Research Article Vol. 25, No. 10 | 15 May 2017 | OPTICS EXPRESS 11679

Optics EXPRESS

All-electronic frequency stabilization of a DFB laser diode

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Abstract: A laser diode's junction voltage is a sensitive measure of its temperature and can be used in a thermal control feedback loop. To compensate for the temperature dependence of the laser's internal resistance, we have measured the dynamic resistance, ∂V/∂I, by modulating the injection current and measuring the demodulated voltage. The junction voltage was thus controlled while operating at fixed DC injection current. Over an external temperature range of 15°C to 35°C, this stabilised the centre frequency (wavelength) of a 1651 nm DFB laser diode with a residual mean frequency shift of 60 MHz (0.5pm), less than the uncertainty on the centre frequency of 80 MHz (0.7 pm). Under the same conditions, conventional thermistor control gave a systematic wavelength shift of −8.4 GHz (−76 pm), and control of the uncompensated forward voltage gave a shift of 9.9 GHz (90 pm).

OCIS codes: (140.2020) Diode lasers; (140.3425) Laser stabilization; (140.6810) Thermal effects; (300.6260) Spectroscopy, diode lasers.

References and links

1. International Telecommunication Union, *Recommendation ITU-T G.694.1 Spectral grids for WDM applications: DWDM frequency grid*. ITU, Geneva, Switzerland (2012).
2. M. Roppelt, K. Grobe, M. Eiselt, and J.-P. Elbers, Investigation of wavelength control schemes in WDM-PONs, Paper 29, Proc ITG Symposium on Photonic Networks (2011).
3. J. Hodgkinson and R. P. Tatam, "Optical gas sensing: a review," Meas. Sci. Technol. **24**(1), 012004 (2013).
4. L. S. Rothman, I. E. Gordon, A. Barbe, D. C. Benner, P. E. Bernath, M. Birk, V. Boudon, L. R. Brown, A. Campargue, J. P. Champion, K. Chance, L. H. Coudert, V. Dana, V. M. Devi, S. Fally, J. M. Flaud, R. R. Gamache, A. Goldman, D. Jacquemart, I. Kleiner, N. Lacome, W. J. Lafferty, J. Y. Mandin, S. T. Massie, S. N. Mikhailenko, C. E. Miller, N. Moazzen-Ahmadi, O. V. Naumenko, A. V. Nikitin, J. Orphal, V. I. Perevalov, A. Perrin, A. Predoi-Cross, C. P. Rinsland, M. Rotger, M. Simeckova, M. A. H. Smith, K. Sung, S. A. Tashkun, J. Tennyson, R. A. Toth, A. C. Vandaele, and J. Vander Auwera, "The HITRAN 2008 molecular spectroscopic database," J. Quant. Spectrosc. Ra. **110**(9–10), 533–572 (2009).
5. Nanoplus, *Summary of specifications for DFB laser diodes from 1450 nm to 1650 nm*. Nanoplus Nanosystems and Technologies GmbH, Gerbrunn, Germany. Available at http://nanoplus.com/en/products/distributed-feedback-lasers/distributed-feedback-lasers-1450-nm-1650-nm/ [accessed 2015].
6. D. J. Klotzkin, *Introduction to Semiconductor Lasers for Optical Communications: An Applied Approach* (Springer, 2014).
7. E. Vezzoni, P. Gambini, and M. Puleo, "Laser frequency stabilization techniques for optical communication," Proc 16th European Conference on Optical Communication (ECOC), 943–950 (1990).
8. D. A. Ackerman, K. M. Paget, L. F. Schneemeyer, L. J.-P. Ketelsen, F. W. Warning, O. Sjolund, J. E. Graebner, A. Kanan, V. R. Raju, L. E. Eng, E. D. Schaeffer, and P. van Emmerik, "Low-cost athermal wavelength-locker integrated temperature-tuned single-frequency laser package," J. Lightwave Technol. **22**(1), 166–171 (2004).
9. B. van Well, S. Murray, J. Hodgkinson, R. Pride, R. Strzoda, G. Gibson, and M. Padgett, "An open-path, hand-held laser system for the detection of methane gas," J. Opt. A: Pure Appl. Opt. **7**(6), S420–S424 (2005).
10. J. Chen, A. Hangauer, R. Strzoda, and M.-C. Amann, "VCSEL-based calibration-free carbon monoxide sensor at 2.3 mu m with in-line reference cell," Appl. Phys. B **102**(2), 381–389 (2011).
11. S. L. Gilbert, W. C. Swann, and T. Dennis, "Wavelength standards for optical communications," Proc. SPIE **4269**, 184–191 (2001).
12. F. Pavese, "An accurate equation for the V-T characteristic of GaAs diode thermometers in the 4-300K range," Cryogenics **14**(8), 425–428 (1974).
13. J. Talpe, G. Stolovitzky, and V. Bekeris, "Cryogenic thermometry and level detection with common diodes," Cryogenics **27**(12), 693–695 (1987).

#286761 https://doi.org/10.1364/OE.25.011679

Received 14 Feb 2017; accepted 20 Mar 2017; published 10 May 2017

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14. L. G. Rubin, "Cryogenic thermometry: a review of recent progress," Cryogenics **10**(1), 14–22 (1970).
15. J. H. Jeong, K. C. Kim, J. L. Lee, H. J. Kim, and I. K. Han, "Junction temperature measurement of InAs quantum-dot laser diodes by utilizing voltage-temperature method," IEEE Photonics Technol. Lett. **20**(16), 1354–1356 (2008).
16. H. Y. Ryu, K. H. Ha, J. H. Chae, O. H. Nam, and Y. J. Park, "Measurement of junction temperature in GaN-based laser diodes using voltage-temperature characteristics," Appl. Phys. Lett. **87**(9), 093506 (2005).
17. K. Uehara and K. Katakura, "New method of frequency stabilization of semiconductor lasers," Jpn. J. Appl. Phys. **27**(2), 244–246 (1988).
18. Z.-Q. Lin, Y. Zhang, Y.-H. Lang, and F.-C. Yin, "Constant temperature control of semiconductor laser based on temperature characteristics of pn junction," Faguang Xuebao **30**(2), 223–227 (2009).
19. Y. Xi, T. Gessman, J. Xi, J. K. Kim, J. M. Shah, E. F. Schubert, A. J. Fischer, M. H. Crawford, K. H. A. Bogart, and A. A. Allerman, "Junction temperature in ultraviolet light-emitting diodes," Jpn. J. Appl. Phys. **44**(10), 7260–7266 (2005).
20. I. Sergachev, R. Maulini, A. Bismuto, S. Blaser, T. Gresch, Y. Bidaux, A. Müller, S. Schilt, and T. Südmeyer, "All-electrical frequency noise reduction and linewidth narrowing in quantum cascade lasers," Opt. Lett. **39**(22), 6411–6414 (2014).
21. A. Albanese, "An automatic bias control (ABC) circuit for injection lasers," ATT Tech. J. **57**(5), 1533–1544 (1978).
22. S. M. Sze, *Physics of Semiconductor Devices* (John Wiley & Sons, 1981).
23. Y. Xi and E. Schubert, "Junction–temperature measurement in GaN ultraviolet light-emitting diodes," Appl. Phys. Lett. **85**(12), 2163–2165 (2004).
24. Laser Components, SPECDILAS D series DFB lasers for spectroscopy, Laser Components GmbH, Olching, Germany (2000).
25. A. Asmari, J. Hodgkinson, E. Chehura, S. E. Staines, and R. P. Tatam, "All-electronic frequency stabilization of a DFB laser diode," Cranfield Online Research Data, https://doi.org/10.17862/cranfield.rd.4004943 (2016).
26. R. Arndt, "Analytical line shapes for Lorentzian signals broadened by modulation," J. Appl. Phys. **36**(8), 2522–2524 (1965).
27. S. Schilt and L. Thévenaz, "Experimental method based on wavelength-modulation spectroscopy for the characterization of semiconductor lasers under direct modulation," Appl. Opt. **43**(22), 4446–4453 (2004).
28. G. Giuliani, M. Norgia, S. Donati, and T. Bosch, "Laser diode self-mixing technique for sensing applications," J. Opt. A, Pure Appl. Opt. **4**(6), S283–S294 (2002).
29. D. Masiyano, J. Hodgkinson, S. Schilt, and R. P. Tatam, "Self-mixing interference effects in tunable diode laser absorption spectroscopy," Appl. Phys. B **96**(4), 863–874 (2009).

1. Introduction

The frequency stability of laser diodes is important for applications such as gas spectroscopy and telecommunications, which have stringent requirements for both short term and long term operation. Telecommunications using dense wavelength division multiplexing (DWDM) restricts lasers to operation within the International Telecommunication Union (ITU) grid [1], operating in the region 1530-1625 nm with a channel spacing ranging from 12.5 GHz to 100 GHz on the frequency (ν) scale, centred with a frequency precision of $\Delta\nu = \pm$ 1.5GHz ($\Delta\lambda = \pm$ 12pm) [2]. High resolution tunable diode laser spectroscopy (TDLS) involves scanning the laser's emission wavelength across a narrow gas absorption line in order to determine the gas concentration [3]. The wavelength drift of the laser is required to be much smaller than the line width of a gas absorption line, which for methane at a wavelength of λ = 1651nm (the example used later in this paper) is $\Delta\nu$ = 4.4 GHz ($\Delta\lambda$ = 40pm) FWHM [4].

Typically for both applications in the near infrared, singlemode laser diodes such as distributed feedback (DFB) lasers are used, with a linewidth of around $\Delta\nu$ = 10 MHz or lower [5]. Although lasers are nominally produced at a given frequency to a tolerance of perhaps $\Delta\nu$ = 12.5 GHz ($\Delta\lambda$ = 0.1 nm) [5], the precise emission frequency is a function of the injection current and device temperature. The operating temperature is affected by a combination of the ambient temperature external to the device package, junction heating effects and thermal gradients within the package. This makes thermal design an important element of laser packaging [6]. If the injection current is fixed and the temperature of the laser's active region can be precisely and accurately controlled, the emitted wavelength should remain constant.

Conventionally a thermo electric cooler (TEC) is used to maintain the operating temperature of the laser diode. Typically most DFB lasers include the TEC within the package, with a thermistor placed in thermal contact with the TEC, a short distance from the active laser chip. The temperature precision that can be achieved by this technique is 0.01 °C

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[7]. However, the method is not ideal as it measures the temperature of the thermistor rather than the active region of the laser. There are multiple conductive pathways with additional convective and radiant paths between these and other components in the case, with temperature gradients between the thermistor and the active laser region. Figure 1 illustrates a simplified condition whereby a single overall gradient dominates. A change in the external ambient temperature will cause a change to the thermal gradient(s), resulting in a systematic error in the emission wavelength [7]. The systematic error can be reduced by careful positioning of the thermistor, shortening the thermal pathways to the laser. The thermistor is often mounted on top of the TEC and the laser on a separate adjacent mount.

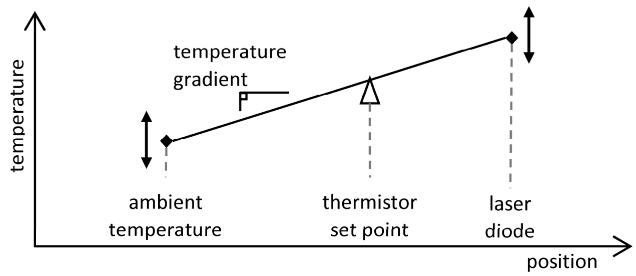

Fig. 1. Simplified illustration of thermal gradients for conventional control using a thermistor. The underlying picture is a combination of multiple conductive pathways plus convective and radiant paths. For a fixed set point temperature, changes to the ambient temperature and / or thermal gradients will cause the control system to alter the laser temperature.

Because of the limitations of using thermistor based control only, a number of additional techniques have been implemented to stabilise the laser diode emission frequency with both high precision and accuracy. Athermalised etalons have been used to achieve sub GHz frequency stability over an external temperature range of 80°C [8]. For TDLS, frequency stability may be achieved by using a reference cell containing the target gas, to lock the laser emission wavelength to the absorption line [9], or by reference to a neighbouring line of a different gas, whose presence can be guaranteed [10]. Gas reference cells are also often adopted as wavelength / frequency transfer standards in telecoms applications [11].

A potential alternative is to use the electrical properties of the laser diode, such as its forward voltage V_f (measured across the terminals), which provides a sensitive indicator of the junction temperature. This technique has been widely used in diode (rather than laser diode) based thermometers to measure temperature in the range 1-400 K with a precision of 1 mK [12–14]. Measurement of the junction temperature of quantum-dot and GaN based laser diodes has also been reported [15,16].

Uehara and Katakura proposed use of this forward voltage to stabilise the temperature and wavelength of a laser diode, and applied this to a 1.3μm buried heterostructure distributed feedback (BH DFB) laser [17]. They were able to achieve a stability of $\Delta\nu$ = 350 MHz ($\Delta\lambda$ = 2 pm) over 30 minutes at a fixed temperature, and a systematic shift of $\Delta\nu$ = 500 MHz ($\Delta\lambda$ = 3 pm) when subject to an external change in the ambient temperature of 10 °C. Lin *et al.* have applied forward voltage based control to a multimode Fabry Perot laser diode [18]. They proposed, as expected, that the injection current affects the junction temperature and that changes to this parameter must be compensated for when using the forward voltage. They also proposed that this might be achieved via measurement of the injection current together with use of an experimentally determined calibration factor (the change in junction voltage with temperature) that itself varies with injection current. The forward voltage has been used for temperature measurement of an LED by Xi *et al.* [19], who used it to characterise devices (and also demonstrated a thermally-induced shift in the peak emission wavelength) but did not use the method for thermal / wavelength control. The forward voltage has also been used by Sergachev *et al.* in a fast (300kHz bandwidth) control loop aimed at reducing frequency noise in quantum cascade lasers [20].

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In this paper we describe a new frequency stabilisation technique, whereby the junction voltage V_j of a laser diode is used to measure the temperature of the active medium. The series resistance of the laser diode can impose a small but significant error when measuring the forward voltage V_f, and must be compensated to recover the underlying junction voltage [21]. Because the series resistance changes with temperature, we have found that real-time simultaneous measurement of this quantity is required for precise control. Applying a sinusoidal modulation to the injection current and measuring the demodulated forward voltage allows us tomeasure this resistance dynamically as ∂V/∂I and compensate for it. Thus, the junction voltage alone is measured, the accuracy of the measurement is improved significantly and the emission frequency is stabilised.

Modulation of the injection current also has the effect of modulating the emission frequency. Thus it is the centre frequency that is stabilised. In this paper, we chose a relatively large modulation (approx 4.4GHz or 40pm) which is much larger than the uncertainty on the controlled centre frequency. Large modulation coefficients are typical of wavelength modulation spectroscopy (WMS) used in gas sensing [3]. In Section 6, we discuss the feasibility of reducing the modulation to a level at or below the residual frequency uncertainty of the laser emission, making the method more suited to other applications.

2. Theory

The relationship between injection current and junction voltage can be expressed using the Shockley equation for an ideal diode [22]:

$$I_f = I_s\left[\exp\left(\frac{eV_j}{\eta kT}-1\right)\right] \tag{1}$$

where I_f is the forward (injection) current, I_s is the saturation current, e is the charge on an electron, V_j is the junction voltage, η is the ideality factor (≈1 for a standard diode), k is the Boltzmann constant and T is the temperature of the junction in K. For $V_j \gg \eta kT/e$ in Eq. (1),

$$I_f \approx I_s \exp\left(\frac{eV_j}{\eta kT}\right) \tag{2}$$

The condition $V_j \gg \eta kT/e$ is justified in our experiments: we measured $V_j > 1.3$V and $\eta kT/e$ ≈26 mV. The saturation current I_s is given by [22,23]

$$I_s = \left[T^3\exp\left(\frac{-E_g}{kT}\right)\right]T^{\frac{\gamma}{2}} \approx T^3\exp\left(\frac{-E_g}{kT}\right) \tag{3}$$

where E_g is the band gap energy measured in volts, γ is a constant and the term $T^{\frac{\gamma}{2}}$ is close to unity. Combining the forward current I_f with the series resistance R_s gives the measured forward voltage V_f. We can model the series resistance as having a linear temperature coefficient α over the operating temperature range (see section 5) such that

$$V_f = V_j + I_f R_s = \frac{\eta kT}{e}\ln\left(\frac{I_f}{I_s}\right) + I_f R_0\left[1+\alpha\left(T-T_0\right)\right] \tag{4}$$

where R_0 is the series resistance at temperature T_0. Substituting Eq. (3) into Eq. (4) gives

$$V_f = \frac{\eta kT}{e}\left[\ln\left(\frac{I_f}{T^3}\right)+\frac{E_g}{kT}\right]+I_f R_0\left[1+\alpha\left(T-T_0\right)\right] \tag{5}$$

Differentiation and simplification gives the change in forward voltage with temperature.

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$$\frac{\partial V_f}{\partial T} = \frac{\eta k}{e}\left[\ln\left(\frac{I_f}{T^3}\right) - 3\right] + I_f R_0 \alpha \tag{6}$$

We can substitute some typical figures for our laser to give an approximate estimate of the magnitude of these thermal changes for the two terms on the right hand side of Eq. (6). Using the following indicative values for variables, $T = 300\text{K}$, $I_f = 170\text{mA}$, $R_0 = 2.6\Omega$ and $\alpha = 1.7 \times 10^{-3}\text{K}^{-1}$ (see section 5), gives a value of $-1.9 \times 10^{-3}\text{VK}^{-1}$ for the first term (junction voltage vs. temperature) and $0.8 \times 10^{-3}\text{VK}^{-1}$ for the second (series resistance vs. temperature). Thus, the series resistance contributes a significant additional temperature dependence to the forward voltage, which requires compensation if the junction voltage is to be recovered.

Now we consider the measurement of series resistance as a dynamic resistance, ie the gradient $\partial V_f/\partial I_f$. Taking Eq. (5) and differentiating with respect to I_f gives

$$\frac{\partial V_f}{\partial I_f} = \frac{\eta k T}{I_f e} + R_0\left[1 + \alpha\left(T - T_0\right)\right] \tag{7}$$

Using the above indicative values gives a value of 0.15Ω for the first term (laser junction) and 2.6Ω for the second term (series resistance). Thus, if the indicative values are appropriate, the dynamic resistance is dominated by the series resistance, however the junction itself makes a small contribution of approximately 6%. Again using our indicative values, we can compare the temperature dependence of the two terms on the right hand side of Eq. (7). The first term (junction dominated) has a temperature dependence of $5 \times 10^{-4}\ \Omega\text{K}^{-1}$, while the second term (series resistance) has a temperature dependence of $1 \times 10^{-2}\Omega\text{K}^{-1}$. This confirms that the series resistance dominates the temperature dependence of the dynamic resistance, with the junction itself contributing around 5%. Importantly, the two effects are both proportional to T (and therefore also to each other) at fixed injection current.

Thus, measurement of the dynamic resistance can be used to determine the series resistance and compensate the forward voltage to recover the underlying junction voltage.

3. Conventional temperature control

To benchmark our technique, we first tested a 1651 nm DFB laser diode for wavelength stability using conventional, thermistor-based temperature control. Figure 2 shows a schematic diagram of the experimental configuration.

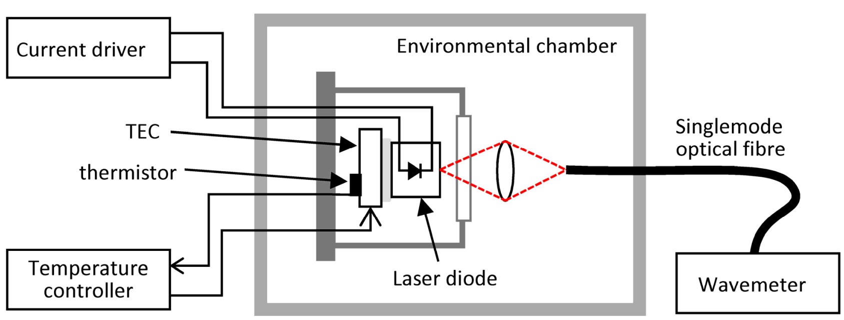

Fig. 2. Schematic diagram of conventional laser diode control using a thermistor.

An InP ridged waveguide laser with a wavelength of 1651nm (Specdilas HHI TO8 MTE module) was investigated. The device included a TEC and 10kΩ thermistor within a TO8 package. The thermistor was connected at the input to a temperature controller (Thorlabs TED200), and the controller's output was connected to the TEC within the package. The injection current to the laser diode was supplied using a current driver (Thorlabs LDC200). The laser diode injection current was kept constant at 167 mA ± 0.5mA and the thermistor temperature was maintained at 25°C ± 0.01°C.

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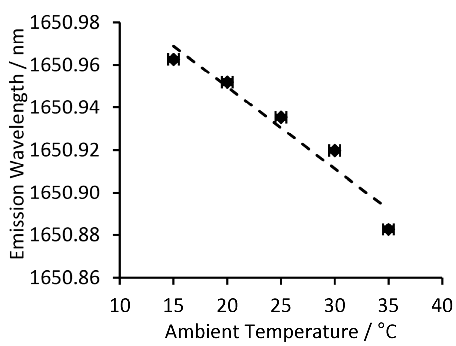
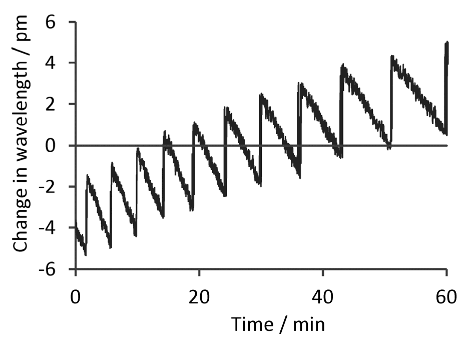
Light emitted by the laser was coupled into a 2m length of singlemode fibre (SMF28) using antireflection coated lenses and a 3-axis alignment block. The coupling efficiency of this arrangement was low (<5%), which had the effect of reducing feedback to the laser in the absence of an isolator; the output was observed using an optical spectrum analyser (Yokogawa AQ6370C-10) and found to be stable and singlemode. The wavelength of the laser diode was measured with a wavelength meter (High Finesse Angstrom WS6/200IR) with a resolution of 0.45pm (50MHz) and absolute accuracy of 1.4pm (150MHz). The wavemeter also provided a higher resolution, expanded view of the detailed mode structure of the laser, which confirmed singlemode operation. For consistency with later results, the wavelength readings were averaged over a period of 300ms.

An environmental chamber was used to maintain a constant external ambient temperature in the range 15 – 35 °C around the device, with a stability of ± 0.5°C. The temperature in the environmental chamber was changed in 5°C steps and monitored throughout the experiment using a thermocouple connected to a scanning thermometer (Keithley 740). After each change in temperature, mechanical expansion / contraction of the alignment block required us to alter the alignment of the laser diode to the optical fibre before making measurements. For each temperature step change, we waited for a period of around 5 minutes to allow the temperature to stabilise before measuring the emitted wavelength.

Figure 3(a) shows the effect of different ambient temperatures on the laser diode wavelength. The results show a clear systematic reduction in wavelength with increasing ambient temperature, of –4.0 ± 0.5 pm/°C at a constant thermistor temperature. The laser diode wavelength would typically increase with increasing operating temperature [24], so this data indicates a reduction in laser diode temperature and wavelength when the ambient temperature increases. This is consistent with a potential "see-saw" effect, whereby the setpoint illustrated in Fig. 1 is fixed and external temperature changes force the control system to pull the laser temperature up or down in the opposite direction.



(a)



(b)

Fig. 3. Results of using conventional control to a thermistor temperature of 25 °C, at a constant injection current of 167mA. (a) wavelength drift with ambient temperature. A best fit straight line (dashed) is also shown. (b) Long term wavelength stability at an ambient temperature of 20 ± 0.5 °C. Data available at [25].

The long term stability of this control method was also investigated over a period of 60 min by setting the temperature of the environmental chamber to 20 ± 0.5 °C and continuously monitoring the wavelength. Changes in the measured wavelength with time are shown in Fig. 3(b). The laser diode wavelength showed a low level of drift with a standard deviation of σ = ± 2.2 pm. We eliminated mode-hopping as a possible cause of sporadic changes in the signal, since this would have required an external cavity separation of the order of 40cm, and such a cavity length was not present in our experiments.

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4. Forward voltage based control

The laser diode forward voltage was used as a temperature sensor to stabilise the wavelength of the laser diode according to the method described by Uehara and Katakura [17], which utilises Eq. (1). The basic principle of the forward voltage method is described in the flow chart in Fig. 4.

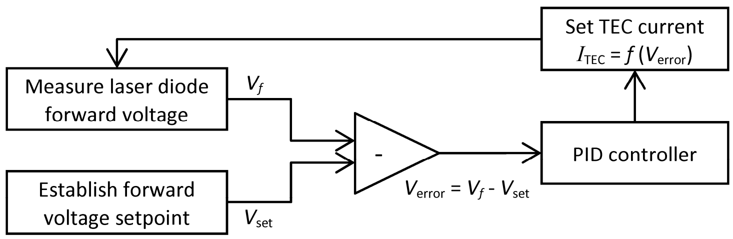

Fig. 4. Laser diode wavelength stability flow chart using forward voltage based control

The forward voltage was measured using a voltmeter (Keithley 195A), and compared to a voltage setpoint, chosen to give the required wavelength at specific temperature (for operation at 25° C and 167mA). The measured forward voltage was passed to a data acquisition card (National Instruments PCI 6259, 16 bit A to D conversion) and thereby to a control program running under the LabVIEW software system. The difference between the measured forward voltage V_f and the setpoint voltage V_{set} acted as an error signal for a control loop. PID control was implemented using an embedded subroutine (PID.vi) with the following settings: P = 5, I = 0.005min and D = 0.00005min (using units as prescribed in the subroutine). A second current driver (ThorLabs ITC510) was used to control the TEC current. The driver was originally designed for laser diode current injection and included both a DC setting and an input for modulation signals. The required change to the TEC control current was calculated by the LabVIEW program and output as an analogue voltage via the data acquisition card into the modulation input of the second current driver in order to close the feedback loop to the TEC. Figure 5 shows a schematic diagram of the experimental configuration.

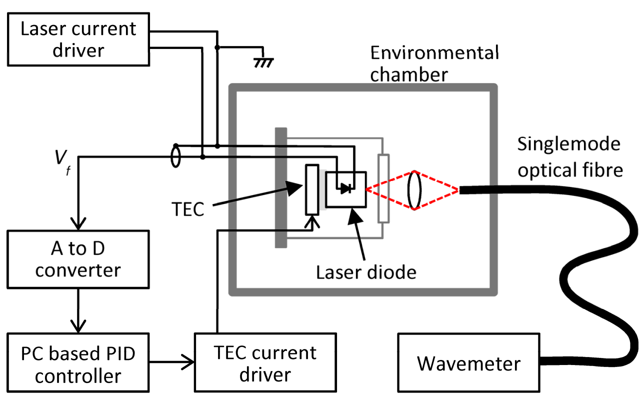

Fig. 5. Schematic diagram of forward voltage laser diode control

Experiments followed the same procedure as described in section 3. Figure 6(a) shows that a systematic error in emitted wavelength persisted, with a similar magnitude (4.5 pm/°C) but opposite sign to that for conventional thermistor control. Figure 6(b) shows the wavelength stability of the laser diode at constant temperature and injection current, over a period of 60 minutes. The wavelength stability was σ ± 1.4pm, which was comparable to that under conventional thermistor based control. The apparent dropout at 39min was a slow change that took place over approx. 1min, when the control loop lost lock and then recovered.

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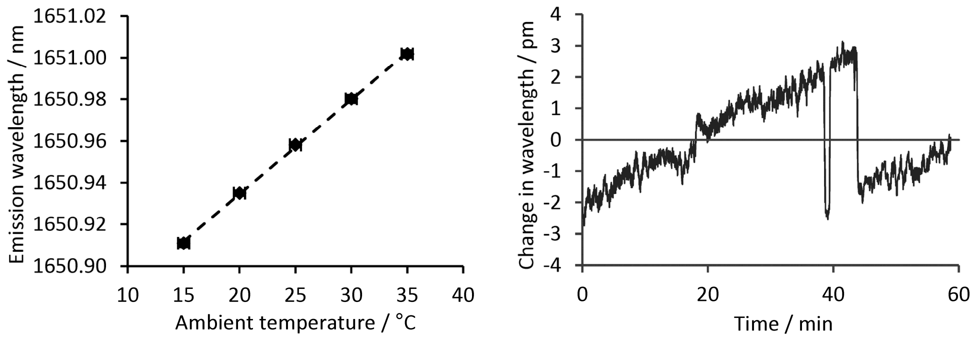


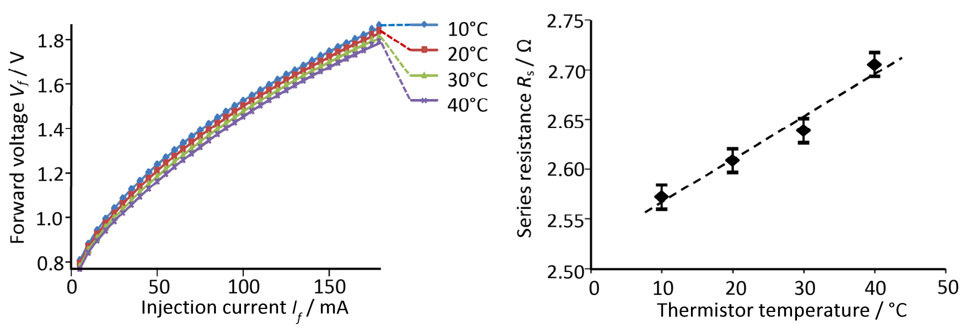
(a) (b)

Fig. 6. Results for laser diode controlled using the forward voltage method, at a constant injection current of 167mA. (a) Variation in wavelength with ambient temperature. A best fit straight line (dashed) is also shown. (b) Long term wavelength stability at an ambient temperature of 20°C. Data available at [25].

The long term wavelength stability and systematic error in wavelength with ambient temperature changes for the forward voltage method were comparable to that of thermistor control. However, tuneable diode laser spectroscopy of gases such as methane, where the absorption linewidth is 40pm FWHM at atmospheric pressure, requires a more stable laser diode wavelength when faced with varying ambient temperatures. For ITU grid operation, the wavelength drift also falls outside acceptable limits even for small (± 3°C) temperature changes. Therefore, an improved wavelength control method is required.

5. Variation in series resistance with temperature

As discussed previously, the junction voltage of a laser diode can provide a precise and accurate measurement of its temperature. However, for DFB laser diodes such as that used in this work, we have found that the combination of an injection current of the order of 100 mA and a small series resistance imposes a small but significant error on the resulting forward voltage, which is what is measured. Figure 7(a) shows a series of V-I curves (plots of forward voltage V_f versus injection current I_f) and different laser diode operating temperatures (controlled in this case using the thermistor at constant ambient temperature), illustrating a change in series resistance with temperature.



(a) (b)

Fig. 7. Electronic characterisation of the laser diode while operating under thermistor control at different thermistor temperatures. (a) V-I plots, and (b) derived values of series resistance as a function of temperature, with a best fit straight line (dashed). Data available at [25].

Figure 7(a) shows that with increasing temperature, the forward voltage decreases. However, the data can also provide a measure of the dynamic series resistance. We measured the value of $I_f.\partial V_f/\partial I_f$ as a function of $\partial I_f/\partial V_f$ and analysed the gradient to give the series resistance, R_s [22], shown in Fig. 7(b). It can be seen that the series resistance increases with

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temperature. The value of $\partial R_s/\partial T_{th}$ in Fig. 7(b) is $4.3 \times 10^{-3} \Omega K^{-1}$, yielding a value of α (Eq. (4)) of $1.7 \times 10^{-3} K^{-1}$. At an injection current of 170 mA, a change in ambient temperature of 20°C produces a change in series resistance of 0.13 Ω and an increase in the forward voltage of 22 mV, a significant offset if the forward voltage is to be used for precise thermal control.

6. Junction voltage based control

The principles of junction voltage based temperature control are illustrated in Fig. 8. Firstly, we measured the DC forward voltage V_f of the laser diode, as described in section 4. Secondly, we applied a high-frequency sinusoidal dither δI to the DC injection current I_f, resulting in a small modulation of both the wavelength and the forward voltage. Monitoring the magnitude of the modulated voltage δV, using a lock-in amplifier, gave a dynamic measure of the series resistance as $\partial V_f / \partial I_f$. Thirdly, we used the value of $I_f R_s$ to compensate V_f and provide the underlying junction resistance V_j. Finally, we subtracted V_j from a chosen setpoint voltage V_{set} and passed the resulting setpoint error to a PID control loop that controlled the current to the TEC. This scheme necessarily involves wavelength modulation of the source, therefore we aimed to control the centre wavelength of the emission.

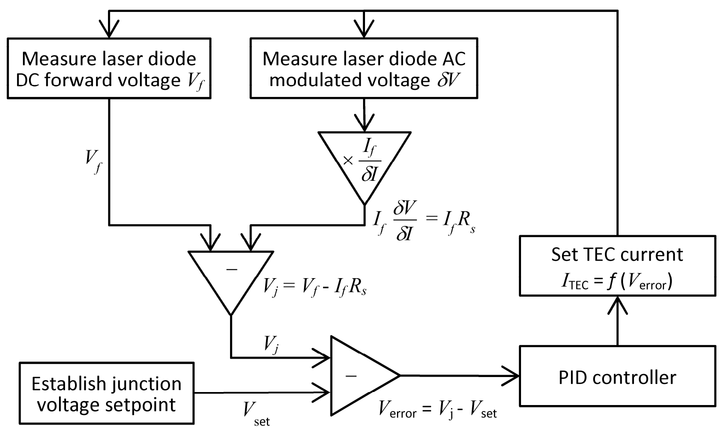

Fig. 8. Flow diagram for junction voltage based laser diode control, using forward voltage measurement with dynamic correction for the series resistance.

The magnitude of the applied modulation was chosen so as to be suitable for TDLS using wavelength modulation spectroscopy at the second harmonic of the modulation frequency f. Typically, the optimum amplitude (for maximum 2f signal) is a factor of 2.2 greater than the chosen gas linewidth [26]. In practice, the chosen amplitude was a compromise between the optimum value of 88pm and the desire to keep the modulation as small as possible.

The high frequency (31kHz) tuning coefficient of the laser diode was determined according to the method described by Schilt and Thevenaz [27]. The amplitude corresponding to the optimum 2f signal was measured, this being 2.2 × the methane linewidth of 40pm at atmospheric pressure, the latter determined using data from the HITRAN database [4]. The tuning coefficient for operation at 31kHz at this optimum setting was then 8.6 ± 0.4pm.

Figure 9 shows the experimental configuration for wavelength control using the laser diode junction voltage. A current driver (Thorlabs LDC200) was used to bias the diode with a DC injection current of 166 mA. In addition to the DC bias, the laser diode was modulated at f = 31 kHz with a modulation amplitude of δI = 4.5 mA p-p, which also gave a p-p wavelength modulation of 39 ± 3 pm. A lock-in amplifier (Stanford Research SR850, τ = 300ms, 24 dB/octave, X output) was used to measure the forward voltage at the first harmonic of the modulation frequency (1f). The voltage output from the lock-in was passed to the data acquisition card and used to compensate the forward voltage in order to recover the junction voltage. The scale factor used for this compensation was determined using a starting value of 2.6 Ω for R_s and then by making minor changes until the controller was stable. Again, voltage compensation and the PID were implemented in Labview. The output from the PID was sent to the modulation input of a second current driver (ThorLabs ITC510) in order to close the feedback loop to the Peltier element.

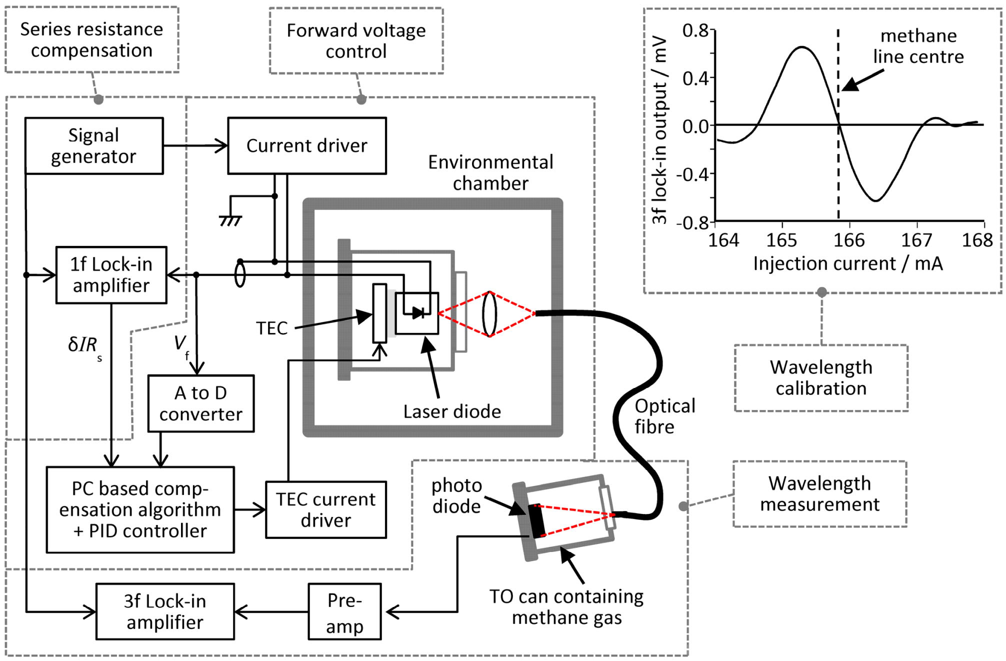

Fig. 9. Configuration of junction voltage method for stabilising the wavelength of the laser diode. Inset: Wavelength measurement calibration showing 3f-demodulated signal from methane reference cell as a function of DC injection current taken at a single, thermistor-controlled temperature.

Had we used the wavemeter described in the previous sections, it would have measured the time-averaged emission corresponding to the envelope of the wavelength modulation (approx. 40pm p-p) resulting from the applied AC current. Although in principle, numerical averaging might have reduced the aliased modulation signal to leave the DC component, in practice the response time of the instrument would have cause signal blurring that interfered with its operation. Instead, the emitted wavelength was measured spectroscopically with the help of a methane reference cell, a TO can filled with 2.5% methane in nitrogen at atmospheric pressure and containing an InGaAs photodiode. We therefore relied on the wavelength stability of the gas line itself; any wavelength instability of the gas line is negligible for this system [4].

To ensure that the laser diode emision coincided with the gas absorption line centre, the laser was first coarsely tuned in operating temperature and injection current. Indeed, it was the settings required to achieve such emission that dictated our choice of operating temperatures and injection currents throughout this study, to ensure comparability of data. The signal from the photodiode pre-amplifier was demodulated at 3f using a lock-in amplifier (Stanford SRS 850, τ = 300ms, 24 dB/octave, X output) in the manner of wavelength modulation spectroscopy [3]. The 3f signal passes through zero at the gas line centre at 1650.96 nm (see Fig. 9 inset), therefore this signal offered a convenient measure of the deviation of the emitted centre wavelength. The wavelength modulation means that the instantaneous wavelength was constantly varying.

To calibrate our wavelength scale, the 3f signal was recorded while simultaneously applying a slow (5Hz) current ramp between 164 and 168mA. The results of this are shown in

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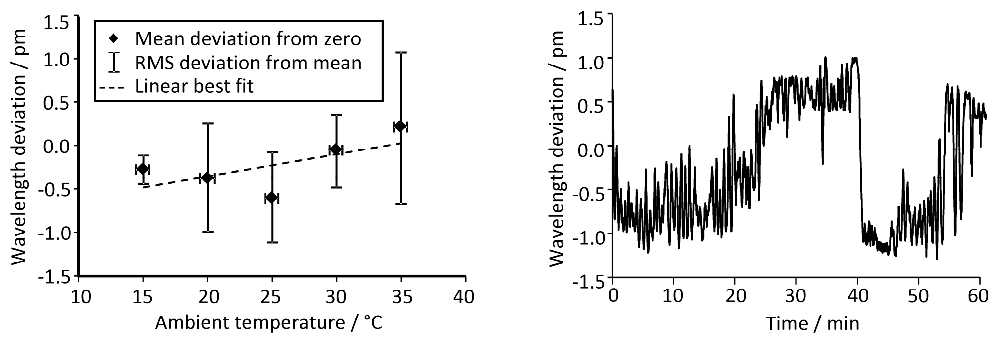
Fig. 9 (inset). The OSA was used to establish a DC tuning coefficient of 23.4 pm mA^{-1}, which was then used to convert the current scale on the x-axis of Fig. 9 (inset) to a wavelength scale. At the line centre zero crossing, the transfer function of the 3f gas line signature then provided a means of converting small wavelength changes to measurable voltages, with a calibration factor of 81 μV pm^{-1}.

Use of 3f detection restricted our choice of modulation frequency. The frequency was chosen to be as high as possible, which would minimise laser excess noise and ensure that we integrated over the maximum possible number of modulation cycles in our measurements. A frequency of 31 kHz achieved these aims while still allowing the 3f harmonic to be detected within the 102 kHz maximum bandwidth of the second lock-in amplifier.

Using the above calibration, the wavelength deviation from the gas line centre was monitored while the laser diode was operated under junction voltage control. Data was collected for different external ambient temperatures in the range 15-35°C. The results in Fig. 10 show that the control technique maintained a highly stable centre wavelength both over time and in the face of ambient temperature changes. Over the entire test, the RMS deviation from the methane line centre was 0.6 pm, which is comparable with the level of stability achieved using conventional control at a single ambient temperature. Any systematic change with ambient temperature could not be fully resolved below the RMS precision.



(a) (b)

Fig. 10. Results for laser diode operated under junction voltage control at a constant injection current of 165.8mA. (a) Wavelength drift with ambient temperature. A best fit straight line (dashed) is also shown. (b) Long term wavelength stability at an ambient temperature of 20°C. Data available at [25].

Figure 10(b) shows the long-term wavelength stability of the laser diode using junction voltage control at an external ambient temperature of 20°C and injection current of 165.8 mA for a duration of one hour. The deviation of the laser diode central peak wavelength from the 3f signal horizontal zero axis gave a precise measure of the wavelength stability. The laser diode remained stable over a period of one hour with a centre wavelength deviation of σ = 0.7pm. The cause of the change in wavelength at around 40min is uncertain; this was not sudden but was a smooth transition that took place over approximately 45s.

Note that these measurements relate to the centre wavelength of the applied modulation, the latter being Δν = 4.4 GHz (Δλ = 40 pm), which was large compared to the measured changes in centre wavelength. This modulation depth was chosen partly to give a large 3f signal from a gas absorption line, and partly because such modulation depths are typical for TDLS. If a smaller modulation were preferred, it should be possible to reduce it without compromising the sensitivity of the voltage measurements. The magnitude of the measured demodulated voltage was a few mV, and control of the centre wavelength required a measurement precision of < 0.7pm/40pm = 1.8%, or around 80μV. As voltage amplifiers are available with noise levels of the order of nV $Hz^{-1/2}$ at kHz frequencies, it should be possible to reduce the modulation depth by a factor of 1000 (to around 0.04pm).

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7. Discussion and conclusions

The relationship between a laser diode's junction voltage and its operating temperature can be used as the basis for a temperature sensor which, within a control loop, can stabilise the temperature and thereby the central frequency of the laser diode if the DC operating current is also fixed. Previous work has shown that measurement of the forward voltage can be employed for this purpose. However, in this study we found no benefit to using forward voltage control compared with a conventional thermistor.

The series resistance of a DFB laser diode was measured over a range of operating temperatures and was found to increase with temperature. Although the series resistance was only between 2 and 3 ohms, for DFB laser diodes requiring injection currents of the order of 100 mA or more, we found that changes in the series resistance with temperature can create a small but significant systematic error in the measured forward voltage.

A new control system was developed based on measurement of the junction voltage of the laser diode to stabilise its emission frequency/wavelength. The laser diode series resistance was measured dynamically as $\partial V/\partial I$, by modulating the injection current with a DC bias above threshold and demodulating the forward voltage at $1f$ using a lock-in amplifier. The output was scaled and subtracted from the DC forward voltage measured across the laser diode, providing real-time compensation that enabled the underlying junction voltage to be measured. The junction voltage was then subtracted from a voltage setpoint and the result used as an error signal in a PID control loop.

The compensated voltage was used to control the laser diode temperature while the laser was held at a fixed bias current, which provided long-term frequency stability (at a fixed ambient temperature) of the same order as conventional thermistor control. However, in the face of external ambient temperature changes, the new method resulted in an improvement in accuracy of approximately 2 orders of magnitude. Any systematic change in frequency with temperature could not be distinguished above the time-varying frequency precision of the technique. Table 1 shows the quantified comparison.

Table 1. Comparison of laser diode frequency (or wavelength) control techniques

Wavelength control technique	Long term stability (60 min)	Systematic drift with ambient temperature
Thermistor	± 240 MHz (± 2.2 pm)	-420 MHz /°C (-4.0 pm /°C)
Forward voltage	± 150 MHz (± 1.4 pm)	490 MHz /°C (4.5 pm /°C)
Junction voltage	± 80 MHz (± 0.7pm)	$\leq$ 3 MHz /°C ($\leq$ 0.03 pm /°C)

Laser diode frequency stability is important in applications such as telecommunications, to ensure the emission frequency remains on the ITU grid within a specified tolerance of $\Delta\nu$ = ± 1.5GHz ($\Delta\lambda$ = ± 12pm) [2], and for tunable diode laser spectroscopy, to enable high resolution measurement of narrow gas absorption lines. For example, the methane absorption at 1650.96 nm has a linewidth (FWHM) of $\Delta\nu$ = 4.4GHz ($\Delta\lambda$ = 40 pm) at atmospheric pressure and low concentration. For an ambient temperature change of 20°C, conventional thermistor control would suffer a frequency change of 8.4 GHz (76 pm), greater than this gas linewidth and outside acceptable limits for telecoms applications. Using junction voltage control would bring this down to a more manageable 80 MHz (0.7 pm), which is much smaller than the gas linewidth. This level of precision would also be acceptable for telecommunications so long as the overall wavelength modulation depth (currently 40 pm or 4.4 GHz) can also be significantly reduced, which is considered feasible.

To achieve this level of frequency stability has required two constraints on laser diode operation. First, operation at a fixed DC current was needed because changes to carrier density can affect the refractive index of the active region, and because the injection current exerts an effect on diode temperature via the Shockley equation. Operation with varying DC injection current would require measurement of that current and use of experimentally determined calibration factors for both the V_j and R_s elements of the control system, via an algorithm or look-up table. Lin *et al* have used the value of $\partial V_f/\partial T$ to correct for changes in diode temperature that are influenced by the injection current [18]; our work suggests that series resistance correction might be required to yield $\partial V_j/\partial T$ in their scheme. Further compensation may be needed for changes in the refractive index of the diode's active region.

Secondly, we applied a small sinusoidal current modulation to the diode, which results in both a small intensity variation and a wavelength modulation (the latter at around 40pm being significantly greater than the measured deviation in centre wavelength). A wavelength modulation is often used in TDLS, where the 2f signal is used to measure target gas concentration [3]. We therefore believe that this technique is well suited for use with TDLS, and it confers a significant advantage in that it does not require the use of a gas reference cell. For applications where the magnitude of the wavelength modulation is a problem, we believe that this could be reduced without compromising the precision of the measurement.

We should also consider whether there are other influences on the measured forward voltage that could create errors for this control technique. It is known that changes in optical feedback can cause a measurable change in the voltage across the device [28]. When the source of the feedback comprises one end of a weakly reflecting external cavity, such changes may be measured as a small sinusoidal deviation in the voltage as the wavelength is scanned. This is the basis for the so-called self-mixing technique to measure displacement of the cavity reflector [28], and can arise both from specular and diffuse reflections. Our previous work with a DFB laser at 1651nm (albeit of a slightly different type) shows that for high, exaggerated levels of feedback, the voltage across the laser diode showed a deviation of up to a few mV [29], which would interfere with the control precision required here. In the experiments described in this paper, we reduced feedback levels using a low coupling efficiency to the singlemode optical fibre. For consistent performance under all circumstances, it is recommended that lasers are operated with an optical isolator.

In summary, we have developed an all-electronic method of stabilising the frequency of a laser diode, with a systematic frequency deviation (under the influence of external changes to the ambient temperature) that is a significant improvement over previous electronic techniques. The level of stabilisation achieved is compatible with the stringent demands of both TDLS and telecommunications. Although we implemented this using laboratory grade, bench-top electronics, we believe that the electronics design could be simplified and miniaturised to be incorporated into laser diode controllers. Use of a current modulation yields a variation in the instantaneous wavelength; this is not a problem for TDLS using wavelength modulation spectroscopy but may in future be minimised to a wavelength modulation at or below the residual wavelength fluctuation noise. Use of the technique requires characterisation of the laser diode's series resistance, which may be automated through the use of V/I curves, and selection of a voltage setpoint that corresponds with the correct operating wavelength. In this respect there is little difference from the present conventional situation, which requires characterisation of the wavelength variation with thermistor temperature. Previous measurement of the forward voltage with laser diodes [17], LEDs [19] and quantum cascade lasers [20] for control or characterisation purposes provides encouragement that the new technique might usefully be applied to a wide range of active optical emitters.

Funding

Engineering and Physical Sciences Research Council (EPSRC) (EP/I002278, EP/H02252X).

Acknowledgments

We are grateful to Howard Potter Laser Technology and High Finesse GmbH for the loan of the wavemeter described in Section 3. Portions of this work were presented at the SPIE Conference Laser Sources and Applications II, 2014, SPIE 9135-46.