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Tunable Diode Laser Absorption Spectroscopy as a Flow Diagnostic Tool: A Review

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Abstract | Optical diagnostic techniques are routinely being used in high speed flow facilities to measure flow properties such as concentration, temperature and velocity, and thus, to study the flow physics. One such technique, tunable diode laser absorption spectroscopy (TDLAS), has proved to be particularly suitable for hostile environments such as shock tunnels and flight tests. The fundamentals, operating principle, applications and scope of the technique in high speed flow research is discussed in this review, with references to some relevant examples.

1 Introduction

Sensors are an integral part of high speed flow research. Various types of sensors are being regularly used to measure velocity, pressure, temperature and concentration of flow particles in various ground test facilities as well as in flights. The importance of optical diagnosis in high speed flows arises from the fact that sensors based on optical techniques are mostly non-intrusive. This is particularly important for hypersonic and high-enthalpy flows, where interaction between the flow and a physical probe, if it occurs at all, will be very strong.

Various optical techniques such as Schlieren visualisation, interferometry, particle image velocimetry (PIV), laser Doppler velocimetry (LDV), planar laser-induced fluorescence (PLIF), coherent anti-Stokes Raman spectroscopy (CARS) and tunable diode laser absorption spectroscopy (TDLAS) have been used for flow diagnosis (Eckbreth, 1996; Hegde et al., 2013; Palmer & Hanson, 1995; Settles, 2001). Each optical technique has its advantages and limitations; for example, PLIF has a very good spatial resolution while time resolution is relatively low, unless you have an expensive laser with fast pulse repetition rate. The Schlieren method is useful for visualising and qualitatively studying flow structures, but its dependence on the gradient of density makes it difficult to achieve direct measurements of state variables. Furthermore, the spectroscopic techniques like CARS and PLIF require high-powered lasers. These techniques can be implemented in a laboratory environment, but are often not practical for flight implementation, at least not with current technology.

Of all these techniques, TDLAS is unique because it has features that make it a feasible technology for harsh environments (Allen, 1998). Sensors based on TDLAS can be made compact and robust as they do not contain moving parts. They can be easily integrated into engine parts and impulse facilities, and are less affected by mechanical vibrations than techniques involving solid-state tunable pumped lasers. The power requirements of TDLAS are low, and the components are relatively inexpensive compared to other optical techniques. This review provides a brief overview about the underlying theory, sources and detection schemes used for the TDLAS technique, and presents case studies of some important applications in the field of aerospace engineering.

2 Theory

According to the Beer-Lambert Law, the fractional change dI in the instantaneous intensity I while a light beam traverses an infinitesimally small distance dl in an absorbing medium is proportional to this propagation distance and the number density N of the sample,

$$\frac{dI}{I} \propto -Ndl \qquad (1)$$

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or

$$\frac{dI}{I} = -kNdl \tag{2}$$

where k is a proportionality constant called absorption coefficient of the medium. This equation assumes that there are no losses due to scattering, and that the distribution of physical properties along the beam path is uniform. The negative sign in the relationship in Equation 2 indicates that the change in intensity is negative due to the absorption process. If I_o is the light intensity incident on the absorbing medium, and I_t is the transmitted intensity at the exit of the medium, integrating the above equation over the total path length l of the sample leads to

$$\ln(I_t) - \ln(I_o) = \ln\left(\frac{I_t}{I_o}\right) = -kNl \tag{3}$$

From this equation, the absorbance A is defined as

$$A = -\ln\frac{I_t}{I_o} = kNl \tag{4}$$

In other words, the transmitted intensity I_t is given by

$$I_t = I_o \exp(-A) \tag{5}$$

This is the most common form of the Beer-Lambert Law. It should be noted that, in some application domains, absorbance is also defined in terms of logarithm to the base 10 instead of the natural logarithm.

The absorption coefficient of the medium k (see Equation 4) is a function of the wavelength/frequency of the laser beam and of the absorption transitions in the absorbing medium. The value of k for a gas at a frequency ν due to a particular transition i is the product of the line strength S_i, which is a specific property of a given transition that varies with temperature for a given line, and the value of the unity-normalised line-shape function $g(\nu)$ at that frequency

$$k(\nu) = S_i g(\nu) \tag{6}$$

The line shape function $g(\nu)$ is determined by the pressure- and temperature-dependent broadening mechanisms in molecules. Detailed discussion on line profiles can be found in standard spectroscopic text books (e.g. Demtröder, 2008). A Voigt profile is a reasonable profile to be used when modelling high speed flows where the pressure broadening effect is important. In cases where pressure broadening is negligible, the Doppler-broadened Gaussian function may also be used to increase the speed of calculations. When multiple absorption peaks overlap, the total absorbance at a particular frequency is obtained by adding their absorption contributions.

The line strength of a particular transition is a function of temperature, and is given by,

$$S_i(T) = S_i(T_0)\frac{Q(T_0)}{Q(T)}\left[\frac{\exp\left(-\frac{hcE_i}{k_BT}\right)}{\exp\left(-\frac{hcE_i}{k_BT_o}\right)}\right]\left[\frac{1-\exp\left(-\frac{hc\nu_o}{k_BT}\right)}{1-\exp\left(-\frac{hc\nu_o}{k_BT_o}\right)}\right] \tag{7}$$

where,

S = line strength
g = line profile function
T = temperature
T_o = reference temperature (296 K)
ν = line centre wavenumber
E_i = lower energy state (expressed in wavenumbers)
k_B = Boltzmann constant
c = velocity of light
Q = partition function

Usually, the last term in the equation, which represents the contribution of stimulated emission, is much smaller than the first term which gives the temperature dependence of the lower-state energy. Hence, this stimulated emission contribution can be neglected and the equation reduces to

$$S_i(T) = S_i(T_0)\frac{Q(T_o)}{Q(T)}\exp\left[\frac{hcE_i}{k_B}\left(\frac{1}{T_o} - \frac{1}{T}\right)\right] \tag{8}$$

The values of $S_i(T_o)$, E_i and $Q(T_o)$ for the targeted transitions can be obtained from a molecular database such as HITRAN spectroscopic database (Rothman et al., 2013). According to Equation 8, the line strengths, and hence the absorbances, of transitions with different ground state energies vary differently with temperature. Therefore, the absolute absorbance due to each transition, as well as the relative amplitudes of the absorption lines, is determined by the temperature of the medium. However, the absolute absorbance is also a function of concentration and total beam path. In most practical situations where TDLAS is applied, the concentration is also an unknown parameter.

Therefore, the relative variation of absorption lines is used to calculate the temperature. This temperature is then used to estimate the concentration from the absolute absorbance.

In the two-line method (Hanson & Falcone, 1978), two transitions with different ground state energies are chosen. From Equation 8, the ratio of integrated absorbances of the two selected lines for a given temperature T is given by,

$$r(T) = \frac{A_1(T)}{A_2(T)} = \frac{S_1(T)}{S_2(T)} = \frac{S_1(T_o)}{S_2(T_o)} \exp\left[\frac{hcE_i}{k_B}\left(\frac{1}{T_o} - \frac{1}{T}\right)\right] \tag{9}$$

where the subscripts 1 and 2 represent the parameters corresponding to the first and second lines respectively. Hence, the ratio of integrated absorbances is a function of temperature, and is independent of the concentration of the sample. Assuming that the conditions along the beam path can be characterised using a single temperature and concentration, the temperature of the gas can be determined from this ratio. Alternatively, a least squares fitting algorithm with temperature as the free variable can be used to compare experimental spectrum with theoretical spectrum, and retrieve the temperature (Sanders et al., 2001). The two lines can be scanned using two different lasers, or using a single laser if both the required lines occur within the scan range of the laser. Different criteria for selecting appropriate lines can be found in Zhou et al., 2003.

The translational temperature can also be obtained from a single absorption line if the absorption peak is predominantly Doppler broadened. This happens when the pressure is known and very low such that the pressure-broadening contribution to the absorption profile is negligible compared to the thermal broadening contribution. In that case, temperature can be obtained from the full-width at half-maximum (FWHM) of the profile using the equation:

$$\Delta\nu_{fwhm} = \frac{2\ln\sqrt{2}\nu_o}{c}\sqrt{\frac{2k_BT}{M}} \tag{10}$$

where M is the mass of the molecule, ν_o the line centre frequency and c is the velocity of light. However, since the temperature is proportional to the square of the FWHM of the profile, an error in determining the Doppler-broadened FWHM can cause a magnified error in the measured temperature, especially when the line width is small.

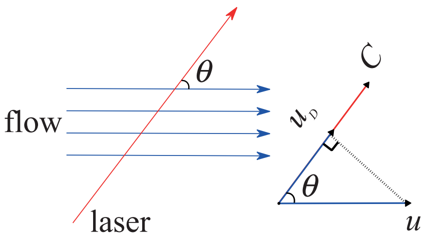

Figure 1: Diagrammatic representation of the Doppler component of velocity *u* in the direction of light velocity *c*.

In order to measure the velocity of a gas flow from the absorption spectrum of a species in the flow, a laser beam needs to be passed at an angle to the flow. Ideally one would pass the laser perfectly parallel to the flow, but there are practical limitations in doing this. So the laser is passed through the flow at the smallest practicable angle to the flow direction for the highest precision. When a light beam passes through an absorbing gas particle travelling at an angle relativeto the beam, there is a component of the particle's velocity in the direction of the light beam. This component causes a Doppler shift in the absorption frequency, that is, absorption happens at a frequency Doppler shifted from the line centre frequency. If u is the velocity of the gas flow and θ is the angle between the flow direction and the beam, then the Doppler component of the velocity of the particle in the light beam's direction is given by

$$u_D = u \cos\theta \tag{11}$$

and the Doppler shift is given by

$$\Delta\nu_D = \nu_o \frac{u_D}{c} \tag{12}$$

where ν_o is the un-shifted laser frequency and c is the velocity of light. This effect is schematically shown in Figure 1. The above equation can be directly used to retrieve the velocity of a uniform gas flow from the Doppler shift observed in the peak of a measured absorption line.

3 Tunable Diode Laser Absorption Spectroscopy

In tunable diode laser absorption spectroscopy, a narrow-line width monochromatic diode laser is used as the light source. The frequency of this diode lasers is scanned across an absorption transition (or multiple transitions) of the targeted species, and the transmitted intensity is monitored using a photodetector to calculate the absorbance at each point of time. The detector is usually a photodiode or a combination of photodiodes with a high speed amplifier. TDLAS

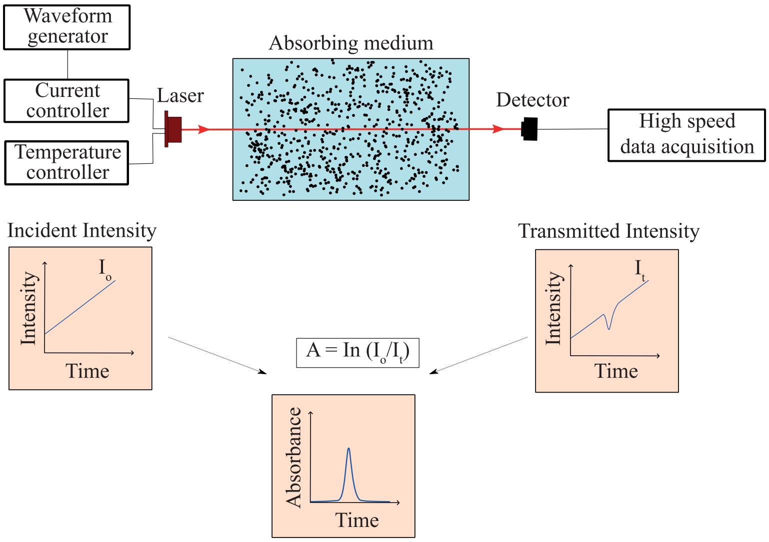

Figure 2: A basic conceptual diagram of TDLAS set up. The graphs represent the incident and transmitted intensities when a ramp current is used to drive the laser and the dip in the transmitted intensity shows the region where absorption occurs.

is a species-specific technique. Components such as laser source and detector in a TDLAS system are chosen based on the frequency of the targeted absorption transitions in the species analysed. The time-resolved absorption is then converted into the wavelength domain by a calibration of the current-wavelength curve of the laser. TDLAS is better in resolution compared to conventional monochromator-based spectroscopic techniques due to the narrow line-width of diode lasers.

Broadly speaking, TDLAS can be of two types – scanned-wavelength and fixed-wavelength. The scanned-wavelength strategy involves tuning the laser's wavelength as mentioned above. For a fixed-wavelength strategy (Baer et al., 1996), the laser frequency is fixed at a particular value, most often at the resonant frequency of the transition, and absorption at that particular frequency is monitored. This makes it possible to conduct measurements at very fast rates, theoretically limited only by the bandwidth of the detection system, which includes a photodetector, an amplifier circuit, and an analog-to-digital converter, and not by the scan rate of the laser. However, fixed-wavelength strategy needs to be used with care since it assumes that absorbance is solely responsible for changes in measured intensity. Any change in the baseline signal, or drift in the wavelength of the measurement, will cause a systematic error unless they are corrected for, and, the laser wavelength needs to be precisely stabilised in order to perform this strategy, especially when the absorption lines are narrow. Therefore, in most practical applications the scanned-wavelength strategy is used, as it automatically provides a value for peak absorbance and background offset.

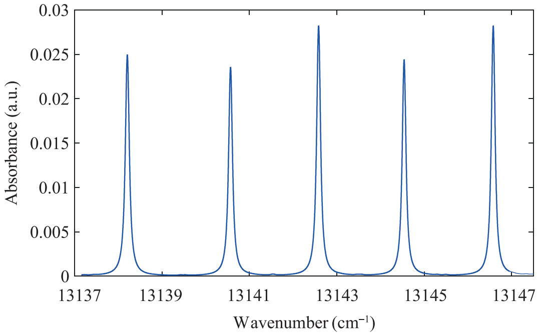

Figure 3: A simulated absorption signal of oxygen molecule near 760.6 nm (~ 13147 cm^{-1}) at room temperature and atmospheric pressure.

The wavelength of a diode laser can be scanned by modulating the laser injection current (driving current), operating temperature or, in the case of a grating-stabilised external-cavity diode laser, by changing the angle of the feedback grating. Current modulation is the most commonly used method due to fast wavelength response of the laser to variations in injection current. High speed modulation is particularly important for applications in hypersonic impulse facilities, where a fast scan rate is required to obtain sufficiently time-resolved flow parameters. A simple schematic representation of TDLAS is shown in Figure 2, and a simulated absorption spectrum of oxygen consisting of six absorption peaks near 760.6 nm at room temperature and pressure is shown in Figure 3.

Figure 4: Images of free-space (left) and fiber-coupled (right) Vertical-Cavity Surface-Emitting Lasers (VCSELs), indicating their compactness.

4 Laser Sources

Diode lasers are convenient light sources for high speed spectroscopy because of their narrowband spectral emission, high-speed tunability, small size and low power-consumption. Although their output powers are relatively small, the output power per unit linewidth is high and can be modulated at high rates.

Fundamental absorption bands of molecules that lie in the mid-IR region, between ~2.5 μm to ~25 μm, are strongly absorbing. However, continuously tunable diode lasers and fast detectors that work at room-temperature conditions are rarely available in this wavelength region. In the recent decade, quantum cascade lasers have been popular sources for this mid-IR region. More complex non-linear techniques such as Difference Frequency Generation (DFG) can be used to produce laser radiation in the mid-IR region (Petrov et al., 1995). These techniques are still being researched to achieve convenient features such as tunability, narrow linewidth, room-temperature operation and high output power.

In contrast, diode laser sources and detectors for near-IR region, ~700 nm to 2.5 um, are widely available in the market. While these near-IR bands, which mostly constitute overtones of the fundamental bands of molecules, are weaker than those in the mid-IR region, the availability of inexpensive continuously tunable lasers in this region has made these bands popular for diagnostic applications. The most common diode laser sources for TDLAS, which emit in the near IR region include Fabry-Perot (FP) lasers, distributed feedback lasers (DFB), vertical-cavity surface-emitting lasers (VCSELs) and external-cavity diode lasers (ECDLs). FP lasers are limited in their wavelength scanning range, and are often useful to scan only one absorption line. While ECDLs have higher output power and larger wavelength tuning range, they are limited by the scanning rate since they use electro-mechanical components for scanning wavelength. DFBs and VCSELs have been the most popular diode lasers used for TDLAS. DFBs have higher output power compared to VCSELs. However, VCSELs have other advantages over DFBs including larger wavelength tuning range, circularly symmetric beam profile, low divergence and low power consumption. Due to their larger wavelength scan range, multiple lines of a single species or of different species can be scanned using a single laser, providing much more spectral information using a single laser (Lackner et al., 2003). MEMS-VCSELs (Kogel et al., 2007; S. Schilt et al., 2010), which combine VCSEL technology with Micro-Electro-Mechanical Systems (MEMS) were developed recently; these lasers have much larger wavelength coverage (even greater than 100 nm) compared to normal VCSELs, which make them an interesting source for detecting multiple species.

5 Detection Schemes

Different detection techniques can be used in TDLAS, depending on the specific requirements of an application. The choice is determined based on different criteria, the most important of which are sensitivity, speed (rate of spectral acquisition), ruggedness, complexity in electronic design, expense and available space in the application of interest. A brief description of each technique is given below.

5.1 *Direct absorption*

Direct absorption is the simplest among all detection techniques. In direct absorption, the laser wavelength is scanned over the wavelength region corresponding to an absorption transition, and the transmitted intensity is directly monitored using a photodetector. This intensity is compared with the incident (unabsorbed) intensity to calculate absorbance using Equation 4. This detection method is suitable only for applications where absorbance is large. In the case of weakly absorbing species, reduction in laser intensity due to absorption is much smaller than the incident laser intensity. Therefore, most of the dynamic range of the analog-to-digital converter in the detection system is used to record the DC offset in the absolute laser intensity, rather than the actual absorption feature. If the absorption is very weak, then bit noise may dominate the absorption spectrum. Furthermore, laser intensity noise has a direct effect on the detected signal, so the signal-to-noise ratio is not great compared to other detection techniques. However, due to its simplicity and speed, which is limited only by the detector and data acquisition, direct absorption is still widely used in a lot of practical applications.

5.2 *Difference amplification*

In difference amplification, a laser beam is split into two components using an optical beam splitter. One of them passes through an absorbing sample and is detected by a signal photodiode. This is the signal beam (sometimes referred to as probe beam). The other beam is directly detected by a reference photodiode without passing through the medium. This is the reference beam. The difference between the photocurrents from these photodiodes represents the absorbed intensity I_a. This signal is amplified and used to calculate the absorbance using the equation:

$$A = \ln\left[\frac{I_r}{I_r - I_a}\right] \tag{12}$$

Here, I_r is the reference beam intensity. When the beams are perfectly balanced, the reference beam intensity will be equal to the laser intensity incident on the sample, and the difference absorption signal will have its baseline at zero. The reference beam intensity is usually recorded separately by blocking the sample beam. This reference signal can introduce additional noise but this problem can be minimised by taking the averaged reference signal over several scans.

Difference amplification has two main advantages over direct absorption: 1) Most of the laser excess noise will cancel out at the difference amplifier when the split laser intensities are perfectly balanced, and 2) Since the DC offset in the laser intensity is removed in the process of subtraction, most of the dynamic range of the detection system can be used to record the absorbed intensity, rather than the absolute laser intensity itself. The disadvantage is that the beams need to be perfectly balanced throughout an experiment in order to minimise errors. Also, the absolute laser power is reduced at least by half during splitting and balancing, which reduces the signal-to-noise ratio.

5.3 *Frequency modulation spectroscopy (FMS)*

Frequency modulation spectroscopy is a high-sensitivity heterodyne technique (Bjorklund, 1980; Silver, 1992), where a laser beam is modulated at a radio frequency. The modulating frequencies used are larger than the full width at half maximum (FWHM) of the absorption feature of interest, so that side bands are formed away from the absorption frequency. One of the side bands can then be used to scan the absorption feature to obtain an absorption spectrum. Detection is carried out at the beat frequency of the side band against the carrier frequency. Modulation can be realised either using an external phase modulator (Bjorklund, 1980) or by directly modulating the injection current of a diode laser (Kobayashi et al., 1982). Sensitivity of this technique is decided by the wavelength tuning characteristics of the laser, the absorption linewidth, and the detection bandwidth.

Complexities involved with the calibration of detection parameters is a drawback of FMS, especially in applications where the absorption profile varies largely with time. In addition, very fast lasers that have high laser power and can undergo large modulation depths are required to obtain good quality spectra while probing atmospheric-pressure-broadened peaks and multiple absorption peaks. Given that the laser is scanning over transitions several GHz in width, detectors of very large bandwidth are also required when the modulation rates are high.

5.4 *Wavelength modulation spectroscopy (WMS)*

Wavelength modulation spectroscopy has been a popular alternative to FMS in applications that require high-sensitive detection. WMS is actually a special case of frequency modulation spectroscopy (Bomse et al., 1992), in which the modulation frequency is much lower (by orders of magnitude) than the FWHM of the absorption line. In this technique, a high frequency sinusoidal modulation is overlapped on the current ramp that is used to scan the laser wavelength, so that the wavelength has an additional sinusoidal modulation while it scans over the absorption feature of interest. Both, the fundamental and side bands, are scanned over the transition. Typical modulation frequencies in WMS are less than 10 MHz while it varies from hundreds of megahertz to several gigaHertz in the case of FMS. The detected signal is then decomposed into its harmonic components, mostly using a lock-in amplifier, and detection is conducted at one of these harmonics. Most of the time, second harmonic is used for detection. This is because, compared to the first harmonic, it is less sensitive to amplitude modulation, which is not a desired effect in WMS. At the same time, the second harmonic is still strong enough to be easily detectable compared to higher harmonics. It has been shown that measurements using 1f-normalised 2f signal has the ability to effectively reject non-absorption-related signal fluctuations and improve the sensitivity of velocity and temperature measurements (Rieker et al., 2009).

WMS removes the background slope in the baseline of the laser intensity and any DC offset in the signal due to background luminosity or DC offset in the injection current. Since detection is conducted at the modulation frequency, most of the 1/f laser noise is also removed. Therefore, it provides an improved signal-to-noise ratio compared to direct absorption and difference amplification. However, this technique also requires complex detection electronics and becomes difficult to implement using off-the-shelf components for applications like a short duration high speed flow facility where laser scan rates above 10 kHz are preferred, as the modulation frequency in WMS needs to be orders of magnitude higher than the laser scan frequency.

5.5 *Log-ratio detection*

A log-ratio amplifier circuit can output a signal which is proportional to the logarithm of the ratio of two currents input to it. Hence, if a laser beam is split into a signal beam and a reference beam which are perfectly balanced, and if the signal and reference photocurrents are supplied to a log-ratio circuit, the output should be directly proportional to absorbance according to its definition from Equation 4. This detection method was introduced to TDLAS as a balanced ratiometric detector (BRD) (Hobbs, 1991), and was later exploited by other researchers for high-sensitivity detection in combustion flows and aerodynamic applications (Miller et al., 1996; Upschulte et al., 1999). Hobbs' BRD circuit consisted of an auto-balancing feedback loop that automatically adjusts the input currents, so that any DC offset in the baseline of the signal caused due to imperfect balancing is removed. Since the magnitude of laser excess noise transmitted to the output signal is proportional to the magnitude of imbalance in the input photocurrents, this strategy helps to increase the signal-to-noise ratio without having the requirement for perfect manual balancing of the split laser beams. Near-shot-noise-limited absorption measurements have been achieved using this technique (Allen et al., 1995; Hobbs, 1997). However the output voltage of Hobbs' circuit is given by

$$V = G\ln\left[\frac{I_o}{I_t} - 1\right] \tag{13}$$

Hence, the output is not directly proportional to the absorbance, and needs post-processing to obtain the actual absorbance. Other log-ratio circuits that give output directly proportional to absorbance, but which do not use the auto-balancing strategy, have also been used.

As for difference amplification and modulation spectroscopy, the output of the log-ratio detector removes the laser intensity ramp, and hence, the dynamic range of the detection system can be more efficiently utilised. One of the disadvantages of the log-ratio circuit has been its limited bandwidth, especially when low-power lasers are used, because the bandwidth of log-ratio amplifier circuits are low at small input photocurrents. In addition, non-common-mode interference due to stray

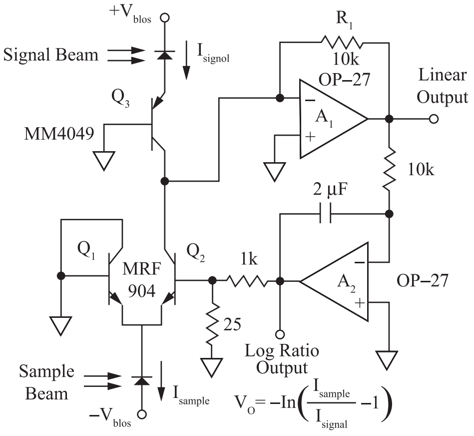

Figure 5: The schematic diagram of a fully functional version of Hobb's circuit (Hobbs, 1991). The term 'sample beam' used in this figure corresponds to 'reference beam' in this paper.

light falling on the detector while working with luminous applications, has been found to cause significant baseline distortion and systematic error in the measured absorption spectrum when low-power lasers are used. A correction method to overcome this problem is discussed in Krishna et al. (2014).

6 Applications in Combustion and Aerospace Research

The non-intrusive nature of TDLAS has been exploited in a wide range of applications. These include chemical (Schilt et al. 2006), biological (McCurdy et al., 2007), industrial (Linnerud et al. 1998), atmospheric (Schiff et al. 1994) and environmental-monitoring (Griffis et al., 2004) applications as well as plasma diagnosis (Röpcke et al, 2006). There have been hundreds of publications written on different applications of TDLAS. Only some papers relevant to high speed flows will be addressed here.

Research on application of TDLAS in combustion flows and aerodynamic research was pioneered by, and continues to be used by, Professor Ronald K. Hanson and his peers at Stanford University (Hanson et al., 1977; Hanson & Jeffries, 2006). In particular, the method of measuring temperature from the ratio of two absorption lines with different ground-state energies (Hanson & Falcone, 1978) has been widely used in combustion research. Combustion in engines can be monitored by measuring the temperature and mass flow rate of combustion products. Research on turbo fan/gas turbine engines (Zhou et al., 2007) and supersonic combustion ramjet (scramjet) engines has particularly gained from this technique, especially in recent years (Griffiths & Houwing, 2005; Li et al., 2011; Schultz et al., 2014; Schultz et al., 2014b; Upschulte, 2000). While most of these works in scramjet has been focussing on exhaust and combustor diagnosis, research focussing on monitoring of scramjet inlet flows (Krishna et al., 2015; Kurtz et al.) is also finding interest because the inlet flow properties such as temperature distribution, angle of attack and velocity can critically affect the combustion process that occurs further downstream. Diode laser spectroscopy has also been used to characterise flow conditions in ground testing facilities such as shock tubes, wind tunnels and reflected shock tunnels (Krishna et al., 2015b; Lyle et al., 2007; Philippe & Hanson, 1991; Wehe et al., 1998).

The real significance of TDLAS sensors lies in the fact that they can be easily integrated into real flight parts. Flight sensors based on TDLAS have already been tested successfully. Successful integration of TDLAS sensors into the flight hardware of Hypersonic International Flight Research Experimentation (HiFire) Flight-1 (Brown & Barhorst, 2011; Sappey et al., 2009) and SCRAMSPACE scramjet flight test (Kurtz et al., 2015) has shown the ruggedness of such sensors in harsh flight environments. Both sensors targeted oxygen absorption lines near 760 nm, rather than water vapour. This is because of the low concentration of water vapour at the heights aimed (~30 km) for in these flight tests. Development of in-situ flight-capable sensor systems for real flight applications involves careful characterisation of components and intelligent engineering to overcome constraints imposed by temperature fluctuations, weight, power consumption, vibration and limited space.

Many of the above-mentioned research examples focus on water vapour as the target species, since it is a major combustion product and has strong absorption features in near-IR region. CO_2 has also been an important target species for many works since it is also a combustion product. Martian atmosphere can also be studied by using carbon dioxide (CO_2) as the test gas in a shock tunnel. CO_2 has strong absorption features near 1.6 µm, 2 µm and 2.7 µm (Meyers & Fletcher, 2011). Ammonia, carbon monoxide and methane have also been targeted in various applications. The current focus of research involves simultaneously measuring flow properties of different species by multiplexing different wavelengths using optical fibre technology, in conjunction with high-sensitivity modulation techniques.

One of the fundamental limitations with TDLAS is that it is path-integrated, and provides only minimal information about spatial distribution of properties. More complex variations of TDLAS such as 2-dimensional (2D) TDLAS, tomography and data analysis methods such as distribution fitting have been used to overcome this limitation. In TDLAS tomography, a laser beam is split into several optical fibres and transmitted through a non-uniform sample at various angles or/and locations of the sample. These beams are detected using an array of detectors, and a tomographic reconstruction of the distribution field is carried out from these spectra (Liu et al., 2012). In distribution fitting technique, a pre-knowledge about the nature of property distribution along the beam path is used to model the path-integrated absorption spectrum and a least-squares fitting is conducted using this absorption model with the unknown parameters as the independent variables (Sanders et al., 2001; Villareal & Varghese, 2005). All these methodologies work better if we have more ‘spectral information’ in our data, which indicate the importance of scanning over a maximum number of lines.

It is hoped that, with advancement in laser technology, tunable diode laser sources with higher optical power, faster scan rates and larger tuning range will be available in the market. New detectors and detection schemes should be developed to push the current limits of speed and sensitivity. New wavelength regimes also need to be explored to detect other molecular species. This is a continuing process that needs support from research in laser materials and electronics.

7 Conclusion

Tunable diode laser absorption spectroscopy (TDLAS) has emerged as a viable technique to make compact flow sensors for practical flow diagnostic applications. Due to a unique combination of features such as high resolution, fast scan rate, ruggedness, low power consumption, compactness and relatively inexpensive components, TDLAS stands out as a convenient sensor technology to study hostile flow environments such as shock tunnels and engine parts. With advances in laser technology and detection techniques, TDLAS is expected to push its limits to obtain better quality spectra of a variety of absorbing species in high speed flows and combustion facilities.

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