ANKARA YILDIRIM BEYAZIT UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES



DISTRIBUTED FIBER OPTIC ACOUSTIC SENSOR BASED ON SAGNAC – MICHELSON INTERFEROMETER

M.Sc. Thesis by

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September, 2020

ANKARA

DISTRIBUTED FIBER OPTIC ACOUSTIC SENSOR BASED ON SAGNAC – MICHELSON INTERFEROMETER

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M.Sc. THESIS EXAMINATION RESULT FORM

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2020, 5 October **Cihad GÜLTEKİN**

DISTRIBUTED FIBER OPTIC ACOUSTIC SENSOR BASED ON SAGNAC – MICHELSON INTERFEROMETER

ABSTRACT

In this study, the data collected from the Sagnac-Michelson interferometer system distributed fiber optic sensor setups used to detect and diagnose illegal entry and exit for places such as borderline, airport, prison, etc. The acoustic effects of four different frequencies were applied in the laboratory environment at three different points on the line, which was formed with a standard fiber communication cable used in communication, twenty km, ten km of reference and ten km of measuring line. While the optical signal circulates on the line, the above-mentioned acoustic effects were applied and the beam reaching the source was demodulated and the acoustic effects were observed by processing the obtained signals. While looking at the first, second and third harmonics, it is analyzed how the harmonics are altered proportionally according to the distance.

Keywords: Fiber sensor, distributed fiber optic acoustic sensor, Sagnac-Michelson interferometer, harmonic analysis.

SAGNAC-MICHELSON İNTERFEROMETRESİ TABANLI DAĞITIK FİBER OPTİK SENSÖR

ÖZ

Bu çalışmada sınır hattı, havalimanı, hapishane, gibi alanlarda izinsiz giriş ve çıkışların doğalgaz-petrol boru ve demiryolu hatlarında hırsızlık, sabotaj gibi durumların tespit ve teşhisine yönelik kullanılan dağıtık fiber optik sensör konfigürasyonlarından Sagnac-Michelson interferometresi sensörü üzerinden elde edilen verilerin analizi yapılmıştır. Laboratuvar ortamında on km referans, on km ölçüm hattı olmak üzere yirmi km'lik, haberleşmede kullanılan standart fiber haberleşme kablosu ile oluşturulan hat üzerinde, üç farklı noktada dört farklı frekans değerinde akustik etkiler uygulanmıştır. Optik sinyal, hattı dolanırken yukarıda bahsedilen etkiler uygulanmış kaynağa ulaşan ışın demodüle edilmiş ve elde edilen sinyaller işlenerek akustik etkiler gözlemlenmiştir. Birinci, ikinci ve üçüncü harmonikler incelenilerek, uzaklığa bağlı olarak harmoniklerde orantılı bir değişim söz konusu olup olmadığı incelenmiştir.

Anahtar Kelimeler: Fiber sensör, dağıtık fiber optik akustik sensör, Sagnac-Michelson interferometresi, harmonik analiz.

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NOMENCLATURE

Acronyms

FOS	: Fiber Acoustic Sensor
DAS	: Distributed Acoustic Sensor
DFOS	: Distributed Fiber Optic Sensors
M	: Michelson Interferometer
MZI	: Mach-Zender Interferometer
OTDR	: Optical Time Domain Reflectometer
Φ OTDR	: Phase-Sensitive Optical Time Domain Reflectometer
OFTDR	: Optical Frequency Domain Reflectometer
POTDR	: Polarization Optical Time Domain Reflectometer
BOTDA	: Brillouin Optical Time Domain Analysis
BOCDA	: Brillouin Optical Correlation Domain Analysis
FBG	: Fiber Bragg Grating
FFT	: Fast Fourier Transform
SNR	: Signal Noise Ratio
CW	: Clockwise
CCW	: Counterclockwise
LD	: Laser Diode
PD	: Photo Diode
TEC	: Temperature Controller
WDM	: Wavelength-division multiplexing
BBC	: Broad Band Coupler

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CHAPTER 1

INTRODUCTION

With fiber-optic distributed sensor networks, the limitations of traditional technologies such as thermocouples and strain gauges due to their physical structure can be overcome, and many advantages are offered, especially in observing difficult or inaccessible environments. In distributed fiber sensor applications, the entire length of the fiber acts as a sensor. Optical fiber is portable and flexible and is not affected by electromagnetic interference. With these features, fiber is an affordable and passive sensor. Fiber optic cables can be easily integrated into the structure during or after the construction of strategically crucial structures such as bridges, pipelines, tunnels. With this method, by providing the function of thousands of conventional point sensors with a single optical fiber cable, significant savings can be achieved in installation, calibration, and support costs and time. Hundreds of kilometers of oil- gas pipelines, borderlines, railway lines, tunnels, etc. Until now, structures and lines that could not be controlled comprehensively due to size, complexity, location, and seasonal climatic conditions can be observed continuously [1].

Distributed fiber optic sensor technology is examined in two categories as backscattering and fiber interferometer based optical sensors [2]. Backscatter based time domain reflectometer (OTDR) is among the detectors on which the most research and development activities are carried out. Since the signal perceived from the sensor is feeble, it is necessary to add trigger systems mechanically to increase the sensitivity, to improve the perception speed of the system and to process the signal in real-time, high-speed designs are required. This increases the complexity, size, and cost of the system [3,4]. Interferometer-based Sagnac, Michelson (MI), Mach-Zender (MZI) methods have gained extensive coverage in the field of sensing technologies due to their low cost and high sensitivity [5]. Although interferometer-based fiber sensors' sensitivity is high, they cannot be used alone for location determination [6]. For this reason, studies on binary combinations are also carried out: Dual Sagnac [7], Sagnac-MI [5,6], Sagnac-MZI [4], dual MZI [8], Dual MI [9].

Because of the above facts, studies have been started on this configuration because the Sagnac-Michelson interferometer is a low cost, easy to install, has a relatively low level of requirements, and its limitations are less than other methods. The acoustic effects of four different frequencies were applied in the laboratory environment at three different points on the line, which was formed with a standard fiber communication cable used in communication, twenty km, ten km of reference and ten km of measuring line. While the optical signal circulates on the line, the above-mentioned acoustic effects were applied and the beam reaching the source was demodulated. The acoustic effects were observed by processing the obtained signals. While looking at the first, second and third harmonics, it is analyzed how the harmonics are altered proportionally according to the distance.

In Chapter 2, information was given about fiber optic sensor technology. The working principle of FOS, its advantages over traditional sensor technologies, what it is categorized according to, its usage areas are mentioned.

In Chapter 3, distributed fiber optic sensor technologies, their advantages over point and quasi-distributed sensors are mentioned. Then, the working principles of interferometer and backscattering based fiber sensor types, which are sub-headings of the distributed fiber sensor category, and studies in the literature are included.

In Chapter 4, fiber sensor topology installed in the laboratory environment, system sub-breakdowns and parameters are taken into account in its design are mentioned.

In Chapter 5, the harmonic analysis of the data taken from the sensor test setup is included.

In Chapter 6, the results of the studies have been evaluated.

CHAPTER 2

FIBER OPTIC ACOUSTIC SENSOR TECHNOLOGY

In recent years, fiber optic sensor (FOS) technology has been used in many areas from health, transportation, security to oil and natural gas drilling works. Fiber optic-based detection technologies offer innovative approaches in many special applications where high tolerance to demanding measurement conditions, precision and remote measurement are required [10].

Research studies on FOS started in the 1960s, with the development of modern low-loss fiber optics in the future, it was possible to move from experimental applications to practical applications. In the early 1970s, detection experiments were conducted with low loss fiber optics. Since then FOS has been developing tremendously. For example, distributed fiber optic sensors are installed to monitor structural damage on bridges and dams. Fiber optic sensors are also used for due diligence in oil wells and pipelines, trains, aircraft wings and wind turbines. This has helped to develop instruments that need accurate measurements as devices that need accurate calculations, including gyros, hydrophones, temperature and chemical detectors, researched for decades. Advances in optical communications have triggered the development of fiber optic and optoelectronic devices. In addition to the high growth rate of fiber optic communication networks, the low cost of main components such as light sources and photodiode detectors, the cost of fiber optic sensor systems has been greatly reduced [10].

It is predicted that the studies on FOS technology will continue to increase and the areas of its use will become widespread. Some fiber sensor types are in the research and development phase, while others have reached maturity and are developed commercially and are used in various applications [10].

2.1. Fiber Optic Basics

A fiber optic consists of three components:

(a) The core
(b) The cladding
(c) The buffer coating

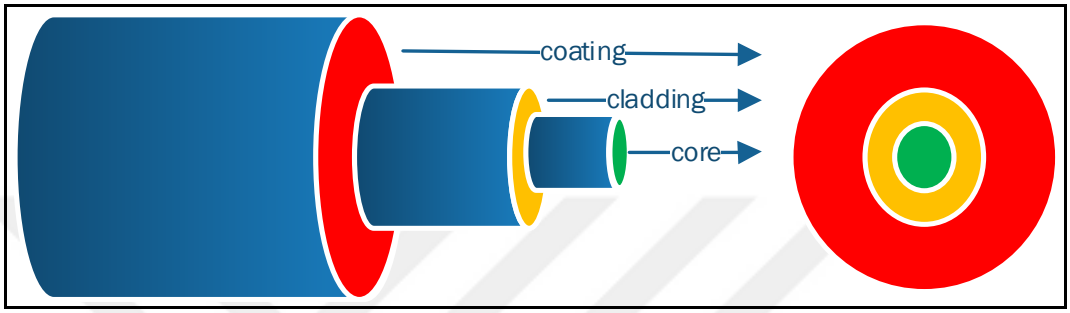


Figure 2.1. Fiber Optic Cable Components

Figure 2.1 shows the structure of a simple fiber optic cable. The core is a cylindrical dialectic rod-like mirror. Light is propagated through the fiber optic core. Although the core and the coating are both made of dielectric material, the refractive index of the core is higher than the coating. The coating performs functions such as minimizing light leakage from the core to the environment, reducing reflections at the core level, providing protection and mechanical resistance by preventing the fiber from collecting dust and dirt. The buffer coating is a layer of the elastic material of the plastic used to protect the fiber optics from physical damage and abrasion [11].

Fiber optics fall into two categories:

(i) Single mode optical fibers.

(ii) Multimode optical fibers.

In addition, fiber optics are characterized by the refractive index profiles as follows: [12]

a) Step index optical fibers.

b) Gradient index optical fibers.

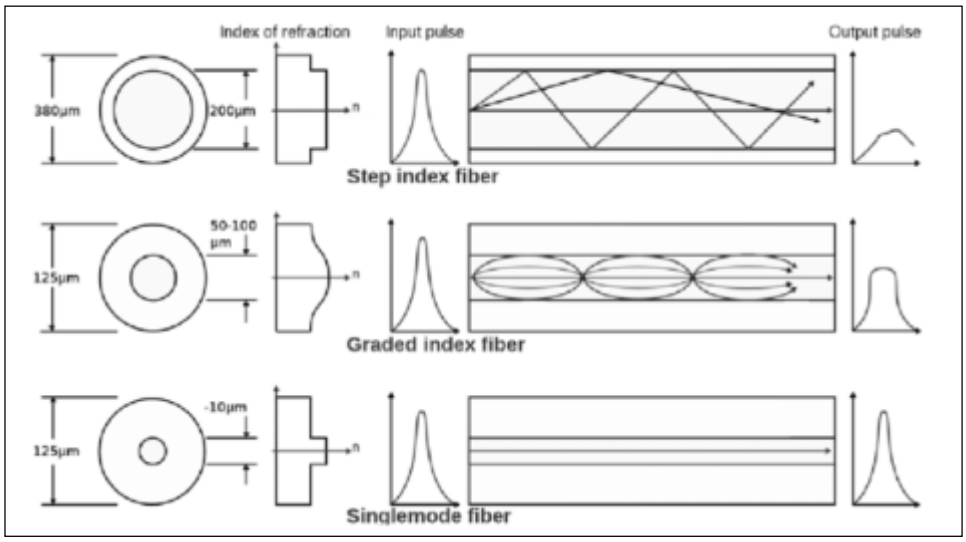


Figure 2.2. Fiber Optic Classification [11]

Step index optical fiber has an index profile constant over the entire cross-section. Gradient-index fibers have a nonlinear but rotationally symmetrical refractive index profile that gradually decreases from the center of the fiber optic outwards. Figure 2.2 shows the various types of optical fibers [11].

2.1.1. Fiber Optic Sensor Principles

The fiber optic sensor unit consists of a light source (LED, Laser, Laser Diode, etc.), fiber optic cable, optical detector and an electronic processing unit. The operational theory of the FOS is shown in Figure 2.3.

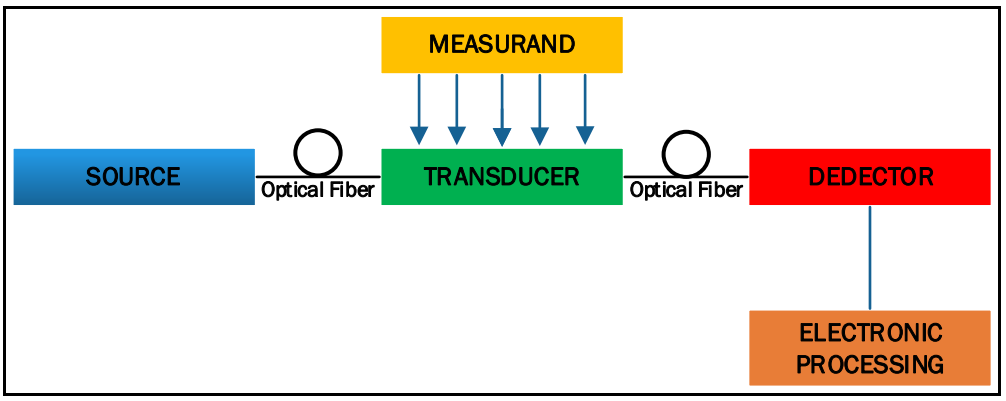


Figure 2.3. Fiber Optic Sensor Basic Components [13]

The light transmitted from the light source, changes in the properties (wavelength, intensity, phase, polarization, etc.) of the reflected or transmitted light through the fiber optic cable due to the physical effects it is exposed to. The desired parameters are obtained by transforming the changes in the light wave into physical quantities by means of an interrogator [11].

2.2. Optical-fiber Sensor Advantages

Optical fiber sensors are ideal detection agents for monitoring changes in the environment and offer many advantages over traditional electronic sensors as seen below:

- Ability to measure rotation, acceleration, electric and magnetic field, temperature, pressure, acoustic, vibration, linear and angular position, strain, humidity, viscosity and chemical measurements
- High immunity to electromagnetic and RF interference
- Easy incorporation into a range of structures, including composite materials due to their compact scale and cylindrical shape with very little intervention
- Inability to transmit electric current
- Remote sensing capability
- Lightness
- Rugged, high resistance to harsh environments.
- Ability to multiplex to form perception networks.
- Low maintenance and repair costs.
- High sensitivity [14,15,16,17].

2.3. Fiber Optic Sensor Applications

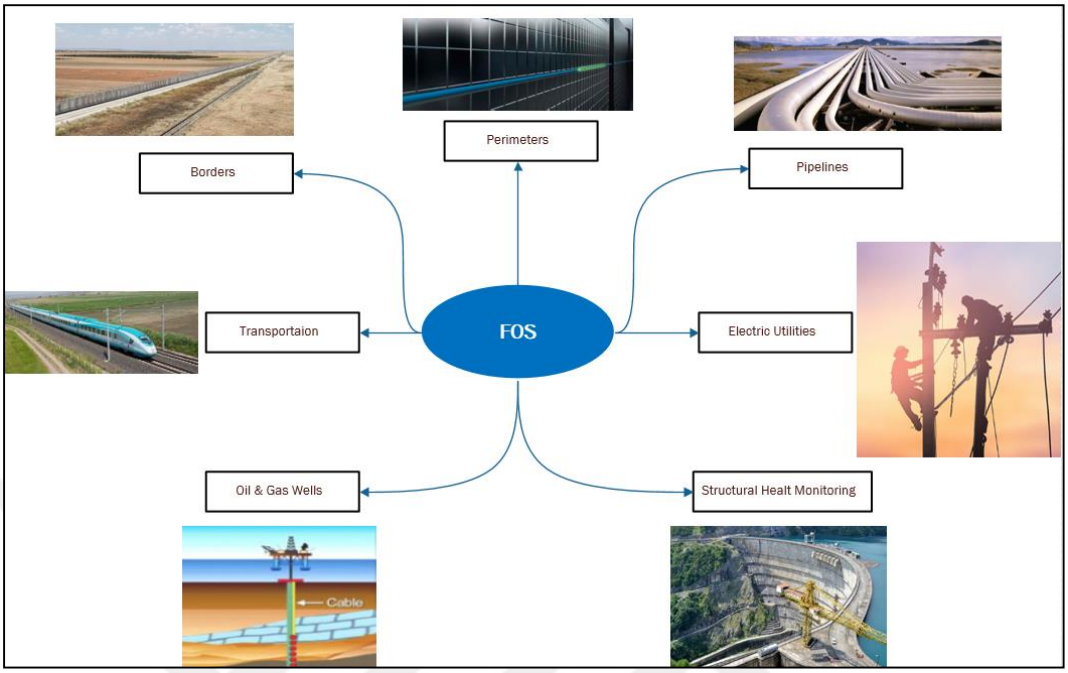


Figure 2.4. Fiber Optic Sensor Applications

Fiber sensor application areas are shown in Figure 2.4.

2.3.1. Perimeter Security

The fiber sensor, used as a concealed electronic barrier for defensive unwanted access, burglary, property damage in sensitive places such as military bases, nuclear power stations, ports, airports and power stations, has been used regularly for perimeter defense in the recent past. Traditionally, they try to provide security by patrolling security forces. This is a method that has limitations in terms of scope, continuity and reliability. Thanks to the facilities provided by the fiber sensor, detection and diagnosis of unauthorized attempts can be achieved more easily [1].

2.3.2. Pipeline Security

Pipelines are among the basic needs of modern life, such as water, gas, oil, etc. It is vital for the transportation of basic needs such as. Pipeline failures and malfunctions can have negative effects on social and economic life, and leaks can cause serious disasters.

Pipelines today are a very safe and efficient means of transmission. There are problems due to situations such as leakage, sabotage, theft, being affected by natural disasters. Accordingly, about 50% of all oil spills are caused by building / material failure, corrosion and soils, while about 50% are caused by the third-party activities, according to the most recent European gas and petroleum industry reports.

As a result, most leaks, malfunctions and errors can be prevented if the activities of third parties are detected before the possible disruptions occur in a reasonable time. Despite frequent activities such as monitoring pipelines by off-road vehicles, walking or flying over them, it is impossible to cover the entire pipeline with real-time monitoring equipment. This is because installing, operating, managing, maintaining and repairing thousands of sensors made up of traditional technologies such as vibration, motion sensors and video cameras that can be installed along the pipeline, including power supply and communication facilities, will incur astronomical costs. These and many other problems can be overcome by utilizing distributed fiber optic sensor networks that are sensitive to temperature, strain, vibration and sound with excellent positional accuracy and high resolution of over 30 kilometers. Considering that fiber optic cables that are insensitive to EMC can operate independently of the power source in harsh environments and are designed for communication facilities, it offers ideal solutions for pipeline monitoring applications. Considering these advantages, distributed fiber optic detection is already widely used and is recognized as a field proven technology in many applications. However, scientific advances in fiber detection continue at full speed. Thanks to the calculation efficiency and modern signal analysis algorithms developed for FOS, the use of new products with advanced detection technologies in new applications with higher sensitivity and detection speed is increasing day by day [18].

2.3.3. Electric Utilities

The power cable insulation is normally preserved in 90^{o}C. This temperature may rise above normal under high load conditions, especially in power cable ducts where the cables are packed and attached to cable trays. In order to keep the temperature level within suitable ranges, distributed fiber optic temperature sensors capable of precise measurement are installed inside the cable insulation [19].

2.3.4. Structural Health Monitoring (SHM)

In recent years, many infrastructure works such as railways, highways and high-speed trains are progressing at an incredible speed. Unpredictable weather conditions, natural disasters and human impact cause various degrees of damage to structures, affecting the safety of infrastructures and pedestrians and limiting or completely stopping access to these services. For this reason, infrastructure health inspection should be carried out continuously. Piezoelectric, piezo-acoustic, seismic etc. Impacts on the building can be detected but building health cannot be monitored in real time. Fiber optic acoustic sensor, which is used as a modern non-destructive detection method, has many advantages such as high sensitivity, strong anti-interference ability, continuous real-time monitoring. By attaching or embedding fiber optic sensors to metal or concrete surfaces, information about stress, strain and crack formation and propagation can be obtained in real time and continuously.

In addition, a single line of fiber optic acoustic sensors can be integrated into a large-scale monitoring and detection system, which significantly improves detection efficiency, saves detection costs, time and human resources, and allows remote monitoring of the wireless transmission network. Thus, a tremendous convenience can be achieved in monitoring the system regardless of the location for real-time detection [20].

2.3.5. Oil & Gas Monitoring

Real-time and reliable monitoring technologies should be used in order to use oil and gas wells effectively and to carry out exploration and monitoring activities at high efficiency. Due to its high tolerance to harsh conditions, fiber optic sensors have been used frequently in oil and gas studies in recent years. Fiber optic sensor-based tracking technology can generate a complete data set from the top of the well down, unlike conventional technology. The time expended on data set development is considerably decreased and system performance improves. In addition, non-contact measurements faithfully reflect the current conditions without changing the original temperature and pressure field in the well. Fiber sensor technology can detect hundreds of signals per kilometer due to its high spatial resolution, which is much higher than traditional sensor detection efficiency. FOS provides significant benefits in oil exploration, oil spill control, hydraulic fracture (HF)

monitoring, vertical seismic profile (VSP) assessment, micro seismic collection, smart well control and gas lift tracking [21].

2.3.6. Railway – Transportation

Strategically important areas such as railways, airports, oil natural gas pipelines, government buildings can be exposed to vandalism, theft, and terrorist incidents. The health and safety of railway equipment, personnel and passengers are getting more and more important with each passing day. Many of the modern approaches used to protect them are not feasible due to environmental conditions on railway lines. Terminals and barriers to be placed around the station will prevent the passage of personnel and passengers.

Industrial type acoustic, seismic, passive infrared, magnetic, electrostatic based commercial products are used for attack detection and diagnosis. However, restrictions caused by electromagnetic interference cause false alarms in the sensors. To reduce the false alarm rate, combinations of these products with several sensors are used.

For railway safety, in addition to these combinations, fiber optic sensors have become widespread due to their resistance to electromagnetic interference, high flexibility, compact structure and reliable results [22].

2.4. Fiber Optic Sensor Classifications

Fiber optic sensors are divided into three categories: the location of the sensing, the operating principle and the application as seen in Table 2.1 [23].

Table 2.1. Sensor Classification Under Three Categories

Category	Types
Applications	Physical Sensors
	Chemical Sensors
	Bio-medical Sensors
Operating Principle	Intensity Sensors
	Phase Sensors
	Frequency Sensors
	Polarization Sensors
Sensing Location	Point Sensors
	Quasi Distributed Sensors
	Distributed Sensors

A fiber optic sensor can be categorized as follows depending on the application:

• Physical sensors: temperature, stress etc. used to measure appropriate physical parameters such as

• Chemical sensors: pH, water, spectroscopic etc. used to measure parameters

• Bio-medical sensors: those used in medical applications such as blood flow measurement, glucose content [23].

When the light transmitted from the fiber sensor changes in the environment, at least one of these four parameters:

- intensity,
- phase,
- wavelenght,
- polarization,

changes. The desired parameters are obtained by transforming the changes in the light wave into physical quantities by means of an interrogator [13].

Based on the sensing location, a fiber optic sensor can be categorized as external or internal. The intrinsic fiber optic sensor has a sensing area in the fiber, so the light never leaves the fiber. Perturbations act on the fiber and actually change one or more of the above-mentioned light properties in the fiber. Light has to exit the fiber in extrinsic sensors to reach the location of the sensor [23].

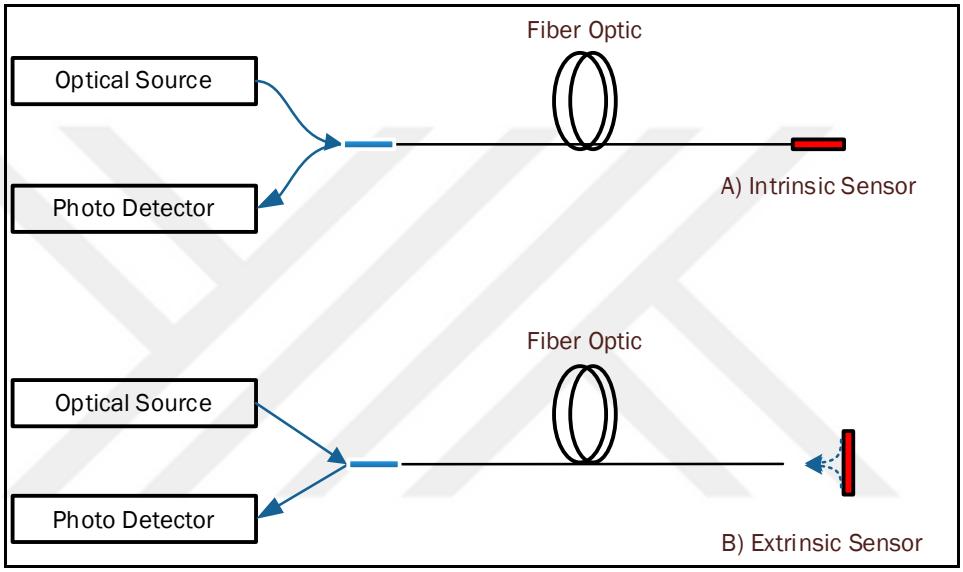


Figure 2.5. FOS Classification based on sensing location

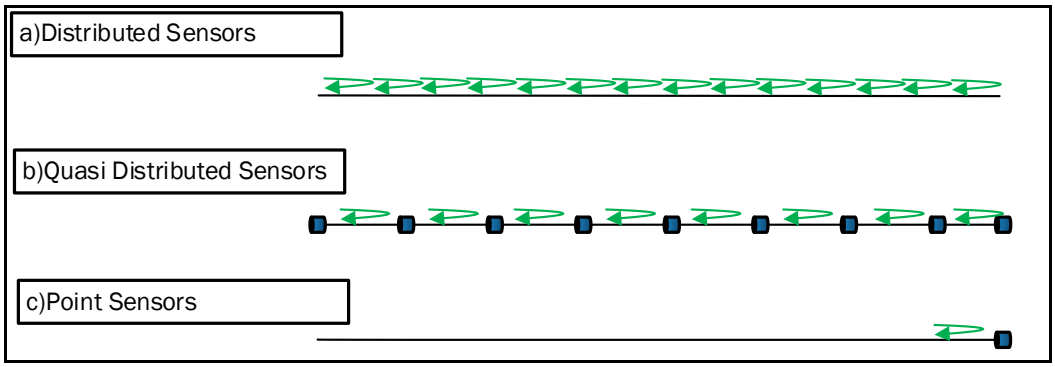


Figure 2.6. Fiber Optic Sensing Configurations (a) Distributed Sensors, (b) Quasi-distributed Sensor, and (c) Single point

The point sensor in Figure 2.6 allows measures like stress and temperature taken from a certain point to be analyzed and controlled. Quasi-distributed sensor realizes the positioning of a limited number of sensors as a linear array and monitoring the desired parameters. The distributed detection enables the measurement parameters of interest to be continuously monitored along the optical fiber and to match these parameters in a spatial way. Traditional sensing methods require sensors such as thermocouples and strain gages at each selected point for temperature and strain measurements. This situation causes complex processes, excessive effort and high cost. However, the distributed fiber optic detection method can provide real-time monitoring of the entire optical fiber line with the appropriate design architecture.

CHAPTER 3

DISTRIBUTED FIBER OPTIC ACOUSTIC SENSORS (DFOS)

Distributed fiber optic sensors (DFOS) have significant potential in infrastructure health monitoring, perimeter security protection, drilling and seismic applications, and intrusion detection applications using the fiber optic cable itself as both a transmission and a sensing medium. It can continuously provide spatial and temporal information simultaneously.

Compared point and quasi-distributed fiber sensors, which can only be used on a small scale and have low privacy, distributed fiber optic vibration sensors provide the following significant advantages:

Large-scale monitoring,

• good hiding,

• instant and continuous monitoring,

• system simplicity.

Distributed fiber optic sensor technology has gained considerable attention and development in recent years. Distributed fiber optic sensor technology is examined in two categories as backscatter and fiber interferometer based optical sensors [2]. Interferometer-based Sagnac, Michelson (MI), Mach-Zender (MZI) methods have gained extensive coverage in the field of sensing technologies due to their low cost and high sensitivity [5]. Intensive studies are also being conducted on systems based on backscatter based optical time-domain reflectometer (OTDR). Optical frequency reflectometer (OFDR) and phase-sensitive OTDR (F-OTDR), polarization-OTDR (POTDR) methods, and OTDR-based systems are preferred according to the application areas. Brillouin

optical time history analysis (BOTDA) or Brillouin optical correlation domain analysis (BOCDA) are among other methods commonly used.

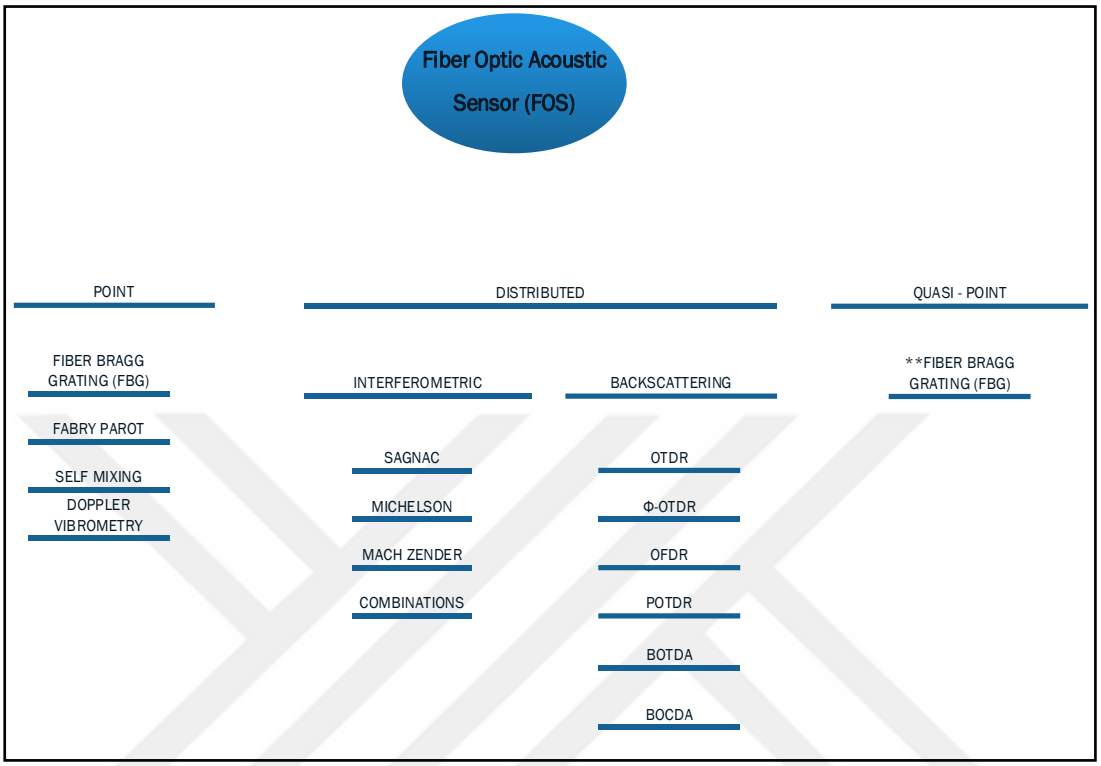


Figure 3.1. Fiber Optic Acoustic Sensor Classification

3.1. Backscattering Sensing Technology

When a light wave spreads through a medium, it interacts with its atoms and molecules. The electric field causes a time dependent polarization dipole because the wavelength is far from mid-resonance. The induced dipole produces a secondary electromagnetic wave and this is called light scattering. If the distances between scattering centers (particles) in fiber optics are smaller than the wavelength of the light, the secondary light waves are compatible for Rayleigh scattering. Hence the resulting density is the addition of scattered areas.

When the medium is completely homogeneous, the ratio of transmitted waves to phase creates the forward-scattered beam. Fiber optic is an inhomogeneous medium, so scattering is caused by microscopic or macroscopic differences in the shape, composition or form of a substance through which light passes. The random ordering of molecules and

the presence of additives cause local density differences (and hence the refractive index). It causes Rayleigh scattering proportional to $1/(\lambda^4)$ attenuation of the forward propagating signal (and the creation of a backward propagating wave);

We can conclude that the scattering is spontaneous as long as the input light is scattered without substantially changing the properties of the medium, this includes Rayleigh, Brillouin and Raman scattering. This regime is excited when the light intensity is so high that the optical property of the medium changes and the transmitted light is proportional to the power of the input light. In other words, progression from spontaneous state to induced scattering leads to a conversion from linear to a non-linear environment behavior regime.

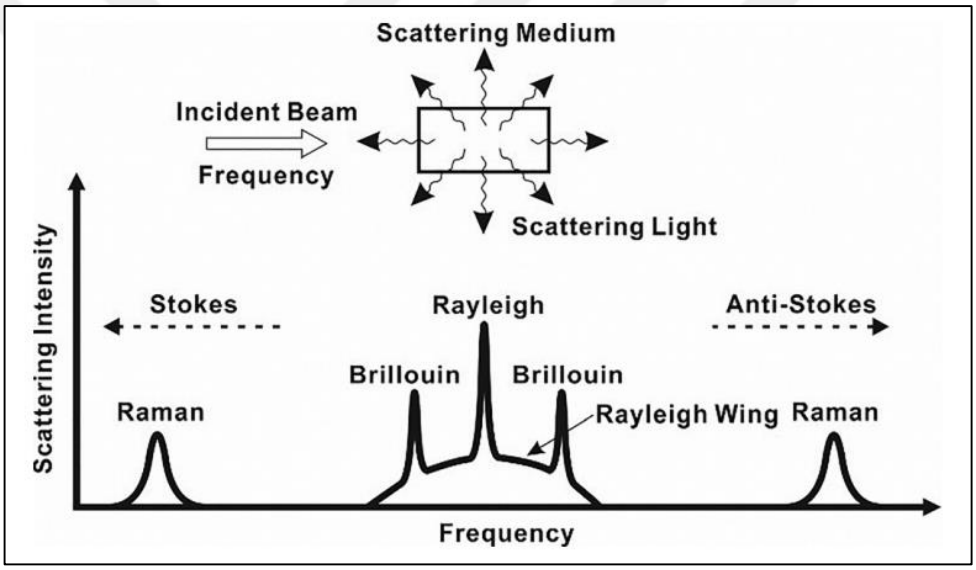


Figure 3.2. A typical spontaneous light scattering spectrum

3.2. Interferometric Sensing Technology

The refractive index and core diameter of the phase modulated fiber optic sensor will change under the influence of external acoustic waves, changing the propagation direction of the optical signal in the cable. Eventually, the phase difference will occur. However, the phase shift of the light wave cannot be directly observed by current detector technologies due to its high light frequency. However, this can be easily detected in terms of the change in light intensity. For this reason, phase change in experiments is generally

converted to light intensity change and then obtained by acoustic signal demodulation technology [25].

The amplitudes of the two beams are expected to be E1 and E2, respectively. If external acoustic disturbances change the phase of one light, it is separated from external interference so that the other light is not affected. Then the interference light level can be expressed as [25].

When Phi0 is the difference in initial phase between two coherent beams, Delta phi is the phase difference caused by phase modulation which is directly related to the intensity of the interference light. The phase shift between two light beams can be calculated by measuring the amplitude of the interfering signal and the predicted physical parameters can be demodulated. Interferometric sensing technology has attracted great interest and research due to its wide application possibilities in pressure, vibration, magnetic field and acoustic sensing [25].

Phase modulated acoustic fiber optic sensors are basically based on three interference concepts: Mach-Zehnder Interference (MZI), Michelson Interference (MI) and Sagnac Interference (SI) [25].

Table 3.1. Performance summary of based on backscattering distributed FOS [1].

Φ-OTDR	Texas A&M University, USA	12	1000	N	Y	2005
		12	200	N	Y	2005
		19	200	N	Y	2007
	University of Ottawa, Canada	43862	5	1 k	Y	2010
		0.2	1	~2.25 k	Y	2011
		1	0.5	8 k	Y	2012
	Chongqing University, China	1	~3	N	Y	2013
	Faculdade de Ciencias da Universidade do Porto, Portugal	45658	5	39.5 k	Y	2013
		125	10	250	Y	2014
		125	10	380	Y	2015
	University of Electronic Science and Technology of China, China	131.5	8	375	Y	2014
		175	25	Y	Y	2014
		44014	44015	~18 k	Y	2015
	University of Ottawa, Canada; Shandong University, China	0.68	1	0.6 M	Y	2014
	University of Shanghai for Science and Technology, China	44	5	N	Y	2014
	Nanjing University, China	24.61	10	Y	Y	2015
		9	2	1 K	Y	2015
POTDR	University of Ottawa, Canada	1	10	5 k	Y	2008
	University of Mons, Belgium	~0.47	5	N	N	2012
	Nanjing University, China	4	10	610	N	2013
		7	10	Y	Y	2013
		10	10	Y	N	2015
BOTDA	Lehigh University, USA; Beihang University, China	0.168	0.625	Y	Y	2011
	Tel-Aviv University, Israel	0.085	43952	Y	Y	2011
		0.1	43891	Y	Y	2012
	Harbin Institute of Technology, China	0.05	0.2	50	Y	2013
BOCDA	The University of Tokyo, Japan	0.02	0.1	200	Y	2007
	Chung-Ang University, Korea; The University of Tokyo, Japan	0.1	0.8	43891	Y	2011
OFDR	Chongqing University, China	0.017	0.1	32	Y	2012
	Tianjin University, China	12	5	2 k	Y	2012
		40	44018	Y	Y	2016
	Tel-Aviv University, Israel	10	40	Y	Y	2014
	Shanghai Jiao Tong University, China	40	43954	600	Y	2015
Φ-OTDR + MZI	Chongqing University, China; University of Ottawa, Canada	1064	5	3 M	N	2013
		1150	5	6.3 M	N	2013
	University of Southampton, Southampton, UK	1	2	500–5 k	Y	2013
	Tian Jin University, China	43953	20	50 M	N	2015
Φ-OTDR + MI	Chinese Academy of Sciences, Beijing, China	10	6	Y	N	2015

3.2.1. SAGNAC

Because of the benefits of special sensitivity, wide tracking range and passive detection, the fiber optic distributed sensor based on the Sagnac interferometer has been widely used in recent years for detection and diagnosis. Sagnac method is used alone, as well as combinations of Sagnac & Mach-Zehnder [4], Sagnac & Michelson [5,6], Sagnac & Sagnac [7]. However, the Sagnac interferometer's construction has some limitations that hinder its use, especially in areas such as long-distance pipeline monitoring [26].

However, it is inevitable to encounter many problems in fiber optic detection systems, especially in projects used in real life. Since the control range usually covers 10km or more, if two or more interruptions occur on the fiber sensor at the same time, no signal interference can be measured by the Sagnac interferometer. This undermines the advantage of Sagnac interferometers against OTDR (Optical Time Domain) reflector in matters such as high noise amount, poor detection signals, high cost and complex technical requirements.

Recent studies are thought to solve this problem with dual FFT location algorithm. Instead of searching for separate null frequencies, the FFT algorithm twice focuses the entire spectrum. It aims to obtain the periodicity of empty frequencies, thus achieving more accurate and stable performance at the location. The two disturbances appear as two distinct peaks in the position curve at different distances, making Sagnac interferometers applicable to multiple disturbances [27].

Although optimization studies have been carried out on Sagnac, problems in certain issues have not been overcome;

(1) the position curve signal-to-noise ratio (SNR) is rather poor. Random peaks may be higher than disturbance peaks.

(2) Complex algorithms are not applicable for applications to be used in practical life.

(3) As the number of disturbances increases, it is difficult to accurately define each disturbance [27].

As seen in Figure 8, in its simplest form, the laser emission is split into two beams by a 50:50 coupler. Light waves complete the fiber cycle by moving in two different directions, clockwise (CW) and counterclockwise (CCW) with equal power. Then, they meet in the coupler, recombining the beams and converted electrically through a photodetector (PD). If an outside force is applied sensing loop at a distance x from the left end of the cable, the beam moving in the CW light direction will modulate earlier than the CCW light due to vibration. Therefore, as beams traveling in the opposite direction complete the cycle, a phase difference occurs that causes a change in interference intensity.

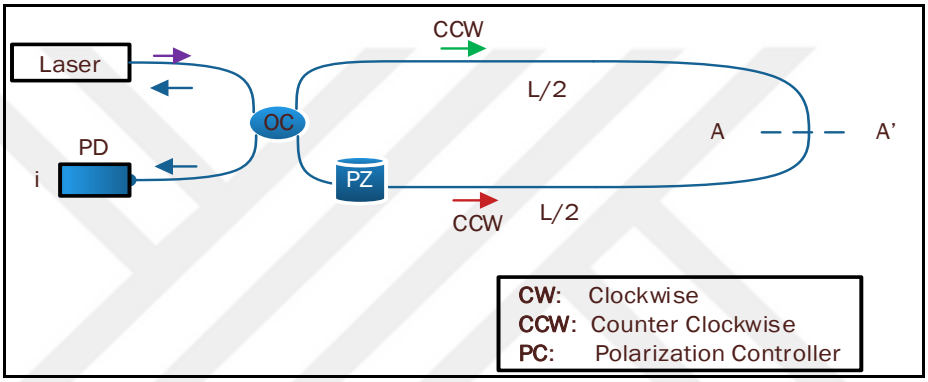


Figure 3.3. Sagnac Interferometer Topology

The direction of the vibrations can be calculated as seen in the equation (1):

$$\Delta\emptyset = \boldsymbol{\beta}(\Delta \boldsymbol{l}) + \boldsymbol{l}(\Delta\boldsymbol{\beta}) = \boldsymbol{\beta}(\Delta \boldsymbol{l}) + \boldsymbol{l}(\boldsymbol{\partial\beta}/\boldsymbol{\partial n})(\Delta \boldsymbol{n}) + \boldsymbol{l}(\boldsymbol{\partial\beta}/\boldsymbol{\partial d})(\Delta \boldsymbol{d}) \quad \textbf{(3.1)}$$

In the formula (1), D indicates the diameter of the core of the sensing fiber. N core refractive index, k0 is the number of light waves in space, ubiquitous and ubiquitous 0 is the wavelength of light in space. The first element in formula (1) is the phase difference caused by a change in the length of the fiber sensor line; the second element is the phase difference caused by the change in the refractive index of the fiber sensor (Elastic light effect); and the third element is the phase difference (Poisson effect) caused by the change in the diameter of the fiber sensor's core [25].

$$\Delta\emptyset = \boldsymbol{\beta}(\Delta \boldsymbol{l}) + \boldsymbol{l}(\boldsymbol{\partial\beta}/\boldsymbol{\partial n})(\Delta \boldsymbol{n}) = \Delta\emptyset\mathbf{1}|\,\Delta\emptyset\mathbf{2} \quad \textbf{(3.2)}$$

In the coupler, beams moving clockwise and counterclockwise are interfered with, and the interference signal carries the phase difference caused by the acoustic effect. The relationship between light intensity and external acoustic signal effect can be expressed as [25]:

$$I - Io\left(1 - cos(\Delta\emptyset)\right) - 4Io(cos^2(\Delta\emptyset/2)) \quad \textbf{(3.3)}$$

3.2.2. MZI

The Mach-Zehnder interferometer is considered a low cost and practical FDDS approach because of its simple configuration and simple positional arithmetic. For FDDS, location accuracy is the most critical feature for practical applications. The location method with easy arithmetic and increased positional accuracy has also attracted much attention [28].

The standard MZI configuration consists of two separate optical paths known as the reference and sensing arms. Figure 2.1 shows the simple schematic structure of the MZI, where a beam splitter divides the incident beam into two parts. It is assumed that they split into two laser beams of equal power. After these two beams pass the reference and sensing arms, a second coupler reassembles them [29].

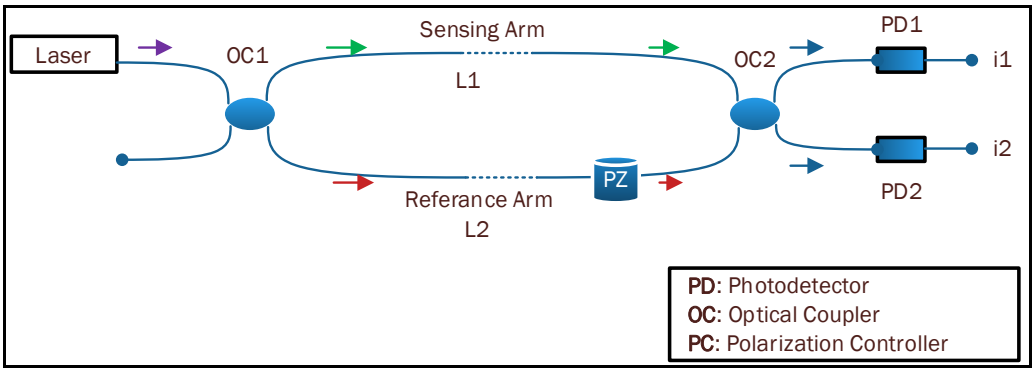


Figure 3.4. Mach Zender Interferometer Topology

The reference arm is wholly isolated from environmental influences, and the sensor line is the optical direction subject to external disturbances such as acoustic impact. The overlap of recombined beams creates a phase change due to the difference in optical path length between the two emitted beams. Photodetectors detect the interference signal between two beams produced after emitting the output fiber volume. When evaluating

the difference in the output signal, the phase change can be associated with the acoustic effect.

Disadvantages,

(1) The need for long fiber lines to increase sensitivity in MZI based FOS makes the sensor volumetrically large devices. Other problems with MZI sensors,

(2) Affected by changes in temperature and pressure

(3) Polarization varies randomly (For this reason, electronic polarization controls that increase the cost and complexity have to be used) [29].

3.2.3. Michelson Interferometer

The Michelson fiber optic interferometer based optical sensing path diagram is shown in Figure 7.

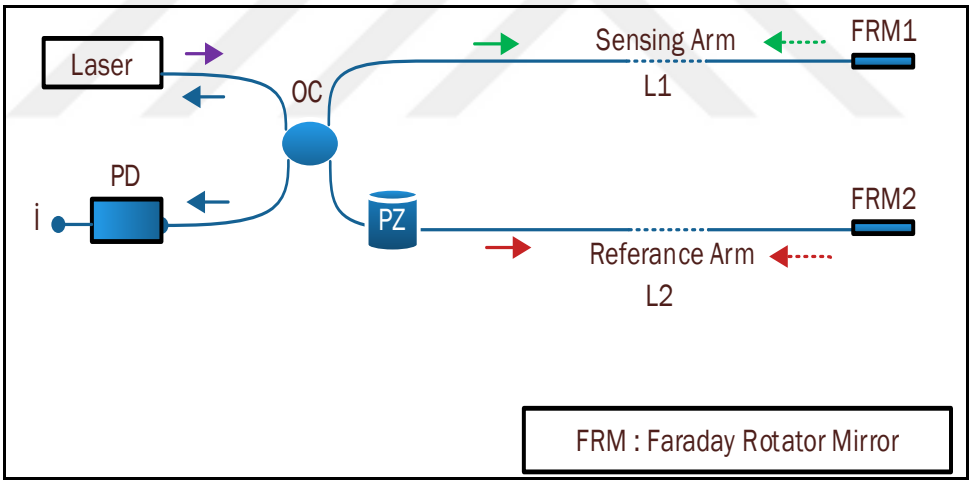


Figure 3.5. Michelson Interferometer Topology

A significant part of the fiber optic interferometer is the reflective end of the reference and sensing fibers. The light signal emitted by the light source is divided into two channels after passing through the coupler, one through the reference fiber arm, the other through the signal arm, which is disturbed by external sound. The two light beams have reflected the coupler when reaching the mirror and interfere with each other. The light of interference carries information regarding sound. It assumes the change of light intensity

after being detected by photoelectric detectors and eventually converts it to an electrical signal. Then, the sound signal can be demodulated by signal processing. The light intensity which the photodetector receives can be expressed as [25].

Where delta phi is the difference in phase caused by the acoustic interference between the signal light and the reference light, the Michelson interferometer structure uses fewer fiber couplers. It reduces the optical loss compared to the Mach-Zehnder interferometer. But its main drawback is that the interference signal reflected the photodetector would also be reflected in the source of the laser, which will harm the laser's normal operation and form the noise. Therefore, to eliminate this kind of noise, the application of an optical isolator needs to be increased [25].

Table 3.2. Performance summary of Based on Interferometric distributed fiber optic sensors [1].

Methods	Group	Distance (km)	SR/ Position Accuracy (m)	Frequency? Yes/No (Hz)	Multi-point? Yes/No	Year
Sagnac	University of Kansas, USA.	0.18	1	Y	N	1996
	Rand Afrikaans University, South Africa	0.2	-	Y	N	1998
	Virginia Polytechnic Institute and State University, USA	0.8	-	Y	N	1996
	University of Southampton, England	40	100	Y	Y	2001
	Huazhong University of Science and Technology, China;	41	100	Y	Y	2014
	Fudan University, China	25	59	Y	Y	2008
		150	-	Y	Y	2015
MZI	Huazhong University of Science and Technology, China	43831	38	Y	Y	2008
	Beihang University, China	20	206	Y	N	2009
	Tianjin University, China	50	±50	Y	N	2008
		45689	±20	Y	N	2015
	Southeast University, China	10	-	Y	N	2013
	Beijing Jiaotong University, China	2	75	Y	N	2015
	Jinan University, China	320	31	9 M	Y	2014
MI	Beijing University of Posts and Telecommunications, China	4012	±51	Y	N	2011
Sagnac + MZI	Rand Afrikaans University, South Africa	0.2	5	Y	N	1998
Sagnac + MI	University of Pretoria, South Africa	0.2	±4	Y	N	1997
	Military University of Technology, Poland	6	40	Y	N	2007

CHAPTER 4

EXPERIMENTAL SETUP

4.1. Fiber Optic Sensor Breakdown

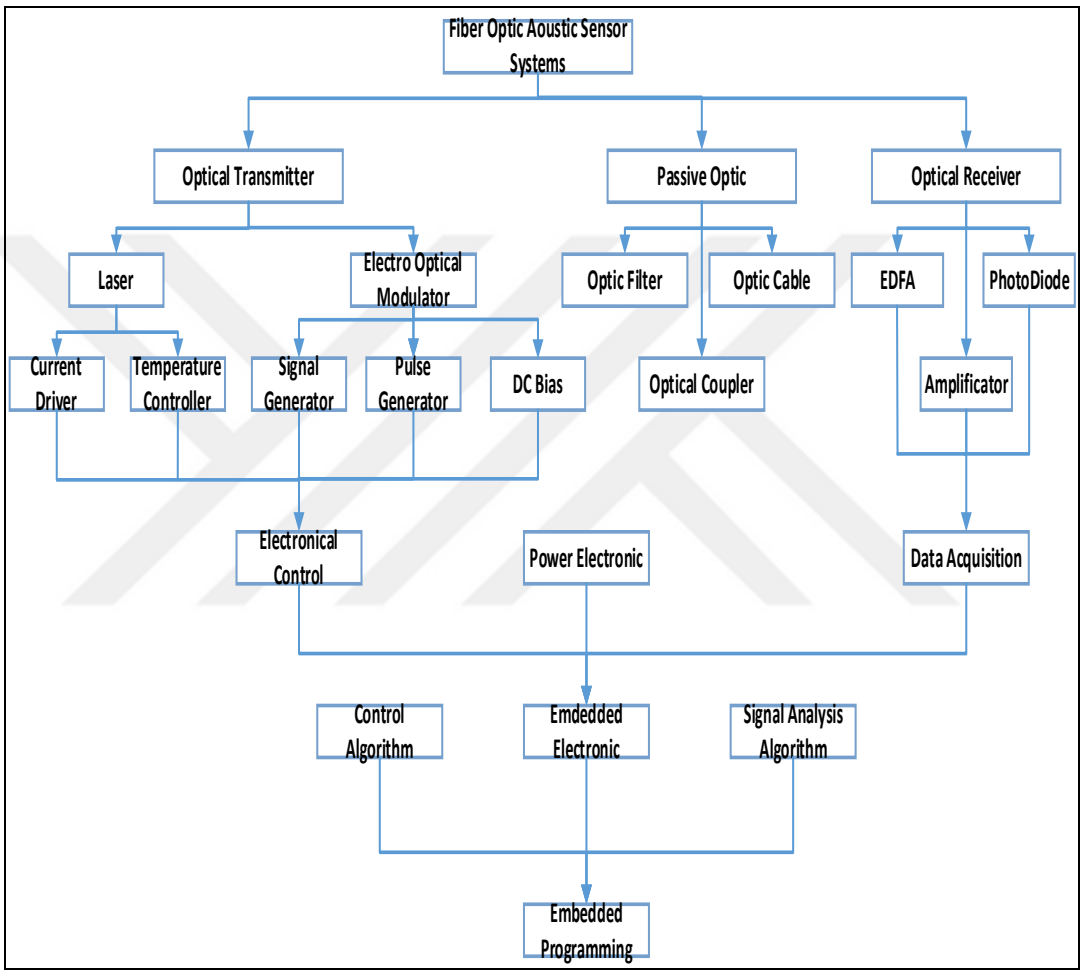


Figure 4.1. FOS Breakdown

4.1.1. Optical Transmitter

4.1.1.1. Laser

Fiber optic sensors create a demand for lighting sources due to their vast application areas. A wide variety of optical sources can be used to energize the sensor devices. The most suitable type of illumination from simple optical sensor types is relatively easy due to limited constraints on the source's nature. In contrast, OTDR based distributed fiber optic sensors require a light beam with high spectral brightness available from short-pulse high-power lasers. Constraints such as the sensor's operating mode, signal processing algorithms, spatial constraints, and accuracy will have a dominant effect on selecting the source type.

There are many sources available for fiber sensors, from pure incandescent sources starting at a few dollars to high-power, wavelength adjustable lasers costing tens of thousands of dollars. Therefore, the price of a particular detection device will vary depending on the price of the selected source.

Other factors in source selection include physical dimensions, electrical input, and light power output, degree of optical output stability (both in terms of power and spatial quality), lifetime, ease of connection to optical fibers, spectral bandwidth, amount of noise, degree of consistency and monochromaticity. Spectral properties are included.

The requirements for resources vary, but they are all expected to have two main functions:

1- They must provide sufficient radiant energy at a specific wavelength or wavelength region of interest and maintain a constant or regular light intensity over the appropriate time interval.

2- It is expected that there will be a working balance between polarization and collimation degrees, which may be important in the operation of the sensor, the density of the source, the degree of monochromaticity, the spectral bandwidth and other relevant factors. These factors differ significantly from sensor to sensor.

The attenuation curve depending on the wavelength of the signal sent from the source, is shown in Figure 13. As shown in the figure, single-mode fiber used in fiber optic sensor

systems has three transmission windows. As can be seen from this attenuation curve, depending on the fiber optic signal's wavelength, the lowest fiber attenuation occurs at the 1550 nm wavelength (f 3 193 THz) located in the third transmission window. For this reason, when the laser to be used as a light source is selected in this band, it will be possible to detect with lower attenuation [30,31].

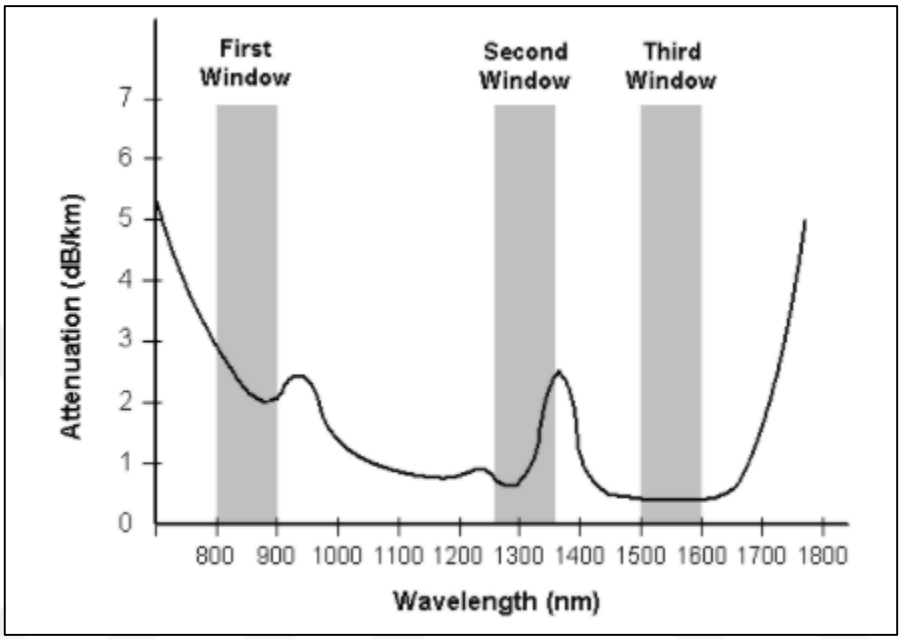


Figure 4.2. The Attenuation-Wavelength Curve and the Transmission Windows of an Optical Fiber

4.1.1.2. TEC

The sources used for FOS generate a considerable amount of heat, and therefore compact systems should be preferred. When the amount of temperature exceeds tolerance values, instability occurs in the operation of the light source. Thermoelectric temperature controllers are used to keeping light sources at operating temperatures. The light source used in FOS is integrated into a laser diode package or a temperature-controlled heatsink plate. The precise temperature controller used for light sources helps to protect the output power and wavelength and prevent extreme temperature conditions that could damage the laser diodes or cause premature aging [32].

4.1.1.3. Laser Diode Driver

Laser diodes are current driven and current sensitive semiconductors. A change in drive current causes changes in the wavelength and output power of the sources. Any instability (noise, transients) in the driver current will affect the laser diode's performance characteristics. In particular, they will change the output power and wavelength. Also, the temperature of the diode junction is directly affected by the current. The current instability of the source will cause junction temperature fluctuations; output characteristics (again power and wavelength) will change [33].

4.1.2. Passive Optic

Single mode fiber (SMF) has small core sizes that can only be propagated in one mode or a ray through the fiber. Mode determines how the light flows in space. Through this single-mode, light spreads along the fiber axis (see drawing to the right). Wave modes have different frequencies in SM cable. Such fiber is useful in situations where long distances are needed to maintain the pulsed incident light's integrity. SM fiber provides low dispersion and high bandwidth [34].

4.1.3. Optical Receiver

The fiber optic sensor works by inferring some parameter properties of the optical signal. Although the transduction (converter) mechanism is optical, the optical signal must be converted into an electrical signal for the data to be processed, recorded, and displayed. This process is performed using a photodetector that converts optical energy into electrical energy. Photodetectors usually detect the optical signal and produce a weak electrical signal, and amplification must be done after the signal is converted to an electrical level. This structure consisting of a photodetector and an amplifier is called a receiver. The structure of the receiver part in the fiber optic sensor system is shown in Figure 4.3.

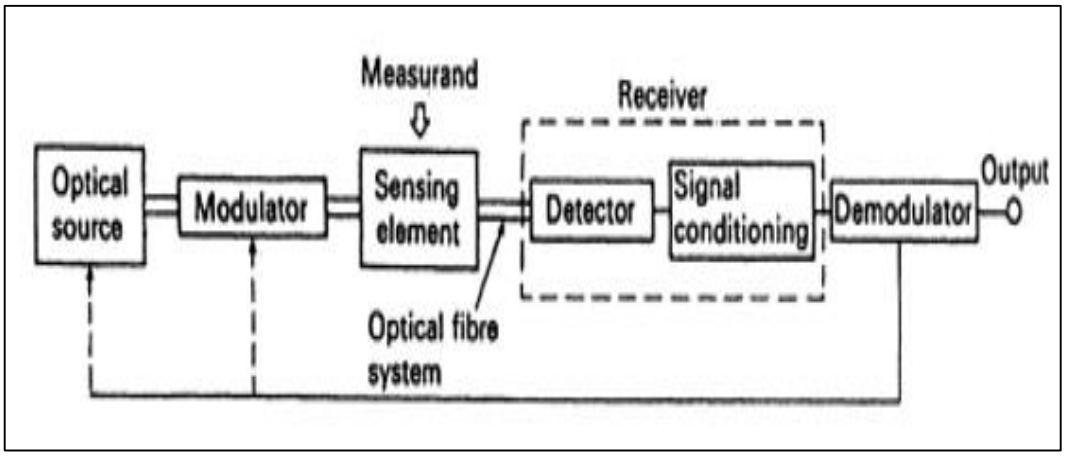


Figure 4.3. The Idealized FOS, Role of the Detector and Receiver

Like fiber optic sensors, photodetectors also vary in itself. The optic detector allows us to detect optical energy (radiance) and measure the phase, wavelength, or polarization of light emitted by fiber sensors. Other passive optical components are described under the header passive optics to provide discrimination before the detector.

Thanks to a linear transfer function in the sensing system, optical energy is transformed into electrical energy. The fiber optic sensor must respond at the wavelength to be detected. The photodetector must have sufficient bandwidth to accommodate the available modulation frequencies. Besides, sufficient precision is required for the range of power levels likely to be encountered. However, it must be ensured that any detector chosen provides an adequate signal-to-noise ratio when the signal is converted to the final electrical signal.

In intrinsic fiber sensors, optical power losses are small as the optical signal travels through the fiber, and output power levels are typically in the range of mW, as low-cost diode lasers are used. In multiplexed arrays, the optical output power is shared between several sensing elements, and the power levels in the detector can drop to the range of nW to uW. In systems based on light scattering such as extrinsic sensors, the perceived output power is deficient, and detection at photon level may be required.

Modulation bandwidths have a wide dynamic range. For single sensors used to detect slowly changing measurement variables, the detector bandwidth of several Hz may be sufficient. A bandwidth of several tens of Hz to MHz is required for rapidly changing

measurement variables such as ultrasound. These are modest requirements considering the available bandwidths used in optical communication networks. For special-purpose sensors such as optical radar (Lidar) and optical time-domain reflectometry (OTDR), the bandwidth requirement extends to the GHz region. The noise component of any signal will depend on several parameters, including the detector's bandwidth, the size of the generated signal, and other circuit parameters. This often becomes a problem when there are a high bandwidth requirement and light level.

4.2. Sagnac-Michelson Topology

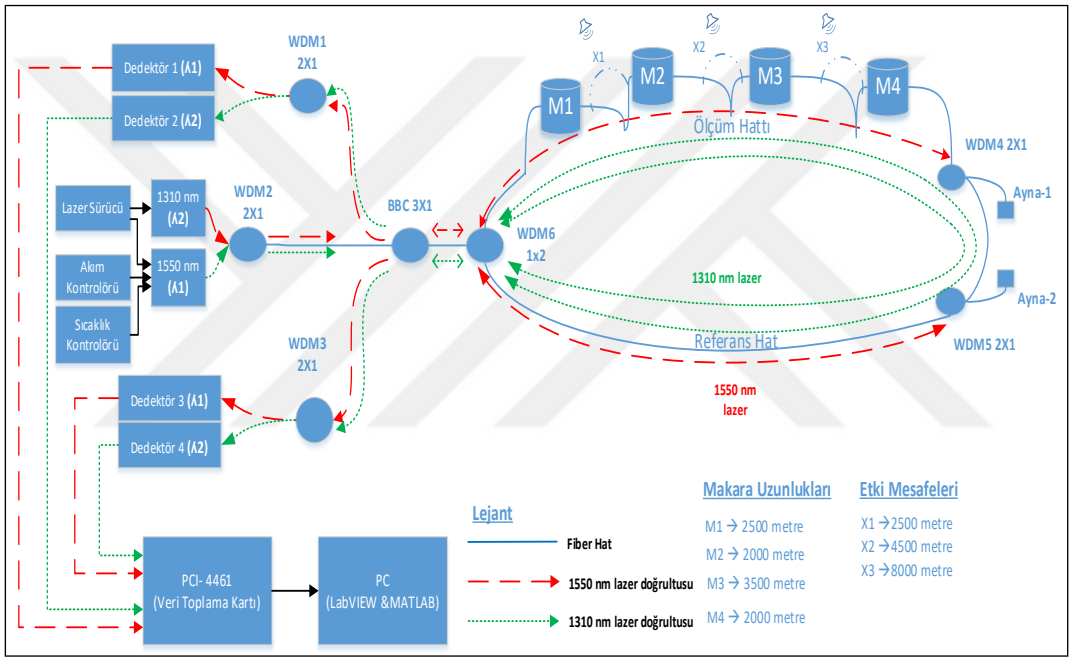


Figure 4.4. Sagnac-Michelson Interferometer Topology

As seen in Figure 4.4, the system consists of a combination of Sagnac and Michelson (MI) interferometers. A laser diode with a wavelength of 1310 nm (λ2) was used for the Sagnac interferometer. 50:50 wavelength division multiplexer (WDM), the laser beam passing through the WDM2 enters the 3x3 broadband coupler (BBC). At the output of the BBC, they complete the cycle by moving along the fiber line as two signals of equal power clockwise and counterclockwise, and they are detected by interfering beams λ2 detectors in the BBC [5].

A laser of 1550nm (λ1) wavelength was used for the MI interferometer. Through the WDM2 and BBC couplers, the light travels in both directions of the loop. In the middle of the loop, there are WDM4 and WDM5 couplers that direct the light to the ports (M1 and M2) with mirrors. Beams are reflected through mirrors and return from the line they follow as they arrive. After the interference of beams encountered in the BBC, the resulting light intensity is detected by λ1 photodetectors thanks to the WDM1 and WDM3 couplers [5].

For the sensor topology to be created with standard fiber cables used in communication, the fiber optic sensor's active and passive circuit elements mentioned under the heading FOS breakdown are brought together. As shown in Figure 16, external effects were applied at three different points (X1→2500 meter, X2→4500 meter, X3→8000 meter) on the line formed by welding fiber spools of varying lengths (M1→2500 meter, M2→2000 meter, M3→3500 meter, M4→2000 meter) with the fusion device.

Except for the fiber cables used for testing, fiber spools are isolated as much as possible from temperature changes and vibrations. Power settings of laser sources are made. By calculating the connector, adapter, coupler and distance losses, the losses that may arise from connection failure, dirt, and dust, bending and breakage at any point were measured by optical power meter at each connection point. The system was checked whether there are changes in the wavelengths of single-mode laser sources depending on time and temperature by using an optical spectrometer. Thus, the calibration process was completed.

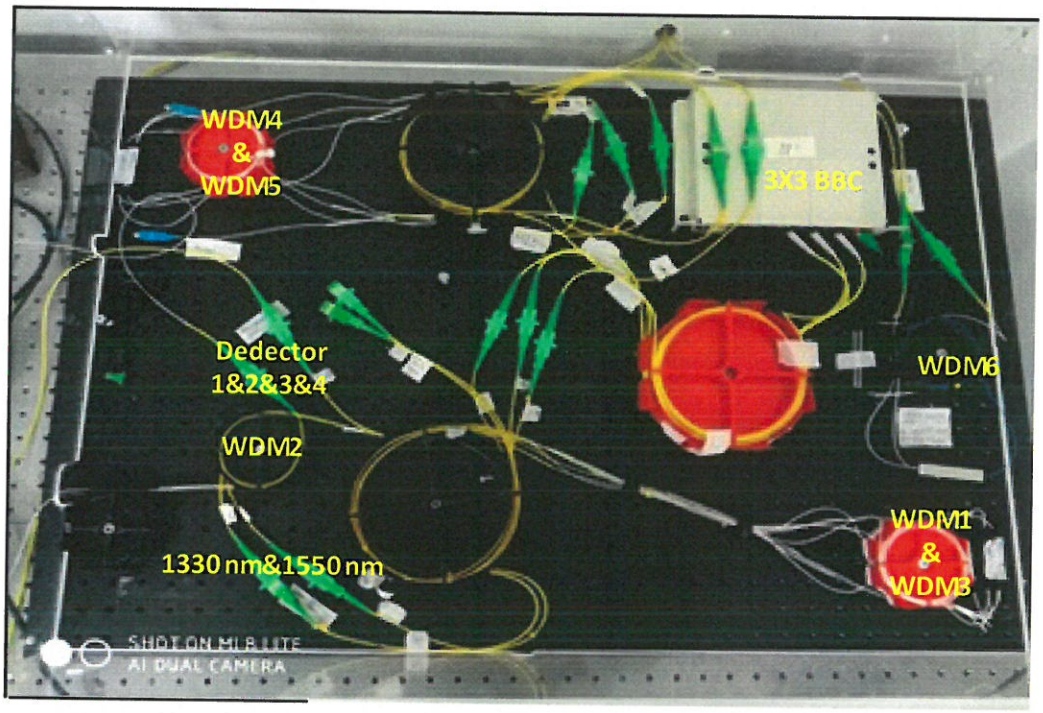


Figure 4.5. Test Setup on The Laboratory

A 20-meter fiber patch cable connection was applied to the fiber cable, which was traversed between the reels to observe the effects, at the X1, X2, X3 positions at 37 Hz, 93 Hz, 182 Hz, 277 Hz frequencies with the aid of a loudspeaker driven by the analog signal source.

With λ1 photo detectors, beams with a wavelength of 1550 nm and a wavelength of 1310 nm with λ2 detectors were converted into electrical signals, passed through a low-pass filter, and then analog data were collected digitally using a data collection card.

CHAPTER 5

EXPERIMENTAL RESULTS

The signals read with the PCI-4461, 2-channel data acquisition card were collected on the LabView Signal Express tool, and then analyzed in MATLAB environment. Figure 5.1-Figure 12 show the magnitude response and 1st, 2nd, 3rd harmonics of the effects of the sensor measurement line at frequency of 37 Hz, 93 Hz, 182 Hz, 277 Hz at 2000 meter, 4500 meter, 8000 meter and the effects perceived by Sagnac and Michelson interferometers.

Figure 5.1- Figure 5.12 show the first, second, and third harmonics of the signals obtained from Sagnac and Michelson interferometers at 2500, 5000, and 8000 meters of 37 Hz, 93 Hz, 182 Hz, 277 Hz effects applied on the fiber sensor line mentioned above are examined.

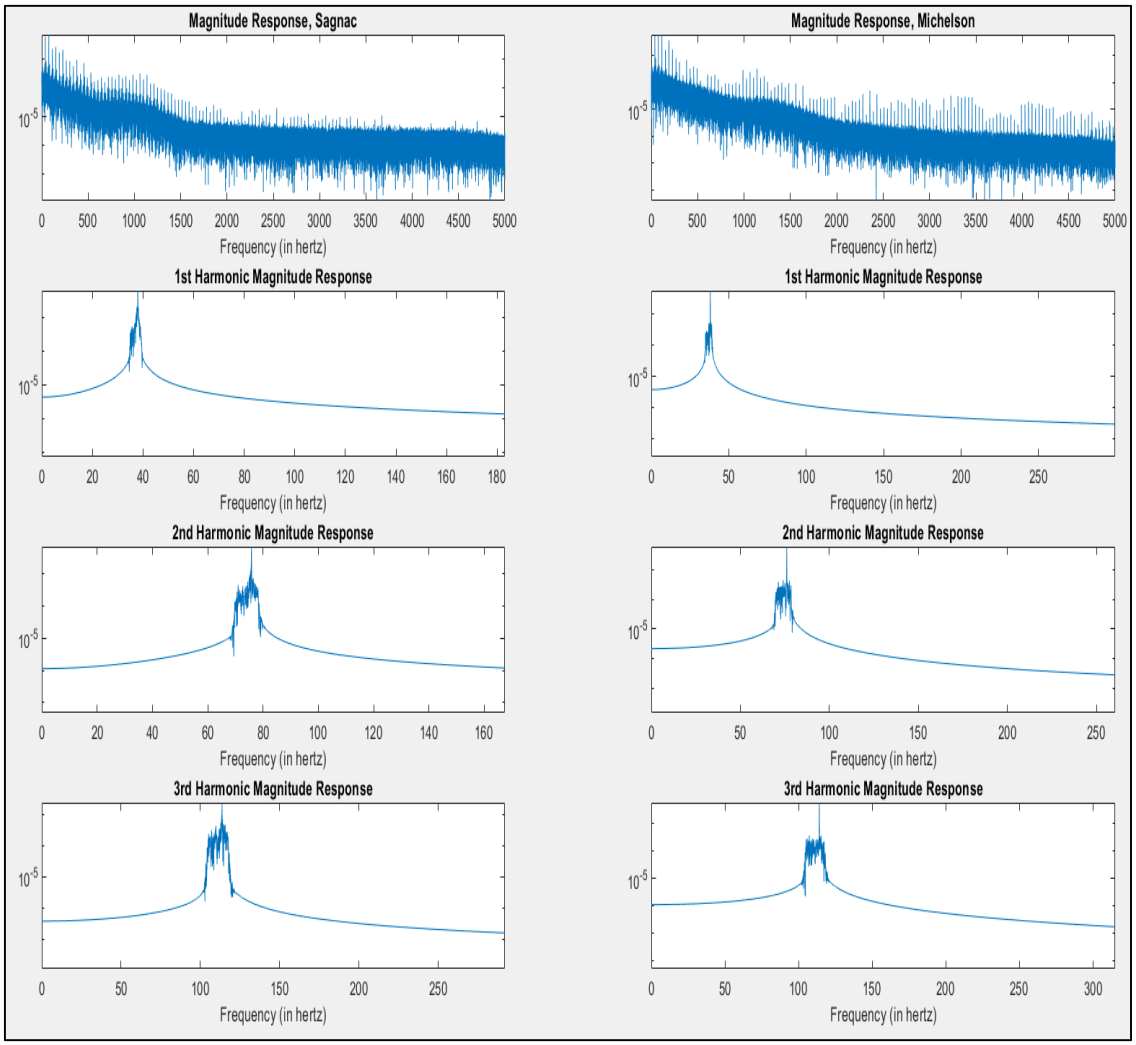


Figure 5.1. 37 Hz 2000 m S-M magnitude response & harmonics of the effects of the sensor measurement

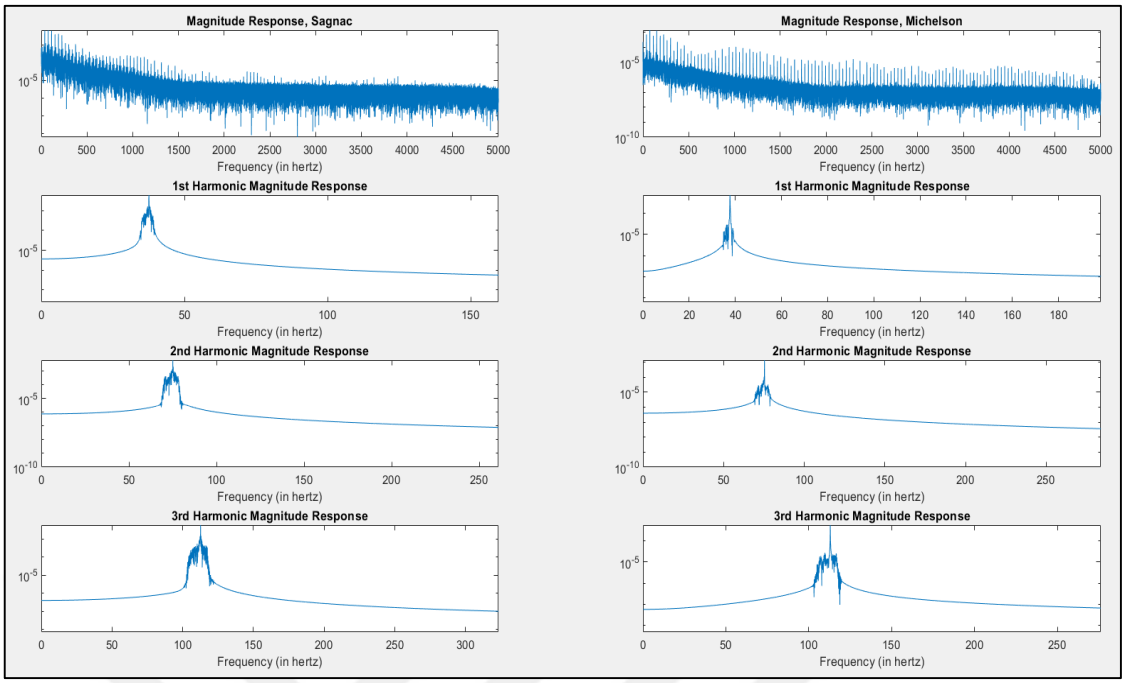


Figure 5.2. 37 Hz 4500 meter Sagnac Michelson magnitude response and 1st, 2nd, 3rd harmonics of the effects of the sensor measurement

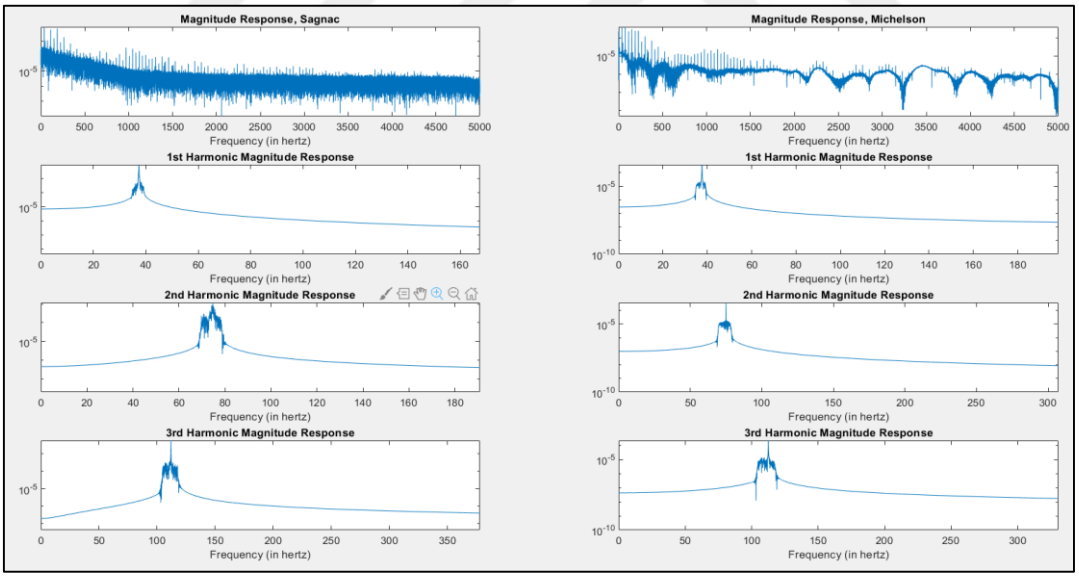


Figure 5.3. 37 Hz 8000 meter Sagnac Michelson magnitude response and 1st, 2nd, 3rd harmonics of the effects of the sensor measurement

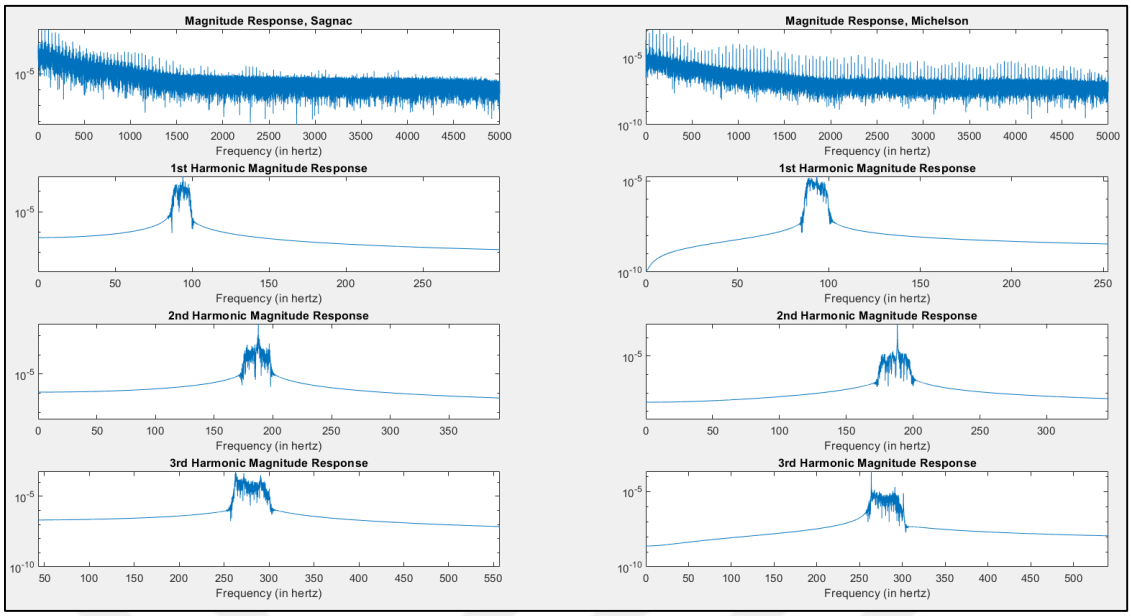


Figure 5.4. 93 Hz 2000 m S-M magnitude response & harmonics of the effects of the sensor measurement

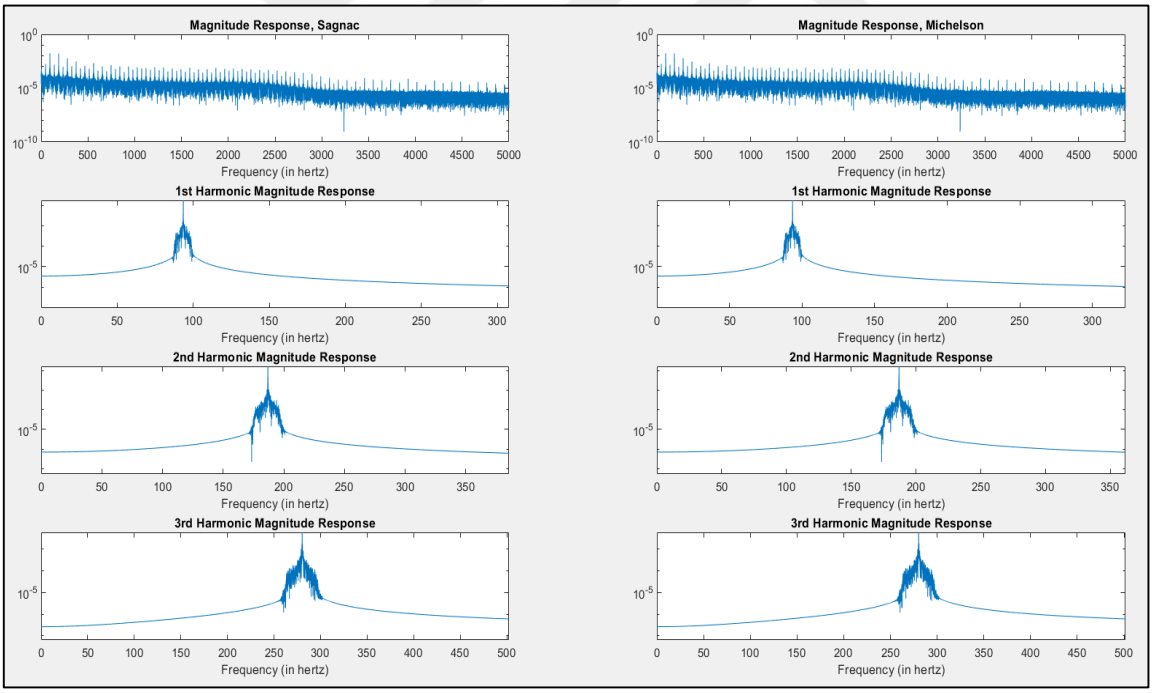


Figure 5.5. 93 Hz 4500 meter Sagnac Michelson magnitude response and 1st, 2nd, 3rd harmonics of the effects of the sensor measurement

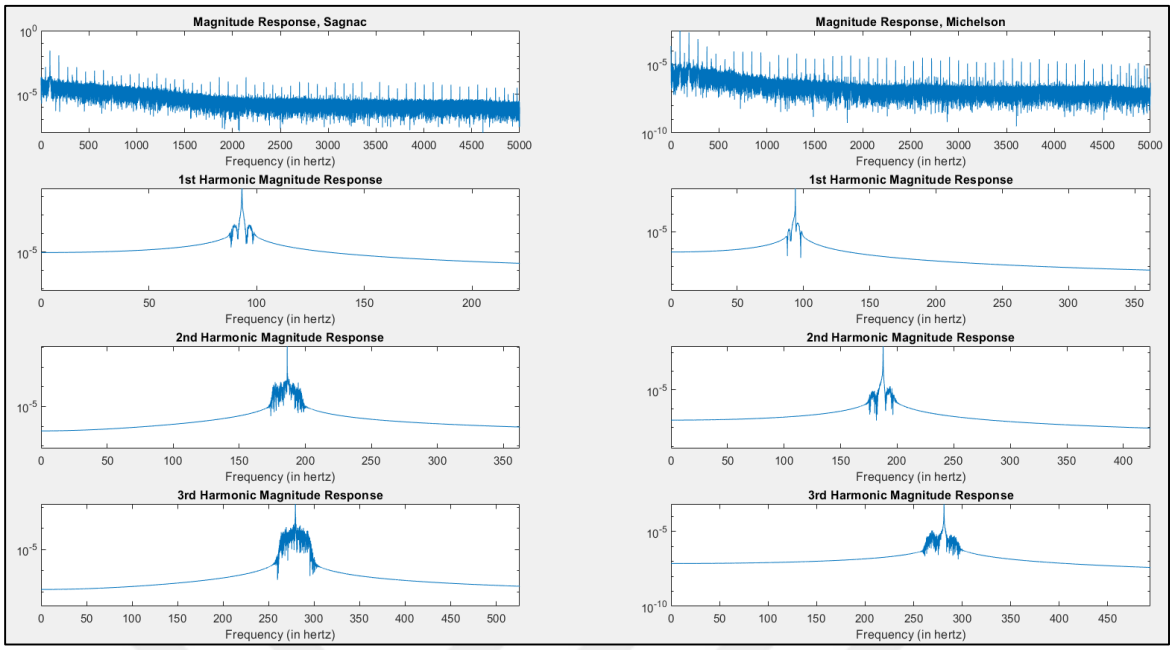


Figure 5.6. 93 Hz 8000 m S-M magnitude response & harmonics of the effects of the sensor measurement

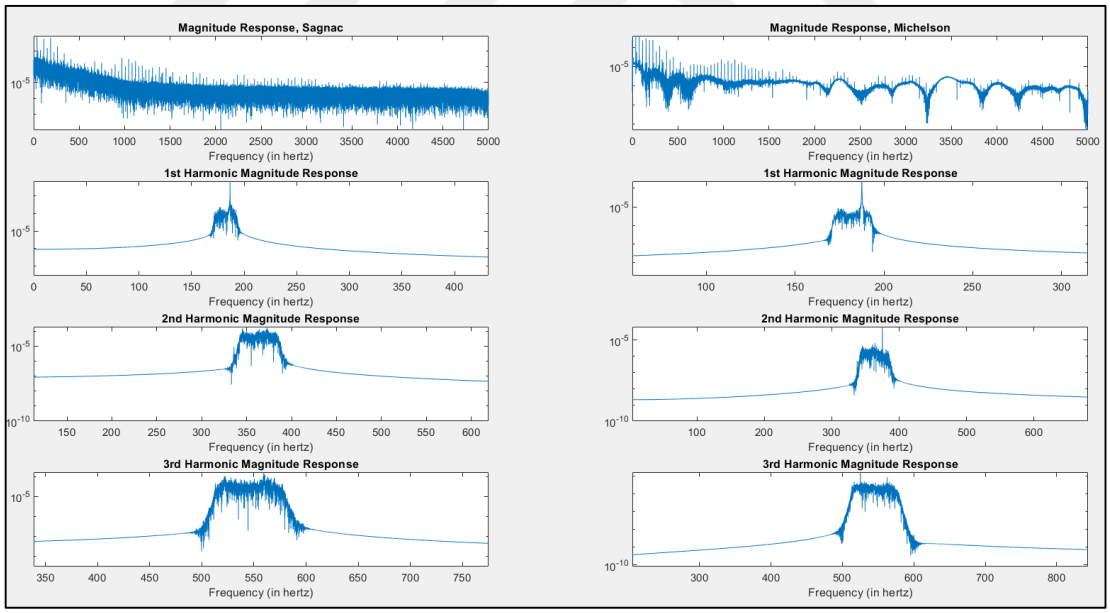


Figure 5.7. 182 Hz 2500 meter Sagnac Michelson magnitude response and 1st, 2nd, 3rd harmonics of the effects of the sensor measurement

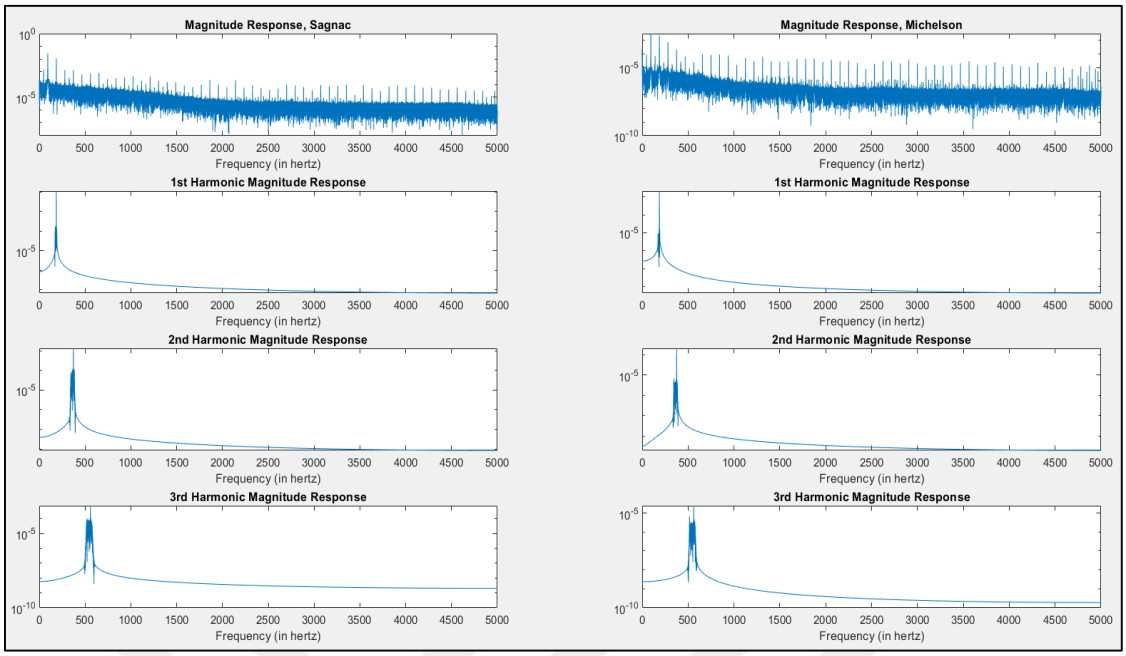


Figure 5.8. 182 Hz 4500 m S-M magnitude response & harmonics of the effects of the sensor measurement

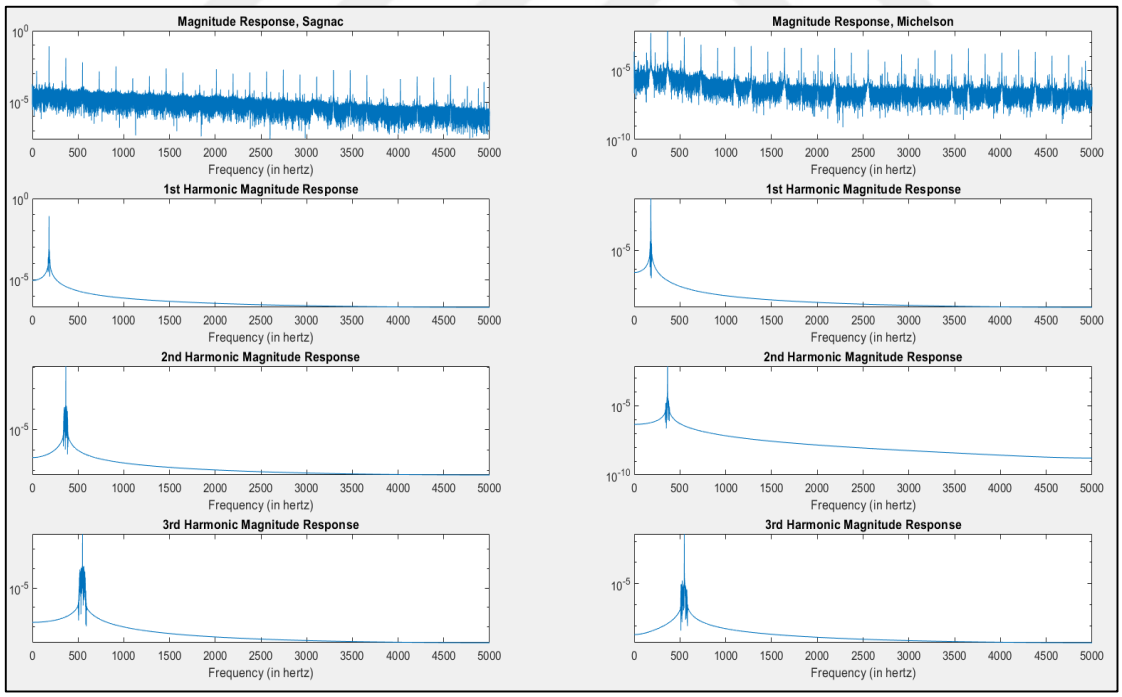


Figure 5.9. 182 Hz 8000 meter Sagnac Michelson magnitude response and 1st, 2nd, 3rd harmonics of the effects of the sensor measurement

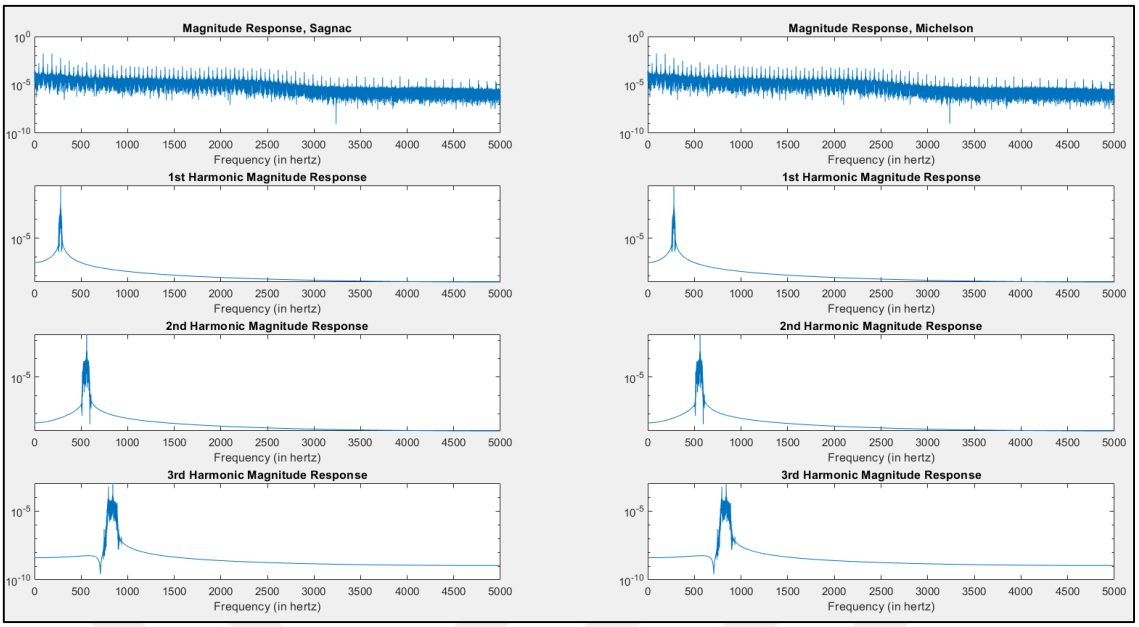


Figure 5.10. 277 Hz 2500 m S-M magnitude response & harmonics of the effects of the sensor measurement

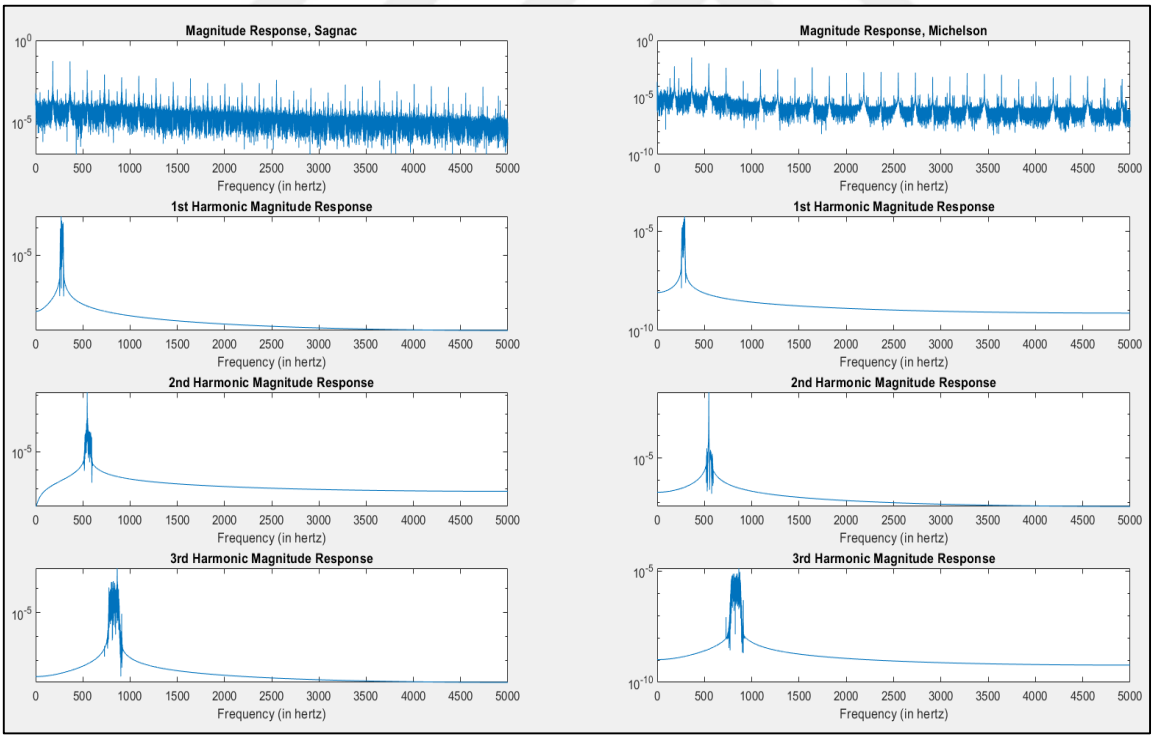


Figure 5.11. 277 Hz 4500 m S-M magnitude response & harmonics of the effects of the sensor measurement

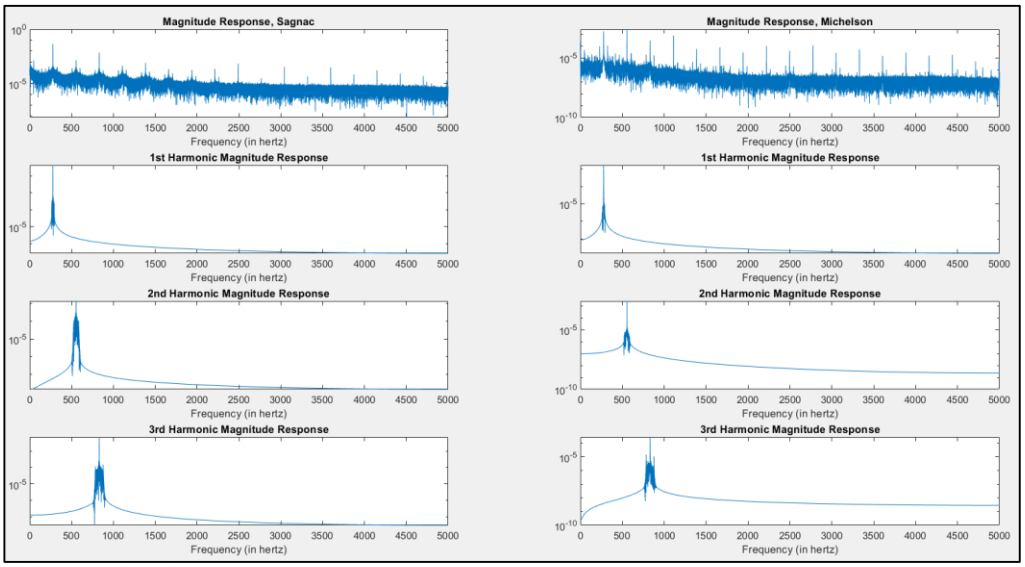


Figure 5.12. 277 Hz 8000 meter Sagnac Michelson magnitude response and 1st, 2nd, 3rd harmonics of the effects of the sensor measurement

Figure 5.13 and Figure 5.14's Pout values of the 1st, 2nd and 3rd harmonics decrease in the Michelson interferometer at 37Hz depending on the distance. The Pout value of the 1st and 3rd harmonics of the signals obtained from the Sagnac interferometer increased similarly depending on the distance, while the 2nd harmonic decreased.

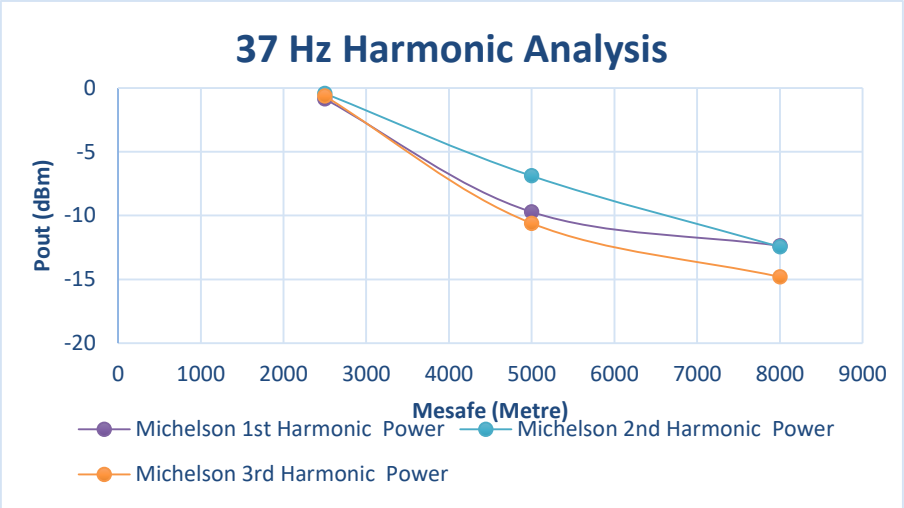


Figure 5.13. Harmonic Analysis of Signals Obtained from Sagnac Interferometers, 37 Hz

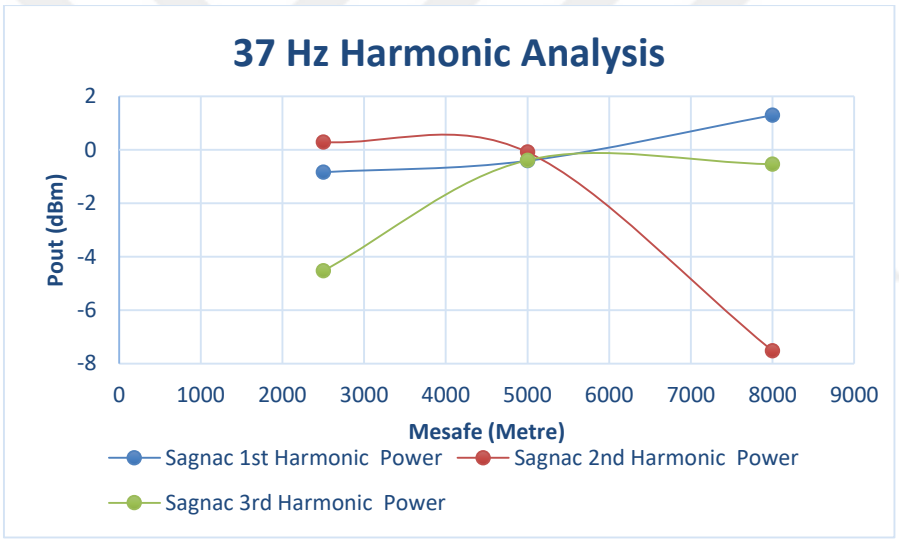


Figure 5.14. Harmonic Analysis of Signals Obtained from Michelson Interferometers, 37 Hz

As seen in Figure 5.15 and Figure 5.16, the Pout value of Sagnac-Michelson interferometers whose 1st, 2nd, and 3rd harmonics were analyzed at 93Hz increased from 2500 meters to 5000 meters, while it decreased at 8000 meters.

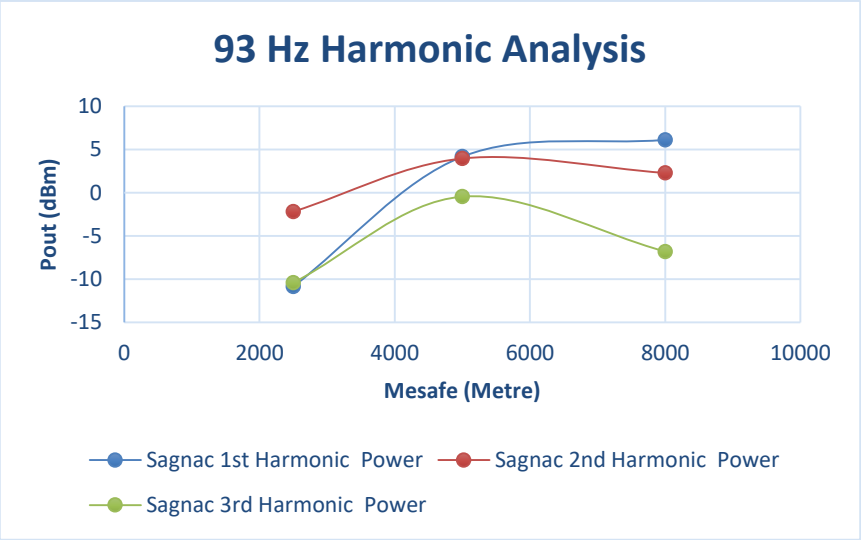


Figure 5.15. Harmonic Analysis of Signals Obtained from Sagnac Interferometers, 93 Hz

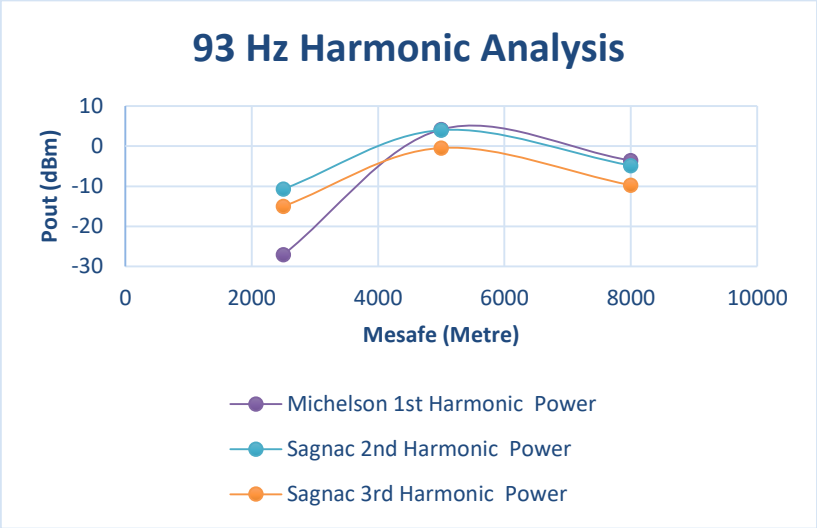


Figure 5.16. Harmonic Analysis of Signals Obtained from Michelson Interferometers, 93 Hz

As shown in Figure 5.17 and Figure 5.18, Pout values of the 1st, 2nd, and 3rd harmonics of Michelson and Sagnac interferometers increased at 182Hz depending on the distance.

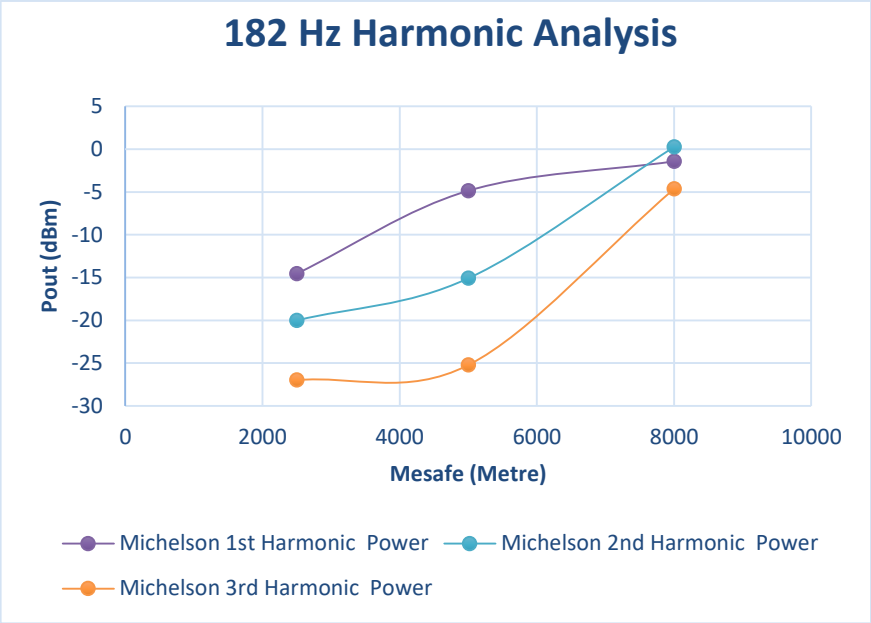


Figure 5.17. Harmonic Analysis of Signals Obtained from Sagnac Interferometers, 182 Hz

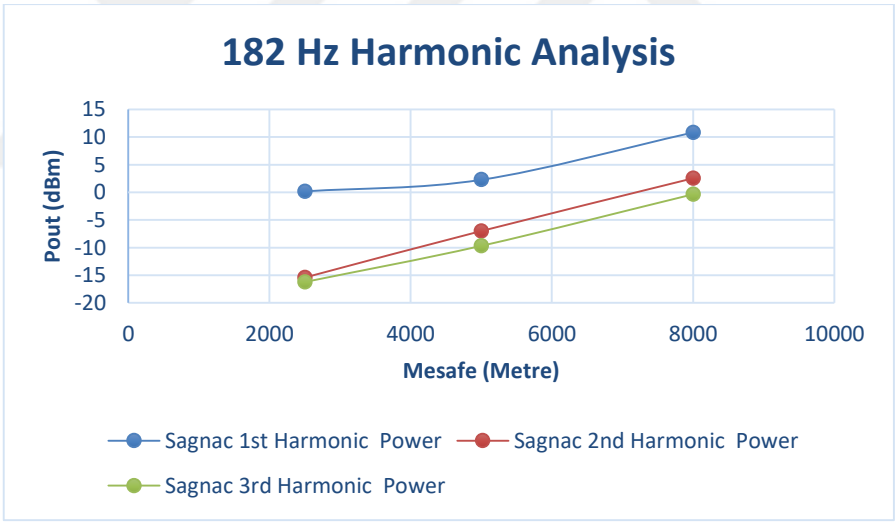


Figure 5.18. Harmonic Analysis of Signals Obtained from Michelson Interferometers, 182 Hz

As shown in Figure 5.19 and Figure 5.20, at 277 Hz the Pout values of the 2nd harmonics of the Sagnac and Michelson interferometers increase from 2500 m to 5000 meters. Towards 8000 meters, harmonics are decreasing again. While Pout values of the 1st and 3rd harmonics of Sagnac and Michelson interferometers decrease from 2500 meters to 5000 meters, they increase at 8000 meters.

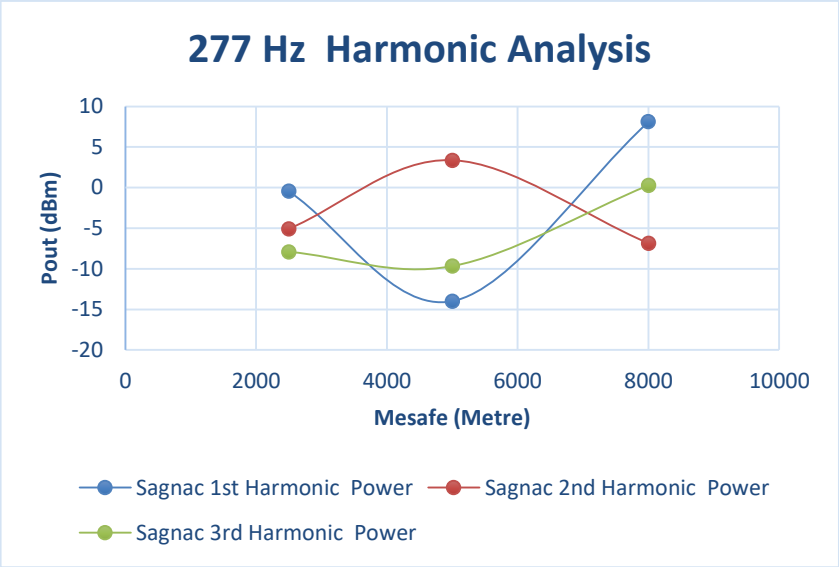


Figure 5.19. Harmonic Analysis of Signals Obtained from Sagnac Interferometers, 277 Hz

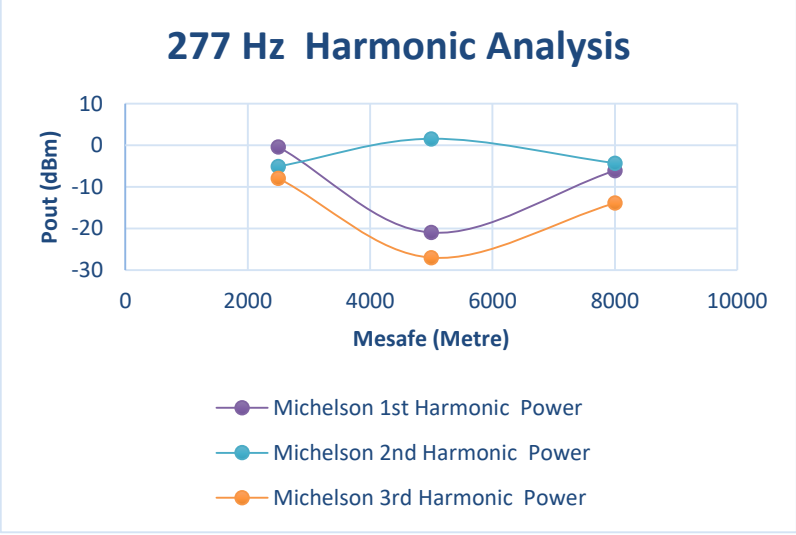


Figure 5.20. Harmonic Analysis of Signals Obtained from Michelson Interferometers, 277 Hz

CHAPTER 6

CONCLUSION

In this study, distributed fiber optic acoustic sensor configurations, the sensor topology of the Sagnac-Michelson interferometer, the test and experimental work done on the experimental setup, and the experimental results were mentioned.

As a result of the studies on the system installed in the laboratory environment, the acoustic effects we applied on the sensor could be observed in real-time with the system designed according to the Sagnac - Michelson topology. FFT graphs of the impact applied at three different points and four different frequencies on the Sagnac - Michelson configuration was examined. Subsequently, the 1st, 2nd and 3rd harmonics of the signals coming from Sagnac and Michelson interferometers were discussed, and the relationship between power and distance was examined.

It is seen that the environmental and electrical network noise in the laboratory environment affects the experimental results. For this reason, it is thought that this can be overcome by using adaptive filter in future studies. In addition, random peaks [27] due to the nature of the Sagnac interferometer can suppress the actual signal. These peaks occur intermittently in the collected data. This can cause difficulties in collecting accurate data.

Another issue is that the polarization of the beam traveling through the fiber changes randomly. Measurements have been made on this subject and the polarization changes randomly. Electronic polarization controller used for instantaneous polarization control, which was previously stated under the heading MZI [29], can be preferred for Sagnac-Michelson interferometers in the following stages.

The project's ultimate goal is to make distance estimation by performing a harmonic analysis of Sagnac - Michelson interferometer signals depending on the distance and intensity of the applied impact. The amplitude characteristic of the Sagnac interferometer, obtained the demodulation of the two interferometers, depend on the disturbance location along the interferometer while it does not depend on the amplitude characteristic of the

Michelson interferometer. Therefore, a part of the two demodulated properties is proportional to the fiber optic location of the fault [6].

As can be observed from the harmonic analysis graphs shown under the Experimental Result chapter's title, contrary to expectations there is no proportional change of 1st, 2nd, 3rd harmonics depending on the distance. It is considered as the instability of the coherence properties of laser sources.

It is a source of motivation for us that there are no studies in the literature where harmonic analysis is performed, and any distance-based inferences are found.

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