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# Packaged 1.5- $\mu\text{m}$ Quantum-Well SOA With 0.8-W Output Power and 5.5-dB Noise Figure

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**Abstract**—We report the demonstration of a lensed-fiber-pigtailed InGaAsP-InP quantum-well semiconductor optical amplifier based on the slab-coupled optical waveguide (SCOW) concept. At a 5-A bias current and a wavelength of 1540 nm, the packaged SCOW amplifier (SCOWA) exhibits a record 0.8-W saturation output power, 13.8-dB small-signal gain, 5.5-dB noise figure, and a maximum electrical-to-optical conversion efficiency of 11%. The estimated coupling efficiency between the large ( $5.6 \times 7.5 \mu\text{m}$ ), fundamental SCOWA mode and the lensed fibers ( $6.5\text{-}\mu\text{m}$  spot size) is 90%.

**Index Terms**—Noise figure (NF), optical waveguides, power amplifiers, quantum-well (QW) devices, semiconductor optical amplifiers (SOAs).

## I. INTRODUCTION

WATT-CLASS low-noise semiconductor optical gain media are beneficial to a number of applications including high-power amplifiers for optical communication systems [1], ultralow-noise mode-locked lasers for optical sampling and signal generation [2], and single-frequency narrow-linewidth lasers for microwave photonics and coherent optical communications [3]. Benefits of semiconductor optical amplifiers (SOAs) relative to solid-state amplifiers [e.g., erbium-doped fiber amplifiers (EDFAs)] include smaller size and weight, higher electrical-to-optical conversion efficiency, larger gain bandwidth, and wavelength designability.

The saturation output power  $P_{o,\text{sat}}$  of an SOA can be increased by a combination of 1) increasing the area of the active region, 2) reducing the optical confinement factor  $\Gamma$ , and 3) reducing the differential gain [4]. Much work has been reported on increasing  $P_{o,\text{sat}}$  by increasing the active-region area through the use of a tapered waveguide. Tapered SOAs having a device output power of 3.5 W at 0.98  $\mu\text{m}$  [5], 0.75 W at 1.3  $\mu\text{m}$  [6], and 0.3 W at 1.5  $\mu\text{m}$  [7] have been demonstrated. The performance of tapered SOAs has been limited by the spatial properties of the output mode which is asymmetric ( $\sim 1 \times 200 \mu\text{m}$ ), astigmatic, and unstable due to filamentation in the tapered section.

The  $P_{o,\text{sat}}$  of waveguide SOAs operating in a fundamental, transverse optical mode has been considerably less than 1 W.

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By reducing  $\Gamma$  to  $\sim 1\%$ ,  $P_{o,\text{sat}} = 0.25$  W and small-signal gain  $G_o = 13$  dB was obtained from an InGaAsP quantum-well (QW) SOA device at 1590 nm [8]. Low- $\Gamma$  SOAs based on InAs-InP quantum dots have demonstrated device  $P_{o,\text{sat}} = 0.37$  W and  $G_o = 13$  dB at 1550 nm [9]. To our knowledge, these results represent the highest output powers from fundamental-mode SOA devices reported by other groups.

We recently reported the demonstration of a new class of high-power low- $\Gamma$  SOA based on the slab-coupled optical waveguide (SCOW) concept [10]. Advantages of SCOW amplifiers (SCOWAs) relative to other fundamental-mode SOAs include: 1) ultralow  $\Gamma \sim 0.3 - 0.5\%$ , 2) low excess optical absorption  $\alpha_i \sim 0.5 \text{ cm}^{-1}$ , and large optical modes ( $> 5 \times 7 \mu\text{m}$ ). In our earlier work, we reported a bench-top fiber-butt-coupled  $P_{o,\text{sat}} = 0.63$  W and  $G_o = 12$  dB at 1540 nm. Here we report a packaged lensed-fiber-pigtailed SCOWA having  $P_{o,\text{sat}} = 0.8$  W and  $G_o = 13.8$  dB at 1540 nm and 5-A bias current. Under these same conditions, we measure the noise figure (NF) to be 5.5 dB.

## II. DEVICE AND PACKAGING DESCRIPTION

The SCOWA material was grown via organo-metallic vapor-phase epitaxy on an n-type (100) InP substrate. The material structure comprises the following layers: 0.20- $\mu\text{m}$  n-InP buffer layer, 1.0- $\mu\text{m}$  n-InP cladding layer with graded doping ( $1.0\text{--}0.2 \times 10^{18} \text{ cm}^{-3}\text{S}$ ), 5- $\mu\text{m}$  lightly doped InGaAsP waveguide ( $5 \times 10^{16} \text{ cm}^{-3}\text{S}$ ,  $\lambda_g = 1.03 \mu\text{m}$ ), nominally undoped QW active region, 0.025- $\mu\text{m}$  p-AlInAs electron blocking layer ( $5 \times 10^{17} \text{ cm}^{-3} \text{Zn, Al} = 48\%$ ), 1.0- $\mu\text{m}$  p-InP cladding with graded doping ( $2$  to  $8 \times 10^{17} \text{ cm}^{-3} \text{Zn}$ ), 0.6- $\mu\text{m}$  p-InP cap layer ( $10^{18} \text{ cm}^{-3} \text{Zn}$ ), and 0.2- $\mu\text{m}$  p + InGaAs contact layer. The QW active layer contains five 8-nm-thick compressively strained (1%) InGaAsP QWs with tensile-strained ( $-0.3\%$ ) InGaAsP ( $\lambda_g = 1.21 \mu\text{m}$ ) barrier and bounding layers having thicknesses of 8 and 12 nm, respectively. The peak photoluminescence wavelength of the QW layers was 1.53  $\mu\text{m}$ .

The device fabrication was similar to that described in [10]. The reflectivity of the SCOWA facets was minimized by a combination of  $5^\circ$ -oriented (110) angle cleaving followed by antireflection coating. The cleaved device length was 10 mm. We estimate  $\Gamma$  to be 0.5% from overlap integrals of the calculated transverse-mode profile and the material structure.

Fig. 1 shows a photograph of the packaged SCOWA. The SCOWA was mounted junction-side down to a Cu-W submount using AuSn solder. The submount was mounted to a Cu baseplate that was temperature-controlled using a thermoelectric cooler. The input and output facets were coupled to lensed single-mode fibers (SMF-28) having 6.5- $\mu\text{m}$  spot size and affixed using laser welding. Prior to packaging, the  $1/e^2$

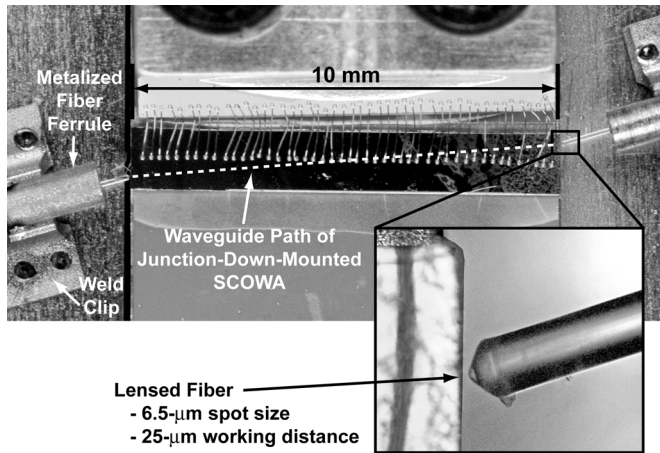


Fig. 1. Top-down photograph of junction-down-mounted SCOWA packaged using lensed-fiber pigtailed. SCOWA length = 10 mm. SCOWA facet angle =  $5^\circ$ . SCOWA soldered to Cu-W submount. Lensed-fiber parameters: fiber = SMF-28, spot size =  $6.5 \mu\text{m}$ , working distance =  $25 \mu\text{m}$ .

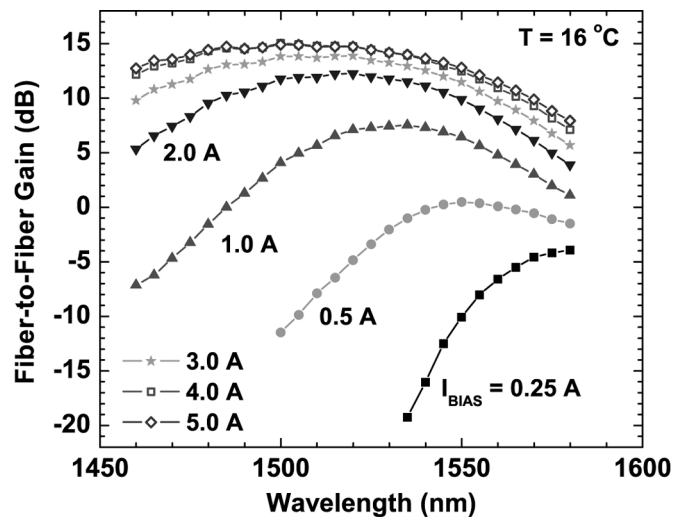


Fig. 2. Small-signal gain spectra of the packaged SCOWA for several bias currents. Baseplate temperature =  $16^\circ\text{C}$ .

widths of the SCOWA near-field mode profile were measured to be  $5.6$  and  $7.5 \mu\text{m}$ , perpendicular and parallel to the growth plane, respectively.

### III. MEASUREMENT RESULTS

The small-signal gain spectra of Fig. 2 were measured using a tunable continuous-wave (CW) laser and a polarization controller (PC) at the SCOWA input, and an optical power meter at the output. The laser power was  $0.2 \text{ mW}$  and the PC was adjusted to provide maximum gain. At a bias current of  $5 \text{ A}$  and  $T = 16^\circ\text{C}$ , the peak fiber-to-fiber gain was  $14.9 \text{ dB}$  at  $1500 \text{ nm}$  and the 3-dB bandwidth was greater than  $100 \text{ nm}$ . The transverse-electric/transverse-magnetic (TE/TM) polarization gain ratio was measured to be  $17$ – $18 \text{ dB}$  and was nearly independent of wavelength. We observe that the gain does not change appreciably as the current is increased from  $4$  to  $5 \text{ A}$ .

Fig. 3 shows the gain saturation characteristic of the packaged SCOWA at  $\lambda = 1540 \text{ nm}$  and  $T = 16^\circ\text{C}$  for several values of bias current. The variable input power was generated using a CW laser, high-power ( $1 \text{ W}$ ) EDFA, and variable optical atten-

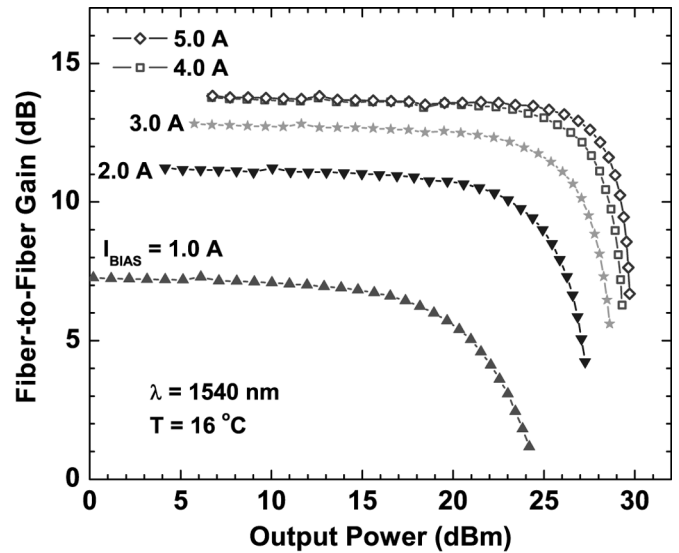


Fig. 3. Gain saturation characteristic of the packaged SCOWA for several bias currents. Wavelength =  $1540 \text{ nm}$ . Baseplate temperature =  $16^\circ\text{C}$ .

uator followed by a PC. The SCOWA output power was measured using an optical power meter. At  $5\text{-A}$  bias, the small-signal gain was  $G_o = 13.8 \text{ dB}$ ,  $P_{o,\text{sat}} = 0.8 \text{ W}$  ( $+29 \text{ dBm}$ ), where  $G = G_o - 3 \text{ dB}$ , and the maximum output power was  $P_{\text{max}} = 0.93 \text{ W}$  ( $+29.7 \text{ dBm}$ ), where  $G = 6.7 \text{ dB}$ . At  $P_{\text{max}}$ , the electrical-to-optical conversion efficiency was  $11\%$ , neglecting the TEC power. Recently, we demonstrated that the SCOWA conversion efficiency can be increased by using a multicontact electrode structure [11]. Prior to packaging,  $P_{o,\text{sat}}$  of the SCOWA device was measured to be  $0.9 \text{ W}$ , revealing that the SCOWA to lensed-fiber coupling efficiency was  $\sim 90\%$  ( $-0.5 \text{ dB}$ ) [12].

The data of Fig. 3 show that the abruptness of the gain saturation roll-off increases at the higher bias currents as the output power approaches  $1 \text{ W}$ . We attribute this sharper roll-off to increased optical loss induced by two-photon absorption (TPA) and TPA-generated free carriers in the InGaAsP waveguide [13]. These TPA-related loss mechanisms limit the SCOWA output power for a given mode size and waveguide composition.

The NF data contained in Fig. 4 were measured using the optical source subtraction method [14]. A tunable CW laser was injected into the packaged SCOWA. The SCOWA output was attenuated and then measured using an optical spectrum analyzer. Calibration factors measured and included in the NF calculation were the source-spontaneous-emission spectral density, the optical losses, and the polarization extinction of the SCOWA. At  $1540 \text{ nm}$  and  $5\text{-A}$  bias, the NF was  $5.5 \text{ dB}$ . As the current was reduced to  $2 \text{ A}$ , the NF decreased to  $4.6 \text{ dB}$ , which may be caused by the gain decreasing more rapidly than the population inversion factor increases. We attribute the very low NF ( $4.6$ – $5.5 \text{ dB}$ ) of the packaged SCOWA to its low excess optical absorption and the high coupling efficiency between the SCOWA and the input lensed fiber. At shorter wavelengths and biases between  $2$  and  $5 \text{ A}$ , the NF increased slightly ( $6.7$ – $7.5 \text{ dB}$ ) due to the larger population inversion factor. At biases less than  $2 \text{ A}$ , the inversion of the amplifier drops significantly, especially towards the shorter wavelengths, resulting in a larger NF.

Although formal lifetime reliability tests have not been performed on the packaged SCOWA, we note that the device

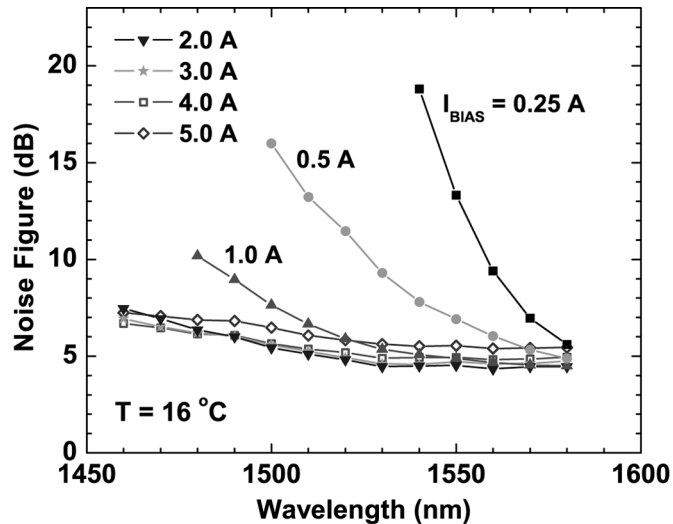


Fig. 4. NF of the packaged SCOWA as a function of wavelength for several bias currents measured using the optical source subtraction technique. Baseplate temperature = 16 °C.

reported here has operated for several hundred hours with no degradation in gain or output power.

#### IV. CONCLUSION

We have demonstrated a packaged, high-power SOA having 0.8-W fiber-coupled saturation output power, 13.8-dB small-signal gain, and 5.5-dB NF at 5-A bias current and 1540-nm wavelength. These results were achieved by combining the SCOW concept with an InGaAsP QW active region and high efficiency coupling (90%) to lensed fibers having optimized spot size. The high saturation output power is obtained by reducing the optical confinement factor by a factor of 5–10 relative to conventional SOAs. For these devices, we find that the CW output power is presently limited by the loss associated with TPA-generated free carriers in the InGaAsP waveguide. Higher output power should be achieved by increasing the mode size or by using a waveguide material with a bandgap large enough to prohibit TPA from the 1.5- $\mu\text{m}$  photons.

The packaged SCOWA demonstrated here is a strong candidate for the replacement of Watt-class EDFAs for some applications because of its relatively small size, wide optical bandwidth, and high electrical-to-optical conversion efficiency. The reported low NF of the SCOWA is also comparable to that of Watt-class EDFAs.

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