Oxygen measurements at high pressures with vertical cavity surface-emitting lasers

J. Wang*, S.T. Sanders, J.B. Jeffries, R.K. Hanson

High Temperature Gasdynamics Laboratory, Department of Mechanical Engineering, Stanford University, Stanford, California 94305-3032, USA

Received: 26 July 2000/Revised version: 2 January 2001/Published online: 20 April 2001 – © Springer-Verlag 2001

Abstract. Measurements of oxygen concentration at high pressures (to 10.9 bar) were made using diode-laser absorption of oxygen A-band transitions near 760 nm. The wide current-tuning frequency range (≥ 30 cm⁻¹) of vertical cavity surface-emitting lasers (VCSELs) was exploited to enable the first scanned-wavelength demonstration of diode-laser absorption at high pressures; this strategy is more robust than fixed-wavelength strategies, particularly in hostile environments. The wide tuning range and rapid frequency response of the current tuning were further exploited to demonstrate wavelength-modulation absorption spectroscopy in a high-pressure environment. The minimum detectable absorbance demonstrated, ∼ 1 × 10⁻⁴, corresponds to ∼ 800 ppm-m oxygen detectivity at room temperature and is limited by etalon noise. The rapid- and wide-frequency tunability of VCSELs should significantly expand the application domain of absorption-based sensors limited in the past by the small current-tuning frequency range (typically < 2 cm⁻¹) of conventional edge-emitting diode lasers.

PACS: 07.07.Df; 42.62.Fi; 42.55.Px

Many industrial combustion processes such as electrical power generation and aeropropulsion operate at pressures well above atmospheric pressure. Sensors monitoring oxygen concentrations for these processes play important roles as diagnostic tools in fundamental research and as part of active control systems. Zirconia sensors [1] have been traditionally used to measure oxygen concentrations in these hostile environments. However, the application of absorption-based sensing with diode lasers is growing rapidly because of the potentially fast time response and the non-intrusive nature of diode-laser diagnostics. Furthermore, diode-laser absorption sensors provide path-averaged measurements, which can be beneficial to elucidate the overall performance of engineering systems.

Oxygen measurements using A-band transitions near 760 nm have been demonstrated with a variety of diode lasers: Fabry–Pérot (FP) [2, 3], short external cavity [4], widely tunable external cavity (ECDL) [5], distributed feedback (DFB) [6, 7], and vertical cavity surface-emitting lasers (VCSELs) [7–9]. To our best knowledge, no diode-laser-based techniques have been used to measure oxygen in high-pressure (≥ 5 bar) environments despite the significance of such measurements for many industrial processes.

Both scanned- and fixed-wavelength absorption techniques have been used in diode-laser gas-property sensors [10]. In the fixed-wavelength scheme the laser wavelength is typically fixed at an absorption-line center. The fixed-wavelength scheme suffers from two complications: non-resonant attenuation and the need for accurate line-shape information. Many industrial combustors contain solid- and liquid-phase aerosols such as soot and fuel droplets, which attenuate the light by scattering and absorption. In addition, the transmission of optical windows may be variable due to fouling or thermal and mechanical stresses. Furthermore, the refractive-index gradient existing in combustion environments may cause beam steering. Multiple non-resonant (i.e. away from the probed gas-transition frequency) lasers are normally required to track these non-resonant attenuations and permit meaningful fixed-wavelength measurements of the resonant gas absorption [11]. Some assumptions on the spectral dispersion of aerosol extinction and window transmission are also necessary to account for the wavelength offset between resonant and non-resonant lasers. The second complication, namely that gas absorption is dependent on transition line shape, recognizes that the line-shape function varies with pressure, temperature, and gas composition. Accurate knowledge of these parameters and their effects on transition line shape is therefore necessary.

The scanned-wavelength scheme can remove both of these complications by rapidly tuning the laser wavelength over a sufficiently large range. A correct baseline representing zero gas absorption can be inferred from the spectral variation of the resonant gas absorption in this scanned-wavelength range. Non-resonant lasers and assumptions on the spectral dispersion of non-resonant attenuations are no
longer required. In addition, accurate line-shape data is obtained directly from the measurements. Thus, the scanned-wavelength scheme offers significant advantages over the fixed-wavelength scheme, especially in hostile and/or multiphase environments.

Due to the limited current-tuning frequency range (typically < 2 cm⁻¹) of conventional edge-emitting diode lasers (DFB or FP), the scanned-wavelength strategy with such devices is limited to atmospheric pressure at room temperature or a few atmospheres at elevated temperatures. Although widely tunable ECDLs have been used for gas-sensing studies and offer many advantages owing to their large wavelength-tuning ranges, they are generally limited to laboratory research tools because of high laser cost and stringent maintenance requirements. In addition, the tuning rate is inherently slow since ECDLs realize large-range wavelength tuning using mechanical components.

Some VCSELs provide a large current-tuning frequency range (> 30 cm⁻¹), which results from their small cavity volume and the strong resistive heating due to their large series resistance associated with the distributed Bragg reflector (DBR) mirrors. This large current-tuning range of optical frequency was considered as a negative factor for gas detection at low pressures because of the corresponding large laser phase noise compared to the small transition line width at low pressures [7]. However, this same laser characteristic is exploited here in a positive way to enable a new class of scanned-wavelength absorption sensors for high-pressure combustion environments where gas transitions have very large line width and thus the effect of laser phase noise is negligible.

Due to their unique topology, VCSELs also have some distinct advantages over the conventional edge-emitting lasers, such as low current threshold operation, high two-dimensional packing density, wafer-scale testing capability, single-longitudinal-mode operation, a circular output beam, and small divergence angle highly desirable for fiber coupling. In particular, the significantly lower manufacturing cost than that of DFB lasers may allow wide deployment of VCSEL-based sensors monitoring various industrial processes.

We first present characteristics of VCSELs important for the development of gas-property sensors. Then we exploit the large and fast current tunability of these VCSELs to demonstrate the first application of VCSELs in high-pressure gas detection using both direct-absorption and wavelength-modulation spectroscopy (WMS) techniques.

1 Laser characteristics

1.1 L − I and V − I

The output power versus injection current (L − I) characteristics of a quantum-well AlGaAs/GaAs VCSEL (CSEM760, Centre Suisse d’Electronique et de Microtechnique, Switzerland) were measured at different heat-sink temperatures (Fig. 1). Also shown is the operation voltage versus current (V − I) at a heat-sink temperature of 25°C. The laser has two distinct voltage drops: the voltage across the laser diode junction and the voltage across the series resistors associated with the two DBR mirrors. The voltage across the diode junction is approximately \( hv/e \) (∼ 1.63 V for 760-nm lasers), where \( h \) is the laser emission photon energy and \( e \) the electronic charge. Therefore, the effective series resistance of the two Bragg mirrors near threshold is \( R_{th} = (V_{th} - hv/e) / I_{th} \cong 260 \) ohm, much larger than the few ohms typical of edge-emitting lasers. Combined with the small cavity volume of the VCSEL, this large series resistance generates very large heat density and thus may lead to very high temperatures of the laser cavity.

Both the gain profile and the Fabry–Pérot mode position red shift with increasing temperature. However, since the temperature coefficient of the band-gap energy is much larger than that of the effective refractive index, the gain-profile peak shifts with temperature much faster than the Fabry–Pérot mode position, and thus the Fabry–Pérot mode position deviates from the gain-profile peak at large injection current. In addition, the gain profile broadens and the peak gain reduces significantly at high temperatures. When this loss of gain with increasing temperature is larger than the increase of gain with increasing current, the output power starts to roll over [12] as shown in Fig. 1.

1.2 Wavelength tuning

Like edge-emitting lasers, the wavelength of a VCSEL can be tuned by varying either injection current or heat-sink temperature. However, due to the large resistive heating and small cavity volume of the VCSEL described above, the wavelength-tuning range and the frequency response are significantly larger and faster than those of edge-emitting lasers.

Figure 2 shows the quasi-static current- and temperature-tuning characteristics of a VCSEL measured by a wavemeter. The temperature-tuning rate is ∼ −0.93 cm⁻¹/K (0.055 nm/K). The current-tuning rate varies from −4.5 cm⁻¹/mA (0.26 nm/mA) near threshold to −9.6 cm⁻¹/mA (0.56 nm/mA) at a current of 13 mA. A quadratic relationship [12] can be used to describe the current dependence of optical frequency at 25°C: \( \nu \cong 13164 - 2.61I - 0.253I^2 \), where \( \nu \) is the optical frequency in cm⁻¹ and \( I \) is the current in mA. The laser-cavity temperature should be the same as the heat-sink temperature at zero injection current, and thus the Fabry–Pérot mode frequency at 25°C