High output power 1540 nm vertical cavity semiconductor optical amplifiers

E.S. Björlin, T. Kimura, Q. Chen, C. Wang and J.E. Bowers

Vertical cavity semiconductor optical amplifiers operating at 1540 nm are presented. The use of AlInGaAs multiple quantum well active regions resulted in record-high saturation output power of +0.5 dBm and 16 dB of fibre-to-fibre gain. These results were achieved in reflection mode operation using optical pumping by a 980 nm semiconductor laser.

Introduction: Low-cost, small form-factor, long-wavelength optical amplifiers are crucial components in fibre optic communication systems. Vertical cavity semiconductor optical amplifiers (VCSOAs) [1] are a promising technology because of their good coupling efficiency to optical fibre, favourable filtering properties, compact design, and polarisation independent gain. Furthermore, VCSOAs are compatible with low-cost manufacturing techniques.

VCSOAs operating at both 1.3 and 1.55 µm have been presented. The best results so far have been achieved around 1.3 µm wavelength using GaInNAs grown on GaAs [2] and GaAs-InP wafer-bonding [3, 4]. Less progress has been made in the 1.55 µm wavelength region. The best results previously reported for this wavelength region was 18 dB of gain (coupling loss not included) measured at 218 K [5]. The devices in [5] saturated at input signal powers lower than −35 dBm. Saturation at relatively low signal power has been a major difficulty for this class of devices, because of their small active volume and the strong feedback from the highly reflective mirrors. The highest previously reported saturation output power is −3.5 dBm [4], which is considerably lower than for other amplifier technologies.

Device design: To achieve high output power from VCSOAs the single-pass gain needs to be maximised, i.e. a large number of quantum wells (QWs) is needed. The mirror reflectivity must be reduced accordingly to allow for strong pumping without the onset of lasing. Optical pumping is advantageous for such structures, as it can produce uniform carrier distribution throughout a large number of QWs. The present VCSOAs were designed for optical pumping and reflection mode operation. The structure consisted of an MOCVD-grown AlInGaAs/InP active region wafer-bonded to two MBE-grown AlGaAs/GaAs DBRs. The active region had 25 compressively strained AlInGaAs quantum wells (QWs) and strain compensating barriers. The QWs were grouped together in five sets of five wells each, positioned on the standing wave peaks in the 5/2-λ cavity. The bonded interfaces were positioned at standing-wave nulls. Fig. 1 shows the standing wave distribution and the refractive index profile in the wafer-bonded VCSOA cavity. The bottom (top) DBR had 30 (10.5) periods, resulting in a calculated peak reflectivity of 0.999 (0.91). The entire structure was undoped. No guiding structures were formed on the wafer; the devices were gain guided and the lateral dimensions of the active region were determined by the size of the pump beam. The back side of the undoped, polished, GaAs substrate was anitireflection coated to maximise the pump power reaching the active region.

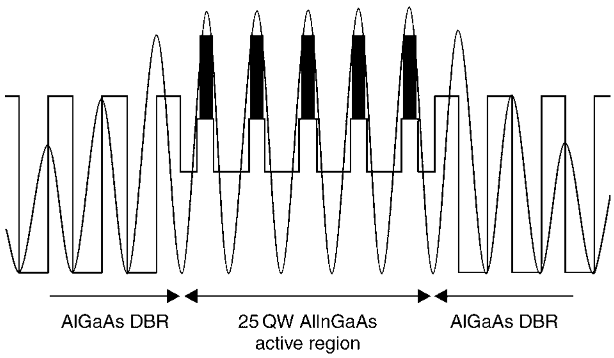

Fig. 1 *Refractive index profile and standing wave distribution in 5/2-λ cavity of wafer bonded VCSOA*

QWs are positioned on peaks; bonded interfaces at nulls

Results: The VCSOAs were pumped by a 980 nm semiconductor laser supplied by Furukawa. The pump beam was coupled into the active region through a fibre and lens, through the substrate and bottom DBR of the devices. The 1.55 µm input and output signals were coupled into, and out of, the VCSOAs through the top DBR using a fibre and a lens. A circulator was used to separate the input and output signals. The beam waist diameter of the signal and pump beam were measured to be 12 µm. The total coupling loss, including loss in the circulator, was determined to be about 4 dB.

Fibre-to-fibre gain was measured against input signal power and wavelength. The chip temperature was held constant at 16°C. The gain spectrum of the VCSOA for a pump power of 107.5 mW is shown in Fig. 2. The points are measured values and the line is a curve fit based on the Fabry-Perot equation [2, 4]. The peak fibre-to-fibre gain is 16 dB and the 3 dB bandwidth is 0.31 nm (39 GHz). Higher gain was measured at lower operating temperatures. A fibre-to-fibre gain of 19 dB was measured at 10°C. Fig. 3 shows the saturation properties of the VCSOA at 16°C for 14.2 dB unsaturated gain. The points are measured values and the line is a curve fit based on the equation $G = G_0(1 + P/P_{sat})^{-1}$, where G_0 is the unsaturated gain, P is the input signal power, and P_{sat} is the input power for which the gain drops by 3 dB. P_{sat} was determined to be −10.7 dBm, resulting in a saturation output power of +0.5 dBm. This is the highest reported saturation power of any VCSOA to date.

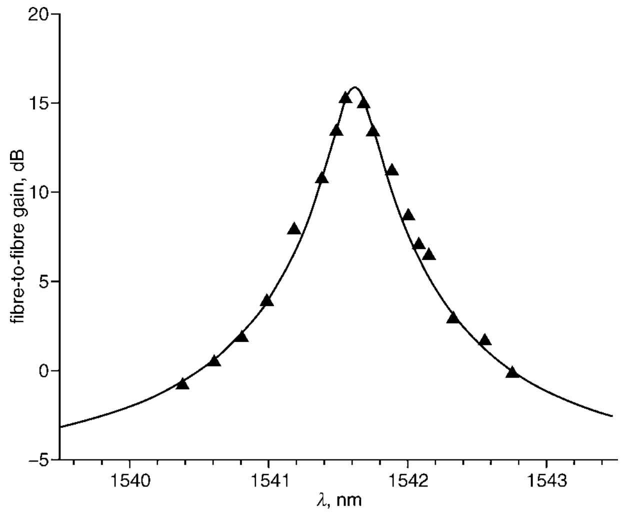

Fig. 2 *Gain spectrum of VCSOA at 16°C for 107.5 mW of pump power*

Peak fibre-to-fibre gain 16 dB; 3 dB bandwidth is 0.31 nm (39 GHz)

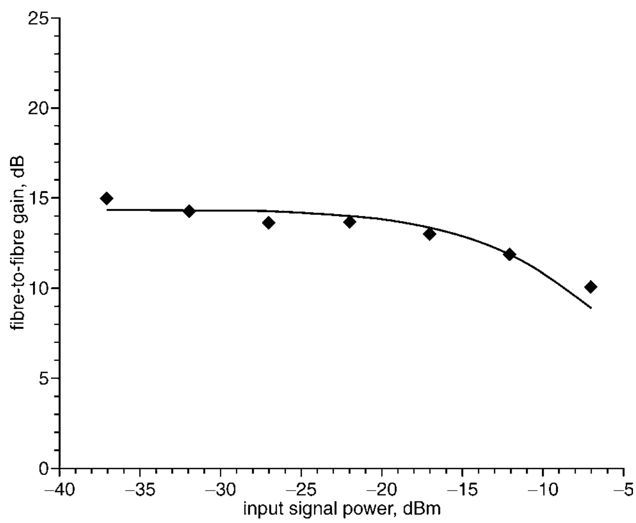

Fig. 3 *Saturation behaviour of VCSOA at 16°C for 14.2 dB small signal gain*

Record-high saturation output power of +0.5 dBm demonstrated

The VCSOAs could not be brought to lasing threshold. This indicates that the mirror reflectivity is sufficiently low so that the high gain produced by the 25 QWs can be fully utilised; lower reflectivity would result in reduced amplifier gain. A single-pass gain of 4.1% was extracted from the curve fit in Fig. 2. This value is limited by device self heating and carrier loss. The cavity mode in the present devices was perfectly aligned to the gain peak at room temperature. Consequently, device self heating at high pump powers or operation at elevated temperatures result in misalignment of the mode with respect to the gain peak. Better results can be expected with a longer cavity, which would produce a more favourable gain-mode offset. Higher gain at lower pump power can be achieved by carrier confinement as reported in [3]. These modifications to the design could allow for further reduced top mirror reflectivity, and thus higher signal gain and higher saturation power.

Conclusion: The use of optically pumped AlInGaAs multiple quantum well active region has resulted in 1540 nm VCSOAs with record-high saturation output power of +0.5 dBm and fibre-to-fibre gain of 16 dB. The present device design is limited by device self heating and carrier loss. Better gain-mode offset would produce better results at elevated temperatures. A carrier confining structure can be incorporated for improved efficiency.

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