Polarisation independent, high resolution spectral interrogation of FBGs using a BFBG-CCD array for optical sensing applications

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ABSTRACT

Optical fibre strain sensors using Fibre Bragg Gratings (FBGs) are poised to play a major role in structural health monitoring in a variety of application from aerospace to civil engineering. At the heart of technology is the optoelectronic instrumentation required to convert optical signals into measurands. Users are demanding compact, lightweight, rugged and low cost solutions. This paper describes development of a new device based on a blazed FBG and CCD array that can potentially meet the above demands. We have shown that this very low cost technique may be used to interrogate a WDM array of sensor gratings with highly accurate and highly repeatable results unaffected by the polarisation state of the radiation.

In this paper, we present results showing that sensors may be interrogated with an RMS error of 1.7pm, drift below 0.12pm and dynamic range of up to 65nm.

Keywords: Tilted or blazed gratings, optical sensor interrogation

1. INTRODUCTION

Structural Health Monitoring is emerging as an important concept for the management of maintenance and through life ownership costs of a range of transport platforms. Civil and military aerospace programmes are already benefiting from technology such as operational loads monitoring where the measurement of strain cycling in structures is used to predict the remaining lifetime of key, load bearing components. The state of the art is found in military aircraft where electrical strain gauges provide the sensory input. Under consideration are evolutions of this technology to improve the strain measurement capability and revolutionary technology that combines the predictive capability of strain measurement with the diagnostic capability of automated damage detection.

This paper addresses optical sensor instrumentation that constitutes an evolution of the current electrical strain gauge technology used in the measurement and management of structural fatigue. Optics offers many potential advantages such as light-weight components (important to aerospace), immunity to electromagnetic interference, ability to multiplex many sensors along a single optical fibre and ultimately, cost and reliability.

Optical Fibre Bragg Gratings (FBGs) [1] are front-running candidates for measuring strains in structures. The devices act as sensors by shifting their reflection wavelengths in proportion to the strain they experience. They are integral to the optical fibre itself and can be imprinted at selected locations anywhere along a fibre. Each FBG is distinguished by its nominal range of reflection wavelengths allowing dense multiplexing if required.

A key feature of the sensor system is the instrumentation required to measure the change in reflection wavelength from each FBG and hence deduce the local strain. One approach entails spectral analysis of the light reflected from the fibre. This often entails mechanically scanned interferometers or diffraction gratings and bulky, sensitive optics.

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This paper describes how FBGs can be used not only as sensor elements but also as a key component in the wavelength measurement instrumentation of sensor systems. The approach is intrinsically rugged and highly compact. It is based on a blazed FBG and a CCD detector array and has no moving parts.

Since their first report in 1990 by Meltz et al [2], blazed fibre Bragg gratings (BFBGs) have been demonstrated for applications in WDM channel monitoring [3], EDFA gain flattening [4], polarization discrimination [5], and edge filter manufacture [6] etc. Several reports have been published showing that BFBGs may be used to outcouple light from the core of the fibre [2]. This technique may be used to form the basis of a diffractive spectrometer [7]. Significant theoretical study on the phenomenon has been carried out, largely by Erdogan and associates, [8-13].

We present experimental results showing that BFBG-CCD spectrometers may be easily fabricated and used to interrogate WDM sensor grating arrays. We investigate the bandwidth and resolution of the technique, the received SNR from a typical grating and the inherent drift with time of the system. We importantly show that the system is insensitive to polarisation state making the BFBG-CCD sensor interrogation method a highly viable, extremely low cost, alternative to traditional sensor interrogation techniques.

2. THEORETICAL STUDY

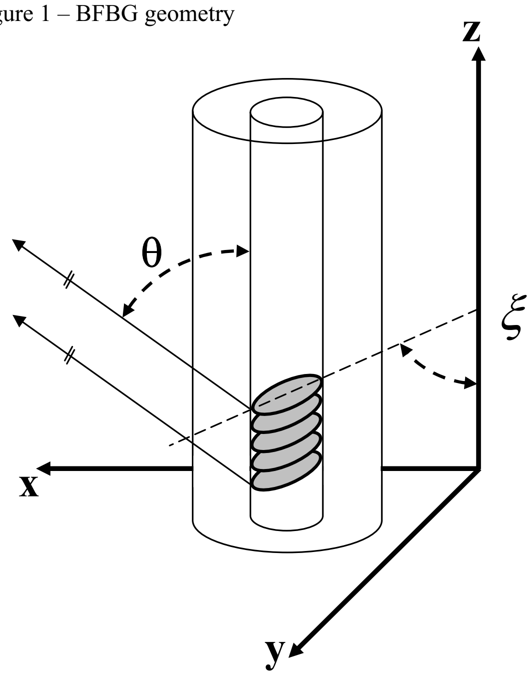
BFBG Theory

The index distribution in a BFBG structure is given by:

$$\Delta n(z,x) = \delta n \cos\left[\frac{2\pi}{\Lambda}\cos\xi z - \frac{2\pi}{\Lambda}\sin\xi x\right] \tag{1}$$

where δn is the amplitude of the index change, Λ is the normal period of the grating, z and x are the coordinate axes defining the fibre orientation and ξ is the internal fringe tilt angle, as depicted by Figure 1. The tilted structure enables light coupling between the core mode and radiation modes.

Figure 1 – BFBG geometry



Until our paper [14] BFBGs were commonly characterised in terms of their transmission or reflection profiles; we have shown [14, 15] that the radiation mode vector is highly directional and that its departure angle is related to fringe angle as follows:

$$\cos\theta = \frac{\cos(\xi)\frac{\lambda}{\Lambda} - n_{eff}(\lambda)}{n_{cl}(\lambda)} \tag{2}$$

where θ is the departure angle, n_{eff} and n_{cl} are the refractive indices of the core and cladding respectively and λ is the wavelength of the radiation.

Side-detection of radiation modes offers many application-specific advantages as a result of their highly predictable spectral-spatial relationship; for example, in conjunction with a CCD array detector the function of side-tapping light with high spatial resolution may be utilised to implement a spectrometer function or to form the basis for low-cost WDM devices.

Radiation modes from a uniform period BFBG are parallel in the x-z plane but divergent in the y-z plane. Wagner et al [7] showed that for a chirped grating the radiation modes become slightly convergent with chirp rate, and they calculated that the focal length, f, of a chirped BFBG to be:

$$f \approx \frac{\Lambda^2 \sin(\xi_{PM}) \tan(\xi)}{\lambda \cos(\xi) C} \tag{4}$$

where C is the chirp rate in nm/cm.

Polarisation dependency of the far-field image

Polarization sensitivity would affect the performance of a sensor interrogation system because random changes in polarization state may be interpreted as a measurand change. Figure 2 shows four simulated far-field images for light radiated by a BFBG with blaze angle of 5˚. Figure 2a and 2b show the grating illuminated with 0˚ and 90˚ linearly polarised 633mn radiation respectively whilst figure 2c and 2d show the same polarisation angles but for 1560nm radiation. Note that at shorter wavelengths, the grating is highly polarisation sensitive, but at wavelengths close to the Bragg wavelength of the grating the effect of polarisation becomes negligible.

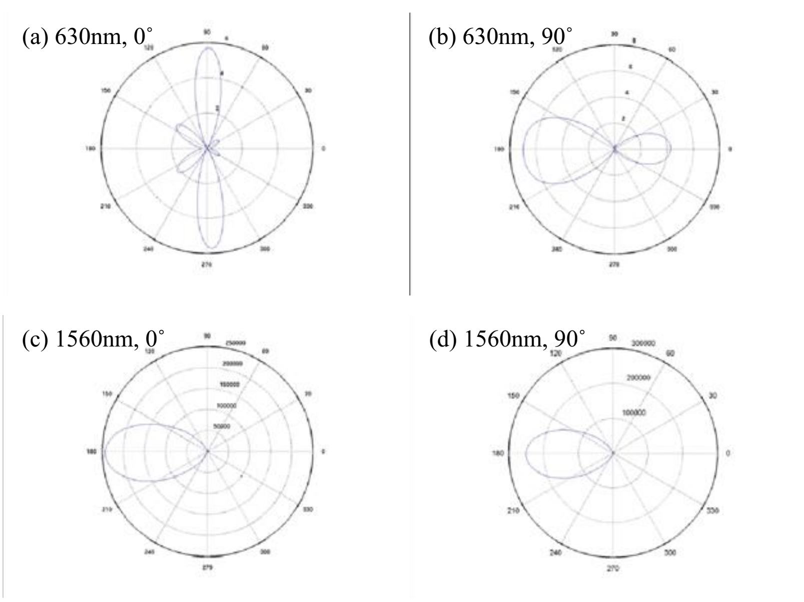


Figure 2 – Simulated far-field images for 0˚ and 90˚ polarised 633mn and 1560nm radiation

3. EXPERIMENTAL REPORT

Apparatus and FBG inscription parameters

Verrillon B/Ge co-doped 125/9u fibre was hydrogenated at 80˚C / 225 bar for 68 hours and stored at -40˚C prior to use. A 10mm FBG was inscribed using the phasemask method with a blaze angle of 7˚. The grating was immersed in index matching gel to remove Fabry-Perot resonances at the core-cladding-air interfaces. Figure 3 shows the experimental apparatus used.

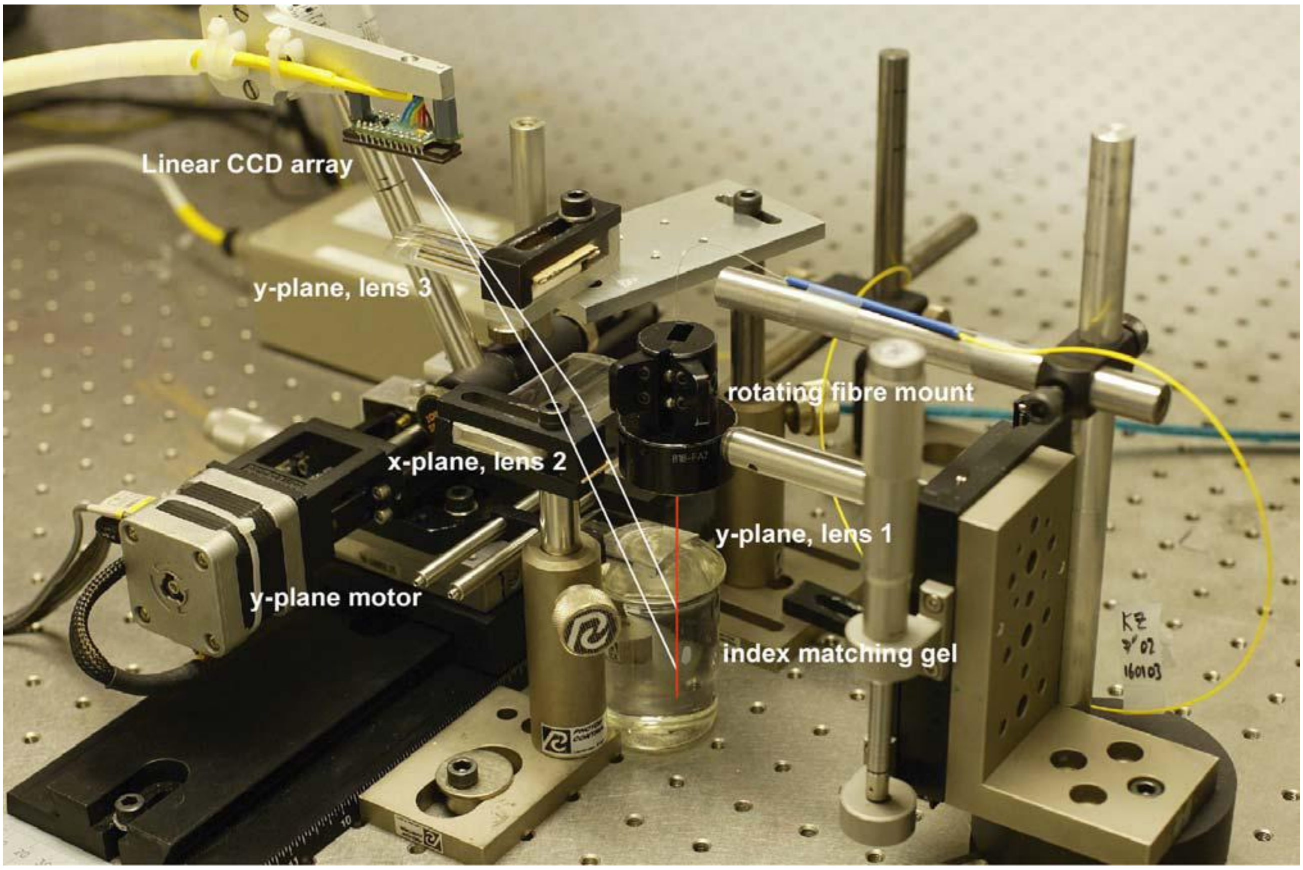


Figure 3: Photograph showing the experimental apparatus used to produce the results in this paper

The fibre was mounted in a rotateable clamp and three lenses were used to focus the light radiated from the BFBG onto the CCD array. Initial course alignment is easily achieved by using a He-Ne 633nm light source (note the requirement for polarisation control at this wavelength, as indicated by figure 2). The CCD array was mounted on a motorised translation stage, moveable in the y-plane to enable far-field images of the radiation profile to be built up (see figure 4b).

A transfer function relating wavelength to most intensely illuminated pixel was easily determined by using a tuneable laser to scan the region of interest. The most intensely illuminated pixel was calculated using the Centroid fitting method (CDA) to increase accuracy and significantly reduce pixelation effects. The transfer function is shown by Figure 4a for two different arrangements with different separations from fibre to CCD, thus altering the gradient of the function. Figure 4b shows the far-field image of a 1511nm with only lens 2 and without any focusing whatsoever. The divergence of the beam profile is caused by the lensing effect of the fibre. As the CCD device is sensitive to visible light, a blackout box was placed over the apparatus to reduce the background noise level.

An optical circulator was used to connect a broadband SLED light source (input port), a FBG sensor array of nominally 2 WDM gratings (transmission port) and the BFBG-CCD interrogation apparatus (reflection port).

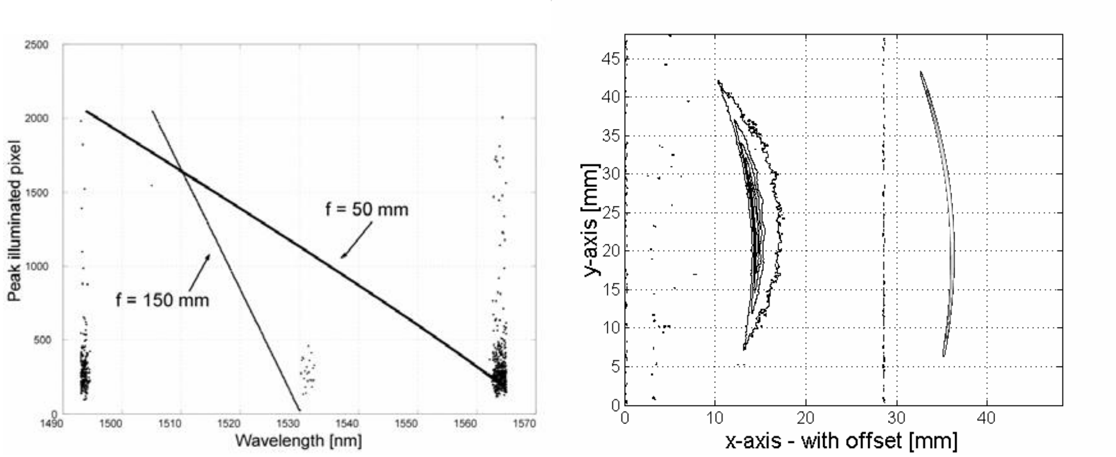


Figure 4: (a) Transfer function for the system with 2 focal lengths; (b) radiation mode beam profile without and with x-plane lensing

Detector array

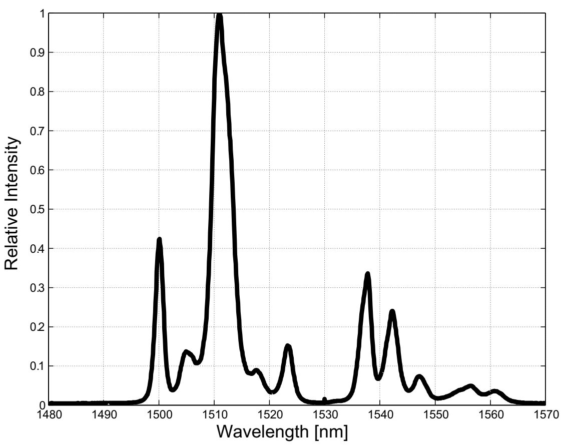


Figure 6: The responsivity of the CCD array

The detector array used in this series of experiments was a Sony ILX511 linear CCD array, coated with Y2O2S:Er,Yb in order to make it responsive to IR radiation. The device is comprised of 2048 - 14 um pixels.

CCD arrays are desirable to use in place of photodiode arrays because they offer longer arrays with smaller pixel size at a fraction of the cost of an InGaAs array. However, this is not without its drawbacks; CCD arrays use CMOS technology which is most sensitive to light in the visible portion of the spectrum. It is possible to coat the array with a substance which emits visible light when illuminated with IR radiation. Unfortunately, the responsivity of these coated CCD arrays is highly non-linear; Figure 6 shows the responsivity measured using a highly accurate tuneable laser at a constant level of output power.

Polarisation insensitivity

In order that the polarisation sensitivity of the system might be tested, a tuneable laser was used to simulate the reflected spectrum from an FBG sensor. The output of the tuneable laser was connected to a polarisation state controller which was, in turn, connected to the BFBG-CCD apparatus. The state controller was programmed to randomly scan all possible polarisation states over a 12 second period. The peak position and amplitude of the simulated sensor was then logged every 250ms for a 20-minute period. Although the amplitude of the detected radiation profile was seen to fluctuate significantly by approximately +/- 18%, the spatial position remained constant. This is in keeping with Figure 2 which shows theoretically that the polarisation dependence of the radiation direction is negligible at wavelengths close to the Bragg wavelength of the grating. Since the system operates by taking a snapshot of the reflected spectral information, the polarisation induced amplitude fluctuations only affect the SNR of the system.

Signal to noise ratio

The signal to noise ratio of the system may be used to give a measure of the overall predicted system accuracy for any particular application. Figure 7a shows the spectrum of the strain sensor FBGs used above. The signal to noise ratio was calculated from the relative intensities of the FBG peak and the maximum noise level of the system (after correction in software for dark current). To show the effect of integration time on SNR, the system was set up to monitor the reflection from a sensor FBG, held at constant temperature with constant illumination level, whilst the integration time was varied. Figure 9b shows the SNR in dB as a function of integration time. At approximately t=120ms, the SNR begins to decrease as a result of the signal saturating the array and the noise floor increasing with integration time.

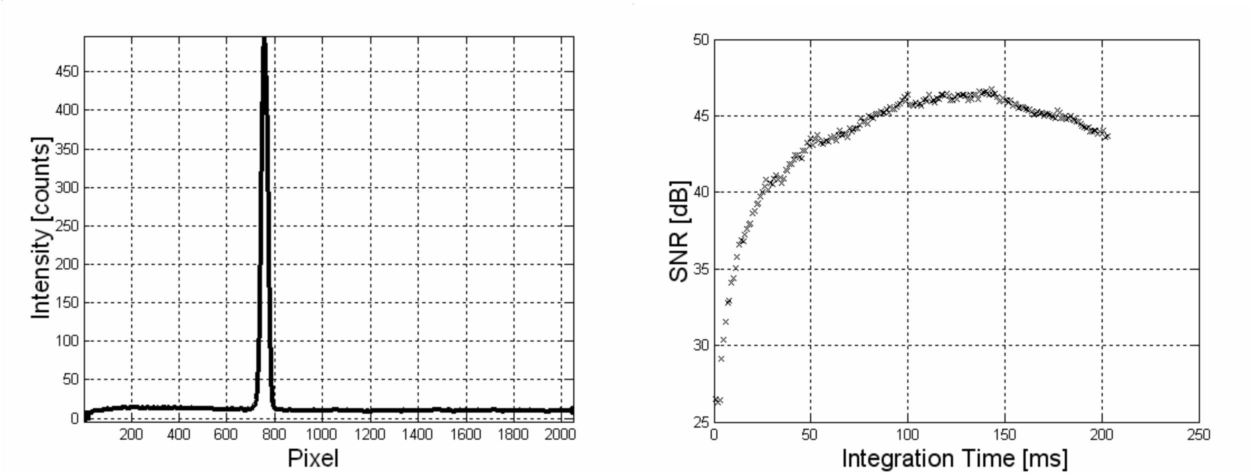


Figure 7: (a) The received spectrum of a sensor FBG, (b) the effect of increasing the integration time on the SNR of the system

System stability

To model the overall stability of the interrogation equipment, the system was used to monitor the reflected spectrum of a temperature sensor FBG, held at constant temperature in a TEC controlled environment chamber for a period of approximately 45 minutes at a sample rate of 1Hz.

Figure 8a shows the recorded value of λ_{BR} against time. The large variations are believed to be caused by temperature changes in either the environment surrounding the BFBG or the TEC controlled sensor. In order to ascertain the fluctuations in the reading made by the system, these large variations have been mathematically filtered out and the clean data is shown in Figure 8b. Figure 8c shows a histogram displaying the distribution of these filtered readings which predictably follow a normal distribution. The RMS deviation from the mean of this histogram is a mere 0.12pm, thus indicating a good level of system stability.

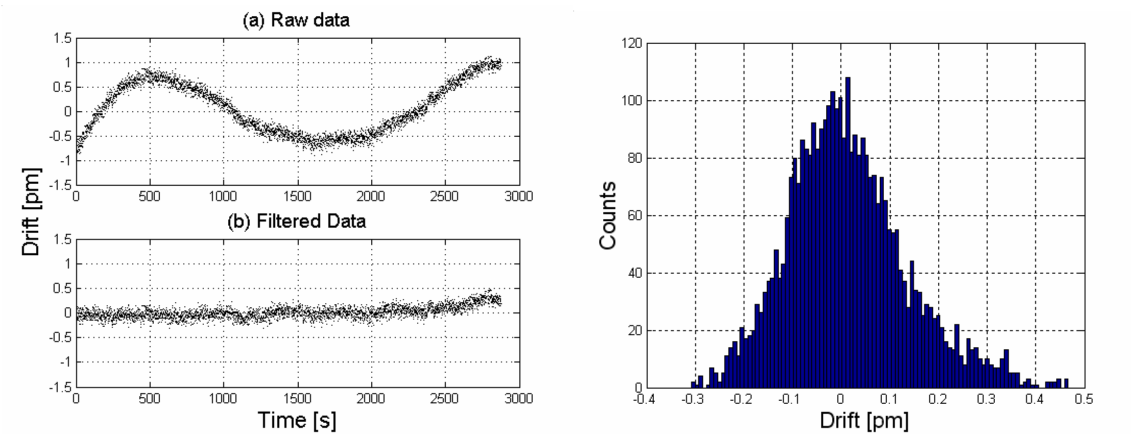
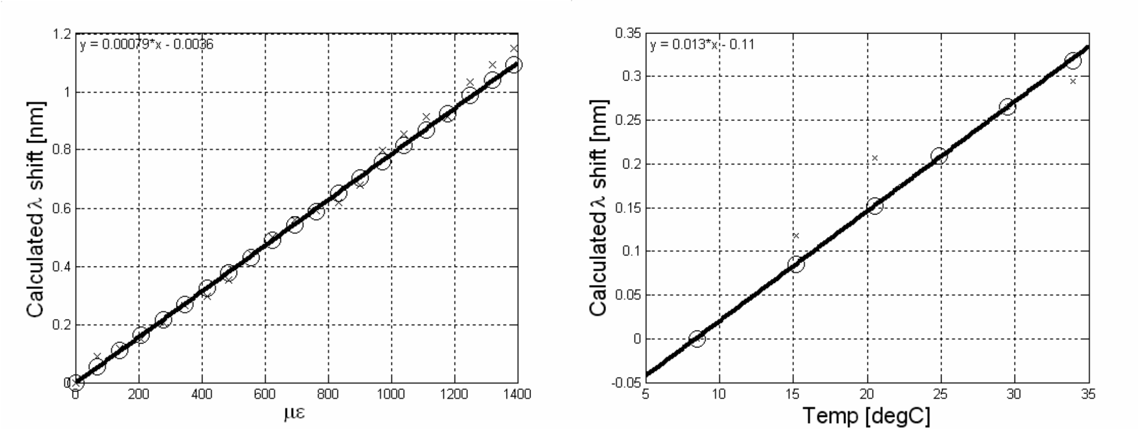


Figure 8: (a) The raw drift data, (b) the drift, filtered for environmental changes and (c) the distribution of the recorded λ_{BR} values

Strain and Temperature sensor interrogation

A grating array, consisting of nominally 2 WDM gratings was connected to the output of an optical and illuminated by a SLED light source. The return port of the circulator was then connected to the BFBG-CCD detection system. The transfer function relating illuminated pixel to wavelength was then applied in software, thus deriving a spectral plot for the grating array.



In separate experiments, gratings from the array were monitored in strain and in temperature changes. For each discrete change of measurand, 10 readings of λ_{BR} were calculated using the CDA, and their average plotted. Figure 8a shows the results for an increase in strain of up to 1400με, whilst Figure 8b shows the results for a temperature shift of 30˚C. They show an RMS deviation from a linear trend of 3.7nm and 1.7nm respectively.

The points marked with 'o' in Figure 8 represent the values of λ_{BR} calculated by the CDA technique, whilst those marked with 'x' are the value calculated simply by looking for the point of maximum optical reflection. The difference in accuracy is clearly demonstrated by these two datasets.

4. CONCLUSIONS

We have presented experimental results showing that an extremely low cost optical sensor interrogation system may be fabricated using a blazed FBG and a linear CCD array. Free space optics have been used to focus the radiation modes onto a linear CCD array which was coated to be responsive in the erbium band. We have further investigated the effects of polarisation orientation on the accuracy of the device and have shown the elevation angle to be independent of polarisation state at wavelengths close to the Bragg reflection wavelength of the BFBG.

We interrogated a WDM sensor array using the system, the results of which show that a dynamic range of more than 65nm is easily possible and that up to 80 sensors could be simultaneously interrogated. We have shown that sensor FBGs may be decoded with a RMS deviation of 1.7ρm. We believe this system will become invaluable to smart structure applications due to its extremely low cost, large dynamic range and high resolution.

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