Broadband Sources for Gas Detection using Fluorescent Rare-Earth-Doped Fibres Pumped by Low-Cost Semiconductor Laser Source

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Abstract
The paper discusses recent results on sources for gas detection using fluorescent rare-earth-doped optical fibres. The sources are being optimised for use with broadband cognitive gas sensors, in particular those using correlation spectroscopy, with the constraint of using low-cost semiconductor lasers as the pump.

Introduction
Broadband sources are attractive for use with fibre optic gas sensing systems. They may also prove useful for white light interferometry. If narrowband lasers are used with multimode fibres, there are potential problems with transmission fluctuations due to modal noise[1]. Furthermore, if monomode fibres are used in an attempt to avoid these effects, there are still potential problems with coherent addition of reflections from the significant number of reflective surfaces usually present in a practical system (e.g. from connectors, lenses, windows of gas cells etc). The extremely low optical contrast presentin gas sensing systems means that even fluctuations as low as -60dB in the detector signal can be a problem when performing trace measurements. Broadband sensing systems, such as those using scanned Fabry-Perot filters[2], or using cells of the gas to be detected[3], as matching optical filters, greatly reduce the coherence problems. At the same time, they allow the recognition of a more complete spectrum, rather than merely a single line.

In order to provide a broadband stable source, filtered white-light filament lamps or medium radiance S-LEDs have been used. Care must be taken with superluminescent E-LED sources, as there can be significant fine structure in their spectrum. This can result in a variable correlation with the modulated fine-line optical filters used for gas sensing, which can give rise to zero-drift.

Fluorescent rare-earth-doped fibre sources offer an attractive source for several reasons:-

(i) They have a stable and reproducible output spectrum, with structure determined only by the fibre materials.
(ii) Many emission bands are possible, covering most of the near and mid-IR bands.
(iii) Most types can be pumped with low-cost semiconductor laser diodes.
(iv) Monomode fibre versions can be produced which are intrinsically compatible with monomode fibre systems.

This work is therefore directed towards the evaluation of **fluorescent** sources for their potential use in gas sensors. In addition, there are many other practical applications in

systems using white light interferometry. Three basic types are likely to be attractive: firstly, monomode types, pumped by low cost sources, which are compatible with monomode sensors; secondly, larger core diameter, higher N.A types, for use with multimode systems; and, finally, superluminescent monomode systems, where high radiance is desirable for highly sensitive systems. We report results on the first two types. The third option has been investigated as a source for fibre gyroscopes but currently dictates the use of a high power pump source having too high a cost for use in most gas sensing systems. Its spectrum is also a function of pump power and can have fine structure due to feedback from reflective surfaces.

Optimisation of a Fluorescent Fibre Source

If it is desired to produce a superluminescent (S-L) source or laser, it is of course necessary to pump the fibre sufficiently to provide gain. Unfortunately, with presently-available **low-cost** semiconductor lasers, it is not generally possible to achieve such levels of gain in most of the three-level fluorescent fibre systems of interest for gas sensing. Even with expected future improvements in laser power, it is likely to be difficult to arrange for **stable broadband** S-L gain, except close to the gain peak of the **fluorescent** fibre. Instead, we aim to maximise the fluorescent output of the fibre with low-cost sources. Assuming there is negligible gain, ie. no significant population inversion, this can be achieved by:-

(i) Maximising pump-laser launch efficiency (this is likely to be ~50% max into a monomode fibre using low-cost optics).
(ii) Maximising collection of fluorescent light by increasing fibre N.A.
(iii) Reducing the effects of self-absorption in the fibre.

The launch efficiency could be increased to close to 100% using high N.A, larger core fibres, assuming the optical surfaces are A-R coated. A high N.A will also increase the collection efficiency [$\sim (N.A)^2$] of fluorescent light. For monomode fibres, it is only possible to increase the N.A, thereby increasing the collection efficiency, and this may increase the **practical** difficulty of achieving an efficient launch into the necessarily-smaller fibre core. In both cases, the use of a high N.A fibre source may require an optical system to match the source N.A to that of the sensor fibre system. (This will also often be necessary, however, when using high radiance LED sources).

In order to reduce the effects of self absorption of fluorescent light in the fibre (primarily a problem at low pump intensities in 3-level systems), it is preferable to pump at the output end of the fibre, via a dichroic beam splitter or WDM coupler (Fig. 1). This configuration is rarely used in fibre amplifiers or in S-L fibre sources, but is particularly advantageous at low pumping levels in fluorescent 3-level systems, such as Er^{3+} at 1.5μm and Tm^{3+} at 1.7μm.

Simplified theory of Low-Level Pumping of Fluorescent Fibre Sources

The general theory governing optical interactions and processes in a rare-earth-doped fibre can be quite intricate[4]. However, under the low-level pumping conditions that are relevant to the cases examined here, a number of simplifying assumptions can be made. If one assumes that at these low pump intensities there are only low population densities in the upper levels, the absorption coefficients can be assumed to be the same as in the non-excited case (and hence taken from measured fibre attenuation curves). Processes

such as stimulated emission, excited-state-absorption etc. may be effectively ignored. Take, for example, the limiting case of an ideal four-level system, under low-level excitation, in which the fluorescent light is not re-absorbed. The theory then predicts that one should use a long fibre to ensure practically all the pump photons are absorbed. Fluorescence photons are generated with a given quantum efficiency, η. A fraction, S, of these photons are captured into the forward propagating fibre mode, producing the desired output. These simple considerations result in the following idealised expression for the fluorescence output power:-

$$P_f = P_p \cdot \eta \cdot \frac{\nu_f}{\nu_p} \cdot S, \tag{1}$$

where P_p is pump power, and ν_p and ν_f are the pump and fluorescent optical frequencies, respectively. This equation applies to both input-end and output end pumping conditions.

If, however, a three-level system is considered, the fluorescent photons are re-absorbed, and there exists an optimal fibre length when using the input-end-pumping configuration. The output fluorescence power is proportional to the integral:-

$$\int_0^L P_p \, e^{-\alpha_p z} \, e^{-\alpha_f (L-z)} \, dz \tag{2}$$

where α_p and α_f are the pump and fluorescence absorption coefficients and L is the fibre length. Expression (2) can be easily integrated and found to have a maximum at a fibre length of:-

$$L = \frac{\log_e \alpha_p - \log_e \alpha_f}{\alpha_p - \alpha_f} \tag{3}$$

In the case of our preferred output-end-pumping, one now finds the expected result that the longer the fibre the better. If the option of the end mirror in fig 1 is taken up, the total output power could be increased, but we have not yet evaluated this configuration. With the mirror, there will again be an optimum fibre length for maximum output. We have a particular interest in Tm^{3+}-doped fibre for gas sensors. Roughly speaking, for the near infrared fluorescence band of Tm^{3+}, the shorter and longer wavelength regions of the band have the characteristics of three and four level systems, respectively. They are therefore expected to show different fibre-length dependencies from the relations discussed above. It should be recalled, however, that output-end pumping tends to minimise the effects of self absorption.

Experiments

We have optically pumped a number of rare-earth-doped materials to examine their potential as fluorescent sources. The arrangement is shown in Fig. 2. A low-cost 780nm laser source, having an output of only 15mW, was used as the exciting source. The 45° dichroic mirror had a high reflectivity at 780nm and transmitted over the spectral range 950nm to 3200nm. We were able to launch typically 5mW into the monomode fibres and typically ~12mW into the larger-core high N.A fibres. The optical spectrometer system, (including the dichroic filter, lenses, monochromator and PbSe detector) was calibrated

using a Graseby blackbody source (type 563), operated at 1050°C. The output spectrum of a monomode, (0.1%) Tm^{3+}-doped, silica fibre (N.A = 0.16, core ϕ = 7.2μm, $\lambda_{cut-off}$=1.5μm, L = 670mm) is shown in Fig. 3. That of a monomode, (0.5%) Tm^{3+}-doped, germanate ($Ge0_2$/PbO/BaO/K_2O/ZnO composition) glass fibre (N.A = 0.2, core ϕ = 6μm, $\lambda_{cut-off}$=1.6μm) is shown in Fig. 4, for various fibre lengths from 22mm to 168mm. The spectral range of this Tm^{3+} source covers many gas absorption bands, for example CH_4 at 1.67μm, H_2O at 1.9μm, and CO_2 at 2.0μm. This is also a region of the near infrared spectrum which is not well served by commercial suppliers of LEDs. The total output level from the fibre sources varies according to the fibre materials, and its length, N.A and diameter. Our best total output power achieved so far for the Tm^{3+}-doped germanate fibre is ~30μW, corresponding to 33nW.nm^{-1} at the 1.67μm methane line. Despite this line position being well away from the Tm^{3+} emission peak, this compares well with a value of 30nW.nm^{-1} previously achieved with a filtered tungsten source when launched into a **large core (50μm, 0.2N.A.) multimode fibre.**

We have also evaluated the fluorescence spectrum versus pump power of these fibres to verify that there is indeed little optical gain occurring at these pump levels (fig. 5). The effects of gain, if present, would narrow the emission spectrum around the fluorescence peak at the higher pump powers. Our measurements on very large core multimode fibres (fig. 6), at much lower pump-power densities, show similar spectra to monomode ones, also showing that the gain level was not significant for either fibre type. Clearly, self absorption is present in thulium-doped fibres. The effects of this self absorption should be apparent as a fluorescence reduction in the short wavelength region of the fluorescent spectrum. However, our use of output-end pumping tends to reduce the extent of this considerably.

The potential of fibre sources further into the mid infrared region is significant, as LED sources in this region tend to have both very low output power and radiance. In addition, there are even less readily available sources of commercial supply and a poor selection of emission wavelengths. We are therefore examining a number of low-phonon-energy glasses for use in the 2.0 to 3.5 μm region and expect to show results for a number of these at the conference.

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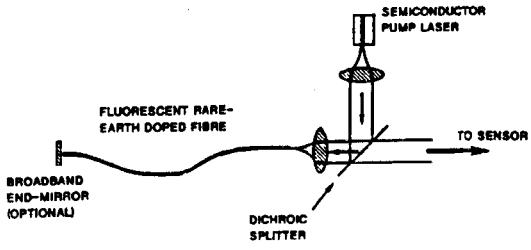

Fig 1: Schematic of fluorescent fibre source

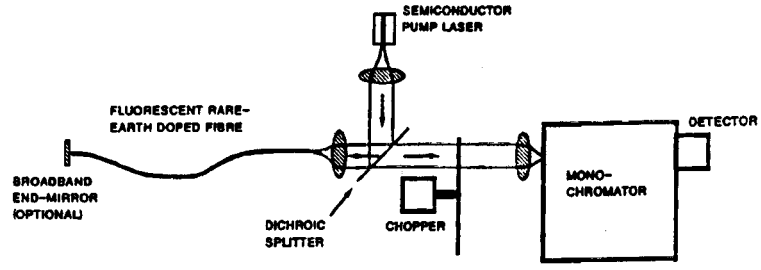

Fig 2: Schematic of test arrangement for fluorescent fibre source
(Note output end pumping to reduce absorption)

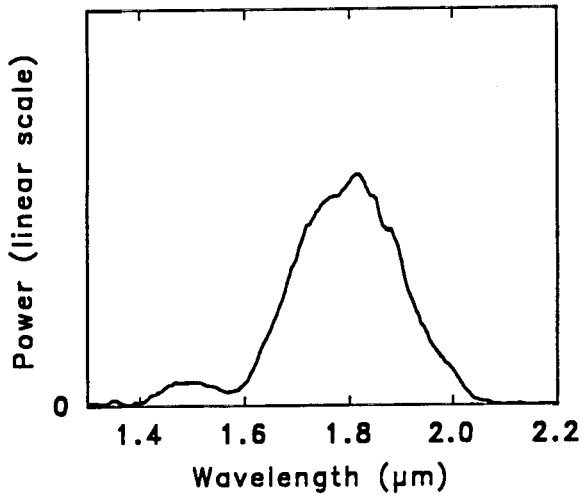

Fig 3: Fluorescence spectrum of monomode Tm^{3+}-doped silica fibre

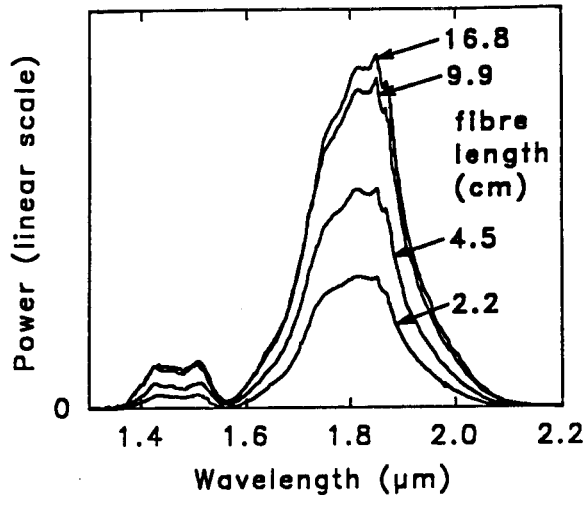

Fig 4: Fluorescence spectrum of monomode Tm^{3+}-doped germanate fibre versus length

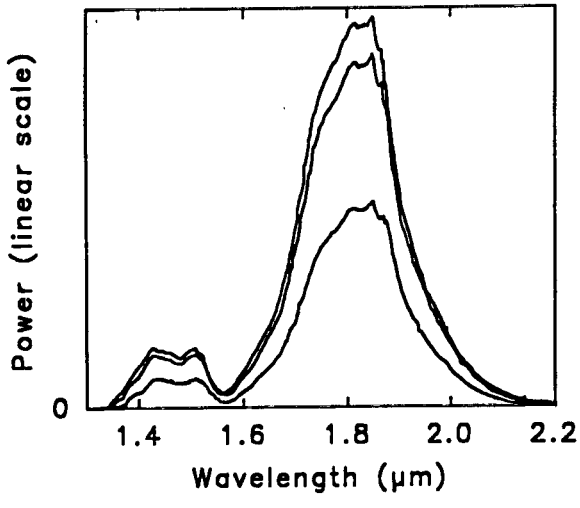

Fig 5: Fluorescence spectrum of monomode Tm^{3+}-doped germanate fibre, at 3 different pump powers

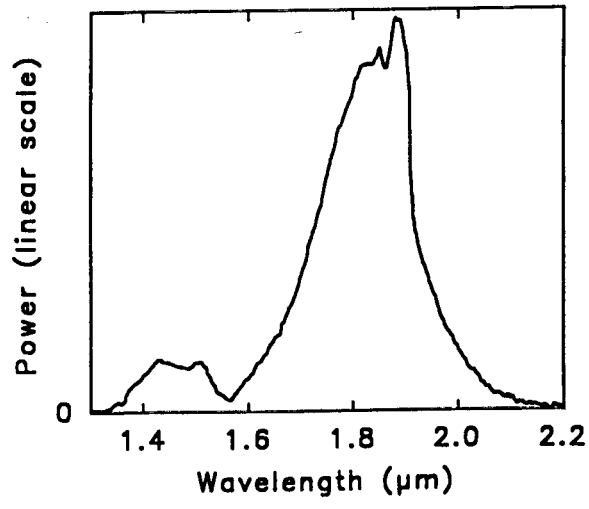

Fig 6: Fluorescence spectrum of multimode Tm^{3+}-doped germanate fibre