BOTDR Measurement Techniques and Brillouin Backscatter Characteristics of Corning Single-Mode Optical Fibers

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Brillouin Optical Time Domain Reflectometry

The Brillouin Optical Time Domain Reflectometer[1] (BOTDR), sometimes referred to as the Optical Fiber Strain Analyzer, is a valuable tool for identifying localized sections of differential strain distributed along an optical fiber. BOTDR techniques enable characterization of strain events in optical fiber cables for diagnostic purposes and are increasingly used in systems designed for special strain or temperature measurement applications. The measurement technique is a non-destructive test and may be administered for factory cable measurements during development or qualification, after installation, as part of maintenance or trouble-shooting of an installed cable, or for special temperature or strain environment tests. This white paper provides an overview of BOTDR detection and measurement principles and the Brillouin scattering characteristics of Corning's single-mode optical fibers that have enabled engineers to use BOTDR techniques to remotely locate and assess strained fibers in deployed cables in link lengths of up to 80 km.

Physical Principle of Operation

When light propagates along an optical fiber a number of mechanisms scatter photons back toward the optical source as well as forward. The basis of optical time domain reflectometry (OTDR) is the time-positional analysis of the backscattered light by an optical detector as forward propagating light travels along the fiber. The different "backscattered" light spectra that can be observed are illustrated schematically in Figure 1. Of interest for the BOTDR is the backscattered Brillouin light.

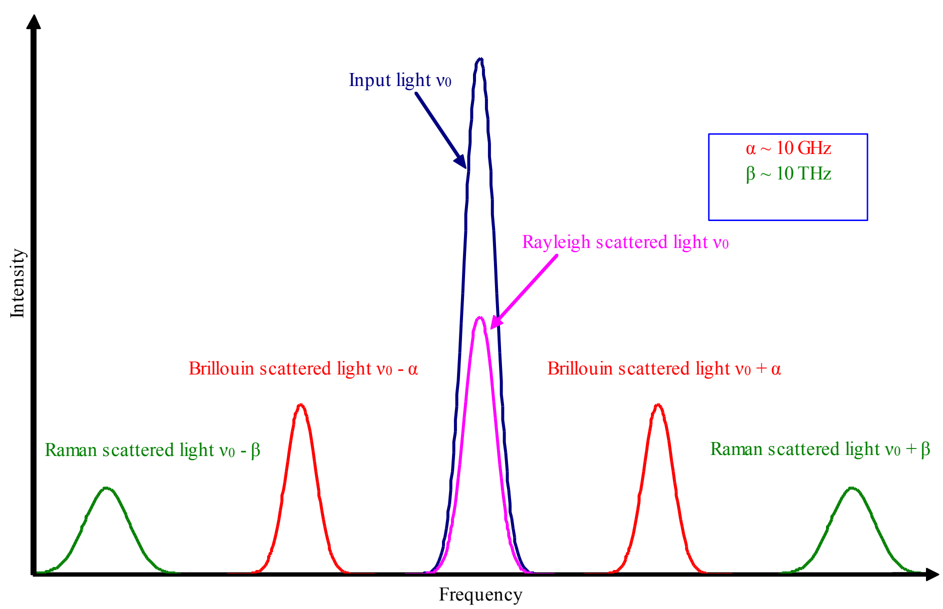

Figure 1. Spectra for different types of backscattered power in an optical fiber.

Rayleigh scattered light has the same frequency (or wavelength) as the incident light. Analyzing this part of the spectrum with a standard OTDR, one can characterize the attenuation behavior as distributed along the length of the fiber under test. Brillouin scattered light is generated by the interaction of the incident light waves and acoustic modes in the fiber. The frequency of the back-scattered light is slightly shifted from the incident light frequency by the value α (see Figure 1):

$\alpha = 2nvf_{opt}/c$ (1)
n = refractive index
v = speed of acoustic waves
f_{opt} = frequency of light wave
c = speed of light in a vacuum

For most silica based strain-free single-mode fibers the base value of α is in the range of 10.83 ± 0.015 GHz (~ 0.1 nm in the 1550 nm window). Localized or distributed strain in the fiber, ε (or fiber relative elongation) will affect its Brillouin frequency shift. When a single-mode fiber is under strain, the Brillouin frequency shift α changes with strain by $d\alpha/d\varepsilon$ ~ 500 MHz/%. Using this relationship, one can transform the measured distribution of α along the fiber into the fiber strain profile as a function of length or position.

The BOTDR measures the Brillouin frequency shift of an optical fiber via a frequency scanning procedure. The backscattered optical power distribution along the fiber is recorded in steps of 1, 2 or 5 MHz in a frequency range of ~11 GHz downshifted from the incident light frequency. The Brillouin spectrum in single-mode fiber is typically unimodal, so the position of the maximum power is defined as the Brillouin frequency shift. As a localized or longer length of the fiber under test is strained, the power maximum shifts to a different frequency. The strain is calculated from the change in frequency using the ratio of 500 MHz frequency shift per 1% strain from the frequency of non-strained fiber as shown above.

Examples of Practical BOTDR Measurements

The examples below illustrate some optical strain measurement results.

Factory Tensile Test of the Optical Cable

In this test a section of cable is gradually loaded with a tensile force (see Figure 2). The cable tensile load is increased to the point at which fiber itself starts to experience fiber strain and the fiber strain margin of the cable can be verified against cable design parameters. Fusion splicing all fibers in the cable in series (i.e., “daisy chained”) allows BOTDR signal analysis of all fibers in the cable and those under strain measurement and those at rest. Thus the strain behavior in all of the fibers can be assessed in the cable simultaneously during the application of the tensile load.

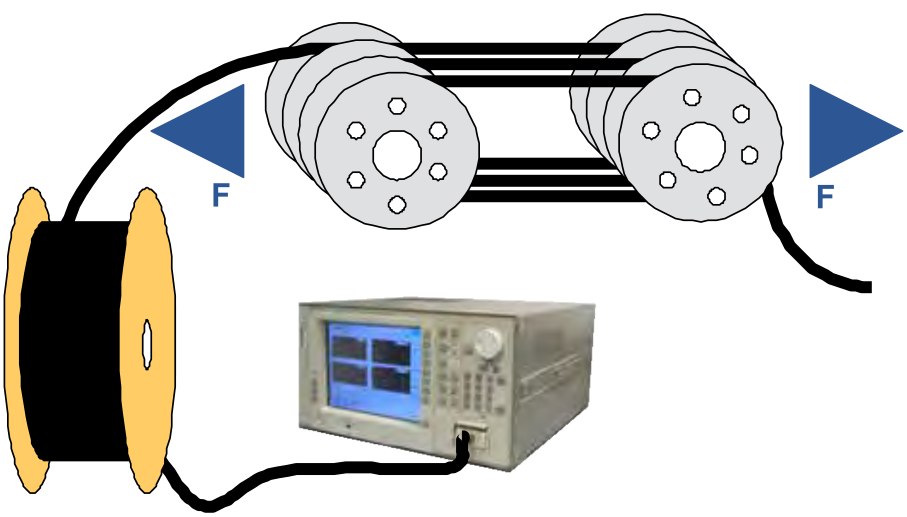

Figure 2. Cable tensile test configuration.

An example of a resulting BOTDR trace for a tensile cable load that causes strain on the fibers is presented below in Figure 3. One can estimate not only strain distribution, but also the uniformity of excess fiber length (EFL) in the cable – fibers with lower EFL will begin to experience strain earlier in the test at lower tensile loads and therefore show a larger shift in Brillouin frequency (fiber strain is plotted on the vertical axis). In this test configuration, it is common for the fiber to experience higher strain at the points where the cable is wrapped around mandrels of the tensile rig where the cable strain is applied, and this is evident in Figure 3. The Brillouin spectrum is seen in the right bottom corner of the window so, by changing the cursor position along the trace, it is possible to monitor the spectrum evolution and, correspondingly, the frequency shift, which is defined as the frequency change in the spectrum peak.

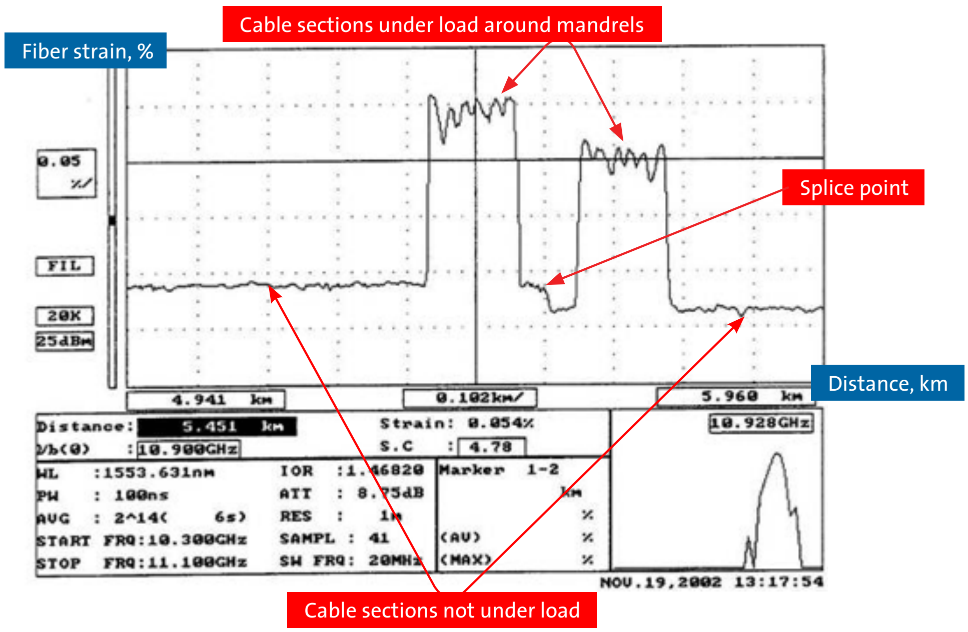

Figure 3. BOTDR trace of the fiber in the cable tensile test.

Field Fiber Strain Measurements

The BOTDR trace below (Figure 4) illustrates a field measurement of fiber strain distribution in a section of directly buried cable which periodically was found to have high tensile load along its length. At one location the maximum recorded fiber strain is close to 0.3%. This strain exceeds the recommended maximum safe strain level determined by Corning for reliable fiber deployment. See Corning White Paper 5053 (Mechanical Reliability: Applied Stress Design Guidelines) for more details of safe stress recommendations for optical fiber processing, installation and deployment.

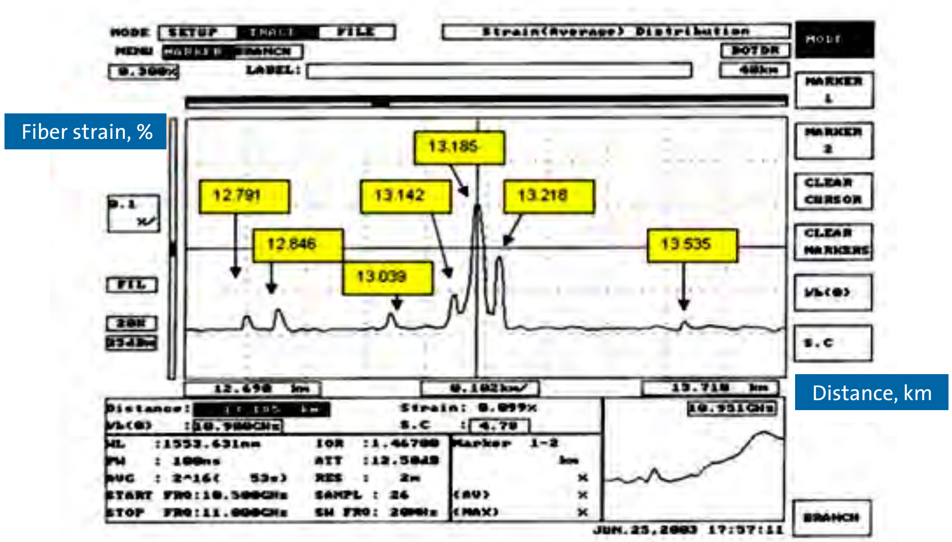

Figure 4. Assessment of localized fiber strain events in a section of directly buried cable.

Temperature Monitoring

Brillouin frequency shift is also sensitive to fiber temperature variations with the coefficient $d\alpha/dT$ equal to 1 MHz/°C. This phenomenon can also be used in different applications, such as temperature control of Optical Ground Wire (OPGW) in ice melting. Temperature monitoring is used to avoid overheating the ground wire which could otherwise lead to damage and failure of the cable and/or fittings. Another application of the BOTDR is to help locate natural gas leakages from gas pipelines (pressurized gas flowing out of the pipeline through a hole decreases the temperature of metal pipe walls). A special optical cable attached to the pipe can serve as a distributed temperature sensor when connected to a special version of a BOTDR. Other uses of temperature instrumentation systems include temperature monitoring of cables in power generation applications such as off-shore wind farms and umbilical applications.

Detailed Analysis of the Brillouin Spectrum for Different Types of Fiber

The importance of correct Brillouin spectrum analysis is evident from the above examples in order to correctly locate strain and temperature events. The different Brillouin scattering properties of different fiber types also needs to be considered when making measurements in order to make accurate predictions about fiber strain or exposure temperature values. This is of particular importance when the primary operating function of the optical fiber cable is for telecommunications applications and the properties or type of optical fibers have been carefully selected.

Here we will compare Brillouin scattering spectra obtained with legacy and advanced single-mode fibers. The legacy products were SMF-28® fiber, SMF-28e® fiber and the prior generation of SMF-28e+® fiber. Today's advanced products are SMF-28® ULL fiber, current generation SMF-28e+® fiber (introduced in 2012 with improved macrobending capabilities), SMF-28e+® LL fiber, LEAF® fiber, ClearCurve® XB fiber and SMF-28® Ultra fiber.

Legacy Fiber: SMF-28® Optical Fiber and SMF-28e® Optical Fiber

The spectrum shown in Figure 5 is typical of many ITU-T Recommendation G.652 compliant fibers, including SMF-28 fiber and SMF-28e fiber. The Brillouin spectrum is unimodal. Fiber strain can be characterized by measuring the frequency shift of the maximum as previously explained.

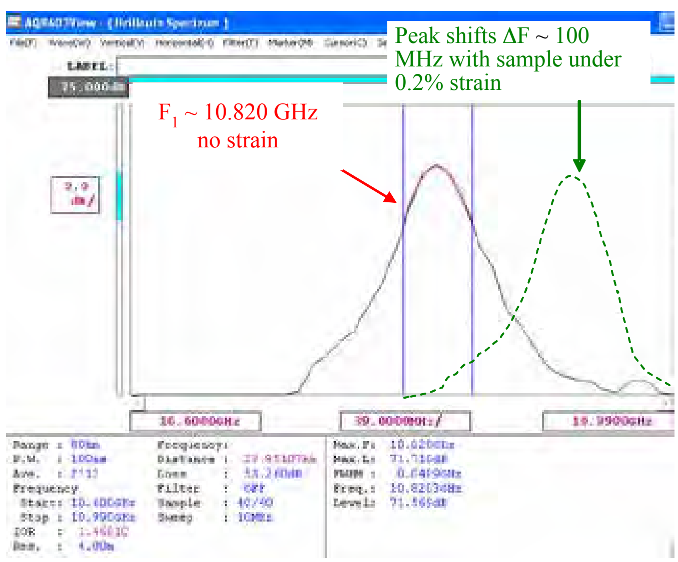

Figure 5. Legacy single-mode fiber Brillouin spectrum.

Legacy Fiber: Prior Generation SMF-28e+® Optical Fiber

BOTDR strain measurements for this fiber type are more complicated as the fiber Brillouin spectrum is dual-moded, with two maxima of similar magnitude. See Figure 6 for an example.

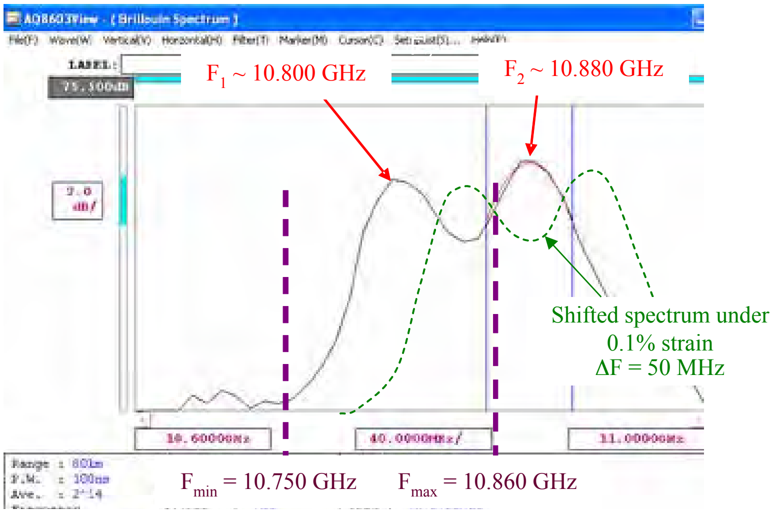

Figure 6. Prior Generation SMF-28e+® fiber Brillouin spectrum.

The appearance of these two resonances reflects the fact that two different acoustic modes interact with the light wave in or near the core area in this fiber.

At the measurements processing step the BOTDR can select either maximum as a reference. As a result, the final "strain" distribution appears noisy as the instrument "hops" between the two maxima as references, see Figure 7. This trace structure obscures the real fiber strain information and does not represent the actual strain in the cable. In order to obtain a correct representation of fiber strain for the prior generation of SMF-28e+® fiber, it is necessary to correct the measurement procedure.

Figure 7. Uncorrected BOTDR trace of non-strained prior generation SMF-28e+® fiber, obtained for standard wide range frequency scan.

One thing which can easily be done is to restrict the range of scanned frequencies by setting the maximum of the frequency scan range, F_{max}, <10.860 GHz (see Figure 6), so only the lower peak $F_1 \approx 10.800$ GHz will be recorded. Of course, in this case the measurable range is restricted to low strain situations (<0.1%) which are still in the safe stress regime for deployed optical fiber.

This is illustrated by the trace in Figure 8 for a zero strain situation. This BOTDR trace was measured on a Corning prior generation SMF-28e+® fiber on a shipping spool by BOTDR frequency scanning in the range 10.750 GHz to 10.860 GHz, where only one maximum is seen (the spectrum is shown in the inserted window in the top right hand corner of Figure 8). The position of the maximum is close to 10.800 GHz.

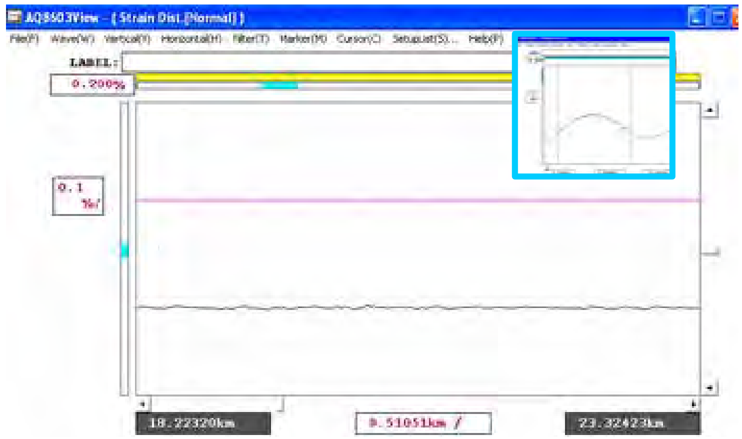

Figure 8. Prior generation SMF-28e+® fiber BOTDR trace with restricted frequency scan range.

If the local strain exceeds 0.1%, one may increase F_{max} to analyze these specific cases. The sections in which strain >0.1% are identified and can be scanned again with a higher F_{max}, e.g., 11.910 GHz. Again, one maximum is referenced, and its shift can be used to calculate the local strain. Upon completion the two traces are combined to complete the span analysis.

Current Generation SMF-28e+® and SMF-28e+® LL Optical Fiber

Current generation SMF-28e+ and SMF-28e+ LL fibers share a Brillouin backscattering spectrum that is typical of many other ITU-T Recommendation G.652 compliant single-mode fibers. The Brillouin spectrum of current generation SMF-28e+ fiber (shown in Figure 9) features a dominant peak at 10.817 GHz ± 0.02 GHz with suppression of the secondary side-lobe by more than 7 dB.

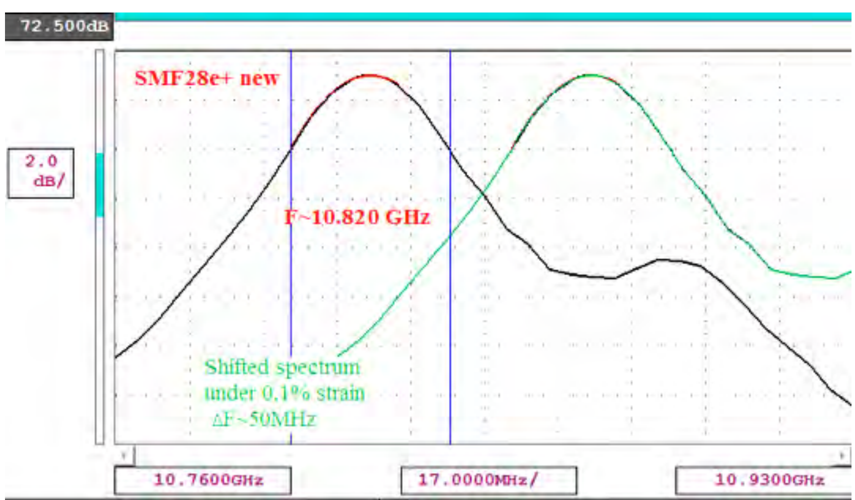

Figure 9. Current Generation SMF-28e+® fiber Brillouin spectrum.

SMF-28® Ultra Optical Fiber

Corning SMF-28® Ultra fiber is designed to combine the benefit of best attenuation among G.652.D fibers and better than G.657.A1 macrobend performance in one fiber. The Brillouin spectrum of SMF-28® Ultra fiber, (shown in Figure 10) features a dominant peak at 10.795 GHz ± 0.02 GHz with suppression of the secondary side-lobe by more than 5 dB. BOTDR equipment always correctly detects only the dominant peak, so there are not any issues with data interpretation. Under strain the spectrum shifts in the same way as in a current generation SMF-28e+® fiber.

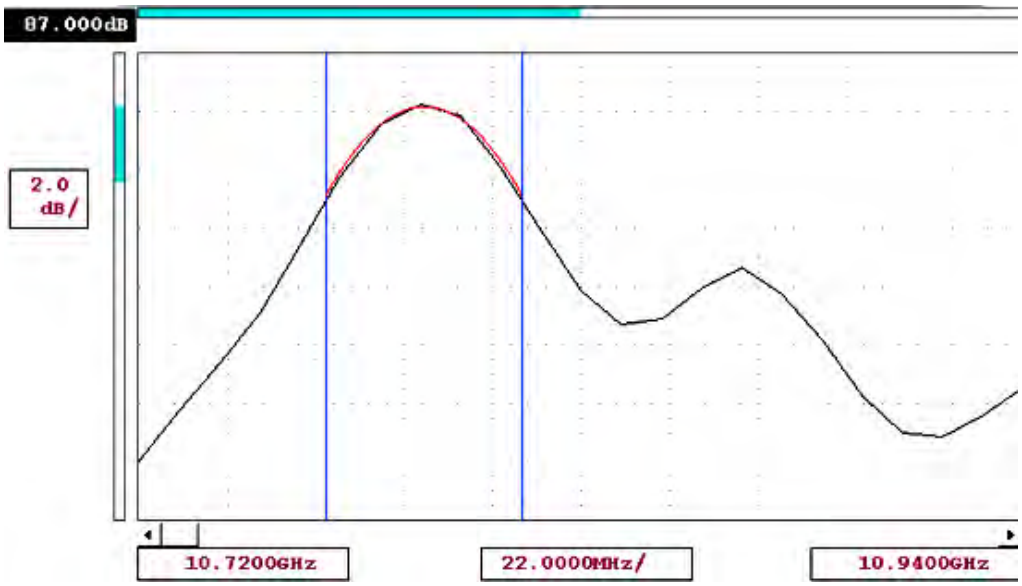

Figure 10. SMF-28®Ultra fiber Brillouin spectrum.

SMF-28® ULL Optical Fiber

SMF-28 ULL Optical Fiber is Corning's Ultra-Low technology attenuation fiber with the leading attenuation performance of any commercially available G.652 fiber type. The Brillouin spectrum of SMF-28 ULL fiber is similar to the spectra of SMF-28 fiber and SMF-28e fiber and features a "Brillouin peak" at a frequency of 10.960 ± 0.02 GHz (see Figure 11). The coefficient $d\alpha/d\varepsilon$ is still close to 500 MHz/1%, so the standard technique of BOTDR measurements is applicable, but the scanning must be performed at slightly higher frequencies (the frequency range must be shifted up by ~120 MHz).

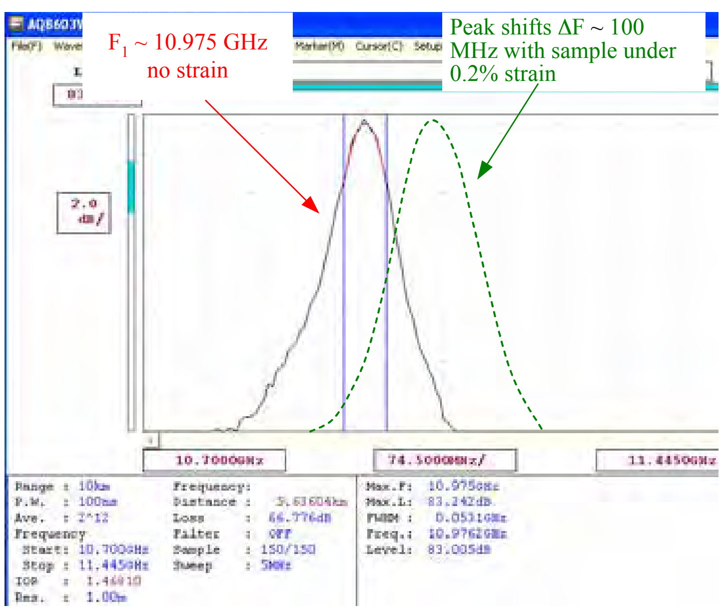

Figure 11. SMF28® ULL fiber Brillouin spectrum.

LEAF® Optical Fiber

Corning LEAF fiber is the most widely deployed ITU-T Recommendation G.655 compliant product worldwide. It has a 4-peak Brillouin spectrum structure as shown in Figure 12. Since the lowest frequency peak magnitude typically exceeds the magnitudes of other three peaks by 5 dB, the BOTDR detection and measurements of LEAF fiber are similar to legacy ITU-T Recommendation G.652 compliant products. Most commercially available BOTDR equipment are capable of correctly detecting the primary "Brillouin peak" and subsequent frequency shifts for temperature/strain shifts assessment.

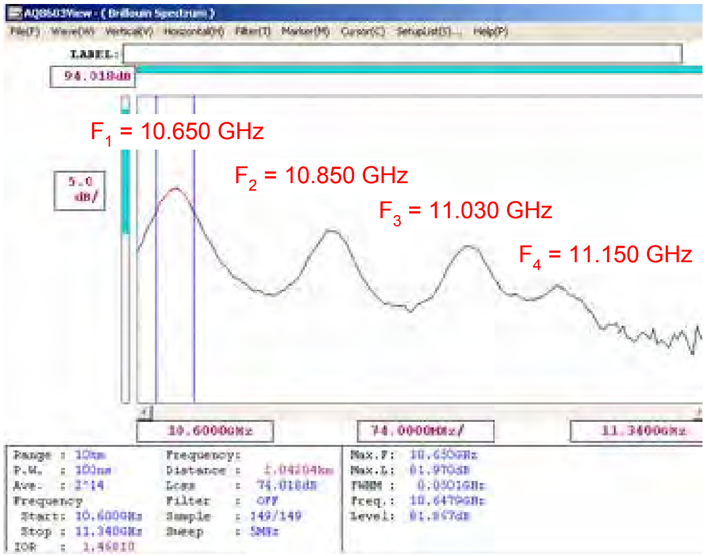

Figure 12. LEAF® fiber Brillouin spectrum, no strain.

ClearCurve® XB Optical Fiber

The Brillouin spectrum of ClearCurve XB fiber in Figure 13 has a dominant peak (>10 dB) at a frequency of 10.815 GHz. This peak is always dominant and BOTDR compatibility is typically very similar to legacy single-mode fiber types.

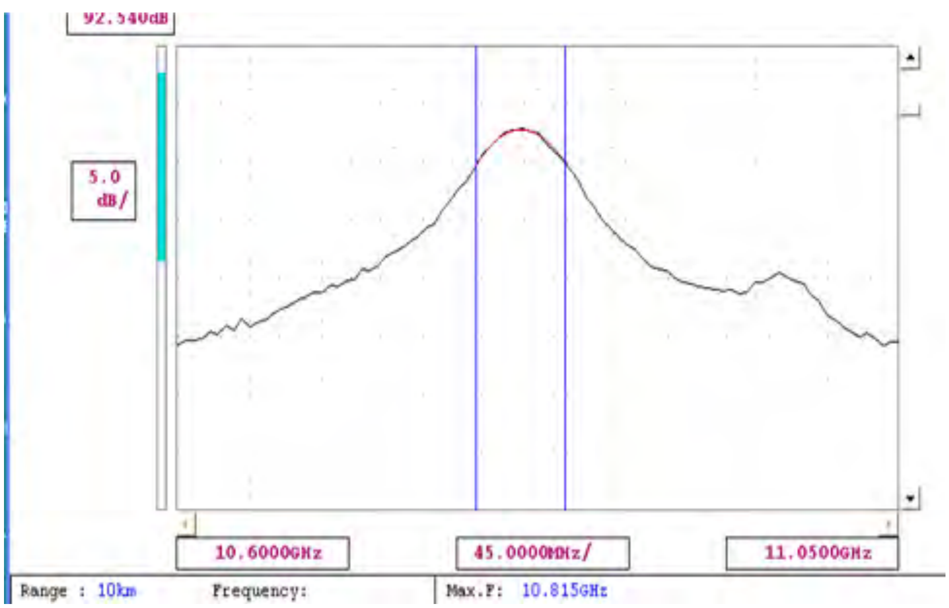

Figure 13. ClearCurve® XB Fiber Brillouin spectrum, no strain.

Conclusion

The BOTDR is a useful technique that allows evaluation of localized strain events and temperature assessment of fiber in optical cables up to 80 km. Different fiber types have their own characteristic Brillouin spectrum. Techniques are described to allow the use of BOTDR for different Corning fiber types including those with spectra that contain more than one maxima.

References

1. Brillouin Optical-Fiber Time Domain Reflectometry – Kurashima et al
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Corning Incorporated
www.corning.com/opticalfiber

One Riverfront Plaza
Corning, New York
USA

Phone: (607)248-2000
Email: cofic@corning.com