Distributed and Multiplexed Fibre Grating Sensors

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Abstract
A short review of distributed and multiplexed fibre grating sensor technology is presented, followed by a more detailed account of work at the University of Southampton, including aspects of temperature and strain discrimination and multiplexed and distributed sensing.

1. Introduction
Fibre Bragg grating sensor research has progressed actively over the last decade since the early landmark papers by Hill[1] and Morey et Al[2]. Bragg gratings are narrowband reflective filters, which are formed by periodic variations of refractive index, easily written into the core of a monomode fibre using UV light[2]**.** They allow the encoding of sensing information as peak reflected wavelength, essentially independent of amplitude fluctuations. Grating sensors have been used to measure many physical parameters including strain[2,3,4,5], temperature[2,6,7,8] and pressure[9,10] (and even chemical parameters[11] when the optical field extends outside the fibre). A major advantage of grating sensors is that they can easily be formed into a multiplexed array along a single length of fibre[3], hence sampling the spatial distribution of a measurand. In addition, multiplexing can allow the formation of 3D sensing rosettes and simultaneous measurement of several parameters by linear regression processing of the outputs of several sensors[8]. More recent techniques[12,13,14] have provided continuous distributed spatial information, and some are capable of characterising the entire wavelength profile of long Bragg gratings with resolution below 1mm[15], and even themselves being multiplexed[16]

2. Review of Multiplexed Fibre Grating Sensors
To interrogate multiplexed gratings, it is necessary to determine the peak reflected wavelengths of each element in a network of gratings, the network acting as a filter with a number of sharp peaks in its spectrum. This interrogation can be done by using either:-

(a) A broadband source and some form of spectrum analyser (the analyser may be either a scanned optical filter and detector or a parallel analyser such as a CCD monochromator)

(b) A wavelength scanned optical source and a fixed detector

© An active grating system, where the gratings act as either laser mirrors or as an integral distributed feedback laser (DFB) followed by a spectrum analyser as in (a)

It should be noted that the transfer response of the tuned source (or filter) is usually of a narrowband type. However, in common with modern spectroscopic methods, Fourier-transform techniques can also be used. Then, the tuneable filter element has a sinusoidal transmission function and the information is recovered by Fourier transformation of the temporal detector response. Grating sensors are most commonly multiplexed in the wavelength domain, but it is also possible to make use of the time domain (propagation delays) and the coherence domain (matching white-light interferometers) and to increase numbers even more by using a fibre switch to select lines of similar sensors. By such combinations, very large numbers of gratings may be interrogated using a single measurement system.

The peak reflective wavelength of gratings was first examined in the laboratory using a broadband source and commercial optical spectrum analysers[1,2]. Subsequent research on fibre grating sensors has concentrated on producing low-cost, compact or high-accuracy interrogation systems to measure the wavelength of the gratings with practical hardware. Wavelength interrogation systems have been constructed using a broadband source and a wide variety of optical filters, for example WDM couplers with a "cross-over" response[5], fibre-based Fabry-Perot filters[17], acousto-optic tuneable filter[18] and matched fibre gratings[19], all having a narrowband (transmissive or reflective) response similar to the grating spectrum, and a family of interrogators using twin-path interferometers (eg Mach Zehnder[4] or Michelson) with a sinusoidal transfer function. The latter method effectively uses the Fourier transform method, which is the basis of many modern spectrometers, and which confers a degree of parallel read-out capability, as some information on the full array is obtained before completing the scan. However, again accepting design principles from recent spectrometers, true parallel readout with miniature CCD-array/diffraction-grating devices[20] can offer signal/noise advantages in the 400nm to 1060nm region where silicon detectors can be used. In another approach to enhancing performance, active systems have been demonstrated where the sensor grating forms a mirror in a fibre laser[21,22], or even forms part of a miniature distributed feedback rare-earth fibre laser[24,25]. The wavelength of the laser is measured using similar filters to those described above, but now the optical intensity is many orders of magnitude higher. Care must now be taken, however, to avoid errors due to self heating in the grating mirror or DFB fibre laser. Finally, it should be noted that, instead of using gratings as sensors, they have also been used as convenient reflective markers for long gauge length sensors. They are particularly attractive for use in reflectometric hydrophone arrays, that initially used broadband reflective splices between separate sections of an optical fibre[26], but may now use in-line gratings[3]. The latter are much easier to incorporate, merely by external UV inscription, and also allow an additional means of low-loss multiplexing in the wavelength domain.

Several sensor systems have been devised to measure the average strain in long sections of fibre between reflective markers using the relative delays of light reflected back from a series of such markers in a fibre. The first of such systems[27,28] used reflective fibre splices, but clearly gratings represent an easier means of forming an array of reflective markers in a fibre.

Apart from the conventional form of in-fibre grating, where the pitch of the grating is of the order of the optical wavelength, long-path gratings with much greater pitches of many wavelengths can be written[29]. These have been used in sensors, mainly as amplitude filters[30], but their much broader filter charactersitics greatly reduce their potential for multiplexing and high measurement precision. In addition, for physical sensors, they have the undesirable property of requiring cladding-mode coupling, so are extremely sensitive to the properties of any external medium in which they are embedded or contained.

3. Review of Distributed Bragg Grating Sensors

In the last few years, a new generation of high-resolution distributed sensors based on Bragg gratings has evolved. These sensors measure the wavelength profile, as a function of position along a grating to derive a thermal or strain profile. Spectral amplitude measurements were initially used to infer regions of constant strain and regions of constant strain[12,13]. Recently, techniques have been developed[31] to calculate the exact wavelength (and hence strain or temperature) profile from these amplitude measurements. Other techniques demonstrated have used a tuneable narrowband source[32] and subcarrier modulation, or a tuneable broadband source and low-coherence interferometry[14,15,16].

Distributed sensors provide a high resolution measurement with no dead-zones. The systems using a narrowband source and subcarrier modulation can only measure monotonic wavelength profiles, which makes them less suited for crack detection for example. The low-coherence method can measure arbitrary wavelength profiles, however the maximum length that can be interrogated is limited by the variable delay.

4. Work at Southampton University

We shall now describe sensor advances in our own laboratories, but first, review briefly our relevant grating fabrication.

4.1 Fabrication of Gratings for Multiplexed and Distributed Sensors

A major advance in the enabling technology for multiplexed fibre grating sensors was the ability to write arrays of gratings during the pulling of fibres. These was first done at Southampton University[33], using a holographic technique (converging UV beams from a 20ns duration excimer laser pulse) as the fibre left the pulling oven, but before it received its primary coating. This not only gives advantages in cost and speed of production but provides a dramatic improvement in the mechanical strength of gratings, as, unlike batch methods involving cladding removal, the pristine nature of the outer silica surface is not degraded.

Long fibre gratings for distributed sensing are fabricated in a sophisticated inscription system, capable of making gratings with any desired pre-programmed wavelength chirp up to 1m in length.[34] The exposed fibre section is translated through the interference pattern generated by a phase mask. A CW UV laser is externally intensity modulated to control the exposure.

4.2 Multiplexed Grating Sensors

Our own favoured technique for interrogating gratings is using an acousto-optic tuneable filter, or AOTF[18] (figure 1). This is an extremely frequency-agile filter device, with a bandwidth of typically 0.5 to 3nm, that can change its peak transmission wavelength over at least an octave range, and with a typical reaction time of 10 μs, in response to changes in the frequency of an RF drive signal, hence allowing the multiplexed addressing of gratings over a wide wavelength range. Not only can the device be rapidly tuned, but it can also be driven simultaneously at more than one

RF frequency, to give an independently tunable passband corresponding to each[35]. By dithering the wavelength of the AOTF, its can also be locked on to track the wavelength of a grating. Because the mean RF drive frequency to the AOTF determines the central AOTF wavelength, the grating wavelength can be monitored extremely precisely by measuring this frequency over as long an interval as desired. We have developed a theory to predict the optimum wavelength deviation to dither the AOTF to obtain the highest accuracy measurement and determine the performance[36]. In early trials, even when using a low-intensity ELED source, real-time strains have been measured with 0.18$\mu\varepsilon/\sqrt{Hz}$ accuracy and greatly improved performance is available with higher radiance sources (eg superluminescent fibres). More recently, by incorporating the tunable filter within a fibre ring laser [37], narrow-line outputs of up to 3mW have been achieved, several orders of magnitude higher than with the passively-filtered ELED.
Two of our experiments illustrate advantages that can be achieved from multiplexing. In the first, a pair of gratings were bonded to a metal cantilever as a bending sensor, one on top and the other directly beneath[38]. Common-mode temperature changes produced the same wavelength change to both gratings, while differential strains produced wavelength changes of opposite direction. Temperature-insensitive strain measurements were made by subtraction. In the second experiment[8], simultaneous measurements of strain and temperature were made by measuring two gratings, written over each other in the same point in a fibre at widely different wavelengths. This method used the phenomenon that the photoelastic coefficient and the thermo-optic coefficient vary differently with wavelength, so the two measured wavelengths may be converted to temperature and strain values using linear regression.
Many applications require gratings to be interrogated simultaneously. One useful characteristic of the AOTF is its ability to produce many passbands simultaneously merely by driving it with several RF signals of different frequency. Simultaneous closed-loop interrogation of gratings has been demonstrated using a single AOTF and different FSK dither frequencies for each grating [39]. The crosstalk was measured to be below the system noise floor.
An AOTF interrogation system with ELED source, similar to that in [18], has recently been used in a series of routine tests for monitoring of destructive cracks in composite materials, as part of an evaluation for aerospace applications [40]. To study the strain field in the region near to a propagating crack, five lines of fibre, with eight fibre gratings in each line, were embedded within "sandwich" (aluminium-skin/carbon-fibre-composite) test panels to form rectangular 5x8 sensor arrays. The sensing lines were interrogated in turn using a monomode fibre switch. One line of fibre from the switch was attached to a temperature stabilised, reference grating which compensated for thermal effects in the AOTF. Trials involved cyclically loading a test panel with a small, central hole with notches at the side of the hole to initiate crack growth. During two-week trials, the measured strain field correlated well with the observed spread of the crack and resulting delaminations in the panel.

4.3 Fibre Sensors Using Gratings as Distance Markers

The grating sensors discussed so far are all point sensors. We have also recently used gratings to measure the average strain in long sections of fibre between reflective markers using the LIDAR concept, ie the relative delays of light reflected back from a series of such markers in a fibre. The first of our systems [27,28] used reflective fibre splices, but clearly gratings have recently been used as an easier means of forming an array of reflective markers in a fibre[41].
We have recently proposed a novel sub-carrier fibre grating sensor (SFG), a widely spaced periodic array of reflective Bragg gratings [42]. Whereas the normal Bragg grating is resonant at optical frequencies, the SFG is resonant at RF eigenfrequencies determined by the spacing of the reflectors. The resonant frequency may be interrogated by observing the interference of RF intensity modulation on an optical carrier signal.
Due to the coherent sub-carrier signal addition, the SFG provides a sharp resonace peak, and hence enhanced sensitivity compared to a two reflector sensor. Additionally, any reduction in the sharpness of resonance provides information on the spatial uniformity of the strain field. It is best suited to large structures where the strain is constant over the length of the sensor. Creating a SFG from sets of arrays of Bragg gratings, with each array group of identical wavelength, offers the potential for multiplexing in the wavelength domain.

4.4 Fibre Grating Arrays Sensed in the Coherence Domain

A recent coherence domain method has been devised for sensing pairs of matched-wavelength gratings, each with diffferent spatial separations [43]. The pairs were interrogated using a scanning Michelson interferometer, and when its path imbalance approximated the separation of the gratings, a burst of interference fringes was observed. Because of the line narrowing effects of the reflective grating filters, each burst can contain several hundred fringes, allowing accurate processing by counting, zero-crossing or Fourier analysis . The grating wavelengths are derived from the fringe-passing frequency and the path imbalance from the peak of the fringe envelope. By combining this method with WDM and TDM, very large numbers of grating pairs may be interrogated.

4.5 Distributed Grating Sensors

Multiplexed arrays of gratings can provide a good approximation to the actual strain field, however a more complete spatial image is obtained using a distributed sensor[12].Distributed grating sensors have many advantages, including high spatial resolution (~0.5mm) and no dead-zones. We have demonstrated a novel broadband interrogation system for distributed grating sensors, capable of measuring arbitrary strain fields. Low-coherence interferometry selected the point in the grating to be interrogated and a tuneable filter measured the local wavelength at this point. Our first method used a fibre Michelson interferometer to select the position and a stretched monitor grating to act as the interrogation filter [14].

A subsequent interrogation system (figure 2) was constructed by adding an AOTF and Er^{3+} - doped fibre amplifier to a commercially available optical-coherence-domain reflectometer (OCDR, HP8504B precision reflectometer). The reflectivity, as a function of distance, was monitored using the OCDR and the filter wavelength was repeatedly incremented to measure the reflectivity profiles of the entire grating at each wavelength. In this way the reflectivity of the grating was obtained as a function of both wavelength and distance. A 40cm chirped grating, with a mechanical strain applied along part of its length, was characterised. The peak-wavelength versus distance information gives the spatial strain field, as shown in figure 3. This figure shows the underlying chirp of the grating with an additional wavelength shift over a certain region due to the applied strain field.

To perform dynamic measurements, the wavelength of a chosen section of the grating could be tracked in real-time by dithering and locking the AOTF in a similar way to measuring grating point sensors. The path length of the reference arm of the interferometer selected the location to be interrogated. By tuning this path length, the entire strain field could be rapidly measured.

Finally, our most comprehensive demonstration was that of multiplexing a pair of distributed grating sensors in a single sensing network. A 3 dB fibre coupler was used to locate the two gratings in separate branch arms, yet at the same path length from the interrogation system. The OCDR system then characterised the network, showing the two gratings as regions of high reflectivity with the same path-length difference along separate arms, but reflecting in different wavelength regions, demonstrating wavelength division multiplexing of the sensors. With the same system, spatial-domain multiplexing of point sensors was demonstrated by characterising a sensor network with four gratings located at different locations along a single length of fibre.

4.6 Active (Lasing) Grating Sensors

The fibre laser based sensing systems currently being researched at the University of Southampton are based on distributed feedback lasers formed by writing Bragg gratings in rare-earth-doped fibres. Our DFB sensors lasers are typically only 50mm long, with the distributed grating mirror formed along most of the Er-doped section. The gratings are written with an internal phase step, as usual with DFB structures. The sensing laser is pumped, via the downlead fibre, with a high-power 980nm or 1480nm semiconductor laser and emits in the 1550nm region. When it is heated or stretched, its output wavelength (and hence frequency) varies due to the changes in resonant wavelength of the grating. Use of birefringent fibres (Hadeler et Al, to be published) allows the simultaneous generation of two lasing outputs from each laser, giving the possibility of heterodyning the outputs to give an RF difference-signal output (typically up to 1.2GHz) that can be measured with great precision (scale factors are typically $-1.6 MHz.K^{-1}$, & $7.9 MHz.\mu\varepsilon^{-1}$. In addition, the absolute wavelength of each lasing output can also be measured on an optical spectrum analyser, to provide a second measured quantity, which allows linear regression to be used for the simultaneous determination of temperature and strain. To date, three sensors have been multiplexed, however this technique could be extended to up to about ten sensors.

5. Conclusions

The field of distributed and multiplexed Bragg grating sensors has been reviewed, and more specific work at the University of Southampton has been described. We have demonstrated gratings as point sensors, as markers defining sensing sections of fibre and as fully distributed sensors. A variety of different multiplexing methods have been devised, but the most sophisticated system allowed multiplexed interrogation of distributed sensors.

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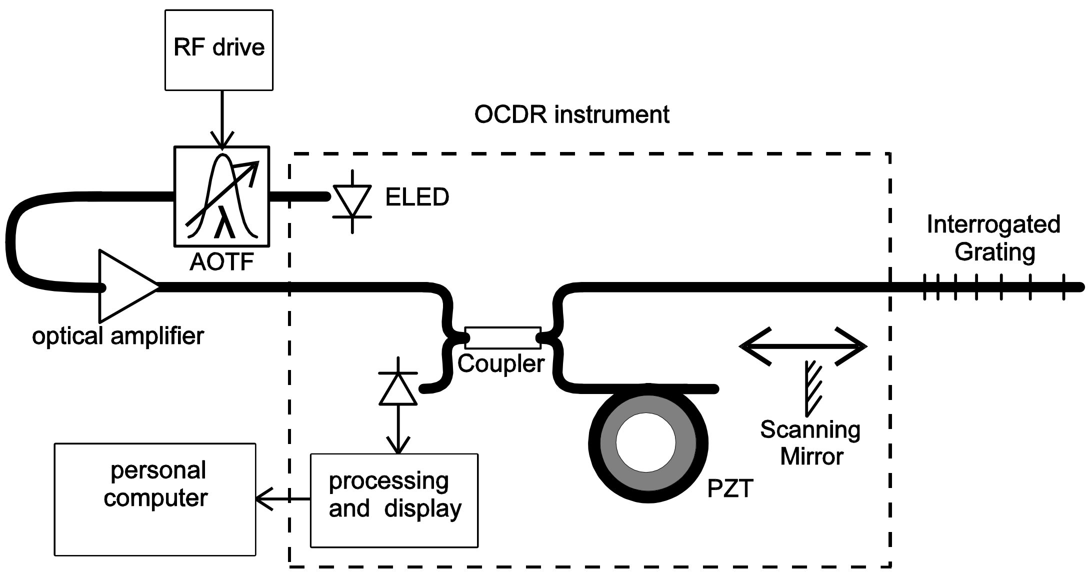
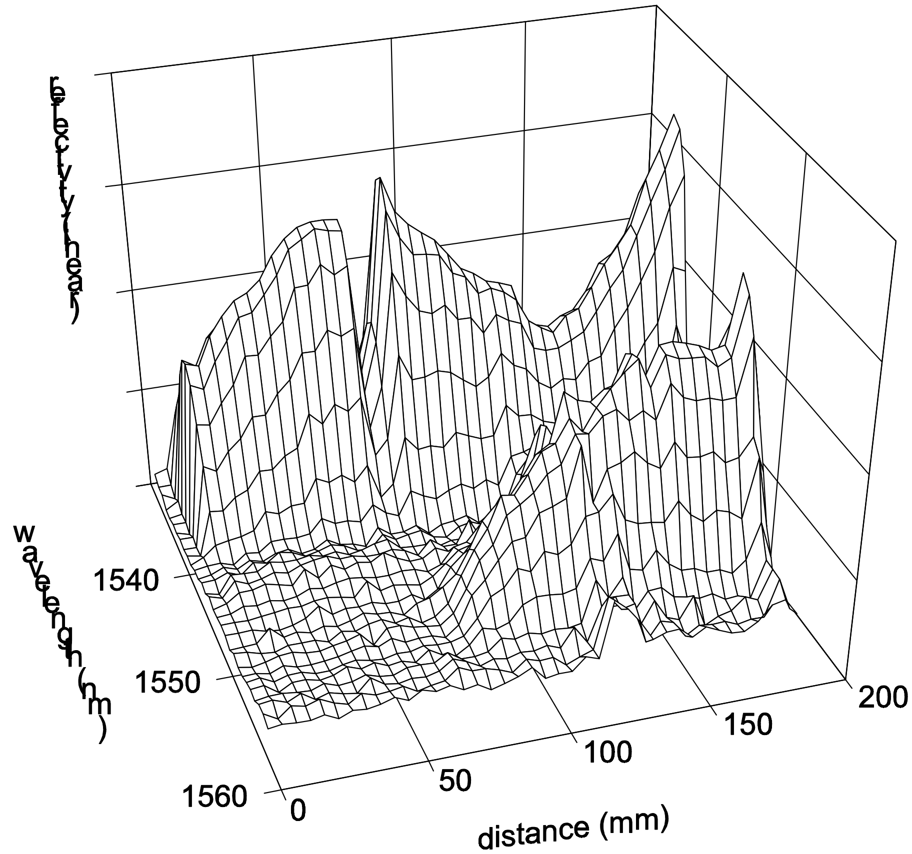
Figure 1 Multiplexed grating interrogation system to monitor cracks in composite materials

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