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DISTRIBUTED TEMPERATURE SENSING IN SOLID-CORE FIBRES

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Abstract

A distributed temperature sensor using the Raman line of backscattered light in solid-core optical fibres is reported. A device having a resolution of 1K over 1km of fibre and with a spatial resolution of 7.5m was constructed using a semiconductor source and detector.

Introduction

Optical fibre temperature sensors have been the subject of research for a number of years. Of late, interest has turned to distributed fibre sensors[1,2], which enable the temperature to be monitored at many independent positions along a single fibre and thus determine the thermal distribution and the location of hot-spots.

The first implementation of a distributed temperature sensor[2,3] relied on optical time-domain reflectometry (OTDR) in liquid-core fibres. In such fibres, a localised temperature rise results in an increased scattering signal which may be detected and located by OTDR. Although the device was satisfactorily demonstrated, the longevity of liquid-filled fibres is unknown and a sensor incorporating an all-solid fibre is thus preferable. Early results on solid-core fibres[2] showed a fairly low sensitivity.

A promising approach has recently been put forward[4] in which only the Raman component of the backscattered light is detected. Although the intensity of the anti-Stokes Raman component is more than three orders of magnitude smaller than that of the total scattered signal, its sensitivity at room temperature is sufficiently high (0.8%/K) to make the device practicable.

In the present letter, the authors investigate the performance of the Raman OTDR technique for temperature sensing. The sensitivity is compared with a theoretical model. A temperature resolution of better than 1K is achieved over more than 100 independent points using a compact apparatus incorporating a semiconductor laser.

Experiment

The experimental arrangement is a fairly conventional multimode OTDR using a wide-contact 850nm injection laser giving pulses of 40ns duration at a pulse repetition rate of 4kHz. The power launched into the fibre is 350mW. The anti-Stokes backscattered light component is separated with an interference filter (11nm FWHM spectral bandwidth). It is then detected by an Si avalanche photodiode followed by a preamplifier having a transimpedance of 100 kΩ and a bandwidth of 30MHz. The signal is further amplified and filtered; the resulting waveform has a 10-90% rise time of 74ns, giving a spatial resolution of 7.5m (resolutions quoted in OTDR literature frequently refer instead to sample separation, which can be misleading). The signal is acquired with a 50ns sample spacing by a high-speed 8-bit A/D converter and averaged 100,000 times in a multi-channel digital averager.

Several fibres were investigated. The results shown in this letter were obtained on a multimode fibre having a numerical aperture of 0.3 and a core diameter of 100µm. This fibre has a large backscatter capture fraction, allows a good launching efficiency from semiconductor lasers and its high GeO_2 content leads to a relatively large Raman signal.

For the purposes of this experiment, the 1.1km length of fibre was arranged into five coils, two of which were placed in an environmental chamber, as illustrated at the bottom of Figure 1.

Results

A typical Raman OTDR waveform is shown in Figure 1. At the remote end of the fibre two very distinct zones of increased scatter signal indicate those sections which have been heated to a temperature of 100°C (compared with an ambient temperature of

24°C). Note that the backscatter signal returns to its expected level between the two hot zones. The small undulations in signal level, which are particularly clearly visible in the first half of the fibre, were found to be stable and reproducible and are most probably attributable to localised fibre diameter variations[5]. However, their effect on the measured temperature distribution turns out, after normalisation, to be negligible.

The temperature sensitivity of the device has been measured over the range -52°C to +100°C. The results are shown in Figure 2 (dots) in the form of the backscatter level (normalised to that measured at ambient) as a function of the temperature of the hot zones. It may be seen that the signal has fallen by a factor of 2 at -52°C. This is accompanied by an increase in the relative sensitivity from 0.8%/K at room temperature to 1.2%/K at -52°C. Ultimately the useful temperature range of the sensor will be limited by the fall in signal level at low temperatures.

The results have been fitted to a curve of the form

$$f\ (T) = \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1} + R$$

which describes the expected variation of signal with frequency shift ν and absolute temperature T. Here h and k represent Planck's constant and Boltzmann's constant, respectively; the term R accounts for the contribution of Rayleigh scattering occurring at wavelengths other than the anti-Stokes Raman line. The values of the parameters R and ν giving the best r.m.s. fit were 17.5% and 535cm^{-1}, respectively, the r.m.s. error being less than 0.25%, i.e. an uncertainty in the temperature varying from 0.25 to 0.5K over the measurement range.

The values of the fitted parameters are in good agreement with those expected physically since, for the broad spectral lines involved here, the effective frequency shift will be determined by the overlap of the filter (centre wavelength shifted by $608cm^{-1}$) and Raman spectra (peak shifted by $460cm^{-1}$ for GeO_2). Moreover, assuming a perfect cleave, a minimum value of 12% for the non-Raman shifted component in the signal was estimated from the strength of the far-end reflection.

In order to demonstrate the operation of the sensor, raw data were scaled using the expression and calibration parameters given above to produce measured temperature distributions. Two examples are shown in Figure 3 for moderate (~ 10K) departures from ambient. Notable features of these curves are baselines which deviate by less than 1K from the known value (24°C), the agreement between the two temperature features and the good correlation with the actual thermal distribution. In fact, similar curves obtained in the same way over the entire range (-52 to +100°C) showed a maximum deviation of ±1K. These results demonstrate a far higher accuracy than has been previously reported in fibre-optic distributed temperature sensors.

Conclusions

We have demonstrated a distributed temperature sensor using solid-core fibre and a semiconductor source able to resolve 1K in fibre lengths greater than 1km with a spatial resolution of 7.5m. The sensitivity obtained agrees well with a theoretical model. Temperature distributions measured with the sensor agreed with known distributions to ±1K over the temperature range -50 to +100°C.

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Figure Captions

Figure 1 — Anti-Stokes Raman OTDR signal as a function of position in the fibre. The temperature distribution is indicated schematically at the bottom of the Figure.

Figure 2 — Backscatter signal measured as a function of temperature (dots). Results have been normalised to unity at 24°C. Solid line is fitted to experimental data (see text).

Figure 3 — Two examples of temperature distributions measured with the sensor. The actual temperature is indicated for each fibre section.