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RECENT DEVELOPMENTS IN INTERROGATING FIBRE BRAGG-GRATING SENSORS FOR COMPOSITE SMART STRUCTURES

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ABSTRACT

Fibre optic Bragg grating sensors are attracting considerable interest for a number of sensing applications because of their intrinsic and wavelength-encoded operation. There is great interest in the multiplexed sensing of smart structures and materials, particularly for real-time evaluation of physical measurands (eg. temperature, strain) at critical monitoring points. The primary emphasis is on dynamic measurement of strain. The requirement is to monitor a large number of in-fibre grating sensors, either continuously in real time, or by polling them with an acquisition time of less than 1 msec. Without such capability, it will not prove possible to interrogate the vibrational modes of structures. In this paper, the various interrogation methods are briefly reviewed and are compared with our new method of using an acousto-optic tunable filter.

Key Words: Fibre optics, Bragg gratings, strain sensors, multiplexing, smart structures.

1. INTRODUCTION

The in-fibre grating is a highly-attractive sensor. In particular, it is extremely compact, and the cylindrical sensing fibre also serves as the optical communications medium (Ref.1). The advantages of this form of sensor for strain sensing are:-

(i) The sensor can be formed in a continuous length of fibre, which also acts as the telemetry link.
(ii) Silica is an excellent mechanical material, with a low-creep characteristic and excellent immunity to corrosion.
(iii) The sensor is small, lightweight and hence readily incorporated in composite materials.
(iv) The cylindrical geometry of the sensor/optical link gives a uniform mechanical structure with no discontinuities to provide stress concentration points.
(v) The sensor is immune to electromagnetic interference.
(vi) Multiple gratings can be incorporated in, and interrogated via, a single length of fibre.

The main technical problems are in reading the wavelength of the gratings, particularly when there is the constraint of requiring instrumentation suitable for space applications. There is also a potential problem of undesirable temperature sensitivity, when required for use as a strain sensor. The latter problem (which is, of course, also seen with resistive strain gauges) is preferably resolved by arranging the interrogation system to perform simultaneous measurement of temperature and strain, or by arranging the thermal response to be cancelled. In our recent work, we have made significant progress in both these directions. Before discussing our new advances, however, we will first summarise the present state of the technology for interrogating Bragg gratings.

2. EXISTING METHODS OF GRATING INTERROGATION

The peak reflectivity of a fibre grating can be measured by many methods. Use of a broadband source, with an optical spectrum analyzer as the interrogator, is an obvious approach. CCD spectrometers are now available with quite reasonable performance for most normal spectroscopic applications. However, the fractional changes in the wavelength of a grating typically arising from normal levels of strain in materials are, in practice, quite small (typically fractional change is 0.074% for 1000 microstrain at 1550 nm). As a result, there is extensive worldwide research aimed at developing specialist high-resolution instrumentation to interrogate these sensors.

A scanned Fabry-Perot interrogation interferometer is an attractive means of producing a tunable optical filter to track a grating (Ref.2). Such a filter is formed using closely-spaced highly-reflective mirrors, which are moved relative to each other. This type of filter can have a spectral transmission with a bandwidth well matched to the reflection spectrum of the fibre grating. A more recent development has been to use a second matched fibre grating (The "slave" grating) as a filter to track the measurement grating (Ref.3). In both these cases, the tracking filter can be scanned using piezoelectric actuators. In the case of the Fabry-Perot filter the mirror spacing is changed. In the case of the "slave" grating, filter is stretched to change its characteristics to match that of the measurement grating.

Perhaps the most accurate means of tracking the wavelength of a grating is to use a scanned optical fibre interferometer. One implementation is to use a Mach-Zehnder (ie. two-path) fibre interferometer, with a piezoelectric stretcher in one arm (Ref.4). With a single wavelength input, the response at the interferometer is a sinusoidal variation in detected signal, as the path length of one arm is linearly extended relative to the other. The frequency of the detected intensity response is proportional to the product of the peak reflective frequency of the sensor grating and the rate of length extension. A measurement of the phase of this signal can provide even more precise information. A resolution of 0.6 nanostrain/√Hz at 500 Hz has been achieved by this approach. The method is highly accurate, but it will probably be difficult to maintain a stable path difference in the interferometer in an aerospace environment.

For real system applications the method of sensor interrogation would preferably have the following characteristics:-

(i) It must be able to be manufactured in a reproducible manner.
(ii) It must follow fast transient changes in wavelength of the grating.
(iii) The size and power requirements must be acceptable.
(iv) The interrogator must be insensitive to vibration and external temperature changes.
(v) The method should ideally be capable of interrogating more than one sensor, to allow a multiplexed network to be addressed.

Many of the published methods fail to meet several of these criteria and none so far appears to meet all these requirements.

3. OUR NEW METHOD OF GRATING INTERROGATION

All the above methods have limitations when it is desired to scan the frequency of a large number of fibre-gratings in a frequency-agile manner. We shall now describe our new method using an acousto-optic tunable filter (Ref.5). This type of filter possesses the desired frequency-agile behaviour required for fast frequency sweeping (or for random polling) of sensors and has a wide tuning range (eg. 1.0μm → 2.0μm is possible for typical devices). At constant temperature, its wavelength is determined solely by the frequency of an RF drive signal and it is therefore suitable for both dynamic and quasi-static strain sensing. It is also well suited for multiplexed sensing systems. In addition, the same detection system can be used to measure the wavelength of the gratings, either in a back-reflected or a forward-transmitted configuration.

The proposed experimental system for automatic locking of the mean frequency of the AOTF to the grating sensor is shown schematically in Fig.1. Light from a broadband source (ELED) is coupled, via the in-fibre grating to be measured, through the AOTF and then to a detector. The device acts as a narrow band optical filter, of approximately 4nm linewidth, the frequency of which is proportional to an RF drive signal. In order to track the instantaneous Bragg wavelength, it is possible to employ a feedback signal to lock the mean optical wavelength of the filter to the instantaneous Bragg wavelength of the in-fibre grating. This method involves dithering the applied RF frequency about a nominal value (ie. frequency-shift-keying: FSK) and detecting the resulting amplitude modulation of the received optical carrier. For symmetrical grating and filter responses, the expected amplitude-modulation component, at the fundamental of the dither frequency, is zero when the <u>mean</u> frequency of the switched filter coincides with the Bragg wavelength of the grating. This condition, where the AOTF frequency hops symmetrically about the grating frequency, can be achieved by adjusting the mean frequency of the FSK signal.

The FSK signal is conveniently generated using a voltage controlled oscillator (VCO), with a low-frequency square wave input, plus a DC bias signal to tune the mean frequency. The electronics system shown in Fig.1 should be able to lock the mean frequency of the AOTF to the condition where the amplitude modulation is zero. The mean frequency of the VCO would then provide an indication of the corresponding instantaneous Bragg wavelength of the sensor. For multiplexing, it would, of course, be necessary to apply an impulse to the VCO input, to cause it to address and then lock onto a different in-fibre grating. Alternatively the filter could be simultaneously driven by multiple RF signals of different frequencies, each signal set to track a particular grating as described above. A further possibility is that the filter could be swept through wavelength range to cover all the gratings and the peak wavelength of each grating observed as it sweeps through.

In our experimental demonstration, we have shown the basic concept of the AOTF addressing system to be feasible, using manual control of the RF drive signal. The broadband source for our work was a 1300 nm, fibre-pigtailed ELED, which launched 50 μW of output power over a 56 nm bandwidth (FWHM). The sensing grating, having a nominal (ie. unstrained and at room temperature) Bragg wavelength of 1298 nm, a peak reflectivity of 99% and a bandwidth of 1 nm (FWHM), was incorporated between the optical source and the AOTF. The AOTF (Crystal Technology, MID-IR AOTF), had a wavelength tuning range of 1.2 μm-2.5 μm and a resolution (FWHM) of 4 nm. We used a commercial RF signal generator (MARCONI 2031) as a VCO. The frequency deviation of the FSK-modulated drive signal to the AOTF was chosen to be 360 KHz to obtain optimum sensitivity. The mean RF drive frequency was manually chosen such as to set the mean AOTF frequency to the nominal Bragg wavelength. This was determined by the condition when the output of the lock-in amplifier was zero.

Fig.2 shows the system output from the optical detector when the modulation-input frequency to the VCO was set to 200 Hz, and with the mean RF drive signal was detuned from the matching condition. The amplitude of the A.C. modulation signal at the detector was zero only when the mean AOTF frequency matched the instantaneous Bragg-grating wavelength. For the purposes of our initial investigation, temperature measurement results were obtained by heating the Bragg grating using a Peltier heat pump, as shown in Fig.3. The temperature sensitivity of the Bragg grating was measured to be -0.91 KHz/°C, a value in close agreement with the value expected. Clearly similar results are expected if the fibre Bragg grating were stretched (-0.098 KHz/$\mu\epsilon$,Ref.1) or pressurised (0.26 KHz/MPa, Ref.6).

We believe this experimental work demonstrates an attractive method for the interrogation of Bragg grating sensors. Although in our first experiment, this was for thermal monitoring, strain or pressure measurement is equally possible using the same fibre gratings. We have shown that this technique offers considerable advantage over previous approaches. In particular, the method has the potential for frequency-agile random access, wide tuning range and the ability to recover after transient signal loss, all of which are likely required in practical multiplexing applications.

4. CONCLUSIONS

We have examined a number of methods for interrogating optical fibre strain sensors. Our preferred sensor types are based on optical fibre gratings. We have demonstrated an attractive new method of interrogating fibre gratings, using a frequency-agile acousto-optic tunable filter system, which is well suited for multiplexed systems. All the above are attractive advances in enabling technology for fibre-based strain sensors for structural monitoring. For a space-borne system, we shall require to build custom-designed electronics to replace the test-gear units used. Many of the required electronic functions are fortunately available in consumer IC form for radio systems, so compact electronic systems are feasible.

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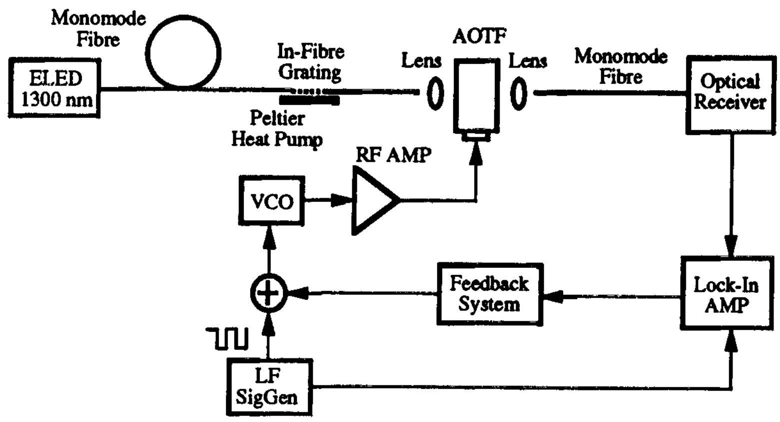

Fig.1 Schematic of interrogating the in-fibre grating using an AOTF

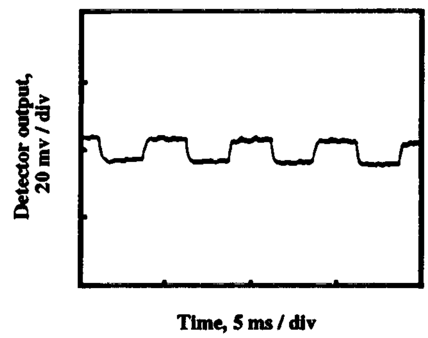

Fig.2 Output from the optical receiver when RF frequency is detuned from the matching condition

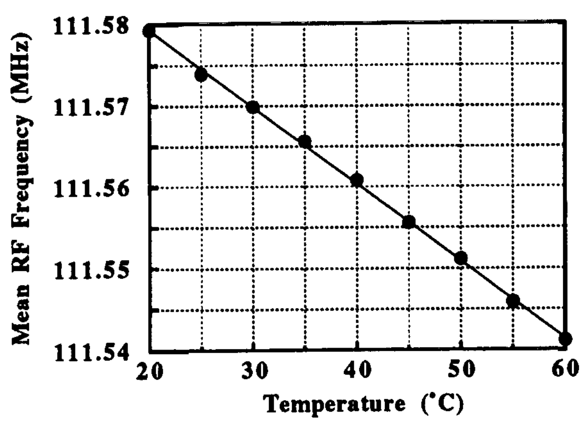

Fig.3 Tracking of fibre grating subject to thermal variation