OFS Pl deadline

2410

Fibre Optic LED-Based Correlation Spectroscopy for O_2 Detection

J. P. Dakin, M. J. Gunning, P. Chambers, and E. A. Austin
Optoelectronics Research Centre,
University of Southampton, United Kingdom, SO17 1BJ.

Abstract
This paper describes the first detection of O_2 by Complementary-Source-Modulation (CoSM) correlation spectroscopy over optical fibre with compact LED sources. Theoretical results for the selective detection of O_2 by the CoSM method are also presented, based on spectral absorption data from the Hitran database.

1. Introduction

The reliable detection and monitoring of gases plays an important role in a range real-world environmental and industrial applications. Many systems for the detection of gases and gas mixtures have been devised, based on optical absorption [1, 2, 3, 4], but few of these match the high selectivity of correlation spectroscopy [5, 6, 7, 8, 9] which takes full advantage of the multi-line absorption structure of the target gas. In this paper, we present new CoSM correlation spectroscopy [10] measurements of O_2 gas, as well as a supporting theoretical analysis based on spectral data from the Hitran database (www.hitran.com).

2. The Complementary-Source-Modulation Approach

2.1 Basic arrangement

The CoSM approach involves the alternate on/off switching of two light sources in anti-phase, passing light from one of these sources through a reference cell containing the target gas (or gases) of interest for detection, and then combining this now-partially-absorbed light beam with a proportion of unaffected light from the other source, in a proportion to give no net intensity modulation. In this paper, we implement, for the first time, a PC-based controller that uses a reference detector and input/output (I/O) card to synchronously monitor the intensity of each component of the combined beam, and then control the relative intensities of the sources to make these components equal (i.e. ensure there is no net intensity modulation). This combined beam is then used to probe for the target gas. As the beam component which has passed through the reference gas sample now has less available optical energy within the narrow spectral region of the target gas spectral absorption lines, a net intensity modulation of the balanced combined beam will be re-established when it passes through a measurement cell containing the gas of interest. This intensity modulation is proportional to the target gas concentration, and, as only differential absorption between the two beam components can contribute to a signal modulation, contaminant gases with non-matching spectral lines will not give significant errors.

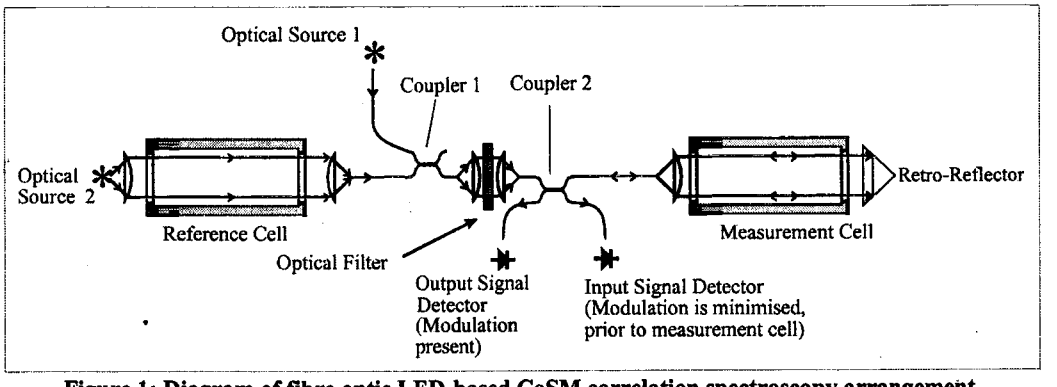

Figure 1: Diagram of fibre optic LED-based CoSM correlation spectroscopy arrangement, employing a retro-reflector and fibre-remote measurement cell

A bench-top, fibre-coupled, CoSM correlation spectroscopy system has been constructed, as shown in fig. 1, to detect a variety of gases using simple low-cost light-emitting-diode (LED) sources. These sources are driven via an I/O card and PC controller, which ensures no net modulation of combined beams. This uses a feedback mechanism based on monitoring the signal response of the combined beam. The measurement signal intensity modulation is also recovered via analogue inputs on the I/O card, and processed by the same PC. The intensity modulation index (ratio of AC to DC components) of this final detected signal is used as a measure of the target gas concentration in the measurement cell. We believe it is the first time O_2 has been sensed in this manner, combining the selectivity of correlation spectroscopy with the use of compact low-cost semiconductor sources and detectors. This cost-effective yet efficient approach, combined with the potential for remote measurement cell location interrogated via a single optical cable, suggests attractive commercial potential for the device.

2.2 Theory

Light from a source, of spectral intensity $P(\lambda)$, is passed firstly through a reference cell of transmission $T_1(\lambda)$, and secondly through a measurement cell of transmission $T_2(\lambda)$, before striking a detector of spectral responsivity $R(\lambda)$. A filter, of transmission $F(\lambda)$, can be inserted to narrow the source spectrum to cover just the gas absorption band to be monitored. The detected signal I_{det}, after all these optical elements or cells, is given by:-

$$I_{det} = \int P(\lambda)T_1(\lambda)T_2(\lambda)F(\lambda)R(\lambda)d\lambda \quad . \tag{1}$$

Well-tabulated values for $T_1(\lambda)$ and $T_2(\lambda)$ are available from the Hitran database for many common gases, and the source, detector, and filter spectra are easily obtained from the manufacturer's data sheets or from our own measurements. In our CoSM scheme, the intensity modulation index of the final signal is needed for calculation of the expected gas detection system response. The two detected beam components after the measurement cell are:-

$$A\int P(\lambda)T_2(\lambda)F(\lambda)R(\lambda)d\lambda \quad \text{(Signal component not passed through the reference cell)} \tag{2}$$

$$\int P(\lambda)T_1(\lambda)T_2(\lambda)F(\lambda)R(\lambda)d\lambda \quad \text{(Signal component passed through the reference cell)} \tag{3}$$

where A is a scalar accounting for beam attenuation in the reference cell, which is effectively set by the PC controller so that the signal difference with no gas present is zero. From the above equations, the difference between these beams may be expressed as:-

$$\int P(\lambda)T_1(\lambda)T_2(\lambda)F(\lambda)R(\lambda)d\lambda - A\int P(\lambda)T_2(\lambda)F(\lambda)R(\lambda)d\lambda \quad , \tag{4}$$

and the detected modulation index (a normalised, unitless, fraction, simply derived by dividing the AC component of the detected signal by the mean DC signal) is given by:-

$$\frac{2\left(\int P(\lambda)T_1(\lambda)T_2(\lambda)F(\lambda)R(\lambda)d\lambda - A\int P(\lambda)T_2(\lambda)F(\lambda)R(\lambda)d\lambda\right)}{\int P(\lambda)T_1(\lambda)T_2(\lambda)F(\lambda)R(\lambda)d\lambda + A\int P(\lambda)T_2(\lambda)F(\lambda)R(\lambda)d\lambda} \quad . \tag{5}$$

This analysis may be used to predict the likely modulation index for a measured gas; in this instance, for O_2. As the type of LED source used in the experimental work is broader than the gas absorption bands, and the detector response is also relatively flat over this region, we simplify the analysis by assuming the functions $P(\lambda)$ and $R(\lambda)$ have constant values P and R, leaving the main remaining spectral variation in the above equations as that of the filter $F(\lambda)$ and that of the gas cells $T_1(\lambda)$ and $T_2(\lambda)$.

Figures 2 and 3 show theory relating to the analysis of O_2. In fig. 2 is shown the transmission spectrum from the Hitran database, analysed using "HitranPC" software from Ontar Corp., for the appropriate Gaussian optical filter function $F(\lambda)$ for our work (i.e. 0.7610 ± 0.0015 μm). Typically, the particular gas absorption lines are not necessarily chosen as the strongest, but rather for their suitability for detection with conventional optical fibre components.

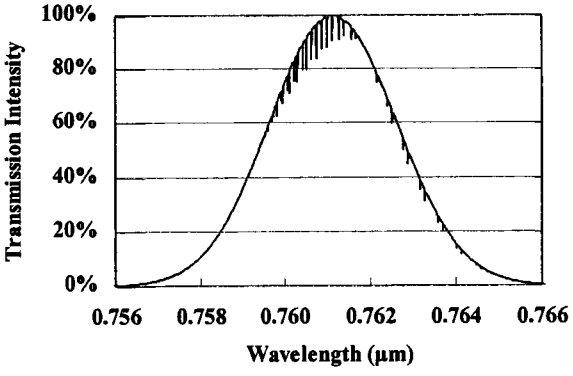

Figure 2: Transmission spectrum of O_2 at STP over a 1 metre path. (Data for a Gaussian filter centred at 0.761 μm and FWHM bandwidth of 0.003 μm)

Figure 3 gives the predicted measurement intensity modulation index results for O_2 derived by numerical integration of the equations above over the wavelength range selected in fig. 2. Clearly, if the filter $F(\lambda)$ has a narrow range around the peak of the gas absorption curve, then the intensity modulation index increases to improve the contrast of the measurement, but reduces the total light. If this leads to too many useful absorption lines being lost, then the main advantage of the correlation approach, that of simultaneously measuring on many

gas lines, is lost. A compromise is necessary to include most of the stronger lines, but exclude weak outer lines. The non-linearity in signal response for O_2 is seen to be negligible.

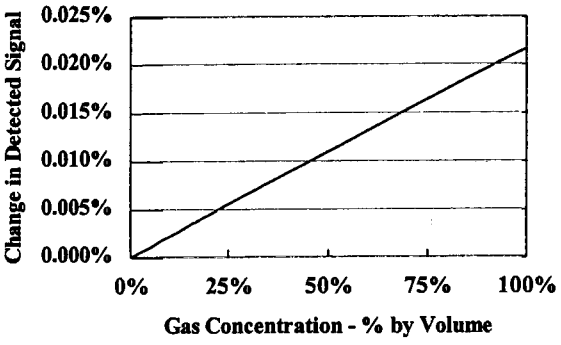

Figure 3: Change in detected signal for sensing of O_2 at STP, using a 1 metre path for both reference cell (100% gas) and measurement cell. (Assumes Gaussian filter centred at 0.761 μm, FWHM bandwidth is 0.003 μm)

3. Experimental Measurement of O_2

Our preferred fibre-coupled experimental arrangement for O_2 detection is that shown in fig. 1. In this instance we use Epitex L760-06AU LEDs, where these were coupled to 440 μm core diameter optical fibres; one directly and one after passing through a reference gas cell. A fibre 3 dB coupler (coupler 1) combined these two beams. One arm of coupler 2 directed part of the combined beam to a reference detector and the other arm guided light to a collimator, which directed light through the measurement cell. For initial experiments, the measurement detector was placed at the end of the measurement cell, but later a retro-reflector was placed at the end of the measurement cell [11, see fig. 1], which allowed the detector to be situated on the return arm of coupler 2. This effectively allowed for fibre-remote measurement cell location. For O_2 sensing at 761 nm, the detectors were Integrated Photomatrix type 10530DAL Si photodiodes with integral amplifiers. The interference filter to narrow the LED spectrum was positioned within dual-lens-collimator optics in the network between the two fibre couplers. In our arrangement, we used of a 3 nm FWHM bandwidth 765 nm filter (CVI Laser Corp F03-765.0-4-1.00 filter) which was tilted to give a new central wavelength of 761 nm. For this arrangement 100 nW of light intensity was received at the reference detector and 25 nW at the measurement detector with the retro-reflective setup. Reference and measurement cell lengths were 1 m and 0.8 m, respectively, and the diameter of the light beam through the cells was 25 mm.

The retro-reflective measurement cell arrangement is particularly attractive: firstly, because it measures the remote cell via a single fibre lead; secondly, because optical pathlength is doubled; and, thirdly, because it is, to a certain degree, self aligning. The alternative fibre=>lens=>lens=>fibre single-pass arrangement (where light from the fibre is collimated, passed through the cell, then re-focussed into a fibre at the far end) requires very careful alignment of relative angular orientations of the collimator and re-focussing optics units, whereas the retro-reflective arrangement only needs simple care to correctly focus one collimator/refocusing unit and to ensure the collimated beam is directed close to the centre of the retro-reflector, so the returning beam will strike the same lens.

Results for the sensing of O_2 using this arrangement, whilst alternatively filling the measurement cell with pure dry N_2 and dry air (circa 20.95% O_2, 78.08% N_2), are presented in fig. 4. The curves show the detector modulation index response (obtained by dividing the AC signal by the mean DC level) with time. Results for both a single-pass scheme and a double-pass retro-reflector arrangement are shown, where the doubling of the measurement signal modulation index is clearly evident for the two-pass configuration, and the magnitude agrees with calculations in Sect. 3 (fig. 3). The transient response was limited by flow of gas into the cell and the mixing and displacement to ensure full removal of the previous gas. The response time of the measurement system was set by the much shorter electronic integration time of the PC-based lock-in processor and filter, which had a 10s time constant for these measurements.

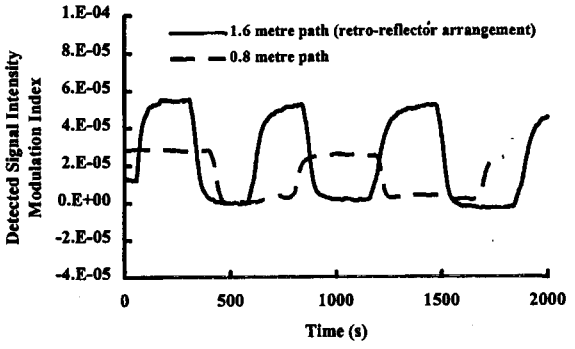

Figure 4: Results for measurement during alternate filling of the measurement cell with pure dry nitrogen and dry air (20.95% O_2) mixtures. (All results at STP, and for a 10 s measurement time constant).

Although early results, it can be seen that the method works well. Initial results suggest a noise-limited detection level below 1 % for O_2. We are presently constructing more stable optical and mechanical arrangements for our measurements, and hope to report on enhanced results at a later time. Crosstalk measurements with other likely gaseous contaminants have to be performed, but we confidently expect to achieve excellent selectivity characteristics of correlation spectroscopy methods [12] when measuring gases with fine line absorption spectra.

4. Conclusions

We have reported new results for gas detection using the CoSM scheme for correlation spectroscopy. This includes simulated responses, using spectral data from the Hitran database, and new measurements of O_2 using low-cost LED sources. To our knowledge, this is the first such investigation for this gas using LED sources with the highly-selective correlation approach, and is also the first such detection of these via optical fibre cables.

5. Acknowledgements

The authors thank the Engineering and Physical Sciences Research Council (EPSRC) for research funding and support from industrial sponsors, via EPSRC's Faraday/INTErSECT research initiative, vis: Accurate Controls Ltd., BOC Edwards, Corus, Health & Safety Laboratories, Kidde plc, National Grid, and NPL. P. Chambers thanks the EPSRC for a student grant. The provision of complimentary 760 nm LED's from Epitex Inc. is gratefully acknowledged.

6. References

1. A. Hordvik, A. Berg, and D. Thingbo, *A fibre optic gas detection system*, Proc. 9th Int. Conf. on Optical Communications, 'ECOC 83' Geneva (1983), pp. 317.

2. T. Kobayashi, M. Hirana, and H. Inaba, *Remote monitoring of NO_2 molecules by differential absorption using optical fibre link*, Appl. Opt., 20 (1981), pp. 3279.

3. K. Chan, H. Ito, and H. Inaba, *An optical fibre-based gas sensor for remote absorption measurements of low-level methane gas in the near-infrared region*, J. Lightwave Tech., LT-2 (1984), pp. 234.

4. S. Stueflotten *et al.*, *An infrared fibre optic gas detection system*, OFS'94, Stuttgart, 1994, pp. 87.

5. R. Goody, *Cross-correlation spectrometer*, J. Opt. Soc. of Am., 58 (1968), pp. 900.

6. H. O. Edwards and J. P. Dakin, *A novel optical fibre gas sensor employing pressure-modulation spectroscopy*, OFS'90, Sydney, Australia, pp. 377, Dec 1990.

7. H. O. Edwards and J. P. Dakin, *Correlation spectroscopy gas sensing compatible with fibre-remoted operation*, Sens. actuators, B, Chem, 11 (1993), pp. 9.

8. J. P. Dakin, H. O. Edwards, and B. H. Weigl, *Progress with optical gas sensors using correlation spectroscopy*, Sens. actuators, B, Chem, 29 (1995), pp. 87.

9. J. P. Dakin, *Evolution of highly-selective gas sensing methods using correlation spectroscopy*, Advances in Optoelectronics for environmental monitoring, Erice, Sicily, Nov 1998 (invited).

10. J. P. Dakin, H. O. Edwards, and W. H. Weigl, *Latest developments in gas sensing using correlation spectroscopy*, Proc. SPIE Int. Conf., Munich, July 1995, paper 2508.

11. J. P. Dakin *Sensor for sensing the light absorption of a gas*, UK Patent Application GB2219656A.

12. H. O. Edwards and J. P. Dakin, *Measurements of cross-sensitivity to contaminant gases, using highly-selective, optical fibre-remoted methane sensor based on correlation spectroscopy*, Proc. SPIE Int. Conf., Boston, Sept. 1991, paper 33.