Wide temperature range $0 < T < 85 \, ^\circ C$ narrow linewidth discrete mode laser diodes for coherent communications applications

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Abstract: Cost effective lasers meeting the linewidth requirements for coherent communication systems are a key element in reducing the overall cost of future coherent systems. We report on monolithic devices with linewidths as low as 138 kHz which operate in a narrow linewidth, single wavelength mode with high sidemode suppression ratio over a wide temperature tuning range of $-10 \, ^\circ C < T < 110 \, ^\circ C$. A linewidth variation of only 23 kHz was measured at a constant emitted power of 4 mW as the device temperature is varied in the range $0 \, ^\circ C < T < 85 \, ^\circ C$.

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References and links
1. Introduction

Coherent communications have become a commercial reality with the deployment of 40G and 100G systems in the core network. For 100G, and certain implementations of 40G, dual-polarisation Quadrature Phase Shift Keying (QPSK) is being employed. In the next evolution of these systems higher order modulation formats have the potential to significantly increase capacity; a further advantage is that increased capacity can be achieved while maintaining the baud rate at levels which allow the use of readily available lower cost electro-optics and high speed electronics [1, 2]. To meet increasing bandwidth demands, coherent technology may also be applied to the access network [3].

Higher order modulation schemes have a lower tolerance to phase noise making low linewidth lasers a requirement [4, 5]; a major challenge is therefore to produce lasers with the requisite performance at low cost. In comparison to External Cavity Lasers (ECL), monolithic semiconductor lasers have relatively simple packaging requirements making them cost effective to produce. In this paper we describe a Discrete Mode Laser Diode (DMLD) which is a lower cost approach with a focus on high volume manufacturability [6]. Characterisation results of two DMLDs designed for low linewidth operation are presented. The first device was designed for wide temperature operation. Single mode operation was measured over a chip temperature, $T$, range of $-10 \, ^\circ C < T < 110 \, ^\circ C$. A minimum linewidth of 138 kHz was measured at 25 $^\circ C$ at an output power of 8.4 mW. The linewidth performance was characterised over the temperature range $0 \, ^\circ C < T < 85 \, ^\circ C$, a variation in the linewidth of only 23 kHz was measured at a constant ex-fibre emitted power of 4 mW over the temperature range. Such performance is attractive as it relaxes the temperature control requirements for ensuring narrow linewidth performance and also reduces inventory requirements when using low cost fixed wavelength devices in communications and sensor applications. We also show that DMLDs can be designed to achieve higher output powers and low linewidth emission. Characterisation results are presented for a second device with an ex-fact output power > 30 mW, with linewidth less than 200 kHz at 25 $^\circ C$. Single mode operation over the temperature range $0 \, ^\circ C < T < 95 \, ^\circ C$ is also demonstrated. In optical coherent communications DMLDs with narrow linewidth can be used as a transmitter laser or local oscillator laser. In addition, next generation coherent systems are expected to operate over increased transmission distances with the use of all optical regenerators. Regeneration of DPSK signals has been demonstrated using Phase Sensitive Amplifiers (PSA), and DMLDs have been developed for PSA applications where low phase noise is a requirement [7, 8]. The device temperature performance enables other potential applications where temperature can be used to tune the wavelength; also the device could operate uncooled.

2. Device structure

Details of the laser structure are as follows: the AlGaInAs Multiple Quantum Well (MQW) laser was grown on an n-type (100)-InP substrate in a metal-organic vapour-phase epitaxy reactor at low pressure. The MQW structure consisted of five compressively strained (1%) 5 nm-thick AlGaInAs quantum wells and six slightly tensile strained (0.2%) 8 nm thick AlGaInAs barriers. The MQW was sandwiched between two 200 nm-thick InGaAsP Separate Confinement Heterostructure (SCH) guide layers with a bandgap wavelength of $\lambda_g = 1.3 \, \mu m$ which also acted as an etch stop layer for the ridge waveguide and slot definition. A 2 $\mu m$ thick p-InP layer was grown on top of the SCH followed by a 200 nm thick highly p-doped InGaAs contact layer. The structure is designed to achieve a low linewidth enhancement factor ($\alpha = 3$) over a wide laser temperature range. At high ambient temperatures lasers made
with AlGaInAs materials show improved performance when compared with those made in conventional material systems such as InGaAsP/InP [9, 10] due to the higher conduction band offset for this material. Single wavelength operation in DMLDs is achieved by introducing index perturbations in the form of etched features positioned at a small number of sites distributed along the ridge waveguide. The single mode emission wavelength is determined by the pattern of the index perturbations and was calculated using the methods described in [11]. The ridge and the etched features are realized in similar processing steps where standard inductive coupled plasma dry etching was used to form the ridge and the etched features. The features are etched partially into the upper waveguide but not through the active region. Electrical contacting was achieved using conventional metals (Ti/Pt/Au) and SiO2 as an insulator for contact definition on the heavily doped (> 1x 10^{19}) p-GaInAs capped layer [12].

The spectral linewidth in semiconductor lasers is proportional to the ratio of the spontaneous emission noise to the total photon number in the laser cavity. To increase the photon number in the DMLD we increased the laser cavity length to 1000 µm and increased the front facet coating to 30% with the back facet coated at 95%.

The second DMLD used in this study was designed for higher output powers. In order to increase the optical power we reduced the number of quantum wells to three and increased the thickness of the SCH to expand the optical mode at the facets to reduce the intensity. Details of the layer structure are as follows: the MQW structure consisted of three compressively strained (1%) 6 nm-thick AlGaInAs quantum wells and four slightly tensile strained (0.2%) 8 nm thick AlGaInAs barriers. The MQW was sandwiched between two 400 nm-thick InGaAsP SCH layers with a bandgap wavelength of \( \lambda_g = 1.3 \) µm which also acted as an etch stop layer for the ridge waveguide and slot definition. A 1.8 µm thick p-InP layer was grown on top of the separate confinement heterostructure followed by a 200 nm thick highly p-doped InGaAs contact layer. The ridge waveguide width was 3 µm and the laser had a cavity length of 1000 µm. Increased output power was also achieved by reducing the front facet coating to 7% with the back facet coated at 95%.

3. Results and discussion

The DMLD, with front facet coating of 30% and the back facet coated at 95%, was packaged in a 14-pin butterfly module which contained a TEC, thermistor and dual stage optical isolator with 60 dB isolation. Linewidth spectra were measured using a standard delayed self-heterodyne (DS-H) technique [13, 14]. The fibre delay length in one arm of the interferometer set-up is 6 km (corresponding to a linewidth measurement resolution \( \approx 17 \) kHz). Light propagating in the short arm of the set-up is modulated using a lithium niobate (LiNbO3) phase modulator to frequency shift the detected heterodyne beat signal to 1 GHz away from the zero Hertz response of the rf spectrum analyser in order to enhance measurement accuracy. Figure 1(a) shows the ex-fibre emission linewidth versus inverse power. A minimum linewidth of 138 kHz was obtained at 8.4 mW at a bias current of 300 mA. The measured DS-H spectrum was fitted to a Lorentzian lineshape to extract the half-width at half maximum value and is shown in Fig. 1(b). The device was characterised over temperature by controlling the chip temperature using the internal TEC in the butterfly module. Figure 2(a) shows the overlapped optical spectra measured at a bias current of 250 mA over the temperature range \(-10 \) °C < T < 110 °C. The peak wavelength and side mode suppression ratio (SMSR) versus temperature are plotted in Fig. 2(b). An SMSR in excess of 40 dB was measured over the temperature range. The continuous wavelength tuning range was 11.6 nm and displayed a linear dependence with temperature corresponding to a tuning rate \( \Delta \lambda / \Delta T \) of 0.097 nm/°C.
Figure 3 shows the fitted linewidth versus temperature for two operating conditions; the first where the power in the fibre is kept constant at 4 mW and the second where the bias current is kept constant at 250 mA. At a constant power of 4 mW a maximum linewidth of 235 kHz was measured at 85 °C and a minimum value of 212 kHz was measured at 25 °C, corresponding to a variation in the linewidth of only 23 kHz over the temperature range 0 °C < T < 85 °C. When the device is operated at a constant bias current of 250 mA a linewidth below 200 kHz was measured over the range 0 < T < 60 °C. The increase in linewidth at higher temperatures is due to the reduction in the optical power for a given input current leading to a reduction in the photon density in the laser cavity. At temperatures below 0 °C and above 85 °C it was not possible to achieve the temperature stability necessary to accurately measure the linewidth using the internal TEC as it was being driven beyond its normal operating limits at these temperatures. The overlapped light current plot measured in the fibre is shown in Fig. 4(a) over the temperature range 0 °C < T < 85 °C. At 25 and 85 °C the threshold currents were 33 mA and 96 mA respectively with slope efficiencies in the fibre of 0.033 W/A and 0.017 W/A respectively. Figure 4(b) shows the peak wavelength and SMSR versus bias current at 25 °C. Mode hop free operation was observed with a wavelength shift versus bias current of 4 pm/mA. This property of monolithic single mode lasers can be used in spectroscopy as the wavelength can be tuned relatively quickly by modulating the bias current. A higher wavelength tuning rate with bias current can be achieved by increasing the carrier density; one approach to achieve this is to use a device with a shorter cavity. Controlling the chip temperature can be used to tune the wavelength; a disadvantage is that using temperature to tune the peak wavelength is relatively slow. However, in applications where high speed tuning rates are not required it could provide a cost effective tuneable source with linewidth comparable to an ECL. A potential application of this device is as a low
cost backup laser source for fixed wavelength WDM systems employing advanced modulation formats. By temperature tuning the wavelength a single device could cover multiple channels, thereby reducing inventory costs. In a DWDM system with 50 GHz spacing 20 channels could be covered by a device with an operating temperature range of 0 °C to 85 °C. The device also has the potential to operate uncooled in applications where precise wavelength control is not required, and this could have applications in cost sensitive markets.

![Linewidth versus temperature graph](image)

Fig. 3. Linewidth versus temperature at constant power in the fibre of 4 mW and also at a constant bias current of 250 mA.

![Overlapped light-current plot graph](image)

Fig. 4. (a) Overlapped light-current plot measured ex-fibre over the temperature range 0 °C < T < 85 °C, (b) Peak wavelength and SMSR versus bias current at 25 °C.

DMLDs can also be designed with higher output powers while still maintaining low linewidth emission. The DMLD, with front facet coating of 7% and the back facet coated at 95%, was mounted p-side up on a C-mount. Light was coupled from the laser chip to the fibre using a lensed fibre focuser assembly. To minimise reflections back to the laser chip the lens was coated with an antireflection coating, the assembly also incorporated an optical isolator to prevent reflections from the fibre tip. The focuser assembly was designed to provide low back reflection of less than −60 dB. Figure 5(a) shows the measured DS-H spectrum fitted to a Lorentzian lineshape to extract the half-width at half maximum value. A value of 194 kHz was obtained at 25 °C at a bias current of 300 mA. The overlapped light current plot, measured ex-facet, is shown in Fig. 5(b) over the temperature range 0 °C < T < 85 °C. At 25 °C and 85 °C the threshold currents were 30.8 mA and 84 mA respectively, with slope efficiencies of 0.102 W/A and 0.070 W/A respectively. At 25 °C an output power of 32.6 mW was measured at a bias current of 400 mA. Placing this device in a package with a coupling efficiency of 63%, or greater, would allow ex-fibre output powers > 20 mW to be achieved. Figure 6(a) shows the overlapped optical spectra measured at a bias current of 300 mA over the temperature range 0 °C < T < 95 °C. The peak wavelength and SMSR versus temperature is plotted in Fig. 6(b). An SMSR in excess of 45 dB was measured over the temperature...
range. The continuous wavelength tuning range was 9.5 nm and displayed a linear dependence with temperature corresponding to a tuning rate $\Delta\lambda/\Delta T$ of 0.1 nm/°C.

![Image](image1.png)

**Fig. 5.** (a) Measured lineshape at 25 °C with a bias current of 300 mA, (b) Overlapped light-current plot measured ex-facet over the temperature range 0 °C < $T$ < 85 °C.

![Image](image2.png)

**Fig. 6.** Spectral characteristics over the temperature range 0 °C < $T$ < 95 °C; (a) overlapped spectra, (b) peak wavelength and SMSR versus temperature.

### 4. Conclusion

We have demonstrated the characteristics of a Discrete Mode laser diode that make it suitable for applications where narrow linewidth emission is required. Single longitudinal mode operation over a temperature range of $-10$ °C < $T$ < 110 °C has been demonstrated with an SMSR ratio in excess of 40 dB maintained even at high temperatures. It has been shown that narrow linewidth emission (< 250 kHz) can be maintained over a temperature range of 0 °C < $T$ < 85 °C. We have also demonstrated that a linewidth of less than 200 kHz and ex-facet output power of greater than 30 mW at 25 °C can be achieved using DMLDs. In optical coherent communications DMLDs can be used as a transmitter laser or local oscillator laser. The device is monolithic making it cost effective to produce and it is fabricated using a single step process leading to further cost reduction in comparison with DFB lasers. These devices are also suitable for other applications where narrow linewidth emission is required including ultra-high resolution spectroscopy, sensing applications and atomic clocks.

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