation method. Optical fibers specified in the same standard group, *e.g.* ITU-T G.652D, but from other manufacturers, may differ significantly in terms of core impurities or the refractive index profile. This can be true even for the fibers coming from one manufacturer but different production batches. For example, the effect of the optical fiber refractive index profile on the Brillouin gain spectrum (BGS) and on the magnitude of the Brillouin gain coefficient (BGC) is significant and needs to be considered for proper fiber selection.

We examined the latest generation of optical fibers, *i.e.* those manufactured after 2019, (all meeting ITU-T standards) in terms of usefulness for spontaneous Brillouin backscattering based strain sensors. Over 30 fibers from 5 manufactures have been tested. Spectral characteristics, number of Brillouin frequencies, as same as they FWHM (full width at half maximum) and intensity level have been investigated. In the last part, the influence of these parameters on strain measurement has been analyzed.

2. Brillouin backscattering for optical fiber sensor

The Brillouin light backscattering phenomenon (BLS), present in optical fibers, is based on the interaction of light and acoustic waves. A light beam from a pulsed laser source is introduced to the one of the ends of the optical fiber. A small part of the light is reflected back towards the transmitter, as a result of interaction with locally excited vibrations of the lattice of the optical fiber structure.

The spectral analysis of the signal resulting from the Brillouin phenomenon allows to determine the peak value of the Brillouin frequency for a given material medium [22]:

$$v_{\mathrm{SBS}} = 2 n_{\mathrm{eff}} V_{\mathrm{A}} \lambda_{\mathrm{L}}^{-1} \tag{1}$$

where: v_{SBS} – Brillouin frequency shift, n_{eff} – effective refractive index of optical fiber, V_{A} – speed of the acoustic wave in the optical fiber, λ_{L} – wavelength of light.

Using the BOTDR device (Brillouin optical time domain reflectometer), it is possible to determine the frequency ν_{SBS} occurring along the entire length of the tested optical fiber. In the Eq. (1), the effective refractive index n_{eff} depends on its distribution in the optical fiber and the method of core doping. As indicated by studies [11,23], these parameters play a significant role in the selection of the appropriate transmission medium for sensor applications. Physical quantities, such as temperature or stress affecting the fiber, have an influence on the change of the refractive index n_{eff}. Thus, the Brillouin scattering phenomenon can be used for the detection of these quantities, which is described by the relationship [24]:

$$\nu_{SBS} = \nu_{B0} + C_T(T - T_0) + C_\varepsilon(\varepsilon - \varepsilon_0) \tag{2}$$

where: ν_{B0} – initial Brillouin frequency, C_T, C_ε – temperature and stress coefficients of optical fiber, T, ε – measured temperature and stress value, T_0, ε_0 – reference temperature and stress value.

Equation (2) describes the Brillouin frequency shift under the influence of temperature changes and stresses along the length of the fiber. In order to distinguish measured value of strain only, it is necessary to use compensation methods, *e.g.* to use two parallel fiber optic lines, one of which will not be susceptible to any stresses.

3. Experimental results

In order to determine precisely the Brillouin spectrum, as defined by Eq. (2), a BOTDR test system was used. Figure 1 shows block diagram of the measurement setup. System contains BOTDR DSTS (distributed strain and temperature sensor) unit from OZOptics, connected to PC for data acquisition and analysis. BOTDR is based on λ_L = 1550 nm laser source, whereas the accuracies of measured strain and temperature are equal to ±16 με and ±0.8°C, respectively. Regarding the optical path, first of all there is a hybrid optical jumper with both angled polished connector (APC) for lower return loss. The de-

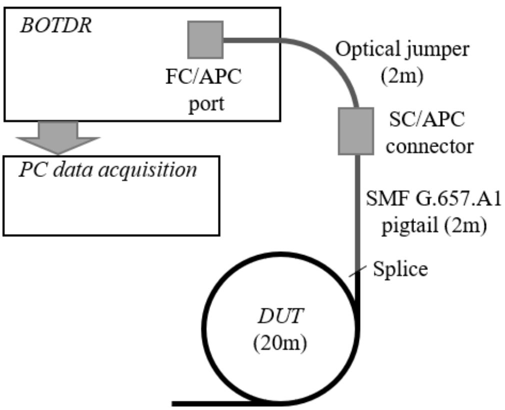

Fig. 1. Measurement system block scheme.

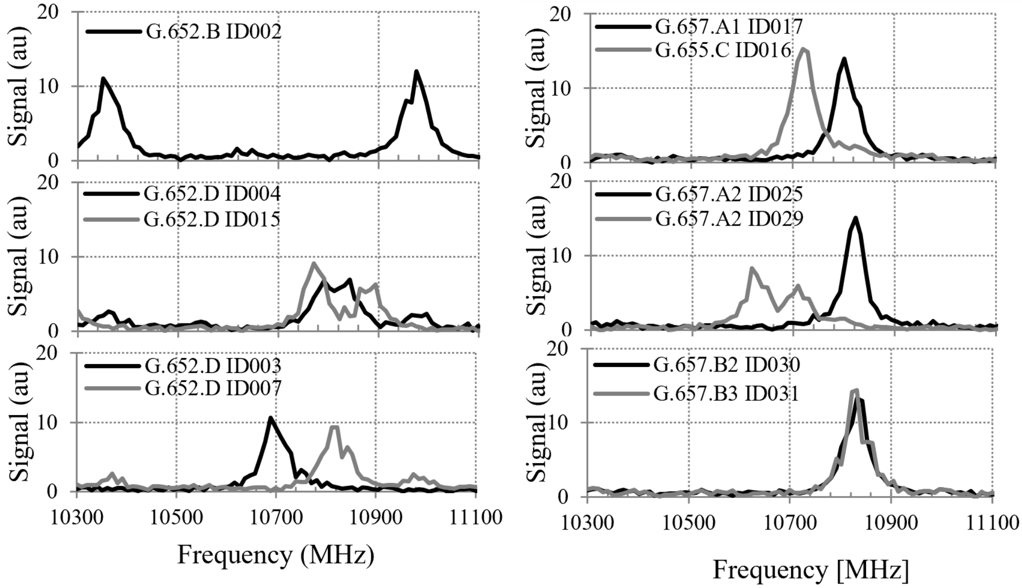

Fig. 2. Rough spectral characteristics of several optical fibers.

vice under test (DUT) was connected to the jumper through the thermally spliced additional optical fiber pigtail. The DUTs were different bare optical fiber types with a fixed length, equal to 20±0.1 m. All the measurements were conducted in room temperature 21±0.5°C.

The BOTDR device is designed to work with single-mode optical fibers (SMF). However, to ensure proper strain and temperature readings, different Brillouin scattering properties of different fiber types need to be considered. Different subtypes of SMF, defined by ITU-T from G.652 to G.657, were examined. Using presented BOTDR system, the spectral characteristics of all 30 fiber samples were measured in order to determine their central frequency ν_{B0}. Data presented in Table 1 summarize fiber characterization, in terms of occurred number of Brillouin frequencies. For this rough measurement, laser width pulse equals 50 ns and rough step 10.24 MHz was used according to the manufacturer's peak search procedure recommendations. Several spectral characteristics which present diversity of Brillouin response in optical fiber, are presented in Fig. 2.

As presented in Table 1, G.652.B group represented by 2 samples (ID001 and ID002) has two wide apart specific peaks with almost the same signal level at 10350 MHz and 10975 MHz. On the other hand, G.652.D group was the most numerous and the most diverse in terms of the number of occurred peaks. Here, characteristics with 1 to even 4 frequencies can be distinguished. A diversity is also present in the level of these signals. Only one optical fiber complied to G.655.C standard was measured, but in comparison to others, DUT had the strongest main Brillouin frequency. Group called G.657

Table 1. Number of peaks of measured optical fibers.

Group named by ITU-T	Sample ID	Number of peaks			
		1	2	3	4
G.652.B	001 - 002	–	2	–	–
G.652.D	003 - 015	1	9	2	1
G.655.C	016	1	–	–	–
G.657.A1	017 - 020	4	–	–	–
G.657.A2	021 - 029	7	1	–	–
G.657.B2	030	1	–	–	–
G.657.B3	031	1	–	–	–

(A1 to B3) describes optical fibers insensitive to macrobending. Except one sample (ID029), all measured fibers are characterized by one strong frequency response near 10.8 GHz.

Basing on results presented in Table 1, the representative group of optical fibers, *i.e.* showing one or several frequency peaks, was chosen for further research. This group contains fibers showing each specific characteristic from every ITU-T group. Detailed frequency response of those fibers has been presented in Fig. 2.

The presence of a single frequency ν_{B0} with high signal level is desirable to obtain reproducible measurements of the strain (or temperature) along the fiber using Brillouin backscattering method. As presented in Fig. 2, some fibers are showing up to 2 frequency peaks. The appearance of those two resonances reflects the fact that two different acoustic modes interact with the light wave in or near the core area. However, those peaks can be very close to each other, as in ID015 and ID029 (and sometimes may be considered as one peak), or very far as in ID002. What is also important, optical fiber frequency response varies in terms of FWHM parameters. At the measurement processing step BOTDR can select either maximum as reference. As a result, the strain measurement appears noisy as BOTDR will jump over one maxima to another. Therefore it is always recommended to select fiber with one Brillouin spectrum. As this is usually fulfilled, there are several other aspects worth to consider. These will be examined in the next part of this paper.

4. Strain measurements results

As a part of the research on the sensing properties of optical fibers, we focused on the selected fibers with spectral characteristics presented in Fig. 2. Those fibers represent a wide range of ITU-T specification and spectral properties. In this paragraph they will be examined in detail to understand how their parameters influence the strain measurement. In order to perform such analysis, the setup from Fig. 1 was used. Initially, the baselines of each optical fiber, for the shortest pulse width τ equal to 10 ns (1 m length resolution), were measured. The results are presented in Fig. 3, where the characteristics for the representative group of optical fibers were separated for better transpar-

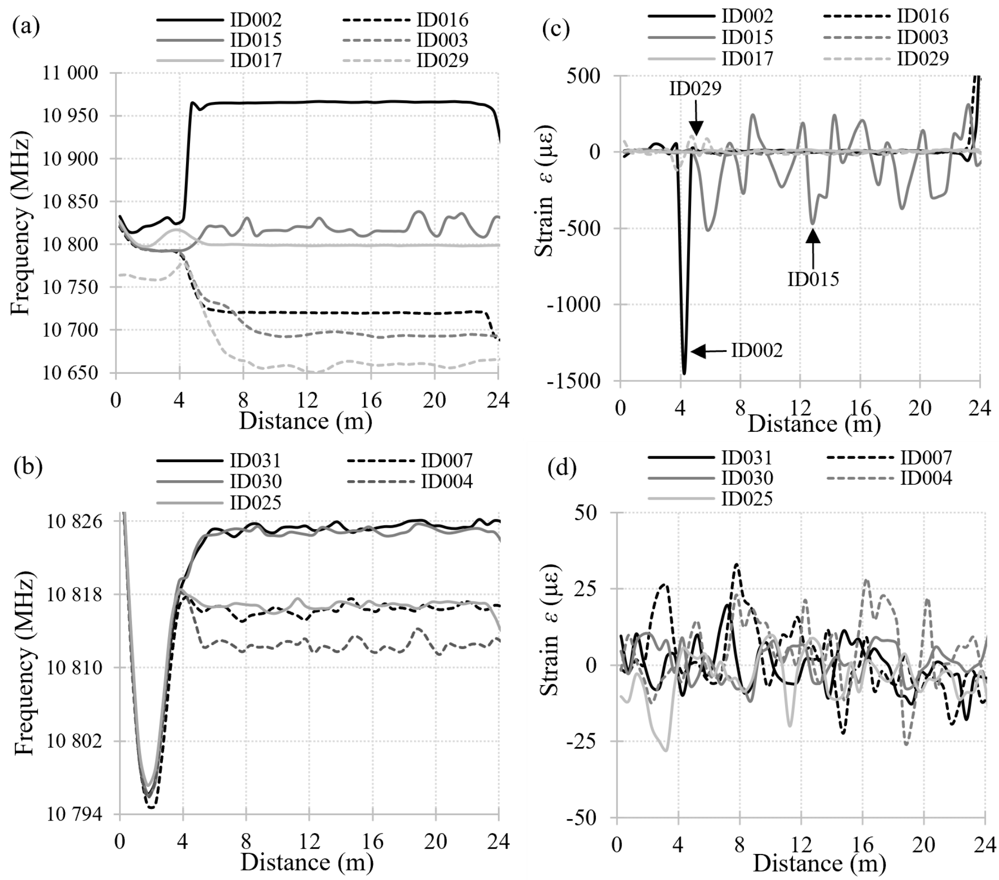

Fig. 3. Baseline (**a**, **b**) and corresponding strain (**c**, **d**) measurements results for representative ITU-T compliant optical fibers.

ency between two graphs. As can be noticed, samples ID003 and ID015 (G.652.D), are same as ID029 (G.657.A2) showing a frequency fluctuation higher than ±1 MHz along the sample length that may influence further strain measurement.

Next, the reference measurement of strain was done on fibers loosely laid on the table in coils of 20 cm diameter. Strain coefficient for all the fibers was factory set and was equal to 18.9150 με/MHz [25]. As can be noticed in Fig. 3**c**, in the case of ID002 or ID029, there is a random peak of strain level. This effect may be a result of optical or geometrical parameters mismatch between two connected fibers. The optical jumper was always the patchcord with G.652.D fiber. The strain results for ID015 sample are in line with previous assumptions. The highest fluctuation ranging from –500 to 200 με of measured strain value are observed. Table 2 summarizes the detailed values of reference ν_{B0} from the baseline and measured strain along the DUT. The value of standard deviation σ was determined based on ν_{B0} or ε readings repeated 10 times. As can be

Table 2. Main peak frequency and measured strain of optical fibers.

ITU-T	Sample ID	Main peak $\nu_{B0} \pm \sigma$ [MHz]	Strain $\varepsilon \pm \sigma$ [με]
G.652.B	ID002	10967.42 ± 0.49	15.35 ± 8.88
G.652.D	ID004	10816.50 ± 0.60	–15.83 ± 11.61
	ID015	10822.53 ± 13.91	45.32 ± 293.36
	ID007	10818.70 ± 0.46	–16.49 ± 7.91
	ID003	10707.45 ± 0.36	3.57 ± 7.48
G.655.C	ID016	10722.35 ± 0.45	–0.01 ± 9.41
G.657.A1	ID017	10800.25 ± 0.33	6.00 ± 6.61
G.657.A2	ID025	10818.61 ± 0.34	6.79 ± 6.81
	ID029	10633.80 ± 0.53	18.07 ± 9.51
G.657.B2	ID030	10826.07 ± 0.45	1.76 ± 9.49
G.657.B3	ID031	10827.14 ± 0.27	6.27 ± 5.34

noticed, strain values measured using most of tested optical fibers are in the range of BOTDR accuracy (except ID015 optical fiber).

5. Discussion

As it was shown in previous chapters, the most common fibers are showing different behavior even in the same standards group. What is even more interesting, the wide variety of fiber parameters can be observed for the same manufacturer meeting a given ITU-T specification. Strain measurement results presented in Fig. 3**b** show that to select optical fiber for such measurement, it is not sufficient to relay on the number of peaks. It is also important to consider the other parameters: FWHM, signal level or peak separation.

Fiber ID015 showing two Brillouin peaks is not providing stable strain measurement. On the other hand, other fibers with two peaks (*e.g.* ID002) are very stable. This is visible when we analyze standard deviation σ in Table 2, where for ID015 it is equal to ±293 με. In order to understand what leads to such huge instability, we have measured frequency response of fiber with ID015 changing pulse width τ from 10 to 100 ns. The relationship between laser pulse width and Brillouin linewidth and frequency was presented earlier for a BOTDA system [26]. Results of this experiment for a BOTDR setup, based on our readings, are presented in Fig. 4. Analyzing the first graph, it can be noticed that for the short pulses only one peak can be observed, instead of dual-frequency spectrum above this value. In addition, for the shorter pulse, the wider FWHM and lower intensity were observed. The influence of pulse width (limited to 200 ns) on the main frequency shift and FWHM is presented in Fig. 4**b**. More data points of pulse width at limited step equal to 5 ns were applied near 40 ns value, where the abrupt changes of ν_{B0}, the same as FWHM, are observed. The main frequency value declined by about 50 MHz, while the FWHM decreased fivefold. This leads to strain measurement instability as the BOTDR system has difficulty in frequency response

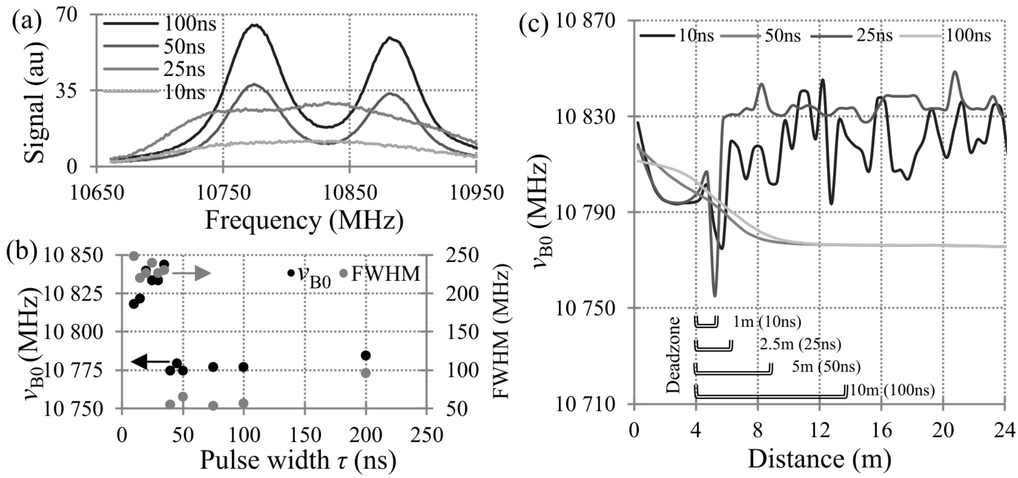

Fig. 4. Influence of optical laser pulse width on: Brillouin spectral response (**a**), main frequency shift and FWHM (**b**), and baseline stability (**c**), for ID015 Corning SMF-28e+ optical fiber.

reading. Such fiber may be a good choice for a long sensor with length above few kilometers and more than 4 m measurement resolution. On the other hand, for a short length strain sensor (dozens of meters with about 1 m resolution) it will be useless. Of course, larger width of optical pulse increases the stability of the measurement, but it also increases the event dead zone, *e.g*. at the beginning of tested optical fiber at 4 m in Fig. 4**c**.

Despite the case of ID015, the remaining optical fibers showed stable parameters in measuring the stability of the measured strain. However, a detailed analysis of the main peak, in terms of its signal level and FWHM, was performed for the entire representative group. The pulse width was equal to 10 ns for these measurements, and the

T a b l e 3. Detailed results of measured representative optical fibers.

ITU-T	Sample ID	Main v_{B0} @ 10 m DUT [MHz]	Signal level [au]	FWHM [MHz]
G.652.B	ID002	10957.44	13.51	143.36
G.652.D	ID004	10792.96	8.80	202.24
	ID015	10817.92	9.60	248.32
	ID007	10794.88	12.23	142.08
	ID003	10696.32	14.46	149.76
G.655.C	ID016	10717.44	19.85	158.72
G.657.A1	ID017	10785.28	16.72	161.28
G.657.A2	ID025	10810.24	14.99	144.64
	ID029	10670.08	10.32	186.88
G.657.B2	ID030	10823.68	16.52	144.64
G.657.B3	ID031	10816.64	16.08	142.08

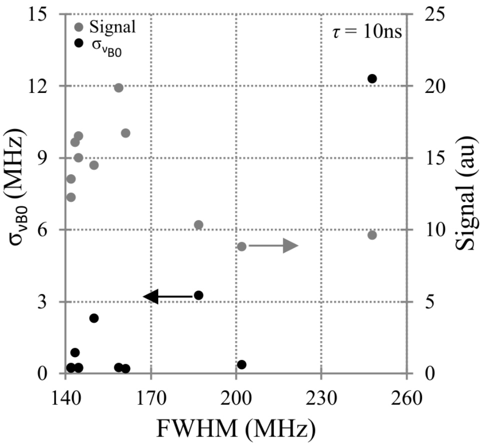

Fig. 5. Dependence of FWHM on: Brillouin frequency standard variation and signal level, based on measured optical fibers from representative group.

results summary is presented in Table 3. The effect of FWHM on the main frequency standard deviation and its signal level is presented in Fig. 5. It can be presumed that the wide FWHM of the main peak translates into its worst standard deviation and lower signal level which will directly impact strain measurement accuracy. However, an unequivocal statement of this relationship requires conducting the research on a larger number of optical fiber samples.

The last Fig. 6, shows additionally spectral characteristics of the main peak for the narrowest and widest case of FWHM of the entire representative group of optical fibers. It can be noticed that the wider peak (optical fiber G.652.D ID015) has a flatter

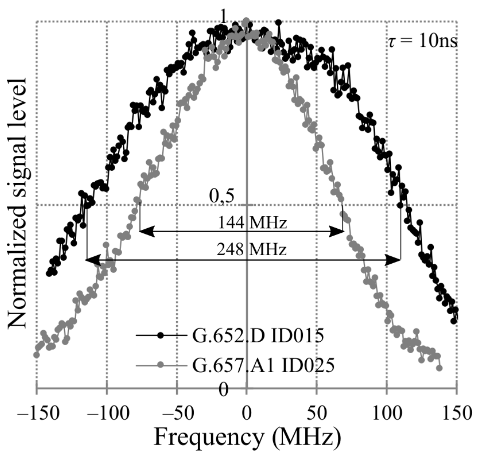

Fig. 6. Comparison of two extreme cases of FWHM from all measured optical fibers.

top, which makes a frequency reading difficult. The frequency signal level in this range has similar values, which combined with the measuring accuracy of the BOTDR device, may lead to an erroneous reading of the correct frequency value.

6. Conclusion

Many commercially available optical fibers may be used for BOTDR based strain sensors. This paper examined the latest generation of optical fibers (manufactured after 2019) in terms of spontaneous Brillouin light backscattering. Over 30 fibers from 5 manufactures have been tested. It has been proved, that fibers which belong to the same standard according to ITU-T, and even provided by one manufacturer, demonstrate a fundamentally different Brillouin backscattering response. Fifteen from 30 examined single mode fibers showed unimodal spectrum, whereas 11 of them belong to ITU-T G.657.A standard. Only one fiber out of 13 from ITU-T G.652.D group showed unimodal response. Half of measured fibers showed two or more resonances frequencies. In that case, two or more acoustic modes interact with a transmitted light wave. Dual-frequency response fibers can be more complicated as BOTDR can select either maximum as a reference for strain measurement. As was shown, this effect can be neglected if other occurring peaks have much lower intensity than the main peak. On the other hand, Brillouin spectrum of optical fibers strongly depends on the laser pulse width. For the most problematic fiber (ID015) and pulse width τ below 40 ns, conversion of dual-frequency response to unimodal was observed. Unfortunately, due to wider FWHM and lower signal level, it provides unstable strain measurement.

It was shown that unimodal nature of Brillouin spectrum cannot be treated as the main parameter for fiber selection. Fibers with two or more peaks, separated from each other will provide stable and accurate strain measurements, whereas a single peak with wide FWHM and low signal level presents noisy results. In order to achieve accurate and reproducible results of strain measurement, it is necessary to perform initial examination of the fibers over the range of laser pulse width. The usefulness of a given optical fiber depends on the sensor application and measurement spatial step.

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