

2016

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[10.1109/JSEN.2016.2535465](https://doi.org/10.1109/JSEN.2016.2535465)

This is an Author's Accepted Manuscript of:

Allwood, G., Wild, G., & Hinkley, S. (2016). Optical fiber sensors in physical intrusion detection systems: A review. *IEEE Sensors Journal*, 16(14), 5497-5509.

[https://doi.org/ 10.1109/JSEN.2016.2535465](https://doi.org/10.1109/JSEN.2016.2535465)

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Optical Fiber Sensors in Physical Intrusion Detection Systems: A Review

Gary Allwood, *Member, IEEE*, Graham Wild, *Member, IEEE*, and Steven Hinckley, *Member, IEEE*,

Abstract—Fiber optic sensors have become a mainstream sensing technology within a large array of applications due to their inherent benefits. They are now used significantly in structural health monitoring, and are an essential solution for monitoring harsh environments. Since their first development over thirty years ago, they have also found promise in security applications. This paper reviews all of the optical fiber based techniques used in physical intrusion detection systems. It details the different approaches used for sensing, interrogation and networking, by research groups, attempting to secure both commercial and residential premises from physical security breaches. The advantages and disadvantages of the systems are discussed and each of the different perimeter protection methods are outlined, namely, in-ground, perimeter fence, and window and door protection. The study reviews the progress in optical fiber based intrusion detection techniques from the past through to current state-of-the-art systems and identifies areas which may provide opportunities for improvement, as well as proposing future directions in this field.

Index Terms—Physical Intrusion Detection, In-ground, Perimeter Fence, Optical Fiber, Security.

I. INTRODUCTION

THERE is a large array of different sensing techniques used for physical intrusion detection, from glass break detectors, magnetic door and window detectors to surveillance cameras and infra-red trip wires, as well as in-perimeter fence and in-ground pressure sensors [1]. A single security setup for a property, whether it is domestic or commercial, may utilize a number of these techniques in creating a complete security system. Moreover, modern systems usually incorporate an inherent level of intelligence for real-time monitoring of sensors via a security control center. This intelligence is essential for reducing the number of false alarms and increasing the effectiveness of the security system in both detection and prevention of potential intruders. The intelligence can be in the form of a simple processing unit or, more commonly, from a programmable logic controller (PLC), and may also be integrated with the building automation system [2].

Traditionally, wired security systems were considered the most reliable and affordable solution for intrusion detection. The main advantage of wired systems is that they can be easily connected to a monitoring service via a telephone line.

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However, these systems could be vulnerable to tampering if the wires themselves were not appropriately protected, requiring professional installation.

With the advances in wireless technology in recent years, wireless security systems have become very popular as they can be easily set up, do not require cabling, and can be remotely armed. However, the disadvantage with these systems is that each sensor may require an external power supply. If batteries are used, they may need to be replaced or charged regularly, especially for surveillance cameras which may only last 24 hours before needing to be charged [3].

Optical fiber security systems offer some unique advantages with respect to the other methods. One of the main advantages is that the optical fiber itself can act as both the transmission medium and the sensor. It is well recognized that optical fiber sensors have many desirable attributes; being small, light weight, environmentally rugged, and have increased sensitivity with respect to traditional sensing techniques [4]. These attributes are ideal for advanced security systems.

There are essentially three broad optical fiber sensing techniques used for security applications, specifically physical intrusion detection systems (PIDS);

- 1) interferometry,
- 2) scattering, and
- 3) fiber Bragg grating based detection.

Older fiber optic sensing techniques for security applications utilize scattering and interferometry. Whilst these techniques may be effective for certain specific applications, they have their own drawbacks that are discussed throughout this paper.

Current state-of-the-art optical fiber sensing (OFS) for physical intrusion detection is primarily based on the use of fiber Bragg gratings (FBGs) [5]. FBGs are specifically sensitive to temperature and pressure variations. However, the signal from an FBG can be manipulated so as to act as a sensor for a large array of environmental disturbances. FBGs have been shown to measure changes in level, weight, and flow, as well as more esoteric measurands such as magnetic field and tilt angle [6]. The versatility of FBGs makes them ideal for security applications.

In this paper, we review the different optical fiber based techniques used for intrusion detection, beginning from the late 1980s through to present state-of-the-art practices. A comparison of the advantages and disadvantages of each system is discussed in reference to the core sensing and interrogation method, as well as the networking capability and the effectiveness of the system as a whole for securing a property against security breaches. This review is restricted

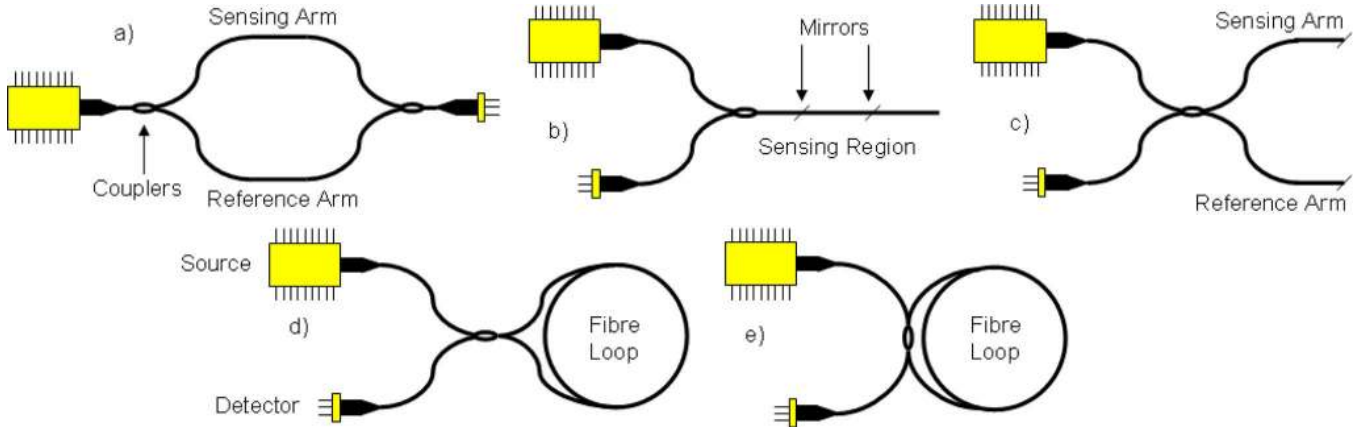


Fig. 1. Intrinsic optical fiber interferometers: (a) Mach-Zehnder; (b) Fabry-Perot; (c) Michelson; (d) Sagnac; and (e) ring resonator.

to work in the literature and does not contain a comprehensive review of commercial products.

II. FUNDAMENTALS OF OPTICAL FIBER SENSING

Nearly all fiber optic sensors (FOS) utilize the strain-optic effect, whereby an applied strain from an external measurand, such as a pressure wave, causes a change in refractive index of the fiber. This change can be measured in a number of different ways, with the goal in security applications to correlate the change into the magnitude and location of a vibration caused by an intruder.

A. Interferometry

The theory of interferometry is mature and well understood, and will not be explicitly explained here, although in general for optical fiber sensing, an optical wave source is split using a 50-50 coupler and directed, either through two separate fibers or in opposite directions through the same fiber, before being recombined at a detector. Any external influence on the fibers will cause the two waves to have a phase imbalance. In security applications this technique can be used to detect the vibrations from an intruder's footsteps. OFS techniques utilizing interferometry come in an array of different configurations. These configurations include; Mach-Zehnder, Fabry-Perot, Michelson, Sagnac, and ring resonance, as shown in figure 1. Each of these configurations are discussed in detail in [7].

In a multimode (MM) fiber, the different modes of the input signal interfere with each other whilst traveling down the optical fiber, which can then be used to create an image or speckle pattern [8]. This method is called speckle pattern analysis or intermodal interference. Any external disturbance acting on the fiber whilst the light travels through it, will cause the image to change, resulting in detection of the disturbance.

B. Scattering Techniques

Optical time domain reflectometry (OTDR) is used extensively in distributed sensing. When a short light pulse is launched into an optical fiber, some of the light is reflected back off the entire length of the fiber. Three different types

of light make up the backscattered light; Rayleigh, Brillouin, and Raman light, which are explained in detail in [9] and depicted in figure 2. The vibrations caused by an intruder may change the amplitude, phase and frequency of the reflected signals, which again can be used to determine the location of the intruder.

C. Fiber Bragg Grating Sensors

FBGs [10], [11] are discrete spectrally reflective components which are written into the core of an optical fiber using a high intensity light source and a phase mask to create alternating regions of different refractive indices. The difference in refractive indices results in coupling between forward and backward propagating waves [12], [13]. Figure 3 shows the fundamental principle of operation for a FBG. The grating can be modelled as an interference filter whereby Fresnel reflection at each interface and the regular period of the grating, Λ , results in constructive interference in the reflection at a specific wavelength, called the Bragg wavelength, λ_B . The Bragg wavelength is given as,

$$\lambda_B = 2n_{eff}\Lambda, \quad (1)$$

where n_{eff} is the effective refractive index of the grating for the guided mode in the fiber core.

Hence, any external environmental disturbance that causes a change in the refractive index or period of the grating results in a change in the Bragg wavelength, and as such can be detected by a FBG. The change in Bragg wavelength as a function of induced strain, ϵ , is given by [11];

$$\Delta\lambda_B = \epsilon\lambda_B \left(1 - \frac{n_{eff}^2}{2} [p_{12} - \nu(p_{12} + p_{11})] \right), \quad (2)$$

where p_{11} and p_{12} are the strain-optic coefficients and ν is Poisson's ratio. A review of FBG sensors and interrogation techniques is given in [6].

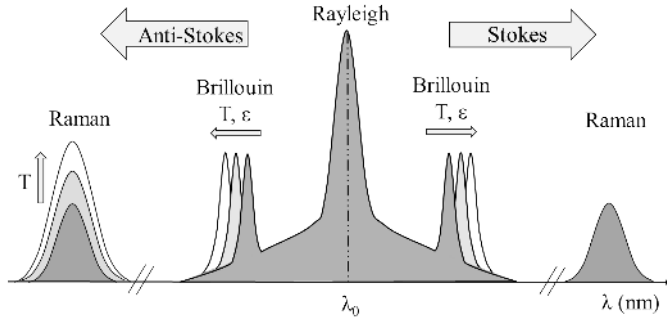


Fig. 2. Backscattered Rayleigh, Brillouin and Raman light in optical fibers, adapted from [14].

III. THE HISTORY OF FIBER OPTIC SENSORS FOR INTRUSION DETECTION SYSTEMS

A. Early Fiber Optic PIDS, prior to 1995

In the 1981 Carnahan Conference on Crime Counter Measures, Montgomery and Dixon [15] described the development of fiber optics as a transmission medium (for pressure, sound, magnetic field, temperature, light, and motion sensors), as well as intrusion detection sensors through fiber breakage. The article discussed the use of fiber optic cables concealed in wire fences or embedded in glass panes for detection of intruders who break the wires or glass. It also mentioned General Telephone & Electronics (GTE) Corporation's development of fiber optic security fences based on the detection of sound near the fence. However, the paper lacked detail regarding the specific demodulation techniques that were under development. In addition, fiber optic seal collars were described where a bundle of optical fibers in a loop were used to secure an enclosure. The ends of the large bundle of optical fibers were imaged and formed a particular pattern. If the seal was broken and replaced by another bundle, the pattern formed would be different.

In 1983, the first scientific paper on FOS which specifically described a technique for intrusion detection applications other than fiber breakage, was reported by Rowe [16]. The paper detailed work performed at GTE from 1978 which investigated the feasibility of an optical fiber based in-ground intrusion detection sensor. The study stated that while there was only a small change in the amplitude of the signal due to micro-bending of the fiber from an intruder, there was a significant rotation of the speckle pattern that was analyzed. Hence, a method for converting the change in polarization into a measurable electronic output for practical applications was proposed. The technique simply splits the horizontal and vertical polarized components and uses a difference amplifier to convert the signal into a usable voltage. The results showed an intruder could clearly be detected when the cable was buried in different types of gravel and at different depths. It was suggested that a threshold detector should be used to minimize the number of false alarms such that only those signals that exceed the threshold value trigger an alarm. In addition, the study showed rain caused no observable effect, whilst an attempt to uncover the fiber was clearly detectable.

In 1984, Robertson and Rarick [17] reported the progress

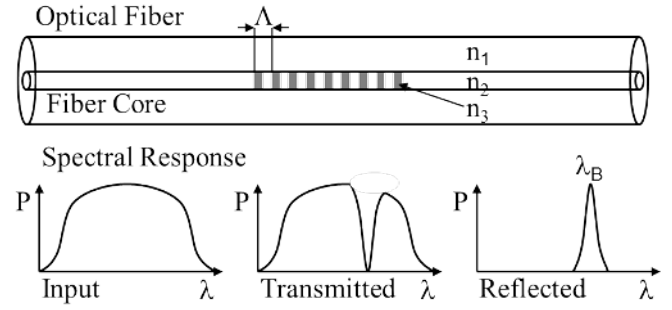


Fig. 3. Fundamental principle of operation for a fiber Bragg grating.

of the U.S. Army Belvoir Research and Development Center into optical fiber technology for physical security. The paper generally focused on the use of fibers as a transmission medium, although the report also describes the development of a fiber optic pressure mat based on micro-bending for the detection of intruders.

From these first advancements came a number of fiber optic security based systems in the following years. In their early work, Leung et al. [18], [19] discussed their in-line security sensor system, which was also based on intermodal interference. Their initial results showed that a cable buried at a depth of 30cm was capable of detecting vibrations from a 60kg person walking 3m from the fiber. They also outlined the improved sensitivity of a distributed sensor system containing 8 fibers which had a resolution of 10m over a distance of 2.5km. They used a system with a cable buried at two different depths, characterized low sensitivity and high sensitivity systems, and discussed the trade-off between sensitivity and false alarm rate (FAR) [19]. Later, the same group investigated the performance of an optical fiber multi-sensor network using frequency domain multiplexing. Although the system was ineffective due to cross talk, which caused phase errors, it was an important step in attempting to solve problems associated with multi-sensor networks [20].

In the 1988 Carnahan Conference on Security Technology, three papers were published on the use of fiber optic cables in PIDS [21]. Whilst all of these papers focused on the use of the fiber as a data transmission medium, it is worth noting the gradual increase in fiber optic technology for security applications through the 1980s. The report by Nason et al. [22], detailed the progression of the stand-alone security systems in the 1970's through to the centralized monitoring systems in the 1980's. This centralization meant that alarm and video data needed to be sent over much further distances at greater speed, meaning fiber optic systems were then a viable solution. The paper by Schwalm [23] reported the development of fiber optic components such as splitters, couplers, multiplexers, switches, and sensors (such as in-fence intrusion detection sensors), as well as cables, light sources, and detectors. The ongoing development of each of these components was the driving force behind the growing demand for fiber optic systems in security applications.

Cogdell [24] suggested, with the use of multiplexing, that multiple FOS can be contained within one optical fiber which

could then be processed away from a protected area, forming the basis of a perimeter defence system. This advancement came from a novel transduction mechanism for monitoring DC measurands. The non-linear displacement to strain mechanism meant it was possible for a single interferometer to be used to monitor a number of sensors.

In 1989, Hazen et al. [25] performed a study which tested several different detection methods to be used as buried pressure sensors. The first method, bending loss, was not sensitive enough when buried in the ground but was better suited to applications where the fiber experienced a significant strain, such as on a perimeter fence. The second method, speckled pattern variation, now referred to as intermodal interference, was the most sensitive method available. However, this mechanism was also extremely sensitive to external factors such as ambient conditions. Therefore, a focus was placed on the polarization of single-mode (SM) fibers which occurred when pressure was applied to the FOS. Interestingly, in order to solve a number of issues, the team decided to use two independent channel detection systems with two analyzers at about 45 degrees from each other. This may be one of the first cases of using parallel fiber optic systems to eliminate detection problems.

In the same year, Kotrotsios and Parriaux [26] reported a fiber optic alarm system which measured the difference in transit time of separate modes launched down the fiber. They claimed this technique increased the dynamic range of the system with respect to reflection based techniques. They also showed that the resolution of the system could be improved by using a Michelson interferometer to analyze the difference in the modes.

Skogmo and Black [27] described a fiber optic barrier integrity monitor, similar to earlier work using the fiber as a breakage sensor. The integrity of a barrier, such as a fence or wall, was monitored by threading optical fibers into the barrier and launching light into the fibers. If there was a loss of light signal, then a breach had occurred. This method was extremely simple, using the optical fiber as a breach switch.

In 1990, Griffiths [28] discussed the developments in optical fibers as intrusion detection sensors focusing on the trade-off between high probability of detection (POD) and low FAR for the different approaches taken. He stated fiber optic continuity sensors, such as those embedded within a barbed steel tape and attached to a fence or wall, were the most reliable sensors and offered very low FAR and extremely high POD. An alarm would be triggered if the fiber is cut, broken or severely distorted acting as a digital breach switch. Speckle pattern sensors could be embedded in the ground or in a fence to monitor low frequency pressure disturbances or high frequency vibrations, such as acoustic signals, although the effectiveness of the system depended on the signal processing and alarm thresholds implemented, and therefore the ratio of POD to FAR. Attenuation sensors were also described for monitoring fiber optic transmission lines. If an attempt was made to tap into the line, then there would be a loss in signal strength and an alarm would be triggered. The choice of technique to implement depends on the specific application and the overall requirements of the security system.

Five years later in 1995, Griffiths [29] reviewed the developments in, and applications of, fiber optic intrusion detection sensors. He described intrusion detection as the elusive question, where optical fibers were the answer. The paper makes a correlation between the developments of fiber optic technology and supporting technology. Parallel developments in electronic components such as laser diodes, as well as connectors, splicers and hand tools, have rapidly increased the use of FOS, whilst minimizing installation and repair times. Two forms of fiber optic sensing methods were outlined; continuity and disturbance. Continuity is a method whereby a receiver continuously receives a low power optical signal and an alarm is triggered if the light path is broken as previously detailed. Disturbance refers to an analogue signal where the variation in light intensity or distribution of reflected light signals represents a certain value of a measurand. A number of different applications in physical security are mentioned. These include taut wire systems where an alarm is triggered if the wire is broken; and fiber optic door contact, where the door contact breaks a light path using a magnet as a switch. This is the basic idea behind an optical fiber reed switch [30]. Furthermore, a fiber optic mesh is detailed, where two or more fibers are woven together forming a mesh barrier; including a robust form used as an underwater barrier. A buried pressure sensor is also described using speckle pattern detection. Moreover, Griffiths describes the progress and advancements made by integrated systems. These high tech security systems communicate simultaneously and control all levels of surveillance and alarm handling.

Bryson and Hawkes [31], [32] described a novel fiber optic perimeter protection system. Their system used multiplexed reflectometric interferometry, originally developed for hydrophones, whereby a vibration from an intruder caused a phase shift in the RF carrier which was demodulated by an optoelectronics unit. The main advantage of this technique was the ability to multiplex a large number of sensors either buried or fence mounted. Interestingly, although their system used reflective x-couplers, they proposed the use of FBGs to increase the number of sensors and improve the system. A comprehensive study of the system performance was performed with a comparison of their technique with buried electronic sensors. An analysis of different threat signatures from an intruder walking or crawling across the fiber, or a vehicle crossing the fiber was undertaken. The detection capability in terms of range and effectiveness of reducing false alarms was also performed. The paper also described two methods of configuring the system to facilitate the large amount of processing power required. The system could be either connected to a separate control system via a standard computer interface, acting as a black box, or a stand-alone 'human-machine' interface could be implemented using commercially available alarm software or customized software in which different sections of a PIDS are overlaid on an aerial photograph.

B. Fully Distributed Fiber Optic PIDS

The specific application in terms of the spatial resolution required and the length of the perimeter would ultimately

determine which fiber optic sensing technique should be implemented. A comparison of some of the advantages and disadvantages of each technique is given in table I.

Park and Taylor [33] reported an in-ground PIDS based on an all-fiber Michelson interferometer. They showed that this method is capable of detecting a person on foot and a vehicle passing over the fiber, and that the amount of pressure applied is proportional to the phase change received. Two years later, in 1998 [34], the same group report an OTDR system with a resolution of 400m over a 6km length of fiber.

Bush et al. [35] produced an extensive report on their buried fiber intrusion detection sensor. Their system incorporated a low cost depolarized Sagnac interferometer. The authors detail the advantages associated with this method, which included high sensitivity and low FAR, as the interferometer was extremely good at distinguishing between singular events and background disturbances. The report described their system in detail, including the physical layout and the optoelectronic circuit used. The results from their field tests showed their system could detect an intruder performing different types of walking and crawling methods, with the aim of by-passing the system.

In 1997, two papers were produced by the Institute of Optoelectronics at the Military University of Technology in Poland. These papers would be the first of many based on fiber optic perimeter detection systems, produced by their research group over the following decade. One of the papers by Ciurpinski & Maciejak [36] describes a perimeter disturbance localization system based on a Mach-Zehnder interferometer coupled with a Sagnac interferometer. The other paper by Szustakowski & Ciurpinski [37] is a review article describing various optical fiber based sensing techniques such as OTDR, Rayleigh interferometers, continuous wave interferometers, and frequency domain sensors based on fluorescent properties of silica fibers. However, the paper is only an overview of these methods and suggests much of the work in each of the areas is ongoing and needs further research.

From 2001 to 2008, Szustakowski et al. [38]–[44] report a new generation of fiber optic perimeter sensors in Sagnac loop configuration. They showed their system could be used for both in-ground and fence mounted perimeter detection. The system uses a digital signal processor to distinguish between disturbances from animals, intruders, and the environment. The various disturbances were cataloged in a look-up library, significantly reducing the number of false alarms. Their group report a number of different configurations using Sagnac and Michelson interferometry, as well as discussing the accuracy of each system, and their ability to classify various events.

Interestingly, all of their recent work focuses on a security system based on intermodal interference or modalmetric detection, as they now refer to it [45]–[47]. The technique is almost identical to the earlier work on intermodal interference except they have performed a much more detailed analysis of the integrity of the system. Using highly sensitive focal plane array cameras for analyzing the output from the MM fiber, they verified the most appropriate optical power for the source and the most effective configuration in terms of lengths of sections of SM fiber, and the type of connections used between the

SM and MM fibers. In addition, an analysis of the frequency response of the system was made. The focus of their study was the protection of museum collections as their system was particularly sensitive to touch and vibrations.

The group then combined the modalmetric sensor with an interferometer, in which one arm of a Mach-Zehnder interferometer contains the modalmetric sensor, forming a hybrid system with improved response time [48]. Finally, they proposed that the system could be used to monitor the integrity of fiber optic data cables [49].

The Senstar-Stellar Corporation, established in 1981, are one of the world's leading companies providing perimeter security in a large array of different industries and sectors. From 2001, Maki et al. [50]–[53] described one of their technology solutions, IntelliFIBERTM, a fiber optic micro-bend sensor cable system used for perimeter intrusion detection. Their technology supports three different cable types; 2-core MM fiber allowing for signal loopback, 4-core for additional networking capabilities, and 4+2-core comprising of four optical cables and 2 copper cables for power the electronic processors. The additional copper cables within the same housing eliminates the cost associated with running separate cables and produces a generally more robust cable overall. As the company offers a solution to end users, the system was rigorously tested and offers a 95% POD and low FAR from the environment due to adaptive signal processing algorithms. The success of their fiber optic sensing system has been enhanced by the simultaneous development and integration of their digital processor electronics technology, Intelli-FLEX.

Crickmore et al. [54], [55] developed a complete land and sea based security system using interferometric fiber optic sensors with the interrogation again based on Michelson interferometry, essentially identical to the Bryson and Hawkes [31] technique, with some additional components such as fiber amplifiers. For land based detection, they used a combination of discrete and distributed sensors. Whilst distributed sensors in buried cables formed a continuous sensing region, discrete accelerometers were also used as they are typically much more sensitive. The accelerometer developed was based on the mandrel principle; any vertical motion of the mass, transferred pressure to the optical fiber wrapped around the rubber, which in turn caused a change in its length which could then be detected by the interferometer. The distributed sensors could detect footsteps up to 5m from the cable, whereas the discrete sensors could discriminate signals from noise up to 15m from the sensor. This combination of discrete and distributed sensors made it easier to characterize the various targets. The system used both wavelength division multiplexing (WDM) and time division multiplexing (TDM) to maximize the number of sensors. Moreover, the system was designed to be interfaced with an open architecture processing system capable of detecting and tracking targets and displaying them on a map on a PC.

Whilst also based on interferometry, the in-ground detection method developed by Kezmah et al. [56] seems to be a cheap, effective technique as it does not require expensive optoelectronic demodulation schemes. The two arms of the interferometer are embedded within the same fiber casing, although they both have a different buffer layer. This means

TABLE I
A COMPARISON OF THE DIFFERENT PID TECHNIQUES

Technique	Application	POD	FAR	Interrogation	Cost	Advantages / Disadvantages
Breach / break	in-ground/fence	very high	very low	simple	low	distributed / limited applications, no multiplexing
Speckle Pattern	in-ground	med - high	low - med	complex	high	distributed / limited applications
Interferometry	in-ground/fence	high	low	complex	high	distributed, long distance / low spatial resolution
OTDR	in-ground/fence	high	low	average	mid - high	distributed, long distance / low- med spatial resolution
Bending loss	in-fence	high	med	simple	low	distributed / limited applications
FBG	in-ground/fence/doors	high	low	simple/complex	low - high	multiple applications / quasi-distributed

that the disturbance caused by an intruder differs significantly from each arm, altering the returning signal by a number of periods. The main advantage of this technique, other than reduced cost, is that the optoelectronic unit is simple and therefore completely programmable; meaning the sensitivity of the signal can be adjusted depending on the specific environment and the level of external noise.

Similarly, Mahmoud and Katsifolis [57] designed a fence based perimeter system, where two sensing fibers and an insensitive lead-out fiber are embedded in a single fiber casing. Their system utilizes a 'microstrain locator' developed by Future Fiber Technologies (FFT) and is based on a bidirectional Mach-Zehnder sensing system which is capable of locating an intruder anywhere along the sensing arms. Their study focused primarily on event classification in order to increase the POD and reduce both the nuisance alarm rate (NAR) and the FAR [58], [59]. This is achieved using complex algorithms that suppress continuous nuisance alarms such as rainfall and wind, as well as recognizing events and classifying them into groups, such as cutting events and climbing events. The system demonstrates the effectiveness of an 'artificial neural network' as a robust classification system that can independently detect and classify an array of intrusion and nuisance events. It is worth noting that FFT is currently a world leader in the design, development, and implementation of optical fiber based security systems with offices in the USA, Australia, Europe, India, and the Middle-East.

A study by Yan et al. [60] focused solely on improved signal processing. They formulate an event classification algorithm for vibrations in a perimeter security system which analyzes both static and dynamic signals. A multiclass classification tree of support vector machines based on wavelet packet decomposition was used to recognize vibration signals with a 94.6% recognition rate from nine different events.

Lan et al. [61] developed a fence mounted disturbance sensor for security application which was also in Mach-Zehnder configuration. Although their design worked effectively at detecting an intruder attempting to climb the fence, environmental disturbances made intrusion recognition difficult and further research on recognition algorithms was required.

McAulay and Wang [62] used a Sagnac interferometer sensor system for intrusion detection. They showed that by having two loops of different lengths it was possible to not only detect an intruder, but also ascertain their location. Although they stated their system could be used as perimeter

defence for an area with a circumference of up to 100km, they do not mention how precisely an intruder's location can be determined.

From 2008 to 2012, Kumagai et al. [63]–[65] produced three intrusion detection papers describing their system which is based on Sagnac interferometry incorporating polarization maintaining fiber. Their fence mounted system was specifically designed to be less sensitive to small vibrations from environmental disturbances as it was installed in the perimeter fence of a facility on the coast of Japan. The results compared the detection rate of intruders with the number of false alarms produced by increasing wind velocity. With the aid of a camera that was triggered to record when an alarm was triggered, their system had a 100% detection rate with a very low number of false alarms even with wind speeds of up to 45ms^{-1} .

Li et al. [66] developed a fiber optic perimeter PIDS based on Mach-Zehnder and Sagnac interferometry. Their system uses a hybrid of TDM and WDM. A pulsed broadband source is split into 6 channels using a WDM. Each of the signals are then put through a 1×20 splitter where each of the 20 ports has a different optical delay line, resulting in 120 discrete optical sensing units. Each of the sensing units could be separated by up to 500m, meaning the whole system could cover a maximum distance of 60km. As their system utilizes state of the art signal processing and data acquisition, over a six month period, it had a FAR of less than 4%.

In 2013, Wu et al. [67] reported a WDM Sagnac PIDS that had a resolution of $\pm 25\text{m}$ over a 50km fiber cable. The system used a single Sagnac loop with two different wavelengths simultaneously launched into it with four detectors used to demodulate the signals.

Speckle pattern analysis, as implemented by Rowe [16], can also be used as a technique for fence mounted intruder detection. Choi [68], Arnaoudov et al. [69], and Kwon et al. [70] all report similar perimeter fence sensing systems based on this technique. The method uses MM fiber that produces a speckled pattern when light is launched into it. Any disturbance caused by an intruder changes the pattern which, after signal processing, can be represented as a fluctuation in voltage. All three groups reported effective results although each of their systems required extensive signal processing to remove external noise caused by the environment. Arnaoudov et al. [69] facilitate the signal processing using a microcontroller and produced a relatively simple hand held sensor module, whereas Kwon et al. [70] use a PC based system

running a National Instruments LabVIEW program for signal processing.

Many groups have reported the use of OTDR for intruder detection. OTDR is based on Rayleigh backscattering from the fiber itself, and is good for extremely long distances, from 1km to 100km. However, an intruder's location can usually only be localized to approximately the nearest 100m. Blackmon and Pollock [71] describe their system which is based on OTDR using a laser source which has a very long coherence length for improved sensitivity and resolution. Their system, known as Blue Rose, is in operation at the Naval Undersea Warfare Center in Newport, USA. The Blue Rose system uses standard single-mode optical fiber with an elastomeric coating which is low cost, and can be used for long perimeter and border security applications. Vdovenko and Gorskov [72] report work on a simulation of a phase sensitive coherent OTDR response to different disturbances which correlates well with earlier work by their group on phase sensitive fiber reflectometers [73], [74].

From as early as 2003, Choi, Juarez, and Taylor [75] described their buried PIDS that specifically used phase sensitive OTDR (ϕ -OTDR) which was designed to enhance coherent effects that are caused by the presence of an intruder or from seismic disturbances. Their simulation results predicted a 35m resolution and a 90m resolution over a range of 10km and 90km, respectively.

From 2005, Juaraz et al. [76]–[80] reported their physically realized system which used a narrow linewidth laser ($< 3kHz$). The orthogonal polarizations of the backscattered light were sent to separate receivers. The waveforms were then subtracted from previously stored traces to show any localized phase discrepancies produced by the vibrations of an intruder. Their results showed detection of footsteps up to 4.5m from the fiber and vehicles traveling near the fiber, consistently over a distance of 12km.

Using the same technique, Madsen et al. [81] showed that the signals received from a person walking and a car traveling nearby can easily be distinguished after signal processing. The advancements made in signal processing and data acquisition significantly improved the probability of detecting an intruder whilst, at the same time, reduced the risk of false alarms that may have arisen from the lasers center frequency drifting. The authors also stated their system was sensitive enough to determine the weight of an intruder, as well as showing the amplitude of the signal detected by a vehicle was proportional to the distance it is from the sensor [82]. Furthermore, their system could perform real-time processing utilizing a field programmable gate array (FPGA) and incorporating LabVIEW software for visual monitoring and control of the perimeter sensor [83]. The system was however limited by the amount of memory on the FPGA unit. This type of work is extremely important in realizing advanced security systems that can anticipate potential intrusions before they occur, by recognizing the difference between animal, human and vehicle signatures, and reducing the number of false alarms.

The optical fiber sensors group from the University of Electronic Science and Technology of China (UESTC) [84] reported a distributed PIDS using a combination of ϕ -OTDR

and polarization optical time domain reflectometry (POTDR). Both the phase and polarization of the transmission light were sensitive to disturbances caused by an intruder; by combining these two techniques their system was extremely reliable. Using a 14km long fiber, the experimental results showed the system had a spatial resolution of 50m with 100% detection rate. Their group also showed a successful ϕ -OTDR PIDS that was capable of detecting intrusion along the entire length of a 62km cable by using a specifically designed optical fiber which was encased in a fiber reinforced plastic [85]. In 2009, this was reportedly the longest and most sensitive ϕ -OTDR distributed sensing system to date. Their more recent work describes a 106km fence based system using POTDR with bi-directional pump lasers to amplify the signal [86]. Again, the group state that at the time of publication, this was the longest perimeter fence system using optical fiber based intrusion detection. However, the additional components required add to the complexity and the cost of the system.

From 2011-2013, Wu et al. [87]–[91] from the same group reported a FBG based intrusion detection fence system. They reported the progress of their quasi-distributed FBG system by analyzing a number of different algorithms to improve the POD and reduce the NAR. These methods include; autocorrelation characteristics analysis, where the proposed system has a predicted POD of 99.5% and a NAR of 0.5% [87], principle component analysis, which results in a recognition rate of 96.52% for eight type of intrusion methods [88], and 3-layer back-propagation artificial neural network, which has a recognition rate of 96.03% [90]. In addition, they stated their system could predict fire threats without any additional components [89]. In 2012, Rao wrote a short review paper on the research performed by the optical fiber sensors group at UESTC [91].

In 2014, Wu et al. reported an OTDR PIDS which utilizes multi-scale wavelet decomposition [92]. The report, from a year and a half long trial of a PIDS for a 220km long national borderline fence in China, stated the system was successfully implemented but did not state the actual recognition rate. Both the OTDR and FBG based systems used similar intrusion detection process flow.

Klar and Linker [93] reported a system specifically designed for detecting underground tunneling used for smuggling, using smart underground security fences. The detection system was based on wavelet decomposition of Brillouin optical time domain reflectometry (BOTDR) and was capable of detecting tunneling vibrations whilst also being insensitive to above ground noise. The approach was previously used in geotechnical engineering for monitoring the excavation effects of large underground tunnels for transportation and water systems. The technique was then adapted to detect soil vibration caused by the excavation of much smaller tunnels. The signal processing incorporated a neural network algorithm designed to specifically recognize the wavelet coefficients from tunnel signatures. Their results indicated that their system could detect tunnels as deep as 20m with a diameter of 0.5m or larger.

Likewise, Ferdinand et al. [14] developed a system based on BOTDR. The specific design of the Brillouin analyzer was not detailed, however, its characteristics were 1m spatial

resolution, over 10km span, $\pm 2.5\mu\text{m}/\text{m}$ strain resolution, and a 3s response time. As the system was developed as a commercial product, a strong focus was placed on the installation technique and the development of a user friendly interface. The field deployed system utilized two separate sensing cables to compare detections and eliminate false alarms.

Jia et al. [94] designed an in-line intrusion sensor system based on interferometry, comprising of a 3dB coupler and a Faraday Rotating Mirror. This technique used the phase angle of the detection signal to determine the location of the intrusion. Their simulations showed that their system could locate an intrusion within a distance of 128m along a 40km sensing fiber. They claimed by using a Fast Fourier Transform method to calculate the phase angle of the signal, rather than loop structures; their system requires simple signal processing and hence is low cost.

A year later in 2009, the same group [95] reported an in-line Sagnac perimeter fence system and a ϕ -OTDR PIDS. Their results showed the properties of walking or running human-beings. They described the gait characteristic, which is the time for an average complete walking cycle, i.e. 2 steps, which is 1.216s; this includes the step period which is about 0.6s and the foot step down time which is 0.2s. They reported a person running has a step period of about 0.4s with a foot step down period of about 0.2s. Therefore, it was suggested that a signal that has a period of 0.3-0.75s and a duration of 0.15-0.25s must be a human signal, rather than a periodic signal from an animal or a random signal from external noises such as weather fluctuations. Again these results were significant in pre-empting an intrusion. The methodology seemed to be effective in determining a human intruder at extremely long distances, up to 40km from the detector. However, there was no reference to how near the person needed to be to the fiber for the signal to be recorded. Also, the person must be walking along the length of the fiber and the study did not include results for a person walking perpendicular to the fiber, hence the term in-line. Moreover, although the methodology was reported to be much cheaper than others, the cost of interferometric detectors is significant, compared to other techniques. The group later reported work on a high speed data acquisition system specifically developed for a chaotic fiber optic fence system [96]. The system was designed for use on a high speed digital oscilloscope developed using LabVIEW. A real-time sample rate of 1GS/s was reported.

Likewise, Wang et al. [97] reported an improved OTDR system using extensive signal processing. Their technique, called complementary correlation OTDR, used Golay codes to overcome limitations between the maximum sampling rate and frequency of the transmitted signal. The physical setup was fairly simple as the system analyzed the transmitted and reflected power to determine if an intrusion had occurred. The implementation of Golay codes increased the signal to noise ratio and hence improved the dynamic range of the system.

Two papers by Okazaki et al. and Morshed reported PIDS essentially based on OTDR. However, the focus of the studies was on novel fibers. Okazaki et al. [98] reported a hetero core fiber where a section of the $9\mu\text{m}$ core was reduced to $3\mu\text{m}$ which acted as an intensity based vibration sensor. The

technique was specifically used to detect vibrations caused by a potential intruder trying to cut or break a glass window pane, by attaching the fiber sensor to a metallic needle attached to a window. The study reported two configurations of the sensor with a trade-off between sensitivity and physical size. Both types were highly sensitive and independent of temperature fluctuations. Morshed [99] reported a very similar technique using a section of multimode fiber joined with FC/PC connectors to a single mode fiber, as the intensity based pressure sensor. The main advantage of this technique was that it was low cost and simple.

Of the four fiber optic based technological approaches, OTDR and speckle patterns (based on non-linear effects), interferometry (including Michelson, Sagnac, and Mach-Zehnder), and FBGs, the latter has seen a great deal of interest in recent years, with significant growth in the security sector in the last decade [100]. However, it has yet to be fully exploited in PIDS. In 2002, Spirin et al. [101] reported a small scale system which was based on OTDR, that also uses low reflective Bragg gratings to segment the fiber. In this way, the system could use a continuous light source and determine in which section perturbation occurred by analyzing the transmitted and reflected optical power. Although they claimed this was a simple low cost technique, in order to scale up the system, many Bragg gratings would be required to maintain the spatial resolution of the system and this would increase the complexity of the signal processing and the overall cost. In fact, the group resorted back to a traditional OTDR system for a large scale test.

C. Quasi-Distributed Fiber Optic PIDS

In 2005, Zhang et al. [102] demonstrate an in-ground seismic wave sensor for detection of troops and vehicles in military applications. They used a network of FBGs that were fixed to an inert mass attached to a spring. This technique amplified the seismic signal from a potential intruder which was then detected by the FBG. This was the first PIDS to utilize the true reflection characteristics of a distributed network of FBGs. The technique used demodulation or reference gratings to convert the shift in wavelength caused by an intruder in to a change in optical power. An example of a single channel interrogation scheme is shown in figure 4.

Four years later, the same group [103] reported significant improvements on their FBG seismic sensor system including; a scanning laser wavelength-based demodulation system, a digital lock in amplifier and FPGA, and a carbon fiber cantilever for overall improved performance. Their results clearly showed the increased sensitivity and reduced response to noise of the FBG based sensor with respect to an electromagnetic sensor.

The study by Jiang et al. [104] expanded on the use of distributed FBG for invasion monitoring. They used Empirical Mode Decomposition and wavelet packet characteristic entropy algorithms to decompose the signals from multiple FBGs to determine the location of an intruder, through in-ground detection and fence detection. The technique was fairly comprehensive and it was effective at analyzing the vibrational signals from a number of different FBGs and calculating an

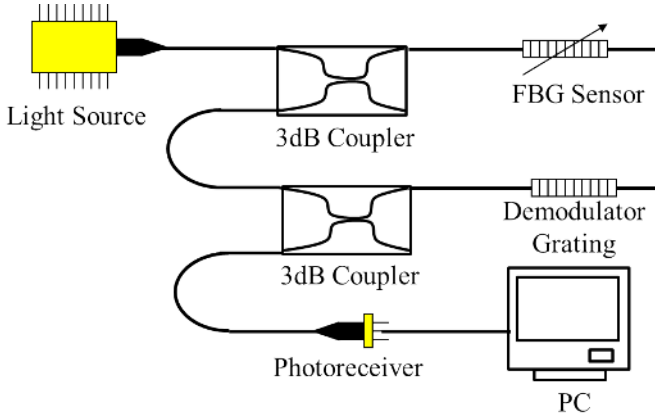


Fig. 4. Interrogation of FBG based seismic system, adapted from [102].

intruder's location. A simple graphical user interface (GUI) was developed using LabVIEW, making it possible to monitor the perimeter in real-time. However, it did not allow for determining false alarms and needed to be optimized.

Hao et al. [105] reported an armored cable based FBG perimeter intrusion detection sensor. The report detailed the results from an in depth field trial showing the system could resolve nuisance events and uses a commercial FBG interrogator to resolve the signals from an array of sensors. However, it does not detail the design of the sensor and simply states that the armored cable protects the sensor against rodents and is crush resistant.

Most recently in 2014, Catalano et al. [5], [106] reported a FBG PIDS for protection of railway assets. They proposed the use of quasi-distributed FBG strain sensors embedded in a pressure mat for perimeter protection and FBG accelerometer sensors for rail track protection. Their results showed an intruder could easily be detected when pressure was applied to the mat or when walking close to accelerometer sensors through detection of acoustic emissions generated from the footsteps. Both sensor networks were integrated into a single system, demonstrating that different FBG sensor arrays could form the basis of advanced PIDS using the same core technology.

The author's own research on optical fiber PIDS is based on FBG technology, but specifically focuses on increased flexibility and usability of low cost complete security systems. This includes the development of an FBG based reed switch for monitoring windows and doors [107], a simple FBG fence mounted system, and the implementation of in ground quasi distributed FBG digital and analog pressure sensors in different flooring materials [108], [109]. Furthermore, the aim is to achieve seamless integration of optical fiber sensors with traditional electronic controllers by utilizing simple, but innovative interrogation techniques [110]. This has the potential to increase the penetration of optical fiber PIDS into both mainstream commercial and residential applications. In addition, it has been shown that optical fiber sensors could be integrated into wireless sensor networks for specific applications [111], capitalizing on the benefits of both technological approaches, with the potential of forming advanced, robust

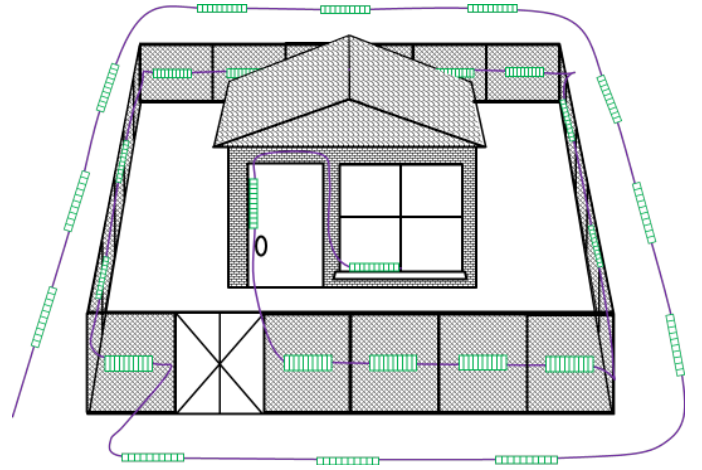


Fig. 5. A schematic of an IDS incorporating in-ground FBGs, fence mounted FBGs, and FBG reed switches within a single fiber.

PIDS. An example of an PIDS incorporating in-ground FBGs, fence mounted FBGs, and FBG reed switches, is shown in figure 5.

IV. THE FUTURE OF OPTICAL FIBER SENSORS FOR INTRUSION DETECTION SYSTEMS

As discussed throughout this paper, the development of all optical fiber based systems for intrusion detection has progressed significantly throughout the last few decades because of the well understood advantageous properties of optical fiber sensors with respect to physical security applications. OTDR is by far the most cost effective solution for very large perimeter intrusion detection. With the implementation of multiple detection methods, such as phase sensitive and polarization sensitive OTDR in conjunction with the significant advances in signal processing for increased sensitivity and resolution, the use of OTDR PIDS will inevitably increase.

Interferometry based systems may still be utilized in specific applications where high precision is required. However, in general the cost of implementing these systems will mean cheaper alternatives would be favored where possible.

The use of FBG sensing technology is expanding rapidly in many applications, such as structural health monitoring and is now starting to emerge into more mainstream industrial processes. This expansion will aid the growth of FBG sensing in PIDS. It has been clearly demonstrated that the improvement of signal processing techniques has a direct impact on the versatility and effectiveness of FBG based systems to ensure high POD and low FAR. Moreover, as the diversity of FBG sensors for intrusion detection increases, such as FBG based reed switches, FBG based in-ground digital and analog pressure sensors and in fence FBG sensing systems, the penetration of FBG technology in physical security applications will increase. FBGs have potential to form a complete security system based entirely on a single technology. In addition, as low cost, simpler interrogation techniques become available for seamless integration into electrically based security systems, incorporating surveillance cameras for example, the use of FBGs in PIDS will further increase.

The authors have identified two areas that will provide significant opportunity for improvement of optical fiber based PIDS,

- 1) electrical and optical integration, and
- 2) improved signal processing for large sensor capacity systems

The integration of different quasi-distributed sensors with low cost electronic controllers will mean a complex and complete PIDS, utilizing digital and analog FOS, and surveillance cameras, can be monitored through one simple supervisory control system. Moreover, surveillance cameras could be powered over optical fibers using photonic power converters, creating an almost entirely optical based system. Large systems, incorporating high numbers of densely packed sensors, will require improved signal processing and data acquisition techniques. Through pattern recognition algorithms PIDS could pre-empt potential intruders in a non-invasive manner. For example, it may be possible to detect unusual movement of a potential intruder around a facility before a physical breach has occurred. Furthermore, whichever fiber technology is implemented, and in order to be a successful system, professional installation processes and user friendly interfaces are an important consideration for the final system design.

V. PATENTS FOR FIBER OPTIC INTRUSION DETECTION SENSORS

It is worth noting that, whilst it is stated in this paper that the first scientific report of an optical fiber based PIDS was in 1983, there were earlier patent applications. The first patent application for a fiber optic security system was filed in 1978 by John A. Sadler [112]. However, this system was essentially an electronic sensing system connected to a control unit by an optical fiber, although, if the fiber was cut an alarm would be triggered. The first truly fiber optic intruder alarm system patent was filed in 1980 by Charles D. Butter [113]. His system used a buried multimode optical fiber as the sensing element itself, and analyzed the speckle pattern changes at a detector as a disturbance or intrusion occurred. A FBG perimeter security system patent was filed in 2010 by Jason B. Lamont [114]. Many more patents based on fiber optic intrusion detection have been filed which will not be detailed in this paper but can be reviewed through Google scholar, should the reader wish to do so.

VI. CONCLUSION

In conclusion, a historical review of optical fiber based PIDS has been given and the general theory of each of the methods has been summarized. Each of the various techniques has been explained and a detailed discussion of the results outlining the advantages and drawbacks of the proposed systems has been performed. Further, a general forecast of potential research directions has been made including improved integration of optical and electrical systems and improved signal processing for high density quasi-distributed, high performance PIDS of the future.

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