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Development of a portable carbon monoxide optical sensor based on an extended cavity diode laser at 1564 nm

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ABSTRACT

Carbon monoxide (CO) is a major trace gas pollutant with road traffic being responsible for most emissions. Tunable diode laser absorption spectroscopy will be used to measure CO in vehicle emissions, thereby identifying offenders. A portable device will be constructed, which is capable of measuring CO at concentrations of 10 ppm. Design emphasis is on using low cost commercial components. An extended cavity diode laser (ECDL) will be used offering a narrow line width (» 350 kHz) and operated at 1564 nm (near infrared) to allow detection of the CO line R(13). This wavelength has been selected primarily because commercial optics components designed for the telecommunications industry at 1550 nm are readily available and relatively inexpensive. A potential tuning range of 20 nm about the central wavelength for the ECDL also offers potential for detection of other combustion related, gas species in this spectral region using the same diode laser. Novel optical arrangements allowing longer absorption path lengths and hence increased sensitivity of the CO sensor will be investigated. In addition to road traffic pollution measurements, the device will be adapted for use with fibre optic technology, to facilitate air quality measurements in remote locations e.g. stack emissions.

Keywords: environmental spectroscopy, extended cavity diode laser, carbon-monoxide, sensors

1. INTRODUCTION

In urban areas, road traffic is the dominant source of CO emissions. CO emissions are highest for engines at idle and decrease with increasing vehicle speed. The exception to this is non-catalyst vehicles travelling at speeds in excess of 100 km/h which experience substantial emissions.[1] Guideline values for CO as published by the World Health Organization (WHO) in 2000 are: [2]

100 mg/m^3 = (90 ppm) for 15 minutes,
60 mg/m^3 = (50 ppm) for 30 minutes
30 mg/m^3 = (25 ppm) for 1hour
10 mg/m^3 = (10 ppm) for 8 hours.

An effective CO monitoring device must be capable of functioning in a road side environment. The sensor under development should ideally be capable of monitoring CO at concentrations of at least 10 parts per million and be able to distinguish CO from other gaseous molecules and particulate matter. A suitable sensor will have to be small enough to be portable, work from a portable power supply and be able to function continuously for several hours without technical intervention. The sensor will also need to be of a robust design so that it may withstand vibrations from traffic and adverse weather conditions. Furthermore if it is intended to use the sensor to identify individual CO polluters it will have to be capable of operating in real time.

Tunable diode laser absorption spectroscopy (TDLAS) offers a suitable mechanism for the detection of CO with the capability of making measurements which are sensitive, selective and almost instantaneous. CO is an infrared active molecule which absorbs electromagnetic radiation at specific frequencies causing the CO molecule to vibrate and rotate. Illumination of a gaseous sample at one of these specific frequencies will reveal a drop in the transmitted light intensity if CO molecules are present. The light source used for this purpose must be highly monochromatic possessing a line width which is less than the width of the spectroscopic feature under investigation and semiconductor diode lasers are capable of satisfying this requirement. Semiconductor diode lasers are compact, low power devices and have found applications in a variety of optical systems e.g. (optical data storage and retrieval, laser pointers) as well as use in the telecommunications industry. Diode lasers have also become popular for use in atomic and molecular spectroscopy

when used in an extended cavity configuration. An extended cavity diode laser possesses several advantages over a free running commercial diode laser in terms of its spectral output namely, narrow linewidth, wider tunability, single longitudinal mode and hence higher power output. These characteristics make an extended cavity diode laser a suitable choice for the identification of carbon monoxide at concentrations of 10 parts per million using absorption spectroscopy.

2. EXTENDED CAVITY DIODE LASER

2.1 Semiconductor Diode Lasers

A laser is essentially an optical oscillator consisting of a resonant cavity, an amplifying medium and a pumping source. In semiconductor diode lasers, the cavity is created by the boundary between the cleaved face of the semiconductor crystal and air, and has reflective properties as a result of the differing refractive indices of the two media. For a GaAs-air interface a reflectance of 0.32 is typical and therefore the length of the semiconductor junction forms the resonant cavity. To prevent light being emitted in unwanted directions from the junction, sides perpendicular to the required direction are roughened. The electromagnetic field generated within the cavity is sensitive to the cavity geometry and length, which determines the transverse electric and magnetic field modes (TEM modes) and longitudinal modes. For a semiconductor diode laser the amplifying medium in its simplest form consists of a *p-n* junction in a doped semiconductor crystal operating in forward bias. Spontaneous emission of photons occurs when holes and electrons recombine (principle of operation of a light emitting diode). The wavelength range of the emitted photons is determined by the band gap of the semiconductor material. Lasing action is achieved by 'pumping' so that a sufficiently high current flows which creates a population inversion within the junction in terms of the electron and hole levels. A spontaneously emitted photon whose direction of travel is back and forward along the optical axis of the cavity will stimulate further photon emissions with the same direction and phase, while population inversion exists. Light leaving the cavity has now been produced as a result of stimulated emission and is monochromatic, intense and coherent in character.

2.2 Wavelength Choice

The choice of a suitable CO absorption line and an appropriate semiconductor diode laser is essential for the CO sensing device to work. While there are many possible absorption bands for CO not all lines are free from spectral interference from other gas species. In particular we require the CO absorption line to experience minimum interference from other molecular species such as CO_2 and H_2O. Having selected an absorption line it is not always possible to find a diode laser that will lase at the absorption wavelength required. The fundamental absorption for CO is centred at about 4666 nm (2143 cm^{-1}) but this is well beyond the range of semiconductor diode lasers. In this respect our choice was limited to the near infrared region to wavelengths starting at 2.3 μm where the lasing wavelengths of diode lasers correspond with the first overtone band for CO at about 2347 nm (4260 cm^{-1}). However the choice of laser was further constrained by the intention to construct a low cost device, therefore only commercial diode lasers were considered. There is less demand for diode lasers beyond 1.6 μm thereby making them expensive. The telecommunications industry favours devices operating in two spectral windows (1.31 μm and 1.55 μm). Therefore near infrared diode lasers at these wavelengths are more freely available and more competitively priced. The second fundamental absorption of CO in the 1.6 μm region conveniently coincides with the 1.55 μm spectral window. The second overtone band for CO has been well researched and line choice within this band is now determined by lack of spectral interference from other molecular species. Our absorption line choice is the CO line R(13) in the second overtone band of wavelength 1564 nm (6393.177 cm^{-1}). Work done by Mihalcea et al [3] has demonstrated that CO line R(13) has minimum CO_2 and H_2O interference. Work done by Sonnenfroh et al [4] also favours the 1.55μm spectral region because it corresponds to the location of weak overtone and combination band transitions for gas species such as CO, CO_2, OH and H_2O.

2.3 Diode laser Linewidth and Tunability

Absorption spectroscopy requires a light source, which has a narrow linewidth, is tunable across the range of the spectroscopic feature of interest and can maintain a steady wavelength for an indefinite period. Observation of the CO (R13) line requires our device to have a linewidth of less than 10 MHz and a tuning range of at least 10 nm. Fabry-Perot diode laser structure and cavity length affects these required laser output characteristics. A Fabry-Perot (FP) diode laser has a resonant cavity created by the reflectance at the ends of the semiconductor crystal. Several longitudinal modes can lase simultaneously appearing under the gain curve for the medium. The length of each mode and hence its wavelength, is dependent on the length L of the cavity since the Fabry-Perot condition for resonance is $m\lambda/2 = L$.

Typical cavity lengths are ≈ 250 μm which gives a free spectral range (length between successive longitudinal modes) of about 5 nm for 1564 nm. The cavity is very susceptible to changes in the optical path length due to temperature and current changes and while this is a disadvantage in terms of maintaining the same wavelength output, it can also be used to tune the wavelength of the diode laser. Temperature adjustment changes the effective refractive index of the media and shifts the gain curve, thence changing the resonant condition of the cavity. Unfortunately tuning is not continuous and longitudinal mode hops may be encountered making it impossible to tune a diode laser to a specific frequency. The injection current in to the device can also be varied. This changes the optical index therefore changing the lasing wavelength. The tuning range depends on the amplifying medium and the fabrication of the laser and is device dependent. The linewidth of a Fabry-Perot semiconductor diode laser is also typically broader than for other lasers (≈ 50 MHz at near infrared) because of the short cavity and low reflectance at the cavity ends. A diode laser with a distributed feedback (DFB) or a distributed Bragg Reflector (DBR) structure can solve this problem because they contain a grating inside the laser cavity allowing only one mode to be selected. A narrower linewidth is achieved but the tuning range of these devices is also less than for Fabry-Perot lasers making the device unsuitable for use in tunable diode laser absorption spectroscopy. The fabrication process required to introduce a grating structure into the laser cavity also makes DFB and DBR diode lasers prohibitively expensive for our purposes.

2.4 Extended Cavities

Optical feedback into the diode laser cavity from stray reflections is usually undesirable triggering lasing in more than one mode thereby inducing power instabilities and causing linewidth broadening. An extended cavity constructed around the diode laser is able to provide optical feedback into the cavity identical to the desired lasing mode, increasing the strength of the desired mode and suppressing the unwanted modes. The resulting single lasing mode has a reduced linewidth because the effective length of the cavity has been increased. Extended cavities also allow a greater mode hop free tuning range than can be achieved by a commercial Fabry-Perot diode laser alone. Different geometries for achieving an extended cavity are in existence but the most common arrangements are the Littrow configuration and the Littman-Metcalf configuration. Our experimental set-up utilises the Littrow configuration. The extended cavity is formed by the back facet of the diode laser and a grating which is held at an angle to the incident θ_i to the beam. The angle of the grating is chosen so that the first order diffracted beam has an angle θ equal to the angle of incidence. The first order beam is hence diffracted back into the diode laser cavity. The zero order beam is reflected out and forms the output for the cavity as in figure 1.

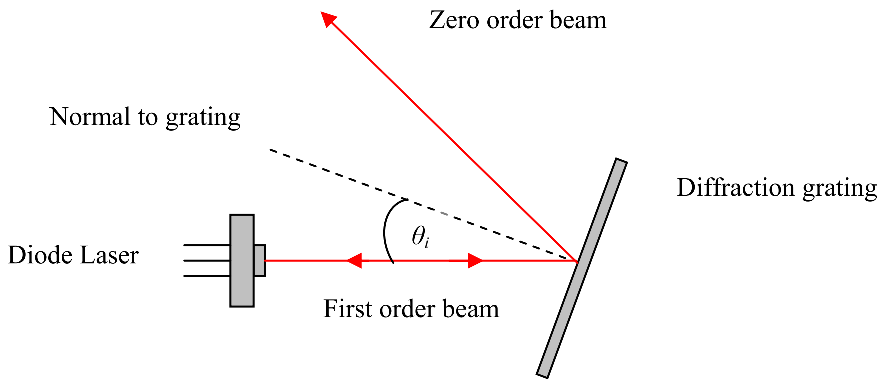

Figure 1: Littrow configuration

For the Littrow condition the diffraction grating equation $d(\sin\theta_m - \sin\theta_i) = m\lambda$ becomes

$$2d\sin\theta = m\lambda \quad (1)$$

where d is the line spacing on the grating, θ is the angle of incidence for the laser beam onto the grating, m is the diffraction order and λ is wavelength of the laser beam.

3. ABSORPTION SPECTROSCOPY

For the purpose of this work a near infrared beam passing through a sample of CO will result in absorption of some of the laser light at the wavelength of interest. The Beer-Lambert law gives the linear relationship between the absorbance of light at a specific wavelength by a gas sample and the concentration of that gas sample. A gaseous sample of concentration c is contained in an absorption cell and is illuminated with radiation of intensity I_0. The transmitted radiation has intensity, I, after travelling a distance l through a gas sample. An absorption spectrum may be obtained by scanning the gaseous sample through a range of wavelengths greater than the width of the spectroscopic feature of interest. The absorbance of light, A, is given by the Beer-Lambert Law

$$A = \log_{10}\left(\frac{I_0}{I}\right) = \varepsilon_\lambda \, c \, l \qquad (2)$$

where ε is the molar absorption coefficient and is a function of λ.

4. EXPERIMENTAL DESIGN

Non-commercial designs for ECDLs are in existence such as that by Arnold et al[5] and Andalker et al.[6] We have chosen to utilise low cost commercial equipment requiring no modifications and will demonstrate its capability for use as a CO sensor. We have selected Thorlabs' thermoelectric-cooled (TEC) laser mount (TCLDM9, €690 Thorlabs, Inc. Germany) which Thorlabs use as part of their own custom ECDL. The TEC contains a four pin socket which accepts all 5.6 mm and 9 mm diode laser packages therefore not constraining our choice of diode laser. The front plate of the TEC accommodates four 3" Extension Rods (ER30875-001, €9.30 each, Thorlabs) which act to hold a Thorlabs kinematic mirror mount rigidly in place at the desired distance along the rods. Thorlabs produce a piezo-electric kinematic mount which they use for their ECDL but for economy we have selected their kinematic mirror mount (KC1/M, €109). The three fine adjuster screws on the mount allow adjustment and coarse tuning of the ECDL. Fine tuning of the ECDL will require small adjustments to be made to the cavity length. It is common practice to use a piezo electric element to control the adjustment. This may be achieved by mounting the piezo element under one of the adjustment screws[7] or by mounting a piezo disk under the grating.[5] We have selected a piezo stack (AE0203D04, €94, Thorlabs) with dimensions (5.0 x 3.0 x 4.5) mm for mounting between the screw and kinematic mount. The piezo stack should not be exposed to bending forces and the mechanical load should be centred on the end face of the element. We have glued a thin aluminium disk to each end of the piezo element. A bevel in one disk centres the screw protecting the piezo from direct stress from the screw point. An optional small ball bearing sits in a recess created by a hole in the other disk and compensates for any lack of parallelism in the kinematic mount (figure 2). When this arrangement is incorporated into

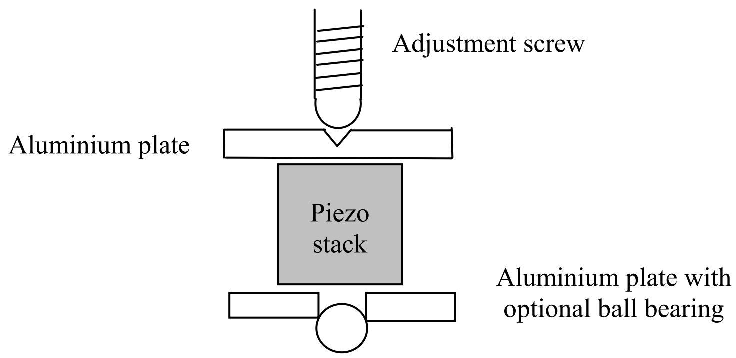

Figure 2: Piezo stack with protective aluminium plates

the kinematic mount a displacement of ≈ 0.2 μm is achieved for +/- 10 V using a standard lab waveform generator. The increased separation of the plates of the kinematic mount as a result of inserting the piezo element requires that the two 'non-piezo' screws be replaced with longer adjuster screws (FAS200, €11 Thorlabs). Thorlabs also supply a custom milled wedge mount for use in their ECDL which is designed to fit into the kinematic mount. When a grating is attached to the mount it is firmly held at an angle of 28˚ to the incident laser beam and so forms the Littrow cavity. At this angle the zero order beam does not clear the sides of the TEC mount and a gold mirror is attached to the front plate to reflect the beam out (figure 3). A grating angle of more than 28˚ would have been preferable allowing the output beam to clear the TEC mount however our choice of grating angle is dictated by our required operating wavelength of 1564 nm and the availability of a grating with a line spacing that will fulfil the Littrow criteria. We have selected a 600 line/mm gold grating designed for use at 1600 nm with blazing at 28˚ 41' (K54-851, €100 Edmund Optics Ltd). The blaze wavelength is defined as that wavelength, in a given diffraction order *m*, for which the efficiency curve reaches its maximum.[8] By choosing a blaze of 28˚ the first order beam diffracted back into the diode laser cavity will have a greater intensity and thereby improve the quality of the output.

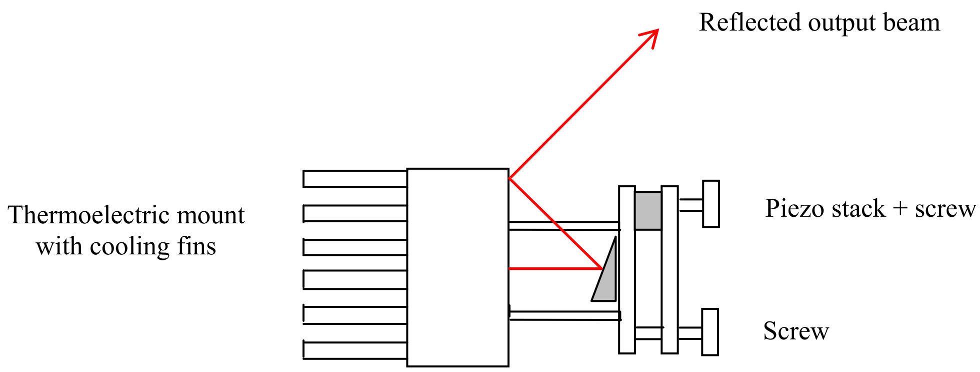

Figure 3: Plan view of extended cavity diode laser in Littrow configuration

In the initial stages a Newport current driver and Newport temperature controller are being used. In later work we will use Wavelength Electronics diode laser current controller and temperature controller board level components (models MPL500, €455 and MPT5000, €495, AMS Technologies, UK). The MPL and MPT series components require no more than 15 volts DC from their power source therefore making it possible to run them from a portable supply. For low noise operation in the lab we are using the Wavelength Electronics recommend Power One regulated linear supplies (HA15-0.9-A, €44 and HC5-6/0VP-A, €62, UnicPower, Germany).

Choice of commercial diode lasers in the 1550 nm region is relatively limited compared to diode laser availability at the visible wavelengths. Only Fabry-Perot type diode lasers were considered for reasons of economy and tunability, further reducing choice. There can be considerable variance in the lasing wavelength of diode lasers with the same model number e.g. plus or minus 30 nm about the typical lasing wavelength. An ECDL has a finite tuning range and cannot be expected to tune over much more than 20 nm, therefore it is necessary to request wavelength selection from the distributor for the intended operating wavelength. Maximum output power for our monitoring device will be less than the maximum output power of our diode laser because losses will necessarily be incurred when the beam is split (figure 4). An intense beam is especially desirable to facilitate measurement of low concentrations of CO. We have selected the FLO-502 diode laser (€460, Laser Components (UK) Ltd) in a 9 mm package with anti-reflection coating. The supplied diode has a centre wavelength of 1560 nm when operated at 25˚ C at the maximum output power of 15 mW. The output beam has an elliptical beam divergence of (25 x 40) degrees requiring a collimating aspheric optic (A438TM-C, €70, Thorlabs).

5. FURTHER WORK

The extended cavity diode laser will be tuned to the absorption frequency of the CO line R13 at 1564 nm by varying the injection current and the temperature of the diode laser. Initially the output beam will be directed through a Pyrex gas cell (GSO5000, €335, Specac, Dublin) with IR transparent sodium chloride windows (GSO5020, €160, Specac) containing a high concentration of CO at atmospheric pressure. The transmitted beam will be detected with a photodetector. Once the operating conditions for producing an output of 1564 nm have been identified, the output beam will be split and treated in a similar way to that discussed by Feher et al[9] (figure 4). Line locking will be achieved by passing part of the beam through the gas cell. The output will be used as a reference so that any variation in the wavelength of the diode laser may be stabilised using negative feedback to the current controller via the PC. The rest of the beam will be used for open path monitoring of CO in the atmosphere. To measure trace quantities of CO pollution from moving vehicles the monitoring beam will be directed across a road and the beam returned using a retroreflector. We expect the signal to noise ratio to increase with path length but a long path length for the monitoring beam will allow more absorption of CO thereby increasing the sensitivity of our device. Novel optical arrangements to increase path length will be investigated. The sensitivity of our device will also be increased electronically by modulating the diode laser current. Lock-in amplifiers will be used to demodulate the signals from the photo detectors. LabVIEW software will be developed to control and automate our device. In addition to the study of vehicle emissions we aim to incorporate fibre optics into the system for monitoring toxins in fuel combustion processes (particularly industrial plants). This will improve beam access in areas such as chimney stacks and other tightly confining spaces thereby significantly increasing the system applications. The coupling of near infrared light from the ECDL into optical fibre is currently in progress.

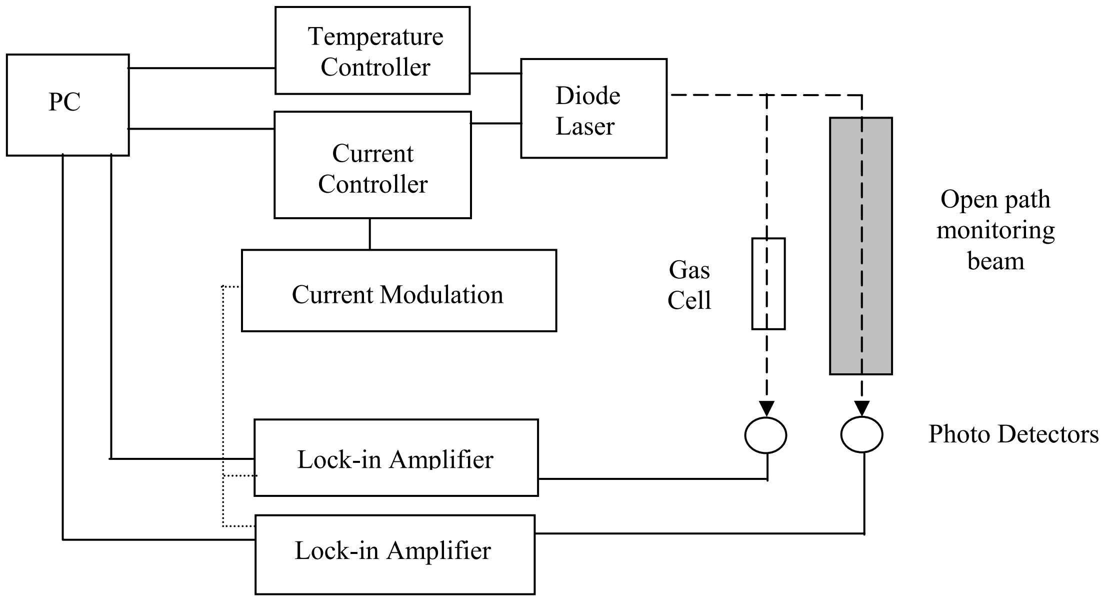

Figure 4: Block diagram showing intended arrangement of the carbon-monoxide monitoring system

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