

Millimeter Resolution Reflectometry Over Two Kilometers

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Abstract Millimeter resolution optical frequency domain reflectometry measurements are achieved over 2 km of length. This level of spatial resolution over kilometer distances enables unprecedented link characterization in emerging short-haul applications such as avionics and FTTx.

Introduction

Optical reflectometry techniques are commonly used to locate and identify components and faults in fiber-optic networks. As short-haul optical networks become more widely employed in avionics, ship-board and FTTx applications, higher spatial resolution measurements are needed for better link qualification and fault localization. Optical Frequency Domain Reflectometry (OFDR) has recently emerged as a measurement technique for high spatial resolution measurements of fiber optic components, assemblies, and short-haul networks. Comparable techniques such as Optical Time-Domain Reflectometry (OTDR) and Optical Low Coherence Reflectometry (OLCR) have constraints which limit their efficacy in some applications. OTDR for example, while an excellent technique for measurements over kilometers of fiber lengths, typically has a spatial resolution limit of tens of centimeters at best. This reduces its applicability to measurements of subassemblies or short-haul networks which may have elements that are closely spaced. While OLCR achieves a spatial resolution on the order of tens of microns, its measurement range is limited to a few meters at a time. This can make measurements of assemblies longer than a few meters tedious and time consuming.

Early discussions of OFDR predicted that its measurement range would be limited to a fraction of the source coherence length, or about 30 m, for a tuneable external-cavity laser (ECL) with a 100 kHz linewidth.¹ The dynamic range of such a system was also predicted to limit visibility of Rayleigh scatter to less than a few meters of fiber length. Recent measurements, however, have demonstrated micrometer resolution over tens of meters and millimeter resolution over up to 500 m of fiber length using an ECL source.²⁻⁴ Rayleigh scatter is clearly visible in both of these cases. In 2005, Geng et. al. used a narrow-linewidth laser to achieve an OFDR measurement at 95 km.⁵ This measurement, though, had severely limited spatial resolution due to the small tuning range of the source. In this paper, we demonstrate OFDR measurements with millimeter-level spatial resolution over a distance of two kilometers, a resolution currently unattainable using OTDR. It is also noteworthy that the data required for the full two kilometer range at full resolution was

acquired in less than 100 ms, making this measurement orders of magnitude faster than comparable OTDR measurements. In addition, we show that the measurement achieves a sensitivity of better than -130 dB, with more than sufficient dynamic range to observe the Rayleigh backscatter as a function of distance along the fiber.

Experiment

The OFDR measurement technique used in this work has been described in detail in previous publications.^{2, 3} The measurement network is shown in Fig. 1. The tunable laser source (TLS) is an ECL with a linewidth specified at 200 kHz. The light from this source is split between the measurement and reference arms of a Mach-Zehnder interferometer. A polarization controller in the reference branch ensures that the reference light is split evenly between the states of a polarization beam splitter. This, in turn, enables consistent measurements regardless of the polarization state of the light from the measurement branch. Light reflected from the fiber under test (FUT) mixes with the reference light at two detectors labeled S and P. Fringes are generated as the ECL is tuned in wavelength as a function of time. Reflection amplitude and phase as a function of distance are obtained via a Fourier transform.

For our measurements, the fiber under test (FUT) consisted of first, a series of simple, angle-polished (FC/APC) connections with a macro-bend in one segment of fiber and second, a short length of fiber containing fiber Bragg gratings (FBGs). The gratings were approximately 5 mm long and spaced 1 cm apart. Each of the 29 gratings nominally reflected the same center frequency of 192.3 THz (1558.7 nm). Both of these test samples were placed at the end of

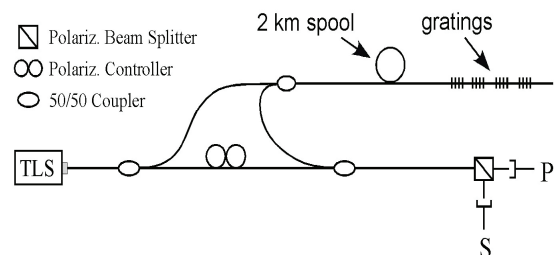


Figure 1. OFDR Measurement network.

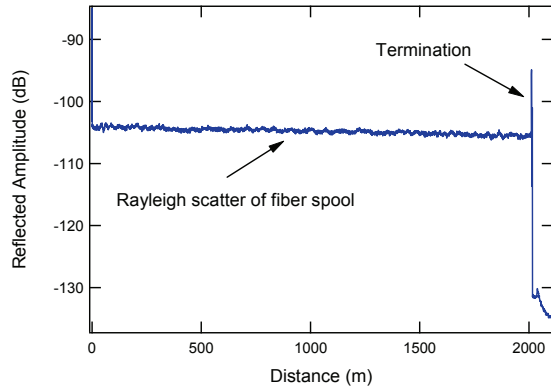


Figure 2. Reflected amplitude vs. distance of 2 km fiber spool with 3 connections at the end. The Rayleigh scatter of the fiber is clearly visible. The loss over distance in the fiber spool is noticeable as the downward slope in this scatter level.

a two kilometer spool of SMF-28 fiber to demonstrate high resolution at a long distance.

In OFDR, the distance range in nanoseconds is half the inverse of the spectral sample resolution in gigahertz. In turn, the spatial resolution is the inverse of the spectral scan range. Two types of measurements were taken in this work for comparison. First, the measurement was made in a “short range” mode. In this measurement mode, the laser was scanned over 10 nm (1.235 THz) resulting in a spatial resolution of 80 μm . Data was acquired with a frequency step of approximately 0.3 GHz which yields a distance range in fiber of about 150 m. In this mode, only the short length of fiber containing the gratings was measured.

Second, the measurement was made in a “long range” mode. In this case, the distance range exceeded two kilometers. Here, the laser scan was limited to one nanometer (123 GHz). In turn, the two-point spatial resolution was reduced to approximately 0.8 mm. A larger scan range would result in higher spatial resolution. The scan range was limited in this case to maintain manageable data sizes. The acquisition time for measurements in long-range mode was less than 100 ms. Measurements of both the two kilometer spool with a few connectors at the end as well as the spool with the gratings attached were made in the long range mode.

Figure 2 shows a measurement of the two kilometer fiber spool with a series of three FC/APC connections at the end in long-range mode, measured around

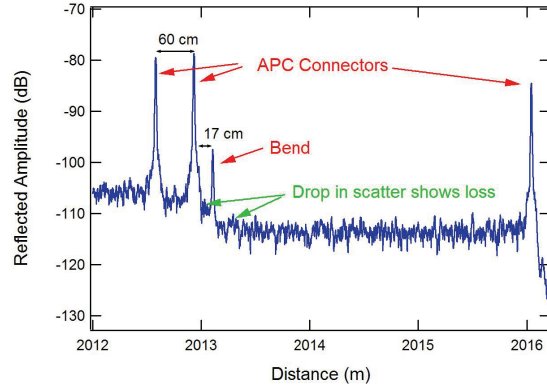


Figure 3. Close-up of the last 4 m of the 2 km system under test showing three closely spaced connectors and a lossy bend in the fiber. Each APC connector is clearly visible. The loss at each connection as well as the loss due to the bend are also readily apparent as a drop in the scatter level at each point. The loss due to the bend was about 2 dB.

1550 nm. The Rayleigh scatter of the fiber is clearly visible above the noise floor which sits below -130 dB. Figure 3 shows a zoomed-in view of the connectors at the end of the spool. The APC connectors appear as sharp peaks in the trace. A macro-bend and its associated loss (note the drop in the scatter level at this point) is clearly visible 17 cm after the second connector. The ability to resolve closely spaced reflective events and associated insertion losses like this at this distance range has not been previously demonstrated and is unique to the OFDR technique described herein.

To further demonstrate the millimeter-level resolution of the OFDR technique, measurements of the gratings in both short- and long-range modes are shown in Fig. 4. This data shows that the gratings are easily resolved at a distance of two kilometers, demonstrating an effective spatial resolution of less than 5 mm at this distance. The grating shape is less sharp at the long distance due to the limited spectral scan range in this mode, which did not entirely capture the reflected spectrum of the gratings (see Fig. 5). In fact, the one of the 29 gratings is not visible in this mode because its spectrum was outside of the scan range due to strain applied by a splice protector. To the best of our knowledge, this is the highest spatial resolution that has yet been achieved over this distance range using OFDR. This quality of OFDR measurement, including range, resolution, and sensitivity, greatly exceeds original predictions for OFDR systems of this type.¹

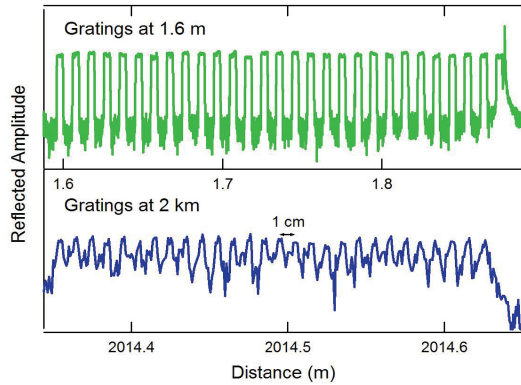


Figure 4. Reflected amplitude vs. distance of the FBGs at 1.6 m (top) and 2 km (bottom). Gratings are clearly visible at both distances, demonstrating a spatial resolution of better than 5 mm.

To show the ability to isolate information from a single grating, the spectrum of an individual grating was calculated by windowing one grating in the time, or optical delay, domain and performing an inverse Fourier transform to return to the optical frequency domain. This spectrum in both short- and long-range mode is displayed in Fig. 5. One can see that, though the spectral scan range was limited in long-range mode, the individual grating spectrum is clearly captured. The capability for spectral characterization of individual events demonstrated here can be beneficial in wavelength-division multiplexing applications and represents another benefit of OFDR over other techniques.

This spectral capability also enables distributed fiber-optic sensing with either FBGs or simply optical fiber as the sensor using OFDR. This capability has been demonstrated by the authors in previous work.^{6, 7} The extension of measurement range to two kilometers with Rayleigh-level sensitivity and high-resolution demonstrated in this paper implies that distributed fiber sensing can also be performed at these distances.

Conclusions

OFDR measurements with millimeter two-point spatial resolution were demonstrated over a distance of two kilometers for the first time. FBGs spaced one centimeter apart were measured at the end of both 1.6 m and two kilometer lengths of fiber.

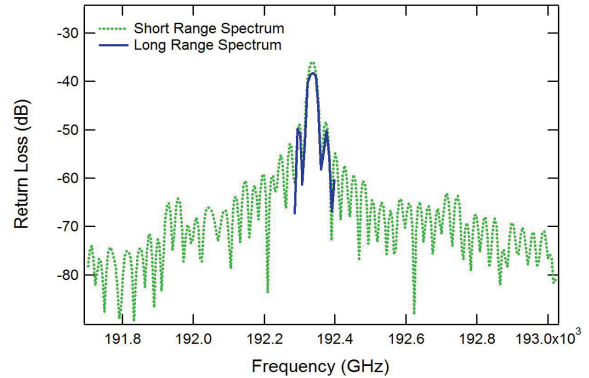


Figure 5. Reflected spectrum of an individual FBG calculated from the data taken in both short-(dotted) and long-range (solid) modes.

Comparisons of these data sets demonstrated that individual gratings 5 mm long were easily resolved in the long-distance measurement. Rayleigh scatter level sensitivity was also demonstrated in these measurements, making possible loss measurements for events within centimeters of each other at a two kilometer distance. In addition, the data required for these results was acquired in less than 100 ms, representing orders of magnitude of speed increase over comparable OTDR measurements. These results greatly exceed first predictions of the limitations of OFDR measurements due to source coherence length. Such high resolution and high sensitivity over these distance ranges enables unprecedented fault detection, localization and analysis in emerging short-haul applications such as avionics, ship-board, and FTTx fiber networks, as well as long range fiber optic sensing.

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