DISTRIBUTED SENSING USING RAMAN-OTDR AND COHERENT-OTDR

A Project Report

submitted by

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THESIS CERTIFICATE

This is to certify that the thesis titled **DISTRIBUTED SENSING USING RAMAN-OTDR AND COHERENT-OTDR**, submitted by **ASHWINRAJ NANDAKUMAR**, to the Indian Institute of Technology, Madras, for the award of the degree of **Bachelor of Technology** , is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: distributed sensing;Coherent OTDR

A distributed optical fibre sensor is a system that exploits an optical fibre as the sensing medium to realise continuous measurements in temporal and spatial domains.Compared to FBG which are highly sensitive to a single point distributed sensing allows us to acquire data from a range of points. Therefore,equivalent to a large quantity of point sensors connected together distributed sensors are cheaper comparatively.Distributed sensing is usually realized by techniques such as optical time domain reflectometry (OTDR) or optical frequency-domain reflectometry (OFDR).Coherent OTDR uses a coherent light source to find the phase added due to strain or temperature.

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CHAPTER 1

Introduction

1.1 Optical Time Domain Reflectometer

Optical Time Domain Reflectometer(OTDR) is a common sensing mechanism used to obtain a back-scattered plot as a function time and in turn to characterize an optical fiber.The OTDR signal gives us the location in the fiber from which it has scattered in terms of time as the rectangular pulse travels along the fiber.The back-scattered light passes through a circulator and is received by the photo-diode. The trace below shows an example of an OTDR plot.

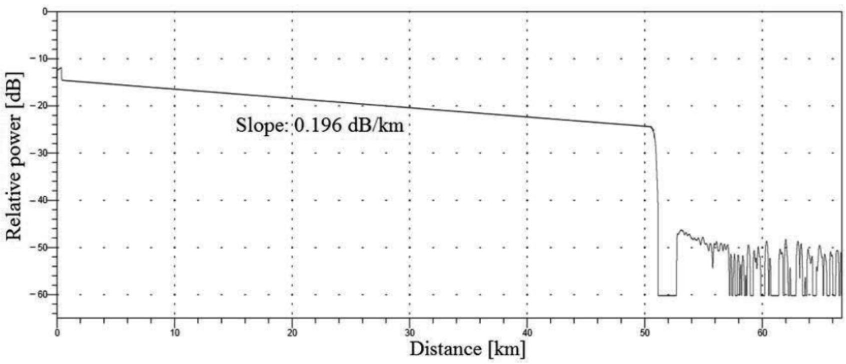

Figure 1.1: An example OTDR trace plot

1.2 Coherent Rayleigh Scattering

Scattering processes inside the fibre have been applied to distributed fibre sensing. Hence it is important to understand the light scattering mechanisms in order to investigate the working principles of different Distributed Fiber Sensors.

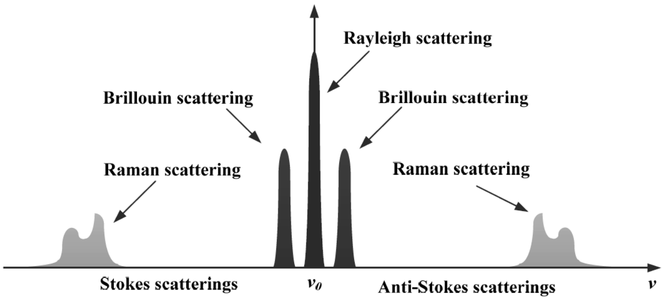

Figure 1.2: Scattered light across wavelength

Rayleigh scattering is scattering of light by molecules or particles that are less than 1/15 of the wavelength of the light. Rayleigh scattering does not change the state of material and is, hence, elastic process i.e even after light interacts with the particles in the medium its quantum state is unchanged.Whereas the other scattering processes shown above with the exception of Rayleigh are inelastic.Rayleigh scattering is due to induced dipoles created from the traveling electric field in the medium.The dipoles oscillate at the same frequency as the incident electric field and this causes the incident light to be scattered in all directions as shown below.

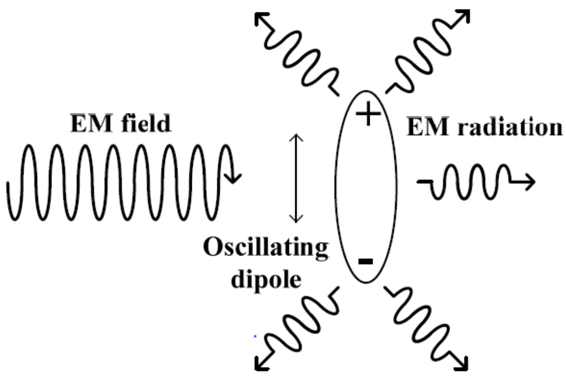

Figure 1.3: Rayleigh scattering dipole

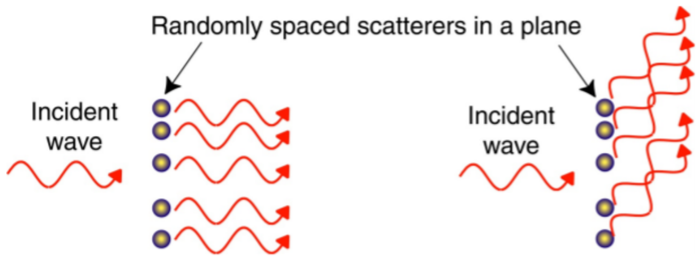

Figure 1.4: coherent vs incoherent scattering

The left image shows that the forward scattering is coherent as the scattering particles have not added any random phase to the incident wave along the vertical plane and the right image shows incoherent light across the vertical plane as each wave scattered travels a random path.Now if a single mode fiber is used the back scattered light is still coherent since dispersion is limited compared to a multi-mode fiber.

For back-scattered wave the FUT it can be divided into small fiber lengths segments. Within each segment the reflected waves will add coherently and give rise to a resultant back-scattered amplitude vector for the k^{th} segment of $p_k a_k exp(j\phi_k)$.Now ϕ is the phase added due to some perturbations in the fiber and a_k is the amplitude which is depended on the fiber loss parameter p_k is the polarization change term due to some polarization-coupling perturbation.In a coherent system if the coherent length of the light source is longer than the optical pulse width, so that there is only interference among the light back-scattered from different perturbations inside the optical pulse.Therefore we make sure that our pulse width is greater than the coherent length of the proposed laser.Therefore we use a coherent laser source and the back-scattered light's phase is monitored to get the added phase due to strain or temperature that alters the fiber's refractive index causing phase. Reflected electric field can be written as

$$E_{reflected}(z) = E_0 * a * p * exp(j\omega t + \beta z + \Delta\beta z)$$

We need to note that there is an accumulation of phase as the changes in refractive index keeps adding phase to the rectangular pulse as it passes through once in the forward direction and again as the back-scattered component.This accumulation of phase need to corrected for at the receiver.But,whatever phase the strain adds we can only extract within a range [0,2π].Therefore, more importantly the frequencies of our strain variation is more important to us.

CHAPTER 2

Simulation

2.1 Coherent detection

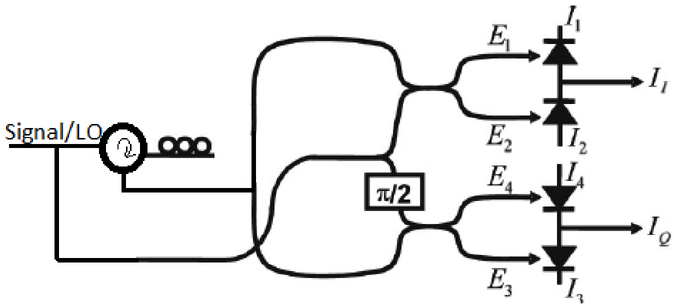

Figure 2.1: coherent detection setup

As shown above the back-scattered signal is fed into as the signal and the local oscillator in our case the operating laser is used such that there is exact frequency matching.The key is the use of a 3-dB optical coupler that adds a $180°$ phase shift to either the signal field or the LO field between the two output ports.

$$E_1 = \frac{1}{2}(Signal + LO)$$

$$E_2 = \frac{1}{2}(Signal - LO)$$

$$E_3 = \frac{1}{2}(Signal + jLO)$$

$$E_4 = \frac{1}{2}(Signal - jLO)$$

Now on passing through the photo detector and subtracting the two signals we get the in-phase and quadrature components and they are further used to determine the added phase.The photo detector's bandwidth is small therefore since the frequencies are exactly matched only the DC terms remain and the higher frequency beat terms are lost. The signals

$$I_i = \sqrt{P_{signal}P_{LO}}cos(\phi_{signal} - \phi_{LO})$$

$$I_q = \sqrt{P_{signal} P_{LO}} sin(\phi_{signal} - \phi_{LO})$$

Here ϕ_{signal} is inclusive of the perturbation phase along with the phase added due to the phase constant term without any perturbation. Now that we are only interested in the perturbed term we must subtract the linear phase constant term. Also to note here that there is a accummulation of phases as the light crosses the fiber an this should be processed at the receiver. A SIMULINK model was also created as shown below.

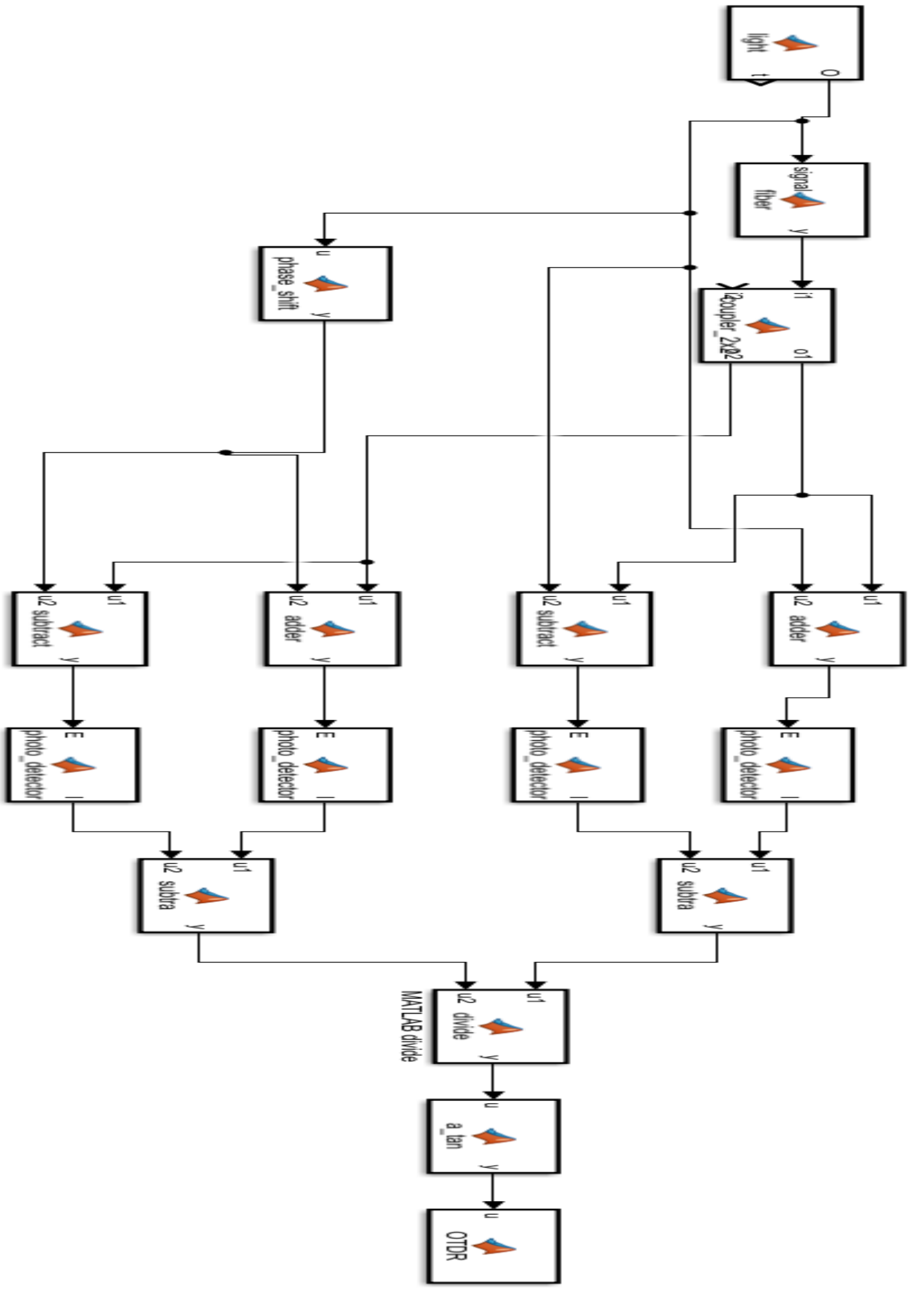

Figure 2.2: simulink setup

2.2 Simulation algorithm

For the simulation code we have assumed that we are using a pulse of width 100ns and this would lead to a resolution of 10m given that the group refractive index=1.5.In-order to avoid any interference scattering points are assumed to be separated by a the resolution length of the fiber.Now we know that back-scattered components have less power therefore we take the peak back-scattered electric field power as -30dBm.The power of the local oscillator is take to be as 13dBm matching our testing case.

Now for the back-scattered signal a 2-dimensional array is used to add perturbations to the signal.The columns of this 2-d array represent the signal and the the rows cover the resolution distance as a whole they combine to give us results on the whole test fiber.

A transfer matrix is used to model the couplers matching the phase shift and the power split as in our setup mentioned above.After which the photo-diode used to measure the intensity have a small bandwidth such that the such the terms corresponding to twice the laser frequency is lost such only the phase term is retrieved along with some DC components constitute of the electrical diode output.

Depending on the current from the photo-diode shot noise and thermal noise are added at the receiver end of the simulation.The bandwidth used is 1GHz,temperature is room-temperature and resistance is 1MegΩ.

Now instead of using tan inverse to find the phase which is limited to a range of [-pi/2,pi/2] we can use the sign of the cosine and sine and therefore detect the phase with a range from [-pi,pi]. But the phase that we have obtained is the accumulation of the phases along the fiber along with the linear phase from the phase constant.So we subtract the linear phase term then later inverse the accumulation of phase and we finally get the perturbed phase as function of distance.

2.3 Simulation results

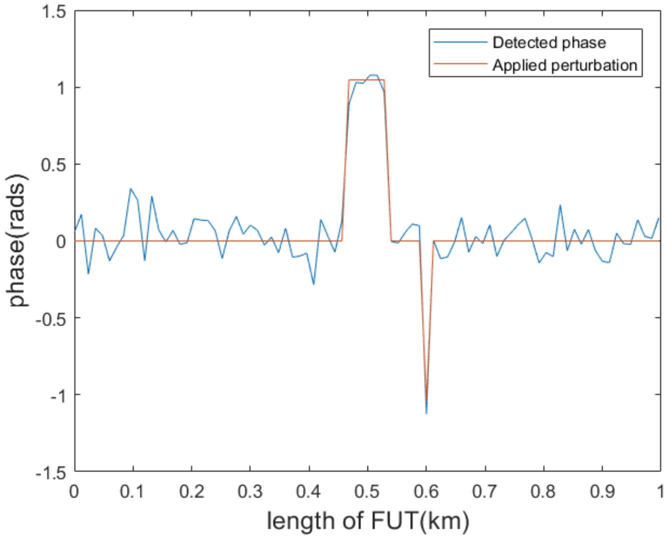

Figure 2.3: Detected phase as a function of length

First the contant phase detection is simulated.Phase added was +pi/3 and -pi/3 and were detected correctly as shown above.

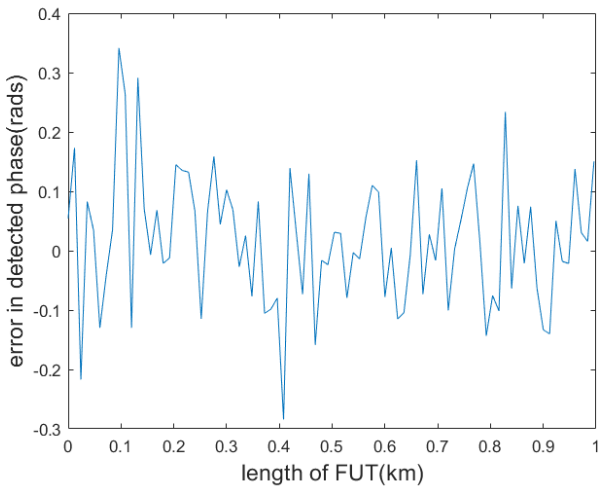

Figure 2.4: Error in the detection due to added noise inclusive of random perturbation noise along with noise at the receiver, shot and thermal noise

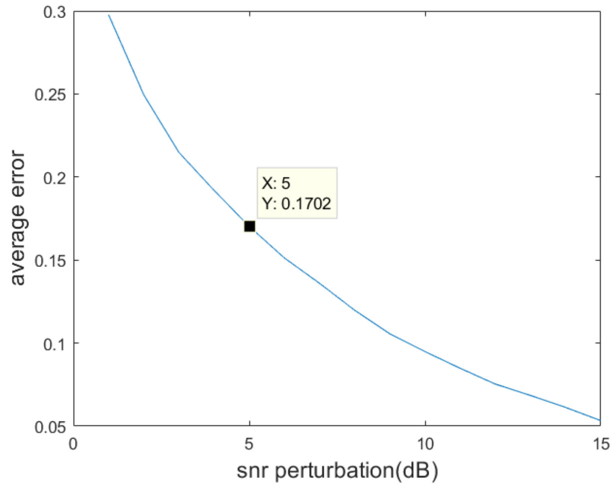

Figure 2.5: Quantifying the error as a function of SNR of added noise to the perturbation parameter

Now varying our perturbation at a frequency.A cosine function is added to the phase term pi/3 with a $freq_{pert}$ 100Hz.And side view of the mesh obtained are as shown below.

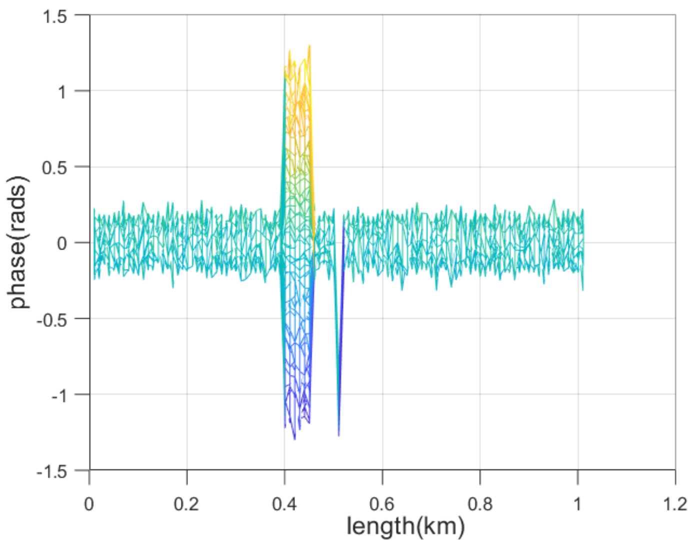

Figure 2.6: Side view of the mesh obtained which is superposition of phase across all time

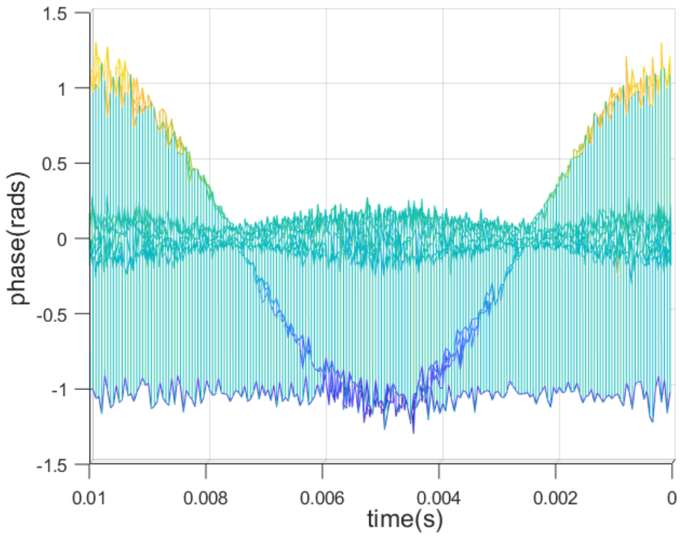

Figure 2.7: The detected phase across time we can clearly see the sinusoidal phase change

Now as per the assumption the FUT used is of 1km.Now for a $freq_{pert}$ should be be sampled at $2 * freq_{pert}$ by Nyquist theorm.For n 3.Time for the signal to reach the end of the fiber is 10^{-5}sec.Using this the maximum $freq_{pert}$ that can be detected is 50kHz.

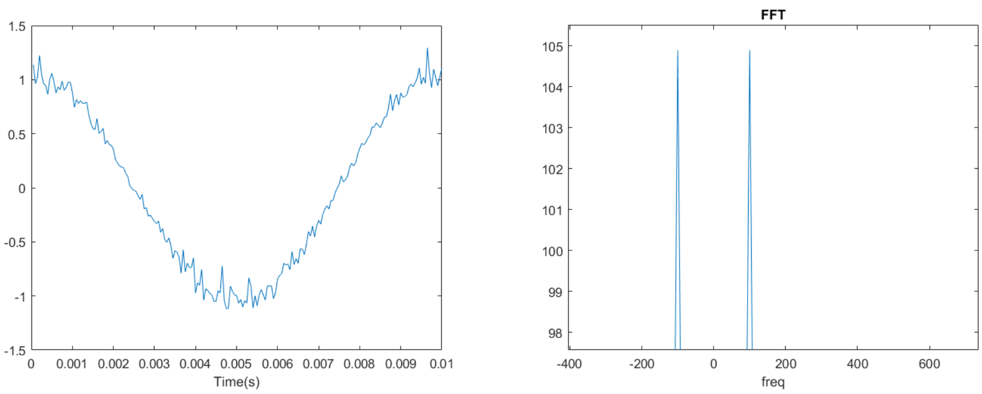

Figure 2.8: The fft of the sinsoidal pertubation confirms the result

CHAPTER 3

Experiment

The proposed experimental setup for coherent Rayleigh scattering is as shown below.

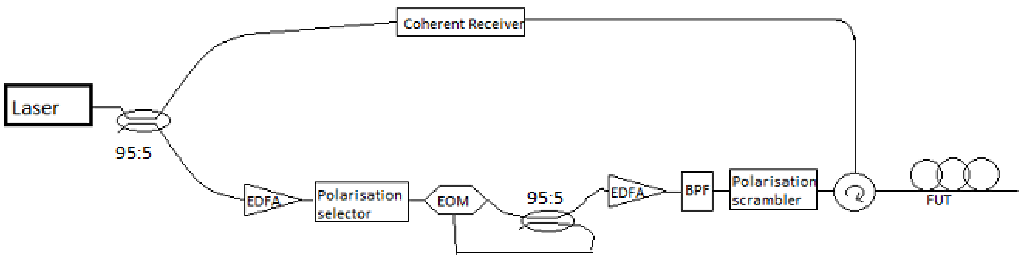

Figure 3.1: The experimental setup

Electro-optic modulator along with the arbitrary waveform generator are used to generate the required rectangular pulse depending on the resolution required.The equation is the spacial resolution $\Delta w = \frac{t_w c}{2n_g}$ where n_g is the is group refractive index.The homodyne detection proposed is same as in the simulation so we don't have any added phase due to difference in frequency of light wave.Since the back scattered power is very small in comparison to the input high amounts of powers might be needed at the LO in order to increase input power but also to bring the back-scattered phase component above the noise floor.While using high powers we need to make sure that stimulated effects don't occur and in input power should be maintained below threshold value of stimulation.The EDFA is also followed by a band pass filter in order to reduce the ASE noise added from the EDFA.Polarization scrambler is used to reduce the different polarization of the back-scattered wave.Using a laser source of power 2.25dBm, upon amplifications and modulation using a 1us pulse the average power with which it reaches the FUT is -5.4dBm.The period of our pulsing is 100us.Using a 10km spool the back scattered lights average power is -29.6dBm.Similarly using a 1km spool and 100ns pulse-width the backscattered power is around -33dBm.Since the coherent detector in the lab has a huge bandwidth photo-detectors and no adjustable gains by the gain bandwidth bottleneck we need a minimum of -5dBm from the back-scattering in-order to be detected.

APPENDIX A

Raman OTDR

Now Stokes and Anti-stokes components are generally used for temperature detection as the ratio of their intensities draws a direct relation to temperature.But in the R-OTDR box only the anti-stokes component is used and constants are matched in-order to find the temperature.The equations are modelled after the

$$Intensity_{anti-Stokes} = \frac{K1}{exp(\frac{K2}{T}) + 1}$$

Upon testing fitting the constants we can calculate K1=48.83 and K2=496.1.

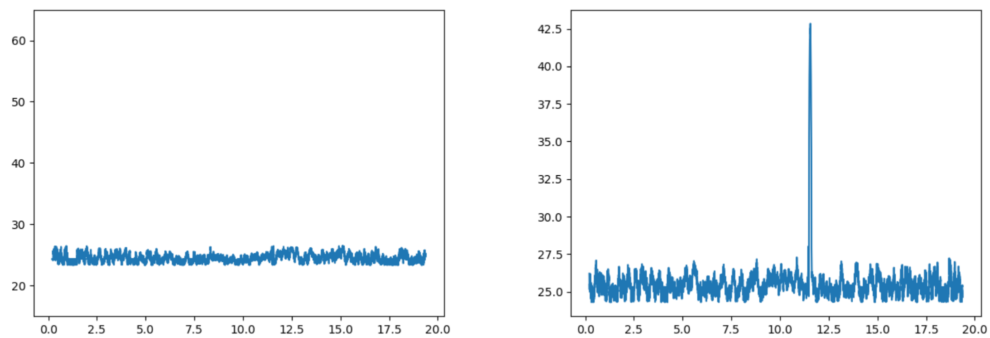

Figure A.1: Temperature plot vs distance

Best results were observed when the same type of fiber spools were used thereby reducing the differences in confinement of the back-scattered light. Splicing losses should be as minimal as possible as they can be mistaken for the change in intensities and correspond to temperature change. But compared to Rayleigh Raman scattering offers lesser intensity in back scattering and therefore we don't need very sensitive photo-diodes compared to Raman.

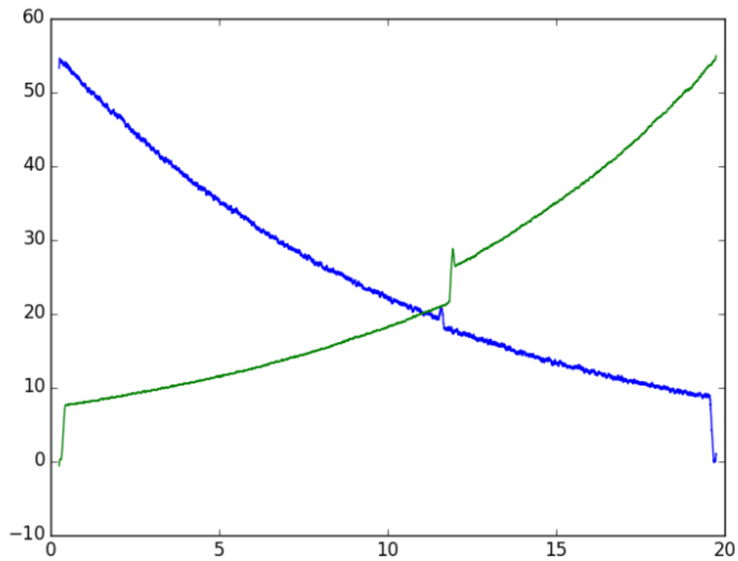

Figure A.2: Trace plot vs distance(km)

Here is the trace plot that show the peak due to Anti-stokes scattering but also have a loss due to splicing.We need both ends of the fiber to get the forward and the backward trace.Now upon multiplying these two plots we can eliminate the exponential component of the trace and get back to a normalized intensity.

REFERENCES

[1] Coherent Rayleigh time domain reflectometry: novel applications for optical fibre sensing, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, 29 SEPTEMBRE 2016,Xin LU.

[2] Fundamentals of Coherent Optical Fiber Communications,Kazuro Kikuchi,JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 34, NO. 1, JANUARY 1, 2016.

[3] Strain sensing based on coherent Rayleigh scattering in an optical fibre,R. Posey Jr., G.A. Johnson and S.T. Vohra, ELECTRONICS LETTERS 28th September 2000

[4] Statistics of Rayleigh Backscatter From a Single-Mode Fiber,PETER HEALEY,IEEE TRANSACTIONS ON COMMUNICATIONs