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Distributed Fiber Optic Sensors – Brillouin Optical Time Domain Analysis (BOTDA) Sensor in Simple Language

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Abstract: This paper simplifies the concepts of fiber optic communication, fiber optic sensors and distributed fiber optic sensors with Brillouin Optical Time Domain Analysis (BOTDA) sensors to present the principles, theory and operation of distributed fiber optic sensors and their applications for non-experts to fathom the principles of the BOTDA sensors.

Index Terms: Fiber Optic Communication, Fiber Optic Sensors, Distributed Sensors, Brillouin Scattering, BOTDA Sensors.

I. INTRODUCTION

Optical fiber (cladded) was developed by Corning Glass works in 1970 and the first fiber optic communication system was deployed in 1975 which used GaAs semiconductor lasers, operating at a wavelength of 0.8 µm, with a bit rate of 45 Mb/s and a 10Km repeater spacing [1]. By 1987, InGaAsp fiber optic systems were commercialized operating at bit rates of up to 1.7 Gb/s on single mode fiber with 50Km repeater spacing. A bit rate of 14 Tb/s was realized in 2006 using optical amplifiers over a single 160km line. The next generation of fiber optic communication (5^{th} generation) is looking at reducing the nonlinear effects by counteracting the negative effects of dispersion by preserving their pulse-shape, as a result optical solitons are being explored [2]. Other developments focus on extending the traditional C band wavelength window to achieve a larger wavelength range: from the widely used 1.53µm – 1.57µm to a much wider wavelength range of 1.30µm – 1.65µm using dry fibers [2].

Low loss fibers have made it possible for several industrial deployments of fiber: fiber-to-the-x (FTTX – FTTH, FTTC etc). FTTH stands for Fiber to the home, FTTC represents fiber to the cabinet.

Optical Communication is a broad field in communications and it is the transmission of information/messages using light as the carrier. The transmission can be through a guided, unguided (e.g Free Space Optical Communication) or a blend of both unguided and guided media. Fiber optic communication systems use guided media (optical fiber) to transmit information superimposed on light from a transmitter to a receiver. Fig. 1 is a block diagram of the fiber optic communication system; it comprises a transmitter, channel (optical fiber), photo-detector and a receiver. The channel for fiber optic communication is fiber and it consists of a core with a higher refractive index, a cladding surrounding the core with a lower refractive index compared to the core and a protective sheath for physical protection. The core has a higher refractive index than the cladding to achieve total internal reflection. Fibers are classified into two broad categories: based on the boundary between the cladding and the core; if it's abrupt then we have a step – index fiber, if the boundary is gradual then it's a graded – index fiber. There are however two types of fibers based on their modes of propagation; mono-mode / single mode fibers and multimode fibers. The modes of propagation M depends on the V number in (1). Fig. 2 shows the refractive index profile of both classes and types of fiber.

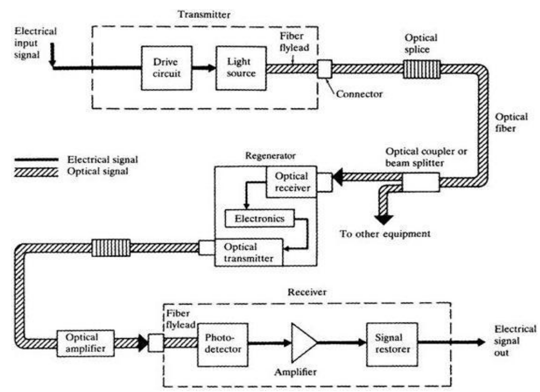

Fig. 1. Block Diagram of an optical communication system [3]

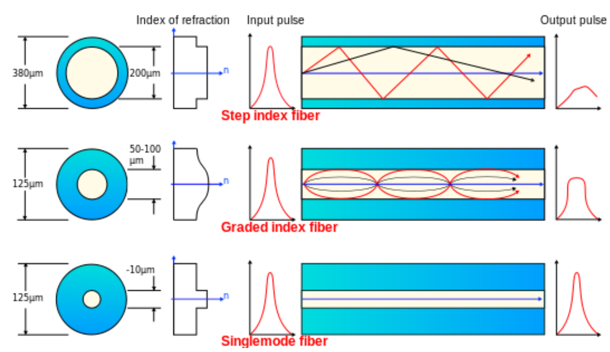

Fig. 2. Refractive Index Profile of various classes and modes of fiber. [4]

The number of modes (M) increases when the V number is greater than 2.405. The V number depends on the core-cladding characteristics as shown below.

$$V = \frac{\omega a}{c}\sqrt{(n_1{}^2 - n_2{}^2)} = \frac{2\pi a}{\lambda} N.A. \qquad (1)$$

Where ω=2πf, n_1, n_2 are the refractive indices of the core and cladding respectively 'a' is the radius of the core, and $N.A.$ is the numerical aperture which is a dimensionless quantity that describes how much light can be allowed into the core of the fiber.

As illustrated by Fig. 3. For V < 2.405 we have a single or mono-mode propagation, multimode propagation occurs for V > 2.405

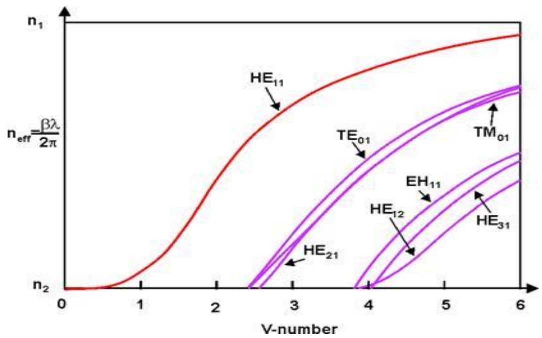

Fig. 3. V – number and the number of modes of propagation,also represents solutions of Maxwell's equations.

Multi-mode fibers are used for short distance (up to about 1km) communications because they suffer a lot of light dispersion, single mode fibers are mostly used for long haul communications (>4000km).

II. FIBER OPTIC SENSORS

A sensor is an electrical or optical transducer that detects or senses some physical or natural characteristic(s) of its proximal or distant environs. It detects changes in the environs and provides a proportional output. A fiber optic sensor (also called optical fiber sensor) uses optical fiber as a sensing element, or as a medium for sending signals from a remote sensor to a receiver [5]. In simple terms: fiber optic sensors are used to measure/sense anything which changes the way light travels through the fiber or changes the properties of the light travelling through or leaving the fiber. Fiber optic sensors have wide applications and they can measure temperature, strain, pressure, displacement, acceleration, flow rate, vibrations, chemical concentrations, electrical and magnetic fields as well as rotation rates etc.

There are several advantages in using fiber optic sensors in many industrial applications, these include but not limited to: harsh environment capability (electromagnetic interference, high temperature, high voltage, high pressure etc.), light weight and miniature size, high sensitivity and bandwidth, long range applications and multiplexed/distributed measurements. Most traditional sensors fall short to these advantages and that makes fiber optic sensors the optimal choice for various industrial sensor applications.

Optical sensors are classified into two broad categories: intrinsic sensors (where light is modulated inside the fiber by the environment) or an extrinsic sensor (where the light is modulated outside the optical fiber).

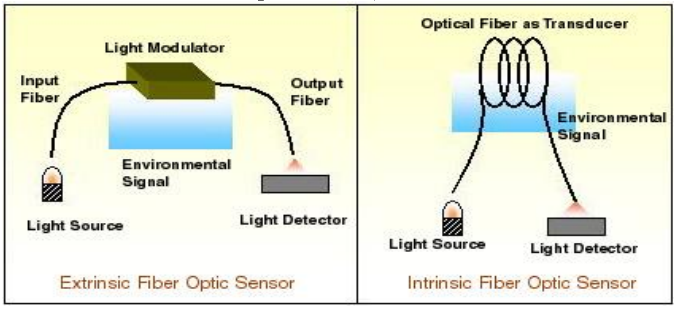

Fig. 4. Extrinsic and Intrinsic Fiber Optic Sensors [6]

The photon field that a fiber optic sensor must vary or modulate informs another means of classifying fiber optic sensors (FOS) as well as the design of the sensor. The electromagnetic (light) wave equation and the variation of the various parameters (optical modulation mechanism) informs the classifications: Intensity modulation, wavelength modulation, frequency modulation, phase modulation and polarization modulation [7] are achieved by varying one or more of the parameters in (2).

$$E(t) = E\cos(\omega t + \emptyset(t)) \quad (2)$$

Where E is the amplitude/intensity, $\omega=2\pi f$ defines the frequency, and $\emptyset(t)$ defines the phase.

To sense or measure a parameter of interest, the optical sensor design must allow this external source to vary one of the terms in (2). We can vary the amplitude $E(t)$ (or intensity), as intensity-modulating sensors does, one can modulate the frequency or wavelength of the light, as do frequency or wavelength modulating sensors (or simply color sensors) [8]. Another type of amplitude modulation involves modifying the polarization characteristics of the light field, yielding a polarization-based sensor [8].

Modulating the phase of the light field may prove difficult because the term $\emptyset(t)$ resides within the cosine term, an inverse cosine must therefore be performed to allow the entire phase angle (frequency and phase) to be available [8]. Once the cosine term is removed, the frequency variable is negated, leaving only the phase term, from which the parameter of interest is deduced [8]. Such a technique requires some form of frequency tracking or a frequency canceling technique such as those used in heterodyne applications [8].

Another important classifications of fiber is based on changes in refractive indices of the core and/or cladding, the main classes are, fiber bragg grating (FBG) sensors, and distributed fiber sensors. Bragg gratings are made by illuminating the core of a suitable optical fiber with a spatially-varying pattern of intense UV laser light [9] this filters out light or wavelength by reflecting them away and allowing other light colors or wavelengths to travel through the fiber. Short-wavelength (<300 nm) UV photons have sufficient energy to break the highly stable silicon-oxygen bonds, damaging the structure of the fiber and increasing
its refractive index slightly [9]. A periodic spatial variation in the intensity of UV light, caused by the interference of two coherent beams or a mask placed over the fiber, gives rise to a corresponding periodic variation in the refractive index of the fiber [9]. One of the well-known applications of FBG sensors is "fiber optic smart structures" where FBG sensors are embedded into the structure to monitor the structure's strain distribution [10]. For an in depth understanding of FBGs see other materials.

III. DISTRIBUTED FIBER OPTIC SENSORS

Other fiber optic sensors do not use fiber Bragg gratings as sensors, instead the fiber itself is used as the sensor, as the name implies, distributed fiber sensors use the fiber to continually monitor changes in its environs. Most sensors

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detect a physical quantity (e.g temperature, pressure) at a point or several points and thus do not detect all changes in the physical quantity being monitored in the environment that the sensor is found. Distributed Sensing solutions enable a continuous distributed measurement along the length of a sensing fiber. With distributed fiber sensing, you can measure the strain or temperature of your test article at not just one location, or a few key locations, but at hundreds of locations with a single fiber optic sensor [11]. This unique technology enables strain or temperature measurements at every point along a simple optical fiber with gage lengths as small as a few millimeters [11]. Instead of needing two to three wires per sensing point, only one optical connection gives you access to hundreds of sensing points. [11]. Distributed fiber optic sensors offer solutions for improved and reliable, yet affordable monitoring in large and complex structures. The qualitative difference between the monitoring performed using discrete and distributed sensors is the following: discrete sensors monitor strain or average strain at discrete points, while the distributed sensors are capable of one-dimensional (linear) strain fields monitoring [12]. See Fig. 5.

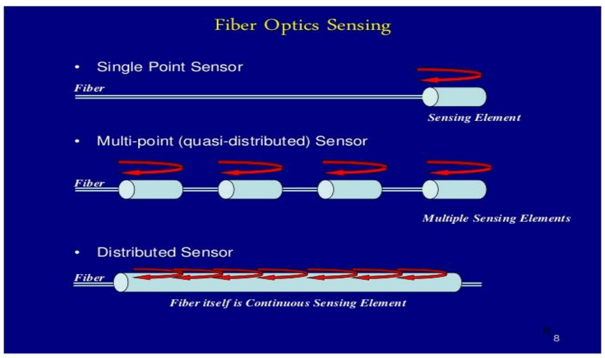

Fig. 5. Simple diagram of distributed fiber optic sensing compared with other forms of fiber optic sensing [14].

Distributed fiber optic sensors can be laid along the whole length of a structure (e.g. a pipe, columns of buildings etc.) and in this manner each cross-section of the structure is practically instrumented [12]. The sensor is sensitive at each point of its length and it provides for direct monitoring, avoiding the use of sophisticated algorithms [12]. Distributed fiber optic sensor technologies have reached market maturity, and can be applied in several industries worldwide as seen in Fig. 5.

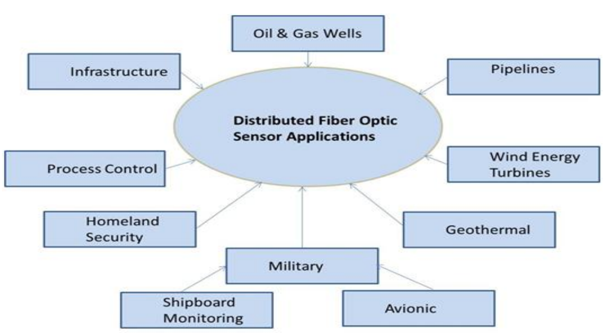

Fig.6. Distributed Fiber Optic Sensors Applications [13].

The fact that distributed sensors are used to monitor a physical quantity leads us to another means of classifying fiber optic sensors as shown Fig. 7 we regroup fiber optic sensors based on the length of sensors and functionality.

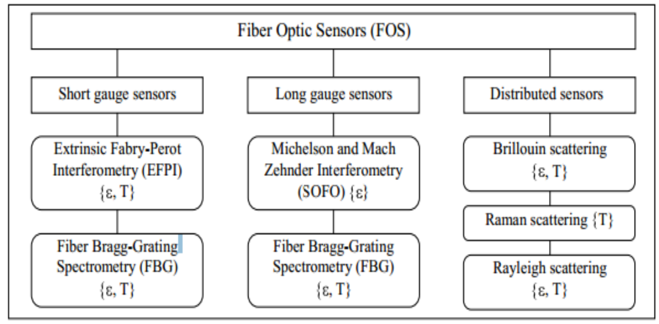

Fig. 7. Classifying FOS based on gauge length and functional principle; ε=strain, T= temperature [12].

For an in-depth reading on the short and long gauge sensors see other text.

IV. DISTRIBUTED FIBER OPTIC SENSORS – BRIEF ON THEORY AND PRINCIPLES OF OPERATION

There are three major principles on which distributed fiber optic sensing operate: Rayleigh scattering effect, Brillouin scattering effect, and Raman scattering effect, each technique is based on the relation between the measured parameters, i.e., strain and/or temperature, and encoding parameter, i.e., the change in optical properties of the scattered light [12]. Rayleigh scattering effect is based on the shifts in the local Rayleigh backscatter pattern which depends on strain temperature [12]. This allows for the strain measurements to be compensated for temperature. Major characteristics of this system are high resolution of monitored parameters and short spatial resolution but the maximum optimal length of sensor is limited to about 70 m (230 feet) [12]. Thus, this system is suitable for monitoring of localized strain changes over relatively short distances [12].

Raman scattering is due to the non-linear interaction between light traveling through a fiber and silica. When high intensity light signal is directed into the fiber, two frequency-shifted components called respectively Raman Stokes and Raman anti-Stokes appear in the back-scattered spectrum [15]. The relative intensity of these two components depends on the local temperature of the fiber [15]. If the light signal is pulsed and the back-scattered intensity is recorded as a function of the round-trip time, it becomes possible to obtain a temperature profile along the fiber [15].

Brillouin scattering, named after Léon Brillouin, occurs when light, transmitted by a transparent carrier interacts with that carrier's time-&-space-periodic variations in refractive index [16], the index of refraction of a transparent material changes under deformation (compression-distension or shear-skewing) [16]. Raman and Brillouin systems work with an Optical Time Domain Reflectometer (OTDR), in which the monitoring unit transmits a short light pulse and uses the time of flight of the back – scattered light to determine the location of the reflection [17].

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Rayleigh scattering, too, can be considered to be due to fluctuation in the density, composition and orientation of molecules, and hence of refraction index, in small volumes of matter (particularly in gases or liquids). The difference is that Rayleigh scattering considers only random and incoherent thermal fluctuations, in contrast with the correlated, periodic fluctuations (phonons) that cause the Brillouin scattering [16].
Brillouin scattering is caused by an interaction between light and lattice phonon modes [18]. Raman scattering is caused by an interaction between light and molecular vibrations [18]. The key difference is that phonon modes are a **collective, long-range phenomenon** involving billions or more atoms, whereas molecular vibrations are localized vibrations of a **single molecule**, which typically only has 2 to 20 atoms [18]. Brillouin scattering denominates the scattering of photons from low-frequency phonons, while for Raman scattering photons are scattered by interaction with vibrational and rotational transitions in the bonds between first-order neighboring atoms. Therefore, the two techniques provide very different information about the sample: Raman spectroscopy is used to determine the chemical composition and molecular structure, while Brillouin scattering measures properties on a larger scale – such as the elastic behavior [16]. Experimentally, the frequency shifts in Brillouin scattering are detected with an interferometer, while Raman setup can be based on either interferometer or dispersive (grating) spectrometer [16].

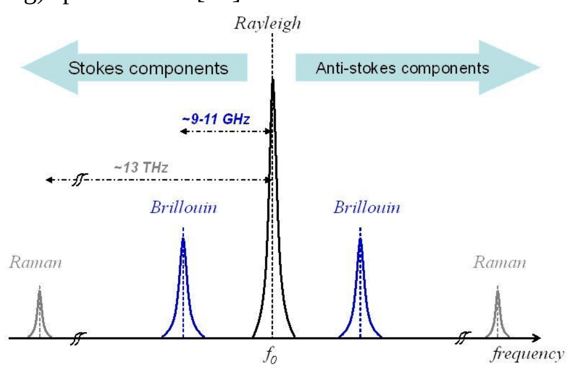

Fig. 8. Schematic spectrum of scattered light resulting from three scattering processes in optical fibers [19].

A. Stimulated Brillouin Scattering

Brillouin scattering can occur spontaneously even at low optical powers, reflecting the thermally generated phonon field. For higher optical powers, there can be a stimulated effect, where the optical fields substantially contribute to the phonon population. For intense beams like laser light travelling in a medium such as an optical fiber, the variations in the electric field of the beam itself may produce acoustic vibrations in the medium through electrostriction or radiation pressure [16]. The beam may undergo Brillouin scattering from these vibrations, usually in opposite direction to the incoming beam, a phenomenon known as stimulated Brillouin scattering (SBS) [16]. For liquids and gases, typical frequency shifts are of the order of 1–10 GHz (wavelength shifts of ~1–10 pm for visible light). Stimulated Brillouin scattering is one effect by which optical phase conjugation can take place [16].

Classically, the thermally generated density fluctuations of a material medium are involved in the scattering of light [20]. The density fluctuations culminate in the compression and rarefaction of regions within the medium, and may be considered to consist of two components, the propagating component and the non-propagating component [20]. When light wave is directed into the medium, scattering from the non-propagating component gives the central Rayleigh line and scattering from the propagating component gives the Brillouin lines, see Fig. 8. The propagating component of density fluctuations acts as a sound wave of high frequency. The damping of such a wave in the material medium is responsible for finite width in Brillouin lines while non-zero lifetime of the non-propagating component produces width in Rayleigh lines [20].

Beyond a particular threshold power of a light beam in a fiber, stimulated Brillouin scattering usually reflect most of the power of an incident beam. This involves a high nonlinear optical gain for the backward-reflected wave: an initially weak counter-propagating wave at the appropriate optical frequency can be strongly amplified. Here, the two counter-propagating waves generate a traveling refractive index grating; the higher the reflected power, the stronger the index grating and the higher the effective reflectivity [21]. V_B
The frequency of the incident beam is slightly higher than that of the reflected beam; the difference in frequency v_B corresponds to the frequency of emitted phonons. This is

the Brillouin frequency shift, it is set by a phase-matching requirement [21]. For pure backward Brillouin scattering, the Brillouin shift can be calculated from the refractive index n (for Brillouin scattering in fiber, the effective refractive index must be used), the acoustic velocity v_a , and the vacuum wavelength λ:

$$v_B = \frac{2n v_a}{\lambda} \tag{3}$$

Brillouin scattering occurs essentially only in backward direction in optical fibers. However, weak forward Brillouin scattering is also likely due to effects of the acoustic waveguide. The Brillouin frequency shift depends on the material composition and to some extent the temperature and pressure of the medium. This dependency is what is exploited for distributed Brillouin Optical Domain Analysis (BOTDA/R, BOFDA, and BOCDA) fiber optic sensors. See other text for Brillouin Optical Correlation/frequency Domain Analysis (BOC/FDA) sensors.

B. BOTDA SENSORS

A commonly used distributed sensing technique is the the Brillouin Optical time Domain Analysis (BOTDA), it was initially proposed to measure optical fiber attenuation in 1989 but later used for distributed sensing in 1990 [26]. BOTDA rides on stimulated Brillouin scattering (SBS), where two counter-propagating light beams, usually a pulsed pump and a probe continuous wave, interact along a sensing optical fiber. At regular time intervals, the probe wave at some location may be amplified by the traveling pump pulse, depending on the frequency difference between these two light waves [22]. By recording the optical frequency of either wave with respect to the other, the narrow (30MHz) Brillouin Gain Spectrum (BGS) is recovered, and the frequency difference, gauged by the position of the peak gain, can be converted to temperature or strain along the sensing fiber [22].

In a more detailed description, the sensing principle is based on the fact that the frequency difference, at which the maximum amplification of the Stokes wave occurs, known as Brillouin frequency shift (BFS), varies depending on the mechanical and thermal states of the fiber [23]. In particular, the BFS increases with both temperature and strain. Spatial resolution, i.e. the ability to measure deformation and temperature changes in a distributed way, can be achieved through using a pulsed pump beam: through this, the interaction occurs along successive regions of the fiber as the pump pulse travels down the sensing cable [23]. By recording the intensity of the Stokes radiation as a function of time, the Brillouin gain can be traced in each region. Measuring the Brillouin gain as a function of time and frequency allows the entire profile of Brillouin shift along the fiber to be obtained, which in turn can be translated to strain/deformation or temperature through the use of appropriate calibration coefficients [23].

BOTDA is a double ended access to the a source and detection system for long sensing lengths combined with high strain and temperature resolution for up to 31 miles (50 km) without signal regeneration [24].

The major factors that control the sensing speed of a BOTDA setup are [22]:

1) Flight Time: the repetition rate of the pump pulses should not exceed $\frac{1}{T_{round\ trip}}$.

$$\frac{1}{T_{round\ trip}} = \frac{2L}{V_g} \quad (4)$$

Where V_g is the group velocity speed of light traveling within the fiber and L is the length of fiber.

2) Averaging N_{avg} : Over ten to thousands pump pulses is required for a satisfactory signal to noise ratio (SNR), especially over long fibers.

3) Scanning granularity: in order to accurately map the Brillouin gain within the required dynamic range of strain/temperature variations V_{freq} ranging from 100 to 200 different frequencies should be probed.

4) Optical frequency: switching speed of the sweep mechanism requires a finite time, depends on the actual implementations: on the order of milliseconds or longer, inclusive of stabilization [22]. The third factor is determined by the expected strain/temperature resolution. The first two factors are dominant for long (tens of kilometers) sensing fibers, resulting in long acquisition times on the order of minutes [22]. On the other hand, when dealing with a relatively short (less than 1km) fiber, the fourth factor, frequency switching speed, becomes dominant [22].

The Brillouin frequency shift can give the temperature or strain information as the following equation [24].

$$v(\varepsilon, T) = v(0,0) + C_1\varepsilon + C_2T \quad (4)$$

Where ε and T are the strain and temperature, respectively, C_1 and C_2 represent the strain and temperature coefficients, respectively, known to be about 0.05MHz/micronstrain and 1.2 MHz/°C for conventional single mode optical fibers used at the 1500nm wavelength range for optical communications [24].

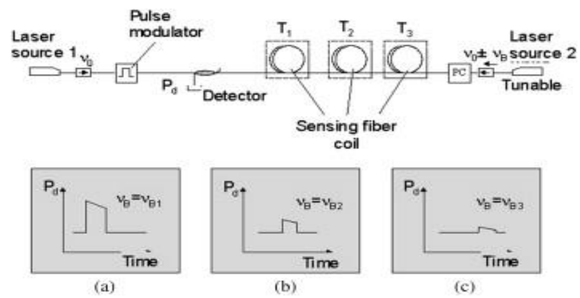

Fig. 8. Basic configuration for BOTDA: (a), (b) and (c) show the waveform of optical power at detector (P_d), acquired when the frequency offset between the two lasers is tuned to the Brillouin frequency shift ν_B of fiber coils 1, 2 and 3, placed at temperatures T_1, T_2 and T_3, respectively [23].

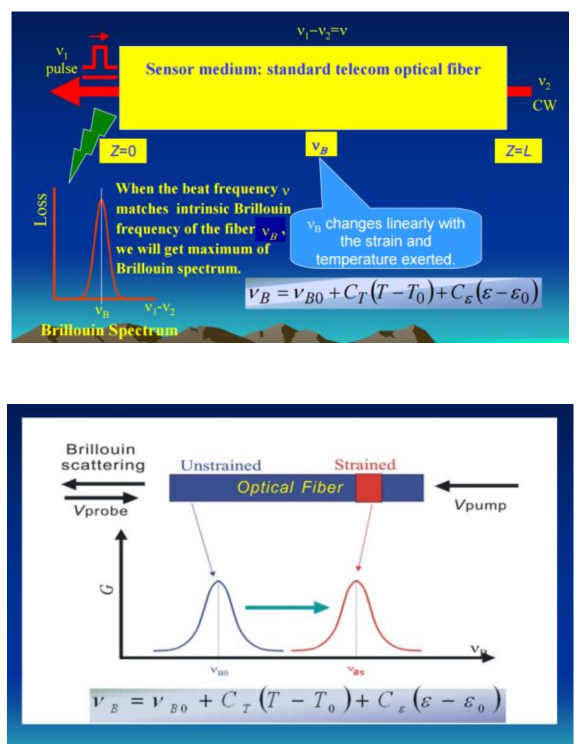

Fig.9. Basic operation/principle and graphs of BOTDA [25].

V. CONCLUSION

This paper to the best of my knowledge presents in simple language a basic understanding of fiber optics, fiber optic communications, fiber optic sensors, distributed fiber optic sensors and explains in detail yet in simple language how an

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example of the distributed fiber optic sensor (BOTDA) operates. It will bridge the gap between non experts and experts in the field fiber optic sensors and any individual who reads this paper will understand how distributed fiber optic sensors work.

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