Cantú, H.I., McKee, A., Childs, D., Watson, S., and Kelly, A.E. (2017) Dynamic performance of detuned ridge waveguide AlInGaAs distributed feedback laser diodes. *Microwave and Optical Technology Letters*, 59(6), pp. 1468-1470. (doi:10.1002/mop.30561)

Dynamic performance of detuned ridge waveguide AlInGaAs distributed feedback laser diodes

H. I. Cantú, A. McKee, D. Childs, S. Watson and A. E. Kelly

The dynamic behaviour of AlInGaAs ridge waveguide distributed feedback lasers is reported in this work covering five detuned wavelengths between 1291 nm and 1326 nm for a laser active layer optical peak gain design centred at 1310 nm at room temperature. The detuning is achieved by modifying the laser grating pitch that performs the mode selection within the laser cavity simultaneously across a single processed wafer. The dynamic behaviour is evaluated using the resonance frequencies of the detuned lasers measured at a range of injection currents for heatsink temperatures of 25 °C and 85 °C. The results confirm that a speed improvement can be achieved at 25 °C by detuning the laser to shorter wavelengths. However, the results also show that a lower direct modulation bandwidth at 85 °C makes the shorter wavelength design less attractive. For communications applications such as 10 Gbps uncooled operation, this trade-off between detuning and modulation bandwidth imply an optimum around -2 nm to +8 nm detuning (measured at 25 °C).

Introduction: Distributed feedback (DFBs) lasers are essential components of uncooled fibre based optical communication applications where low chromatic dispersion is required over long transmission distances. In addition, single mode operation and intensity stability enable superior dynamic performance compared to that of the traditional Fabry-Pérot (FP) laser. The DFB lasers spectral purity is determined by an internal Bragg grating structure whose principles of operation are based on the coupled wave theory developed by Kögelnik and Shank in the 1970s [1]. The design of the grating itself is at the heart of the dynamic performance of the DFB laser, given the relationship between peak and differential optical gain, grating wavelength detuning, and the achievable value of the resonance (relaxation) frequency that limits the modulation bandwidth of the device. All these factors are also temperature dependent, adding to the design complexity.

The authors in [2] proposed to improve the dynamic behaviour of DFB lasers by increasing their differential gain using wavelength detuning to shorter wavelengths. While the authors in [3] showed model and experiment results arguing that for a compressively strained 5 quantum well AlInGaAs system, the best way to preserve dynamic behaviour across temperature was to detune the lasing wavelength 25 nm longer than the peak optical gain wavelength.

In this work the detuning technique and its effects on the dynamics of DFB lasers is explored for lasing wavelengths between ~20 nm below and ~16 nm above the peak optical gain (at 25 °C).

A range of samples have been fabricated and tested in this work, where the pitch (Λ) of the grating layer has been varied gradually in order to detune the lasing wavelength from the peak optical gain of the multi-quantum wells (MQWs). All these lasers are designed on InP based ridge waveguide (RWG) technology, have a cavity length (L) of 250 µm, a room temperature threshold current (I_{th}) between 8 mA and 12 mA, and a slope efficiency (SE) above 0.35 W/A. For 1310 nm operation (Λ~203.4 nm), the nominal grating strength κL was 1.35, where κ is the grating coupling coefficient. No phase shifts were introduced to modify the periodicity of the grating. Each DFB laser has a front facet anti-reflective coating (AR) and a back facet highly reflective coating (HR).

Table 1 illustrates the general characteristics of the detuned laser samples. The nominal wavelength of the DFB lasers without any detuning would be ~1310 nm when operated at 25 °C.

Grating design and spectral performance: The DFB laser epitaxial structure consists of an AlInGaAs-InP strained MQW design that provides the optical gain under carrier injection. A grating layer made of InGaAsP quaternary material and overgrown InP is placed directly above the active layers in order to produce the periodic change in dielectric constant required to perform the longitudinal mode selection. Figure 1 is a transmission electron microscopy (TEM) image that illustrates the position of the grating layer relative to the active layers in each sample. Figure 1 also shows the profile of the periodic grating as well as the grating pitch (Λ) that determines the value of the lasing wavelength. The values for the grating pitch, as well as the lasing wavelength at a current injection (I) of 50 mA for each sample is specified in Table 1.

An example of the spectral output of one of the DFB laser samples is shown in Fig. 2. The DFB spectral plots correspond to sample S.5, which has been detuned by +16 nm from the nominal wavelength of 1310 nm to the longer wavelength of 1326 nm (at 25 °C). The spectral output shift to longer wavelengths observed at the high temperature of 85 °C is typical of DFB laser sources which shift typically by a rate of ~0.1 nm/°C due to the temperature dependence of refractive index [4]. The side mode suppression ratio (SMSR) is maintained above 40 dB across the temperature range from 25 °C to 85 °C (I=50 mA).

The spectrum of a FP laser, produced in the same wafer (i.e. identical epitaxy) as the DFB samples but with the grating layers etched away, is also shown in Fig. 2. The FP laser spectrum serves to illustrate the position of the peak optical gain in wavelength, or where the available optical gain is a maximum for the case when an uncoated uniform cavity has been tested ($\Lambda = \infty$). For the AlInGaAs-InP epitaxy design in these samples, the drift of the peak optical gain wavelength increases by ~0.5 nm/°C which is several times the rate of the DFB peak shift.

Table 1: Wavelength (λ), threshold current (I_{th}), grating pitch (Λ), slope efficiency (SE) and characteristic temperature (T_0) for all the DFB laser samples characterised in this work.

Sample ID	λ, 25°C (nm)	λ, 85°C (nm)	Λ (nm)	I_{th}, 25°C (mA)	I_{th}, 85°C (mA)	SE, 25°C (W/A)	T_0, (K)
S. 1	1291	1297	200.4	10	32	0.36	52
S. 2	1300	1306	201.9	10	28	0.4	59
S. 3	1308	1314	203.4	8	21	0.46	63
S. 4	1318	1323	204.9	8	17	0.35	81
S. 5	1326	1332	206.4	12	19	0.42	131

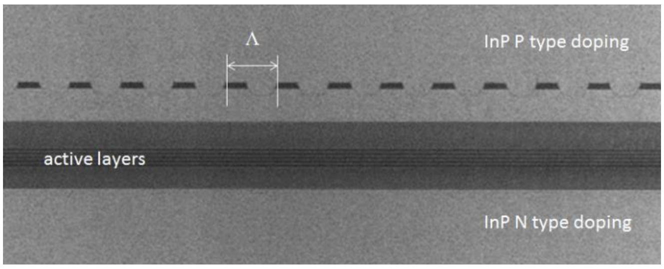

Fig. 1 *DFB laser TEM image of epitaxial structure near the active layers and along the waveguide direction of propagation.*

Evaluation of DFB laser dynamics: Devices were AuSn die bonded on to specially designed high speed AlN tiles with impedance matching resistors. The tiles were placed on a temperature stabilised brass stage up to 85 °C. Small signal S-parameter measurements were carried out using an Agilent 8703A lightwave component analyser. The method of subtraction developed by Morton [5] has been implemented in this work to extract the value of resonance frequencies from the electro-optical transmission (S_{21}) characteristics for each laser sample.

Figure 3 shows the extracted values of room temperature resonance frequencies for the five studied samples at several bias currents. These data are plotted as a function of $\sqrt{(I-I_{th})}$ in order to compensate for the effects of threshold variation with detuning. Detuning to shorter wavelengths (S.1) showed a clear increase of resonance frequency value as much as 1 GHz compared to the minimally detuned sample (S.3), and

3 GHz increase compared to the sample detuned to longer wavelength (S.5). Calculated modulation efficiencies were: 2 GHz/√mA (S.1), 1.7 GHz/√mA (S.2), 1.7 GHz/√mA (S.3), 1.6 GHz/√mA (S.4) and 1.4 GHz/√mA (S.5).

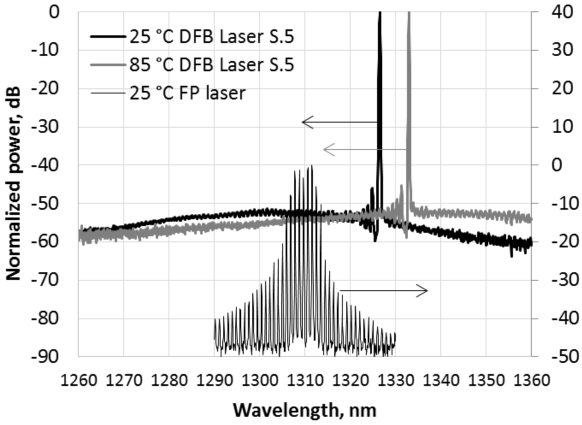

Fig. 2 *Spectral output of DFB laser sample S.5, and spectral output of FP laser ($\Lambda = \infty$) grown on the same wafer.*

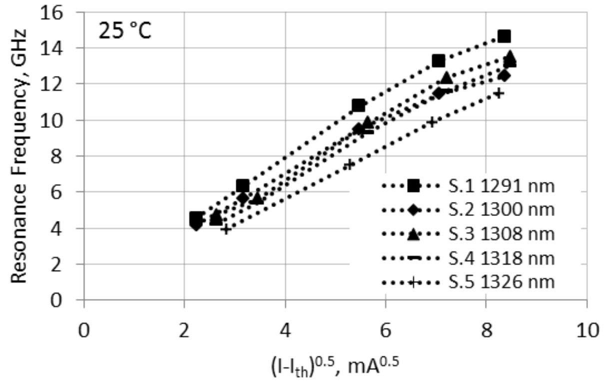

Fig. 3 *Extracted values of resonance frequencies at room temperature*

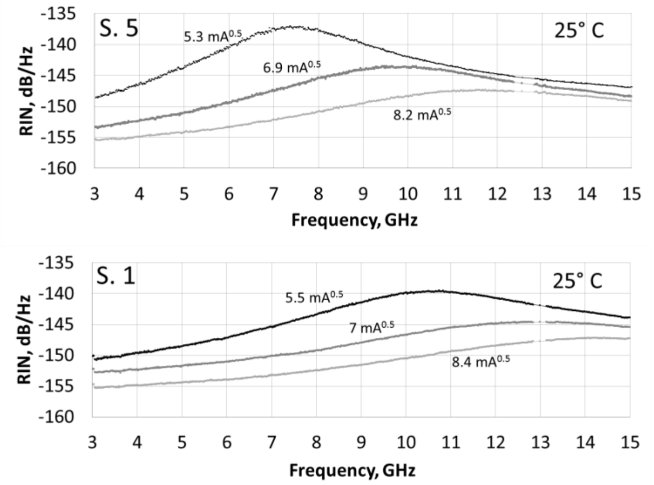

Fig. 4 *Measured values of relative intensity noise (RIN) for detuned samples S.1 and S.5 at room temperature*

Measurements of relative intensity noise (RIN) were also performed in order to establish the effects of detuning on the noise level, as well as to confirm the values of resonance frequencies extracted with the subtraction method. Figure 4 shows measured results for S.1 and S.5. The peak noise levels versus frequency at each current injection value $\sqrt{(I-I_{th})}$ agree well with the extracted resonance frequency values shown in Fig. 3. Both S.1 and S.5 achieve a low RIN level of -147 dB/Hz at high drive current.

Transmission measurements (S_{21}) were repeated for each sample at 85 °C. The extracted resonance frequency values are shown in Fig. 5 for each sample at different injection currents. A notable deterioration of the modulation efficiency of the two samples detuned to shorter wavelengths (S.1 and S.2) was observed, while the sample that had been slightly detuned to longer wavelengths (S.4) showed the highest values of resonance frequency at high injection current. Calculated values of modulation efficiency for all samples were: 1.2 GHz/√mA (S.1), 1.2 GHz/√mA (S.2), 1.4 GHz/√mA (S.3), 1.4 GHz/√mA (S.4), and 1.3 GHz/√mA (S.5).

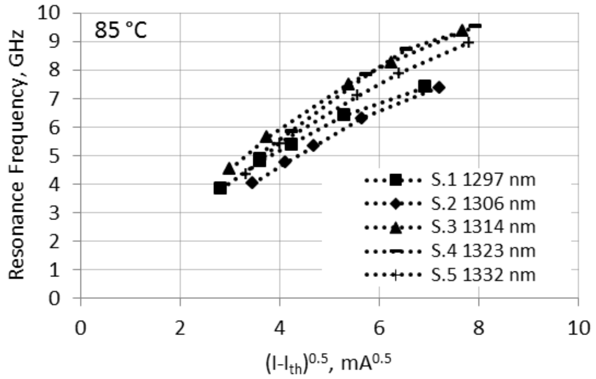

Fig. 5 *Extracted values of resonance frequencies at 85 °C*

Conclusion: In this work, we have shown that detuning the wavelength of AlInGaAs ridge waveguide DFB lasers below the peak optical gain wavelength by ~20 nm can improve the modulation bandwidth and meet the requirements for 10 Gbps applications at room temperature. Comparing both the 25 °C and 85 °C results, it can be seen that maintaining the laser speed at high temperature is most challenging. Therefore the DFB laser grating design for uncooled high speed operation should be optimised for 85°C where the shorter wavelength grating design suffers from low modulation efficiency (1.2 GHz/√mA, S.1) compared to designs with no detuning or slightly detuned to longer wavelengths (1.4 GHz/√mA, S.3, S.4). This result suggests that the trends predicted for detuning vertical cavity lasers in [3] apply for the case of detuned in-plane 1310 nm DFB ridge waveguide lasers. We find that -2nm to +8nm detuning is optimal if the dynamic behaviour of the laser is to be preserved between 25°C and 85°C.

Acknowledgments: This work was supported by the European Commission Horizon 2020 iBROW grant #645369.

H. I. Cantú, and A. McKee (CST Global LTD., UK)
E-mail: hcantu@compoundsemi.co.uk

D. Childs, S. Watson, and A. E. Kelly (University of Glasgow, School of Engineering)

References

1. Kögelnik, H., Shank, C. V.: ‘Coupled wave theory of distributed feedback lasers’, *J. Appl. Phys.* 1972, **43**, pp. 2327-2335
2. Nishimoto H., Yamaguchi M., Mito I., and Kobayashi K.: ‘High-Frequency Response for DFB LD due to a Wavelength Detuning Effect’, *IEEE J. Lightw. Technol.*, 1987, **LT-5**, (10), pp. 1399–1402
3. Staffan Björlin, E., Geske, J., Mehta, M., Piprek, J., and Bowers, J. E.: ‘Temperature Dependence of the Relaxation Resonance Frequency of Long-Wavelength Vertical-Cavity Lasers’, *IEEE Photon. Technol. Lett.*, 2005, **17**, (5), pp. 944–946
4. Agrawal, Λ, Dutta N. K.: 'Distributed-Feedback Semiconductor Lasers', in: 'Semiconductor Lasers’ (Van Nostrand Reinhold, USA, 1993, 2nd edn.), pp. 346– 348
5. Morton, P. A., Tanbun-Ek, T., Logan, R. A., Sergent, A. M., Sciortino, Jr. P. F., and Coblentz, D. I.: ‘Frequency response subtraction for simple measurement of intrinsic laser dynamic properties’, *IEEE Photon. Technol. Lett.*, 1992, **4**, (2), pp. 133–136