Overview of coherent reflectometry techniques: characterization of components and small systems

M. Wegmüller, P. Oberson, J.P. von der Weid*, O. Guinnard, L. Guinnard, C. Vinegoni, M. Legré, N. Gisin

Group of Applied Physics, University of Geneva, 20 Ecole-de-Médecine, CH-1211 Genève 4, Switzerland, *mark.wegmuller@physics.unige.ch*
* Center for Telecommunications Studies, PUC-Rio, Rio de Janeiro, 22453-900 Brazil

Abstract

Coherent reflectometry techniques have important advantages over direct detection techniques: larger sensitivity, larger dynamic range, better resolution, and spurious light suppression. The measurement range is typically limited to <1 m for Optical Low Coherence Reflectometry, and to <~1 km for Coherent Optical Frequency Domain Reflectometry. Especially the second technique is therefore well suited for measurements of optical modules with extended components and for small systems.

Introduction

The advantages of coherent reflectometry techniques are well known. In fact, they are still the only techniques giving two point resolutions in the mm range. Of the two major coherent reflectometry techniques Optical Low Coherence Reflectometry (OLCR) and Coherent Optical Frequency Domain Reflectometry (OFDR), the first is well established and widely used for component characterization [1]. In typical OLCR implementations, the measurement range is however limited to below 1 m. None of the proposals to extend this value have been retained on a large basis so far, mainly for the sake of having robust and compact OLCR devices.
Although a sub-metric range is well adapted for the characterization of single, compact components, it is too small for larger, more complicated optical modules including several composites as couplers, WDMs, taps, modulators, etc. The path length in such devices can easily reach some tens of meters, and OFDR has to be employed. Although this technique is well known for several years, it has not seen broad commercial implementation so far. The main reason is that the constraints on the source are heavy, and a simple, non-expensive yet reliable source giving the desired performance was lacking. In this paper, a novel OFDR device based on a simple, mechanically tunable fiber laser [2] is presented. After giving the characteristics of this device, several applications relevant for small systems metrology are presented.

Principles of OFDR

To avoid all confusion, let us first stress that only the technique of coherent OFDR is considered here (there exists also a 'normal', non-coherent OFDR technique which is the frequency domain analogous of OTDR and measures the modulation transfer function [1]). The coherent OFDR technique (Fig.1) is based on the detection of a beat signal between the distributed reflections from the fiber under test (Rayleigh backscatter, connectors, etc.) and a fixed Fresnel reflection (local oscillator). Using a linear frequency sweep of the laser, one can straightforwardly map the measured beat frequencies on a distance scale, whereas the normed square power for a given beat frequency gives the reflectivity at the corresponding distance. For a good general overview of the OFDR principles and limits, the reader is referred to [3]. In the OFDR used for the measurements presented here, several important improvements have been implemented described in the following along with the specifications of the present device.

Range: The measurement range of OFDR is limited by the coherence length of the source and by its phase noise. The first one leads to signal fading, the second one reduces the dynamic range [3]. The fiber laser employed presently has a very large coherence length of about 3.3 km (FWHM bandwidth of 10 kHz) [1]. Fig.2 demonstrates the corresponding signal fading of about 5 dB/km, and the reduction in the dynamic range, limiting the useful range to about 2 km. Using more sophisticated (and complicated) sources or signal corrections, an order of magnitude larger ranges have been demonstrated [4]. However, the spatial resolution drops below the one achievable with OTDR, so the interest of such methods is questionable from an applications point of view. Fig.3 demonstrates that the 2 km range of our OFDR device is sufficiently large to assure a smooth transition between OFDR and OTDR applications.

Resolution: The maximum two-point resolution is given by the frequency excursion of the source. However, this value can be seriously deteriorated by nonlinearities in the frequency sweep. In our device, this is corrected for by using the signal from a reference interferometer from which the instantaneous frequency is calculated. For the fiber laser used, a maximum detuning of 0.3 nm is employed (41 GHz), giving a resolution of 5 mm as illustrated by Fig.4. The two point resolution also depends on the measurement range and on the number of points used. This is because the slope of the frequency excursion has to be reduced for a larger range so that no aliasing in the sampling is encountered (i.e. maximum beat frequency<Nyquist-frequency). The two point resolution and the measurement range become

$$\Delta l_{2p} \approx \frac{6.5}{N} L_{max} \quad , \qquad L_{max} \approx \frac{c}{6n} \frac{N}{\delta\nu} \ ,$$

respectively, where N is the number of sampling points (typically 8192), $\delta\nu$ the maximum frequency excursion, c the speed of light, and n the group index. Consequently, for a given range, the resolution is given by 0.08% of the distance range. For the maximum 5 mm resolution, the range is 6.6 m.

The importance of having a good resolution is clear from Fig.5. A line of 6 pigtails connected with FC-APCs was measured using different resolutions. This was achieved by changing the number of points N of the OFDR acquisition. Using 512 points (20 cm resolution, curve at top), the high quality connector at 8 m is covered by the Rayleigh light, and the fiber break after the last connector can not be discerned from the connector reflection (see inset). With 8192 points (12 mm resolution), the Rayleigh level drops by about 12 dB, and the small reflection from the high quality connector can be easily detected. Further, one clearly sees that the fiber break is after the last connector and not in front of it, an important feature for applications like fault detection in optical modules.

A consequence of having a high spatial resolution is that the Rayleigh backscattering (RBS) becomes very noisy due to the coherent speckle. Note that this is a physical limit (and not a technological one) affecting all high-resolution reflectometry methods. As less scatterers take part in the interference, the RBS becomes more peaked. This can somewhat be reduced by dithering the center frequency and averaging. In our device, the possible change in center frequency is however restricted by mechanical constraints of the fiber laser, and the smoothed RBS still varies somewhat. If one can average over sufficiently large distances, small losses can still be identified, as is demonstrated by Fig.6 which shows a measurement of a bad splice with 0.4 dB loss.

Polarization dependence, sensitivity, and dynamic range: As for all coherent techniques, the signal will depend on the polarization state of the reflected light. This can be advantageous to get information about the beatlength distribution (see below), but is typically an unwanted effect in standard applications. We therefore included a polarization diversity detection scheme in our OFDR device, reducing the polarization dependence of the reflected light to less than 0.5 dB. The sensitivity and dynamic range of the present device is -110 dB and 80 dB, illustrated in Fig.4. As was mentioned before, the dynamic range decreases with distance (see Fig.2) because of the source phase noise. Using time domain averaging, a sensitivity of -152dB with a dynamic range of 106 dB has been demonstrated in earlier work [5]. This technique however requires a very stable phase of the reflected signal, which is only achievable for short measurement distances.

Some measurement examples using OFDR

Due to its high sensitivity, dynamic range, resolution, and accuracy, OFDR is useful for a vast range of different applications in fiber metrology, like e.g. measurements of WDM components [6], distributed gain measurements in EDFAs [7,8], or local birefringence [9.10].

Measurement of distributed gain in EDFAs: The coherent detection scheme of OFDR leads to a strong rejection of background light from ASE or residual pump light. OFDR is therefore ideally suited for non-destructive, distributed gain measurements in EDFA. Fig.7 shows a measurement of the gain distribution in a 12 m long, 500ppm Er-doped fiber pumped by 1480 nm light. The set of curves was obtained by gradually increasing the pump power from no pump at all (lowest curve) to +15 dBm (top curve). Clearly, pump saturation led to gain clamping, with a maximum gain reached at 4.5 m. After that distance, the Er ions were no longer inverted due to a lack of pump power, and the signal is reabsorbed. Cut-back measurements were in very good agreement with the OFDR gain measurements, typically to within the OFDR precision of 0.5dB.

Note that it is difficult to exactly model the gain distribution, as the necessary model parameters are hard to measure with sufficient precision. This is demonstrated in Fig.7 by the solid and dashed lines, where two sets of model parameters obtained in different ways were used [8]. The dotted line on the other hand was obtained by varying the model parameters for good agreement with the measurement.

Measurement of distributed birefringence: The polarization dependence of the coherent detection used in the OFDR can be exploited to get information about the evolution of the polarization state along the fiber [9,10]. Due to the enhanced range of the OFDR at hand, we can get a much better statistics of the distributed fiber birefringence. Moreover, the polarization independent signal from the polarization diversity detection is used to subtract the (polarization independent) Rayleigh structure, thereby removing the frequencies that are not related with the fiber birefringence. Fig.8 shows the polarization dependent reflections from a 1km long low PMD fiber after removal of the Rayleigh noise and normalization to zero mean power. This curve is then Fourier transformed to get information about the rotation period of the polarization vector, i.e. the beatlength. The figure shows that there is not one specific, well-defined beatlength period, but a distribution of such values. While the structure of the peaks changes somewhat for different launch polarizations, the mean value of the distribution is fairly constant (variations of about 0.5m, i.e. 5%, were observed for the present example). An interesting feature is that the value of birefringence is found to vary along the fiber. From the normalized return signal, it can be seen that the polarization changes slower towards the end of the fiber. Indeed, by Fourier transforming only a section of the curve in Fig.8, mean values for the beatlength of 9.4m and 13.1m were found for fiber sections from 100-300 and 700-900m, respectively. Note that when we inverted the fiber, we found the beatlength to be decreasing, demonstrating that this feature is not an artefact of the measurement technique, but indeed reflects the polarization properties of the fiber. For comparison, we performed a similar measurement on a high PMD fiber (1.9 ps/√km). Using the same range of 2km as before, the polarization dependent signal was found to be often flat and 3dB lower than the polarization independent one. This happens if the polarization is rapidly varying on a distance scale smaller than the OFDR resolution, so that only an averaged value is obtained. Looking at these flat sections with an increased resolution indeed revealed fast polarization changes. The measurement was therefore done with a much higher OFDR resolution on a 100m section of the fiber. As Fig.9 shows, two distinctive peaks can be discerned as is expected from the theory in [9] for a fiber with well-defined birefringence. The (mean) beatlength accounts to 55 cm.

Conclusions

For the measurement of optical modules and small systems, the range of typical OLCR devices, very valuable for component characterization, is not sufficient. OTDRs on the other hand lack the advantages of a coherent detection scheme. With the progress of technology, coherent OFDR devices can now be realized that are capable of making the transition between the two techniques.

Such a novel OFDR device, based on a mechanically tuned fiber laser, was presented here. With its range (6 m to 1 km), resolution (0.08% of range), sensitivity (-110 dB), and dynamic range (80 dB), it is well adapted for a vast range of different applications in fiber metrology, like e.g. measurements of all kinds of components and their combinations (connectors, WDMs, couplers, taps, modulators, and to some degree even isolators or circulators), distributed gain measurements in EDFAs, or distributed local birefringence measurements.

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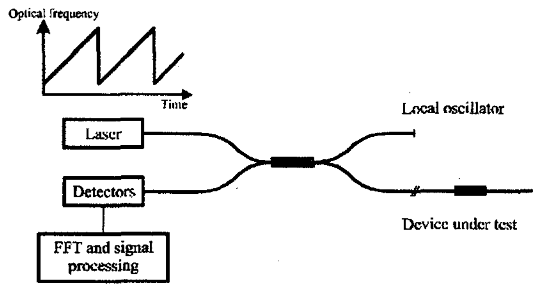

Fig.1: Set-up of the OFDR

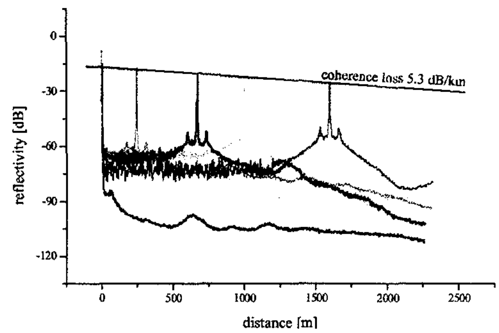

Fig.2: Fresnel reflections at different distances. The two pedestals are from acoustic perturbations

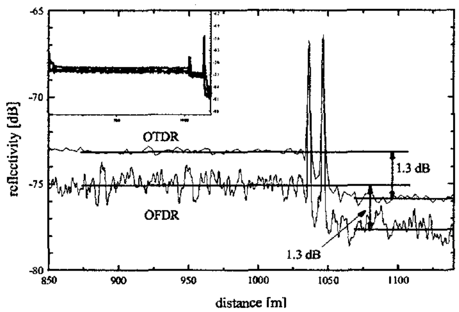

Fig.3: Measurements of a 10m jumper after a 1km SMF using OFDR and OTDR

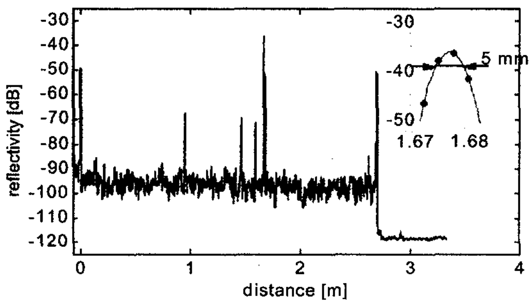

Fig.4: Short range measurement of a series of fibers with FC/PC and FC/APC connectors

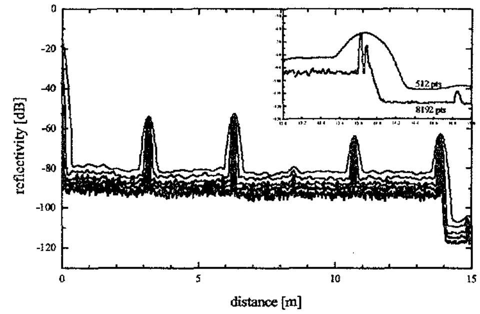

Fig.5: OFDR traces of a line of 6 jumpers using different two point resolution settings

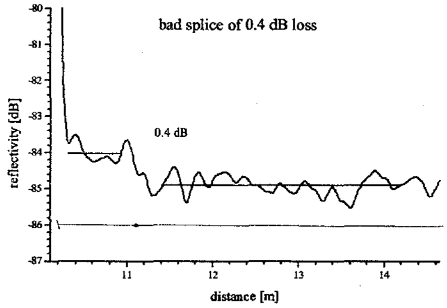

Fig.6: Measurement of a bad splice

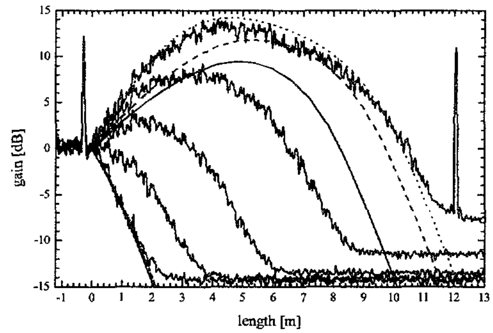

Fig.7: Distributed gain measurements in an 500 ppm Er-doped fiber for different pump powers.

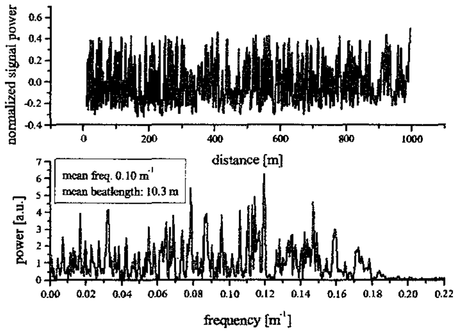

Fig.8: OFDR measurement of distributed birefringence of a low PMD standard fibre

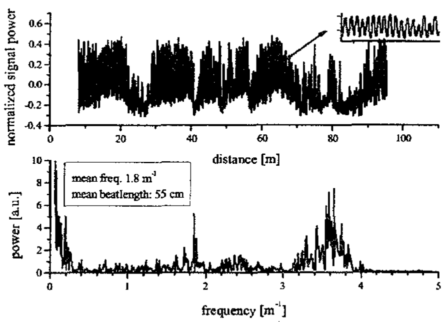

Fig.9: OFDR measurement of distributed birefringence of a large PMD fibre