Methane Sensing with a Novel Micromachined Single-Frequency Fabry–Perot Laser Diode Emitting at 1331 nm

V. Weldon, J. O'Gorman, J. J. Pérez-Camacho, D. McDonald, J. Hegarty, and B. Corbett

***Abstract*— Spectroscopic-based gas sensing is demonstrated using micromachined single-frequency Fabry–Perot (FP) laser diodes emitting at 1.331 μm with a side mode suppression ratio of greater than 24 dB over a significant emission wavelength tuning range. The utility of these novel mode controlled FP lasers for spectroscopic detection of gases is assessed by investigating the methane-absorption band in the 1.33 μm region. By probing the narrow linewidth R2 rotational absorption line, we demonstrate a low gas detection limit of 28 ppm·m and confirm the suitability of micromachined lasers in such applications.**

***Index Terms*— Gas sensing, longitudinal mode control, single-frequency laser diode, wavelength modulation spectroscopy.**

THE USE OF single-mode distributed feedback (DFB) and distributed Bragg reflector (DBR) laser diodes [1], [2], in spectroscopic-based gas sensing is well established. Recently, vertical-cavity surface emitting lasers (VCSEL's) which also emit in a single mode have been used for spectroscopic-based oxygen sensing [3]. While these devices can achieve high sensitivity and high selectivity gas sensing, DFB and DBR laser diodes are primarily available at wavelengths close to the well–known telecommunications windows at 850 nm, 1.3, μm, and 1.55 μm whilst VCSEL operation has only been demonstrated in limited wavelength regions. These and other factors, particularly expense in the case of DFB and DBR laser diodes, have mitigated against their widespread deployment for gas sensing applications.

Good single-longitudinal mode emission can also be achieved with multilongitudinal mode Fabry–Perot (FP) lasers by manipulating the spectral distribution of the laser mode structure [4], [5]. Suppression of unwanted modes can be accomplished by the introduction of controlled defects in a ridge waveguide laser by etching slots at accurately defined locations of $\ell/2, \ell/4, \ell/8$, along the cavity length (ℓ). When these slots are accurately (<1 μm) placed relative to the device facet, interference of the light reflected from the cleaved laser facets with that scattered at the slots results in controlled suppression of the FP modes in what otherwise would be a multimode laser structure [6], [7]. The resultant modification of the device FP cavity resonance spectrum results in good single longitudinal mode emission.

In this letter, we demonstrate the utility of this micromachining approach for obtaining single-mode emission in low-cost laser diodes for use in niche but growing application areas such as spectroscopic-based trace gas detection for environmental emissions monitoring and process control.

A conventional InGaAsP ridge waveguide FP laser diode emitting at $\lambda = 1.33$ μm was modified by etching slots to achieve single longitudinal mode operation. Comprehensive details of the device processing are given elsewhere [6]. For spectroscopic-based gas sensing, single-frequency operation of the laser diode is required over a significant wavelength tuning range. This is generally accomplished by variation of the device temperature and current. The temperature dependence of the single-mode emission characteristics of this first device was measured using an optical spectrum analyzer ($<$0.1 nm resolution) and is shown in Fig. 1. Over a temperature range 21.5 °C $\leq T \leq$ 28 °C and with a constant injection current of 75 mA (1.5 times threshold current), emission is predominantly in a single mode with a side-mode suppression ratio (SMSR) which is consistently greater than 24 dB. The measured emission wavelength dependence on current is shown in Fig. 2. The emission wavelength tunes approximately linearly with current at a rate of $\Delta\lambda/\Delta I = 7.7 \times 10^{-3}$ nm/mA with the laser heat sink temperature held constant at 25 °C. The temperature tuning characteristic of the dominant mode peak wavelength is also shown in Fig. 2. The wavelength emission tunes linearly with temperature at a rate $\Delta\lambda/\Delta T = 7.8 \times 10^{-2}$ nm/°C over a limited range with two mode hops of 5-nm step size in the region 0 °C $\leq T \leq$ 40 °C. Hence, to demonstrate the use of these, as yet nonoptimized, micromachined laser devices for gas sensing the operating current and temperature were chosen to ensure good single mode emission over an optimum wavelength range consistent with the absorption spectrum of an appropriate gas.

We targeted the $\nu_2 + 2\nu_3$ overtone/combination absorption band of CH_4 in the 1.33-μm spectral region. The experimental technique used here for spectroscopic-absorption-based gas sensing is well established [8], [9].

From Fig. 1 it is seen that the micromachined FP laser diode exhibited particularly good single-mode emission char-

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V. Weldon, J. O'Gorman, J. J. Pérez-Camacho, D. McDonald, and J. Hegarty are with Optronics Ireland, Physics Department, Trinity College, Dublin 2, Ireland.

B. Corbett is with the National Microelectronics Research Centre, University College Cork, Cork, Ireland.

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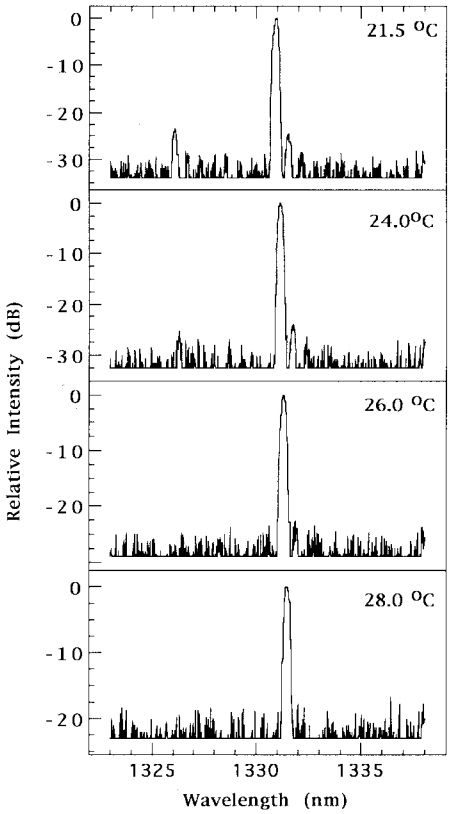

Fig. 1. Emission spectra of the mode controlled FP laser diode at four temperatures with a constant drive current of 75 mA illustrating single-frequency operation with a side-mode suppression ratio greater than 24 dB.

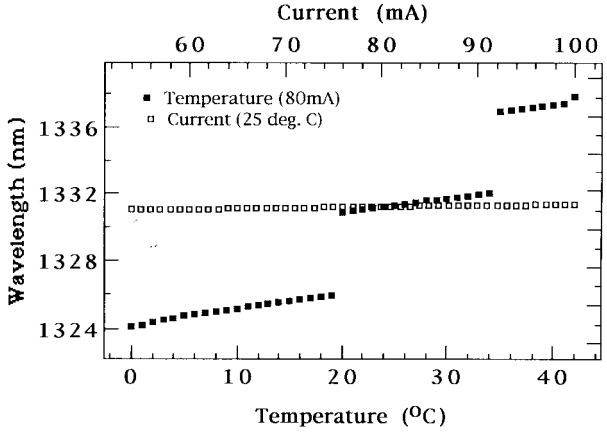

Fig. 2. Measured dominant mode peak emission wavelength (λ) of the single-frequency FP laser diode versus current at a constant temperature (T) of 25 °C and versus temperature at a constant current of 80 mA.

acteristics in the temperature range 20 °C $\leq T \leq$29 °C which corresponds to a wavelength tuning range 1331.00 nm $\leq \lambda \leq$ 1331.65 nm. This range coincides with the central Q branch wavelength region in the $\nu_2 + 2\nu_3$ absorption band of CH_4. Fig. 3(a) shows the Q branch absorbance spectrum obtained for a 10% sample of CH_4 buffered with nitrogen to a total pressure of 1000 mbar over a path length of 8 m. This absorbance spectrum was obtained by temperature tuning the laser diode emission wavelength. Atmospheric collision broadening results in a broad absorption feature in

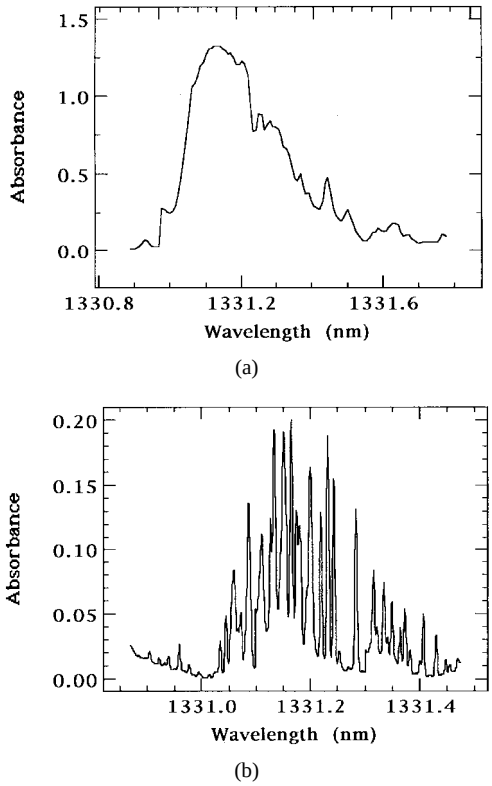

Fig. 3. (a) Measured absorbance spectrum of the Q branch of the $\nu_2 + 2\nu_3$ band of CH_4 at 1.33 μm over a path length of 8 m at a partial pressure of 100 mbar buffered by N_2 to 1000 mbar. (b) High resolution composite absorption spectrum of Q branch, as shown in (a) above, but at a path length of 24 m and a total CH_4 pressure of 1 mbar obtained by current tuning of the laser diode emission at three fixed temperatures.

the wavelength range 1331.0 nm $\leq \lambda \leq$1331.6 nm. The effect of collision broadening can be reduced by reducing gas pressure allowing resolution of the fine structure of the Q branch. Fig. 3(b) shows a composite high resolution absorption spectrum of the Q branch, in three parts, for a sample of 100% CH_4 at a reduced pressure of 1 mbar, over a path length of 24 m, obtained by current tuning the emission wavelength at three fixed laser diode heat sink temperatures. It is worth noting that these individual absorption lines, with typical linewidths of 4.5 $\times 10^{-3}$ nm (700 MHz), broaden and overlap as the pressure increases. Consequently the peak absorption of the Q branch at atmospheric pressure is considerably greater than the R and P rotational sideband absorption lines.

The Q branch at atmospheric pressure, shown in Fig. 3(a), is not amenable to detection by wavelength modulation spectroscopy (WMS) techniques using narrow linewidth sources. For example, the Q branch peak height at 1000 mbar, measured in this work, is 5.4 times that of the $R2$ rotational sideband. However, the spectral width (FWHM) of the pressure broadened Q branch is relatively large at 0.278 nm (47 GHz). It is therefore unsuitable for low detection limit measurements using WMS since the optimum modulation amplitude required for implementation of this technique is approximately 2.2 times the HWHM spectral absorption linewidth [10]. In the work reported here, this would be unrealistic since it corresponds to a current modulation amplitude of 41 mA and, hence, would place extreme tolerance constraints on

both the emitted power and the emission wavelength linearity with injection current. Consequently, we targeted the isolated rotational sideband absorption line assigned $(R2)$ in the $\nu_2 + 2\nu_3$ overtone/combination absorption band at around $\lambda = 1325.4$ nm in order to demonstrate gas sensing using WMS with our available device. This narrow linewidth [0.029 nm (5 GHz)] feature was chosen since it is isolated and accessible using our slotted devices. The low detection limit was not directly measured, but as is conventional, extrapolated from the magnitude of the (WMS) absorption signal obtained, in our case, with a 50-ppm concentration of CH_4 in nitrogen at a total pressure of 1000 mbar over a 28-m path length. A low modulation frequency of 600 Hz and a modulation amplitude of 2.2 times the Lorentzian halfwidth of the absorption line was used. Assuming a linear relationship between the second harmonic WMS signal and concentration and a minimum signal-to-noise ratio (SNR) of one at the detection limit, a minimum detectable CH_4 level of 28 ppm·m using a lock-in amplifier time constant of 333 ms is determined. This is equivalent to an absorbance of 1.3×10^{-5}.

Etalon fringes were present during the low detection limit determination but were widely spaced in wavelength compared with the CH_4 absorption linewidth and were stable and reproducible during the measurement period. The detection limit measured here is limited by the excess noise of the laser and so may be significantly improved by increasing the modulation frequency to the MHz regime. Also the SMSR (24 dB) is moderate and needs to be significantly increased to compete with, for example, DFB devices (SMSR typically 50 dB) in these applications. In comparison sub-ppm·m detection sensitivity has been achieved using DFB laser diodes [11] when targeting the $2\nu_3$ overtone of CH_4 at 1.66 μm. However the total line strength of this band is a factor of four greater than the $\nu_2 + 2\nu_3$ overtone/combination band at 1.33 μm targeted here.

In conclusion, we have demonstrated the use of single-frequency micromachined slotted ridge waveguide laser diodes for spectroscopic based gas sensing. This demonstration is significant since in principle single-frequency lasers diodes at any wavelength, within the laser material gain spectrum are achievable, but in practice their availability is driven by other applications e.g., telecommunications and data communications. Our experiments show that laser diodes fabricated using slotted laser technology have the required performance for sensing and metrology applications. In comparison with the cost of the alternatives, this technology enables manufacture of single-frequency laser diodes for cost sensitive applications at noncommunications wavelengths.

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