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Rectangular pulse generation based on pulse reshaping using a superstructured fiber Bragg grating

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Recent advances in ultrafast laser technology call for new all-optical methods for precisely manipulating and controlling the shape of short pulses. The most widely known pulse-shaping technique involves filtering of the spatially dispersed frequency components of a short pulse using bulk gratings and appropriate phase and amplitude masks [1]. Alternative coherent pulse shaping techniques have also been developed. For example, in Ref[2] pulse shaping was achieved using second-harmonic generation in aperiodic quasi-phase-matching structures. The use of arrayed-waveguide gratings for optical processing applications has also been proposed [3].

Fiber Bragg Gratings (FBGs) can also be viewed, and used, as spectral filters of controllable phase and amplitude. FBGs offer all the advantages associated with fiber components, such as ready integration into fiber systems, minimal coupling losses, and in addition offer tunability through control of the grating's strain and temperature. For a weak FBG, i.e. one in which light penetrates through the full grating, its frequency response is given by the Fourier transform of the index modulation profile along the grating length. This principle has been used in the past, in conjuction with conventional uniform FBG designs, to generate a train of dark pulses [4], and to obtain a matched filter for the detection of 100ps square pulses [5]. However, advances in the fabrication of FBGs now allow the fabrication of gratings with almost arbitrary amplitude and phase characteristics, greatly extending the range of applications of the approach. Control of the grating's frequency response is obtained by spatially modulating a uniform grating's refractive index profile with a sampling function that corresponds to the desired impulse response of the grating. Recently, we demonstrated the use of relatively simple superstructured gratings for pattern generation and recognition [6], as required for optical code division multiple access applications (OCDMA), and have also demonstrated the use of an FBG to perform pulse repetition rate multiplication from 10 to 40 GHz [7]. In this work, we have progressed the approach, and successfully demonstrated the fabrication and use of a truly complex superstructure grating designed to transform short optical pulses (2.5 ps at 10 GHz) into a corresponding train of 20 ps rectangular pulses. Such pulse forms are suited to nonlinear optical switching applications, in which a square switching window is required.

The ~2.5 ps input pulses were generated using an actively and harmonically mode-locked Er-fiber ring laser, operating at a repetition rate of 10 GHz. They had a spectral half-width of 1.04 nm (Fig. 2a) and a temporal FWHM of 2.53 ps (Fig. 3a), indicating almost transform-limited soliton pulses (time-bandwidth product = 0.326). They were coupled onto the FBG by means of a fiberized optical circulator.

The grating was designed, such that the product of its spectral electric-field response (amplitude and phase) with the spectrum of the incident soliton pulses gives the required temporal reshaping.The overall grating bandwidth was limited to 6 nm to accommodate the full bandwidth of the soliton pulses down to -25 dB from the spectral peak. For our target 20 ps pulses (see inset Fig.3) we can accommodate a total of 13 spectral lobes, with alternate optical phase. Note that the power spectrum of a perfect rectangular pulse is a sinc^2 function which extends to infinity either side of its main lobe. Using this reshaping approach we inevitably restrict the bandwidth. In order to avoid the ringing in the temporal domain that would otherwise

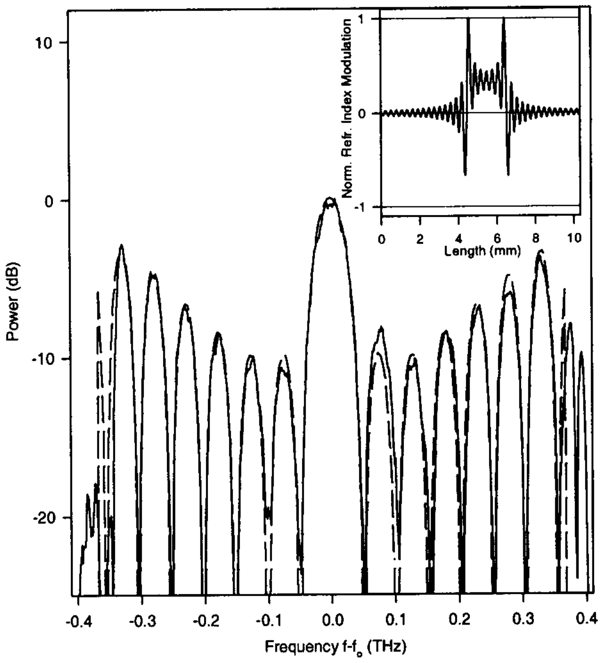

Fig. 1: Actual (solid line) and designed (dashed line) frequency response of the grating; the sampling function of the grating is shown in the inset.

ensue, we therefore apodized the output pulse spectrum (through the grating response) to smoothen the effects of this truncation. The power spectrum of the filter we designed is shown by the dashed line in Fig. 1. The main features of the ideal sinc^2 power spectrum are still evident despite the apodization, i.e. the zeros at every 1/T from the center frequency, where T = 20 ps, and the sidelobes of interchanging optical phase. The grating sampling function is given by the inverse Fourier transform of the grating's spectral response and is shown inset in Fig. 1. Its full length in time is t = 100 ps, corresponding to a grating length of $0.5 \cdot t \cdot c/n = 10.3$ mm, and consists of several sections of alternating phase. The grating was subsequently fabricated, using a continuous grating writing technique, based on grating plane by grating plane exposure [8]. The actual spectral response obtained is compared to the design in Fig. 1 (solid line), and clearly demonstrates the quality and control provided by this writing technique.

The power spectrum of the pulses reflected off the FBG is shown as curve (b) in Fig. 2. This is compared to the calculated truncated and apodized sinc^2-shaped spectrum that was used to design the FBG (Fig. 2c). A good agreement between the two shapes is clearly demonstrated. The amplitude of the first lobes is ~12.5dB lower than the central lobe, close to the corresponding figure for the ideal sinc^2 function (13.3 dB). The temporal characteristics of the resultant pulses were measured with an autocorrelator. The autocorrelation of a rectangular pulse of duration T is a triangular pulse of full length 2T. The acquired autocorrelation trace is compared in Fig. 3 to that of the incident pulses, and the calculated autocorrelation trace corresponding to the spectrum of Fig. 2c. Once again the agreement is extremely good indicating excellent phase control within the grating. The actual temporal profile of this calculated pulse is shown inset in Fig. 3.

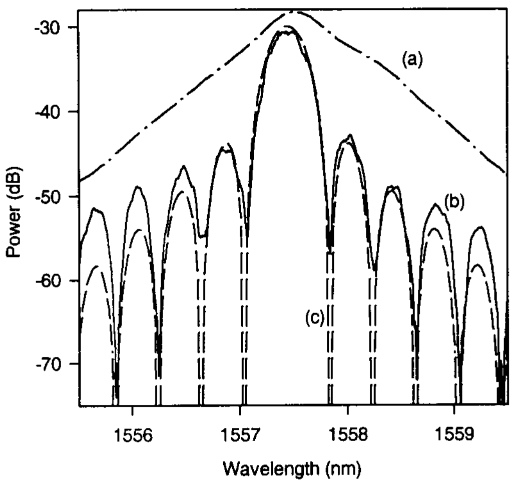

Fig 2: Power spectra of (a) the input pulses, and (b) the shaped pulses; (c) is the calculated spectrum of the pulse shown in Fig. 3(inset)

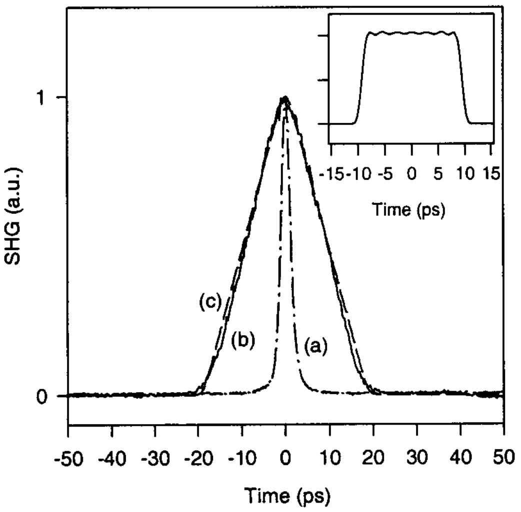

Fig. 3: Autocorrelation traces of the input 2.5 ps soliton pulses (a), and the output pulses (b). The dashed curve (c) corresponds to the calculated autocorrelation of the pulse shown in the inset.

In conclusion, we have achieved the generation of rectangular 20 ps pulses with a repetition rate of 10 GHz by shaping a train of 2.5 ps soliton pulses. Pulse shaping was performed by spectral filtering of the incident pulses using an FBG, the refractive index of which was appropriately modulated along its length to yield the desired spectral characteristics. In both cases, the results agreed well with the calculated predictions. The generation of rectangular pulses serves as a good example of a demanding (and useful) pulse shaping application, as it requires good control of both the phase and amplitude characteristics of the filter/shaper. We believe that the work described here demonstrates that fiber grating technology has now truly developed to the extent that FBGs can be reliably and accurately fabricated to produce complex optical filters with almost arbitrary phase and amplitude response.

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Review of distributed and multiplexed fibre grating sensors and discussion of problem areas

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ABSTRACT

Based on an earlier version presented at OFS13 in Korea, a short review of distributed and multiplexed fibre grating sensor technology is given, followed by details of work at the University of Southampton, including aspects of temperature and strain discrimination and our own methods for multiplexed and distributed sensing. The paper concludes with a short discussion of the problems that should be avoided in order to construct viable systems for engineering requirements.

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 processing of the outputs of several sensors using linear regression[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 any of the following approaches-

(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

(c)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:-

(a) WDM couplers with a "cross-over" response[5]

(b) 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

(c) 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 adopting design principles from modern-generation 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 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 linewidth greatly reduces the potential, both for multiplexing and for 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 observe variations of strain in different regions of a long grating[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, but 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 work on grating fabrication techniques.

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 were first fabricated 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 were 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 a 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 has the advantage of being remarkably frequency-agile, with a typical reaction time of 10 µs. The filter changes its characteristics 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 several independently-tuneable passbands, each one corresponding to the frequency of the different RF inputs to the device[35]. By dithering the wavelength of the AOTF, its peak transmission wavelength can also be locked on to track the wavelength of a grating. Because the mean of the 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 0.18µε / Hz accuracy. Greatly improved performance is potentially available with higher radiance sources (eg. superluminescent fibres). More recently, by incorporating the tuneable 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 the 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 bending-strain measurements were made by subtraction of the response of the lower sensor from that of the upper sensor. 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, but the grating periods designed such that they reflected at two widely different wavelengths. This method took advantage of 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] (See figure 1).

To study the strain field in the region near to a propagating crack, five lines of fibre, each with eight in-line fibre gratings, were embedded within "sandwich" (aluminium-skin/carbon-fibre-composite) test panels to form a rectangular 5x8 sensor array. Each of the individual fibre sensing lines were then interrogated in turn, using a monomode fibre switch. One output line of fibre coming 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 extended trials of typically two-week duration, 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, i.e. an optical-time-domain sensor system measuring the relative delays of light reflected back from a series of such markers in a fibre. Our first system arrangements[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 using 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 a series of RF eigenfrequencies, the value of which is 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 addition of the sub-carrier signals, the SFG provides a sharp resonance 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, each array of gratings in the set reflecting at the same 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 different 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 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 points 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 sensor 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 its 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 -1.6MHz.K^{-1}, & $7.9\text{MHz.}\mu^{-1}$. 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, but in future it is confidently expected that the use of this technique could be extended to address up to ten sensors.

5. POTENTIAL MEASUREMENT PROBLEMS

It is now appropriate to list, and briefly consider the problems that must be avoided in order to ensure there are no measurement errors in grating interrogation systems. Clearly, in any form of measurement there will always be errors, so it is important to understand the sources of these in order to be able to minimise them. Gratings start by having substantial advantages over conventional electrical sensors (eg. resistive strain gauges) as they are essentially immune to many of the problems associated with these (E-M interference, lightning strikes & other electromagnetic pulses, earth-loops, change in electrical properties due to corrosion or partial short-circuiting by electrolytes such as salt water, changes in contact resistance, etc.) Particular attention must, however, be paid to the following aspects:-

Spectral overlap of gratings: If gratings in a multiplexed system have overlapping spectra, then the interrogation system will, when monitoring a desired grating, experience undesirable changes due to changes in wavelength (or even changes in the intensity of reflected signal) in an adjacent grating; ie. there will be crosstalk. Such changes may be particularly severe if all the gratings are in line in a single fibre as under these circumstances there will not only be effects due to reflective signal addition from adjacent gratings but also problems arising from "spectral shadowing" (ie. filtering effects of the light passing twice through any gratings which are situated in the fibre line at a point nearer to the interrogation system than the grating it is desired to interrogate) If the reflection of the gratings is high, this shadowing effect will be more severe, and also additional effects due to multiple reflections may start to become significant.

Sidebands in the measured gratings, the interrogation filter or the tuneable light source: The effects of sidebands in any of the measured gratings or in a tuneable filter (eg. AOTF, Fabry-Perot, etc.) used to interrogate a grating array will lead to measurement errors, if the sidebands extend to cover the response from an adjacent grating. Of course, similar problems will also occur if a tuneable light source has emission sidebands covering adjacent gratings.

Changes in grating spectrum due to spatially-varying physical field (strain, temperature, pressure) in the grating: If the grating is influenced by a non-uniform longitudinal strain pattern, then the normal narrowband reflective spectrum of the grating will be lost, the spectrum will broaden and it may become significantly asymmetrical and irregular. This will increase the possibility of crosstalk and may lead to severe errors if the peak reflective wavelength is measured. Centroid measurement will give a better measure of the true mean level of strain in the grating. Non-uniform strain patterns can clearly arise when gratings are embedded in inhomogenious media (eg. in woven carbon-fibre composites, concrete, etc.).

Sharp variations with wavelength in any optical components in the interrogation or sensing loop: Problems of this nature may arise due to many possible causes. Relatively gradual spectral gradients may be present in the output of a luminescent source such as an LED or a rare-earth-doped fibre source, or occur as a result of wavelength dependent transmission of the fibre network, including any couplers, or be due to spectral variations in the response of the silicon detector, etc. These will generally give small errors if the slope in the combined response is small and the grating being interrogated has a narrow line spectrum. However, several of these components can give much sharper changes in their spectra. Taking the light sources, for example, superluminescent LEDs and rare-earth-doped fibres can exhibit very significant spectral spikes if reflections occur back into the amplifying region. Most high radiance SLEDS exhibit strong spectral peaking when driven at their maximum ratings. Fibre systems can be engineered with less back reflections, but the high gain possible with fibres means care still has to be taken. The fibre network can exhibit small-amplitude, but rapid spectral changes due to low-finesse Fabry-Perot cavities between the fibre end surfaces in connectors or between opposite faces of glass windows on detectors. Also, if the fibre system allows significant fibre microbending losses to occur (likely, for example, in fibres embedded under pressure in composites), then light coupled into cladding modes by fibre bends can, in subsequent bends, be coupled back into the monomode core of the fibre. This returning light can interfere in a rather unpredictable manner with the light already present and give rise to a wide variety of small but sharp spectral features. Such effects are a potential problem in either the transmission or the sensing fibre.

Polarisation-dependent changes: If the sensing gratings are birefringent, the reflective spectrum will, in general, consist of two principal reflective peaks of different wavelength, one wavelength corresponding to each polarisation mode. The cause of this is that the sensing fibre in which the grating has been written may exhibit some degree of initial birefringence due to lateral strain or a slightly oval cladding cross section. Even if this is not the case, the grating inscription method (UV illumination from one side) is inherently asymmetrical and may induce birefringence. In addition, if gratings are embedded in composites under the action of side pressure, some birefringence will occur due to this strain field. Fortunately, polarisation changes alone will not give rise to errors, as the final detector only measures intensity changes. Unfortunately, however, the optical source (eg. ELED) and many optical and fibre components in the network to this detector may have a significant polarisation dependence in their transmission. These include couplers, acousto-optic tuneable filters (AOTFs), diffraction grating monochromators. The effect of these is to give a strong polarisation dependence to the system response when the wavelength of peak reflectivity of the grating is different for different polarisations (ie. birefringent grating). The errors due to polarisation effects can be very severe[44]

Reference 44 , which was based on collaborative work between University staff and the group of Ecke at IPHT, Germany, discusses this problem in more detail and shows how scrambling the polarisation, in either the time or wavelength domain, gives substantial practical improvement to a system based on spectral analysis of the reflected signals using polarisation-sensitive CCD spectrometry.

6. 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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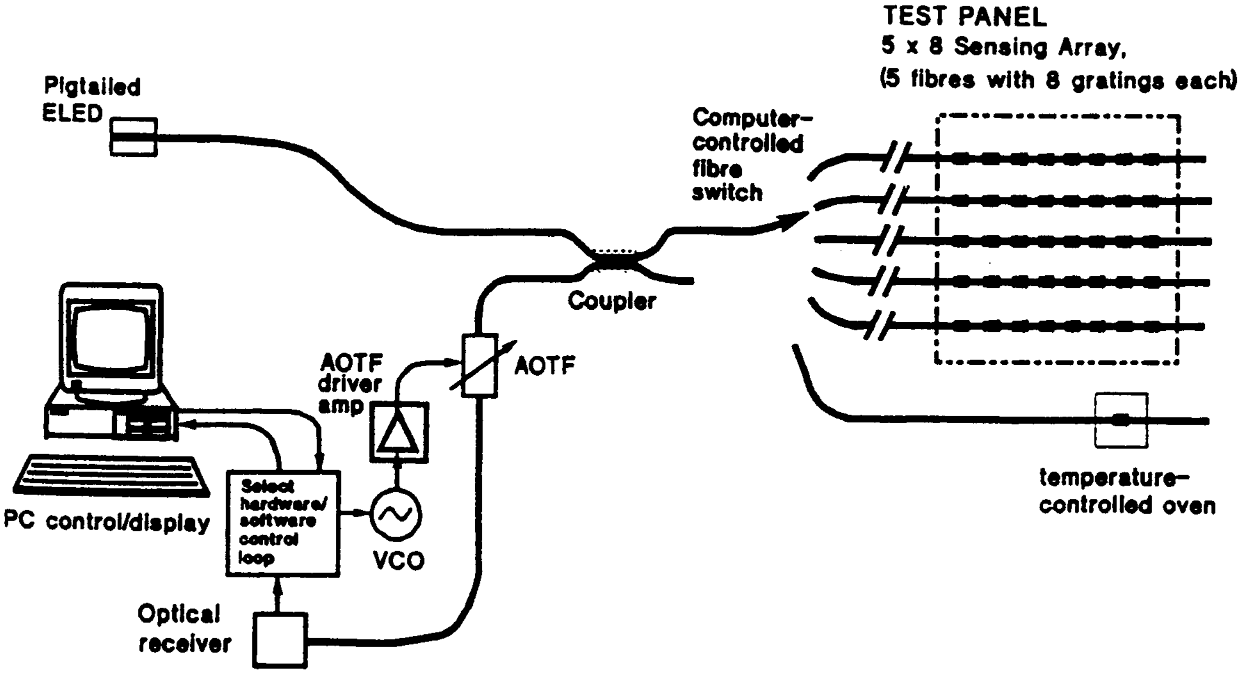

Figure 1 Multiplexed grating interrogation system using AOTF

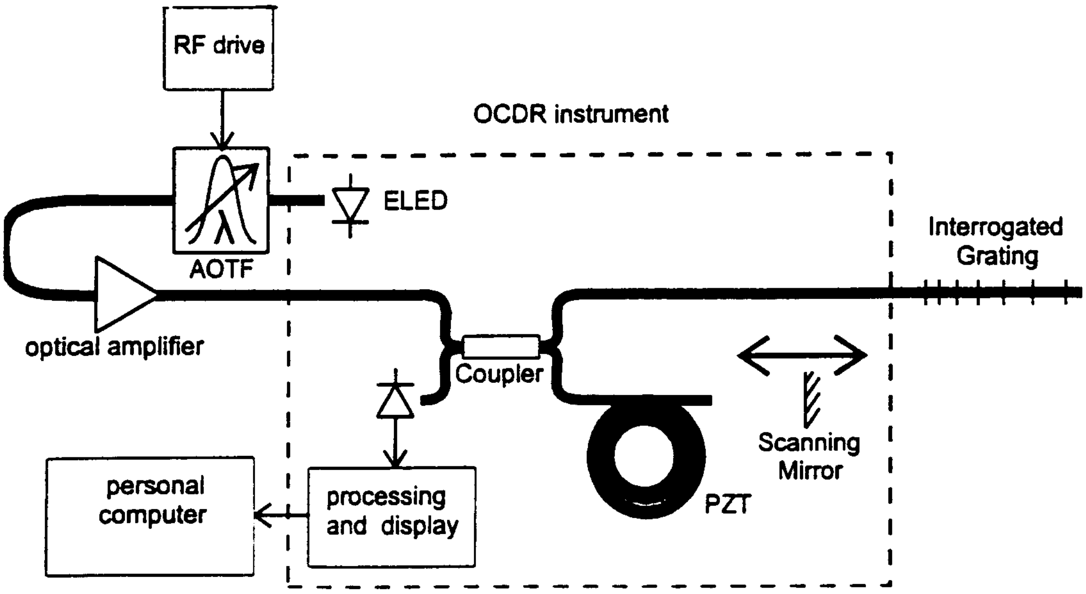

Figure 2 Distributed grating interrogation system using a commercial OCDR

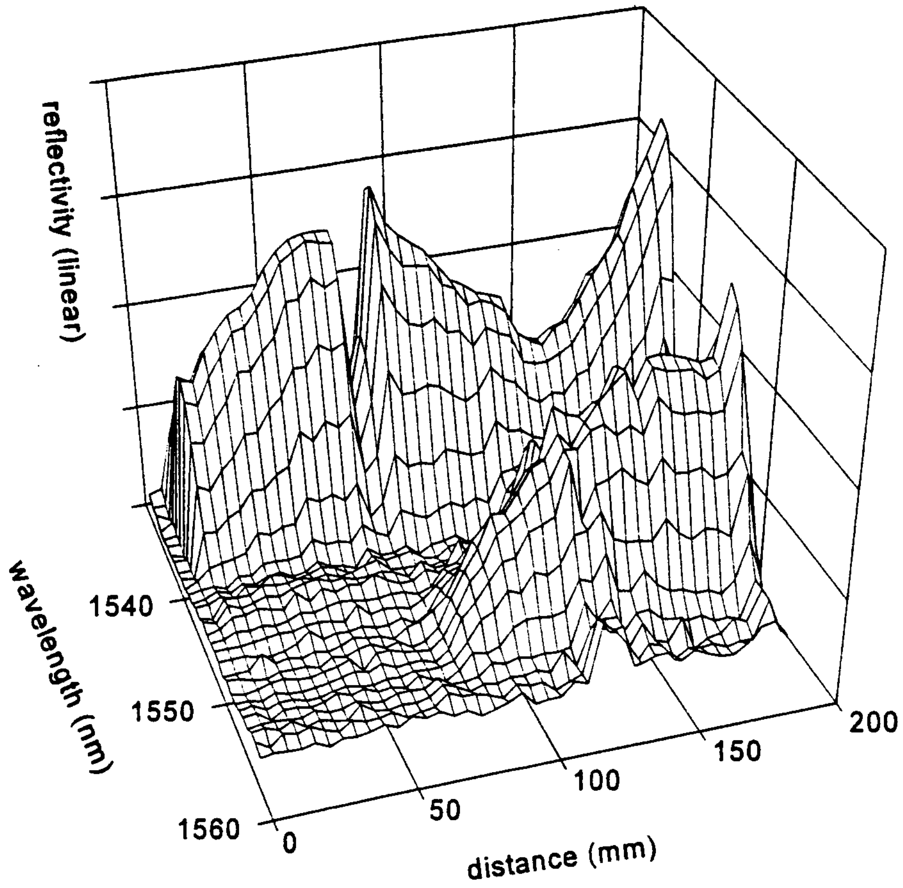

Figure 3 Wavelength division multiplexed distributed grating sensors