Fibre Optic Acoustic Sensing for Intrusion Detection Systems

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ABSTRACT

In this study, acoustic emissions (AEs) were detected through a variety of different flooring materials using a fibre Bragg grating (FBG). The AEs were generated using a low velocity impact test, and by footstep. The acoustic vibrations cause a strain in the optical fibre, and hence alter the wavelength reflected by the FBG. This strain induced wavelength shift can then easily be detected by converting this wavelength shift into an intensity change. This is done using an intensiometric detection system, where a laser is tuned to the 3dB point of the FBG, and the optical power transmitted and reflected is modulated by the spectral shift of the FBG. The intention is to use FBGs as an in-ground intrusion detection system to detect the AEs generated by an intruder walking within range of the sensors. This type of intrusion detection system can be applied to both external (in soil, etc) and internal (within the foundations or flooring of the home) security systems. The results show that the AEs can clearly be detected through wood, ceramic tiles, aluminium and concrete.

INTRODUCTION

Optical fibre sensors are used for a wide variety of applications, from static and dynamic strain sensing to chemical and biological sensing (Rao 1997). They also have many advantages over other sensing methodologies. These advantages include greater sensitivity, reduced size and weight, and immunity to electromagnetic interference. In general, optical fibre sensors are greatly underutilized in security applications. The use of optical fibre systems is increasing in the security industry for both intrusion detection and information transmission, since these systems are generally more secure than direct wire (Purpura 2008).

In security sensing applications, older optical fibre sensing technology, such as scattering and interferometry, are typically used. Current optical fibre sensing work is primarily based on optical fibre Bragg gratings (FBGs). FBG sensors were first reported by Morey, Meltz, and Glenn (1989), after demonstrating their transverse holographic fabrication method for FBGs (Meltz, Morey, & Glenn 1989). FBG sensors have been used for the detection of, temperature, strain, pressure, etc. Initially, FBGs were used as spectral transduction elements, which made them immune to optical power fluctuations, as the information was encoded on the wavelength, which is an absolute quantity. As such they can be implemented in Wavelength Division Multiplexing or Time Division Multiplexing systems (Kersey 1994). These systems require spectral decoding of the sensor signals, which can be costly and processor intensive. An alternative is to use FBGs in an intensity based edge filter detection system. Here, the intensity information from the FBG can easily be correlated to the change in the measurand, as the relative spectral shift in the FBG filter results in an optical power change. The disadvantage of intensity based detection systems is that input optical power fluctuations are reintroduced into the system. However, the advantages of intensity based detection, specifically the simplicity of detection and reduce cost, since spectral decoding in not required, greatly outweigh the corresponding disadvantages in certain applications, e.g. the output of a digital intensity signal. In terms of security applications, simple and effective systems will always be preferred options.

Acoustic vibrations effectively cause a strain in an optical fibre and hence alter the reflected wavelength from the FBG. As such FBGs can be used in an in-ground intrusion detection system to detect the acoustic emissions generated by an intruder walking within range of the sensor. This type of intrusion detection system can be applied to both external, (in soil, etc) and internal (within the foundations or flooring of the home) security systems. In this work we investigate the ability to utilise FBGs as AE receivers for in-ground intrusion detection systems. Low velocity impact tests were used to generate the acoustic emissions in the various flooring samples, with the FBGs coupled to the underside of the samples on top of underlay to give an accurate practical configuration.

THEORY

Acoustic Emissions

AEs are stress waves that propagate through a material. AEs can be generated internally by microcracks or inclusion decohesion under external loading (Staszewski, Boller, & Tomlison 2004). Rapid local stress redistribution as a result of loading causes the material defects to release elastic energy. The energy results from crack growth, crack surface movement, or dislocations. AEs can also be generated by phase transformation or melting. These internal sources of AEs represent a passive as well as a static method of damage detection. AE can also be generated by external sources, specifically impacts, or actively generated by actuators

Fibre Bragg Grating Fundamentals

A FBG (Othonos & Kalli 1999, Kashyap 1999) is a spectrally reflective element written into the core of an optical fibre. The FBG is made up of alternating regions of different refractive indices. The difference in refractive indices results in Fresnel reflection at each interface. 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,

$$\lambda_B = 2n\Lambda \quad , \qquad (1)$$

where n is the average refractive index of the grating.

Equation 1 indicates that any measurand that causes either a change in the refractive index or grating period can be detected with the FBG. For measuring acoustic and ultrasonic signals, the measurand is applied strain. A change in grating period is a direct result of the applied strain, while the change in refractive is a result of the strain-optic effect. Figure 1 shows the principle of operation for a fibre Bragg grating.

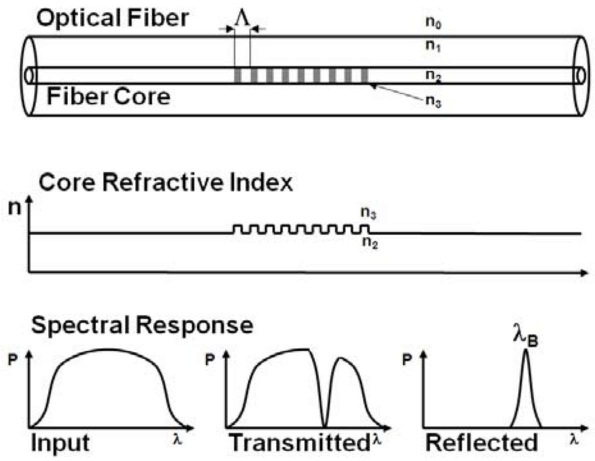

Figure 1. Fundamental principle of operation for a fibre Bragg grating

The physical structure of a fibre Bragg grating is shown in Figure 1 as well as it's refractive index profile and spectral response. The change in the Bragg wavelength as a function of applied strain can then be written as,

$$\Delta\lambda_B = \varepsilon\lambda_B\left(1 - \frac{n^2}{2}\left[p_{12} - v\left(p_{12} + p_{11}\right)\right]\right). \qquad (2)$$

where, v is Poisson's ratio, and p_{12} and p_{11} are the strain optic coefficients. Equation (2) then enables the strain applied to grating, be it from an incident pressure wave (in the case of hydrophones) or in the form of a strain wave (for mechanical vibrations), to be converted into the shift in the wavelength which can be easily determined via an interrogator.

Transmit Reflect Detection

There are essentially two broad interrogation methods available for the detection of high frequency acoustic signal with FBGs. These are edge filter detection methods, and power detection methods (Lee & Jeong 2002). In edge filter detection methods (Perez, Cui, & Udd 2001), the shift in the FBG spectrum is detected by use of a spectrally-dependent filter which results in a change in intensity at the detector. The FBG is illuminated by a broadband source, such as a SLD. The change in the wavelength reflected causes the transmitted intensity to vary as the filters transmittance varies as a function of wavelength. In power detection methods (Webb et. al. 1996), the shift in the FBG wavelength is detected by using a spectrally-dependent source, which results in a change of intensity at the detector. There are two power detection methods, linear edge source, and the narrow bandwidth source.

In narrow bandwidth source based power detection (Webb et. al. 1996), either the reflect component or the transmitted component from the FBG can be used. However, both the transmitted and reflected components occur simultaneously. As the strain from the acoustic field varies the Bragg wavelength, the FBGs 3dB point is also shifted. As a result, the amount of optical power reflected from the FBG will change, either positive or negative, depending on which edge of the FBG was used, and the direction of the measurand. The same variation also occurs to the optical power transmitted through the grating, although in the opposite direction. Since the components vary in opposite directions, they can be differentially amplified to increase the overall signal. Figure 2 shows the optical circuit for the TRDS. The principle of operation for the TRDS is illustrated on in Figure 3.

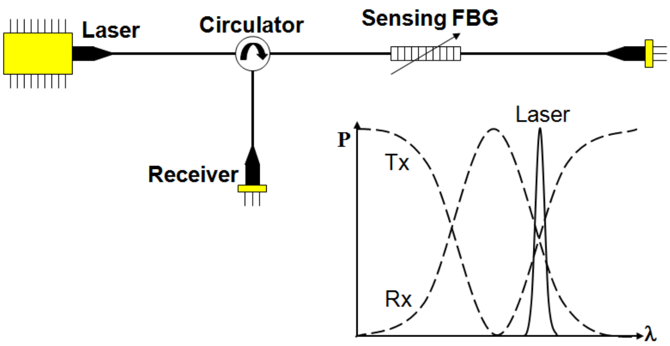

Figure 2. Optical circuit of the TRDS, with the tunable laser (TL), and the transmit (Tx) and reflect (Rx) receivers. The inset shows the spectrum of the optical components

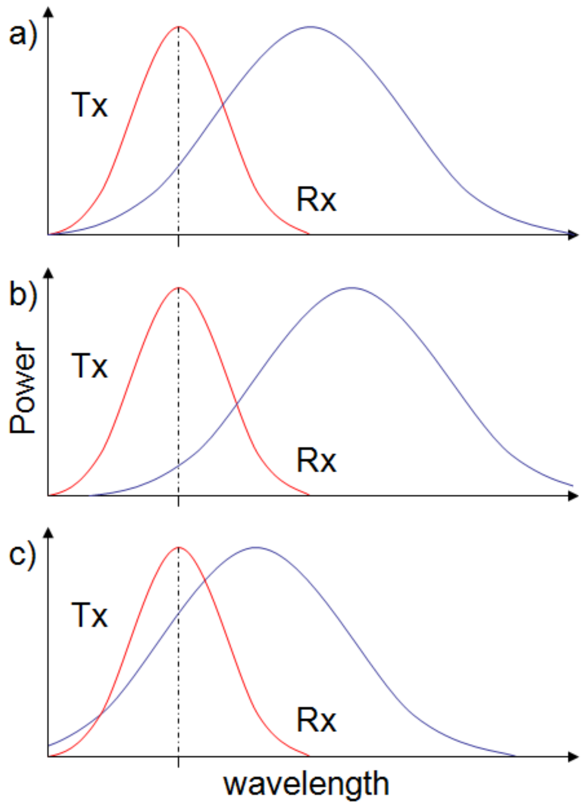

Figure 3. Operating principle of the TRDS, a) shows the FBG with no change in measurand, b) a positive change, and c) a negative change

EXPERIMENTAL METHOD

The first step of the experiment was to characterise the spectral response of the FBG and the tunable laser. The experimental setup is shown in Figure 4. This was used to determine the operating point for the FBG AE sensor. The optical circuit uses a broadband superluminescent diode (SLD) as the light source, and an Optical Spectrum Analyser (OSA). The loss function of the OSA (Anritsu MS9001B1) was used to measure the spectral response of the FBG (Photronix Technologies). The OSA was also used to look at the output of the tunable laser source (Anritsu MG9637A). The laser was tuned to give an output that matched the 3dB point of the FBG used. This ensured that 50 percent of the power was transmitted through the FBG and 50 percent was reflected. Figure 4 shows the schematic of the experimental setup for the spectral measurements.

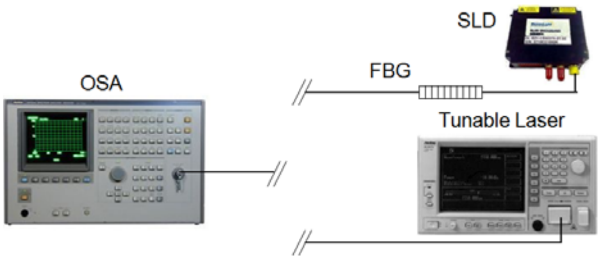

Figure 4. Experimental setup for the spectral measurements of the FBG using the SLD (top) or the tunable laser (bottom).

In the second step of the experimental procedure the laser output was connected to a circulator (FDK YC-1100-155) so that both the transmitted and reflected signal could be detected. In order to increase the amplitude of the output signal both outputs were put through the Intensiometric Detection System previously reported (Wild & Hinckley 2008). This was to ensure that whilst the FBG was under no strain the output would be zero, as the transmitted and reflected signals would have equal but opposite magnitudes. Any change in signal would then be amplified as the combination of the two signals. The difference signal was connected to a digital storage oscilloscope (Agilent DSO3062A), which was in turn connected to a PC for transferring the data. Figure 5 shows a schematic of the experimental setup.

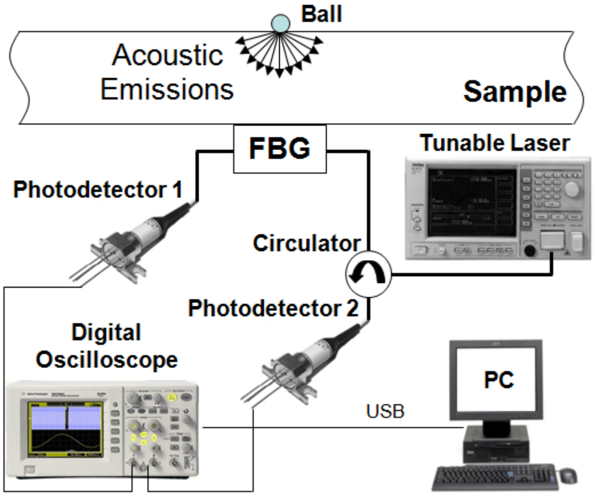

Figure 5. Setup for the AE experiments

The FBG was placed between a piece of underlay and various materials; a piece of solid timber flooring, a piece of laminate flooring, a ceramic floor tile, a porcelain composite tile, and a sheet of aluminium. All samples were approximately 1cm thick, 30cm long and 20cm wide, with the exception of the aluminium which was approximately 0.5cm thick.

Each sample was placed on the floor before a standard footstep test was performed, where a 60kg man wearing a common soft soled training shoe, raised his foot approximately 10cm and stepped on to the sample with one foot for approximately 1 second. Preliminary tests showed that a footstep could easily be detected through all of the materials. Therefore, to test the sensitivity of the system, a low velocity impact test was performed. Here a small rubber ball, approximately 2cm in diameter, weighing 5g, was used to generate an acoustic emission. The rubber ball was dropped from approximately 0.5 metres above the sample and the acoustic signal was recorded using the DSO. In each case, the ball was initially dropped directly above the FBG, then dropped at the edge of each sample approximately 30cm from the FBG. In addition to the AEs generated by the drop test, the high frequency response of the sensor was tested using actively generated acoustic signals. These signals were generated from a function generator (Agilent 33250A). Finally, a FBG was embedded approximately 5mm into a slab of concrete. In addition to the acoustic tests, this sample was also used in a footstep test, given that the sensor embedded within the concrete was significantly less sensitive. The output was recorded by the DSO. The experimental setup for the actively generated acoustic emissions is shown in Figure 6.

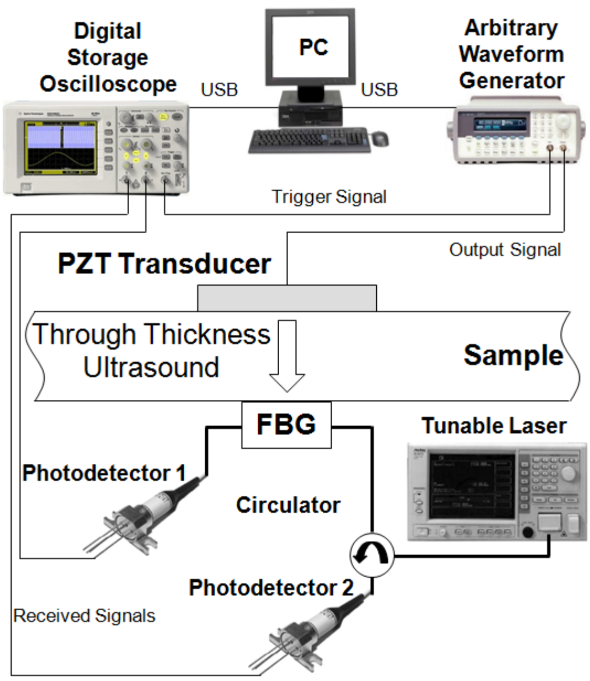

Figure 6. Setup for the actively generated acoustic signals.

RESULTS

Figures 7 – 11 show the output of the DSO for solid timber, laminate flooring, ceramic tile, porcelain composite tile and aluminium, respectively, for the low velocity impact test of each sample. Each figure shows the voltage output (10mV/div) for the transmitted (yellow) signal and the reflected (green) signal, as well as the fast Fourier transform (magenta) of the transmitted signal, with respect to time.

The amplitudes of the outputs for each of the materials were doubled by graphing the differential signal. Figure 12 shows the differential output from the timber sample for example.

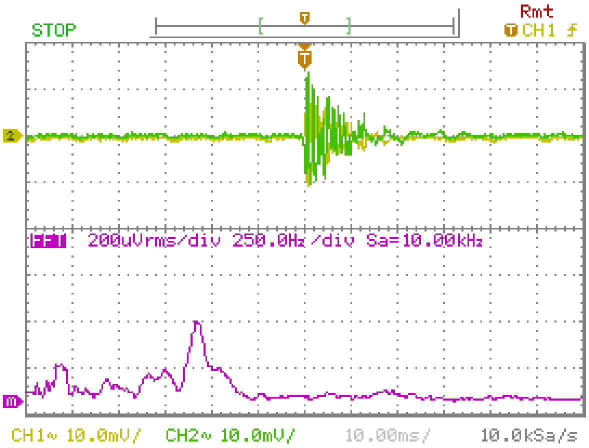

Figure 7. Solid timber low velocity impact test.

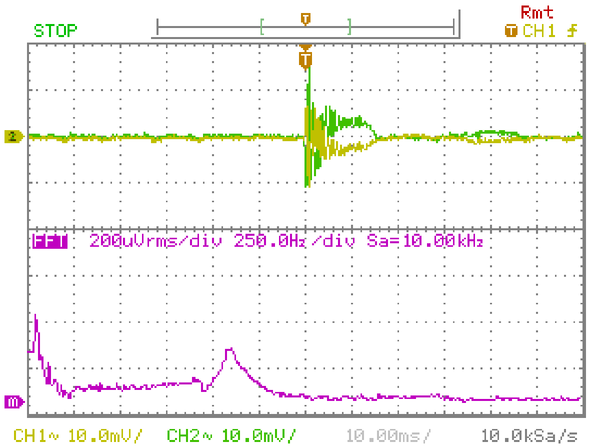

Figure 8. Laminate flooring low velocity impact test.

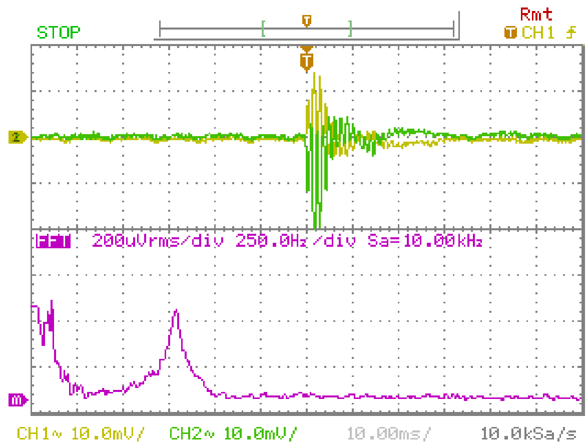

Figure 9. Ceramic tile low velocity impact test.

Figures 13 and 14 show the high frequency response from the FBG, through the ceramic tile and the sheet of aluminium, respectively. In both cases the differential signal was used to amplify the output to almost 2mV, (4mV/div). There was no observed high frequency response from the other samples.

Figures 15 and 16 show the output (4mV/div) from the FBG embedded in concrete from the footstep test and a low velocity impact test. The small rubber ball did not produce a significant signal, hence a steel ball, approximately 2cm in diameter weighing 30g, was utilised for the concrete sample.

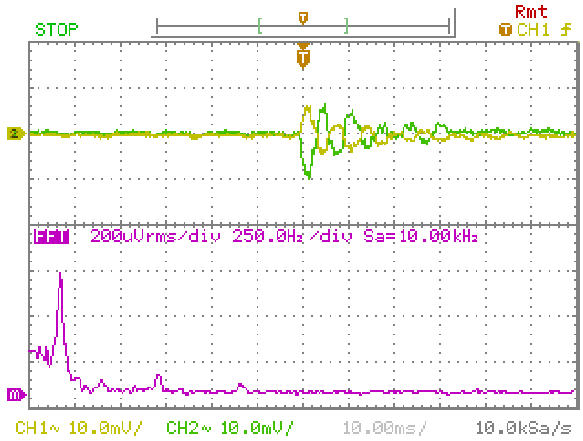

Figure 10. Porcelain composite tile low velocity impact test.

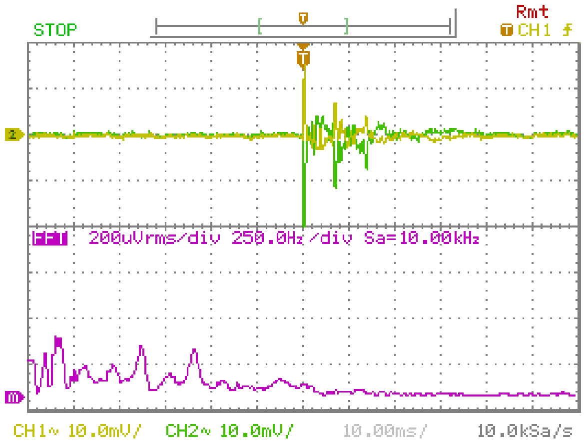

Figure 11. Aluminium sheet rubber ball test.

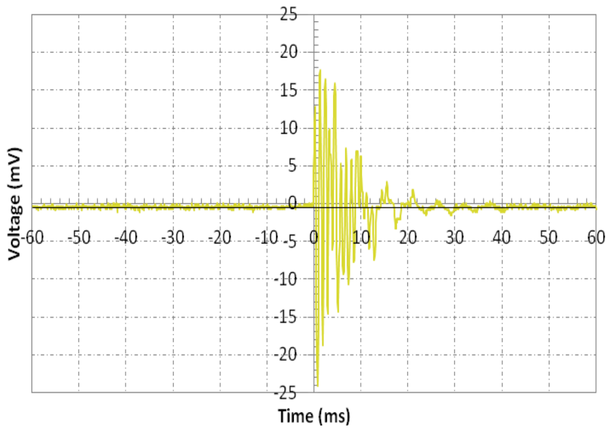

Figure 12. Solid timber rubber ball test differential output.

DISCUSSION

As shown in Figures 7 – 11, the acoustic signals generated from the low energy impact tests were easily detected through the materials used. The acoustic signals generated from the footstep test were significantly greater, meaning that they would be detected without the need for any additional signal amplification. Only a small amount of additional circuitry will be required for the practical intrusion detection system. Specifically an envelope detector and a comparator will give a direct detection result. This will require the spatial sensitivity of the sensor to be well understood in the application.

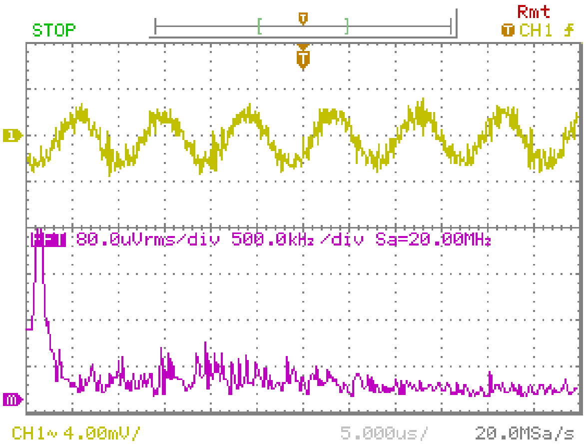

Figure 13. Ceramic tile response to 108.5 KHz signal

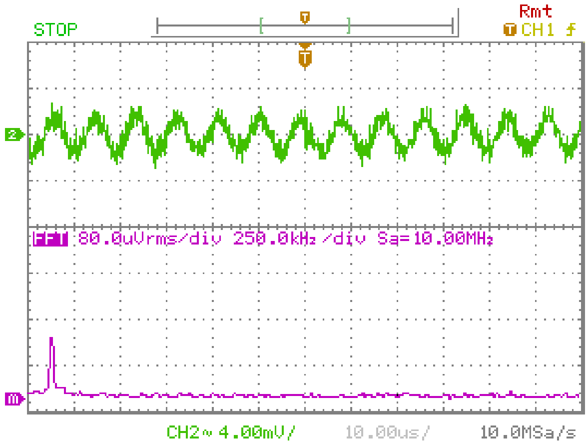

Figure 14. Aluminium response to 112.2 KHz signal.

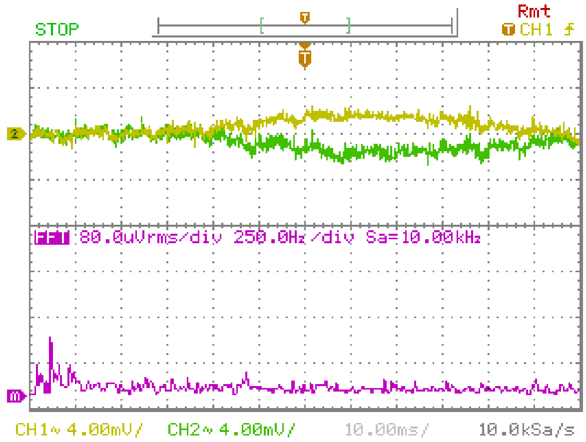

Figure 15. Concrete footstep test.

Figures 13 and 14 show that high frequency signals can be detected through a ceramic tile and aluminium, although only very specific frequencies relating to the resonant mode of the transducer were detected. Unfortunately the output of the frequency generator used was only 10V which limited the range of results obtainable. Future experiments using equipment with greater electrical output may show high frequency responses to a range of frequencies and a wider variety of materials.

Figures 15 and 16 show it is possible to detect acoustic signals using an FBG embedded in concrete. This could have a number of applications not just limited to in-ground intrusion detection. However, embedding FBGs in concrete has it's complications as they cannot be moved or replaced easily if they are damaged. One of the advantages of using underlay in this study was that the FBG was placed between the underlay and the material which ensured a good quality signal was detected, as well as protecting the fibres from being damaged.

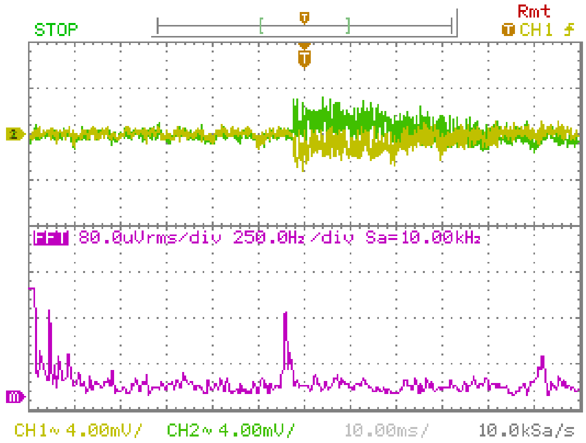

Figure 16. Concrete low velocity impact test.

FUTURE WORK

Although all of the materials used could be effectively utilised in an intrusion detection system, in future work the solid timber or laminate flooring will be used as these materials require underlay. Future studies will establish the configuration of FBGs required for the location of a person to be determined. Initially, the intention is to construct a 2m x 2m section of flooring with 3 FBGs arranged in a triangle underneath the flooring, and confirm that a person's position can be triangulated from the difference between the intensity of the recorded AE signals using time-division multiplexing. The FBGs will be embedded within the underlay. Hence, a complete network of fibres incorporating any number of FBGs could be completely embedded within the underlay material, which could simply be rolled out where required and the flooring panels placed on top of it.

CONCLUSION

FBGs can effectively detect the acoustic emissions through various materials from a person walking on top of them. This technology could be used as an in-ground intrusion detection method for security applications.

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