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Design of a fibre optic sequential multipoint sensor for methane detection using a single tunable diode laser near 1666 nm

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ABSTRACT

The design of a fibre optic sequential multipoint sensor using a single DFB laser source for measurement of average concentration of methane has been reported. A theoretical model for sequential multipoint sensor is developed. The validation of the sensor is conducted using methane gas cells connected in series via fibre optics to form 2-Cell and 3-Cell networks. The second harmonic detection of wavelength modulation spectroscopy (2*f*-WMS) is employed. Normalisation of the 2*f* signals with respect to the laser average intensity and the detector gain is used to correct for transmission variation. The measurements are performed at four laser modulation depths to compare the 2*f*-WMS signals for the target test conditions. The Q(6) transition of the $2\nu_3$ band of methane near 1666 nm has been selected because the transition is relatively free of interference from water vapour and absorption by other major gases in that region. The sequential multipoint sensor has some unique advantages over the single cell and multiplexed multipoint sensors. These include the average concentration measurements, the use of only a single laser source, a detector, and a fibre optic to connect series of gas cells, no need for multiplexing techniques to distribute the laser intensity among multi gas cells, and relatively simpler data analysis.

1. Introduction

Methane is considered a greenhouse gas; methane is released during coal extractions and outbursts in underground and surface mines. When it reaches a concentration of 5–15% (mixed with air) in an enclosed environment, such as underground coal mines, methane becomes dangerously explosive [1]. Therefore, proper oversight and determination/implementation of essential precautions require the development and deployment of accurate methane sensors to monitor methane production and release. Tunable diode laser (TDL) sensors based on optical absorption and wavelength modulation spectroscopy (WMS) have been used for combustion diagnostics [2], engine exhaust monitoring [3], analysis of landfill gases [4], mines air pollution monitoring [5] and explosives detection [6]. Incorporating with fibre optics, a simultaneous, non-intrusive, and reliable method for in situ measurements of gas concentration and temperature in various harsh environments can be achieved [7]. The first system for methane measurement using TDL and fibre optics was reported in 1983 by Chan et al. [8]. Chan et al. [9] used fibre optics with a length of 2 km and a light emitting diode (LED) at 1665 nm to detect methane of $2\nu_3$ band. Gladyshev et al. [10] reported a novel single frequency tunable diode laser and a gas cell for detection of methane $2\nu_3$ band at 1645 nm.

Previous studies on the use of fibre optics in the measurement of methane concentrations have been mainly limited to a single point measurement using only one gas cell [11,12]. A single point measurement will not provide the gas dispersion (distribution) profile. The methane outburst, for instance in an underground coal mine, can occur at any point of the tunnel. Therefore, simultaneous multipoint measurements are required to obtain the gas distribution profile along the tunnel. The first multipoint fibre optic methane sensor was reported by Stewart et al. [13]. They used a fibre splitter and multiplexing technique to distribute the power of a 1665 nm distributed feedback (DFB) laser between couple of gas cells. The outputs of the gas cells were detected by a series of photodiode detectors individually. Under this method, the detection of methane in individual gas cells is independent of the other gas cells, even though the gas cells remained connected to a single laser source, the results are analysed and reported separately for each gas cell.

In this paper, the design of a fibre optic sequential multipoint sensor using a DFB laser and a photodiode detector for the average concentration measurement of methane over a series of gas cells is reported. It is of a great safety measure that an average concentration is known in underground mine tunnels to reduce risk of methane explosion and provide a safer working condition. The design incorporates several gas cells which are connected in series

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Nomenclature

$1f$	first harmonic component
$2f$	second harmonic component
α	frequency modulation amplitude (cm^{-1})
$\alpha(\nu)$	spectral absorbance
i_0	magnitude of the linear laser intensity modulation
i_2	magnitude of first harmonic of the non-linear laser intensity modulation
$\bar{I}_0$	average laser intensity ($W\,m^{-2}$)
$I_0(\nu)$	incident laser intensity ($W\,m^{-2}$)
$I_L(\nu)$	transmitted laser intensity over path length of L ($W\,m^{-2}$)
G	electro-optical gain of the detector
$k(\nu)$	spectral absorption coefficient (cm^{-1})
$\overline{k(\nu)}$	average concentration (%)
$H_n(\bar{\nu}, \nu_m)$	nth harmonic Fourier component
L	path length (cm)
ϕ_1	phase shift between laser linear intensity modulation and frequency modulation
ϕ_2	phase shift between laser non-linear intensity modulation and frequency modulation
S_{2f}	magnitude of the second harmonic signal
S_{2f}^{max}	maximum peak amplitude of $2f$ signal
S_{2f}^{P-P}	peak-to-peak amplitude of $2f$ signal
$S_{2f}^{max}\Big\vert_{Norm}$	normalised maximum-peak $2f$ signal
$\tau(\nu)$	transmission coefficient
$\bar{\nu}$	laser centre frequency (cm^{-1})
$\nu(t)$	laser frequency (cm^{-1})
ν_m	modulation depth (cm^{-1})
ω	wavelength modulation angular frequency ($rad\,s^{-1}$)

by fibre optics forming a sequential multipoint sensor. Average concentration measurement is independent of the concentrations and connection positions of the individual gas cells. The gas cells can be spaced out up to a few hundred metres via fibre optics connections, similarly to a single point measurement, laser power can be transmitted through fibre optics few kilometres down to a gas cell where the measurement takes place.

The measurement scheme is based on the second harmonic detection of scanned wavelength modulation spectroscopy (2f-WMS) normalised to the average laser intensity and the detector gain. The Q(6) transition of the $2\nu_3$ band of methane near 1666 nm has been selected because the transition is relatively free of interference from water vapour and absorption by other major gases [14], and also telecommunication fibre optics components are commercially available in this region [15]. The experimental investigations have been carried out on sequential 2-Cell and 3-Cell networks incorporating seven gas cells prefilled with methane at different concentrations. The sequential multipoint sensor offers unique advantages over the single point and multiplexed multipoint measurements. The design is cost effective and requires simpler processing and fewer components compared with the multipoint multiplexed technique. It also performs simultaneous multipoint measurements over a wide area and provides average concentration measurements nevertheless using similar configuration and processing procedure of a single point measurement. To the best of the author's knowledge, it is for the first time that an experimental investigation has been conducted for sequential multipoint methane sensor applying 2f-WMS technique. The proposed design is much more suitable for methane emission measurements in underground mines because it requires only one fibre optics for connecting a series of gas cells to form the sequential multipoint network [16].

2. Fundamentals of wavelength modulation spectroscopy (WMS)

The fundamental of absorption spectroscopy is based on the attenuation of spectral intensity [W/m^2] that happens when radiation interacts with species molecules and is represented by Beer–Lambert law [17,18].

$$\tau(\nu) = \frac{I_L(\nu)}{I_0(\nu)} = \exp(-\alpha(\nu)) = \exp(-k(\nu) \cdot L) \tag{1}$$

where $\tau(\nu)$ is the transmission coefficient, $I_L(\nu)$ and $I_0(\nu)$ represent the transmitted and incident laser intensities, $\alpha(\nu)$ is the spectral absorbance, $k(\nu)$(cm^{-1}) is the spectral absorption coefficient, and L [cm] is the interaction length or the path length. Many models are reported to describe WMS in various applications [19,20]. The model presented here is based on the previous works; adopted and rewritten into a form providing the magnitudes of the second harmonic (2f) signal components extracted by a lock-in amplifier (LIA) for real application of gas sensing. Modelling WMS starts with modelling the laser intensity and wavelength dependent absorption. When the laser injection current is sinusoidally modulated with an angular frequency of ω, the instantaneous output frequency of the laser, $\nu(t)$, is written as:

$$\nu(t) = \bar{\nu} + \nu_m \cos(\omega t) \tag{2}$$

in which $\bar{\nu}$ (cm^{-1}) is the laser centre frequency and ν_m (cm^{-1}) is the modulation depth. These parameters must be defined accordingly to the laser operational setup for these measurements. The laser intensity is also modulated, and the incident laser intensity can be modelled by [21]:

$$I_0(t) = \bar{I}_0[1 + i_0 \cos(\omega t + \varphi_1) + i_2 \cos(2\omega t + \varphi_2)] \tag{3}$$

$\bar{I}_0$ is the laser average intensity, i_0 and i_2 are the magnitude of the linear and first harmonic of the non-linear laser intensity modulation (IM) which are normalised by $\bar{I}_0$, and φ_1 and φ_2 are the phase shifts between the laser intensity modulation and frequency modulation (FM) for linear and non-linear terms of intensity modulation. The non-linear terms cause distortion in the background 2f signal; however, in the case when small modulation depths are applied, the distortion is negligible [22]. The parameters i_0, i_2, φ_1, and φ_2, are to be measured experimentally for the laser operation settings, i.e. the injection current, modulation frequency, and modulation index. When slow frequency ramp signal is superimposed onto the high frequency sinusoidal modulation for scanning the target absorption line, the value of $\bar{I}_0$, i_0, and i_2 change accordingly throughout the scanning stage. Consequently, the laser parameters should be measured at the corresponding ramp signal to the 2f peak signal. The transmission coefficient for the laser beam through the absorbing feature is defined in terms of the Fourier series as follows [22]:

$$\tau(\nu(t)) = \sum_{n=0}^{\infty} H_n(\bar{\nu}, \nu_m)\cos(n\omega t) \tag{4}$$

If the laser light transmitted through the absorption cell is impinged onto a photodetector, the individual harmonic Fourier components at nth harmonic of the modulation frequency can be extracted by a LIA. The processed signal is a proportional to [23]:

$$I_0 H_n(\bar{\nu}, \nu_m) L \qquad \text{for} \quad n \geq 1 \tag{5}$$

To model the detector signal, the incident laser intensity equation multiplies to the first terms of the transmission function. For X and Y components of the LIA, measuring the 2f signal, the detector signal