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Determination of Localized Loss in Cabled Fiber Using OTDR Measurements of Relative Mode Field Diameter

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Abstract:
We demonstrate enhanced sensitivity of a commercial OTDR by employing novel bidirectional analysis techniques. The method is applicable to measurements of cabled fiber where fluctuations in local mode field diameter are due to factory variations.

OCIS codes: (060.2270) Fiber Characterization and (060.2300) Fiber Measurements.

1. Introduction

Optical-time-domain reflectometers (OTDRs) have long been standard equipment for the characterization of optical fiber [1,2]. It is well-known that by transmitting a pulse down a fiber, and analyzing the back-reflected light, the loss of a fiber can be characterized. It is also well-known that to accurately characterize splice-loss using this technique, one should take traces from each end of an optical fiber, and employ bidirectional analysis [3]. Bidirectional analyses can also be used to characterize local variations in both structure and loss along the length of the fiber [4].

The usefulness of bidirectional analysis of local loss in fiber depends on the resolution of the measurement and especially the signal-to-noise ratio of the traces. In this paper we demonstrate that by taking bidirectional traces at both the target resolution and also at a lower resolution, the effective range for local loss analysis on a commercial OTDR can be nearly doubled. This capability is made possible by the fact that the Mode Field Diameter (MFD) variations in loose-tube cabled fiber typically have a length scale much longer than the resolution of interest, and hence can be measured using less noisy, lower-resolution OTDR traces. The low-noise MFD measurements can then be used to aid in the bi-directional analysis of the noisier, higher-resolution OTDR traces of interest.

2. Bidirectional Analysis of OTDR Traces

From a single OTDR trace the user sees the level of back-reflected light as a function of distance down a fiber. The signal level is a function of both the MFD of the fiber and the fiber loss. By taking bidirectional traces (traces originating at each end of the fiber) the effect of the varying MFD can be eliminated, and the loss along the fibers length can be calculated. This is achieved by differentiating the difference of the forward and backward traces:

$$L(x) = \frac{\partial}{\partial x}(10 \cdot \log_{10} T_{back} - 10 \cdot \log_{10} T_{forward})/2 \tag{1}$$

Here $T_{forward}$ and T_{back} are the forward and backward OTDR traces in linear units, while $L(x)$ is the loss as a function of distance along the fiber in units of dB/km. The local loss $L(x)$ is useful for locating and identifying problems with installed fiber. To calculate $L(x)$, it is essential to carefully align the two traces so that $T_{forward}$ and T_{back} are measured along the same axis.

The error in $L(x)$ increases when the data is noisy. The lower the resolution of the traces, the more noisy the traces since the total energy launched into the fiber decreases with decreasing pulsewidth. Also, the OTDR traces are have a lower signal-to-noise ratio for the parts of traces where the round-trip distance that the light travels is the greatest, for that is when the signal is lowest. Therefore T_{back} is noisier near $x=0$, and $T_{forward}$ is noisier near $x=L$. As a result, $L(x)$ is not as well determined near the ends of the fiber ($x=0$ and $x=L$) as it is near the center.

3. Mode Field Diameter Correlation Length—Measurements on Cabled Fiber

As part of our bidirectional analysis, we also take the sum of the two traces:

$$\eta(x) = (10 \cdot \log_{10} T_{back} + 10 \cdot \log_{10} T_{forward})/2 \tag{2}$$

The *relative* backscatter function $\eta(x)$ is a function of the fiber's numerical aperture, doping concentration, Rayleigh scatter coefficient, and core diameter [4], all of which should vary slowly along a fiber's length. It is related to the usual backscatter function by an additive constant. For a cabled fiber that was part of a single draw, the variations in η as a function of distance are largely caused by variations in mode field diameter, which determines the numerical aperture. We have made extensive measurements of the quantity $\eta(x)$ for both laboratory spooled fiber and buried cabled fiber, and found that for the case of cabled fiber its autocorrelation length (180-1200m) is longer than most OTDR resolutions of interest (20m-200m). In addition, one expects that $\eta(x)$ will be constant in time after a cable is buried, and we have confirmed this with measurements of buried fiber repeated over several years. Thus $\eta(x)$ in cabled fiber can be measured at a lower resolution, where the OSNR is higher, and the results can then be used to enhance higher-resolution but noisier bidirectional OTDR traces taken at different times. Note that for spooled fiber, the variations in $\eta(x)$ have been observed to be on the same scale as the spool diameter and hence must be measured with a resolution less than or equal to the spool diameter, so that this method is not applicable for spooled fiber.

We use the measurements of $\eta(x)$ to more accurately calculate $L(x)$ for a long field fiber (57 km). Figure 1a shows polarization-scrambled, bidirectional traces taken with 100ns pulses (20 m resolution, 1 minute averaging time), and is noisy near the ends of each trace. The polarization scrambling is necessary for high resolution (20 m or less) to compensate for polarization interference effects of the order of the beat length, 10-20 m in this case [5]. The reflections visible in these traces are from mechanical splices. Figure 1b shows $\eta(x)$ on the same fiber calculated from similar OTDR traces that were taken with lower-noise 275 ns pulses (60 m resolution, 1 minute averaging time). The discontinuities in Fig. 1b are at the splices between each of the 25 different segments on the 57 km span. An expanded view of $\eta(x)$ of the last span is also shown. Although not shown, we verified with the 20 m resolution data that within all of the segments, $\eta(x)$ varies slowly, and 60 m resolution is sufficient.

The relative backscatter function measured at lower resolution (60 m) can then be used to enhance the higher resolution (20 m) data shown in Figure 1a to calculate the loss along the fiber. To do this, we use a modified version of Equation (1) where at each point along the fiber the SNR is optimized by taking the appropriate combination of data from each of the two high resolution traces $T_{forward}$ and T_{back}, along with the determination of $\eta(x)$ from the lower resolution measurement :

$$L(x) = \frac{\partial}{\partial x}\kappa(x)\cdot(\eta - 10\cdot\log_{10} T_{forward}) - \frac{\partial}{\partial x}(1-\kappa(x))\cdot(\eta - 10\cdot\log_{10} T_{back}) \tag{3}$$

κ (x) is chosen to optimize the signal-to-noise ratio (SNR) of $L(x)$. For example, when the OTDR noise levels in both traces are similar, a good choice for κ (x) would be:

$$\kappa(x) = \frac{T_{forward}(x)}{T_{forward}(x) + T_{back}(x)} \tag{4}$$

Finally, in Figure 1c we show the local loss $L(x)$ calculated from both Equation (1) and from Equation (3). In this figure the portion of $L(x)$ near an area of localized loss is shown in detail at both 1550 nm and 1625 nm to illustrate the effectiveness of the method. By comparing the results at both wavelengths, it is easier to determine which loss variations are real and which result from OTDR noise. For example, there is a repair fusion splice loss at 55.7 km that was seen in the MFD-enhanced calculation (Eqn. 3) but missed in the standard bidirectional analysis (Eqn. 1).

4. Enhancing the Range of an OTDR

The slow variation in η can also be exploited to extend the range of an OTDR at a given resolution. Bidirectional OTDR traces were taken on a 114 km length of installed fiber formed by concatenating two 57 km fibers. Traces were taken using two different resolution settings: 200m (using 1000 ns pulsewidth and 1 hour averaging time), and 60m (using a 275 ns pulsewidth with 5 minutes averaging time). The higher resolution (60 m) traces are shown in Fig. 2a and show evidence of noise at the end points of the fiber. In Fig. 2b we show the $\eta(x)$ function determined from the lower resolution (200 m) traces. The resulting local losses $L(x)$ as calculated from both Equation (1) and from Equation (3) are shown in Fig. 2c along with an exploded view of the last segment in the cable. The error in the estimated loss in this segment in the standard calculation (Eqn. 1) is visible.

5. Conclusions

We have demonstrated that the noise and resolution of the loss versus distance calculations for cabled fiber can be improved by using measurements of the relative backscatter function $\eta(x)$ at a lower resolution to optimize the signal-to-noise ratio of the higher-resolution traces . Using this method we have calculated the local loss $L(x)$ for a 57 km span of buried fiber at a resolution of 20 m, and also for a 114 km span at 60 m resolution.

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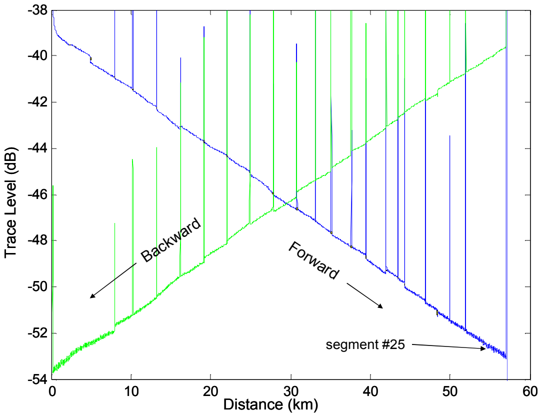

Figure 1a: Bidirectional high-resolution traces taken on an installed 57 km cable. These traces were taken at 1550 nm with a 100 ns pulse width, and the acquisition time was one minute. The peaks are due to mechanical splices.

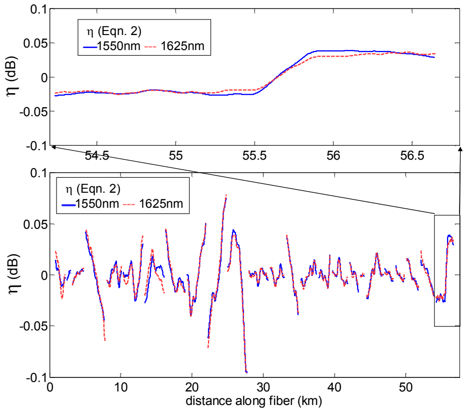

Figure 1b: η vs. distance calculated from OTDR measurements at 1550 nm (—),and 1625 nm (- - -) using OTDR traces taken with a 275 ns pulse width. The lower curve shows the entire 57km fiber span; the gaps are discontinuities at splice locations. The upper curve is a close-up of the final segment in the span.

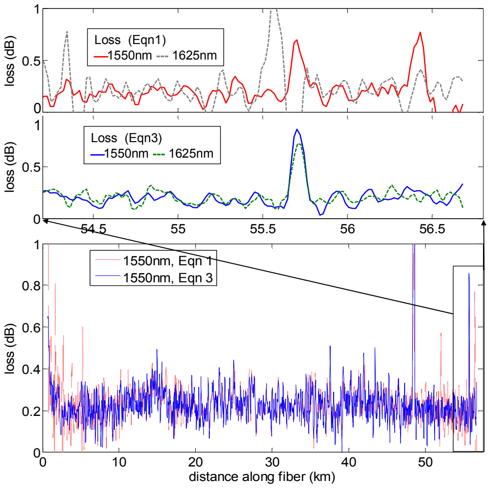

Figure 1c: Local loss/km vs. distance for the 57 km fiber, calculated using Eqn..1, and the MFD-enhanced method (Eqn. 3). Each upper trace shows a close-up of the loss calculated at two λ using one of these methods. The MFD-enhanced method yields less noisy results than the traditional method (Eqn. 1). These traces focus on fiber loss, and do not include splice loss.

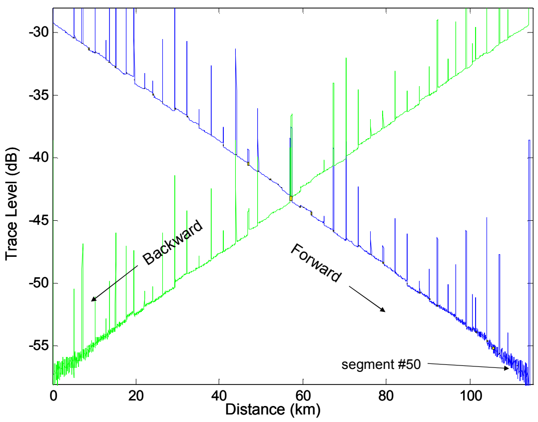

Figure 2a: Traces taken on a 114 km fiber (formed by concatenating two 57 km fibers). These traces were taken using a 275 ns pulse width, and a 5 min. acquisition time. The peaks are due to mechanical splices.

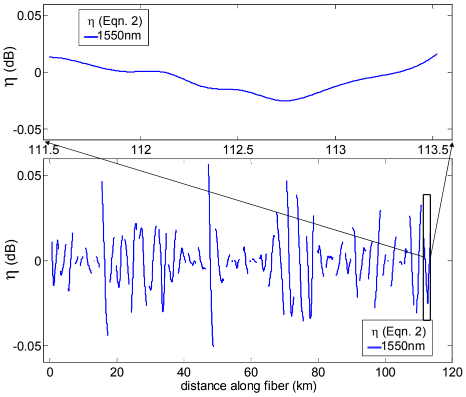

Figure 2b: η vs. distance calculated using OTDR traces taken with a 1μs pulse width. The lower curve shows the entire 114 km fiber span, and the gaps are discontinuities at splice locations. The upper curve is a close-up of the final segment in the span.

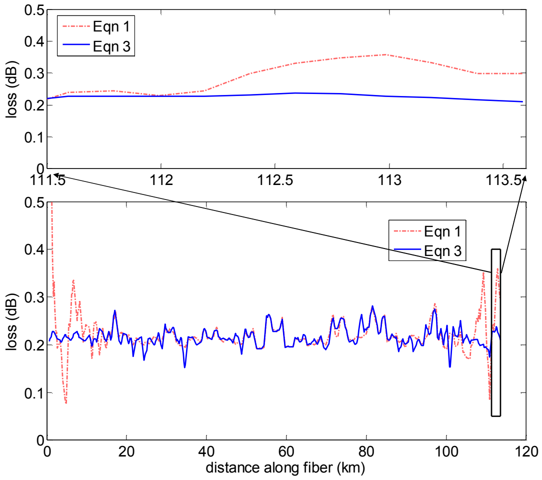

Figure 2c: Local loss/km at 1550 nm vs. distance for the data from Fig.2a calculated using Eqn. (1) and the MFD-enhanced method Eqn. (3). The upper trace shows the loss over the same 100 meter section shown in Figure 2b for both methods of calculation. These traces focus on fiber loss, and do not include splice loss.