Sensors and Actuators A 222 (2015) 96–101

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Analysis of inaccuracy induced by intensity variation of a DFB laser in fibre optic multipoint 2*f*-WMS measurements of methane near 1666 nm

Javad Shemshad [a,b,*]

[a] Department of Electrical and Electronics Engineering, Adana Science and Technology University, Adana, Turkey
[b] School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, QLD 4072, Australia

ARTICLE INFO

Article history:
Received 29 June 2014
Received in revised form
17 November 2014
Accepted 18 November 2014
Available online 11 December 2014

Keywords:
Wavelength modulation spectroscopy
Methane concentration
Fibre optic multipoint sensor
DFB laser
Intensity variation

ABSTRACT

The analysis of methane concentration measurement inaccuracy induced by the intensity variation of a DFB laser at 1666 nm in a multipoint fibre optic sensor has been reported. The measurement is based on wavelength modulation spectroscopy (WMS) with second harmonic (2*f*) detection technique. The 2*f* signals are normalised to the average laser intensity and the detector gain to eliminate the effect of transmission loss and laser intensity variation on the measurements. The measurements are conducted at two laser intensities, defined as nominated intensity and 73% of the nominated intensity, to quantify the measurements errors due to the intensity change. The experimental results show that a significant change in the laser intensity yields differences in the 2*f* signals; as a result, errors were induced. A model is developed to quantify the errors in the concentration measurements. The maximum deviations for single cell, 2-Cell, and 3-Cell measurements to the given concentration of 10%, 7.5%, and 5.667% are calculated to be 9.764%, 7.2235%, and 5.368%, respectively. The concentration error increases with the cell number because of the accumulated background transmission loss of the gas cells in 2-Cell and 3-Cell in comparison to a single cell measurement.

1. Introduction

Tunable diode laser (TDL) sensors based on optical absorption and wavelength modulation spectroscopy (WMS) have been used for combustion diagnostics [1], engine exhaust monitoring [2], analysis of landfill gases [3], mines air pollution monitoring [4] and explosives detection [5]. 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 [6]. Chan et al. [7] reported the first fibre optic sensor for methane measurement using a light emitting diode (LED) at 1330 nm. Chan et al. [8] used fibre optics with a length of 2 km and an LED at 1665 nm to detect methane $2\nu_3$ band. In another study, Gladyshev et al. [9] used a TDL and a gas cell for detection of methane $2\nu_3$ band at 1645 nm. The first fibre optic multipoint methane sensor was reported by Stewart et al. [10]. Multiplexing technique and a fibre splitter were used to distribute the power of a 1665 nm distributed feedback (DFB) laser between couple of gas cells. Shemshad [11] reported the first fibre optic sequential multipoint methane sensor. A single DFB laser at 1665 nm and couple of methane gas cells connected in series were used to measure the average methane concentration.

Although there have been significant studies reported on developments of fibre optic gas sensors, however, a quantitative study of the effect of laser intensity variation on fibre optic gas sensors is still favourable. In this paper, to the best of the author's knowledge, for the first time, analysis of inaccuracy in methane concentration measurements induced by a DFB laser intensity variation in a fibre optic multipoint sensor is reported. The measurement is based on the second harmonic wavelength modulation spectroscopy (2*f*-WMS). 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 [12]. The experimental investigation has been conducted on sequential 2-Cell and 3-Cell networks incorporating seven gas cells prefilled with methane gas at different concentrations [11].

To investigate the concentration measurement inaccuracy due to the laser intensity change, the measurements were conducted at two laser intensities. The DFB laser power was tuned to operate at

* Correspondence to: Department of Electrical and Electronics Engineering, Adana Science and Technology University, Adana, Turkey. Tel.: +90 322 455 0000.
E-mail addresses: j.shemshad@uqconnect.edu.au, jshemshad@adanabtu.edu.tr

http://dx.doi.org/10.1016/j.sna.2014.11.011
0924-4247/

a nominated intensity and 73% of the nominated intensity to simulate the laser intensity change. The second harmonic (2*f*) signals at the two laser intensities and for different methane concentrations were measured and normalised to the average laser intensity and the detector gain. The experimental results show that a significant reduction in the laser intensity of approximately 27%, yields, differences in the measured 2*f*-WMS signals. This induces errors in the concentration measurements which have quantitatively obtained for single, 2-Cell, and 3-Cell connections for different concentrations.

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 [13,14]. In a study by Shemshad [11], a theoretical model is developed to describe a sequential multipoint sensor consisting of numbers of gas cells. Assuming n identical gas cells with equal background and insertion losses of κ in each gas cell, are connected in series, thus the Beer Lambert Law can be written as:

$$\tau(\nu) = \frac{I_D(\nu)}{I_0(\nu)} = \kappa^n \times \exp(-k(\bar{\nu})nL) \tag{1}$$

where $\tau(\nu)$ is the transmission coefficient, $I_0(\nu)$ and $I_D(\nu)$ represent the initial laser intensity and transmitted intensity after passing through n gas cells, respectively; L (cm) is the path length, and $k(\bar{\nu})$ is defined as the average concentration of target gas within the sequential multipoint sensor. Many models are reported to describe WMS in various applications [15,16]. The model presented here, provides the magnitudes of the 2*f* signals extracted by a lock-in amplifier which is most suitable 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, $\upsilon(t)$, is written as:

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

in which $\bar{\nu}(\mathrm{cm}^{-1})$ is the laser centre frequency and $\nu_m(\mathrm{cm}^{-1})$ is the modulation depth. These parameters must be defined accordingly to the laser operational setup for these measurements. The transmission coefficient for the laser beam through the absorbing feature is defined in terms of the Fourier series as follows [17]:

$$\tau(\nu(t)) = \sum_{n=0}^{\infty} H_n(\bar{\nu}, \nu_m)\cos(n\omega t) \tag{3}$$

If the laser light transmitted through the absorption cell is impinged onto a photodetector, the individual harmonic Fourier components at *n*th harmonic of the modulation frequency can be extracted by a lock-in amplifier. The processed signal is a proportional to [18]:

$$I_0 H_n(\bar{\nu}, \nu_m)L \quad \text{for } n \geq 1 \tag{4}$$

A simplified model for the second harmonic signal is expressed as [19]:

$$S_{2f} = \frac{G\bar{I}_0}{2}\left|H_2 - \frac{i_0}{2}(H_1 + H_3)\right| \tag{5}$$

where G is the electro-optical gain of the detector and not required to be measured as it cancels out in the normalisation procedure. Note that the 2*f* signal also depends on H_0 and H_4 terms. This model is more appropriate for gas sensing application in atmospheric pressure [20].

3. Experimental design

3.1. Experimental setup

The experimental setup for multipoint WMS measurement is shown in Fig. 1. The experimental investigation used fibre optic collimated gas cells (Wavelength References Inc.), a DFB laser system with 1666 nm centre wavelength (Toptica Photonics model LD 1666-DC/TC 110), a 400 kHz bandwidth photodetector (Thorlabs model PDA 50B-EC); a DSP lock-in amplifier (Stanford Research Systems, model SR830), and a 300 MHz bandwidth digital oscilloscope (Tektronix model DOP 3034).

The gas cells were sealed glass tubes with 9 mm OD and 16.5 cm length containing pre-defined methane concentrations mixed with nitrogen as background gas. Seven gas cells with CH_4 concentrations of 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, and 10% balance in N_2 with the accuracy of 99.9% were used in the measurements. The total pressure of mixture of CH_4 and N_2 in the gas cells was in the range of 740–750 Torr. Fibre optic pigtailed collimators were attached at both ends of the gas cells to couple the laser light in and out through the glass tube. The glass tubes and fibre optics collimators were placed in a case and precisely line-of-sight aligned to allow for maximum transmission occurrence.

The DFB laser was a fibre pigtailed laser with an internal isolator of 30 dB and course tuning range of 5 nm via Peltier temperature cooling element. The laser can be scanned over the entire wavelength range with a minimum resolution of 1 °C and 1 mA by temperature and current controller, respectively. The DFB laser can produce maximum output power of 13 mW and 8 mW at temperature/current settings of 3 °C/80 mA and 48 °C/100 mA, respectively. The temperature tuning coefficient is 14.7 GHz/K (0.14 nm/K) at set current of 81 mA over the temperature range of 3–48 °C. The current tuning coefficient is 0.9 GHz/mA (0.008 nm/mA) at the set current of 86 mA and chip temperature of 23 °C. As an initial test, the output power of 10 mW at temperature setting of 23.5 °C and DC injection current of 80 mA was measured.

The laser wavelength was double modulated by superimposing a sine wave and a triangle ramp to the laser DC injection current. The modulated laser output was connected to the gas cell, the transmitted laser intensity through the gas cell was first detected by the photodetector and then by the lock-in amplifier to extract the harmonic signals. The harmonic signals were measured (50 averages) and displayed on the digital oscilloscope. In order to quantify the WMS measurements, modulation parameters of the laser such as modulation depth, intensity modulation amplitude, and FM/IM phase shift, must be precisely obtained. The DFB laser used in the experiment has been experimentally characterised previously [11].

3.2. Procedure of 2f-WMS measurements

An important factor in sensor design is absorption line selection; an optimum transition can greatly improve the sensor performance [21]. Shemshad et al. [12] investigated the most suitable band of methane absorption lines in near infrared spectrum. It was found that the Q band transitions of $2\nu_3$ band make it a suitable target for spectroscopic detection of methane in near infrared region. In this study, the Q(6) transition of the $2\nu_3$ band of methane near 1666 nm has been selected. The $2\nu_3$ band of methane consists of transition lines with a small spectral separation between the lines. By applying a large modulation depth, the non-absorbing wings from the adjacent lines may interfere with the measurement. Through the experimental process, a range for modulation depth was obtained, and the modulation depth of 0.104 cm^{-1} was used. The effect of modulation depth on 2*f* signal has been theoretically investigated by Shemshad et al. [12]. This can be experimentally and fundamentally discovered by investigating the detector output.