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Sagnac Interferometer with Reflectors for Detecting and Localizing Phase Sensitive Events in Fiber Optic Cables

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ABSTRACT: A Sagnac interferometric system to detect, identify and locate phase sensitive events in fiber optic cables, with early warning capabilities is presented. The system makes use of two standard fibers that are already installed. Two Super Luminescent Diodes (SLD) are used as the sources. The sensing fiber is terminated by a fiber mirror reflector. The monitoring is done from a centralized location where the detection opto- electronics is located. Spatial event localization within 200m is demonstrated for a monitoring length of 40Km

KEYWORDS: Sagnac-interferometer, fiber optic sensors, interferometric sensors, pipeline protection.

I.INTRODUCTION

Distributed optical fiber sensors are commonly used for monitoring of pipelines, optical communication links and for the protection of restricted areas. Earlier, the detection methods were based on intensity modulated sensors, which does monitoring based on the variation of optical intensity as a result of the bending of fibers, tapping of fiber optic links etc. Thus detection was possible only after the event had actually occurred. However, the sensing scheme which is able to detect phase sensitive events can provide advance warning, using the fiber cable as a distributed sensor. The two possible methods for the detection of phase sensitive events are Phase Optical Time Domain Reflectometry (Φ-OTDR) and Interferometry.

In Φ-OTDR method, light pulses from a highly coherent semiconductor laser are injected into the fiber, and the Rayleigh backscattered light is detected by a sensitive photo detector.The Φ-OTDR measures phase changes corresponding to the events, and thus provide an efficient detection. Localization of events is possible, with the distance being proportional to the time delay. But, the distributed sensing length is typically limited to a few kilometers (30 km) of the fiber [1].

Another method for the detection and localization of phase sensitive events is based on interferometry. Since, optical detectors cannot detect the optical phase directly; the phase change is converted in to an intensity change using interferometric schemes like Mach-Zehnder, Michelson, Fabry-Perot or Sagnac. Among these sensors, Mach-Zehnder and Sagnac sensors are used for the detection of sound and vibrations because of their easy configuration and higher sensitivity compared to other types. Sagnac circuit provides less complexity compared to Mach-Zehnder, and it can provide a single fiber sensor circuit. The amplitude variation in the Sagnac Sensor is more position sensitive. By combining properties of the Sagnac interferometers with color coded reflectors such as fiber gratings, it is possible to measure the presence of a time varying signal and localize it on a single optical fiber [2][3].

The Sagnac interferometer may be used to measure time varying environmental effects such as acoustics. The environmental effect to be measured impresses an induced phase difference between the counter propagating light beams of the Sagnac loop. The magnitude of the induced phase difference will depend on the position of the signal from the center of the Sagnac loop where the sensitivity is zero since both counter propagating light beams arrive at the same time, the frequency of the signal and its amplitude[4][5][6].

Since the time varying Sagnac interferometer configuration is less position sensitive, to determine the position and location of a time varying disturbance is suggested by making use of reflectors along with the fiber optic sensor. There can be two possible configurations, either making use of color coded reflectors such as fiber gratings or a single reflective element with an additional arrangement of phase modulators [7].

In this work, a fiber optic interferometric system was designed and analyzed to detect, identify and locate the phase sensitive events along fiber optic communication cables, which is capable to generate warning to prevent the damage and cost occurring. The design aspects as well as the frequency response and the sensitivity of the system are discussed in detail.

II. THEORY & SYSTEM DESIGN

A. Reflective type Sagnac Interferometer

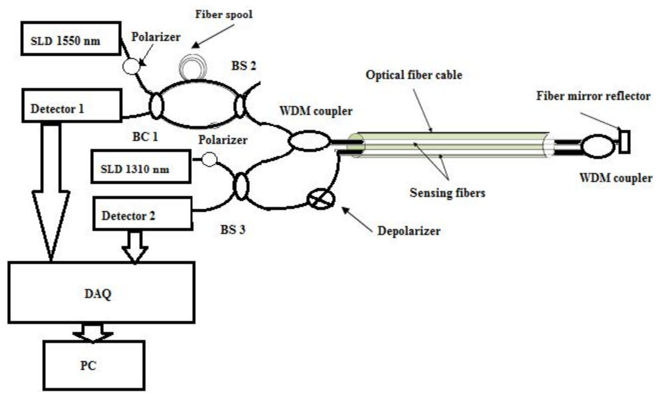

Fig 1. Schematic diagram of reflective type Sagnac sensor

The light beam from a Super Luminescent Diode (SLD-1550nm) is split in to two paths at the First beam splitter (BS). The two beams counter propagate in the loop in paths that differ in length, and reach the second beam splitter, and both of them splitted again in to two , one part of both beam travel in the sensing fiber path, while the other two are terminated to prevent back reflection. When there is any vibration on the sensing fiber, the beams passing through them suffer a phase change and are reflected back by the help of the fiber optic mirror provided at the end. The two beams reflected back are again splitted in to two at the beam splitter 2.Then they propagate through the two paths to reach the beam splitter 1. All the four beams reaching the beam splitter cannot interfere. The two beams which have traveled the same optical path length will interfere. If there is no phase change between the beams (no vibration), then there will be no output on the detector. And if the phase difference is 180^0, then all the combined output will be at the detector. If the phase change is between 0^0 and 180^0, the beam will split to detector and source, and the interference signal at the detector will be a measure of the phase change and thus a measure of the vibration.

The response of the single fiber Sagnac loop is flat over the sensing fiber leg. This response is different from an unfolded Sagnac loop, which has no sensitivity in the center of the loop, and increasing sensitivity near the central fiber beam splitter. The distributed sensing can be achieved, where the amplitude of a time varying event may be measured by the single fiber Sagnac sensor and the position can be monitored by the ratio of the two detector outputs (response of single fiber Sagnac and loop Sagnac). By using wavelength division multiplexing elements, the single fiber Sagnac and loop Sagnac can be run independently [7].

B. System Design

A distributed vibration sensing system based on the above principle is designed. The design analysis covers selection of optical sources with proper characteristics, intrinsic loss estimation of the system and sensitivity of the opto-electronic detection etc. The effect of type of cabling and type of cable laying method, the effect of polarization in the

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system are also analyzed.

(1) Source Selection Considerations

For the efficient working of a Sagnac sensor, the light source should be broad band. This ensures a short coherence length, thus reducing the effects of interference from backscattered light, which could arise from Rayleigh scattering in the fiber or Fresnel reflection at the joints. Thus, Two SLD's of wavelengths 1550 nm and 1310 nm are selected. The power outputs of the sources are selected as 5mW on the basis of power budget analysis.

a) Wavelength

The sources should have stable wavelength characteristics over the entire operating temperature range. The wavelengths 1550nm and 1310 nm are selected, as these are the lowest loss and lowest dispersion regions of silica based optical fiber. And the availability of fused WDM in these wavelengths also helps the use of these wavelengths.

(2). Cable type and cable laying

There are several types of cable designs to protect the optical fiber inside from outside temperature, mechanical and environmental influence to realize reliable signal transmission. For all sensing applications, optical sensing cables need to transfer the outside disturbances to inside fibers as much as possible to get necessary sensitivity.

The two main types of fiber optic cables are, loose tube cables and tight buffered cables. Among these, the tight buffered cable is found to be more sensitive to vibration [10]. The sensing fiber cables can be attached along with the pipelines in the case of pipe line protection. Otherwise, the sensing cable can be laid at a depth of 1.27 m irrespective of soil conditions. This is specified as the standard trench depth. Trench shall be dug to a minimum depth of 1.25 meter plus the diameter of the cable [normally 2 cms]. This will ensure top of the buried cable at a minimum depth of 1.25 meter. The trench shall not have a sharp bed or steep curvatures to ensure strain free cable installation [11].

(3). Power Budget and Monitoring Span

Longer fiber length reduces the strength of the received signal and the spectrum strength also get reduced. The insertion loss of corning SMF 28 is 0.2dB/Km for 1550nm, and 0.35 dB/Km for 1310 nm. The signal strength at detector can be made sufficient for better sensitivity, by increasing the source output power. Based on the power budget analysis, the sources having a power output of 5mW is required to cover 80 km[10].

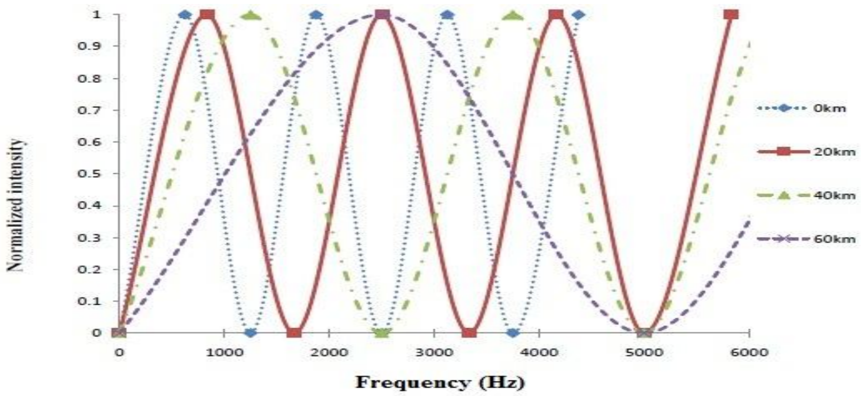

Fig 2. Spectral response of unfolded Sagnac sensor (l= 80Km)

For a monitoring length of 80 Km cable, the attenuation loss in the sensing fiber will be about 32dB. But the optical signal can be made sufficient to detect the events by selecting the suitable sources as discussed previously and also by the proper design of detector circuit. The selected photo detector has a high responsivity of about 0.85A/W, which can provide a better detection.

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(4). Frequency Response and Estimation of Sensitivity

The frequency characteristics and spatial characteristics of a Sagnac loop interferometer are analyzed [11]. The dependence of modulation frequencies with respect to the disturbance positions and also the variation of modulation frequencies with different loop lengths are given in the Fig 2.

When any disturbance is applied, the single Sagnac loop has no sensitivity near the centre of the loop and increasing sensitivity near the 3dB coupler. The sensitivity at the centre of the loop can be increased by the use of a phase modulator in the circuit, which can provide a known value of phase modulation to the signal. And, this additional phase modulation can be demodulated at the detector circuit [8].

Typical applications require localization accuracy within 100 m for a monitoring span of 80km. The frequency response of the sensor should be in the range 10Hz to 10 KHz. The frequency range that can be achieved depends on the path length imbalance that can be used, namely the coherence length of the source.

Normalized responsivity can be used as a figure of merit of the fiber optic sensor. The normalized responsivity (NR) normalizes the sensor's responsivity by the total phase shift in the sensor. Effectively, this is the same as normalizing by the length of the fiber on the sensor. A good acoustic sensor might have an NR of -300dB re rad/µPa. If the sensor is interrogated by a laser at 1550nm, the total optical phase in 80 Km fiber is given by, 233.74dB re rad and the responsivity of the sensor is equivalent to -66.26 dB re rad µ Pa^{-1} m^{-1}. The smallest signal feed that can be resolved by a sensor is determined by the optical noise floor of the system ϕ_{min} $Hz\text{-}^{1}$, and the sensor's responsivity [8].

(5). Effect of Polarization

Two-beam interferometry relies on the coherent mixing of two optical signals, which is strongly polarization dependent. If the states-of-polarization (SOPs) of the two optical beams are aligned with one another, perfect mixing will occur and the visibility will be maximized. On the other hand, if their SOPs are orthogonal with respect to each other, there will be no coherent mixing and the visibility will go to zero, resulting in a 'polarization induced signal fade' (PIF).

The visibility of the interferometer can be defined as,

$$V = \frac{2\sqrt{I_R + I_S}}{I_R I_S}\cos\eta = V_0 \cos 2\eta$$

Where, η is the half angle between the output SOP's (State of polarization) and V_0 is the optimum visibility. When $2\eta=180^0$, the polarization states are orthogonal and V=0. When V=0, there is no interference and hence no signal, resulting in a polarization induced signal fade[9].

To eliminate the polarization fading problems, a polarizer can be provided after the laser source and a depolarizer can be included in the sensing path. The depolarizer make the light beams polarized in a random manner, and it prevents the orthogonal SOP's[11].

(6). Approaches for Realizing vibrations in Laboratory

For the simulation of real world, the data must be acquired using a portable recording device. A mechanical shaker can be used to produce vibrations. Before the data can be used for simulation, it must be compensated to conform to the physical limits of the shaker, frequency content of the vibration signal, and the DC offset and other factors [13].

Acoustic signals of different frequencies and amplitudes can be produced using a function generator or by programming in MATLAB, which is then applied using a loudspeaker. The speaker jack can be driven with LABVIEW also. LABVIEW allows using the sound card.

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III. EXPERIMENTAL

A. Experimental Setup

The passive optical modules are assembled as shown in Fig 3. The equipment module consists of a fused WDM (1310/1550) coupler and three 3dB (2x2) couplers, as given in Fig 3(a). The reflector module consists of a WDM (2×1) coupler and a Fiber Mirror Reflector (FMR) which shown in Fig 3(b).

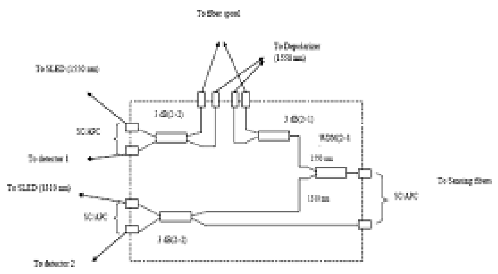

Fig 3(a). Design layout of equipment module

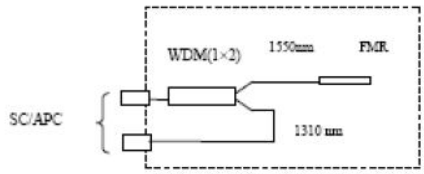

Fig3(b) Design layout of reflector module

The photographs of terminal modules are shown in the fig 4.

Fig 4 .Terminal modules of reflective type Sagnac sensor (a) Equipment module (b) Reflector module

Reflective type Sagnac sensor is setup using the terminal modules. The experimental set up is given in the fig 5. The experimental setup contains two SLD sources of wavelengths 1550nm and 1310 nm, the terminal modules, fiber spools as sensing fibers, two detectors, and a DAQ card. The vibrations are applied using a set up comprising of a function generator and a loud speaker.

Fig 5. Experimental setup using terminal modules

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The photo detector outputs are given to a Computer through a DAQ card. The signals are processed in Lab view. The output signals at detector1 and detector 2(white and red in color respectively) are shown in fig 6.

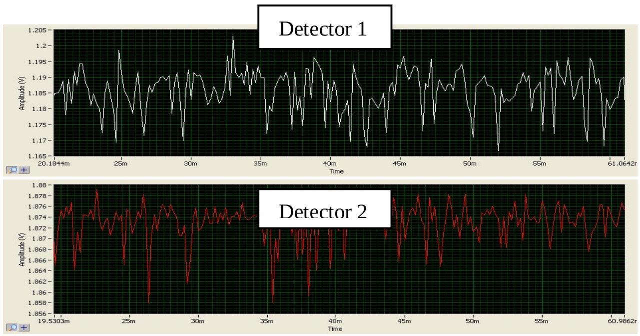

Fig 6 . Output signals of Single fiber Sagnac Sensor(Detector 1) and unfolded Sagnac sensor(detector 2)

IV RESULTS AND DISCUSSION

Vibrations are given at different locations along the sensing fiber, and the localization of events are found out by programming in Lab view. When the vibration signal is applied at 20.3 Km from the terminal module (equipment side) along the sensing fiber, and the location is resulted as 20.497 Km, with a spatial resolution of 197m. This is given in fig 7.

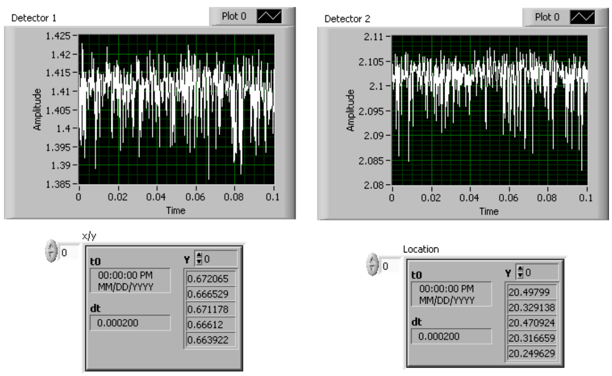

Fig 7 .Localization result

The actual locations of events are compared with the measured locations. A graph of actual location Vs measured location is given in fig 8.

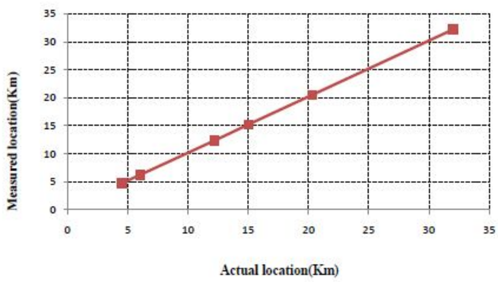

Fig 8. Comparison of localization results

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V. CONCLUSION

Reflective type Sagnac sensor is useful for the detection, identification and localization of phase sensitive events happening near the fiber optic cables. The proposed sensing system can provide a monitoring span of 40 km with localization accuracy within 200m. The distances can be extended to 80km, but with compromise on the spatial resolution of the detected events.

The signature analysis for different types of events can be improved by analyzing the amplitude, duration, and spectral content of the disturbance, using look up tables, pattern matching, artificial intelligence, and neural network approaches. Disturbances which are similar to post events can thereby be identified, and the analysis and recording of new events can be utilized to develop background for identification of future events. An alarm monitoring system also can be integrated and can also be interfaced to CCTV systems, email systems, external sms servers etc via TCP/IP.

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