High-Output Saturation Power Variable Confinement Slab-Coupled Optical Waveguide Amplifier

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Abstract: A variable optical confinement concept was incorporated into a slab-coupled optical waveguide amplifier to increase output saturation power. This amplifier demonstrates an unsaturated gain of 21.1 dB and an output saturation power of +27.6 dBm.

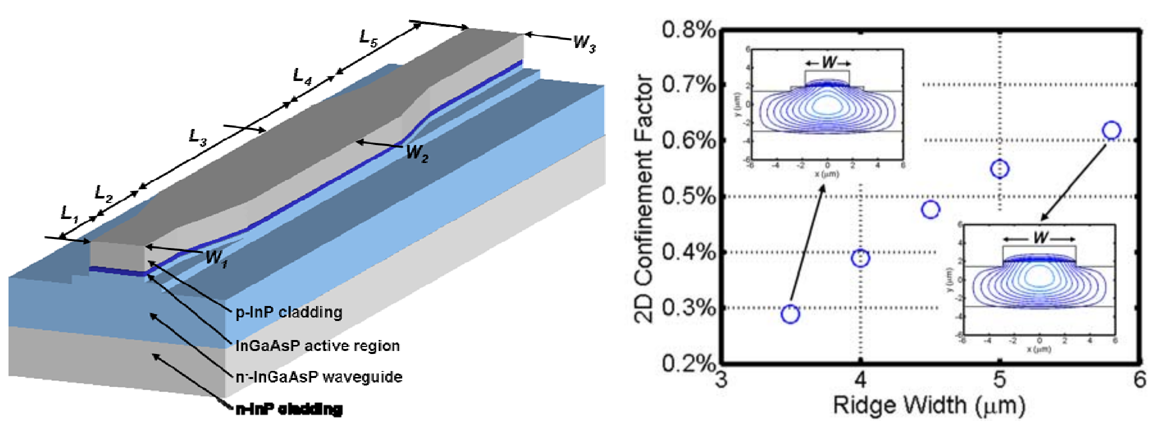
OCIS codes: (250.5980) Semiconductor optical amplifiers; (250.5300) Photonic integrated circuits

1. Introduction

Semiconductor optical amplifiers (SOAs) are used in optical communication systems for signal amplification, switching, and wavelength conversion. Compared to other optical amplifiers such as erbium-doped fiber amplifiers, SOAs are more compact and power efficient, have higher gain bandwidth, and are compatible with modern monolithic photonic integrated circuit technology. Recently, a multi-quantum well SOA demonstrated > +19.6 dBm chip output saturation power and < 4.5 dB noise figure (NF) over 120 nm of bandwidth [1]. The slab-coupled optical waveguide amplifier (SCOWA) was developed to reach higher output saturation power levels [2,3]. This type of SOA exhibits a large fundamental mode (~5 μm x ~7 μm) and has demonstrated > 1 W chip output saturation power and a 5.5-dB NF. To increase the output saturation power of conventional SOAs, Saini et al. incorporated circular vias with a varying density along the length of the SOA to tailor the local resistance [4]. In doing so, the current is inherently adjusted in each section of the device to create a separate pre-amp section, gain section, and power-amp section, the latter of which is intended to increase the output saturation power. Here, we have incorporated a variable optical confinement concept into a SCOWA. A ridge taper is utilized to transform and enlarge the optical mode and reduce the quantum well optical confinement factor, both of which lead to higher output saturation power. Compared to a standard SCOWA that does not incorporate a mode transformation, the variable confinement SCOWA (VC-SCOWA) has 2 dB higher output saturation power, a high unsaturated gain of 21.1 dB, and low NF.

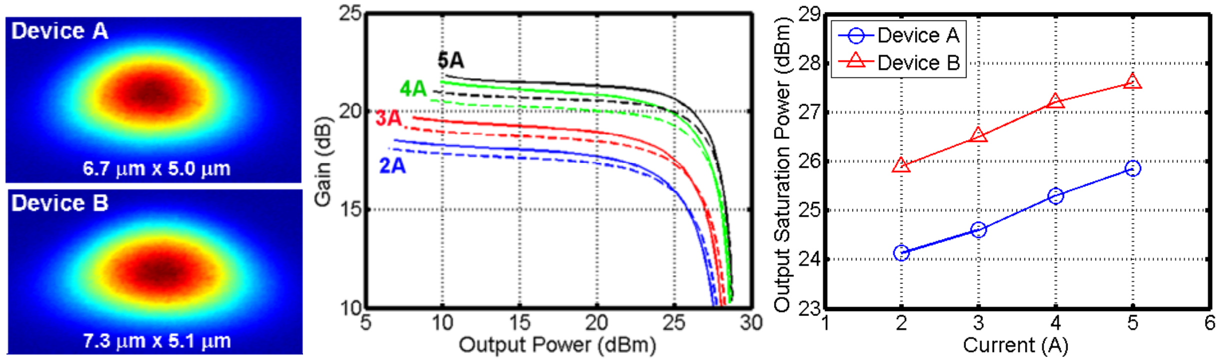
2. Device Design

A plan-view schematic of the VC-SCOWA is shown in Fig. 1(a). The device structure is grown on an n-type InP substrate by metal-organic chemical vapor deposition. The InGaAsP waveguide is 4.9 μm thick and is n-doped to $5 \times 10^{16} cm^{-3}$. The active region consists of five 8-nm thick InGaAsP quantum wells, four 8-nm thick InGaAsP



(a) (b)

Figure 1. (a) Plan-view schematic of VC-SCOWA. (b) Simulated 2D confinement factor as a function of upper ridge width (W) for a fixed lower ridge width of 5.8 μm.



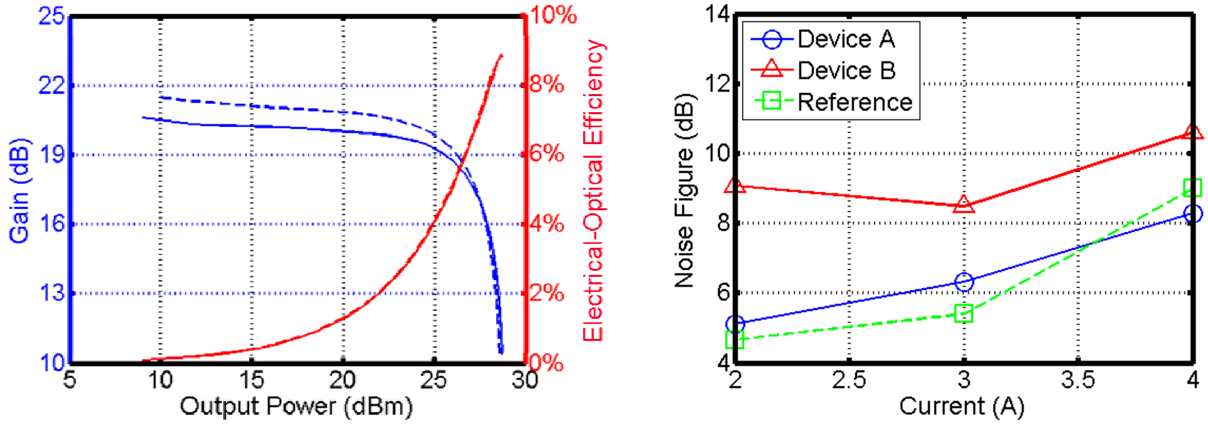
(a) (b) (c)

Figure 2. (a) Measured near field mode profiles. (b) Measured gain as a function of output power for different current levels (solid curves are for device A and dashed curves are for device B). (c) 3-dB output saturation power as a function of current level.

barriers, and two 12-nm thick InGaAsP outer bounding layers. The p-InP cladding is 1.6 μm thick and has a graded doping, and finally the p^+-InGaAs contact layer is 100 nm thick. The ridge structure consists of an upper ridge that tapers in width and a lower ridge that has a fixed width. The upper ridge width at the input of the device (W_1) can be designed to maximize the input fiber-coupling efficiency. The upper ridge width then flares to be the same width (W_2) as the lower ridge where the quantum well optical confinement factor and gain per unit length are maximized. The upper ridge width then tapers to its final width (W_3) to increase the optical mode size, reduce the quantum well confinement factor, and as a result, increase the output saturation power. In this way, the VC-SCOWA integrates a pre-amplifier section for low NF (NF can be reduced by increasing the input fiber-coupling efficiency), a gain section, and a power-amplifier section for high output saturation power. The VC-SCOWA concept is further illustrated in Fig. 1(b), which shows the simulated 2D quantum well optical confinement factor as a function of the upper ridge width. Inset are the simulated 2D optical mode profiles for the smallest and largest simulated widths. As the upper ridge width is decreased, the mode transforms; it increases in size and the confinement factor decreases. The device resistance also increases as the upper ridge width decreases. As such, there is a minimum upper ridge width limitation to prevent deleterious heating effects. When the device temperature increases, the index of the active region layers increases leading to a higher optical confinement factor and smaller mode size. This is counter to the underlying VC-SCOWA concept. In this work, two different devices are compared. The first, device A, is a standard SCOWA with a fixed ridge width (no taper) of 5.8 μm, and total length of 1 cm. The second, device B, is a VC-SCOWA with W_1 = 4 μm, W_2 = 5.8 μm, and W_3 = 4 μm (the lengths of the sections are L_1 = 1 mm, L_2 = 1 mm, L_3 = 5 mm, L_4 = 2 mm, and L_5 = 1 mm).

3. Results and Discussion

Figure 2(a) shows the measured output near-field mode profiles for device A and device B at a current level of 3 A, an input optical wavelength of 1.54 μm, and input optical power of 1 mW. The $1/e^2$ mode field diameters are 6.7 μm and 5.0 μm for device A, and 7.3 μm and 5.1 μm for device B. The gain saturation characteristics of the devices are shown in Fig. 2(b) for different operating current levels. The unsaturated gain of device B is lower than that of device A due to the ridge tapers and the fixed overall length of 1 cm. However, due to the mode transformation, device B saturates at a higher output power level. The 3-dB output saturation power is shown as a function of current for both devices in Fig. 2(c). The output saturation power of device A is nearly 2 dB higher than that of device B at all of the current levels measured. Figure 3(a) shows the gain and electrical-optical efficiency as a function of output power for both devices at an operating current of 4 A. At this current level, the unsaturated gain of device A is 21.6 dB and that of device B is 20.5 dB. The electrical-optical efficiencies are nearly identical. The benefit of the higher saturation variable confinement design can be understood by observing the device characteristics at different operating points. For an output optical power of +10 dBm, both device A and device B are unsaturated and device A yields 1 dB higher gain. At an output optical power of +25 dB, device A has a gain of 19.9 dB and device B has a gain of 19.2 dB. If the devices are operated at their point of peak electrical-optical efficiency, the gain of device A is 10.8 dB and that of device B is 11.5 dB. Because of the higher output saturation power of device B, this device should yield improved characteristics when used in conjunction with a large signal intensity modulation format such as on-off keying (OOK) or pulse position modulation (PPM). The NF of the



(a) (b)

Figure 3. (a) Gain and electrical-optical efficiency as a function of output power at current level of 4 A (solid curves are for device A and dashed curves are for device B). (b) Noise figure as a function of current level.

devices was characterized using an optical measurement technique. Figure 3(b) shows the NF as a function of current level. For device A, the NF was measured to be 5.3 dB at 2 A, and increases with increasing current level. The NF of device B was measured to be somewhat higher, in the range of 8.5-10.6 dB. The reason for the higher NF is that the input fiber coupling efficiency of device B was significantly lower than that of device A. To demonstrate that the high NF is due to the low input fiber-coupling efficiency and not the mode transformer taper for higher output saturation power, the NF was also measured for a reference device that has no flare at the input (therefore identical ridge geometry and in turn fiber-coupling characteristic as device A), and only a taper at the output side to increase the mode size. The NF for this reference device is also shown in Fig 3(b) and was between 4.7-9 dB for the current levels measured. To improve the NF of device B, the ridge design at the input can be optimized for increased input fiber-coupling efficiency.

4. Conclusions

We have demonstrated a new type of SOA, the VC-SCOWA, which incorporates a mode transformation taper to increase the mode size and reduce the optical confinement for increased output saturation power. Compared to a SCOWA without a taper, the VC-SCOWA demonstrates nearly 2 dB higher output saturation power (+27.6 dBm). The VC-SCOWA also demonstrates a high gain of 21.1 dB and low NF. To improve device performance, the quantum well confinement factor can be increased in the gain section of the device by redesigning the active region. This would allow for even higher overall gain, but still large output saturation power. The ridge geometry at the input of the device can also be optimized to increase the input fiber-coupling efficiency and reduce the NF. Lastly, a vertical taper mode transformer can be incorporated instead of a horizontal taper. This would allow for the desired mode transformation without an increase in device resistance.

5. Acknowledgement

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6. References

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