Multi-species gas sensing using monolithic widely tuneable laser diodes.

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ABSTRACT

Widely tuneable laser diodes operating in the $1520 \leq \lambda \leq 1570$ nm are characterised and compared for use as sources for tuneable laser diode gas absorption spectroscopy. Three gases hydrogen cyanide, ammonia and acetylene with overlapping absorption features within the 50 nm tuning range of the devices were targeted employing wavelength modulation spectroscopy with second harmonic detection.

Keywords: Tuneable laser, wavelength modulation spectroscopy, gas sensing

1. INTRODUCTION

Widely tuneable single frequency lasers, such as sampled grating distributed Bragg reflector and modulated grating Y-branch laser diodes recently developed for optical communications, present exciting opportunities for applications in absorption based multi-gas sensing regimes. Such wide wavelength tuning is not possible with conventional single frequency distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers, and hence their use is limited to the detection of one gas. Widely tuneable laser diodes are more complex than standard DFB lasers used for single-species gas sensing and have undesirable artefacts in their operating characteristic. The tuning ranges of the widely tuneable lasers have been characterised and look-up tables, which yield high wavelength accuracy and high SMSR across the tuning range.

The use of widely tuneable laser diodes as sources in a multi-gas analysing system using wavelength modulation spectroscopy and second harmonic detection of acetylene hydrogen cyanide and ammonia have been investigated. The critical issues relevant to the application of such widely tuneable diode lasers to spectroscopic based high selectivity multi-gas sensing are outlined. The general emphasis of the work described here is not on detection limits but to selectively detect three gases with overlapping absorption bands.

2. EXTENDING THE TUNING RANGE OF DBR-TYPE LASERS

The tuning range of conventional DFB and DBR lasers is approximately 5-10nm which is significantly smaller than the available gain bandwidth of multiple quantum well semiconductor lasers (more than 100nm) and Erbium doped fibre amplifiers (about 40nm in the C or L band) [1]. Consequently, much research has targeted the development of integrated lasers with extended tuning ranges beyond the refractive index limit [2-4]. The basic principle behind all schemes that have been developed for wide tuning is that a refractive index difference is changed rather than the index itself. Therefore, the relative wavelength change is equal to a relative change in index difference, which can be significantly larger for similar absolute refractive index variations. In the following sections we will describe the most common scheme for achieving the broad tuning range.

2.1 Vernier effect between two comb reflectors

The Vernier caliper is a well-known instrument for high-resolution length measurement. The same principle can be applied to a tuneable laser (Fig. 1) if the laser has two mirrors with a comb-shaped reflectivity spectrum. The mirrors are designed such that the peak reflectivity spacing of the front mirror (δ_f) and the rear mirror (δ_r) differ by a small amount.

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McGlynn, McLaughlin, O'Sullivan, Ryder, Walsh, Eds., Proc. of SPIE Vol. 5826
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Lasing can then only occur in the frequency range where the two peaks coincide, since the round-trip loss is inversely proportional to the product of both mirror reflectivities. The phase section can be used to adjust the longitudinal modes, such that a mode can be aligned with the loss minimum. The coincidence of two particular peaks is often called a "super-mode" and the large frequency changes observed when applying the Vernier tuning mechanism are consequently called super-mode jumps. Intermediate tuning, from one longitudinal mode to the next, is obtained by tuning both reflectors simultaneously. Quasi-continuous tuning over a wide tuning range involves the synchronised adjustment of both the reflectors and the phase section.

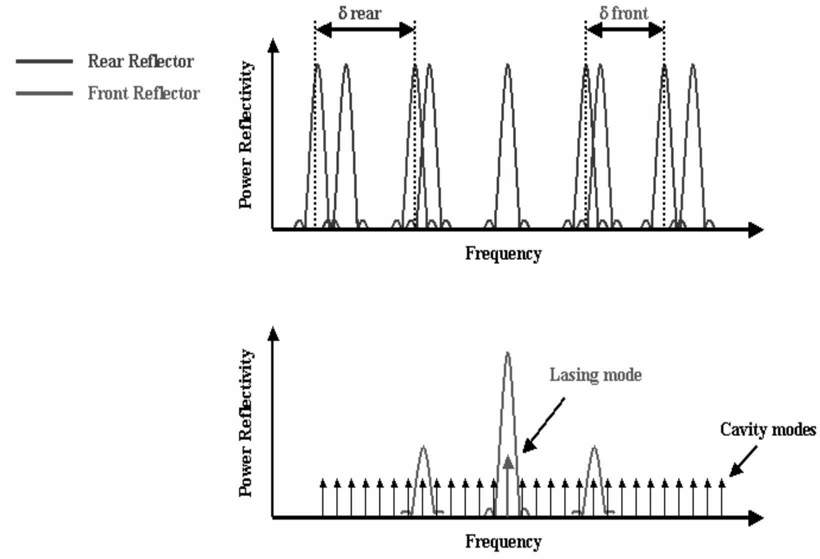


Figure 1: Vernier principle applied to a tuneable laser which has two mirrors with comb-shaped reflectivity spectrums with different pitches. Lasing occurs in the frequency range where the reflection peaks coincide.

2.2 Sampled Grating DBR

The sampled grating DBR (SG-DBR) laser consists of four independently biased sections; two sampled gratings, a passive phase section and a gain section as illustrated in Fig. 2. A "sampled grating" consists of a conventional uniform grating with elements periodically removed along its length. This sampling of the grating gives the mirrors a comb like reflection spectrum with multiple equally spaced peaks [5]. The mirrors are designed such that the peak separation of the front grating (δ_f) and the back grating (δ_r) are slightly different. The laser will then operate at the wavelength of the cavity mode that falls within the wavelength band where a reflectivity peak of the front grating overlaps a reflectivity peak of the back grating. The phase section is used to precisely align the cavity mode with the coinciding reflectivity peaks. This permits the use of the Vernier effect to achieve wide quasi-continuous wavelength tuning.

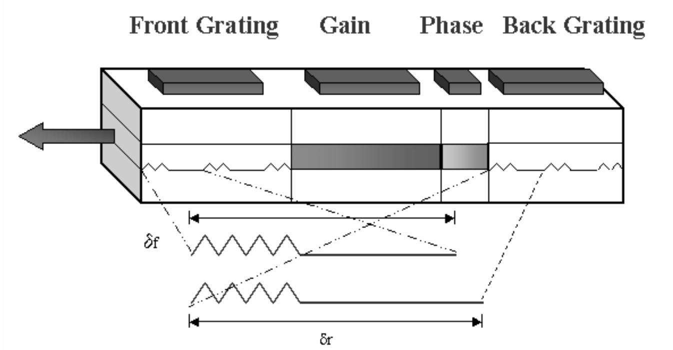


Figure 2: Four section SG-DBR laser diode consisting of two sampled grating regions a phase section and a gain section. The front and back grating sections have different periods.

2.3 Modulated Grating Y-Laser.

One of the main disadvantages with the SG-DBR is that light has to propagate through the front reflector to exit the laser. The output power will vary a lot more with tuning in these devices due to free carrier absorption in the front reflector. In the MG-Y laser this is overcome by placing the two comb reflectors on the same side of the cavity when put in the Y-branch configuration, as illustrated in Fig. 3.13, this is the concept of the MG-Y laser [6].

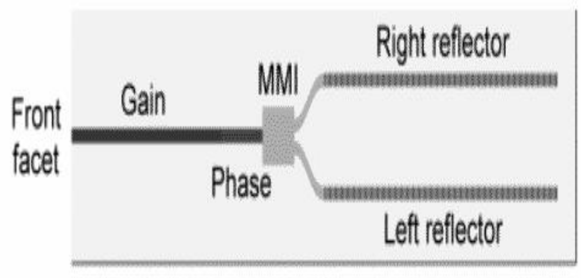


Figure 3: Top view schematic of the MG-Y Laser [6].

In the MG-Y laser the different functions are separated into different sections (Fig 3). The gain section amplifies the light, multi-mode interferometer (MMI) splits the light into 2 equal beams, bends increase the separation between the waveguides and the reflectors filter out certain frequencies. The additive Vernier effect is used to select one lasing wavelength. Both reflectors have slightly different peak spacing so the frequency where both peaks overlap will reach the laser threshold first. A higher side mode suppression ratio can be achieved compared with the multiplicative Vernier effect (used with the SG-DBR), because the neighbouring peaks add partly out of phase.

3. ADVANCED STATIC CHARACTERISATION

Multi-species gas sensing using widely tuneable lasers poses unique challenges compared with telecommunications applications of these devices and also compared with state-of-the art single-species gas sensing. Wavelength control in a widely tuneable laser requires the alignment of reflection peaks from two grating mirrors with a cavity mode at the desired wavelength. This entails control of four separate currents to achieve complete wavelength coverage over the entire tuning range. Characterisation of these devices and selection of the optimum bias current operating points is important to demonstrate suitability for multi-gas sensing. These operating points will be selected on the basis of device linearity and distortion, output power and the ease of tuning to the relevant gas absorption lines.

The two control currents, which offer the most information with respect to characterising the laser devices, are the two coarse reflector-tuning currents. In the case of the SG-DBR these currents are the front and back grating currents (I_F, I_B), and for the MG-Y laser the left and right grating currents (I_L, I_R). The extended tuning ranges of the devices were measured using the experimental set-up illustrated in Fig 4.

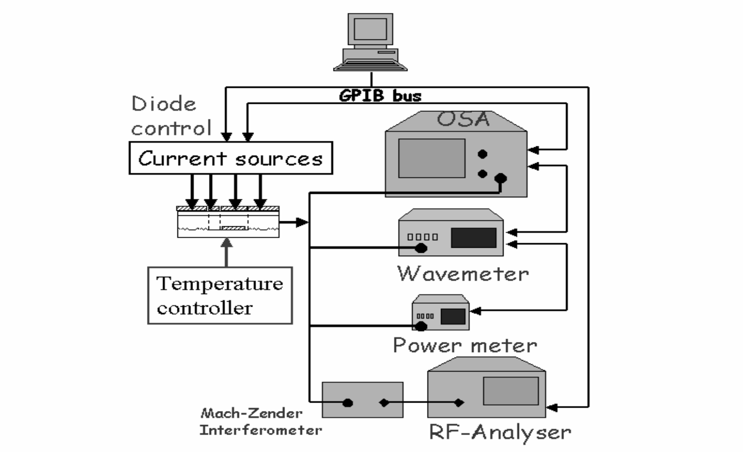
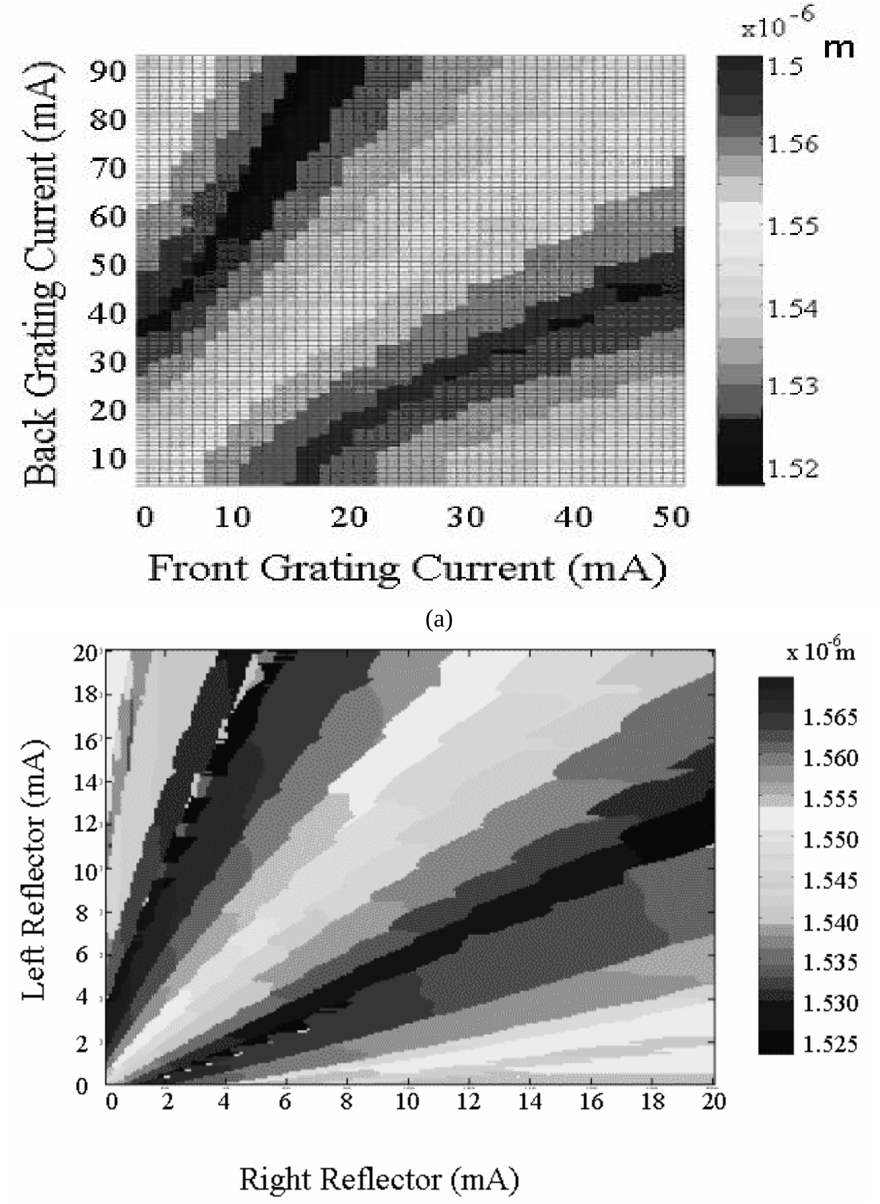


Figure 4: Experimental arrangement for measuring characteristics.

The current sources biasing the laser, the optical wavelength meter, optical spectrum analyser, RF analyser and power meter are controlled by a computer using a GPIB card. With this arrangement the coarse tuning currents are set autonomously and the power and wavelength are measured at each point. Fig 5 (a) is an example of a wavelength-plane for the SG-DBR as a function of the coarse tuning currents. The active section was biased at 120mA (I_G), no current was applied to the phase section and the heatsink temperature was fixed at 20^{o}C. As illustrated in Fig 5 (a), on the wavelength surface, several plateaus are apparent, each corresponding to the coincidence of a pair of reflectivity peaks of the two SG-DBR mirrors and termed a super-mode. Along the super-mode, smaller wavelengths hops can be observed, corresponding to cavity mode jumps. Fig 5 (b) is a plot of the wavelength plane for the MG-Y laser with the active section biased at 150mA, phase section left unbiased and a heatsink temperature of 25^{o}C. The contour plots in Fig 5 clearly identify eight super-modes per device with a wavelength tuning range between 1520-1570nm, which is equal to the repeat mode spacing of 50nm. The repeat mode wavelength spacing occurs when the overlap of the reflection spectra of both grating reflections repeat. The contour plots contain all the relevant information for setting the emission from the laser to a specific wavelength, output power and SMSR. Any point on these contour plots can be selected with the correct front and back grating current combination. From a practical point of view it should be possible to set the laser wavelength to a certain wavelength using simple digital commands. A computer should then translate these into the appropriate values of the lasers control currents. For this, a look-up table of operation points is needed.



(a)

(b)

Figure 5: (a) Emission wavelength of the SG-DBR laser as a function of the front and back tuning currents, I_F and I_B, at fixed phase current I_P = 0mA and active section current I_G =120mA (b) Emission wavelength of the MG-Y laser as a function of the left and right tuning currents, I_L and I_R, at fixed phase current I_P = 0mA and active section current I_G =150mA.

3.1 Spectral Linewidth

In any spectroscopic based gas detection application a knowledge of the system resolution is important. For tuneable laser diode absorption spectroscopy, in particular, it is desirable that the laser emission linewidth remains a factor of ten less than the gas absorption linewidth for all operating conditions of the laser. Typical gases of interest for laser absorption spectroscopy in the 1.5μm wavelength region have Doppler broadened linewidths of around 400MHz at room temperature. Since the laser output has a non-zero linewidth, a broadening of the measured absorption line will inevitably be present, especially in the low-pressure regime. The spectral width of the laser line arises due to fluctuations in the phase of the optical field [7, 8]. Fluctuations arise from two basic sources, a) spontaneous emission which alters the phase and intensity of the lasing field and b) carrier density fluctuations (unique to semiconductors).

3.2 Linewidth Measurements

Theoretically it can be proven that the linewidth has a Lorentzian distribution when written as a function of the optical frequency. The delayed optical heterodyne technique offers a very simple means to measure the linewidth of the laser. A Heterodyne technique configuration is shown in Fig 6, the key requirement for these measurements is a stable, narrow linewidth reference laser (100kHz). In this set-up, both lasers are mixed into a fibered coupler, its first output is connected to an optical spectrum analyser, which allows us to match approximately the two wavelengths. The reference laser (LO) is tuned to a frequency just lower than the average frequency of the laser under study. This creates a heterodyne beat tone between the LO and each of the frequency components in the signal spectrum. The LO laser frequency had to be tuned to within 1GHz of the signal laser frequency to allow the mixing product to fall within the bandwidth of the detector.

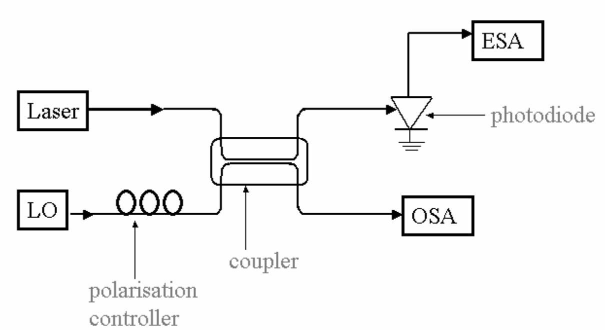


Figure 6: Schematic of the high resolution heterodyne experimental set-up for measuring laser linewidth using an external cavity laser for a local oscillator.

The resulting optical heterodyne power spectrum is illustrated in Fig 7. The lineshape was fitted with a Lorentzian profile and a linewidth of 2.88MHz was measured.

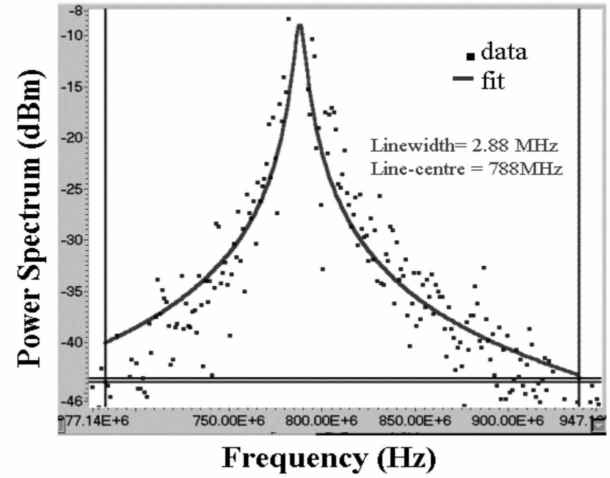


Figure 7: Optical heterodyne power spectrums of a SG-DBR I_{GAIN}=150mA all other sections are unbiased. Also shown is the fitted Lorentzian lineshape used to extract the linewidth.

4. APPLICATION TO GAS SENSING

The aim of this section is to detail the detection of multiple gases using widely tuneable laser diodes (SG-DBR, MG-Y) in a WMS detection scheme. Many gas species have overtone and combination bands in the near infrared region of the spectrum. Some of these gases with overtone/combination bands in the near infrared are shown in Fig. 8. All of these gases have been detected using single frequency telecom lasers, using WMS or FMS with harmonic detection. These high sensitivity detection techniques are particularly required in gas sensing applications at near infrared wavelengths since absorption band strengths are significantly less than in the fundamental absorption band regime. However, since the DFB laser diode has a narrow wavelength tuning range, only one gas can be targeted per device except where absorption features overlap [9]. This multiple device system quickly becomes complex and costly which is undesirable for implementation in a sensor for industrial applications as the number of gases to be detected increases [10]. Replacing all of these DFB lasers with a single widely tuneable laser device will reduce the complexity of the detection system. The chosen targeted gases, C_2H_2, HCN and NH_3 all have overtone and combination bands in the 1.55μm region of the spectrum.

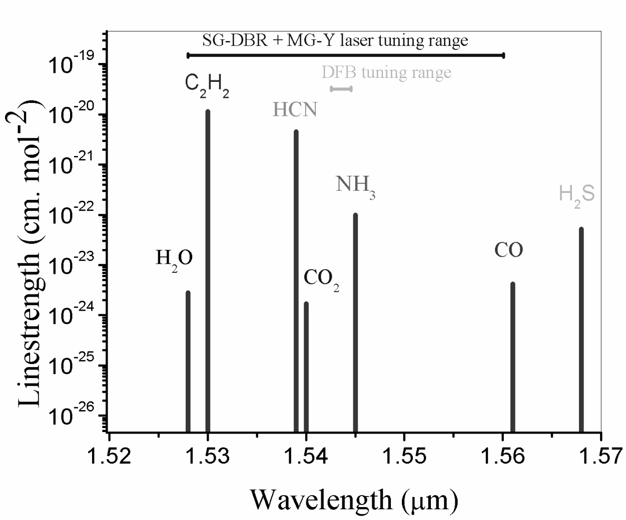


Figure 8: Absorption lines of some environmentally important gases in relation to the tuning ranges of widely tuneable lasers

The vibrational overtone/combination absorption line-strengths of gases in the near-infrared region of the spectrum are significantly less than the fundamental line-strengths in the mid-infrared. Hence high sensitivity wavelength modulation spectroscopy (WMS) techniques were used for the simultaneous detection of HCN, NH_3 and C_2H_2 described here [11]. WMS is a well-known technique for high sensitivity optical absorption measurements by use of diode lasers. Its advantage over direct detection is that it shifts the detection to higher frequencies where the *1/f* laser excess noise is reduced. It also removes much of the base-line slope seen in direct detection. A schematic of the experimental arrangement for multi-gas detection is shown in Fig. 9. The set-up includes a system for WMS with second harmonic detection and an etalon for spectral analysis of the widely tuneable laser output. The fibre-coupled output from the laser was split into five paths (referred to as first, second, third, fourth and fifth paths), using two 1x2 and one 1x3 fibre splitter. The first three paths were sent through the individual gas cells and onto InGaAs photodiodes. The gas cells with fibre input and output are 16.5 cm in length and contain 50 mbar HCN, 50 mbar NH_3 and a combination cell containing 5 mbar C_2H_2 and 5 mbar HCN, this calibrated gas mixture is thus convenient for demonstrating simultaneous detection of both HCN and C_2H_2. It was not possible to include NH_3 in this gas cell due to its polar nature, which makes it a very "sticky" molecule that adsorbs to most surfaces [12]. The fourth path was directed onto a detector to record the reference intensity. The fifth beam was collimated and sent through an etalon with a FSR of 18.61 pm and onto a InGaAs detector to monitor the laser-tuning rate. To reduce back reflections of the laser light from the fibre-to-air interface in the connectors, angle polished connectors (APC) that have a return loss of 60 dB were used. Furthermore to reduce Fabry-Perot effects in the fibre-lens-gas cell interface, the cell was equipped with wedged (0.5 degree) glass windows. Also the cell windows are coated with a broadband anti-reflection coating.

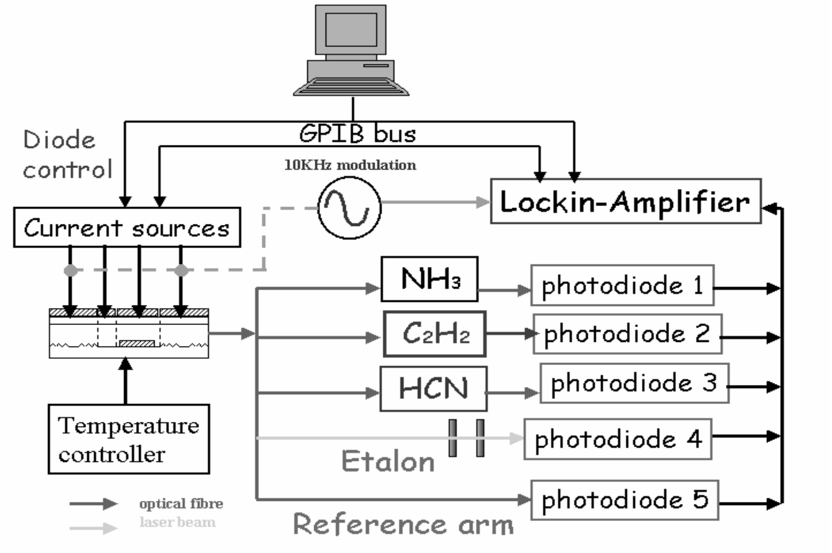


Figure 9: Experimental arrangement

4.1 Simultaneous multiple-species gas sensing

The target gases HCN, C_2H_2 and NH_3 all have overlapping absorption bands within the tuning range of the lasers. The ability to selectively detect three gases with overlapping absorption bands by accurately tuning the emission wavelength of the SG-DBR and MG-Y laser to a position where individual absorption lines do not coincide is now demonstrated. The emission wavelength of the SG-DBR and MG-Y laser was tuned across the absorption bands of the three gases from 1529 to 1560 nm at a modulation frequency of 10 kHz. The *2f* outputs from the lock-in amplifier are displayed in Fig 7 for the SG-DBR and Fig. 8 for the MG-Y laser. The spectra shown in Fig. 10 and Fig. 11 were not optimised for sensitivity but for selectivity so as to resolve all the absorption lines as effectively as possible.

Over limited tuning regions between mode-hops across the scan, the laser tunes continuously and performs similarly to single-section DFB laser diodes, so we expect detection limits to be similar. Fig 10 and Fig. 11 display regions where overlapping absorption lines do not coincide thus enabling multi-gas sensing. When the regions where the spectra of the individual gas absorption lines do not coincide are identified, the emission wavelength of the laser can be switched to any number of lines where the peak height can determine the concentration. This is a powerful demonstration of high specificity gas sensing achievable using widely tuneable lasers by probing specific rotational features in the optical absorption spectrum of the target species.

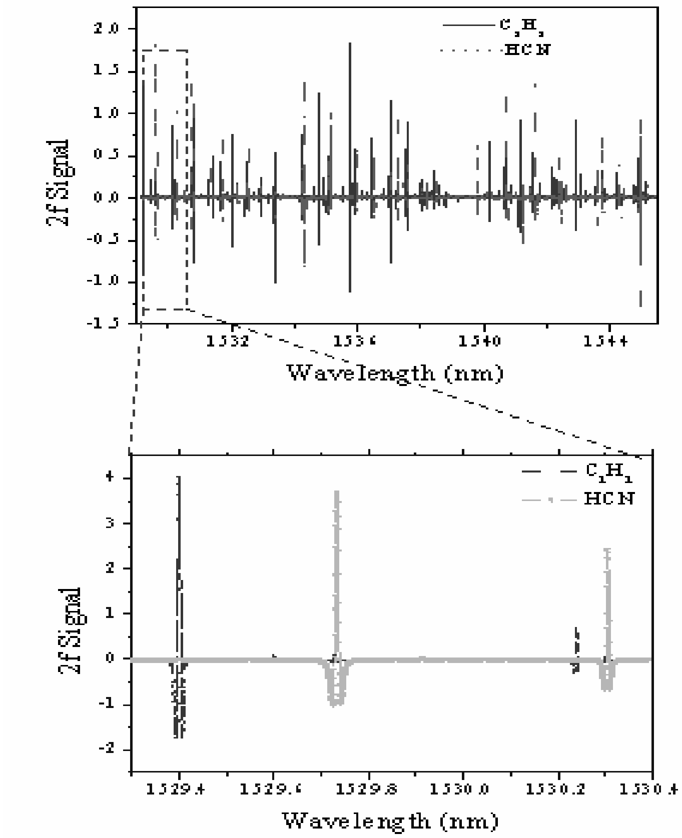


Figure 10: High specificity multi-species gas sensing enabling detection of NH_3, C_2H_2 and HCN by tuning SG-DBR laser to regions where absorption lines due to individual gases are well resolved.

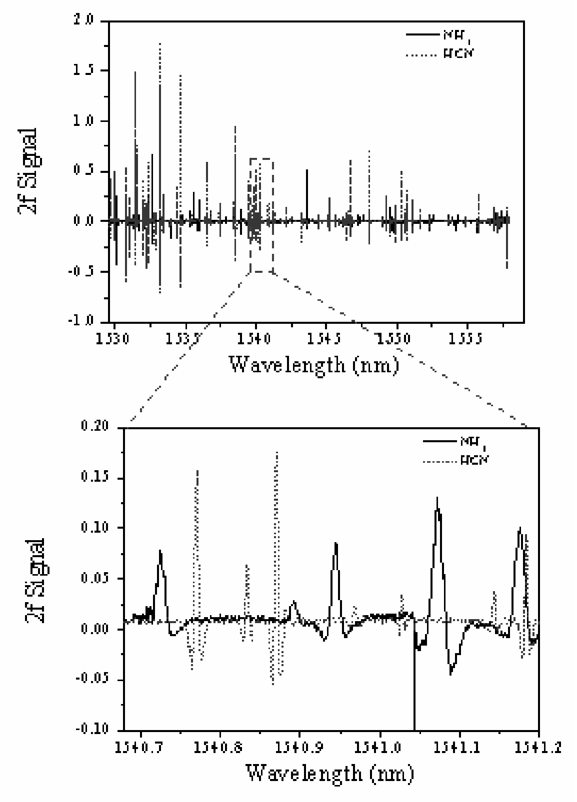


Figure 11: High specificity multi-species gas sensing enabling detection of NH_3, C_2H_2 and HCN by tuning MG-Y laser to regions where absorption lines due to individual gases are well resolved.

5. CONCLUSIONS

The work described here demonstrates the application of widely tuneable monolithic laser diodes, which were developed for the telecommunications industry, as tuneable spectroscopic sources in multi-gas detection systems. The ability to selectively detect three gases HCN, C_2H_2 and NH_3 with overlapping absorption bands demonstrates the high specificity achievable using widely tuneable lasers by probing specific rotational features in the optical absorption spectrum of the target species. This measurement is among the first demonstration of simultaneous detection of multiple species using a multi-section, injection current tuned MG-Y laser and is a promising demonstration of the possible usefulness of these lasers.

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