

Optical-frequency domain reflectometry: roadmap for high-resolution distributed measurements

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An overview on optical frequency-domain reflectometry (OFDR) methods is given with experimental results. Existing methods are classified and compared in terms of performance parameters, technical requirements and applications. Among them, the operation of incoherent OFDR is presented. Our system is capable of localizing and quantifying optical reflections over about 2 km of fiber but has a relatively low spatial resolution of 10 meters. Nevertheless, this resolution is not a fundamental limit and can be improved either by increasing the frequency span or utilizing coherent OFDR. We then discuss the challenges and prospective applications of using high-resolution coherent OFDR method.

Introduction

High-resolution reflectometry is a very useful tool in the context of component metrology [1] and of the fault localization in short-haul optical networks that are used in avionics and FTTx [2]. In addition to discrete reflections, it can be used to measure distributed backscattering and therefore to measure the spatial distribution of optical parameters all along the optical fibers (birefringence, differential group delay) [3]. In this letter, we describe the sweep frequency incoherent OFDR system and its properties. We then turn to potential applications of an improved set-up that is implementing the coherent OFDR technique.

Comparison of OFDR techniques

Optical frequency domain reflectometry methods mainly fall into two categories: incoherent OFDR (IOFDR) and coherent OFDR (COFDR). In the first category, the cw optical carrier (probe signal) is intensity modulated by a constant-amplitude RF signal whose frequency is changed periodically over a certain frequency range either stepwise (step-frequency method) [4] or continuously (sweep frequency method) [5]. This probe signal is then launched into system under test (SUT). Rayleigh backscattered and backreflected optical signals are detected as a function of modulation frequency and processed in a vector network analyzer to obtain frequency response of the fiber (Network analysis OFDR, NA-OFDR). Fourier transformation of the frequency response then gives the time-domain impulse response provided that the scanned frequency range is sufficiently large. In an alternative sub-group called Incoherent frequency-modulated continuous wave (I-FMCW), the detected probe signal is mixed with the modulating RF signal in the electrical domain [6]. Resulting output that contains mixing products is then observed by means of a spectrum analyzer. The frequency axis represents the delay times experienced by probe signal. Knowing the speed of light within the fiber, time axis is converted into physical distance. In the second category (COFDR), the carrier frequency of the optical source is swept linearly and phase-continuously in time, and the frequency-modulated optical signal split into two paths, one of which probes the SUT whereas the other is used as reference signal. Superposition of the probe signal and the reference signal on the detector yields

the beat frequencies that are related to the optical amplitude and phase response of the SUT. Fourier transform of the photocurrent provides the map of reflections as a function of distance. This method is often called as coherent FMCW. COFDR has typically sub-millimeter spatial resolution over tens to hundreds of meters [1]. Measurement range of 100 km was recently demonstrated [7] which necessitates the utilization of very narrow linewidth laser source. Figure 1 summarizes the different trends in OFDR that have been published in the scientific literature.

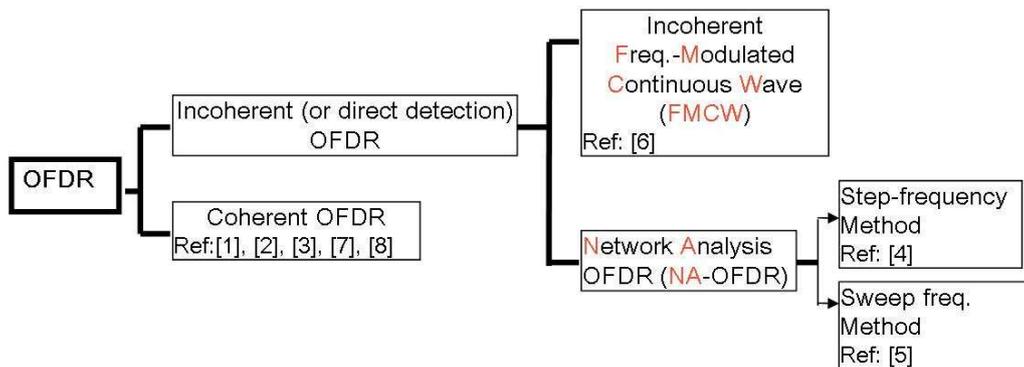


Figure 1: Classification of OFDR methods

Experimental investigation of Sweep frequency IOFDR

Our experimental set-up is shown in Figure 2.

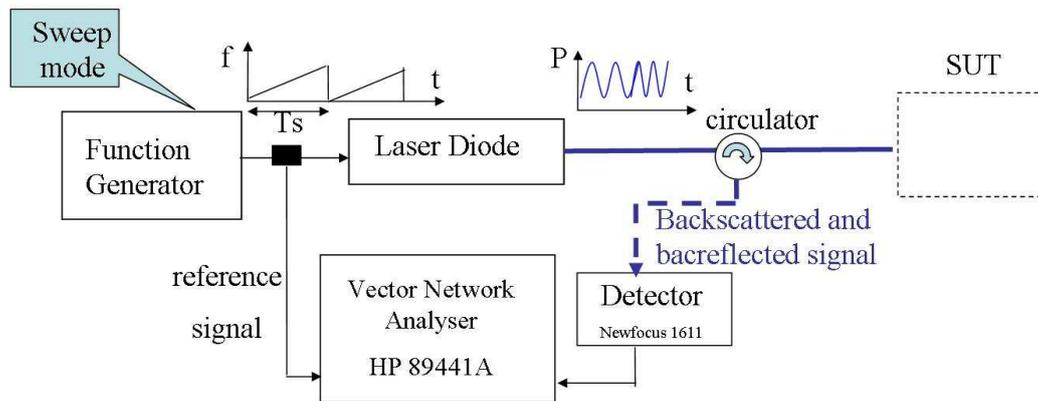


Figure 2: Experiment set-up of sweep frequency NA-OFDR

The sinusoidal signal (output of the function generator) whose frequency is swept over a certain span modulates the intensity of the laser. This modulated signal (test signal) is launched into the SUT. Backscattered and backreflected signals from SUT are directed to the detector by a circulator. The role of the vector network analyzer is to measure the amplitude and the phase of the test signal with respect to the reference signal. This operation was realized over a frequency span of 10 MHz limited by the maximum frequency range

of the network analyzer. The repetition rate was 1ms. The number of frequency points on the network vector analyzer was 1601. Figure 3 shows the amplitude and phase of the test signal. By using the frequency response provided by the vector network analyzer, impulse response of the SUT was calculated by the way of inverse Fourier transform. For the preliminary experiments, SUT was a fiber bobbin which has a discrete reflection in the end. Figure 4 shows the impulse response of the SUT with a fiber length of 2.2 km.

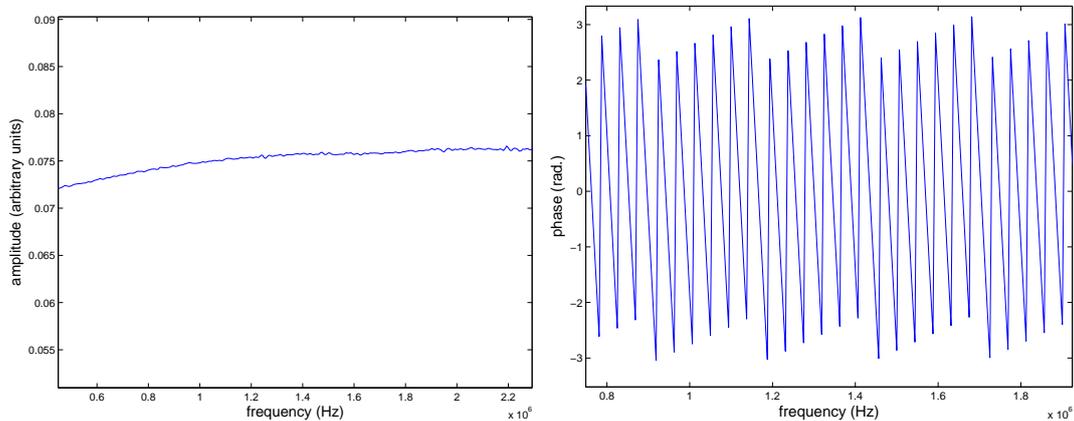


Figure 3: OFDR data for the fiber of 2.2km with an optical reflection in the end. Amplitude vs frequency (left). Phase vs frequency (right)(zoom over 1 MHz frequency range).

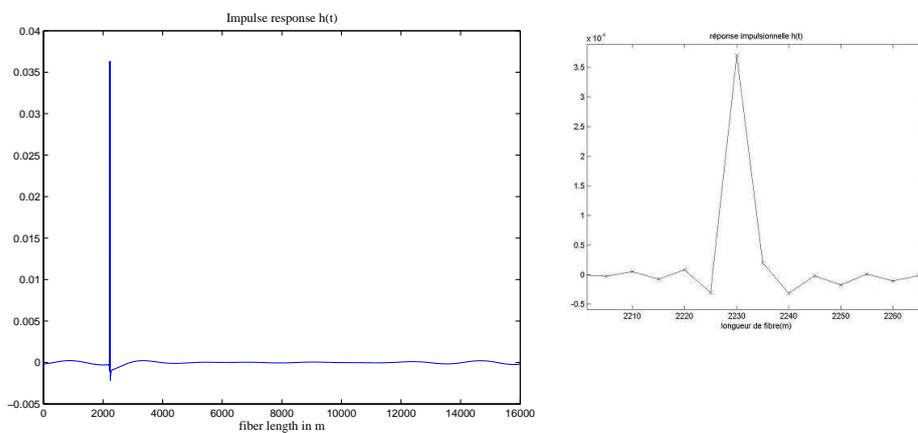


Figure 4: Impulse response vs distance (left). The zoom on the reflection peak (right).

Three fiber spools of different lengths were tested and end reflection peaks were localized. Results were compared with the measurements realized by OTDR (Fig.5). Frequency span of 10 MHz limits the spatial resolution to 10 m. This spatial resolution was experimentally demonstrated. The distance range (L_{max}) is determined by both the frequency span (Δf) and the number of frequency points (N) via the formula: $L_{max} = \frac{c}{2n} \frac{N-1}{N\Delta f}$ where c is the speed of light and n is the refractive index of the fiber. This formula gives a distance range of about 30 km. However, in practice the distance range was limited by the sensitivity of the detector to about 5 km.

Fibre	OTDR	sweep frequency NA-OFDR (peak position)
Fiber1	2227 m \pm 1 m	2228 m \pm 5 m
Fiber2	751 m \pm 1 m	753 m \pm 5 m
Fiber3	55 m \pm 1 m	58 m \pm 5 m

Figure 5: Fiber lengths measured by OTDR and OFDR

Perspectives with Coherent OFDR

When realizing COFDR set-up, the key component is the narrow linewidth, mode-hop free tunable laser source (TLS) whose frequency can be chirped linearly and continuously in time. The spatial resolution is determined by the frequency tuning range. The measurement distance is limited by the coherence length of the TLS [8]. Our main motivations to build our own COFDR set-up are summarized as follows: It will be possible to realize distributed measurements of certain parameters (e.g. birefringence, non-linear properties) in new types of fibers such as Photonic Crystal Fibers and bismuth fibers. These new fibers are utilized on very short distances (a few meters), therefore conventional OTDR technique is not suitable. Realization of distributed sensors requiring sub-millimeter resolution will be a very important application of our COFDR set-up. Utilisation of the COFDR set-up is also foreseen for the quasi-distributed temperature sensors. These sensors are conventionally based on the utilisation of Fiber Bragg gratings and OTDR. However, due to the dead-zone of the OTDR, the distance between two sensing points (Bragg grating) is limited. The COFDR technique will permit to alleviate this limitation.

Conclusions

We built a simple frequency sweep IOFDR set-up by using off the shelf equipments that allows localizing reflections in the long distance optical fiber. COFDR is the dominant high resolution reflectometry technique and finds several applications in current optical fiber sensors and metrology [8]. We are going to enhance our set-up by implementing COFDR technique for distributed/ quasi-distributed sensor applications.

References

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