



Athermal operation of multi-section slotted tunable lasers

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Abstract: Two distinct athermal bias current procedures based on thermal tuning are demonstrated for a low-cost, monolithic, three section slotted single mode laser, achieving mode-hop free wavelength stability of $\pm 0.04 \text{ nm} / 5 \text{ GHz}$ over a temperature range of $8\text{--}47^\circ\text{C}$. This is the first time that athermal performance has been demonstrated for a three-section slotted laser with simple fabrication, and is well within the 50 GHz grid spacing specified for DWDM systems. This performance is similar to experiments on more complex DS-DBR lasers, indicating that strong athermal performance can be achieved using our lower-cost three section devices. An analytical model and thermorefectance measurements provide further insight into the operation of multi-section lasers and lay the foundation for an accurate predictive tool for optimising such devices for athermal operation.

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1. Introduction

Widely wavelength tunable lasers are key enablers of wavelength-division multiplexing (WDM) systems, with sampled grating distributed Bragg reflector (SG-DBR) [1] and distributed feedback (DFB) [2] laser arrays demonstrating wide tunability. Although tunable DFB and DBR lasers demonstrate good optical power and wavelength stability, the high-resolution processing and complex regrowth steps involved in their fabrication can result in low yield and high manufacturing costs [3]. This high cost may be a barrier to the implementation of scalable fiber-to-the-x (FTTx) solutions, with architecture such as passive optical networks (PONs) requiring low-cost tunable lasers on the optical network unit (ONU) side [4]. To facilitate such systems, it would be advantageous to implement single-mode lasers with relatively simple fabrication; that is, with no regrowth and low cost etch processes. To this extent, laterally coupled DFB lasers and surface-grating DBR lasers that use a single growth step have been employed [5,6]. However, the patterning of these devices still requires electron-beam lithography, which itself is expensive and time consuming. A potential solution to this cost issue is to simplify the fabrication process even further by etching high order grating features on the surface of the waveguide, thereby avoiding the aforementioned high-resolution processing and regrowth steps. Such slotted lasers could be fabricated at low costs and high yield, and have been found to exhibit low threshold currents, narrow linewidths and high slope efficiencies [3, 7, 8].

To provide wavelength stability, typical WDM systems are cooled by thermoelectric coolers (TECs). This leads to expensive packaging costs and high energy consumption, which also reduces scalability. One solution to this is to athermalise the laser diode, making its lasing wavelength insensitive to temperature change by varying the currents across the laser sections, provided that the necessary optical power for the optical link and device reliability is realised at elevated temperatures. In order to athermalise a laser, it is necessary to control the thermal drift of mirror loss and cavity modes, and offset these against each other [9]. Although the design and fabrication of such lasers initially proved difficult [10], the performance and wavelength stability of athermal tunable lasers has improved significantly in recent years [11], with recent work by Zhu et al. achieving wavelength accuracy of ± 3 GHz over a 15–70°C range [4]. This required control over the current supplied to 5 sections of the DS-DBR laser and feedback

from a centralised shared wavelength locker [12]. An alternative to tunable lasers is materials based athermalisation, in which a waveguide consisting of two or more materials is engineered to balance the confinement factor with the thermo-optic coefficient such that the thermal drift is close to zero [9]. Towards this, materials-based athermal ring resonators [13] and DBR gratings [14] having been demonstrated in the literature. Furthermore, if athermalising a full WDM laser array, it is necessary to take thermal crosstalk between adjacent lasers into account, since this has been shown to be a significant issue in photonics integrated circuits (PICs) [15].

While various athermal control schemes for tunable lasers have been proposed, these often add an extra layer of complexity to what are already comparatively high-cost lasers. Thus, it is the goal of the current research to implement athermal control for a low-cost, multi-section, high order grating laser under continuous wave operation, which is relevant to a wide range of cost-sensitive photonics applications. This work also investigates the fundamental operation of these multi-section slotted lasers in greater detail through the development of a phenomenological model and through thermoreflectance measurements. It is intended to use these measurements to developing a tool for predicting optimal multi-section athermal laser design for a variety of applications.

2. Laser design and operation

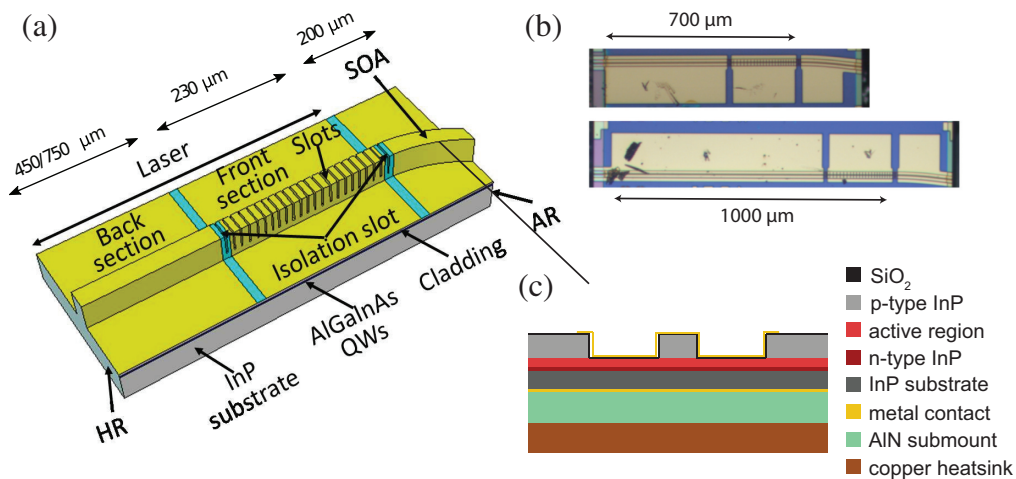


Fig. 1. High order slotted laser. (a) Schematic, (b) optical image and (c) epitaxy of the three section laser, showing the ridge waveguide in the centre.

Figure 1 shows a schematic of the slotted laser structure featuring the surface high order grating, which has been described in [7] and [8]. The $2\text{ }\mu\text{m}$ wide ridge waveguide is split into three sections: gain (back), grating (front) and semiconductor optical amplifier (SOA). The front current controls the grating reflectivity peak (Bragg peak), the back controls the gain as well as the phase of the lasing mode, and the curved SOA section amplifies the signal while also forming part of the waveguide. The front section is fixed in length at $230\text{ }\mu\text{m}$, while lasers of varying back section length have been developed, resulting in total cavity lengths of 700 and $1000\text{ }\mu\text{m}$ (Fig. 1(b)). Note the $200\text{ }\mu\text{m}$ SOA is curved at 7° to reduce the reflection from the front facet. The front grating section has 24 slots separated by $\sim 9\text{ }\mu\text{m}$, which act as a 37th order active DBR reflector of the laser and provide sufficient feedback from the front side for lasing. The number of slots is a trade-off between maximising the reflectivity and minimising the bandwidth of the reflection peaks, yielding a calculated amplitude reflection and transmission of approximately 0.43 and 0.4, respectively. A high reflectivity (HR) coating is applied to the back facet to improve

threshold and slope efficiency and an anti reflection (AR) coating is applied to the output facet to avoid feedback. An array of 12 lasers with lasing wavelengths spanning 28.5 nm is achieved by changing the pitch of each lasers' grating using the Bragg equation

$$p = \frac{m\lambda_{bragg}}{2n_{eff}},$$

where p is the grating period, m is the grating order n_{eff} is the effective index and λ_{bragg} is the wavelength of the Bragg peak. This results in a total grating pitch change of $\sim 0.205\text{ }\mu\text{m}$ over the whole array.

The epitaxial structure, shown inset in Fig. 1(c), contains an active region consisting of five AlGaInAs quantum wells with an emission peak at $\sim 1545\text{ nm}$. Above this are a $1.6\text{ }\mu\text{m}$ thick p-doped InP layer, 50 nm -thick, p-doped InGaAsP layer, and a 200 nm InGaAs contact layer. The laser fabrication process involves forming the ridge and slots via two inductively coupled plasma (ICP) etch steps using Cl_2 and N_2 gas, after which the laser ridge is passivated and metal contacted. The laser is subsequently coated in high reflection (HR) and anti-reflection (AR) films, before being eutectic bonded onto an AlN carrier. It should be noted that the lasers in the current study do in fact use e-beam lithography to form the grating patterns due to the lack of an i-line stepper in the foundry, but this is not a technical requirement of the device fabrication. These lasers have found to exhibit strong performance under continuous wave (CW) operation. In previous work [3], an array of 12 slotted lasers demonstrated full C-band coverage and a threshold current of $25\text{--}35\text{ mA}$ at 20°C , with a side-mode suppression-ratio (SMSR) $> 40\text{ dB}$ and a linewidth below 500 kHz .

When athermally controlling the device, it is mounted on a copper block, which uses a thermoelectric cooler (TEC) and an embedded thermistor to fix the operating temperature. Three separate current sources provide a bias to each laser section and the SOA, with the output of the laser coupled in free space into either a photodiode (power measurements) or a single-mode fibre and optical spectrum analyser (wavelength measurements).

3. Laser athermal characterisation

Figure 2 shows the shift in wavelength with respect to changing the front and back currents for a 1 mm cavity laser at a submount temperature of 20°C . The tuning map is found by sweeping the front and back currents and reading the peak wavelength on the optical spectrum analyser while maintaining the submount temperature constant. The behaviour of these lasers at low currents is driven by the carrier effect, while the wavelength shift at higher currents is due to temperature effects.

The features of the tuning maps suggest two distinct control schemes, which we refer to as continuous and discontinuous tuning. In the continuous scheme, which is applied to a 1 mm cavity laser, the longitudinal mode is not switched at any stage. In this case, the front and back currents are swept within a targeted range at 5°C increments until a mode-hop occurs. We can use this to define a current path that avoids any discontinuities due to mode hopping. This is denoted as the red line in Fig. 2, with a square denoting the currents at 20°C . At higher temperatures, the SOA is used to maintain adequate power levels: as the SOA is outside of the laser cavity, it is sufficient to characterise a single SOA section for output power against injection current and use this to compensate for changes in power for any cavity length. Note that as the wavelength red-shifts with increasing temperature, the currents follow the red path from right to left. Figure 3(a) shows the wavelength, section currents and SMSR for the slotted device along this current path. This method yields athermal operation up to 47°C with a wavelength stability of $\pm 0.04\text{ nm} / 5\text{ GHz}$, minimum SMSR of 37.5 dB . An output power stability of $\pm 0.035\text{ dBm}$ was achieved as seen in Fig. 4(a), which also shows the wall plug efficiency during athermal operation. Achieving stability above 47°C using this scheme proves problematic, as using higher back section currents

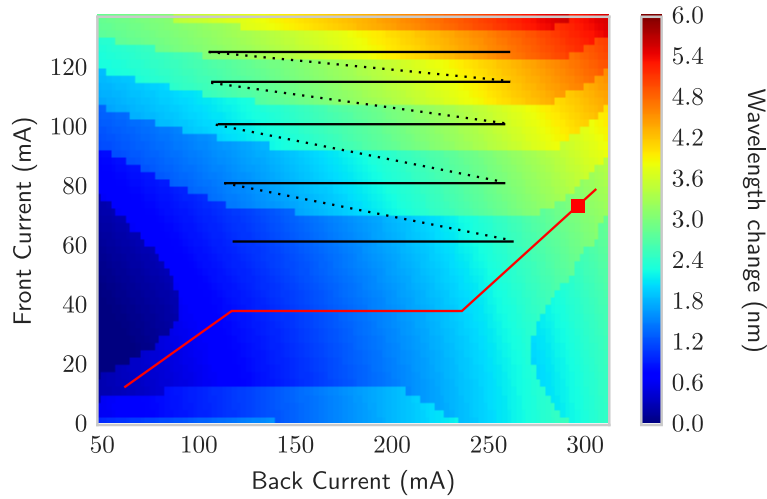


Fig. 2. Laser tuning map. Experimental tuning map for a 1 mm long laser cavity at 20°C, where black and red lines represent discontinuous and continuous current paths, respectively. The red square corresponds to an ambient temperature of 20 °C during athermal operation.

results in less stable behaviour, in large part due to the gain peak redshifting leading to mode competition from the adjacent Bragg peak.

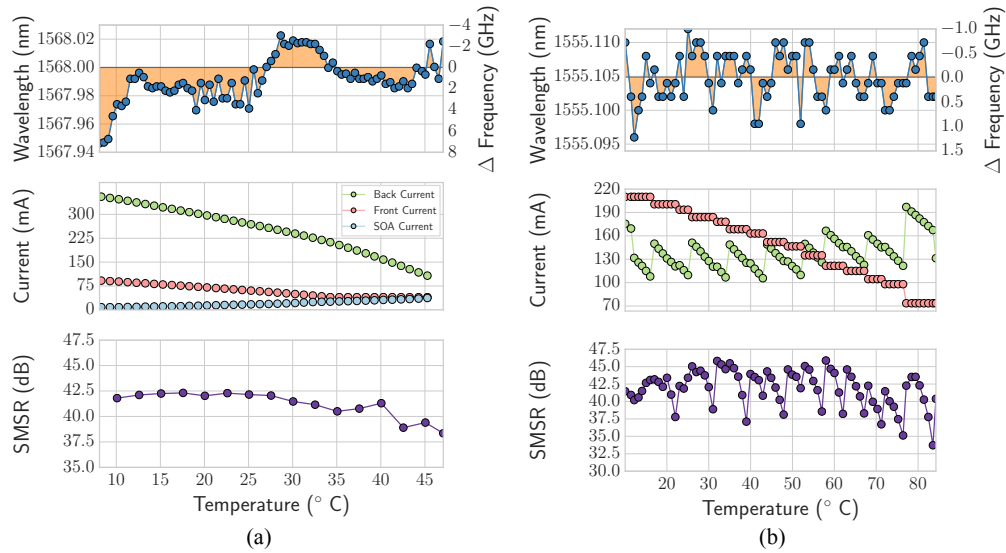


Fig. 3. Wavelength tuning performance for (a) continuous and (b) discontinuous tuning schemes, showing (i) wavelength stability, (ii) applied currents, (iii) SMSR.

Rather than avoiding mode hops, the discontinuous athermal control scheme utilises this behaviour to increase the range of athermal performance, switching the longitudinal mode by changing the current in the front section. Once the device is lasing on one of these modes, the

back section is tuned to keep the mode wavelength stable, with continuous athermal performance for a 10°C temperature range, at which point the algorithm switches to a new mode by increasing or decreasing the front current as required. As mode hops are no longer avoided, it is possible to utilise larger front currents in this scheme to achieve athermal performance over an extended temperature range. The black lines on the laser in Fig. 2(a) are indicative of the tuning currents in this case. Figure 3(b) shows the wavelength, section currents and SMSR for the slotted device along its current path. This method yields extended athermal operation from 10°C up to 85°C (note: we did not operate the TEC below 10°C to avoid water condensation on our unpackaged devices), with a wavelength stability of $\pm 0.01\text{ nm} / 1.25\text{ GHz}$ and a minimum SMSR of 32 dB. This performance is equivalent to experiments on more complex DS-DBR devices [4] but has the additional benefit of being achieved on our low cost devices. Additionally, output power was kept above 10 dBm with a maximum of 13.1 dBm as seen in Fig. 4(b). The wall plug efficiency in Fig. 4 does not take the TEC power into account, since the TEC is only used to simulate various ambient conditions and is not used for temperature control. We observe a maximum wall-plug efficiency at higher temperatures, as the currents used for stabilization of the laser are lower.

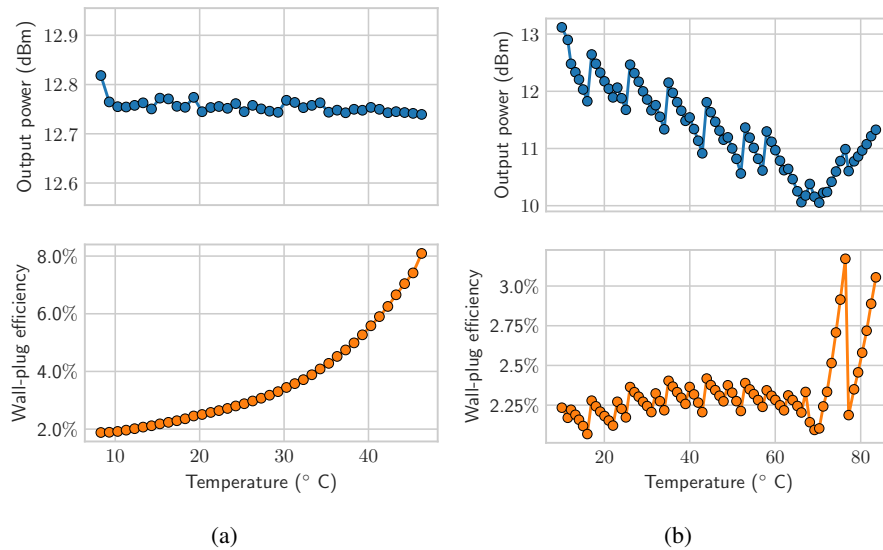


Fig. 4. Output power (top), wall-plug efficiency (bottom) for (a) the continuous tuning scheme with the output power stabilised using the SOA and (b) the discontinuous tuning scheme.

For some WDM systems, it is necessary to operate an array of lasers rather than a single device. Figure 5 extends the discontinuous control scheme to three lasers on a 12-laser array, which span $\sim 28.5\text{ nm}$. In this case, the wavelength stability drops to $\pm 1.75\text{ GHz}$ (which is still within the spacing required by DWDM), while the maximum temperature decreases to 80°C on the blue end of the array. Thus, it should be possible to athermalise a full laser array: however, the thermal cross-talk between adjacent lasers would be a significant factor in the successful operation of this system. Taking this crosstalk into account will require further modelling, building on our previous work [15].

4. Laser surface temperature measurements

In addition to demonstrating the athermal performance of the laser, it would be advantageous to study the temperature distributions in each section of the laser during operation. While the

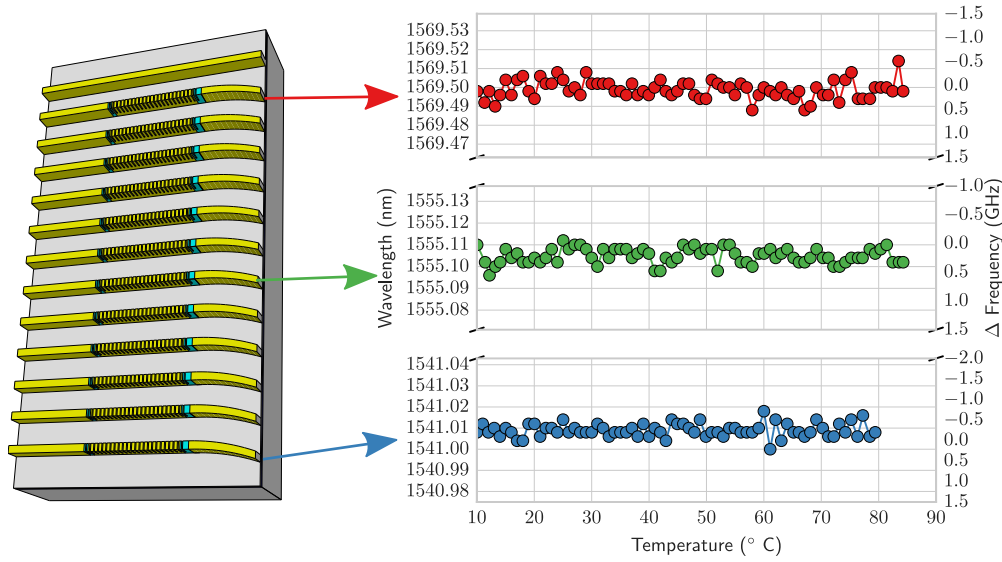


Fig. 5. Wavelength tuning performance for three lasers (numbers 1, 6 and 12) in a 12-laser array at a submount temperature of 20°C.

operating temperature of each section can be found using wavelength measurements of the laser output, these provide only a spatially averaged temperature within each section. However, since the various laser sections are not thermally isolated, it is likely that temperature gradients will exist along the waveguide during normal operation. Measuring the surface temperature distribution directly proves difficult using traditional techniques: infrared (IR) thermography has poor resolution (5-10 μm) and struggles with the low emissivity of the gold contacted laser, while the micro-thermocouples used in scanning thermal microscopy (SThM) absorb the light of light-emitting surfaces, resulting in measurement errors [16]. Herein, we obtain temperature fields across the device using CCD based thermoreflectance imaging (CCD-TR) [17]. CCD-TR does not face the aforementioned issues and provides images of the temperature field at up to 250 nm resolution. The technique involves measuring a small relative change in reflectivity of a sample with respect to a change in temperature. Over small temperature excursions, this temperature change can be approximated as first order, i.e.:

$$\frac{\Delta R}{R} = \left(\frac{1}{R} \frac{\partial R}{\partial T} \right) \Delta T = \kappa \Delta T \quad (1)$$

where $\Delta R/R$ is the relative change in reflectivity, ΔT is the surface temperature change, and κ is the temperature-dependent thermoreflectance coefficient, typically in the range $10^{-3} - 10^{-4}$ [1/K] [18]. Due to this weak dependence, lock-in detection is required to extract small signals from the noisy signal. CCD-TR specifically operates using a periodic current source and a phase locked CCD camera in a standard microscope configuration. Each pixel effectively becomes a locked-in detector, which allows for wide-field thermal imaging with up to 250 nm resolution in a standard optical microscope (20x magnification, NA=0.65). Full details of the technique and the application space are provided in the comprehensive review by Farzaneh et al. [16].

Figure 6 shows CCD-TR images of a 700 μm laser at ambient temperatures of (a) 15, (b) 25 and (c) 35°C, each of which comprises of three images 150 μm x 250 μm in size stitched

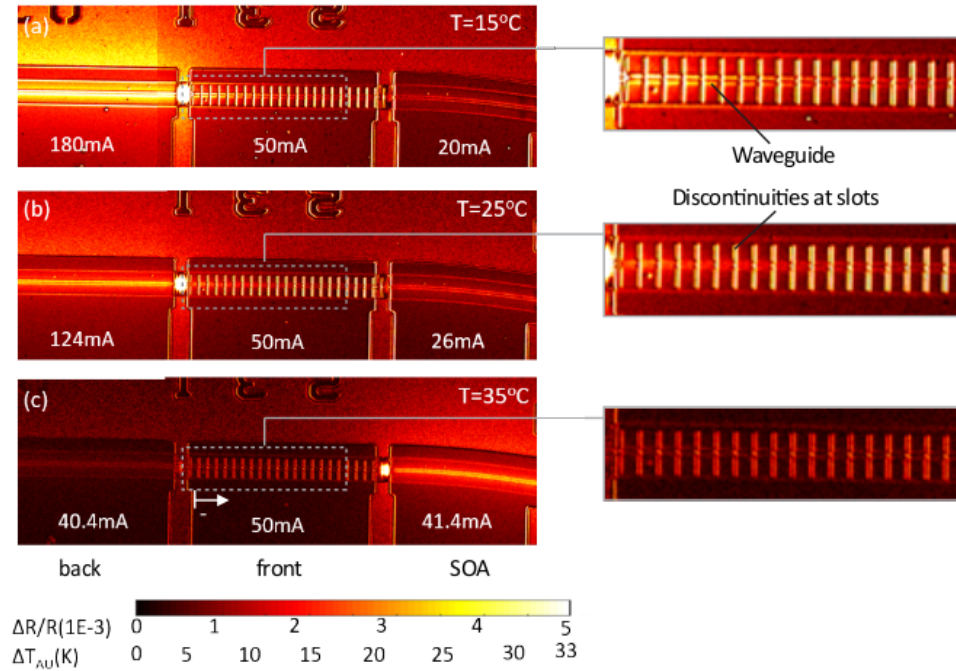


Fig. 6. CCD-TR images. Temperature profile of three section laser operating athermally at ambient temperatures of (a) 15°C, (b) 25°C and (c) 35°C. Inset are the currents to each section to maintain athermal performance. $\Delta R/R$ is the relative change in reflectivity and ΔT is the amplitude of the temperature increase from the ambient temperature in each case. Magnified views of the front sections are also provided.

Table 1. Mean temperatures across the back and SOA section, along with the resultant temperature gradient across the front section.

T_{TEC} [°C]	I_{back} [mA]	I_{front} [mA]	I_{SOA} [mA]	ΔT_{back} [°C]	ΔT_{SOA} [°C]	dT/dx [mK/ μ m]
15	180	50	20	22	6	-29.6
20	154	50	22.4	18.7	5.2	-4.1
25	124.4	50	26	15.5	8.6	-2.2
30	88.8	50	31.5	11.2	12.5	-1
35	40.4	50	41.4	5	18.5	+1.3

together. At each temperature, the current in the back, front and SOA sections are chosen in line with the continuous tuning scheme to maintain athermal performance. The CCD-TR technique yields surface plots of differential reflectivity, which can be converted to temperature by performing a steady state calibration on the gold sections to find the thermoreflectance coefficient ($\kappa = -1.5 \times 10^{-4}$ [1/K]). At each of these operating conditions, we observe very different temperature distributions across the waveguide. For the range of current densities used in these CCD-TR experiments, we observe relatively constant temperatures in the back and SOA sections, but observe temperature gradients across the front section. These are more obvious in the magnified images of the front section in Fig. 6. In these images, we also observe regions of apparently significantly elevated temperature at the slots and around the laser contact pads. These

measurements are artefacts due to a drawback of CCD-TR; namely that changes in reflectivity due to changes in height or material are equated to changes in temperature. Since the grating is etched into the structure, sharp discontinuities are observed due to the 1.35 μm deep slots, which can be removed from the temperature distribution via low-pass filtering. The accuracy of this filter can also be verified since the slot width and spacing are also known. Table 1 tabulates this thermal gradient, along with the steady state temperature of the back and SOA sections.

In addition to informing a laser model under CW operation, these temperature distributions could also be used to develop a model for a slotted laser operating under time division multiplexed (TDM) conditions. In such transient systems, the lasers are directly modulated, with a rapid wavelength drift observed at the beginning of the burst [19]. Mitigating this drift by taking into account the spatial and temporal temperature gradients of these lasers would be key to scalable burst-mode PON applications.

5. Device modelling

In order to develop a predictive tool for slotted laser wavelength tuning behaviour and athermal performance, it is necessary to simulate the laser tuning maps as shown in Fig. 2. As we are modelling 2D tuning maps for a large number of devices, the significant run time of existing discretised time domain models, as described in [20], becomes an issue. As such, an analytical model has been developed with the goal of reproducing the tuning maps of multi-section devices with minimal run-time. To find the tuning behaviour of the laser it is necessary to solve for the wavelength shift of the Bragg peak ($\Delta\lambda_{\text{Bragg}}$) and the shift in the wavelength of longitudinal modes of the cavity ($\Delta\lambda_L$). Since the grating is etched into the structure, a 2D scattering matrix method [21] is used to calculate the reflectivity spectrum of the grating and thus the loss associated with the etched slots. The wavelength shift of the reflection peak is found by considering the front (grating) and back (gain) sections separately and solving the carrier and photon density rate equations [22], which are:

$$\frac{dN}{dt} = 0 = \frac{\eta_i I}{qV} - R(N) - v_g g(N)P, \quad \frac{dP}{dt} = 0 = (\Gamma v_g g(N) - \frac{1}{\tau})P + \Gamma R'_{sp} + P_i, \quad (2)$$

where η_i is the injection efficiency, I is the injection current, q is electron charge, V is the active region volume, v_g is the group velocity, Γ is the confinement factor, R'_{sp} is the spontaneous emission contribution and P_i is the rate of photons entering the grating from the gain section when above threshold. P_i is calculated assuming the steady state approximation $P_i = \frac{n_i(I - I_{th})}{q g_{th} V L}$ where I_{th} is the threshold current, g_{th} is the threshold gain and L is the length of the grating [22]. Values for these constants can be found in [20] and [22]. $R(N) = AN + BN^2 + CN^3$ where A is the Non-radiative linear recombination, B is the Bimolecular recombination and C is Auger recombination coefficient. The photon lifetime τ can be defined in terms of the waveguide and mirror losses, while the gain $g(N)$ is described as a linear function of the front section carrier density, i.e.:

$$\tau = \frac{1}{v_g(\alpha_s + \alpha_m)}, \quad g(N) = \frac{dg}{dN} \frac{N - N_o}{1 + \epsilon P}, \quad (3)$$

where α_s is the waveguide loss, α_m is the minimum mirror loss at the Bragg peak, N_o is the carrier density at transparency and $\epsilon = \epsilon_0 \Gamma$, where ϵ_0 is the non-linear gain saturation coefficient. Solving for the roots of equation 2 yields the average carrier and photon density of the front region, N_F and P_F . The change in the Bragg peak wavelength due to the carrier density change is:

$$\Delta\lambda_N = \frac{dn}{dN} \frac{N - N_o}{n_g} \lambda, \quad (4)$$

with λ set to the approximate lasing wavelength of $1.55 \mu\text{m}$ in this case. As a first pass, the temperature of the front section is found empirically via a quadratic fit of current versus wavelength data, yielding $\Delta\lambda_T = \Delta T d\lambda/dT$, where $\frac{d\lambda}{dT} = 0.09 \text{ nm}/^\circ\text{C}$. Note that this measurement provides only a spatially averaged temperature along this laser section. From Fig. 6 we have found that there are non-negligible thermal gradients present across the individual sections. This thermal cross talk needs to be taken into account to accurately predict tuning behaviour. Using CCDTR, a temperature gradient transverse to the waveguide was measured and normalised as $\Delta T_n(y) = \Delta T(y)/\Delta T(0)$, where y is the transverse distance from the waveguide. This normalised profile is then used to approximate the thermal gradients present across both sections for the required range of injection currents. These thermal gradients are then added to the averaged section temperatures. The wavelength shift of the Bragg peak is now simply the sum of the carrier density and thermal induced wavelength shifts, $\Delta\lambda_{\text{Bragg}} = \Delta\lambda_T + \Delta\lambda_N$.

The wavelength shift of the longitudinal modes is found in a similar fashion to that of the Bragg peak shift. The average carrier and photon density of the gain region, N_B and P_B are calculated using equation 2. In order to account for feedback from the front section, we set $P_i \sim RP_F m$ where R is the power reflectivity of the grating. We then proceed to calculate the wavelength shift of the longitudinal modes in the same manner as for the Bragg peak. Finally the longitudinal mode which will ultimately lase is found by calculating the round trip gain of each mode:

$$g_{\text{round}} = r_1(\lambda) \times r_2 e^{g(\lambda)L} \geq 1 \quad (5)$$

where $r_1(\lambda)$ and r_2 are the grating and end facet reflectivities respectively. In order to accurately model the SMSR $g(\lambda)$ is approximated as $g(\lambda) = \frac{dg}{dN}(N - N_o) - b_1[\lambda - (\lambda_o - b_2(N - N_o) - b_3(\Delta T))]$ where b_1 sets the gain spectrum width and b_2 and b_3 account for gain peak detuning due to carrier density and temperature changes respectively. Now the mode with the highest g_{round} will correspond to the lasing mode. Finally, this process is iterated for a range of front

Table 2. Simulation Parameters

Parameters	Symbol and unit	Values
Active layer thickness	$d (\mu\text{m})$	0.08
Active layer width	$w (\mu\text{m})$	2
Non-radiative linear recombination	$A (10^8 /s)$	1
Bimolecular recombination coefficient	$B (10^{-10} \text{ cm}^3/s)$	1
Auger recombination coefficient	$C (10^{-30} \text{ cm}^6/s)$	3.5
Absorption and scattering loss	$\alpha_s (\text{cm}^{-1})$	20
Transparency carrier density	$N_T (10^{18} \text{ cm}^{-3})$	0.9
Differential gain	$\frac{dg}{dN} (10^{-16} \text{ cm}^2)$	2.7
Spontaneous emission contribution	$R'_{sp} \sim (10^{23} \text{ cm}^{-3})$	1.02
Fundamental gain saturation coefficient	$\epsilon_0 (10^{-16} \text{ cm}^3)$	6
Group index	n_g	3.6
Confinement factor	Γ	0.13
Injection efficiency	η_i	0.8
Grating reflectivity	r_1	~0.4
Back facet reflectivity	r_2	0.95
$g(\lambda)$ parameters	$b_1 (\text{cm}^{-1} \text{ nm}^{-2})$	0.05
	$b_2 (10^{-17} \text{ nm cm}^3)$	-2.7
	$b_3 (\text{nm}/^\circ\text{C})$	0.5

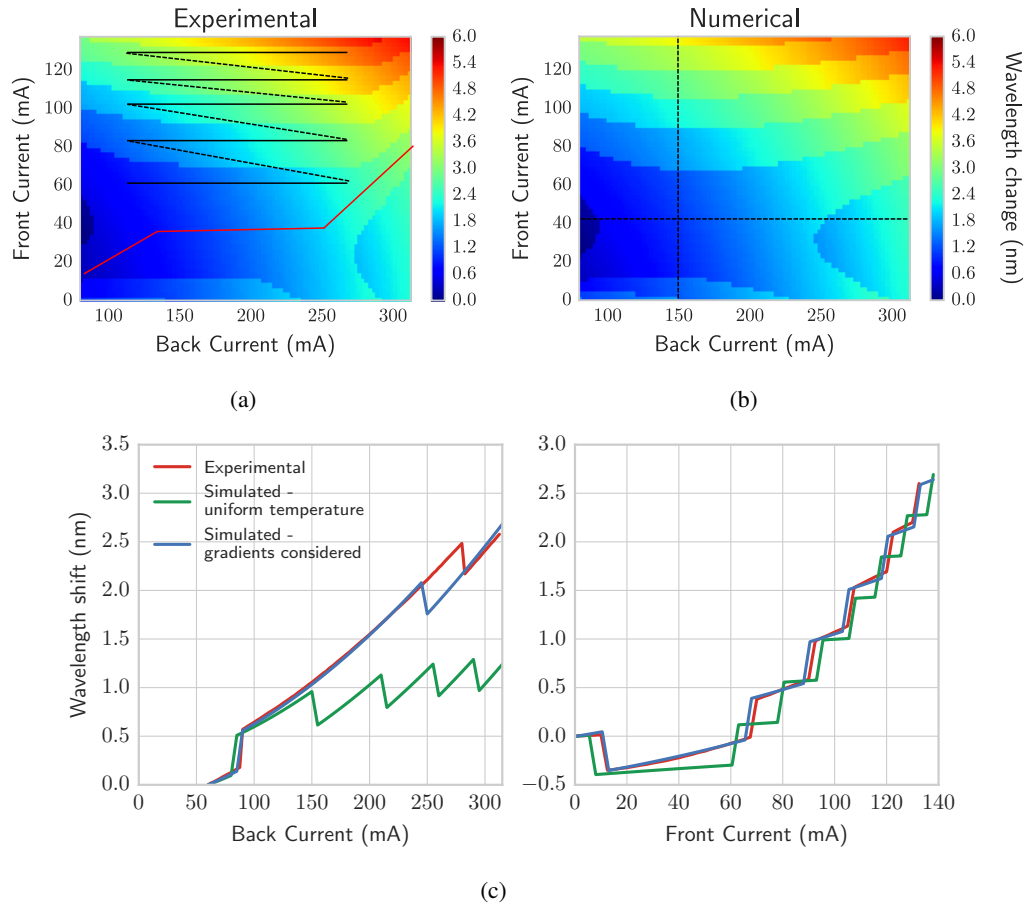


Fig. 7. Analytical model of laser behaviour. (a) Experimental tuning map for a 1 mm long laser cavity at 20°C, where black and red lines represent discontinuous and continuous current paths, respectively, (b) corresponding simulated map. (c) Wavelength shift across the paths highlighted on (b), with and without temperature gradients.

and back input currents to yield a tuning map of wavelength with respect to the currents injected in each section. The SMSR is calculated via the standard analytical approach, which can be found in [22]. Values of the simulation parameters are listed in Table 2.

The experimental and simulated tuning maps are compared in Figs. 7(a) and 7(b) respectively. The model reproduces both the wavelength shift and the location of the mode hops. Figure 7(c) shows the wavelength shift across the current paths shown as dashed lines in Fig. 7(b); first assuming uniform temperature, then taking gradients into account. This shows that the temperature distributions obtained using CCDTR are essential in order to capture the thermal cross talk between adjacent sections and faithfully model the laser tuning behaviour. We observe excellent agreement between the experimental and simulated results, although the model tends to slightly under-predict the wavelength shift due to temperature effects at currents in excess of 240 mA. This is likely due to the analytical approach not taking non-uniform photon density profiles

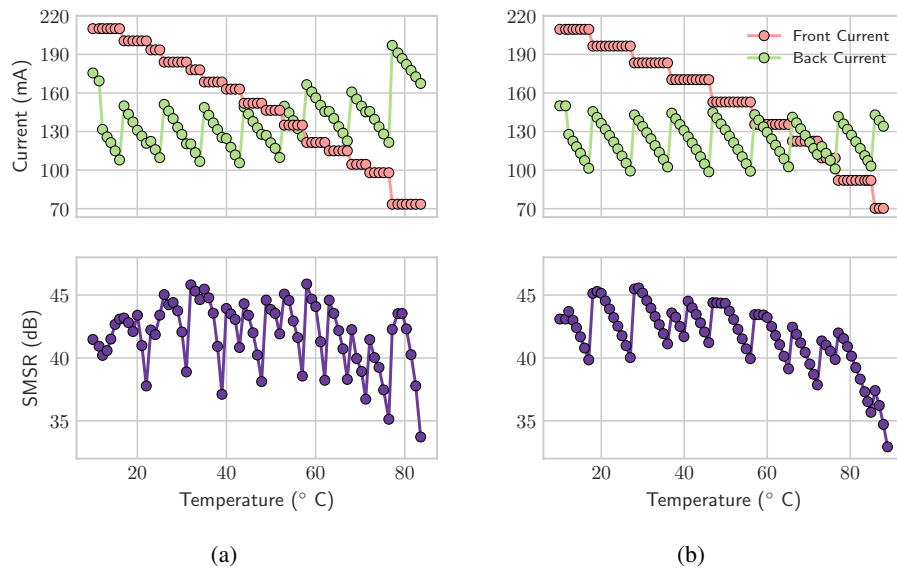


Fig. 8. Discontinuous tuning schemes, showing applied currents and SMSR found by (a) experiment and (b) device modelling.

within the grating into account, which can become significant at high gain section injection currents.

Finally, Fig. 8 compares the modelled currents and SMSR for the discontinuous tuning scheme. For a given laser design, the simulation provides an approximate prediction of required injection currents necessary to maintain athermal performance over a given temperature range, as well as the expected SMSR behaviour. The model overestimates the SMSR in some cases, likely due to the multimode nature of mode competition which is not encompassed fully by our analytical approach.

6. Conclusion

This work demonstrates two athermal bias current control procedures for a three section slotted single mode laser, achieving the same wavelength stability and temperature range as have been demonstrated for DS-DBR lasers but on lasers with a simpler fabrication. Additionally, an analytical model was developed that yields current tuning maps that are in close agreement with the experimental results at lower back section currents. To validate the assumptions made by this model, the CCD-TR technique has been used to experimentally measure the temperature distribution along a multi-section laser. These plots reveal significant temperature gradients across the laser, while implementing such a gradient significantly improves the agreement between experiment and model. These findings will inform high-fidelity future simulations of athermal multi-section devices, allowing for the optimal design of low-cost lasers for athermal WDM applications.

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