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10.1 nm range continuous wavelength-tunable vertical-cavity surface-emitting lasers

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Indexing terms: Vertical cavity surface emitting lasers, Laser tuning

A record wide continuous wavelength tuning range of 10.1 nm is demonstrated in vertical-cavity surface-emitting lasers (VCSELs) with monolithically integrated thin-film metal heaters. Single longitudinal mode and single transverse mode are maintained throughout the tuning range. The thin-film heater can stand higher temperatures over a wider tuning range. It is also separated and electrically isolated from the laser, and can be applied to most existing VCSEL structures.

Introduction: Wavelength-tunable vertical-cavity surface-emitting lasers (VCSELs) are highly attractive for wavelength division multiplexed (WDM) transmission systems and free-space optical interconnects in massively parallel computers [1]. The circular beam and low divergence angles permit high coupling efficiency into singlemode optical fibres. In addition, low threshold current, wafer scale fabrication, and high density two-dimensional laser arrays make them promising for free space optical interconnects. A two-electrode VCSEL with a continuous tuning range of 1.8 nm [2], 4.0 nm by using an external mirror [3], and a three-electrode VCSEL with tuning range 2.2 nm and 8.2 nm [4, 5] have been reported. In this Letter, we report a record wide continuous wavelength tuning range of 10.1 nm in a VCSEL with an integrated thin-film heater with 174 mA heater current. The thin film heater has several advantages. First, it has very simple design and fabrication process. No multiple level mesa contacting scheme is needed. Secondly, the heater is completely separated from the laser. It can be added to most existing VCSEL structures after they have been fabricated. The heater can be optimised without changing the VCSEL structure or sacrificing its performance. Thirdly, it can resist higher temperatures to achieve a higher tuning range. We used AuBe and Au contact metal for the thin film heater. Thicker and more resistive metal could be used to achieve lower heater current and wider temperature tuning range. An integrated thin-film heater has been used in edge-emitting distributed feedback (DFB) lasers [6] and a large wavelength tuning range has been achieved in DBR lasers [7].

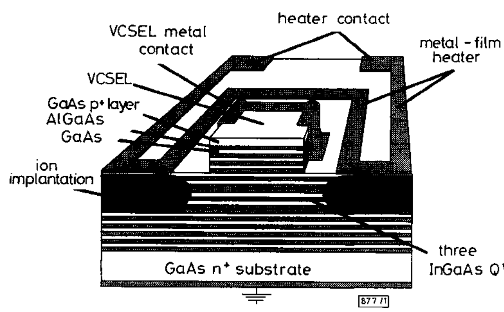

Fig. 1 *Schematic diagram of tunable VCSEL*

Fabrication: Fig. 1 illustrates the schematic structure of the VCSEL grown by metal organic chemical vapour deposition (MOCVD). It consists a 35 pair n-doped quarter-wave GaAs/AlGaAs distributed Bragg reflector (DBR) stack, three InGaAs/GaAs strained quantum well active layers, a 25 pair p-doped top DBR mirror, and a p^+ GaAs cap layer. Mesas of size $12 \times 12\mu m^2$ and height 2μm are formed by wet chemical etching. Ion implantation is used for electrical isolation. A 0.2μm-thick spin-on-glass (SOG) is then deposited, and the contact windows on the mesa tops are opened by a selfaligned process. The striped thin-film heater, consisting of 80nm AuBe and 40nm Au, is wrapped around the VCSEL to increase the total length and resistance. The heater in our current design is 144μm long, 8μm wide, and has a resistance of 34Ω. The wavelength is tuned by applying DC current through the thin-film metal and heating the single VCSEL locally. Fig. 2 shows a photograph of the tunable VCSEL.

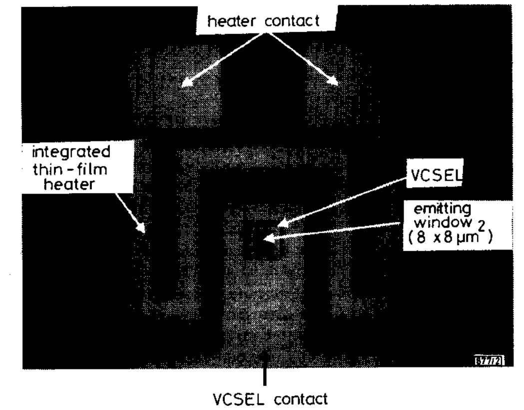

Fig. 2 *Photograph of tunable VCSEL with integrated metal-film heater*

Experimental results: The device is mounted on a TE cooler and maintained at a constant temperature of 15°C. The emission wavelength is 949nm under CW operation. Uniform threshold current of 4.2mA and output power of 1.2mW are obtained for all lasers before applying heater current. Under constant optical output power, the wavelength is tuned from 948.8 to 958.9nm when the heater current increased from 0 to 174mA. Fig. 3*a* shows the lasing spectra under various heater currents. The peak separation is ~1nm. Fig. 3*b* shows the wavelength against heater current. A total tuning range of 10.1nm is obtained. If we plot the wavelength against the square of the heater current, the result would be approximately linear which shows that the wavelength is proportional to the thermal power generated by the heater.

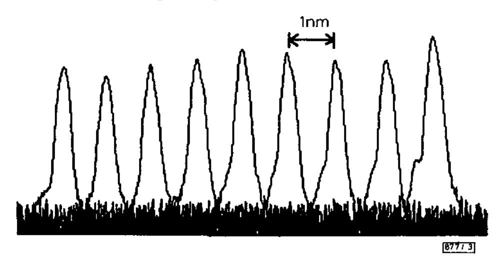

Fig. 3 *Lasing spectra under various heat currents*

Each peak separation is 1 nm

Discussion: The tuning range is currently limited by the heater current. The metal film burned out when heater current exceeded 174mA. The temperature can be further increased by increasing the pumping current. A tuning range of 12nm was achieved, however higher order spatial modes gradually appeared. By using thicker metal with higher resistivity, a higher singlemode tuning range could be obtained.

To keep the output power constant, it is necessary to increase the pumping current. The injected carriers caused a decrease in refractive index due to free-carrier plasma and band-filling effects which cause the wavelength to blue-shift. On the other hand, the thermal effect causes the wavelength to red-shift. From our measurement only red-shift is observed by increasing the injection current, so the wavelength tuning mechanism is dominated by the thermal effect.

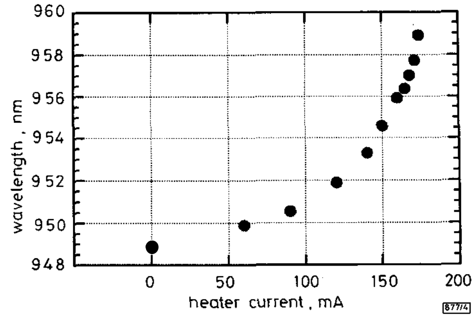

Fig. 4 *Wavelength against heater current*

We also measured the spontaneous emission spectrum of the VCSEL. The full-width-at-half-maximum (FWHM) gain bandwidth is 50nm. The DBR resonance wavelength is at 949nm, and the gain peak is at 964nm. As the temperature increases, the gain spectrum red-shifts at 4nm/°C which is five times faster than the DBR resonance wavelength (red shift 0.83nm/°C) [9]. Thus the gain peak moves further away from the DBR peak, which results in lower gain and higher threshold current. If we design the VCSEL gain peak to be on the shorter wavelength side of the DBR resonance wavelength at room temperature, it is possible to have nearly constant gain and maintain constant threshold current under tuning. A wider tuning range is also expected.

In summary, we have demonstrated for the first time a record wide continuous wavelength tuning of 10.1nm in vertical-cavity surface-emitting lasers with monolithic integrated thin-film heaters. Single longitudinal and transverse mode is maintained throughout the tuning range. The tuning range is currently limited by the heater current. Wider singlemode tuning range could be obtained by using a higher resistivity metal-film heater.

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High power COD-free operation of 0.98µm InGaAs/GaAs/InGaP lasers with non-injection regions near the facets

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Indexing terms: Gallium indium arsenide, Gallium arsenide, Gallium phosphide, Semiconductor junction lasers

The authors demonstrate the catastrophic-optical-damage-free high-output-power operation of 0.98µm InGaAs/InGaP/GaAs buried-ridge-structure lasers with non-injection regions near the facets. A maximum output power of 466mW and fundamental operation at 100mW were achieved.

Introduction: Er-doped fibre amplifiers (EDFAs) are essential for long-span high-bit-rate optical communication systems. For pumping EDFAs, 0.98µm lasers have been actively studied to obtain high power and highly reliable operation [1–5]. One of the various factors which induce laser degradation during long-term operation is electric surge, which causes a sudden failure of the lasers. This can be avoided by increasing the output power at which catastrophic optical damage (COD) occurs, or by realising COD-free lasers whose maximum output power is limited by the thermal saturation. One approach to accomplishing this is the introduction of a window region at the facet, where the bandgap energy of the material is larger than the energy of the laser light [6]. This avoids absorption of laser light at the facets. Therefore, facet heating can be suppressed. However, the process is usually much more complicated than that of ordinary lasers.

Introducing non-injection regions near the facets is another way to increase the power at which COD occurs. This reduces the non-radiative recombination at the facets. Therefore, facet heating, which narrows the bandgap energy at the facet, can be suppressed. Moreover, this device fabrication process is almost the same as the ordinary process. However, non-injection may cause saturable absorption, which causes abnormal lasing behaviour around the threshold current. In the case of 0.98µm strained-quantum-well lasers, the internal loss is very low. Therefore, little or no characteristic degradation due to the saturable absorption can be expected. In this Letter, we demonstrate the high-power COD-free operation of InGaAs/GaAs/InGaP buried-ridge waveguide-structure lasers realised by introducing the non-injection regions near the facets. The maximum output power was found to be 466mW, which is limited by thermal saturation.

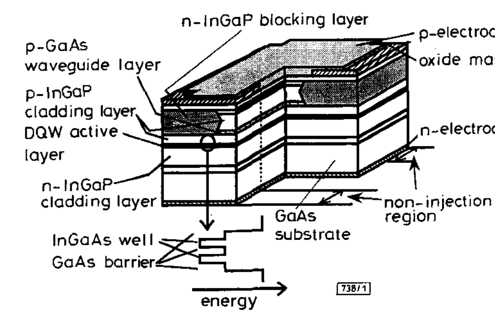

Fig. 1 *Schematic cross-section of laser with non-injection regions near facets*

Device structure: Fig. 1 shows a schematic cross-section of the InGaAs/GaAs/InGaP buried-ridge structure. The active layer consists of two 7nm InGaAs strained quantum wells separated by three 8 nm GaAs barrier layers. The GaAs waveguide layer, whose