PH4051D Project Part I

Report

Distributed Acoustic Sensing Using Chirp Enhanced Optical Frequency Domain Reflectometry

Submitted in partial fulfillment of
the requirements for the award of the degree of

Bachelor of Technology
in
Engineering Physics

Submitted by

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Under the guidance of

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Declaration

I declare that this report, titled **"Distributed Acoustic Sensing Using Chirp Enhanced Optical Frequency Domain Reflectometry"** submitted in partial fulfillment of the degree of **B.Tech in Engineering Physics** is a record of original work carried out by me under the supervision of **Dr M K Ravi Varma**, and has not formed the basis for the award of any other degree or diploma, in this or any other Institution or University. In keeping with the ethical practice of reporting scientific information, due acknowledgements have been made where the findings of others have been cited.

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11 December 2023

Certificate

This is to certify that this report, titled **"Distributed Acoustic Sensing Using Chirp Enhanced Optical Frequency Domain Reflectometry"** is a bonafide record of the project done by Reuben S Mathew (*Roll no.* **B200150EP**) under my supervision, in partial fulfillment of the requirements for the award of the degree of **Bachelor of Technology** in **Engineering Physics** from **National Institute of Technology, Calicut**, and this work has not been submitted elsewhere for the award of the degree.

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Place: National Institute of Technology, Calicut
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December 2023

National Institute of Technology Calicut

Abstract

Distributed Acoustic Sensing (DAS) is a technique that enables strain monitoring in fiber optic cables, through spatially resolved measurements. This technology has found use in various monitoring applications, like structural health, border and pipeline monitoring. A number of methods have been devised to probe the fiber optic cable and collect data about strain or temperature changes. This report goes over the basic principles, some of the sensing techniques and lay the groundwork for further hands-on testing of distributed acoustic sensing systems, especially involving the use of chirping in optical frequency domain reflectometry.

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Chapter 1

INTRODUCTION

1.1 Background and Motivation

Optical fiber cables were invented in early 1960s to be utilized for high speed and broadband optical fiber communications. This technology brought forth a revolution in modern communications technology, that is changing our lives. Apart from this, optical fibers can also be used as distributed sensors that enable measurement of strain or temperature at any point along the fiber through light scattering. This method, broadly known as Distributed Acoustic Sensing (DAS) provides cost effective, versatile and robust sensors for safety monitoring in bridges, buildings, military borders and pipelines. DAS relies mainly on the different light scattering mechanisms such as Rayleigh, Brillouin and Raman scattering[2]. This report will be focusing on Rayleigh scattering, and DAS systems based on it; Optical Time Domain Reflectometry (OTDR) and Optical Frequency Domain Reflectometry (OFDR). [1] This report will go over the fundamental principles of Rayleigh scattering in the context of DAS, OTDR, Phase sensitive OTDR (ϕ-OTDR) and OFDR techniques specifically using chirped pulses, and chirping methods.

Chapter 2

SCATTERING

2.1 What is scattering

When light interacts with obstacles or other objects, it gets redirected. Scattering light is a random statistical process that happens in all angular directions.

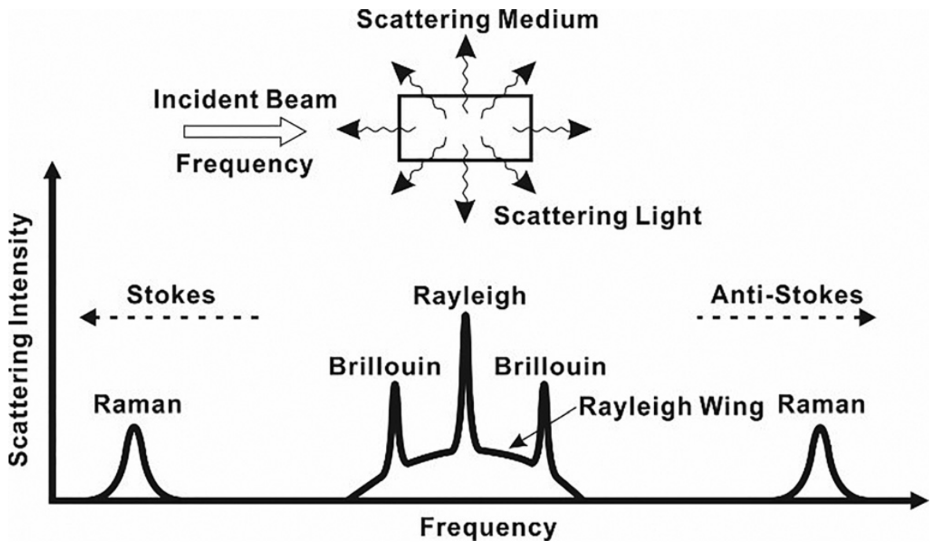

Figure 2.1: A typical spontaneous light scattering spectrum

Figure 2.1[2] shows the frequency spectrum of scattered light. The central peak corresponds to Rayleigh scattering, originating from centers smaller than the wavelength of light. Brillouin scattering occurs due to light interaction with acoustic phonons, Raman scattering occurs through molecular vibrations. Both Brillouin and Raman scattering are inelastic scattering phenomena that results in frequency shift between incident and scattered light.[2]

For the purposes of this report, the focus will be on Rayleigh scattering and its application in Distributed Acoustic Sensing.

2.2 Rayleigh Scattering

Rayleigh scattering is a very common phenomena. It accounts for the blue color of the sky. In amorphous optical materials, like silica, there are always random density fluctuations due to irregular microscopic structures. In a fiber cable, these irregularities are 'frozen in' when the fiber is drawn and cooled. They cause Rayleigh scattering, and set the lower limit for propagation loss in optical fibers.[4]

The intensity of scattered radiation is given by:

$$I = I_0 \left(\frac{1 + cos^2\theta}{2R^2} \right) \left(\frac{2\pi}{\lambda} \right)^4 \left(\frac{n^2 - 1}{n^2 + 2} \right)^2 \left(\frac{d}{2} \right)^6 \tag{2.1}$$

where R is the distance between particle and observer, θ is the scattering angle, n is the refractive index and d the diameter of the particle. We can see that scattering intensity is dependent on incident wavelength as λ^{-4}. We can also see that the intensity of Rayleigh scattered light is the same in the forward and backwards direction. In a fiber, light can travel long distances both directions. Forward Rayleigh scatter light moves with the incident pump, while the Rayleigh backscattered light goes back to the start of the fiber (Figure 2.2[2], showing a section of the fiber), and the information carried in this light forms the basis of operation for Optical Time Domain Reflectometry (OTDR) and Optical Frequency Domain Reflectometry(OFDR).

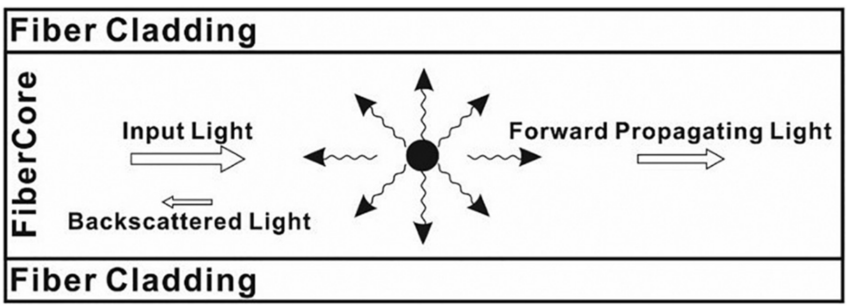

Figure 2.2: Schematic of spontaneous Rayleigh scattering in optical fibers

Chapter 3

SENSING TECHNIQUES

This section discusses the various Distributed Acoustic Sensing techniques and goes over the basic working principles for each.

3.1 Optical Time Domain Reflectometry (OTDR)

One of the simplest Distributed Acoustic Sensing methods, OTDR involves sending a pulse of light, and measuring the backscattered light as a function of time, then mapping the signal in time to points on the fibre. M. K. Barnoski Et al.[7] proposed the first experimental setup, using a 130 nsec pulse from a GaAs injection laser couples into the fiber, and measuring the return with a photodetector.

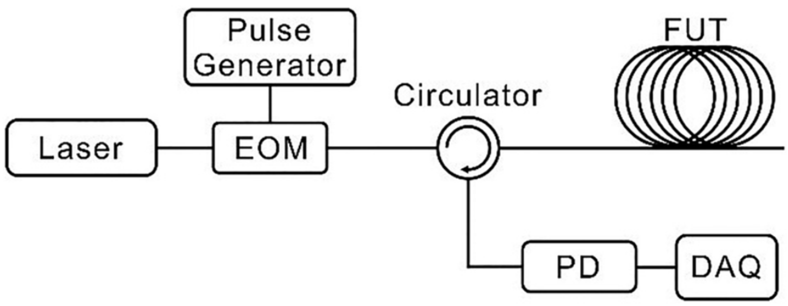

Figure 3.1: A standard OTDR configuration. EOM: electro-optic modulator; PD: photodiode; DAQ: data acquisition device; FUT: fiber under test

For a pulse reaching detector at time t after it is sent into the fiber, the distance along the fiber is calculated as:

$$z = \frac{c}{2n}t = \frac{v_g}{2}t \tag{3.1}$$

where v_g is the group velocity in the fiber and the factor of 2 accounts for the fact that the pulse has to down the fiber and back. As Rayleigh scatter is linear, the power backscattered is proportional to the forward propagating power, given the fiber is uniform along its length. The spatial resolution is dependent of the pulse width, and it is not possible to distinguish between events that happen in a single pulse. The spatial resolution Δz is given by:

$$\Delta z = \frac{v_g \tau}{2} \tag{3.2}$$

where τ is the pulse width of the probing pulse. Backscattered power returned to the input end is given by:

$$P(z)_{BS} = \frac{v_g \tau}{2} \eta \alpha_s(z) P_0 \left[-2 \int_0^z \alpha(x) dx) \right] \tag{3.3}$$

where P_0 is the optical input power, $\alpha_s(z)$ is the attenuation factor due to Rayleigh scattering, and $\alpha(x)$ is the total attenuation coefficient, η is the collection efficiency of scattered light captured by the fiber and depends on the refractive index and numerical aperture.[2]

There is a tradeoff between Signal-to-Noise Ratio (SNR) and spatial resolution Δz.High pulse power increases SNR and allows for long range measurements. However this increased power requires a higher pulse width so as to keep the power below the threshold for nonlinear effects, which could lead to undesirable effects and damage the fiber. For better SNR, multiple readings taken and averaging is done.

Measurement of Rayleigh backscattering signal is an essential process in characterizing fiber-optic transmission lines which can reveal loss in the fiber and locate breakage or damage in the fiber by monitoring for abrupt decrease in reflection power. OTDR used in communication network troubleshooting adopts anf electronics response time of 10ns corresponding to 1m resolution and obtains a high dynamic range.

3.2 Phase Sensitive Optical Time Domain Reflectometry (ϕ-OTDR)

ϕ-OTDR, first proposed by Taylor [3] is similar to conventional OTDR, except the laser source is a narrow linewidth and stable frequency laser with coherence length much longer than length of the Fiber Under Test(FUT). This setup utilizes the interference between backscattered light from different scattering centres within a single pulse width (Figure 3.2[6]), whose relative phase can change based on external disturbances. This method can provide higher sensitivity than the normal OTDR technique.

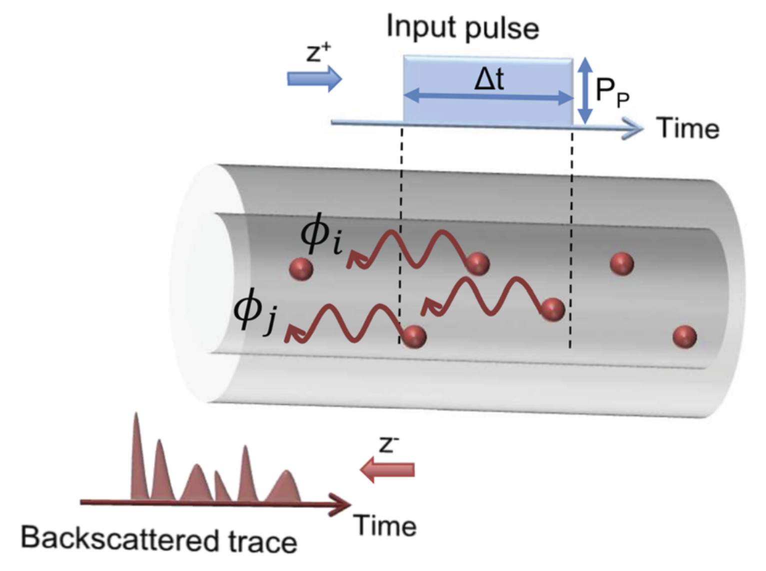

Figure 3.2: Rayleigh backscatter from scattering centres

The scattering centres, which are randomly distributed along the fiber, produce a random speckle feature in the backscattered trace. Any perturbation can shift the relative orientations between the centres, causing a shift in the relative phases of the scattered light and a change in the backscattered trace. Hence the perturbed and unperturbed traces can be compared to detect any disturbances along the fiber. The variations in traces can also show local variations synced with frequency, in the case of vibration sensing.

A ϕ-OTDR system requires a laser with minimal frequency drift, as well as narrow line width. Frequency drift could change the input polarization state to the fiber, which could be misinterpreted as false signals induced Rayleigh scattering

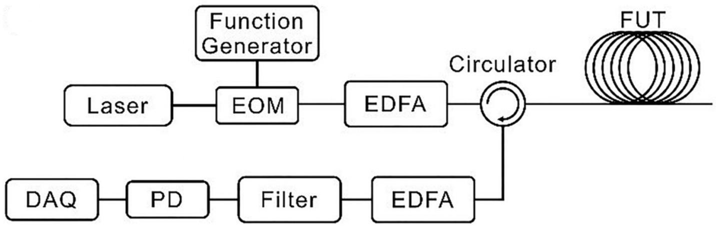

Figure 3.3: Experimental setups of the ϕ-OTDR system for vibration amplitude measurement,EDFA: erbium-doped fiber amplifier;PD: photodiode; DAQ: data acquisition device; FUT: fiber under test.

change. The narrow linewidth also enhances interference for high phase sensitivity.

Setups based on this technique, which are optimized for vibration detection, can be used in a number of applications, like bore-well monitoring, pipeline monitoring and electrical distribution line monitoring. As this technology is developed further, and cost is reduced, its uses show increasing potential.

This setup also suffers from drawbacks mentions in OTDR, that is the tradeoff between SNR and spatial resolution. Preliminary field tests by Yuelan Lu Et al. had demonstrated a 12km range with spatial resolution fo 100m through direct detection. This can be further improved through various techniques like using polarization maintaining fiber, balanced detection etc., achieving a spatial resolution of 2m over a 1km long fiber.[8]

3.3 Optical frequency domain reflectometry

The spatial resolution of OTDR systems are limited by the SNR to resolution tradeoff. Optical Frequency Domain Reflectometry (OFDR) allows for high resolution and dynamic range by decoupling the spatial resolution from the pulse width.

3.3.1 Working principle

In OFDR, a light pulse with it's frequency varying linearly with time is used. This pulse is split into a reference and probe signal. The probe signal goes through the fiber, gets backscattered, returns and interferes with the reference signal. The probe will be behind the reference by a time delay indicative of the length the probe traveled into the fiber before being backscattered. Due to linear sweep, it can be seen from the graph in Figure 3.4 that there will be a constant frequency shift f_B which produces a beat signal at the detector.

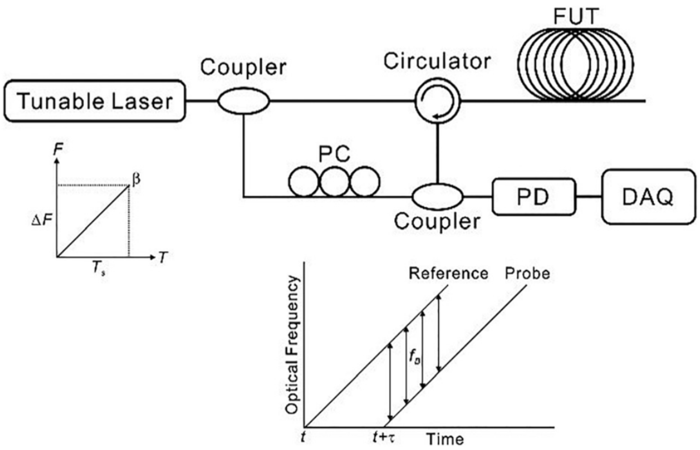

Figure 3.4: Experimental configuration of OFDR. PC: polarization controller

The difference in frequency will depend on the time delay of the probe signal, hence the distance in the fiber can be calculated by finding out the beat frequency, by taking a Fourier transform of the output signal.

If the input frequency swept signal is given by:

$$E(t) = E_0 exp\left\{j\left[w_0 t + \pi t^2 \beta + \theta(t))\right]\right\} \tag{3.4}$$

After the backscattering, the time delayed version of original signal:

$$E_{FUT}(t-\tau_{FUT}) = \sqrt{R}E_0 exp\left\{j\left\lfloor w_0(t-\tau_{FUT}) + \pi(t-\tau_{FUT})^2\beta + \theta(t-\tau_{FUT})\right\rfloor\right\} \tag{3.5}$$

The signals interfere and are detected, expressed as:

$$I(t) = |E(t) + E_{FUT}(t-\tau_{FUT})|^2 \tag{3.6}$$

$$= E_0^2\left\{1 + R + 2\sqrt{R}cos\left[w_B t + w_0\tau_{FUT} - \frac{1}{2}w_B\tau_{FUT} + \theta(t) - \theta(t-\tau_{FUT})\right]\right\} \tag{3.7}$$

where $w_B = w\pi\beta\tau$ is the beat frequency. $\theta(t) - \theta(t-\tau_{FUT})$ is negligible for measurements within coherence length. The backscattered signal can be mapped to distance as:

$$f_B = 2\beta\tau_{FUT} = 2\beta L\frac{n}{c} \tag{3.8}$$

$$L = f_B \frac{c}{2n\beta} \tag{3.9}$$

where $\beta = \frac{\Delta F}{T_s}$, ΔF is the frequency span and T_s is the time span of the sweep. The spatial resolution is now a function of ΔF:

$$\Delta l = \frac{c}{2n\Delta F} \tag{3.10}$$

Therefore the spatial resolution is now decoupled from the pulse width.[2]

The frequency sweep can be achieved by using a Tunable Laser Source (TLS), that can provide spatial resolutions at a micrometer level. But tunable lasers are expensive and the frequency variation is nonlinear with respect to control parameters.

For this project, we will be focusing on using chirping to achieve the required frequency sweep.

The short coherence length of lasers limit the range of such systems to tens of metre, but techniques like phase noise compensated OFDR, using an optical fiber delay loop and laser phase noise cancellation were demonstrated to measure disturbances in fibers as long as 50km, and such approaches have to be researched further to aid the scope of this project.

Chapter 4

CHIRPING

As mentioned previously, this project will be focusing on OFDR, using a chirped pulse to achieve the frequency sweep. Chirped pulses have the pulse time stretched and has frequency changing with time. There are multiple ways to achieve chirping:

- Pulse with high frequency bandwidth sent through grating to separate the frequencies (Figure 4.1[9]). Each wavelength gets diffracted by a different angle, and then travels a longer path, separating the wavelength spatially
- High intensity pulse sent through nonlinear crystal to separate the frequencies in space. Each wavelength sees a different refractive index and group velocity.
- Acousto-optic modulator - Uses the acousto-optic effect to shift the frequency of light with sound waves.

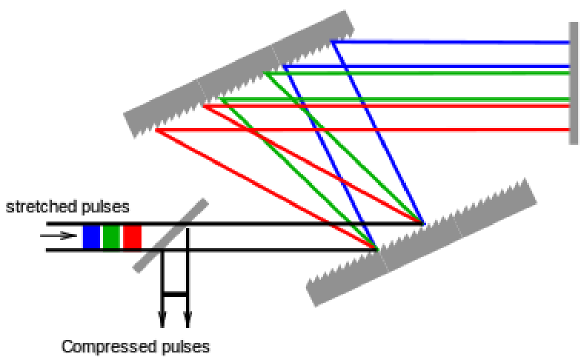

Figure 4.1: Chirping utilizing gratings

It can be seen that a constant frequency pulse that is enveloped by an exponential envelope gives rise to a chirped pulse with linear frequency variation in time.(Figure 4.2[4])

$$E(t) = E_0 exp\left(i2\pi\nu_0 t\right) exp\left(-at^2 + ibt^2\right) \tag{4.1}$$

$$\nu_0 = -\frac{d\phi}{dt} = \nu_0 + \frac{n}{\pi}t \tag{4.2}$$

This is a linear sweep.

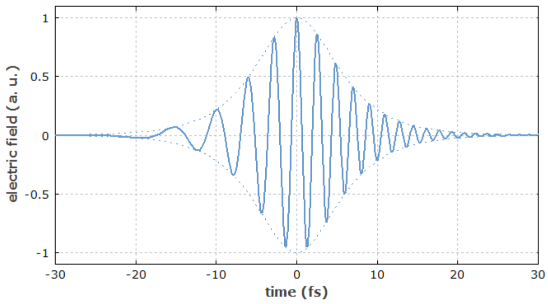

Figure 4.2: Chirped pulse waveform

In OTDR and ϕ-OTDR, intensity of the input light can be increased by Chirped Pulse Amplification (CPA), leading to better SNR and range. For our purposes, this modulated pulse chirp can be used for OFDR. This is more cost effective and easier to use than a tunable laser source.

Chapter 5

FURTHER WORK

This literature survey has laid the basic framework for the next step in the project. This involves obtaining a basic fiber optics kit to test out the different sensing setups, characterize their ranges and sensitivity. Any practical problems that would arise from actual hands-on work would have to be solved. The ultimate goal of this project is to develop an Optical Frequency Domain Reflectometry instrument using chirped pulse probes. (Figure 5.1)

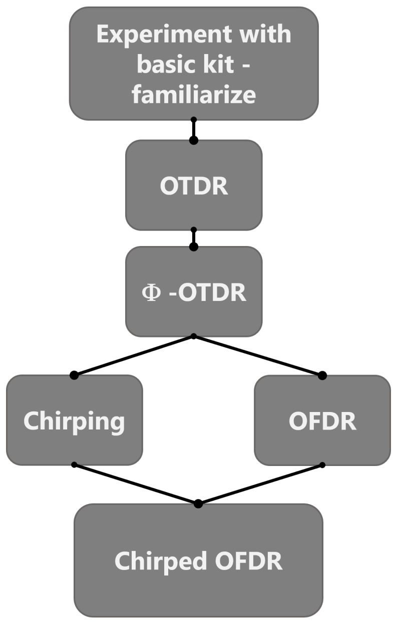

Figure 5.1: Future work plan

This work is being done as part of proposal to Tranzmeo IT Solutions Pvt Ltd for designing, fabricating and testing of a distributed acoustic sensing device with improved range.

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[10] The plans and directions for the project are based on discussions with Dr M K Ravi Varma, Professor and Salma Jose, Research Scholar