ABSTRACT

A new fibre sensor which measures temperature-distribution is proposed. The sensor uses optical-time-domain reflectometry to determine temperature-induced changes in the levels of the backscatter signal. Experiments using liquid-core fibres have demonstrated a sensitivity of 0.018 dBk^{-1} over distances of more than 100m. The proposed sensor is able to monitor the temperature of over 100 points simultaneously. Solid core fibres have also been used; they exhibit a wide temperature range, but somewhat reduced sensitivity.

1144

INTRODUCTION

The development of all-optical fibre sensors for monitoring a wide range of physical parameters is currently of considerable interest. It is attractive to consider an optical measurement of temperature, pressure, strain and vibration at a remote location situated in a hazardous environment, or which suffers from severe electrical interference. In many cases it is desirable to determine the spatial distribution of the sensed quantity. For example, in certain applications it is necessary to monitor the variation of temperature[1,2] within a machine, pipe or oven, or within a reservoir.

In the present contribution we propose and demonstrate the operation of a novel distributed temperature sensor in which optical time-domain reflectometry (OTDR) is used to determine temperature-induced changes in backscatter signal at any point along a specially-designed fibre. The choice of fibre is important, since in this application strong changes in scatter return with temperature are an advantage. We have chosen in the first instance a liquid-core fibre, since it is known[3] that liquids exhibit large variations in both refractive index and Rayleigh scatter coefficient with temperature. Smaller variations are expected in solid-core fibres, leading to a lower temperature sensitivity. The temperature range of operation however, will be much larger.

PRINCIPLES OF OPERATION

The time variation of scattered power p(t) returning to the launching end of a multimode fibre is related to forward pulse energy E_o by[4]:

$$p(t) = \tfrac{1}{2} E_o \alpha_s S v_g \exp -\int_o^t \alpha v_g dt$$

where α_s is the scattering-loss coefficient, v_g, the group velocity and α the fibre attenuation. S is the capture fraction, i.e. the proportion of the scattered light which is trapped by the fibre and guided back to the launching end. For a step-index multimode fibre S is given by[5]:

$$S = \frac{3}{8} \frac{NA^2}{n_1^2} = \frac{3}{8} \frac{n_1^2 - n_2^2}{n_1^2}$$

where NA is the numerical aperture and n_1 and n_2 are the core and cladding refractive indices.

If the fibre is uniform along its length, (i.e. α, α_s and S are independent of position in the fibre), then p(t) takes the form of a decaying exponential, the rate of decay being dictated by the attenuation α. In practice, deviations from exponential behaviour are frequently observed and are usually the result of localised changes in scattering loss and attenuation, or, less obviously, in core diameter[6] and numerical aperture[7]. If such localised changes in backscatter power can be controllably induced by an external effect, such as temperature, then it is possible to use OTDR as the basis for a spatially-distributed sensor.

For a sensitive temperature measurement a fibre is required which exhibits large changes of scatter loss, capture fraction (i.e. NA) or total attenuation in response to temperature variations. The total attenuation may be designed to increase as the external temperature rises using, for example, controlled microbending, or the increase and broadening of absorption bands[2]. Temperature variations are then seen as changes in the rate of decay of the backscatter trace. However, the use of this effect limits either the sensitivity or the dynamic range of the sensor if a large number of points along the fibre are to be sampled, since the power available for the measurement at distant points is reduced by the attenuation at upstream high-temperature points. On the other hand, a sensor based on variations in scattering coefficient largely avoids this problem, since changes in backscattered power are directly detected.

Liquids are known to have relatively large changes in scatter coefficient and refractive index with temperature. Consequently, initial experiments were performed using liquid core fibres. In this case increasing temperature produces both an increase in scattering loss and a decrease in numerical aperture.

Thus we have the choice of monitoring the temperature using either α_s or S. Unfortunately, the two effects act in opposition; however, the effect of numerical aperture variation can be eliminated using modal filtering[8].

EXPERIMENT

Liquid-core fibres were produced by filling silica capillary tubing with hexachlorobuta-1,3-diene[9]. The tubing typically had a 300µm outer diameter and 200µm bore and was coated on-line with brown-coloured polyimide to improve the strength and eliminate propagating cladding modes. The losses were typically 12 to 13 dB/km at λ = 0.85µm.

The experimental arrangement is shown in figure 1. Laser pulses of 10ns duration are focussed into a launch fibre via a beamsplitter and a lens. The receiver consists of a Si APD followed by a transimpedance amplifier. The backscatter waveforms are digitised by a transient recorder and sent to a computer for averaging and processing.

The use of a launch fibre has the dual function of transmitting the optical pulse to the sensing fibre with low loss and of acting as a mode filter. The numerical aperture of the launch fibre (0.3) is substantially smaller than that of the liquid core fibre (0.53 at 20°C) and hence only low-order modes of the latter are accepted and guided back to the detector. Since temperature-induced changes in capture fraction affect only the highest-order modes of the liquid-core fibre, this arrangement eliminates the effect of NA changes on the received backscatter power. This is possible only because liquid-core fibres have a perfect step-index profile. In fibres with graded profiles, modal filtering does not completely eliminate that the effect of numerical aperture variations. Even in step-index fibres some residual sensitivity exists owing to the mode conversion which occurs at longitudinal index changes. This effect is small, and, moreover, adds to the temperature sensitivity resulting from changes in scatter return.

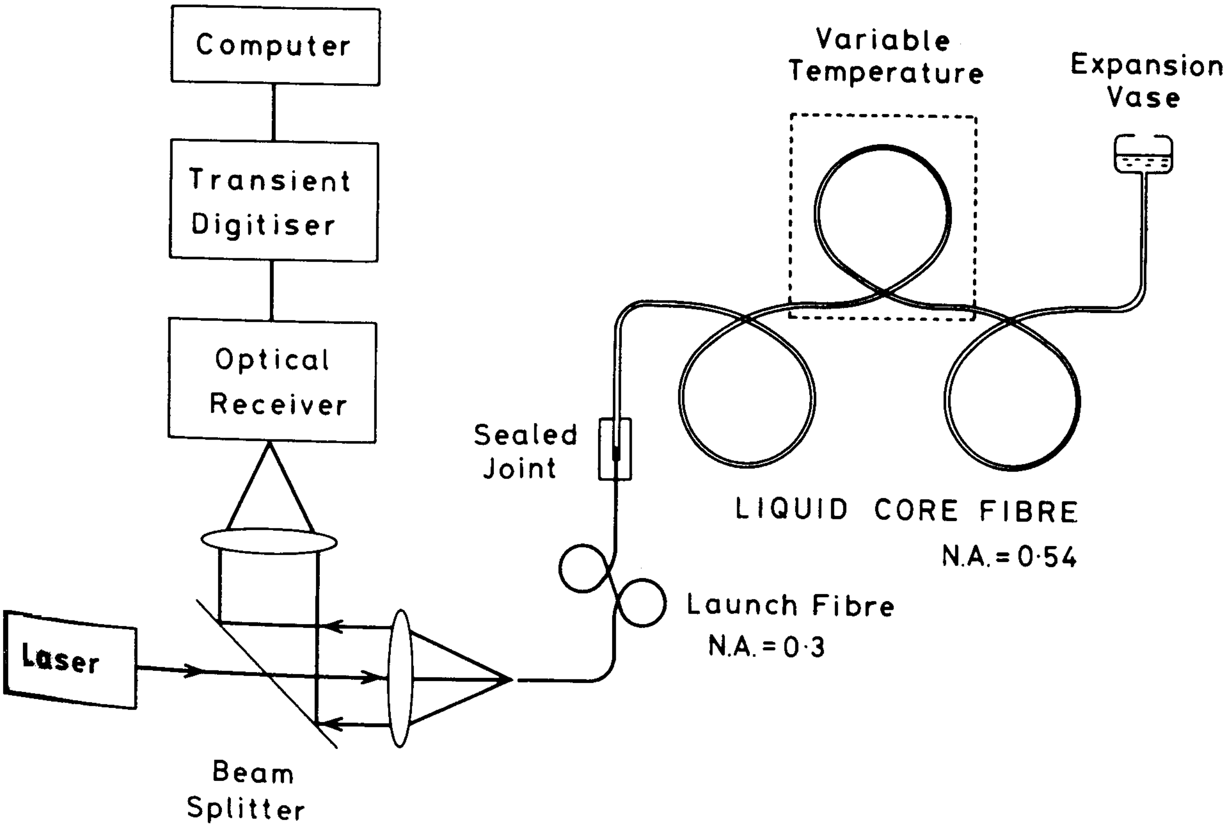

Figure 1

RESULTS

Typical backscatter waveforms are shown in Figure 2. In each case, Sections 1 and 3 were held at 20°C, while the temperature of the central 15m, Section 2, was varied as indicated. It is clear that the scattered power returning from Section 2 is directly related to the local temperature.

Because the increase in fibre loss due to scatter in Section 2 is relatively small, the level of the signal returning from Section 3 will be largely independent of the temperature of the preceeding sections. Figure 2 thus demonstrates the ability of the sensor to sample many separate points simultaneously and independently.

Measurements were made over the range 5-80°C although, potentially, the sensor can operate from 0-200°C. The sensitivity of the device was assessed by measuring the backscatter power-ratio at the temperature transitions as a function of the temperature difference. The resulting sensitivity curve us given in Figure 3. The relationship between the temperature-difference and the power ratio (expressed in dB) is linear, with a slope of 18 mdBK^{-1} (i.e. a signal change of 0.42% per degree).

The highest measurable temperature is that at which the NA of the liquid-core fibre falls to that of the launch fibre. For the fibres used in the present study, this occurs at around 160°C. The range may be extended by increasing the difference between the numerical apertures of the launch and liquid-core fibres.

The spatial resolution of the device is limited by the pulse width of the laser, the bandwidth of the receiver and, more fundamentally, by dispersion in the sensing fibre. Typically a resolution of 1m is available over at least 100m, giving a minimum of 100 independently resolvable temperature measurements.

Solid core fibres can also be used for temperature sensing and the results of a preliminary experiment is shown in Figure 4. The fibre is held at 24°C over most of its length and two portions, approximately 15m in length, are heated to 240°C. The latter regions return markedly larger backscatter signals than adjacent fibre sections. Further measurements have shown that, as in liquid core fibres, the observed changes in scatter return are linearly dependent on the temperature-difference. The solid-core distributed-

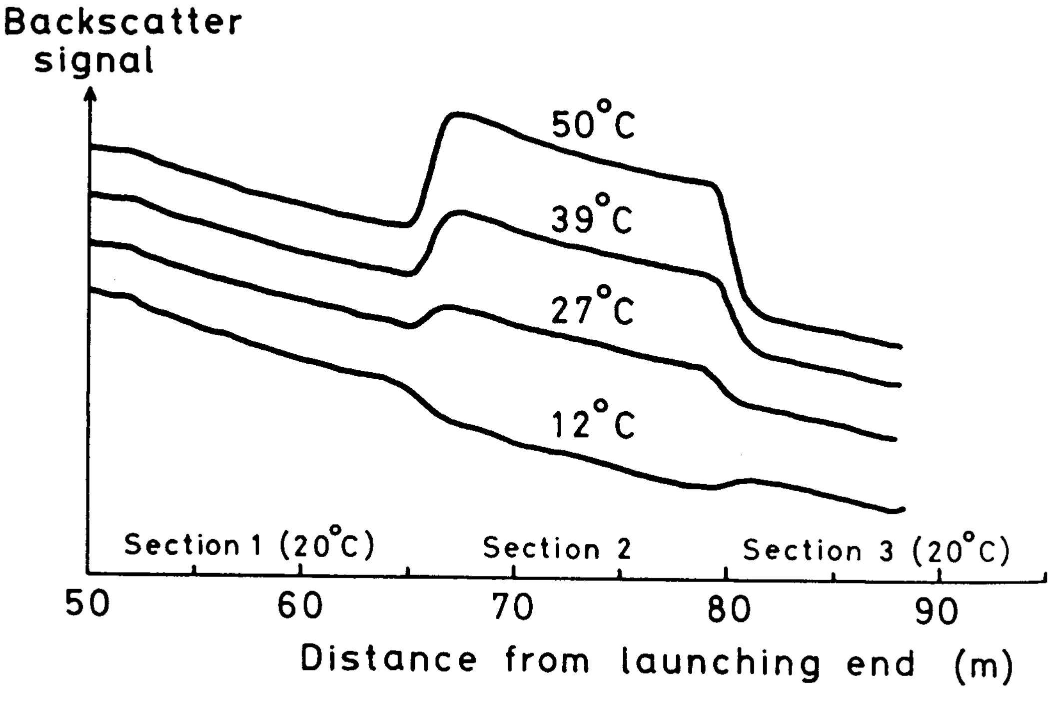

Figure 2

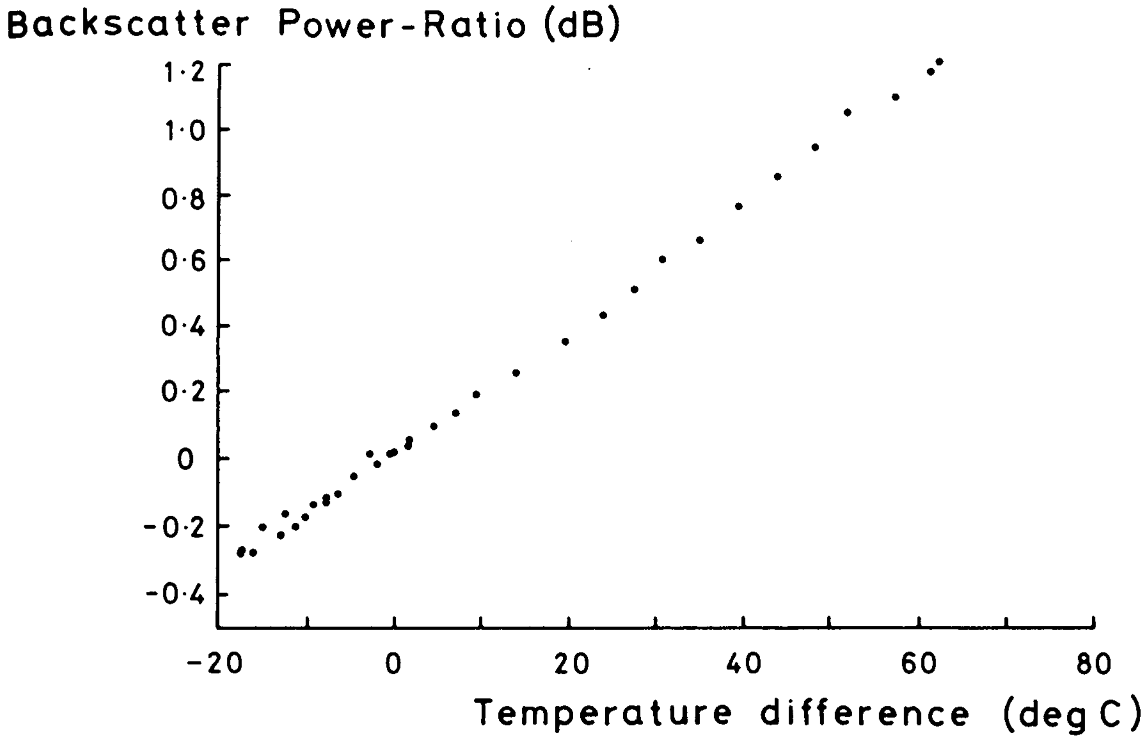
Fibre filled with Hexachlorobuta-1,3-diene

Figure 3

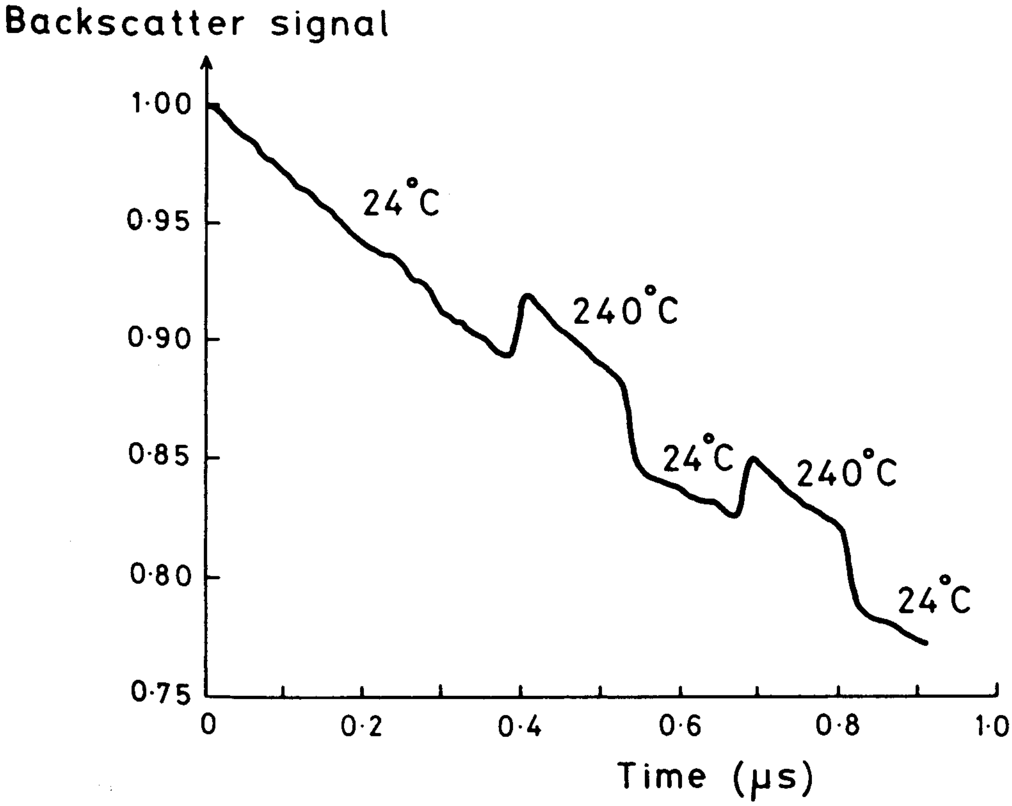
Solid-core fibre

Figure 4

temperature sensor is capable of operating up to 400°C with polyimide coatings and at higher temperatures still if the fibre is uncoated. The sensitivity is at present lower than that of liquid-core fibres although indications are that this can be improved.

CONCLUSIONS

The distributed temperature sensor described above can be seen as the first of a class of sensors which use the backscatter technique to sense spatially-distributed changes in scattering loss, bending loss, refractive index or absorption. With appropriate fibre design the changes can be induced by temperature, pressure, strain or vibration.

ACKNOWLEDGEMENTS

The authors are indebted to R. J. Mansfield and E. J. Tarbox for providing the capillary tubes and to M. P. Gold for useful discussions. Financial support from the UK Science and Engineering Research Council (AHH) and the Pirelli General Cable Company (DNP) is gratefully acknowledged.

REFERENCES

1. M. Gottlieb and G. B. Brandt: "Fiber-optic temperature sensor based on internally-generated thermal radiation". App. Opt. 1981, 20, pp. 3408-3414.
2. M. Gottlieb and G. B. Brandt: "Temperature sensing in optical fibers using cladding and jacket loss effects" App. Opt. 1981, 20, pp. 3867-3873.
3. I. L. Fabelinskii: "Molecular scattering of light", Plenum Press, New York, 1968.
4. S. D. Personick: "Photon probe: An optical-fiber time-domain reflectometer" Bell Syst. Tech. J., 1977, 56, pp. 355-366.
5. E. G. Neuman: "Theory of the backscattering method for testing optical fibre cables" Electron. Commun., 1980, 34, 157-160.
6. A. J. Conduit, D. N. Payne, A. H. Hartog: "Optical fibre backscatter loss signatures: identification of features and correlation with known defects using the two-channel technique" Proc. 6th European Conference on Optical Communication, pp. 152-155, York, 1980.
7. P. DiVita and V. Rossi: "The backscattering technique, its field of applicability in fibre diagnostics and attenuation measurements" Opt. and Quantum Electron., 1980, 11, pp. 17-22.
8. M. Eriksrud and A. R. Mickelson: "Experimental investigation of variation of backscattered power level with numerical aperture in multimode optical fibres", Electron. Lett., 1982, 18, pp. 130-132.
9. D. N. Payne and W. A. Gambling: "New low-loss liquid-core fibre waveguide", Electron. Lett., 1972, 8, pp. 374-376.