Gas Sensing Based on Optical Fibre Coupled Diode Laser Spectroscopy: A new approach to sensor systems for safety monitoring

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1. ABSTRACT

We describe an entirely passive fibre optic network which senses, amongst other species, CH_4 and CO_2, with sensitivity and selectivity compatible with safety sensing in the mine environment.

The basic principle is that a single laser diode source targeted to a particular species addresses up to 200 sensing points which may be spread over an area of dimensions ten or more km. The detection and processing electronics is typically located with the laser source. Several laser sources can be introduced in parallel to enable monitoring multiple species. The network itself, entirely linked through optical fibre, is inherently intrinsically safe. It is self checking for faults at the sensing location and continuously self calibrating. In the methane sensing mode its sensitivity is sub 100ppm and it responds accurately up to 100% methane. It is therefore capable of detecting extremely hazardous gas pockets which are completely missed by other sensor technologies. The network has demonstrated stability with zero maintenance or recalibration over periods in excess of two years. We believe that this system offers unique benefits in the context of mine safety and ventilation system monitoring.

KEYWORDS: *METHANE DETECTION; OPTICAL SYSTEMS; TUNNELS.*

2. INTRODUCTION

Sensing systems for hazardous and toxic gases are extremely important and diverse in detection principles and applications requirements. The technique which we shall describe here has been principally demonstrated to measure methane gas concentrations which are particularly important in mining and in some ventilation systems especially in underground tunnels. Numerous systems are already in use and of these the principal mechanisms involved are catalytic detectors, most notably pellistors and mid infrared, so called non dispersive spectroscopic systems. Both have well known limitations associated with calibration, measurement range and stability and particularly with pellistors, susceptibility to poisoning and the need for routine maintenance and recalibration.

The system which we shall describe in this paper utilises tuneable diode laser spectroscopy (TDLS) and optical fibre coupled detection cells linked to a central control unit. The system has now undergone extensive proof of principle testing and has demonstrated its capability to detect and measure methane concentrations from 100pm to 100%, to automatically recalibrate itself, to detect faults at particular sensor locations, and to operate with total intrinsic safety over detection ranges of many kilometres. Furthermore this is achieved within an economically competitive framework. The capital cost compares favourably with competitive systems but the maintenance and recalibration costs are very substantially reduced.

This paper will concentrate on evaluations performed over extended periods on landfill sites from which the methane gas collected is used in electrical power generation. The operational environment requires system tolerance to a wide range of solvents and vapours in addition to spasmodic system flooding and seasonal temperature variations. Whilst this demanding environment did initially stimulate design modifications, these modifications have evolved into a system which has demonstrated a continuous operation with zero maintenance for a period in excess of two years – a performance we believe to be unique among methane gas measurement systems.

3. BASIC SYSTEM PRINCIPLES

TDLS is described in full detail elsewhere (Reid et al 1978, Culshaw et al 2002). The basic concept (figure 1) is that a single frequency diode laser is tuned by varying the diode current to sweep through the gas absorption line. Since diode lasers and their associated components are well developed for wavelengths in the near infrared then, in the case of methane gas, the gas line which is chosen is at approximately 1.665 μm wavelength. At typical atmospheric temperatures and pressures the line width of the absorption peak is in the region of a few GHz compared to the order of MHz for the diode laser. The current tuning increases both the operational wavelength and the power output, both approximately linearly, as the current is increased. The simplest approach is consequently to measure the ratio of the power transmitted through the gas to the power generated by the laser diode which directly maps out the absorption line.

However much can be gained by applying a sinusoidal higher frequency component, f_m, (typically a few kHz) to the drive current which in turn produces a frequency modulation on the laser diode. A detector which is tuned to the fundamental frequency, f_m, at which the diode current is modulated responds to the slope of the absorption line (combined with the slope of the power versus current output curve). The second harmonic takes the second derivative of the absorption line (and the second derivative of the power versus current output curve which in practice is very small). The third harmonic contains information concerning the third derivative and so on. There are numerous benefits for applying frequency modulation in this way, one of which is that the detection frequencies begin to operate in a region where 1/f noise begins to reduce and a second of which is that the derivative processing can significantly enhance the detection and signal recovery processes.

We have described TDLS in much more technical detail elsewhere (Johnstone et al 2008) as indeed have numerous other authors. The basic principles are well documented.

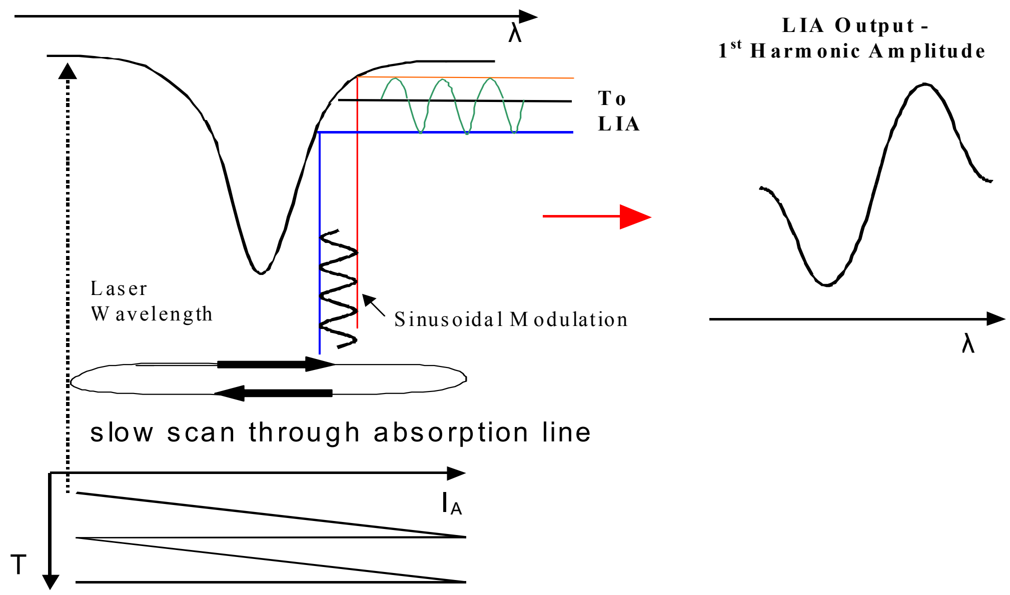

Figure 1: The basic principles of tuneable diode laser spectroscopy (TDLS). LIA refer to a lock in amplifier operating at f_m

4. SYSTEM PERFORMANCE AND FEATURES

4.1 Sensitivity, selectivity and stability

The system gives consistent and reliable readings over a range of 100ppm (figure 2) to 100% methane and is also capable of dealing with very rapid transients (figure 3 demonstrates this from 100ppm to 50%).

The selectivity of the system depends upon the overlap of absorption lines from other species with the 1.665 μm line which we are using. The principal potential interfering species in atmospheric monitoring are water vapour and carbon dioxide and we have demonstrated that at the normal range of concentrations expected in air, interference from these species is below 1 ppm equivalent of methane which equates roughly to the background concentration of methane in the normal atmosphere.

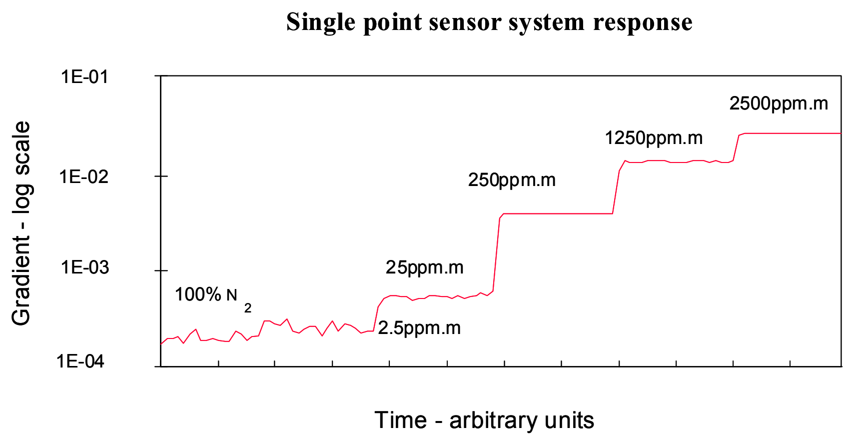

Figure 2: The sensitivity measured for a single 5cm cell interrogated at 1.665 µm (note that this is limited by interference fringes rather than by optical power levels).

System stability is assured through two procedures. The first is that a reference point is always established in each wavelength sweep at a wavelength outside the methane absorption band. This reference point in effect ensures that the individual cells in the network (see below) continue to transmit light and is consequently a fault finding and reference power level monitoring process. The second procedure is that at each and every sweep (a few times per second) a measurement is taken of the concentration in a sealed reference cell which is located within the control unit – or in some versions of the system, an sample of reference gas can be introduced into the calibration cell. This reference measurement cell ensures that the wavelength sweep and the depth of frequency modulation is consistently and accurately recalibrated and this is referenced into the data processing at every measurement time.

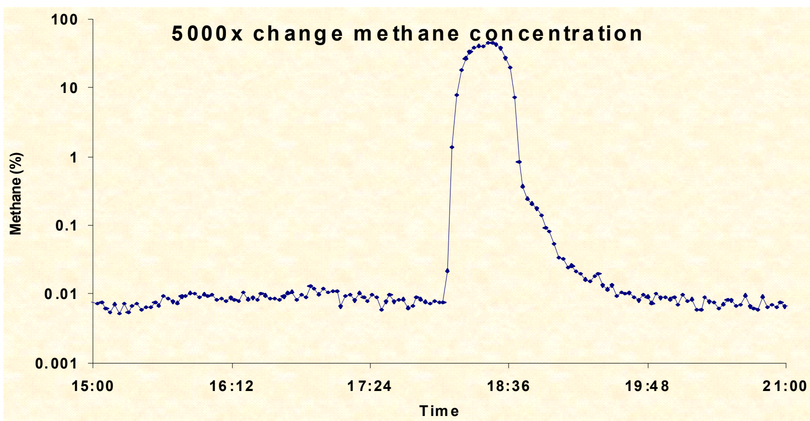

Figure 3: The transient response of the system from very low (100ppm) to very high (many tens of percent) methane concentration . The delay during the fall period is predominantly due to the time for the cell to reach its new equilibrium concentration.

The measurements from individual cells are integrated over a few wavelength sweeps so that system updating for all points is completed typically in a matter of seconds. The repeatability and stability over long periods (years) which we have obtained using this technique is better than 5% of reading and is typically better than 2%.

4.1.2 Network Architectures

The basic elements of the system configuration are shown in figure 4 from which it is immediately obvious that all the necessary electronic and electrical equipment is located at a central control point and the entire outside network linked through optical fibres is electrically passive. Furthermore the optical power delivered to each individual sensing point is typically at least 30dB below the normal accepted threshold for intrinsic safety. The network shown in the figure is much simplified to illustrate the principles. In practice one branch of the network remains in the control room for calibration purposes and the exterior on site system is a multistage tree and branch network capable of accommodating up to 300 sensing points addressed from a single laser. The total power budget, even at 300 points, can accommodate up to a 10dB excess loss in each cell without compromising detection performance at 100ppm. Consequently the system can accommodate a significant attenuation due to the accumulation of contaminants in the cell itself and whilst doing so alerts the user to the onset of such attenuation through simple continuous optical power monitoring. Only when the losses are excessive is it necessary to service or replace the detection cell, a procedure which as cell designs improved we have found to be but rarely necessary.

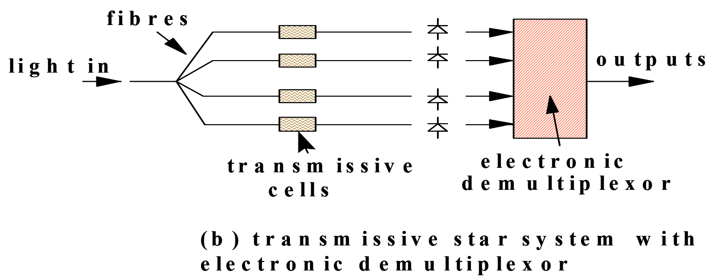

Figure 4: The basic tree configuration used within a multiplexed system where a single laser illuminates a network of cells.

The cells themselves are of extremely rugged basic design (figure 5) comprising graded index lenses attached directly to the end of a single mode optical fibre in a protective housing. The overall packaging, an example of which also is shown in figure 5, can readily be tailored to individual requirements – figure 5 shows the ruggedised landfill version. The open path of the cell itself is typically 5cm in length.

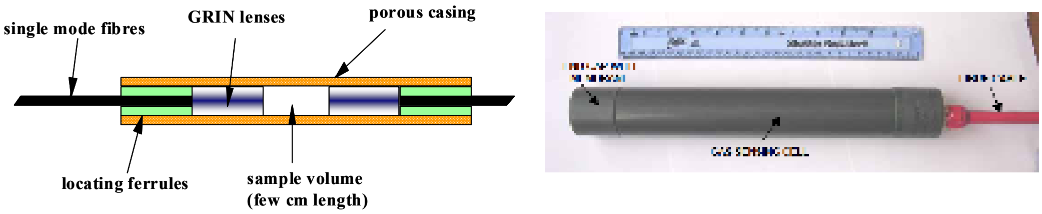

Figure 5: The basic elements of the gas sensing cell design and the photograph of a practical fully ruggedised cell as used for methane detection on landfill sites.

A further benefit of this architecture is (figure 6) is that it can be readily adapted to address numerous species and table 1 summarises just some of the species which can be monitored within the near infrared region in which optical fibres are transparent. The interrogating laser array can either be sequentially switched into a common signal processing system or alternatively a range of laser modulation frequencies and separate lock-in analysers corresponding to each modulation frequency can be chosen to facilitate continuous monitoring for all of several species simultaneously. The former arrangement is clearly far simpler to implement.

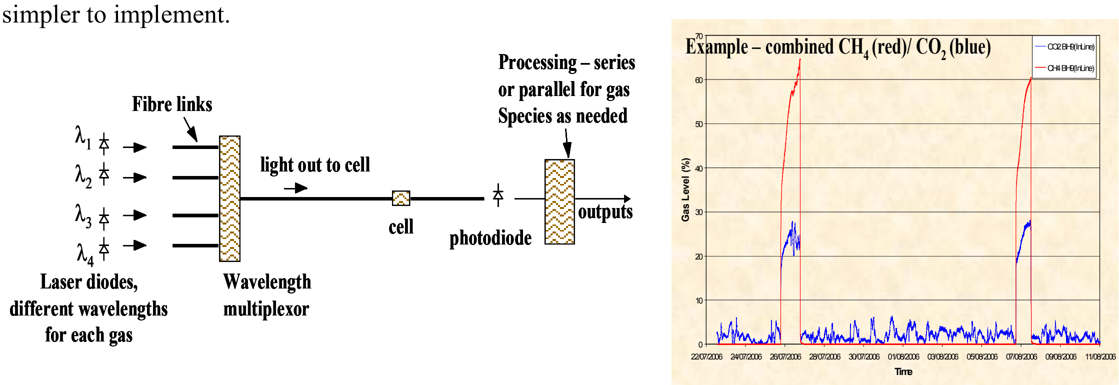

Figure 6: The architecture basics for multiple species detection utilising either sequential laser source switching or sub carrier/lock-in multiplexing.

The attenuation experienced in typical optical fibres in the near infrared is significantly below 1dB per km. Consequently the system can address sites extending over 10 km or more and is therefore well suited for operation in mines, large ventilation systems in tunnels, extensive landfill sites and petrochemical plant.

TABLE 1 Absorption lines for some important gases

Gas	Absorption Line Wavelength (λ_o), (nm).	Line Strength (S) ($cm^{-2}atm^{-1}$) x 10^{-2}	Estimated Sensitivity (ppm.metre) (direct absorption)
Acetylene C_2H_2	1530	20	0.002
Hydrogen Iodide H1	1541	0.775	0.04
Ammonia NH_3	1544	0.925	0.03
Hydrogen Cyanide HC	1550	?	?
Carbon Monoxide CO	1567	0.0575	1
Carbon Dioxide CO_2	1573	0.04	1
Hydrogen Sulphide H_2S	1578	0.325	0.1
Methane CH_4	1665	7	0.006
Hydrogen Fluoride HF	1330	32.5	0.001
Hydrogen Bromide HBr	1341	0.0525	1
Water vapour H_2O	1365	52.5	0.001
Oxygen O_2	761	0.019	1.5
Nitrogen Dioxide NO_2	800	0.125	0.2

5. FIELD TRIAL RESULTS

We have conducted extensive field trials to evaluate the performance of the system under practical conditions. The principal ones have involved assessments on landfill sites (figure 7) within the gas collection system and to monitor gas seepage from the perimeter. The former application involves methane gas concentration in the tens of percent whilst the latter examines trace concentrations to trigger below the lower explosive limit (5% by volume). These sites have involved a single laser addressing typically 60 monitoring points, the signals from which are returned to a single central processor. The map shown in figure 7 gives some idea of the scale and complexity of one of these trial systems.

Some typical results are shown in figure 8 which concerns data from the gas collection system and illustrates some unexpected fluctuations which are traced to changing water levels in the generation area. Figure 9 shows continuous monitoring results from some perimeter wells and demonstrate the occasional short term leakage of methane gas from the main body of the site itself. The data which has been accumulated has been extensive and corresponds in total to several million hours of sensor operation time.

These trials have also resulted in substantial enhancements to the sensor cell and network configuration designs which have been refined to the extent that we have observed more than two years of continuous operation without maintenance or recalibration of a fully instrumented complex landfill site.

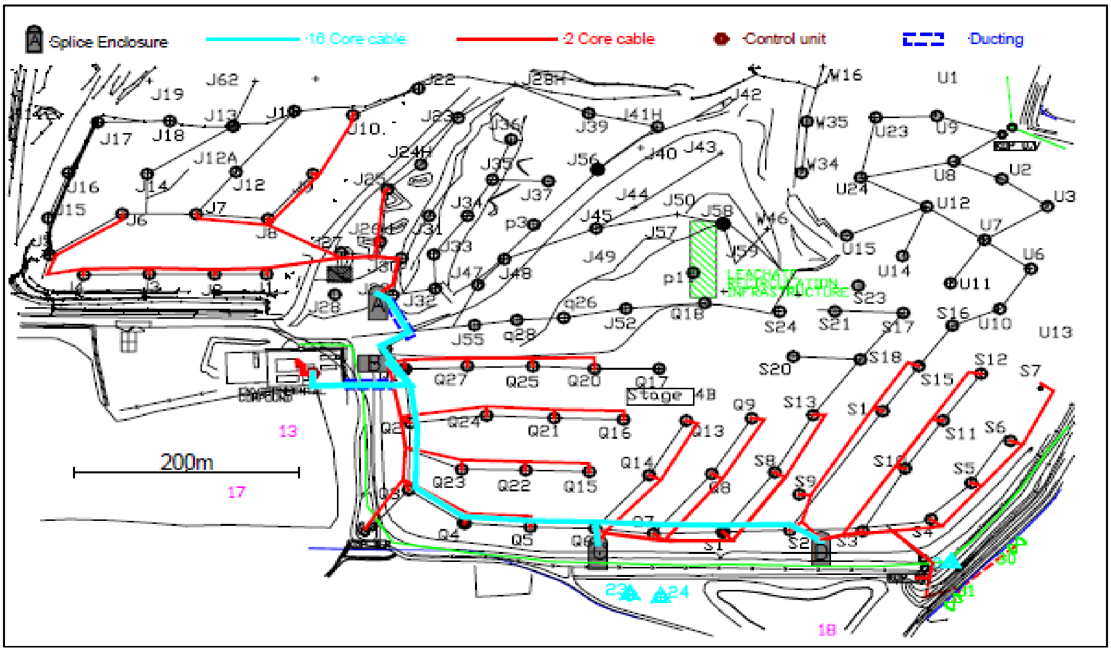

Figure 7: Map of a typical installation illustrating the complexity of a system which can be addressed using a single laser source.

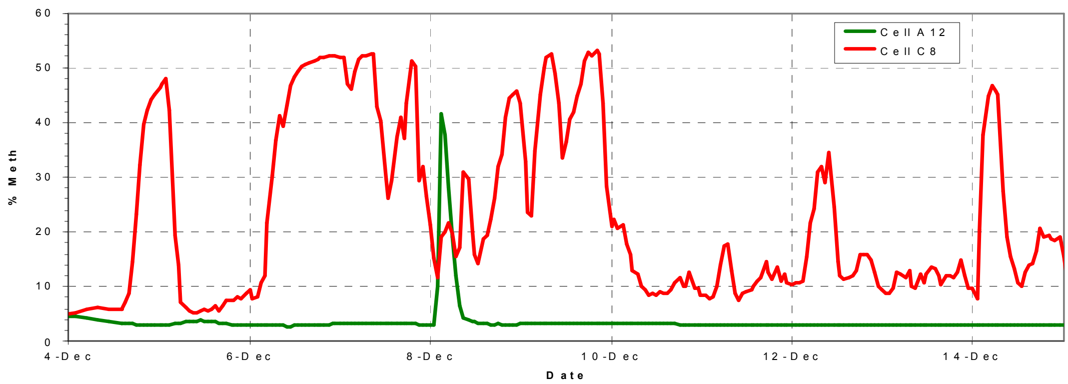

Figure 8: Typical data gathered from the collection wells illustrating both significant fluctuations in methane gas concentration levels and the ability of the system to respond accurately and consistently to high and low concentrations of methane.

The basic viability of the system has therefore been convincingly demonstrated within a harsh and challenging environment. Technically the system gives results which we believe are unparalled in accuracy, stability and reliability when compared to those achievable using alternative techniques. Furthermore since all the cabling components are identical used in optical fibre communication systems the installation processes are well defined and within the capability of skilled technical staff. The system is also intrinsically safe for operation in hazardous environments.

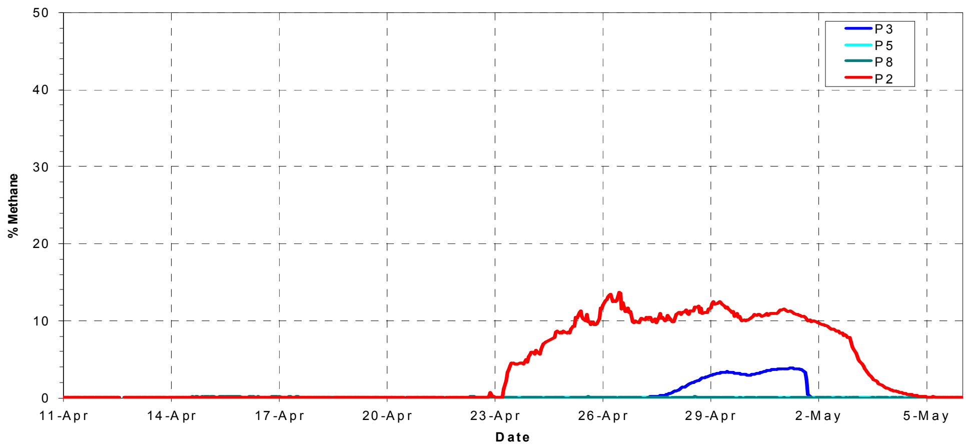

Figure 9: Typical data collected from peripheral monitoring wells for safety assessment illustrating anomalous concentrations over short periods of time.

6. DISCUSSION

These field trails have proceeded in parallel with more basic investigations into factors such as the influence of pressure and temperature on reading accuracy and the use of the technique to obtain very precise maps of absorption line spectra. The principles of these techniques have been reported in detail elsewhere (McGettrick et al 2008) and the results serve to emphasise the overall versatility and flexibility of the system concept. We have also evaluated the system in high pressure and high temperature applications, for example in monitoring of the performance of fuel cells for medium to large scale electricity generation.

We believe that the system concept showed considerable promise for applications such as tunnel ventilation and mine monitoring and preliminary installations are currently under evaluation. The overall environment – which in both cases needs to be compatible with human occupation - is significantly less demanding thermally and chemically than the landfill site so we have every reason to be optimistic about the outcome.

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7. REFERENCES

Proceedings

Culshaw, B., Johnstone, W., McLean, A., Mauchline, I., Moodie, D., Stewart. G., 2002 "Large scale multiplexing a point sensor for methane gas detection" Optical Fiber Sensors Conference Technical Digest, 2002. OFS 2002, 15$^{th.}$ Publication Date 2002 on page(s) 261-264 vol 1.

Journal Article

Reid, J., Shewchun, J., Garside, B.K., Balik, E.A., 1978, "High sensitivity pollution detection employing tuneable diode lasers", Applied Optics, Vol.17 Issue 2. pp.300-307.

Johnstone, W., McGettrick, A.J., Duffin, K., Cheung, A., Stewart, G., 2008 "Tuneable Diode Laser Spectroscopy for Industrial Process Applications: Systems Characterization in Conventional and New Approaches". Sensors Journal, IEEE. Vol 8, Issue 7, pp1079-1088.

McGettrick, A. J., Duffin, K., Johnstone, W., Stewart, G., Moodie, D.G., 2008 "Tuneable Diode Laser Spectroscopy With Wavelength Modulation: A Phasor Decomposition Method for Calibration-Free Measurements of Gas Concentration and Pressure" Journal of Lightwave Technology, Vol.26 Issue 4, pp.432-440.