Medical temperature profile monitoring using multiplexed fibre Bragg gratings

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ABSTRACT

We describe work on a system able to measure the temperature at a number of points along a single optical fibre probe, designed for in-vivo temperature profile monitoring. The sensing elements are in-fibre Bragg grating sensors and three forms of signal processing have been investigated. System 1 uses interferometric wavelength shift detection with a monochromator providing the WDM. System 2 used a scanning in-line Fabry-Perot filter and system 3 uses a monochromator with a CCD based readout scheme. The performances of the three approaches are compared.

Keywords: Optical fibre sensors, Bragg gratings, temperature, multiplexing

1. INTRODUCTION

In recent years there has been a growth in the use of thermal therapy as a minimally invasive alternative to surgery. Microwaves, RF fields, lasers and ultrasound have all been used to induce temperatures above normal in regions of the body for the treatment of various conditions. In all these procedures, it is important to control the temperature to obtain maximum benefit and ensure safe operation and so ideally the temperature profile within the body should be measured in some way.

This is a demanding problem and one which current technology is only partially able to solve. As part of a research programme funded by the Wellcome Trust, we have been developing a novel form of instrumentation that will allow the simultaneous measurement of temperature at a number of selected points along an optical fibre. Being optical fibre based, the probe may be small (<1mm in diameter), which is advantageous in reducing patient discomfort, in reducing the perturbation of ultrasound fields and in achieving a fast response to changing temperatures. The probe is also immune to the effects of electromagnetic radiation and will not appreciably distort any electromagnetic fields in its vicinity. As a consequence of these non- or minimally-perturbing characteristics, temperature may be monitored during treatment with microwave, RF or ultrasound radiations without causing artifacts.

2. PROBE DESIGN

The sensing elements are in-fibre Bragg grating sensors. A great deal of literature is now available concerning the construction and operation of these devices as sensors[1]. In brief, the gratings may be formed by illuminating germania doped optical fibres from the side with ultra-violet light with a periodically varying intensity pattern (Meltz et al 1989). This exposure causes a permanent periodically varying refractive index within the fibre core which reflects light close to one particular wavelength,

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where the periodicity of the grating is exactly half of one wavelength. Subjecting the fibre to a change of temperature (or strain) causes the periodicity and hence the reflected wavelength to vary, so by illuminating the fibre with light from a broad band optical source, say, and examining the wavelength of the light reflected from the grating, the temperature of the fibre may be deduced.

It is easy to address more than one such sensor by ensuring that over the operating temperature range, each device is designed to reflect light within a different 'window' of the source spectrum. The number of sensors that may be unambiguously addressed is then determined by the desired working range and the source bandwidth. Choosing realistic figures for an example, a source bandwidth of 20nm would allow up to 20 sensors to be used, each with a temperature range of 100°C. By writing the different sensor gratings close together, the temperature profile of the fibre environment may be recovered.

In-fibre Bragg gratings do not offer the very high resolution obtainable from interferometric fibre sensors, where resolutions of 10^{-3} °C are obtainable[2], but their performance has been shown to be sufficient for the applications envisaged here. Moreover, any lack in performance is more than made up for by their ease of multiplexing, as described above.

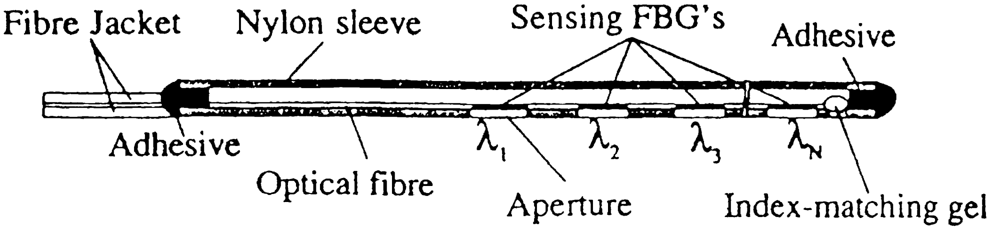

Fig. 1. Probe design.

The design of the probe is shown in figure 1 above. In the region of the sensing elements, the fibre is inserted in a stiff nylon sleeve. This sleeve serves two purposes: firstly, it removes the risk of the fibre breaking and being left in the patient; secondly it prevents the communication of any stress from the surrounding tissue to the sensing fibre. This would otherwise produce a strain within the fibre which would cause wavelength shifts in the gratings that are indistinguishable from those produced by temperature.

3. SIGNAL PROCESSING

We have investigated three different methods of recovering the Bragg wavelengths of the gratings. The systems are described and contrasted below:

3.1 System 1

An outline of this system is shown in figure 2. The source is a Superluminescent diode with a bandwidth of 18.5 nm (818-836.5 nm) capable of outputting 0.6 mW in singlemode fibre. The interferometric wavelength scanner was a bulk-optic Michelson interferometer developed by Queensgate Instruments. The interferometer had a path imbalance of 0.6 mm, giving a free spectral range of 1.16 nm in the wavelength range of interest. One mirror in the interferometer was mounted on a piezoelectric translator and was scanned with a serrodyne waveform at 300 Hz so as to carry the interferometer over one free spectral range.

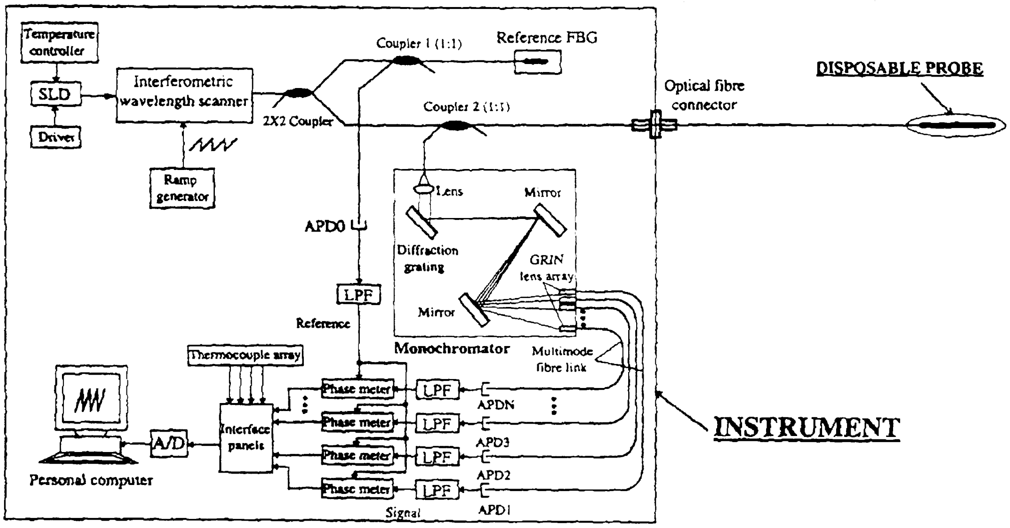

Fig. 2. System 1 schematic.

The transmission spectrum of the Bragg grating array is shown in figure 3. The wavelengths are chosen so that within the anticipated temperature range each grating can never overlap with its neighbour. An additional grating was held at constant temperature to act as a reference.

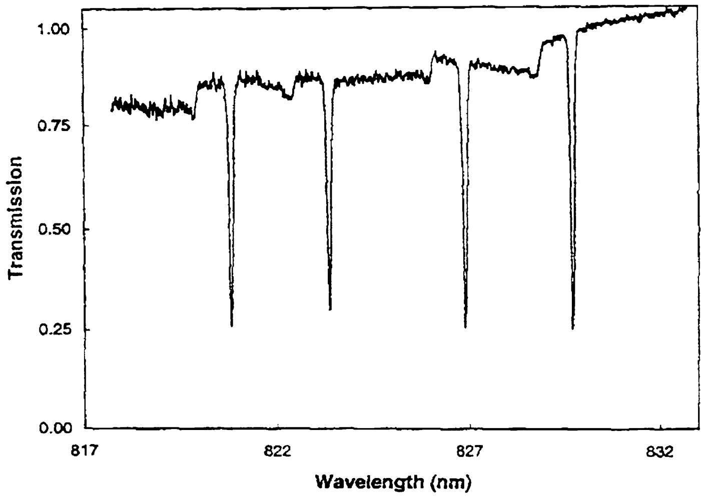

Fig. 3. Transmission spectrum of grating array.

Wavelength demultiplexing was carried out using a 1200 lines/mm diffraction grating to direct the output from each grating to 100 μm core fibre pigtailed with GRIN lenses. Powers of around 10 nW were carried by the fibre to avalanche photodiode receivers. After detection, 300 Hz electrical carriers were obtained; by comparing the phase of the carriers with the signal from the reference grating, the temperature may be deduced[3].

The sensitivity of the system was measured to be 2.1 degrees/°C. The system noise was investigated by mounting the reference grating and one of the probe gratings together in a constant temperature environment. In this way, the drift was determined to be less than 0.1°C over a 10 minute sampling time. In a separate experiment the performance of one of the gratings was compared with a standard thermocouple sensor; from this the accuracy was determined to be ±0.2 °C with a 1Hz update rate.

3.2 System 2

In the second version of the system, the interferometric wavelength scanner was replaced with a pigtailed tunable Fabry-Perot filter which fulfilled the roles of both wavelength shift detection and wavelength division multiplexing, as shown in figure 4. The design was similar to that introduced by Kersey[4] except for the post detection signal processing. The Fabry-Perot filter was driven with a 16 bit digital ramp at 40 Hz. The central wavelength of the grating was determined by averaging the counts corresponding to the leading and trailing edges of the scanned waveform. Once again a reference grating was used to remove thermal drifts in the Fabry-Perot filter.

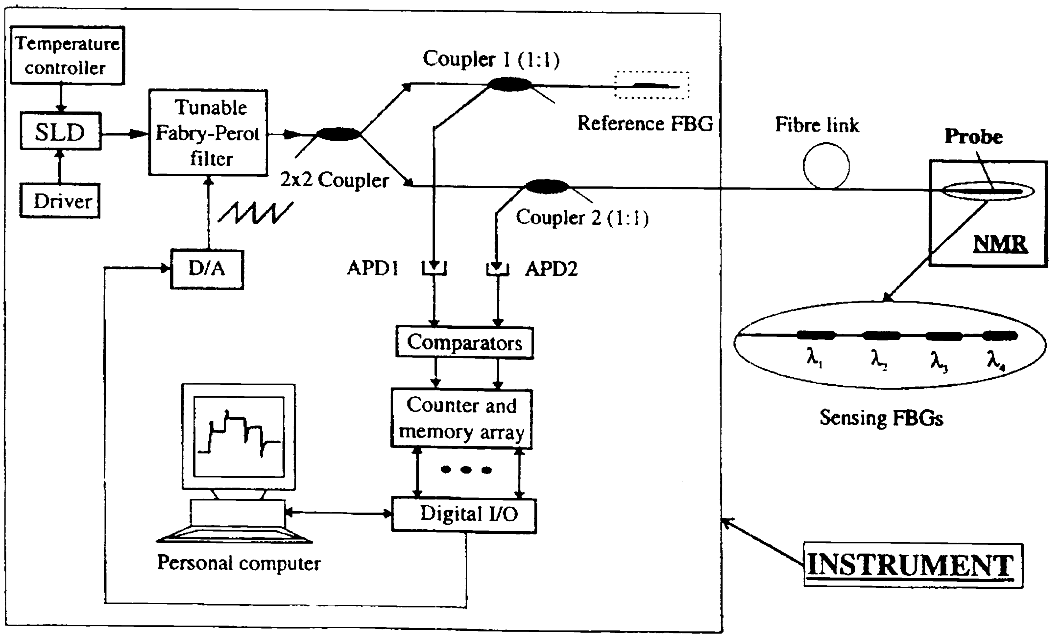

Fig. 4. System 2 schematic.

The temperature resolution of the system was determined to be ±0.2 °C with a measurement time of 0.4 s resulting from averaging the results 16 times. By increasing the averaging time to 1.6 s the resolution was improved to ±0.1 °C. This latter figure was equal to the limit produced by the quantisation of the digital ramp. The accuracy of this system was ±0.8 °C, mainly determined by the non-linearity of the PZT in the Fabry-Perot filter. In principle this could be removed by measuring the non-linearity.

3.3 System 3

The final system is shown in figure 5. As in system 1, a diffraction grating is used to perform wavelength division multiplexing, but this time the wavelength shift of each grating is determined using the dispersion provided by the diffraction grating, by examining the spectrum using a linear CCD array.

Initially the performance of this system was evaluated with a single sensing grating; extension to several gratings being trivial. The diffraction grating had 1200 lines/mm and a 50 cm focal length lens was used. With this configuration, the pixel spacing of 13 μm corresponded to a wavelength shift of 21 pm or about 3 °C. To obtain a useful resolution it is obviously necessary to determine the central wavelength of the Bragg grating to much better than one pixel. This was done initially by sampling the CCD signal using a digital storage oscilloscope. The set of data was then transferred to a computer and the central wavelength determined by fitting a Gaussian profile to both sensing and reference gratings. The separation of the two wavelengths was then used to deduce the temperature of the sensor.

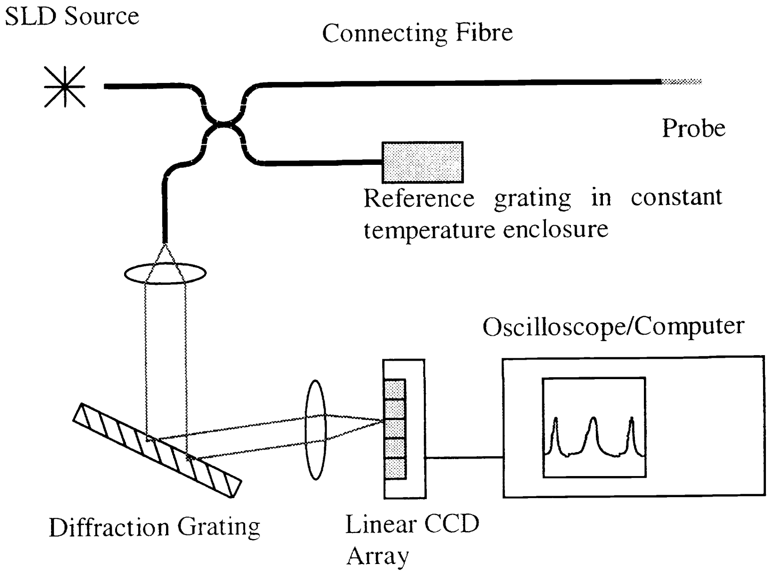

Fig. 5. System 3 schematic.

For the data presented below, the Bragg grating had a rather asymmetric profile which led to problems when the Gaussian fitting method described above was used. Instead, a fast Fourier transform of the sampled data was carried out yielding over 500 frequency components from which the first 15 were used to synthesise a low-pass-filtered version of the data. The peak of this synthesised function was obtained from the Fourier coefficients and used as the Bragg wavelength.

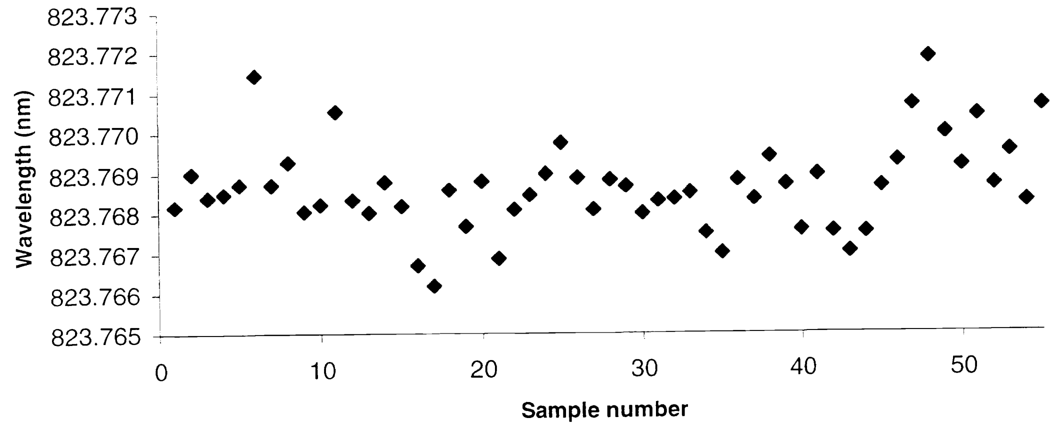

Fig. 6. Wavelength variation at constant temperature

The resolution of the system was determined by mounting the sensing grating in an ice/water mix and repeatedly sampling the spectrum over a period of 2 mins. The pixel stream read out of the CCD was averaged 8 times by the oscilloscope for each sample point (corresponding to a signal acquisition time of less than 0.1 s. The results obtained after converting the pixel number to wavelength are displayed in figure 6. Over the measurement period, the r.m.s. deviation corresponded to a temperature error of ±0.2 °C. Note that these initial experiments were performed without the reference grating shown in figure 5.

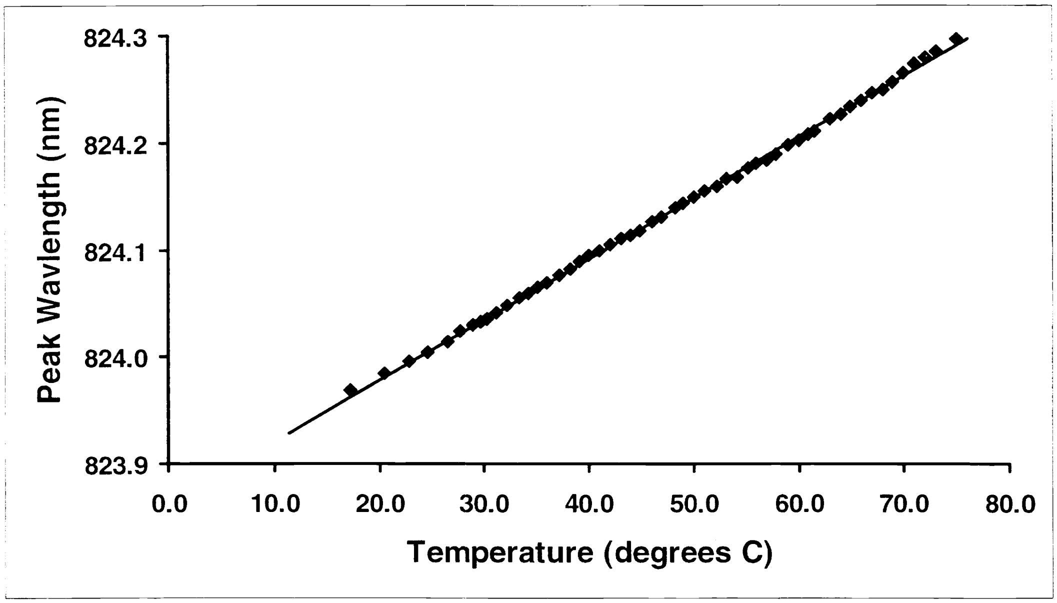

Fig. 7. Peak wavelength versus temperature read from thermocouple.

The probe was then placed in an oven together with a standard thermocouple and data taken over a range of 60 °C. Figure 7 shows a plot of wavelength recovered from the Bragg grating versus temperature obtained from the thermocouple. The r.m.s. deviation from linearity of the data suggests a measurement error of ±0.4 °C. However, it should be noted that at the higher temperatures there was considerable fluctuation in the temperature of the oven with the thermocouple varying of several tenths of a degree during the measurement time; we therefore believe that the true resolution of the system should be closer to the value obtained at steady temperature.

4. DISCUSSION

The performances of the three systems are summarised in Table I below.

System	1	2		3
Bandwidth (Hz)	1	2.5	0.6	10
Resolution (±°C)	0.1	0.2	0.1	0.2

Table I. Comparison of the three systems.

At first sight it appears that the final system is a clear winner: not only does it deliver good performance but it is also likely to be considerably cheaper to manufacture than the others. However, it should be noted that work still needs to be done to assess the long-term stability (accuracy) of these systems; and in particular our experience with system three is fairly limited. Currently, we are constructing a better-engineered version of this system for *in vivo* animal trials at the Cancer Research Institute, Perth, Australia. It had been hoped to report on the trials in this paper, however delays mean that they are now scheduled for the week before Photonics East 98, so results should have been presented at the meeting.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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