DISTRIBUTED TEMPERATURE SENSOR USING Nd^{3+}-DOPED OPTICAL FIBRE

Indexing terms: Optical fibres, Measurement, Optical measurement, Time-domain reflectometry

We report the measurement of temperature distribution with an Nd^{3+}-doped multimode optical fibre. By exploiting the temperature-sensitive absorption bands of the doped-glass core, temperature was measured to an accuracy of 2°C over the range −50°C to 100°C. A spatial resolution of 15 m over a fibre length of 140 m was obtained.

Introduction: Optical-fibre distributed temperature sensors have a wide range of applications in industry and in the environment. These include the monitoring of temperature in power lines, transformers, chemical plants, oil refineries and coal mines. This type of sensor is particularly suited to fire detection in large buildings, which would otherwise require a large number of discrete sensors. An optical fibre distributed sensor enables the temperature to be monitored simultaneously at many locations with one instrument.

Several methods for measuring temperature distributions using both liquid- and solid-core optical fibres have been reported.[1–3] This letter investigates a novel approach in which the optical fibre is doped with a temperature-sensitive material. The temperature of all parts of the fibre may be recorded using a conventional optical time-domain reflectometer.

Nd^{3+} doped fibre: The active dopant in the sensing fibre is Nd^{3+}, which is added to the core material during the fibre preform fabrication.[4] The fibre was manufactured with a core diameter of 50 μm to enable efficient launching of a semiconductor laser into the fibre.

The usable length of fibre over which temperature can be measured with a conventional backscatter set is limited to a length with a loss of 10 dB. The change in backscatter signal with temperature increases with the absorption loss, so there is a tradeoff between temperature sensitivity and the total length over which temperature may be measured. A nominal core dopant concentration of 5 parts in 10^6 of Nd^{3+} was used to optimise the temperature sensitivity over 200 m of fibre.

The fibre attenuation against wavelength was obtained using the cutback method. From the attenuation plot shown in Fig. 1 it is seen that there are strong, characteristic Nd^{3+} absorption peaks at 74 nm, 800 nm and 880 nm. It is also noted that the loss falls to 10 dB/km at a wavelength of 1·0 μm.

Temperature dependence of fibre attenuation: The fibre attenuation against wavelength was measured at −50°C, 0°C, 50°C and 100°C and referenced to the measurement at 0°C. All the Nd^{3+} absorption bands showed a strong temperature dependence, while the attenuation outside these bands remained constant with temperature.[5] The percentage change in fibre attenuation, measured at a wavelength of 904 nm, is plotted against temperature in Fig. 2. A temperature sensitivity of 0·2%/°C was measured for this fibre which contained 5 parts in 10^6 Nd^{3+}. Experiments on other fibres showed that the percentage change in absorption with temperature increased with dopant cocentration.

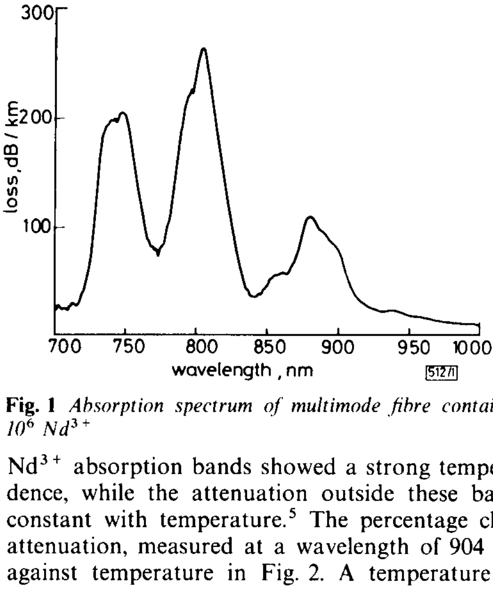

Fig. 1 *Absorption spectrum of multimode fibre containing 5 parts in 10^6 Nd^{3+}*

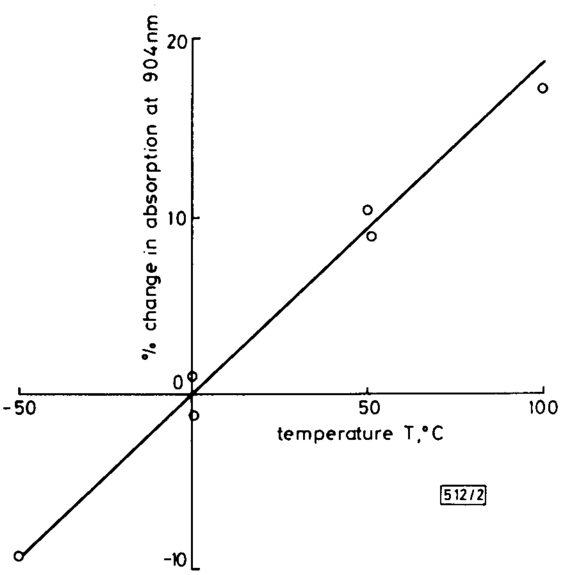

Fig. 2 *Dependence of absorption of Nd^{3+}-doped fibre on temperature: percentage change relative to 50 dB/km loss at 0°C*

The fibre attenuation is seen to be a linear function of temperature within the experimental accuracy shown by the points in Fig. 2.

The highest temperature measured was limited by degradation of the acrylic fibre coating. A greater temperature range could be measured if a high-temperature coating such as polyimide was applied to the fibre.

OTDR temperature sensor: Backscatter measurements were used to spatially resolve the local attenuation along the fibre length. A conventional multimode OTDR system using a 904 nm semiconductor laser was employed. The system produced pulses of 40 ns width at a repetition rate of 4 kHz. An Si APD followed by a 100 kΩ transimpedance preamplifier was used to detect the return signal, which was further amplified and filtered before being acquired by a 20 megasample/multichannel A/D convertor. This results in a sample spacing of 5 m, with the analogue bandwidth effectively reducing the spatial resolution of the backscatter points to 7·5 m. Measurement of local attenuation requires the slope to be taken between two points, thus giving a spatial resolution of 15 m. Real-time averaging allows 100 000 waveforms to be averaged in approximately 2½ min.

Processing of results: The backscatter power measured from one end of the fibre is given by

$$P(t) = \tfrac{1}{2}E_0 V_g \alpha_S(z) S(z) \exp\left[-2\int_0^z \alpha_L(z)\, dz\right] \tag{1}$$

where E_0 is the input pulse energy, V_g is the group velocity, S is the scatter capture fraction, α_S is the Rayleigh scatter loss and α_L is the local attenuation.

By measuring the fibre from both ends it is possible to separate local attenuation from the capture fraction,[6] resulting in the following expression:

$$\alpha_L = \frac{1}{4}\frac{d}{dt}\left[\ln\left(\frac{P_1(z)}{P_2(z)}\right)\right] \tag{2}$$

where $P_1(z)$ is the backscatter power from a given point as measured from end 1 and $P_2(z)$ is the backscatter power from the same point as measured from end 2.

The expression is implemented by taking a backscatter trace from each end of the fibre and reversing the second trace such that equivalent sample points may be overlayed. The ratio of each point of the two traces is a function dependent

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only on the loss coefficient. The local attenuation is obtained by taking the two-point slope of the natural logarithm of this ratio. The measurement of local attenuation is used to obtain the temperature distribution along the fibre.

Results: The local attenuation backscatter trace with all the fibre at a temperature of 22°C is shown in Fig. 3. A signal/noise ratio of 40 dB was obtained after averaging, which is equivalent to a local attenuation resolution of 0·2 dB/m. With a temperature sensitivity of 0·1 dB/km/°C a temperature resolution of 2°C is estimated. However, the backscatter traces show a 13 dB/km variation in local attenuation along the fibre. This is partly due to microbending caused by loose-coiling the fibre on drums, although there is also evidence of an enhanced dopant concentration at 40 m. Changes in microbending and nonuniform dopant deposition will limit the accuracy of temperature measurement.

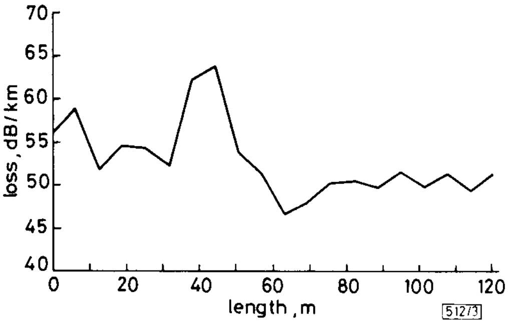

Fig. 3 *Local attenuation backscatter signal from optical fibre at 22°C*

Local attenuation backscatter traces were taken while the temperature of the centre 60 m of fibre was varied from −40°C to 80°C. The 40 m of fibre at each end was held constant at 22°C. The local loss distribution normalised to the fibre loss at 22°C is shown in Fig. 4. The first and last 10 m of signal are lost owing to detector saturation caused by fibre end-face reflections. From Fig. 4 we see that the temperature sensitivity of the fibre is nonuniform owing to the variation in doping level, with a maximum sensitivity at 40 m, corresponding to the increased doping level. At a specific point in the centre of the heated region, where the local attenuation is known, the temperature was measured with an accuracy of 2°C over the range 0°C to 40°C. Outside this temperature range the accuracy was better than 10°C.

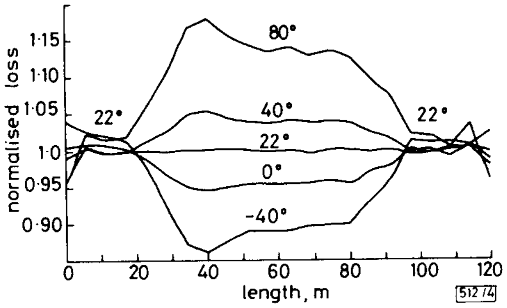

Fig. 4 *Local attenuation backscatter signal normalised to local attenuation at 22°C*

Centre of fibre was heated from −40°C to 80°C while ends were kept at 22°C

Conclusions: A distributed temperature sensor based on changes in absorption in an Nd^{3+}-doped fibre has been demonstrated for the first time. Temperature distributions can be measured with 2°C accuracy and a spatial resolution of 15 m over a length of 140 m. An increase in sensor length may be achieved by splicing lengths of doped fibre between lengths of conventional low-loss fibre. Significant improvements are expected by optimising the fibre fabrication process to ensure an even distribution of Nd^{3+} along the length.

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