Demonstration of high saturation power/high gain SOAs using quantum well intermixing based integration platform

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In this letter we report the performance of semiconductor optical amplifiers (SOA) employing regions of high and low optical confinement designed for high saturation power and high gain using a novel quantum well (QW) intermixing (QWI) and MOCVD regrowth fabrication scheme. The scheme enables the monolithic integration of the high performance SOAs with high gain laser diodes, high efficiency electroabsorption modulators (EAM), and high saturation power photodiodes. The SOAs presented here exhibit saturation powers in the 19-20 dBm range with nearly 15 dB of gain.

Introduction: High functionality, high efficiency, and size reduction offered by single chip photonic circuits inspires the present effort towards increased levels of monolithic integration. The performance of the photonic integrated circuit (PIC) as a whole is ultimately limited by the performance of the individual components within the circuit. High functionality active PICs can require multiple QW band edges, differing gain or optical confinement at similar wavelengths, and radically different internal structures for components such as high saturation power photodiodes. Integration schemes that enable high flexibility for the independent optimization of the individual components within the PIC are essential for monolithic circuits to operate at the performance levels offered by circuits comprised of discrete components.

High-performance multiple QW band-edge widely-tunable transmitters have been demonstrated using our quantum well intermixing (QWI) integration platform [1]. With the addition of simple blanket MOCVD regrowth steps, we have extended the QWI integration platform to achieve QW active regions of both low and high optical confinement and high saturation power photodiodes operating at 40 Gb/s [2, 3]. In this work we exploit the capability of achieving both high and low optical confinement on a single chip for the demonstration of high saturation power/high gain SOAs.

Low optical confinement (LOC) MQW active regions are an attractive choice for employment in SOAs requiring high saturation power since the photon density within the QWs can be kept relatively low. Using the LOC-QW scheme, impressive saturation powers of +23 dBm and +28 dBm have been reported (4, 5). It should be noted that until recently the record SOA saturation power was +17 dBm (6). Here we report SOAs exhibiting 19-20 dBm saturation output powers with nearly 15 dB of chip gain using a fabrication scheme that will enable the SOAs to be placed in highly functional PICs containing widely tunable lasers, QW EAMs, and high saturation power photodiodes.

Experiment and Theory: Device fabrication initiates on an MOCVD grown epitaxial base structure consisting of ten 6.5 nm compressively strained QWs, separated by 8.0 nm tensile strained barriers, centered within two InGaAsP:Si (1.3Q:Si) layers designed to maximize the optical confinement at ~12.6% in the QWs. The samples are subjected to our QWI process as described in [7], in which the as-grown c-MQW is shifted in peak photoluminescence wavelength from 1530 nm to 1410nm in regions where passive waveguide, low optical confinement QWs, or high saturation power photodiodes are desired. An MOCVD regrowth is then performed for the growth of a thin InP:Si layer followed by a 1.3Q:Si stop etch layer, a 145nm InP:Si confinement tuning layer (CTL), a 5 o-MQW with similar compositions and thicknesses to that of the c-MQW, and a InP:Zn cap layer. Since the CTL layer functions to move the active wells away from the peak of the optical mode, the layer thickness is a key aspect in the design. In this work it was chosen such
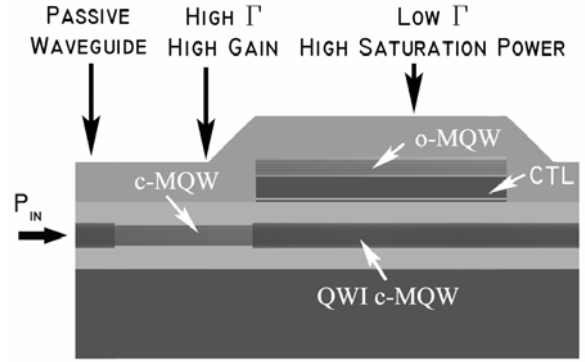

Fig. 1 *Side view schematic of the SOA device structure illustrating the c-MQW high modal gain region (left), and the o-MQW with reduced modal gain (right) for the realization of a high saturation power/ high gain SOA.*

that the optical confinement factor in the o-MQW was ~1.3% to achieve saturation output powers in the 20 dBm range. Following the o-MQW regrowth, wet etching was used to selectively remove the o-MQW structure in regions it is not desired, a similar sequence was performed for the realization of high saturation power photodiodes [3], and the p-type InP:Zn cladding and p-contact InGaAs:Zn layers were grown. A thorough discussion of the theory and growth aspects can be found in [8]. Standard lithography methods were used to define 5µm wide surface ridge SOA devices with varying lengths. The three unique waveguide sections in the resulting SOA structures are shown in Fig. 1:

Results: The cleave back method was used to characterize Fabry Perot ridge lasers to extract the injection efficiency and optical loss of both active region types. The injection efficiency was found to be 70% and 73 % in the c-MQW and o-MQW active regions, respectively. The optical loss was found to be 20 cm^{-1} and 3 cm^{-1} in the c-MQW and o-MQW active regions, respectively. A two-parameter fit was used to plot the threshold modal gain versus current density as shown in Fig. 2. The fit yielded a modal gain parameter of 94.1 cm^{-1} in the o-MQW active region and 9.1 cm^{-1} in the o-MQW active region, which is in good agreement with the simulated difference in optical confinement factor.

The SOA devices employed curved/flared passive input waveguides for reduced facet reflections. Single section low confinement SOAs with lengths of 1000µm and 1500µm along with a dual section SOA containing 150µm high optical confinement section followed by 1350µm of low optical confinement section were soldered to AlN carriers, wirebonded, and placed on a copper stage cooled to 18˚C for characterization. A continuous wave (CW) 1550 nm light source was fed through a polarization controller and coupled into the SOA waveguide using a tapered fiber. The TE polarization state was used during all testing due to the polarization sensitivity of the compressively strained QWs. The coupled chip power was determined by reverse biasing the
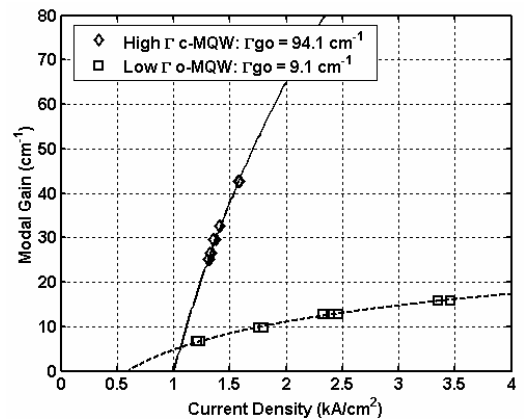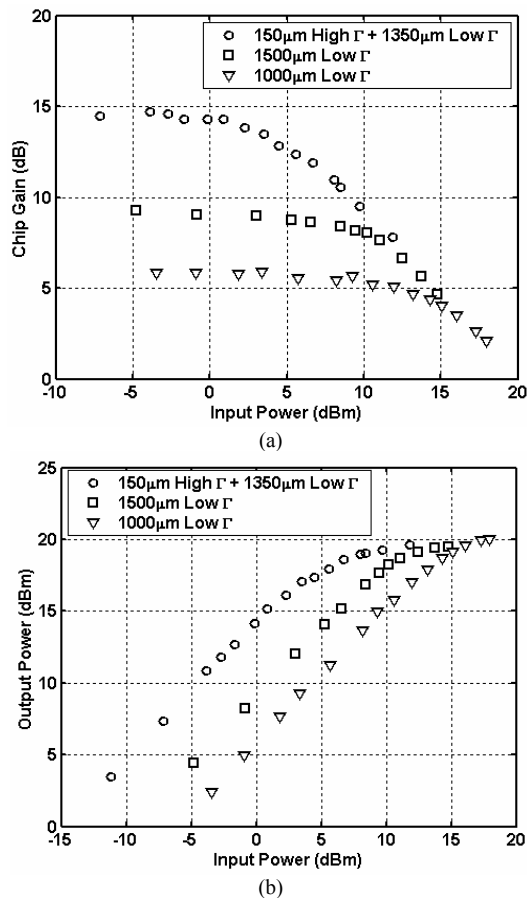

Fig. 2 *Experimental modal gain versus applied current density for 3µm wide Fabry Perot lasers employing high confinement c-MQW (diamonds) and low confinement o-MQW (squares) active regions.*

(a)

(b)

Fig. 3 *(a) Chip gain versus input power and (b) output power versus input power for SOA devices at 1550nm. The applied current density was 9 kA/cm² in the low-Γ o-MQW sections and 20 kA/cm² in the high-Γ c-MQW sections.*

SOA and measuring the generated photocurrent. The long length of the SOAs was such that unity internal quantum efficiency could be assumed. The SOA was then forward biased at various current densities and the generated output power and chip gain were determined by the generated photocurrent in an integrated photodiode. The amplified spontaneous emission (ASE) was subtracted out such that it was not included in the output power or gain calculation.

The chip gain versus input power and output power versus input power characteristics are shown for the three SOA types in Fig. 3a and Fig. 3b, respectively. In all figures, the operating electrode current density was 9 kA/cm² in the o-MQW regions and 20 kA/cm² in the c-MQW regions. As can be seen in Fig. 3, a 1000μm long single section o-MQW device provides 6 dB of gain with a saturation output power of over 20 dBm while a 1500μm long single section device provides over 9 dB of chip gain with a saturation output power of 19.5 dBm. By placing a 150μm c-MQW high gain section in front of a 1350μm o-MQW section, the device gain is increased to nearly 15 dB while maintaining a saturation output power of over 19 dBm at 1550nm. Over 13.5 dB of gain was maintained for wavelengths from 1530 to 1560nm. Based on the results of this experiment, optimum o-MQW section lengths, c-MQW section lengths, and CTL thickness can be determined for improved device gain/saturation characteristics.

Conclusion: In this work we demonstrate high saturation power SOAs fabricated using an integration platform ideal for the monolithic integration of the SOAs with widely-tunable lasers, high performance QW EAMs, and high saturation power photodiodes. The SOAs presented here demonstrate saturation output powers in the 19-20 dBm range and chip gains of nearly 15 dB.

References

1   J. Raring, E. Skogen, S. DenBaars, and L. Coldren, "Demonstration of negative chirp characteristics over wide wavelength range using monolithically integrated SG-DBR laser electroabsorption modulator," *IEEE Electronics Letts*. vol.40, pp. 1599-1600 ,2004

2   E. Skogen**,** J. Raring, S. DenBaars, and L. Coldren, "Integration of High-Gain and High-Saturation Power Active Regions using Quantum Well Intermixing and Offset-Quantum Well Regrowth," *Electron. Lett.*, Vol. 40, pp. 993-94, 2004.

3   J. Raring, E. Skogen, C. Wang, J. Barton, S. DenBaars, and L. Coldren, "Quantum well intermixing and MOCVD regrowth for the monolithic integration of 40 Gb/s UTC type photodiodes with QW based components," To be published *IEEE Electronics Letts*. 2005.

4   K. Morito, S. Tanaka, S. Tomabechi, and A. Kuramata, "A broadband MQW semiconductor optical amplifier with high saturation output power and low noise figure". Semiconductor Optical Amplifiers and their Applications Meeting. PD1-1. San Francisco, CA June 30 2004.

5   P. W. Juodawlkis, J. J. Plant, R. K. Huang, L. J Missaggia, and J. P. "High Power 1.5μm InGaAsP-InP Slab-Coupled Optical Waveguide Amplifier*," IEEE Photon. Technol. Letts*. vol. 17, Feb, 2005.

6   K. Morito, N. Ekawa, T. Watanabe, and Y. Kotaki, "High-output-power polarization-insensitive semiconductor optical amplifier", *J. Lightw. Technol.,* vol. 21, no. 1, pp. 176-181, Jan. 2003.

7   E. Skogen, J. Raring, J. Barton, S. DenBaars, and L. Coldren, "Post-Growth Control of the Quantum-Well Band Edge for the Monolithic Integration of Widely-Tunable Lasers and Electroabsorption Modulators," *J. Sel. Topics in Quantum Electron.*, vol. 9, September/October, 2003.

8.   J. Raring, E. Skogen, S. Denbaars, and L. Coldren: "A Study of Regrowth Interface and Material Quality for a Novel InP Based Architecture," *Journal of Crystal Growth. vol.* 273/1-2 pp. 26-37 Dec. 2004.