A 1531.52 nm tunable diode laser-based system for high-sensitivity remote monitoring of acetylene and ammonia leaks in industrial plants

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Abstract: We demonstrate a 1531.52 nm tunable diode laser -based sensor system that can be used to build a dense, wide-area sensor network for *in situ* multi-point detection of acetylene (C_2H_2) and ammonia (NH_3) leaks in industrial safety applications. The detection limit of the sensor is 16 ppm for C_2H_2 and 228 ppm for NH_3 using a 28 cm long single-pass gas cell. High temperature measurements are also demonstrated in a tube furnace using a 1392.54 nm laser-based sensor. The accuracy of temperature measurement is 92.13% at 500 K and 96.79% at 700 K.
Keywords: tunable diode laser spectroscopy, ratio thermometry, chemical sensing.

1. Introduction

Industrial safety applications require reliable, rapid and highly sensitive gas sensors for long-term monitoring of several gases for early-warning systems as well as process control. The heavily industrialized state of Gujarat has been vulnerable to gas leaks in industries that have caused several deaths in recent years. It is necessary to develop robust gas sensors that can withstand hazardous field conditions and operate largely unattended over long periods. In this paper, we report the development of a prototype of a sensor network that can be used to - (a) simultaneously detect C_2H_2 and NH_3 leaks at multiple points in large industrial plants, and (b) measure very high temperatures that are often the precursors of pipeline weakening. The sensor system is based on tunable diode laser spectroscopy (TDLS) which is a non-invasive gas sensing technique that can be used to detect multiple gases simultaneously with very high sensitivity and extremely low cross-sensitivity. Calibration-free measurement techniques [1,2] contribute heavily to the success of such sensors in hazardous environments. In the simplest form of TDLS, known as direct detection, the emission wavelength of a narrow-linewidth semiconductor laser is tuned across a rotational-vibrational absorption line of a gas using a low-frequency current ramp, and the spectral distribution of the transmitted light intensity is recorded. The absolute lineshape is recovered by normalizing the absorption signal by the laser intensity. The mole fraction and pressure are extracted by fitting a simulated lineshape to the experimentally recovered absorption line. Higher detection sensitivities are obtained by using wavelength modulation spectroscopy (WMS) [3] in which a high-frequency sinusoidal modulation is applied to the laser in addition to the low-frequency ramp and phase-sensitive harmonic detection is performed (predominantly $2f$ WMS). Temperature is calculated from the ratio of integrated absorbance of two molecular transitions that have a large difference in their lower state energies.

2. Experimental setup and results

2.1. Multi-point detection of C_2H_2 and NH_3 over a fiber-optic network

A schematic of the sensing system is shown in Fig. 1(a). A 40 mW, 1531.52 nm distributed-feedback tunable diode laser (Toptica Photonics, LD-1550-0040-DFB-1) is used to interrogate the C_2H_2 and NH_3 transitions at 1529.772 nm and 1529.849 nm respectively. The laser output is split into four parts and sent through standard telecom optical fiber spools of length 2 km, 2 km, 5 km and 10 km respectively. Four 28 cm long gas cells placed at the ends of the spools represent four remote detection points. The leaks are simulated by abruptly introducing a mixture of C_2H_2 and NH_3 into gas cells 1, 3 and 4, while only C_2H_2 was introduced into cell 2. The sensor responds nearly instantaneously. The acquired direct detection signals are shown in Figs. 1(c), 1(d), 1(e) and 1(f). A digital signal processor-based compact unit (Texas Instruments, TMS320F28377D) was used for signal generation, acquisition and processing. An Allan variance analysis shows that the detection limit for an optimum integration time of 33 s is 16 ppm and 228 ppm for C_2H_2 and NH_3 respectively for 28 cm path length when $2f$ WMS is used. A 10 dB attenuation of the laser power (equivalent to splitting the laser output into several parts), only marginally worsened the detection limit for C_2H_2 to 18.5 ppm for a slightly higher integration time of 74 s.

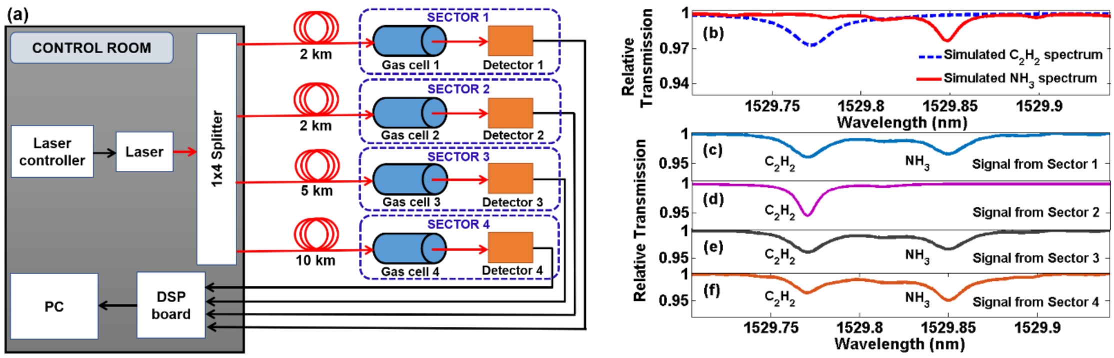

Fig. 1: (a) Schematic of the experimental setup for multi-point detection of C_2H_2 and NH_3, (b) Simulated absorption spectra of a mixture of C_2H_2 and NH_3, (c), (d), (e) & (f) Experimental signals obtained from Sector 1, Sector 2, Sector 3 and Sector 4 respectively.

2.2. Temperature measurements using ratio thermometry

The temperature measurements are carried out in a tube furnace (shown in Fig. 2(a)). A 10 mW, 1392.54 nm distributed-feedback tunable diode laser (Eblana Photonics, EP1392-DM-B) is used to interrogate the water vapour transitions at 1391.672 nm and 1392.185 nm. The laser output is collimated and passed through the furnace that has a built-in thermocouple as shown in Fig. 2(b). Fig. 2(c) shows the acquired water vapour lines at 300K, 500K and 700K. The furnace temperature is calculated from the ratio of areas under the absorption lines. A comparison between the set temperature and calculated temperature is shown as inset in Fig. 2(c). This non-contact approach is ideal for high-temperature environments in which conventional sensors would not survive.

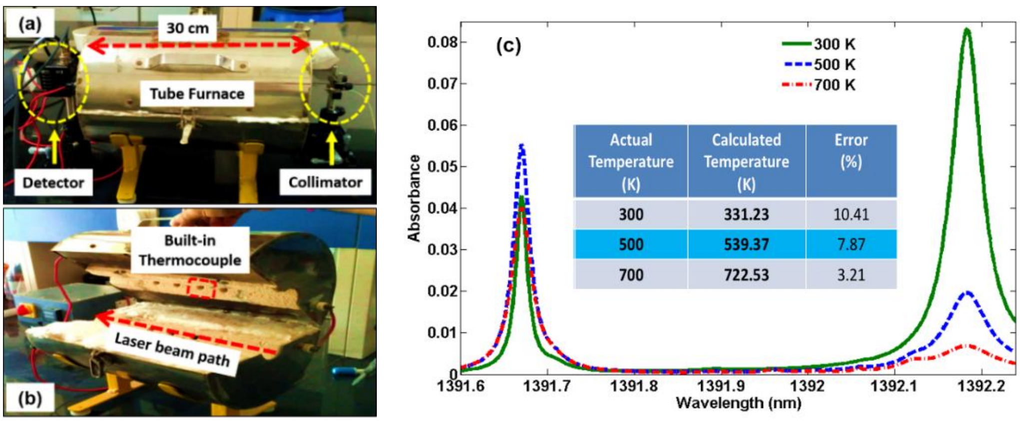

Fig. 2: (a) Experimental setup for temperature measurement, (b) Interior of furnace showing the path of the laser beam, (c) Absorption lines of water vapour at 300 K, 500 K and 700 K. Inset shows comparison between set temperature and temperature extracted by ratio thermometry.

3. Conclusion

The potency of the fiber-optic network-based sensing system arises from its inherent robustness and flexibility. The use of a single laser diode of reasonable price (approximately INR 1.5 lakhs) and very long life (~10000 hours), and the low loss (0.2 dB/km) of optical fibers make this approach robust, flexible and hugely economical for long-term, remote monitoring of large industrial plants. Fiber-optic beam delivery leads to immunity to electromagnetic interference and ability to withstand harsh operational conditions. The sensor network can be readily reconfigured and extended to interrogate wider and complex areas. Leaks are sensed nearly instantaneously, while the processing time is approximately 6 s if the mole fraction and pressure of the gas are to be extracted.

4. References

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