Measurement of signal losses on optical fibre cable due to vibrations using optical time domain reflectometer

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Abstract

The last couple of decades have witnessed a steep rise in extensive research on fiber optical communication fields. Researches have been done for past few decades on distributed sensor and also fabricating the fibre optic to make sensor to detect vibration. The purpose of this paper is to present a fiber optic sensor based on the monitoring of vibrations and signal losses in a single mode optical fiber. In this study, a single mode optical fiber was subjected to vibrations from these sources, Flask shaker (Gallenkamp model), gasoline generator (Elepaq-EC6500 5.5KVA), the university heavy duty truck (Mercedes-Benz Zetros), and the medical complex power plant. The vibrations were generated on the optical fibre cable line along the road that leads to capitol at the university medical complex of the optical fibre network. The signal losses due to vibrations on the optical fiber to determine the vibration sensitivity were investigated using a commercial optical time domain reflectometer (Anritsu MT9083AI Access Master). Three scenarios were observed, a signal loss of 2.62dB was measured in the first scenario, 2.70dB in the second scenario and a signal loss of 2.76 was measured in the third scenario.

Keywords: fibre optics, optical sensors, vibration measurements, single mode fibre

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Introduction

An optical fiber is a cylindrical dielectric waveguide made of low-loss materials such as silica glass. It has a central core in which the light is guided, embedded in an outer cladding of slightly lower refractive index. Fiber optics transmits data in the form of light particles or photons that pulse through a fiber optic cable. The glass fiber core and the cladding each have a different refractive index that bends incoming light at a certain angle. When light signals are sent through the fiber optic cable, they reflect off the core and cladding in a series of zigzag bounces, adhering to the principle of total internal reflection. To renew, or boost, the signal throughout its journey, fiber optics transmission sometimes requires repeaters at given intervals to regenerate the optical signal using Erbium-doped optical fiber amplifiers.

Fiber optic sensors work based on the principle that light from a laser or any super luminescent source is transmitted via an optical fiber, experiences changes in its parameters either in the optical fiber or fiber Bragg gratings and reaches a detector which measures these changes. A typical fiber optic sensor system consists of a fiber-optic cable connected to a remote sensor or an amplifier. The fiber optic cable consists of a glass or plastic core surrounded by a layer made of cladding material. (Fidanboylu, 2009)

Fiber Bragg Gratings (FGBs)

Fiber Bragg Gratings (FGBs) are optical fiber devices that consist in a longitudinal periodic perturbation of the refractive index of the core of an optical fiber. Such periodic variation of the optical properties of the fiber confers to its unique optical properties that make these devices ideal for optical sensing applications. In fact, since the first permanent in-line grating was reported in 1978, more and more scientific groups have devoted research into such devices. In fact, the numbers of reported works related to vibrations using FBGs have grown significantly since 1994, although the first strain and temperature sensor was presented in 1988. One of the most valuable properties of FBGs is their strong dependence of the resonance peak on very small variations of the Bragg period which makes them ideal for strain sensing. They also have additional advantages, for example, their small size that makes them suitable to embed into composite materials or concrete, or their dense wavelength multiplexing capability that makes possible multipoint sensing in complicated civil structures such as bridges or highways. Also, this structure can be used to simultaneous measurement of several parameters such as temperature or humidity and vibrations using wavelength multiplexing techniques. (Yoany, 2010)

The optical properties of an FBG device arise from a series of partial reflectors arranged with a determined spatial period. In the optical fiber FBG, such reflectors are fabricated by altering the refractive index of the core of the optical fiber in a periodic manner, creating dielectric partial mirrors, and consequently a series of interferences occur as the light travels through the device. In consequence, certain wavelengths which have a constant relation with the period of the refractive index perturbation experiment a strong transmission blockage. Such wavelengths are reflected by the FBG structure, while the device keeps unaltered the rest of the wavelengths, therefore the FBG acts as a wavelength selective reflector. Fiber Bragg Gratings are created by “inscribing” or “writing” the periodic variation of refractive index into the core of a special type of optical fiber using an intense ultraviolet (UV) source such as a UV laser. A special germanium-doped silica fiber is used in the manufacture of FBG because it is photosensitive, and it is possible to induce refractive index shifts in areas exposed to strong UV radiation. Consequently, the FBGs are fabricated by exposing them to a very regular UV pattern.

A sensor is a device that detects, or senses, a signal or physical condition. One of the major sensor types that have emerged in recent years is a fiber optic sensor. As technology has advanced, these sensors are now widely used in areas such as aerospace, medicine, construction among others (Dakin, 1989). In addition there have been revolutionary inventions in the field of fiber optics which has increased the growth of interest in optical fiber sensors as they offer many advantages of optical transmission over electrical transmission. The fiber sensors are becoming more attractive over other sensors by the day, because it is immune to electromagnetic interference, non-electrical, high accuracy, easy to install, noncontact, explosion proof, small size and weight.

Vibration in physics is the periodic back-and-forth motion of the particles of an elastic body or medium, commonly resulting when almost any physical system is displaced from its equilibrium condition and allowed to respond to the forces that tend to restore equilibrium. (Krohn, 1992)

Early vibration monitoring were carried out on important machines such as power station turbines and generators to give an early warning of impending conditions which may develop and lead to complete failure and destruction of the components in machines. Continuous monitoring of vibration reduces not only the maintenance and operating costs but also avoids frequent interruptions of undesirable engine working. In general vibration is measured by electro-mechanical devices, such as piezoelectric, piezoresistive, or capacitive accelerometers. Such types of measurements require physical contact with the vibrating object. (Dantala, 1985)

In scope of this research work, we shall present vibration sensor that could be used in smart structures or, in other words, for bestowing self-sensing capabilities upon materials, or whole structures. This capability could reduce maintenance costs that are often very significant. The proposed sensor could be used to measure signal losses, natural frequency and other parameters that may change as damage is inflicted upon materials, thus information about integrity of a material may be obtained by studying these characteristics.

The light intensity inside a fibre can be represented as (1) (2)

$$I(r,\emptyset) = \frac{1}{2}\sum_{m=0}^{N'}\sum_{l=0}^{N'} A_m A_l J_{n_m}(U_m r) J_{n_l}(U_l r).$$

$$\cos(n_n\emptyset)\cos(n_l\emptyset)\exp(-i(\Delta\beta_{m_l} z - \Delta\emptyset_{ml})) \quad (1)$$

Here m and l represent the index of each propagating mode, A_m and A_l are the amplitudes of each mode, $\Delta\beta_{m_l}$ and $\Delta\emptyset_{ml}$ are the difference between the propagation constants and the phase of two modes, U_m and U_l are equal to;

$U_m = \sqrt{B_0^2 n_l^2 - B_{z,m}^2}$, and Y is proportionality constant.

This expression can be rearranged as follows:

(2) $$I(r,\emptyset) = \frac{1}{2} Y \sum_{m=0}^{N'} [A_m^2 J_n^2 (U_m r) cos^2 (n_m \emptyset)$$

$$+ \sum_{l=m+1}^{N\prime} A_m\, A_l J_{n_m} (U_m r) J_{n_l} (U_l r)$$

$$. \cos(n_n \emptyset) \cos(n_l \emptyset) \cos(\Delta\beta_{m_l} z - \Delta\emptyset_{ml})]$$

If the fiber is exposed to some force $F(t)$, the propagation constant of each mode changes in correlation with that force, and the difference $\Delta\beta_{m_l}$ is proportional to the applied force.

(3) $$\delta(\Delta\beta_{m_l} z) \propto F(t)$$

The corresponding change of intensity is equal to:

(4) $$I(r,\emptyset) = \frac{1}{2} Y \sum_{m=0}^{N'} \{[A_m^2 J_n^2 (U_m r) cos^2 (n_m \emptyset)$$

$$+ 2 \sum_{l=m+1}^{N\prime} A_m\, A_l J_{n_m} (U_m r) J_{n_l} (U_l r) cos(n_m \emptyset)$$

$$. \cos(n_l \emptyset) \cos[\Delta\beta_{m_l} z - \Delta\emptyset_{ml} + \gamma_{ml} F(t)]\}$$

Methodology

In the quest to find out the impact of vibrations on an optical fibre network, vibrations were produced on optical fibre cables from various sources of different degrees. The vibrations were generated on the optical fibre cable line along the road that leads to capitol at the university medical complex of optical fibre network, and the signal losses arising from these vibrations were measured and read using an OTDR (Anritsu MT9083AI Access Master) in the ICTU office. Three scenarios were considered in other to compare the signal losses from these different sources of vibration. An OTDR (optical time domain reflectometer) was used to measure each case scenario to compare the signal losses generated from the vibration sources. The OTDR was used at the server room in the ICTU Administration office of university of Benin, the OTDR was connected to the central router in the administration office that routes all the fibre networks in the university and was configured to take the readings. In the first scenario there was no vibration induced on the optical fibre cable as the OTDR was used to send a signal across the optical fibre cable line along the road that leads to capitol at the university of Benin medical complex and readings were generated and recorded from the OTDR. In scenario two the flask shaker(Gallenkamp model), the Gasoline generator (Elepaq-EC6500 5.5KVA), and the power plant located at the road where the fibre cable was laid were powered on to cause a vibration and the resulting signal loss arising from the vibrations of these equipment's were measured. Scenario three featured the heavy duty truck (from the fire service department of the university) which was powered on in addition to the, gasoline generator, the power plant and the flask shaker. The heavy duty truck was moved around the vicinity to cause a greater impact vibration and again the signal loss was measured. These readings include the OTDR trace, the end- to -end loss, reflectance or reflected loss, splice loss and other parameters.

Results and discussions

From the results obtained from the OTDR, a table consisting of the data analysis and the trace was generated, it contains the signal loss measured, the number of events points, the total wavelength, the pulse width (determines how much a fibre can be measured before running into noise), the total losses, the reflectance, splice loss and other parameters

Table 1: Data Analysis from Scenario One

ANALYSIS RESULTS - - PROJECT WORK6.SOR					
Feature #/type	Location (km)	Event (dB)	– Event (dB/Km)	Loss (dB)	Refl (dB)
1/N	0.0292	-0.16	-5.407	0.11 (2P)	
2/N	0.5235	-0.12	-0.242	0.03 (2P)	
3/G	0.7139 – 0.7599	-0.03	0.156	2.14 (2P)	
4/N	0.9673	0.03	0.107	0.57 (2P)	
5/E	1.0811	-0.00	-0.040	> 3.00	>-14.09
Overall (End – to - End) Loss: 2.62 dB					

Table one above represents the data analysis from scenario one. From the table, it is clearly shown that five events were recorded. These events shows were the signal losses have been recorded and are indicated in figure 1 (OTDR Trace) below as truncated lines or the small triangular shapes on the trace. The long vertical line at points (0.0, A, B) indicates reflected losses and the total length of the fibre cable in km, and the trace also indicates the refractive index in the fibre cable.

The sharp drop on the traces indicates loss due to bending in the fibre cable or bending loss. The length of these sharp drops implies the degree of loss encountered at the event points. However, it should be noted that these sharp drops could also indicate topographic faults underground were the fibre cables are laid.

In this scenario an end-to-end loss of 2.62 dB was also obtained. Other parameters obtained from this experiment are; Reflectance or Reflected loss = -66.82dB; Splice loss = 1.412dB.

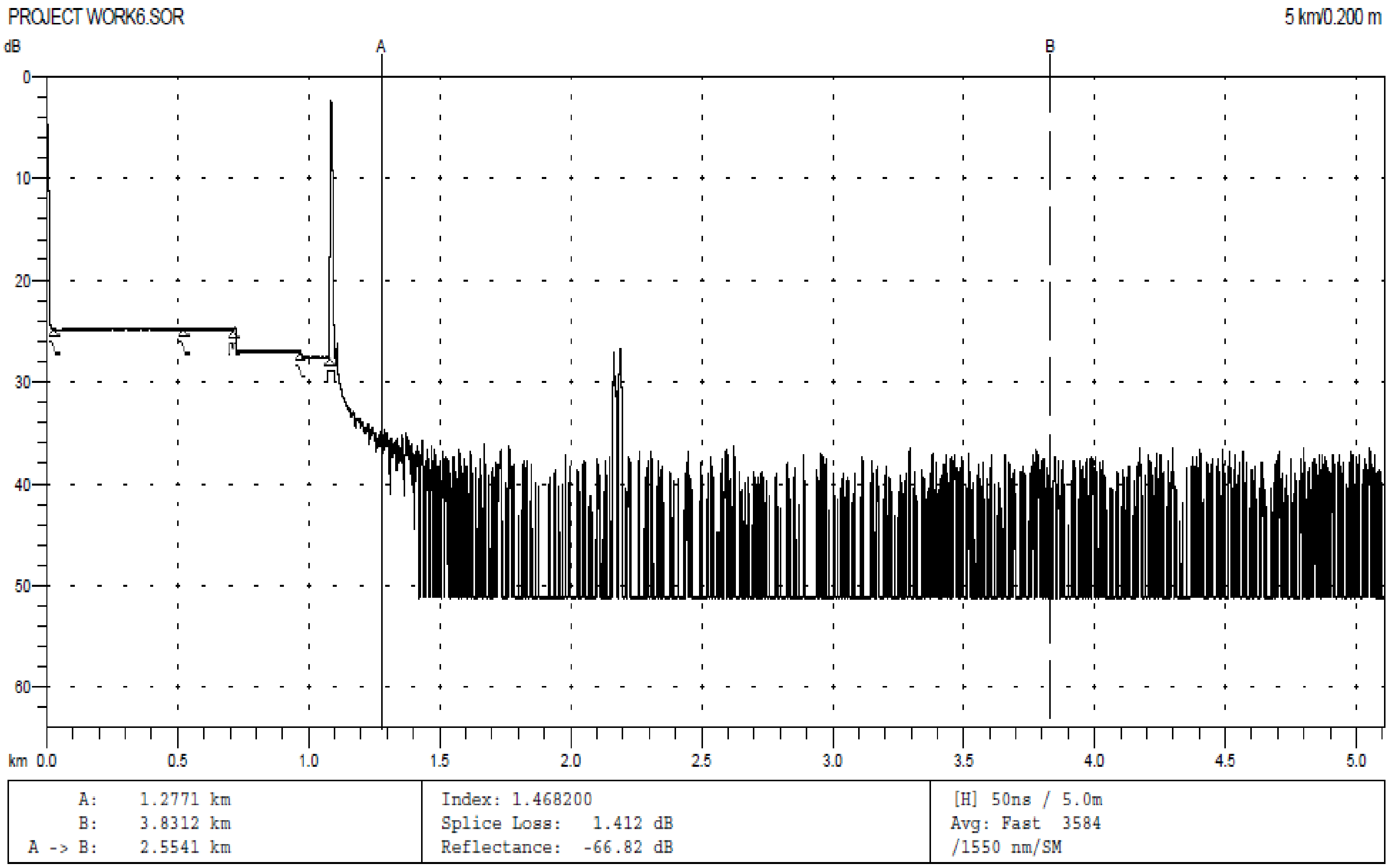

Figure 1: OTDR Event tracing of scenario one

Table 2: Data analysis from scenario two

Analysis Results - - Project Work5.Sor					
Feature #/type	Location (km)	Event – (dB)	Event (dB/Km)	Loss (dB)	Refl (dB)
1/N	0.0292	-0.09	-3.056	0.04 (2P)	
2/N	0.6126	-0.06	-0.098	0.03 (2P)	
3/G	0.7145 – 0.7597	0.02	0.177	2.19 (2P)	
4/N	0.9667	0.01	0.042	0.56 (2P)	
5/E	1.0811	0.00	0.006	> 3.00	>-14.21
Overall (End – to - End) Loss: 2.70 dB					

Table two above represents the data analysis from scenario two (vibrations from flask shaker, the gasoline generator and the power plant). From the table, it is shown that five events were also recorded. These event points shows were the signal losses have been recorded and are indicated in figure 2 (OTDR Trace) below as truncated lines or the small triangular shapes on the trace. The long vertical line at points (0.0, A, B) indicates reflected losses and the total length of the fibre cable in km, and the trace also indicates the refractive index in the fibre cable.

The sharp drop on the traces indicates loss due to bending in the fibre cable or bending loss. The length of these sharp drops implies the degree of loss encountered at the event points. But it should be noted that these sharp drops could also indicate topographic faults underground were the fibre cables are laid. In this scenario an end-to-end loss of 2.70 dB was also obtained. Other parameters obtained from this experiment are; Reflectance or Reflected loss = -64.06dB; Splice loss = -0.702dB.

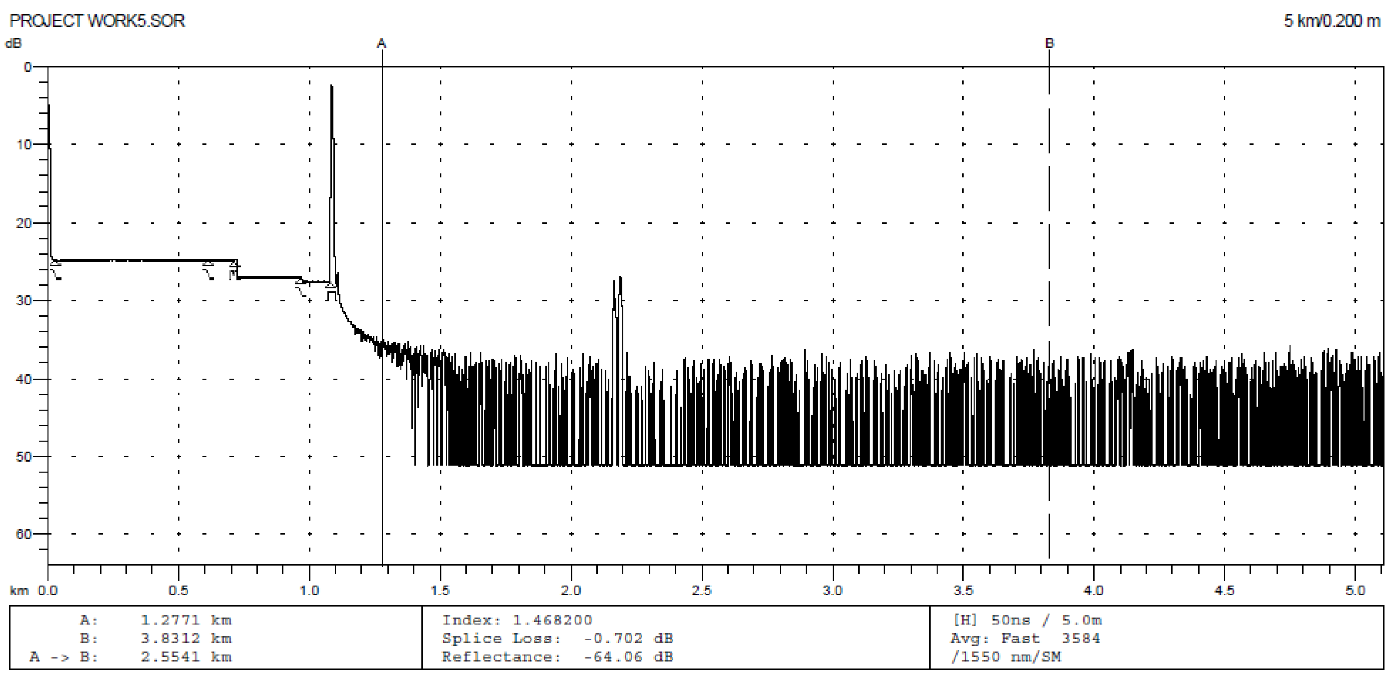

Figure 2: OTDR Event tracing of scenario two

Table 3: Data analysis from scenario three

ANALYSIS RESULTS - - PROJECT WORK4.SOR					
Feature #/type	Location (km)	Event – Event (dB)	(dB/Km)	Loss (dB)	Refl (dB)
1/N	0.0282	-0.03	-1.194	0.02 (2P)	
2/G	0.7117 – 0.7599	-0.00	-0.005	2.20 (2P)	
3/N	0.9119	0.07	0.341	-0.03 (2P)	
4/N	0.9673	0.02	0.356	0.53 (2P)	
5/N	1.0364	-0.02	-0.221	0.02 (2P)	
6/E	1.0811	-0.02	-0.406	> 3.00	>-14.31
Overall (End – to - End) Loss: 2.76dB					

Table three above presents the data analysis from scenario three (vibrations from flask shaker, the gasoline generator and the power plant, and heavy duty truck). As evident in the table, it is evident that five events were also recorded. These event points shows were the signal losses have been recorded and are indicated in figure 3 (OTDR Trace) below as truncated lines or the small triangular shapes on the trace. The long vertical line at points (0.0, A, B) indicates reflected losses and the total length of the fibre cable in km, and the trace also indicates the refractive index in the fibre cable.

The sharp drop on the traces indicates loss due to bending in the fibre cable or bending loss. The length of these sharp drops implies the degree of loss encountered at the event points. We should, however, not lose sight of the fact that these sharp drops could also indicate topographic faults underground were the fibre cables are laid.

In this scenario an end-to-end loss of 2.76 dB was also obtained. Other parameters obtained from this experiment are; Reflectance or Reflected loss = -67.25dB; Splice loss = 5.614dB.

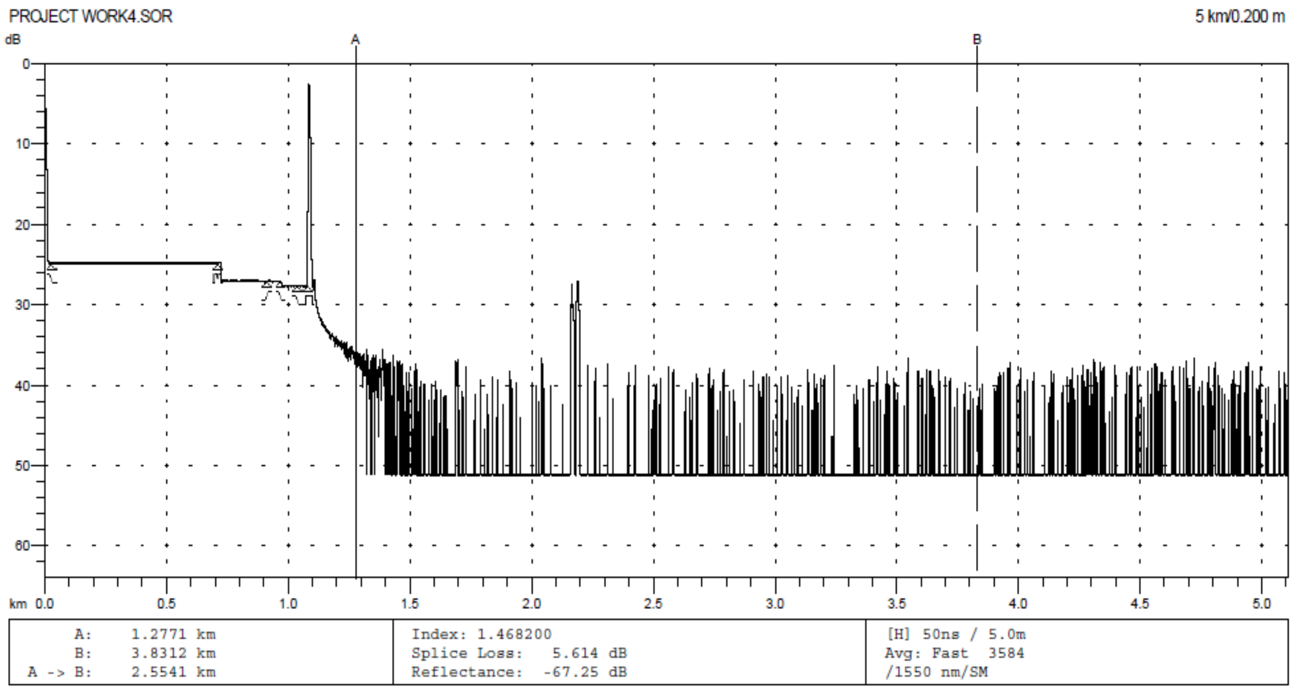

Figure 3: OTDR Event tracing of scenario three

Comparisons of results

From the results obtained above, it is predictive that in scenario one when no vibration was carried out that the total end-to-end loss was 2.62dB. But the signal loss value increases to 2.70dB in scenario two when the flask shaker, gasoline generator and power plant were powered on to cause an impact vibrations on the fibre cables. A greater end-to-end loss was recorded in scenario three when the heavy duty truck was powered on in addition to the flask shaker, generator and power plant, the truck was moved around the vicinity to cause a greater impact vibration on the fibre cables and an end-to-end loss of 2.76dB was obtained.

The difference in the end-to-end losses is due to the vibration from different sources and we can thus say that from our result, the greater the vibrations induced on the fibre cable the greater the signal loss and vice versa. For better clarification we have designed an area 2D plot of the signal losses which explicitly differentiates the signal losses of each experiment with respect to distance.

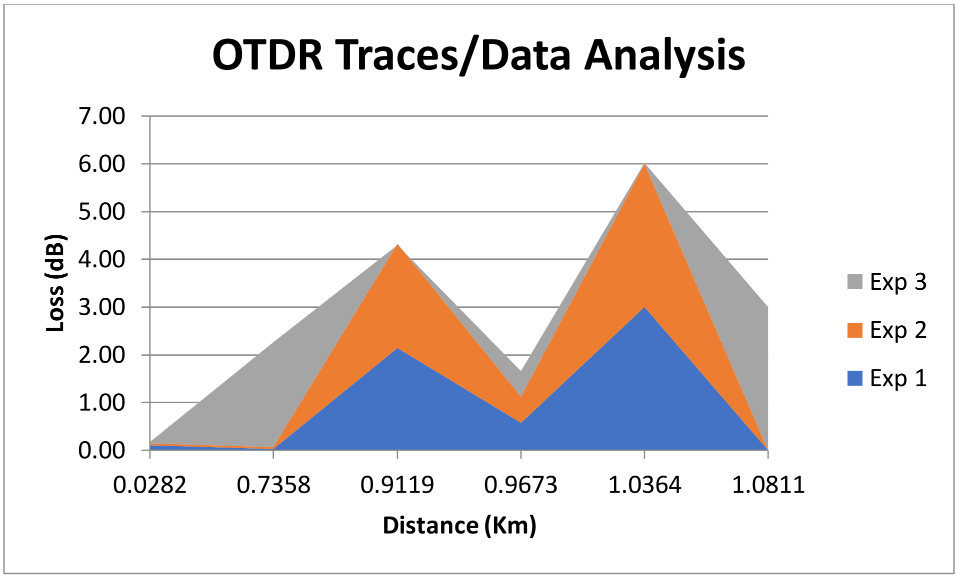

Figure 4: Area 2D plot of the OTDR data analysis

Reflectance or Reflected Loss

Reflectance or optical return loss (which has been called "back reflection") of a connection is the amount of light that is reflected back up the fibre toward the source by light reflections off the interface of the polished and surface of the mated connectors and air.

From our experiments the optical domain reflectometer (OTDR) measures the amount of light that is returned from both backscatter in the fibre and reflected from a connector or splice. The amount of light reflected was determined by the differences in the index of refraction of the two fibres joined, a function of the composition of the glass in the fibre, or any air in the gap between the fibres. The peak that identifies a reflective event was measured and reflectance calculated.

The reflectance from our experiment one, when there was no vibration was (-64.06) which is a little bit higher than the generalized reflectance value for a single mode optical fibre which is (–60.00dB) because of external constraints. In experiment two when there was an impact vibration from the flask shaker, gasoline generator, power plant, the reflected loss increased to (-66.82), and finally the reflected loss increased to (-67.25) in experiment three when a greater impact vibration from the flask shaker, power plant, gasoline generator, and the heavy duty truck was induced on the ground where the fibre cable was laid.

Conclusions

It has been demonstrated that it is possible to detect vibrations and measure their parameters using the optical fibre based sensor. From our research we have actualized the facts that, the fibre optics sensor system can also be used not only to collect the data but also to respond to it. Vibrations have a great effect on fibre cables (i.e. the greater the vibrations induced on the fibre cable the greater the signal loss and vice versa.), therefore vibration monitoring could be carried out to give an early warning of impending conditions which may result in earthquakes and other natural disasters. Fiber optic sensor provides better accuracy and results over other vibration sensors. There are other fascinating reasons, such as small size, light weight, immunity to electromagnetic interference, high temperature performance, large bandwidth etc.

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