Temperature sensing by thermally-induced absorption in a neodymium doped optical fibre.

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Abstract

Absorption of 1.06μm radiation in neodymium-doped fibre and subsequent anti-stokes fluorescence is observed in neodymium-doped fibre at elevated temperatures. The increase in absorption is used as the basis for a distributed temperature sensor over the range 20-800°C. The temperature dependence of fluorescence at 940nm is used in an optical fibre point temperature sensor.

Introduction

Several temperature sensors based on optical fibres doped with rare-earth ions have been reported[1,2,3]. These are limited by two factors: (a) the high absorption rapidly diminishes the useful signal and (b) the absorption and fluorescence bands are considerably broadened by the host glass which dominates temperature dependent broadening.

We report initial studies of a novel temperature sensor using Nd^{3+} doped fibre, based on short wavelength fluorescence measurement first reported by Garlick et al[4]. The theory for this process is described in the next section. The experimental results show an absorption at 1.064μm which is strongly temperature dependent. Accompanying this absorption is fluorescent emission from 800nm to 1000nm. The absorption and hence the fluorescence are negligible at low temperatures, but increase with temperature following a Boltzmann distribution.

This process, which is strongly temperature dependent, is demonstrated in a distributed and a point temperature sensor.

Theory

The energy levels of the rare-earth ion, neodymium, with four-level lasing action is shown in Fig. 1. Normally, lasing action takes place between the levels $^4F_{3/2}$ and $^4I_{11/2}$, giving rise to emission at 1.064μm. Three level lasing action may also be observed between levels $^4F_{3/2}$ and $^4I_{9/2}$ at a wavelength of 900nm.

The energy difference E between the $^4I_{11/2}$ and the $^4I_{9/2}$ level is 3.97×10^{-20}J. The population N_2 of the $^4I_{11/2}$ level, with no optical pumping is due to thermally-excited electrons given by Boltzmann's equation

$$N_2 = N_1 e^{-E/kT} \tag{1}$$

At room temperature the ratio N_2/N_1 is 5.4×10^{-5}.

Absorption at 1.064μm between the $^4I_{11/2}$ level and the $^4F_{3/2}$ level is given by:

$$\alpha \propto N_1 e^{-E/kT} - N_3 \tag{2}$$

The magnitude of the ground state population N_1 may be ascertained from the measured absorption of the fibre at 900nm, which has been measured as 1100dB/km. The population of the $^4F_{3/2}$ level N_3 is small and may be neglected.

Fluorescence occurs from the $^4F_{3/2}$ level down to the $^4I_{11/2}$ and $^4I_{9/2}$ levels. The fluorescent intensity is also dependent on the Boltzmann relation of equation (1). The temperature sensitivity of a material depends on the energy of the first excited state above the ground level. Fig. 2 shows the theoretical attenuation for the neodymium-doped fibre used here and also for a samarium-doped fibre with similar absorption.

The temperature sensitivity is given by

$$\frac{d\alpha}{dT} = \frac{\alpha_0 E}{kT^2} e^{-E/kT} \tag{3}$$

where α_o is the absorption between the ground-state and the fluorescent level. The temperature sensitivity is maximised when the energy of the first excited state is given by

$$E = 2kT \tag{4}$$

At 20°C the ideal energy is 8×10^{-21}J which corresponds to an energy level of 400cm^{-1}.

The temperature sensitivity is also a function of absorption, which to maintain a reasonable signal-to-noise ratio in a point or a distributed sensor should be 20dB total at 20°C. In an OTDR with 500m of fibre the absorption in neodymium-doped fibre should ideally be 20dB/km. This corresponds to an absorption of 3.6×10^{3}dB/km at 900nm which can be achieved in neodymium-doped fibres.

Experiment

To test this idea a point temperature sensor was constructed using 35m of single-mode optical fibre doped with 150ppm of Nd^{3+}. The fibre was inserted in a high-temperature oven and the absorption and fluorescence spectra were measured for temperatures up to 900°C.

The absorption spectra in Fig. 3 shows a temperature-dependent peak at 1.08μm corresponding to the lasing wavelength of neodymium-doped glass. The change in absorption at 1μm is due to the temperature-dependent tail of the 900nm absorption. The thermally-induced absorption at 1.08μm is compared with the theoretical values in Fig. 2. There is good agreement betwen theoretical and experimental values allowing for the broad range of excited state energies in glass.

When the fibre was pumped at 1.064μm, fluorescence was observed over the wavelength range 800nm to 1000nm as shown in Fig. 4. The central peak at 910nm is due to fluorescence from the $^4F_{3/2}$ level down to the ground-state. The side peaks at 830nm and 970nm, which are significant at 800°C, are due to fluorescence from the $^4F_{5/2}$ level down to the ground level and the $^4I_{11/2}$ levels respectively. These emissions are strongly temperature-sensitive and are suitable for a dual wavelength temperature sensor. Unfortunately the fluorescence lifetime of 150μs prevents this emission being used in a distributed sensor.

The temperature-dependent absorption is however, ideally suited to distributed sensing. An optical time-domain reflectometer was constructed to demonstrate this application as illustrated in Figure 5. 150ns pulses from a Q-switched Nd:YAG laser at 1.064μm were launched into the doped fibre via a launch fibre and a beam splitter. The launch fibre served to reduce front face reflections from the doped fibre by spatially filtering the mode pattern from the laser. The backscatter traces were processed to obtain a measurement of local attenuation against position as shown in Fig. 6. The attenuation is clearly seen to increase in the hot fibre and to remain constant in the rest of the fibre at room temperature. This experiment demonstrates the fibre's application as a hot spot detector with low loss at room temperature. The poor spatial resolution seen in Fig. 6 is due to the long laser pulses available in this particular experiment.

Discussion

The large energy of the first excited state in neodymium gives a weak absorption at 20°C and therefore this fibre is limited to applications requiring measurements of 500°C or more. However, other rare-earths such as Samarium and Europium have excited-state energies of 1.98×10^{-20}J and 7.15×10^{-21}J respectively. These would lead to absorption changes at room temperature of 1.7%/°C and 0.6%/°C respectively in fibres with similar doping levels to the neodymium-doped fibre used here. An increase in the doping level by 2 orders of magnitude for neodymium-doped fibre or a factor of 2 for samarium-doped fibre would optimise this sensor for room temperature.

The attraction of this technique is the low intrinsic absorption at the pump wavelength which enables long range OTDR to be used. The temperature sensitivity is only dependent on the energy of the first excited-state of the rare-earth dopant. Monitoring of fluorescence for point sensing or low-resolution distributed sensors enables a dual-wavelength technique to be used. This will eliminate detector saturation due to end reflections and reduce errors due to bending losses.

Conclusions

We have demonstrated a novel temperature sensing scheme using thermally induced absorption at 1.064μm in Nd^{3+}-doped optical fibre. A basic OTDR was used to measure temperatures up to 700°C with a 10°C accuracy. We have also shown how fluorescence at a wavelength shorter than the pump may be used for temperature sensing. Temperature resolution and range may be improved by doping fibres with other rare earths and improving the measurement apparatus.

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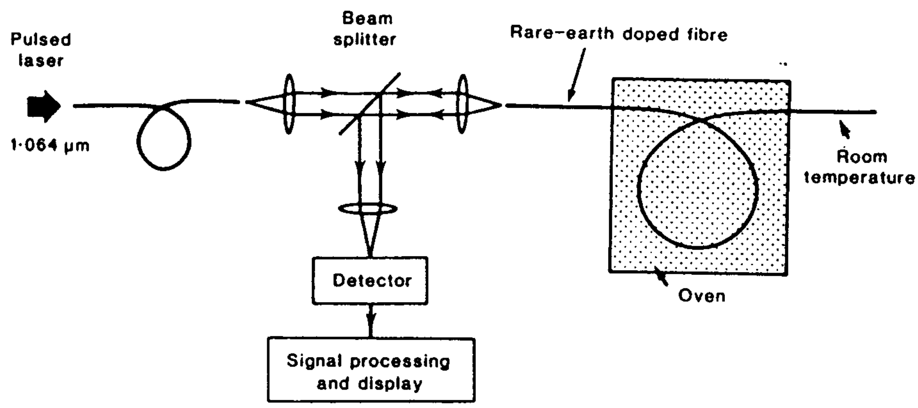

Figure 5. Experimental O.T.D.R. used for distributed temperature sensing.

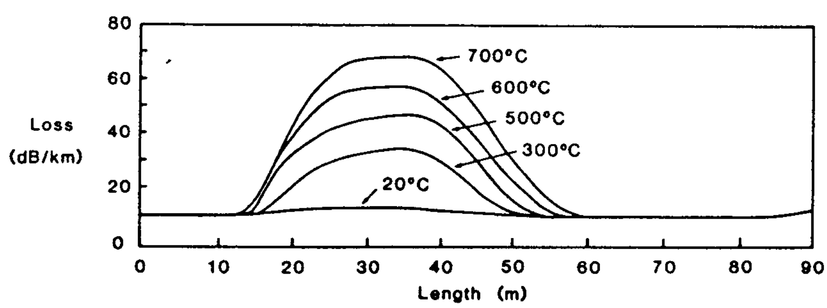

Figure 6. Measurement of a hot spot using an O.T.D.R at 1.064um. in neodymium doped optical fibre.

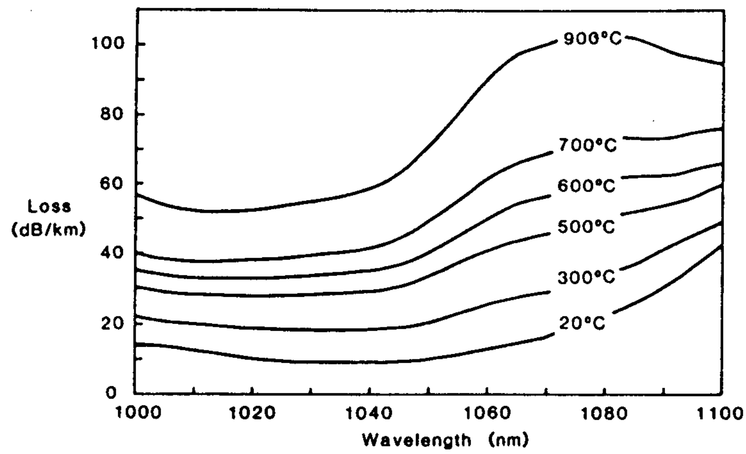

Figure 3. Measured attenuation of neodymium doped fibre.

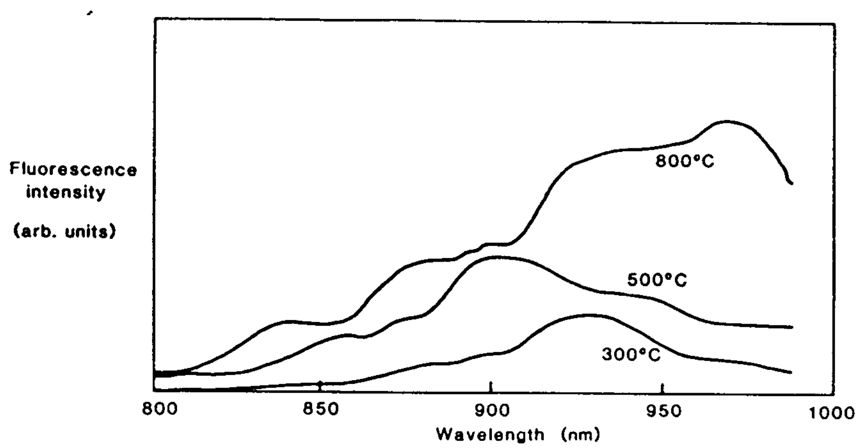

Figure 4. Short wavelength fluorescence spectra of neodymium doped fibre when pumped at 1.064um.

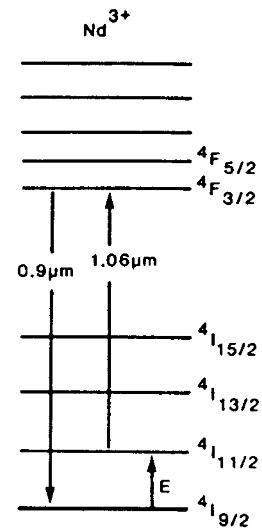

Figure 1. Energy levels of neodymium ions.

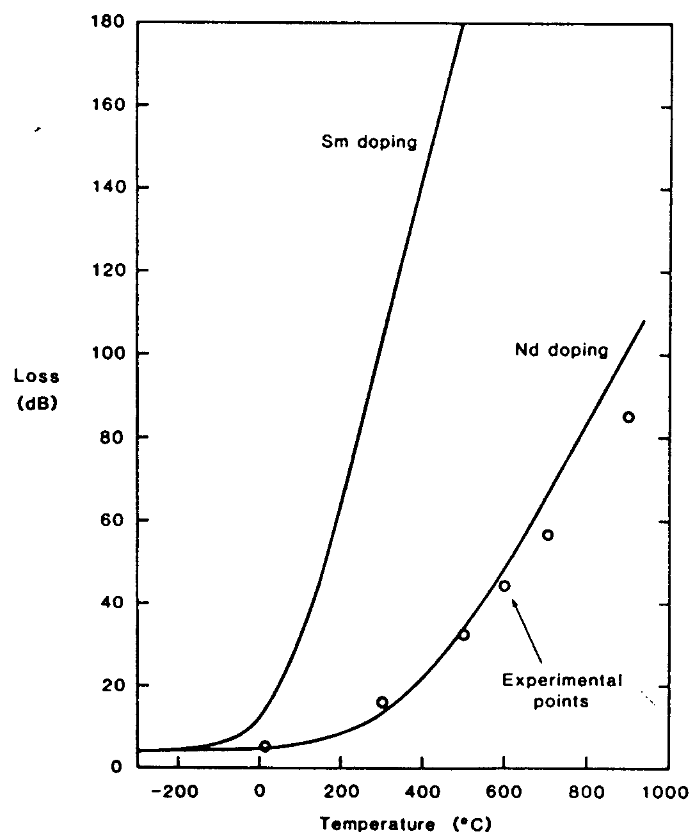

Figure 2. Calculated thermally induced absorption in neodymium and samarium doped fibre. Experimental points are from measurements of neodymium doped fibre.