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Optical Fiber Bragg Grating Based Intrusion Detection Systems for Homeland Security

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Abstract—This paper describes the use of optical Fiber Bragg grating (FBG) sensors for use in various intrusion detection systems for homeland security. We show that a FBG sensor can be used effectively as an embedded in-ground acoustic sensor, sensitive enough to detect the acoustic emissions associated with walking on a concrete surface. Also, the FBG can be used as an in-ground pressure switch for intrusion detection through temporary flooring materials, such as tiles and wooden laminate. In addition, we verify the use of FBGs as in-fence perimeter breach detectors. Finally, we show how an FBG can be used as a reed switch for use in intrusion detection systems for doors and windows. The combination of the different intrusion detection techniques illustrate the versatility of FBGs in security applications, showing this single technology can be used to form a complete intrusion detection system for homeland security. Furthermore the paper details the progress made towards a real-time in-ground sensor network for advanced security applications.

Keywords—*fiber Bragg grating, in-ground, intrusion detection, pressure switch, perimeter fence, reed switch.*

I. INTRODUCTION

There is a large array of different sensing techniques used for security applications, from glass break detectors and magnetic door and window detectors to surveillance cameras and infra-red trip wires, as well as, in fence perimeter and in-ground pressure sensors [1]. A single security setup may utilize a number of these techniques in creating a complete security system. Moreover, modern systems usually require intelligence for real-time monitoring of sensors, to reduce the number of false alarms and to increase the effectiveness of the security system. This intelligence can come in the form of a simple processing unit or, more commonly these days, from a programmable logic controller (PLC) [2]. A PLC is a special industrial computer, specifically designed to take in signals from real world processes and react in a certain way as defined by the program. PLCs, by definition, are easily programmable and form the basis of a supervisory control and data acquisition (SCADA) system.

In addition to the different sensing techniques, there are also different methods of transmitting the associated signals, namely wired security systems, wireless security systems, and optical fiber security systems. In the past, wired security

systems were considered the most affordable and reliable systems, although they usually have to be fitted by professionals to ensure wires, run from each sensor to the control panel, cannot be easily tampered with. The main advantage of wired systems is that they can be easily connected to a monitoring service via a telephone line. Wireless security systems, on the other hand, can be easily setup as they are battery powered, do not require cabling, and can be remotely armed. The disadvantages with wireless security systems are that they require a relatively large amount of power, meaning batteries need to be replaced regularly, especially for surveillance cameras which may only last 24 hours before needing charging [3]. Additionally, most wireless security systems don't have the ability to be connected to a telephone land-line.

Optical fiber security systems offer some unique advantages whereby the optical fiber acts 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. These attributes are ideal for advanced security systems. Older fiber optic sensing techniques for security sensing applications utilize scattering and interferometry [4], although these systems have their own drawbacks. Current optical fiber sensing for security is primarily based on fiber Bragg gratings (FBGs). FBGs are specifically sensitive to pressure variations making them ideal for security applications. FBGs have also been shown to detect temperature, level, and flow, as well as, more esoteric measurands such as magnetic field and tilt.

This paper focuses on the use of FBGs as sensors in an integrated intrusion detection system. The versatility of the FBG means we have been able to utilize it as: 1) an in-ground acoustic sensor, 2) an in-ground pressure switch, 3) an in-fence perimeter breach detector and 4) as a reed switch for intrusion detection in doors and windows.

II. THEORY

A. FBG Overview

FBGs are now a mature sensing technique that is well tested and understood. The grating, consisting of regions of

high and low refractive indices, is written into the core of an optical fiber acting as a mirror which reflects a very specific wavelength, known as the Bragg wavelength. If a broadband light source is launched into the fiber, all other wavelengths will be transmitted through the grating whilst the Bragg wavelength is reflected. The Bragg wavelength is determined by twice the average refractive index of the grating multiplied by the grating period. A change in the grating period is a direct result of an induced strain, while a change in the refractive index is a result of the strain-optic effect. In order to use the FBG as a sensor, the change in Bragg wavelength due to an environmental fluctuation is of main concern. The relative change in Bragg wavelength ($\Delta\lambda_B/\lambda_B$) for an applied strain (ϵ) or change in temperature (ΔT) can be approximated by;

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\epsilon + (\alpha_\Delta + \alpha_n)\Delta T \quad (1)$$

where p_e is the strain optic coefficient, α_Δ is the thermal expansion coefficient, and α_n is the thermo-optic coefficient [5].

B. Intensiometric Interrogation

Rather than using expensive detectors to interrogate the shift in the optical signal, the wavelength shift can be translated into an optical intensity change through the use of either a spectrally dependent filter, such as a matched FBG, or a spectrally dependent light source. As the Bragg wavelength of the sensing FBG varies, the amount of optical power at the receiver will change.

C. Transmit Reflect Detection

Traditionally, only the signal reflected from the FBG is monitored for the change in the optical power in intensiometric interrogation methods [6]. However, when using a spectrally dependent light source that is narrower than the FBG (as in a laser), the signal transmitted through the FBG could equally be monitored [7], with the only difference being the direction of the change, i.e. as the reflected power increases, the transmitted power decreases and vice versa. Hence, to increase the sensitivity of the system we can easily differentially amplify the transmitted and reflected signals.

Figure 1 shows the principle of the transmit-reflect detection system (TRDS). If the FBG has a similar bandwidth to the laser, and the laser is tuned to a wavelength just above the Bragg wavelength, the TRDS can be used as a digital sensor. Before the signal (strain or temperature) is applied, all of the optical power will be transmitted, as in Figure 1 (a). As signal is applied to the FBG, the Bragg wavelength will shift, matching the laser, resulting in the majority of the optical power being reflected, shown in Figure 1 (b). When used as an analog sensor, the laser is tuned to give half the power reflected, and half the power transmitted. Any applied dynamic signal will then result in a change to both the transmitted and reflected components.

Figure 1. (a) The FBG off set from the laser, maximum power transmitted and minimum reflected, and (b) matched FBG and laser, giving maximum reflection, and minimum transmission.

III. METHODOLOGY

A. In-ground Acoustic Sensing

For the in-ground acoustic sensing, the FBG sensor was interrogated using the analog TRDS. FBGs were embedded beneath numerous different flooring materials; such as solid timber, laminate flooring, a ceramic tile, a porcelain tile, and an aluminum sheet. A series of preliminary low velocity impact tests, using a small rubber ball and a small steel ball, and a high frequency response were performed for all of the different samples. The results from this initial work showed that the FBG sensor was very sensitive [8].

A FBG was also embedded within a 1cm thick concrete slab. The fibre was suspended in the middle of the concrete slab while it was set, with both ends of the optical fiber free from the slab via ingress and egress strain relief points. The slab was then placed on the floor of the laboratory so that it could be stepped on. A simple footstep test was performed, where a 60kg man wearing a soft soled shoe, stepped onto the sample with one foot. The FBG was connected in the optical circuit. Here the laser was directed to the embedded FBG via an optical circulator. The signal reflected from the FBG was then directed to the first receiver via the circulator, while the signal transmitted was directed to the second receiver. Figure 2 shows the experimental setup. As needed for the analog TRDS, the laser was tuned to give balanced reflected and transmitted components, such that half of the optical power was transmitted through the FBG and half of the optical power was reflected from the FBG.

B. Pressure Switch

Experiments on lateral loading of an FBG had proven to be very positive in terms of using this as a switch with a TRDS [9]. As such, the same setup as the acoustic sensing

experiment was used, but now instead of actively generated acoustic signals or acoustic emissions from drop tests, pressure in terms of a lateral load was applied to the various flooring materials. This required the laser diode and the FBG to be optically mismatched, so that there was a static dc offset from the transmitted and reflected signals, acting as a digital TRDS. The FBG was placed between a piece of underlay and three different flooring samples; a piece of solid wood flooring, a piece of laminate flooring, and a ceramic floor tile, as shown in Figure 3. The simple footstep test was performed multiple times for each sample. The same optical circuit was used for the pressure measurements; however, the two receivers required for the TRDS were incorporated into an intensimetric detection system [10], with the required difference and amplification (Gain = 1, relative to ~2.5 volts) circuitry included.

C. In-Fence Perimeter Sensor

A FBG was attached to the centre of a small section of wire fencing, 1.1m x 0.7m. The fencing consisted of 1mm thick steel, woven together forming hexagonal sections which were 5cm in diameter. This was then connected to the optical circuit, as shown in figure 4. The fence was then lightly tapped approximately 0.5m from the FBG, so as to mimic a vibration caused by an intruder attempting to climb the fence.

D. Reed Switch

For the reed switch, the TRDS was again used as a digital sensor. The optical circuit, illustrated in Figure 5, shows the tunable laser directed towards the FBG via the circulator, and the two receivers used to detect the reflected and transmitted components. To detect the magnet in the reed switch, the FBG was located between a ferromagnetic (steel) and a diamagnetic (aluminum) metal. As the magnet was placed on the aluminum, the FBG was laterally stressed between the metal layers.

Figure 2. Experimental setup for the embedded in-ground FBG acoustic sensor, showing the optical circuit.

Figure 3. Experimental setup for the in-ground FBG pressure switch sensor, showing the optical circuit, but using the intensimetric detection system (which contains the previously used photoreceivers with the required difference circuitry).

IV. RESULTS

Preliminary in-ground tests showed that a footstep could easily be detected through all of the materials, with exception of the high frequency response. The high frequency signal could only be seen through the ceramic tile and aluminum sheet; in all other tests the signal was easily recorded. A detailed report of all of these results is given in [8]. Perhaps the most significant result of the initial in-ground pressure tests was the detection of acoustic signals from a footstep by a FBG embedded in concrete. The results are shown in this paper.

Figure 4. Experimental setup for the fence mounted FBG sensor, showing the optical circuit.

Figure 5. Experimental setup for the optical fiber Bragg grating Reed switch, showing the magnetic transducer and the optical circuit.

Figure 6 shows both the transmitted and reflected signals (top) and the corresponding Fourier transform (bottom) from the FBG embedded in concrete. The signals are easily detectable without any amplification. The relatively low signal size (2mV) can be attributed to the small input optical power ($\sim 0.35\text{mW}$) from the tunable laser. Increasing this value would increase the sensitivity of the system. The low signal to noise ratio may be related to the small strain signal applied to the FBG through the concrete, given that the FBG is bare, and there will be a mismatch between the glass fiber and the concrete in terms of the acoustic impedance. In addition to this, amplification in the electrical domain would also enable the in-ground acoustic sensor to detect smaller signals, such as the acoustic emissions from a smaller person.

Figure 7 shows there is a significant increase in dc output when the FBG is stepped on, with a variation of at least 0.5V, when using a relatively low power laser (0.35mW). Furthermore, the signal to noise ratio is relatively high, facilitating the digitizing of the signal via a comparator (relative to a suitable value) and also minimizing any bit errors and hence false alarms. The results show that FBGs embedded below flooring could work effectively as pressure switches and could easily be configured to trigger an alarm.

Figure 8 displays the transmitted and reflected signals received from the FBG attached to the wire fence. It clearly shows that a vibration caused by an intruder attempting to climb the fence could be detected without amplification and therefore be used to trigger an alarm. Additional analyses may be required to ensure false alarms caused by environmental vibrations such as wind, are minimized, although, as the signal is relatively strong this could easily be achieved by setting the trigger value quite high. Performing signal processing could also reduce the risk of false alarms.

Figure 6. Concrete footstep test.

The results of using the FBG as a reed switch can be seen in Figure 9. Here we see the transmitted and reflected components (the bottom two curves) and the corresponding difference signal (upper curve). This signal is perfect for switching application, and the change from +1 volt to -1 volt in the difference signal can be easily digitized by way of a comparator. The high signal for the reed switch came from using a relatively high powered laser (6.4mW) compared to the previous intrusion detection experiments.

V. FUTURE WORK

Future work will include multiplexing of three or more sensors for triangulation of acoustic signals and the development of a real-time in-ground security monitoring system. Multiple sensors could also be attached to a fence, where multiplexing and signal processing could be used to detect the location of an intruder, in a similar way to the work previously reported in [11]. A temperature in-sensitive pressure switch will also be developed. Moreover, a security system, utilizing all of the developed techniques, interfaced with a central PLC, will be tested, forming a complete security based SCADA system.

Figure 7. DC output from the FBG pressure switch as pressure is applied.

Figure 8. Transmitted and reflected signal from the fence mounted FBG.

Figure 9. Transmitted, reflected, and the difference signals from the FBG Reed switch as the magnet was applied to produce a lateral load.

VI. CONCLUSION

We have demonstrated three different optical fiber sensing techniques that contribute a complete optical fiber based security system. We have shown that FBG sensors have the potential to replace existing electrical pressure mats, perimeter fence sensors and reed switches used for intrusion detection systems for homeland security. Furthermore, we have shown FBGs could be used as in-ground acoustic sensors forming a smart network for real-time monitoring of potential intruders.

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