Rayleigh-based Optical Reflectometry Techniques for Distributed Sensing Applications

K. YÜKSEL ALDOĞAN[1]

[1] İzmir Institute of Technology, İzmir/Turkey, kivilcimyuksel@iyte.edu.tr

Abstract - **In this paper, we discuss the operation principles, sensing mechanisms, challenges and application areas of the optical reflectometry techniques exploiting Rayleigh scattering phenomenon, considering both time- and frequency-domain schemes. Among various distributed optical fiber sensor (DOFS) systems interrogated by optical reflectometry techniques, a special emphasis was given, in this paper to distributed acoustic sensor (DAS) interrogation methods. Recent progresses obtained through our research collaborations are also presented.**

Keywords – **Rayleigh scattering, optical reflectometry, fiber optic sensors, distributed sensing.**

I. Introduction

OPTICAL fibers have revolutionized the modern telecommunications. Communication industry is not the unique domain benefiting from the advantages of the optical fibers. Owing to high capacity (low loss, high bandwidth), and by the advent of the optoelectronic devices, optical fiber technology has also been studied as a potential way of realizing innovative sensor implementations.

The requirements of today's science and technology such as optimal efficiency, productivity, reduced energy consumption, and high safety level can be addressed by novel smart sensing systems based on optical fibers. The increasing demand for data-based decision-making and accurate automation & control systems further increases the need for advanced sensor systems that are capable of monitoring variations of the physical and chemical parameters in a spatially distributed manner along various structures. For this purpose, distributed optical fiber sensors (DOFS) represent a powerful class of alternative technologies to the conventional electrical sensors due to their unprecedented features such as low-weight, small dimensions and immunity to electromagnetic interferences [1].

Many successful demonstration of DOFS have been benefiting from these advantages across multiple sectors. Historically, oil & gas industry (i.e. well and pipeline monitoring) was the pioneer in terms of commercial adoption of distributed temperature sensing systems based on Raman and Brillouin scattering. Nowadays, many other successful implementations of DOFS can be listed, particularly in the domains of manufacturing, power & energy, transportation, aerospace, medical, and security.

The major factor driving the growth of DOFSs is their remote sensing capability in difficult operating conditions and challenging surroundings, where for instance, the sensing fiber can be placed along a long and/or inaccessible spaces while the interrogator unit is kept at a safe distance. The single-mode optical fiber used as sensing element is usually same as the fiber used in telecom cables.

The intrinsic Rayleigh scattering, observed in the optical spectrum from 800 to 1750 nm, is the primary source of attenuation in modern telecommunications [2]. The structure of the optical fiber material is, by nature, disordered by density variations giving rise to random fluctuations of the refractive index on a smaller scale than the optical wavelength. When the optical wave encounters these discontinuities, it scatters in every direction, a small part of which is re-captured by the fiber and propagates back towards the source (called Rayleigh backscattered signal) [2]. This backscattering effect in the optical fiber has been exploited in various sensor systems where the interrogation units make use of the optical reflectometry techniques to perform spatially-resolved measurements of Rayleigh backscattered signal (RBS) [2].

The interrogator schemes fall into two main categories depending on their operational mode: Optical Time-Domain Reflectometry (OTDR) and Optical Frequency-Domain Reflectometry (OFDR) families (cf. Table 1 for comparative analysis of the performance parameters and applications [2]).

Both OTDR and OFDR are deployed for measuring a wide variety of parameters, ranging from temperature, strain, acoustic/vibration, magnetic field, 3D shape to refractive index, and chemical composition.

Among all the Rayleigh-based distributed sensing applications, distributed vibration or acoustic sensing (DAS) has become extremely popular research area and experiencing the fastest transition into commercialization due to the great potential in adapting and utilization of this technology in real-life applications such as seismic, oil well, and railway trackside monitoring systems [3].

A. Optical Time-Domain Reflectometry-OTDR

An OTDR launches short optical pulses (probe signal) into the sensing fiber. The returning light (test signal) is separated from the probe signal and is fed into the receiver where the optical power of the test signal is measured as a function of time. The power evolution with time of the detected (backscattered and reflected) signal provides the distributed information of position and magnitude along the fiber under test.

The key parameters of the dynamic range (or sensing range) and the spatial resolution in OTDR need to be balanced [4].

Conventional OTDR which is the most common maintenance and troubleshooting tool for optical fiber communication networks, has been evolving into several variants, principally to serve as an interrogating system for quasi-distributed and distributed sensors. The following can be listed in the OTDR family: ν-OTDR (Photon-counting OTDR) [5,6], POTDR (Polarization OTDR) [7,8], ϕ-OTDR (Phase OTDR or coherent-OTDR) [9-11], and λ-OTDR (Wavelength tunable-OTDR) [12].

B. Optical Frequency-Domain Reflectometry-OFDR

Instead of working in the time domain as OTDR, OFDR operates in the frequency domain (or *Fourier* domain), covering both incoherent- and coherent types [13].

Optical frequency domain reflectometer (OFDR) providing millimeter resolution over medium to long measurement ranges has also been attracting great attention as an interrogating tool for several sensor systems. It can be considered as a competing technique to OTDR family, especially for acoustic sensing applications.

In the basic configuration of –coherent– OFDR, the optical carrier frequency of a tunable laser source is swept linearly in time without mode hops. Then, the frequency-modulated continuous-wave signal (*probe signal*) is split into two paths, namely the *test arm* and the *reference arm*. The former includes the sensing fiber whereas a reference reflector (also called *local oscillator*) is placed in the latter. The test signal (containing Rayleigh backscattering and Fresnel reflections) coherently interferes at the coupler with the reference signal. Superposition of the interfering signals is converted into electrical domain by the detector which yields the beat terms that are related to the optical amplitude and phase responses of the reflection sites in the sensor fiber.

In an OFDR, the narrow linewidth, mode-hop free tunable laser source whose frequency can be chirped linearly in time, is the key technology for improving the sensing range and the spatial resolution [14]. OFDR and P-OFDR have been implemented in temperature [15-17], strain [18], and vibration [19] measurements.

Table 1: Comparison of Rayleigh-based distributed sensors.

	OTDR	ν-OTDR	ϕ-OTDR	OFDR
Spatial resolution	1-10 m	1-10 cm	1-10 m	5mm-10cm
Measurement range	10s km	100 m	A few km	100s m
Complexity	moderate	high	high	high
Applications	Fire Leak Load SRI Loss	Strain SRI Current	Intrusion Strain Vibration	Strain Temperature Vibrations Magnetic field (POFDR)

II. Distributed Acoustic Sensing

Distributed acoustic sensing (DAS) (also known as distributed vibration sensing, DVS) is a fiber-optic sensing technique based on the detection of RBS light in optical fibers using ϕ-OTDR (Phase OTDR), that has been a field of intensive research for more than ten years [20]. ϕ-OTDR is based on a pulsed laser source that must be highly coherent, contrary to conventional OTDR systems. Among all the vibration sensing techniques, ϕ-OTDR has been given growing attention because of its ability in the realization of distributed measurements that are capable of both characterizing and localizing a vibration or acoustic phenomenon present along a long-distance optical fiber [3, 21].

ϕ-OTDR schemes can be divided into two main categories according to the detection method employed; namely, direct detection and coherent detection ϕ-OTDR. The straightforward direct detection scheme relies on the measurement of local changes in the backscattered signal's power over time. With coherent detection (homodyne or heterodyne), the backscattered signal is mixed with a reference signal, and the amplitude as well as the phase component of the backscattered signal can be extracted (cf. Figure 1) [21]. The backscattered signal power is not linearly related to the magnitude of the vibrations. Therefore, direct detection schemes provide information only about the frequency content of the vibration. Nevertheless, the extraction of phase can be used to deduce both the magnitude and frequency of external vibrations.

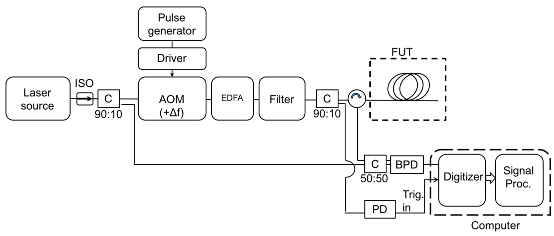

Figure 1. Implementation of the coherent ϕ-OTDR system (heterodyne detection).
ISO: isolator, FUT: Fiber Under Test, AOM = acousto-optic modulator, EDFA = fiber amplifier, C = Coupler, BPD = balanced photo-receiver

A typical phi-OTDR trace recorded by the experimental setup is shown in Figure 2. It consists of two sections; the first part is the Rayleigh backscattered signal up to the end of FUT having an exponentially decaying speckle pattern as expected, the second part represents the receiver noise (thermal noise and shot noise).

When a local perturbation applied, relative positions of the scattering centers in the perturbed zone change, resulting in a change on the measured intensity from that zone. Therefore, subtracting the amplitude traces from the first trace, clearly points out the position of the applied vibration.

In order to improve the signal to noise ratio (SNR) and provide high-precision dynamic strain measurement capability, recent research has focused on the implementation of weak fiber Bragg gratings (FBGs) as artificial scattering centers (having known reflectivity and position) rather than the Rayleigh backscattering signal as realized in a standard Φ-OTDR system.

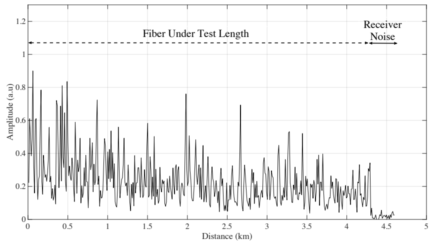

Figure 2. A typical single ϕ-OTDR trace recorded by the experimental test setup.

Efforts have been made using so-called frequency sweep [22] and passive 3x3 coupler [23] demodulation schemes. A sensor scheme based on equally-spaced, low reflectivity FBGs interrogated by direct detection Φ-OTDR has been recently demonstrated (cf. Figure 3) [24], where the tradeoff between the maximum number of gratings and grating reflectivity has been analyzed by simulations.

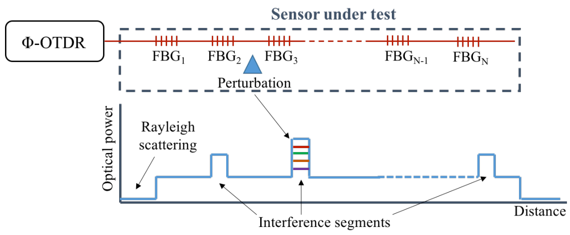

Figure 3. Schematic diagram of the FBG array system interrogated by Φ-OTDR [24]. FBG: Fiber Bragg Grating.

III. Conclusion

In this paper, optical reflectometry methods used for DOFS systems are categorized and general background information is provided. Motivations, challenges and requirements of DOFS interrogation schemes are discussed.

Results obtained by different research groups in terms of performance characteristics and future perspectives together with the recent progresses obtained via our collaborative research will be elaborated in the presentation.

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