applied optics

Gain-coupled distributed feedback laser based on periodic surface anode canals

YONGYI CHEN,[1] PENG JIA,[1,2] JIAN ZHANG,[1] LI QIN,[1,*] HONG CHEN,[1,2] FENG GAO,[1,2] XING ZHANG,[1] XIAONAN SHAN,[1] YONGQIANG NING,[1] AND LIJUN WANG[1]

[1]State Key Laboratory of Luminescence and Application in Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China
[2]University of Chinese Academy of Sciences, Beijing 100039, China
*Corresponding author: qinl@ciomp.ac.cn

Received 19 May 2015; revised 24 August 2015; accepted 30 August 2015; posted 22 September 2015 (Doc. ID 241188); published 13 October 2015

A single-longitude-mode, broad-stripe, gain-coupled, distributed-feedback laser based on periodic surface anode canals (PSACs) is demonstrated. The PSACs, produced by i-line lithography, enhance the contrast of periodic current density in the active layer without introducing effective photon coupling; calculated grating κL is only 0.026. Power of 144.6 mW at 968.8 nm, with spectrum linewidth less than 0.04 nm on every uncoated cleavage facet, is obtained at a current of 1.2 A with a side-mode suppression ratio >29 dB.

OCIS codes: (140.3490) Lasers, distributed-feedback; (140.3570) Lasers, single-mode; (300.3700) Linewidth; (300.6360) Spectroscopy, laser.

http://dx.doi.org/10.1364/AO.54.008863

1. INTRODUCTION

Distributed feedback (DFB) semiconductor lasers are important components in the fields of communication links and broadband networks, which require single longitude mode, narrow linewidth, and high power. Uniform index-coupled DFB lasers with antireflection-coated facets have the intrinsic drawback of lasing two degenerated modes [1]. This is often solved by either introducing different facet reflectivity [2] or inducing a phase shift in the corrugation inside the laser [3,4]. However, the former method suffers from random facet phases, which are hard to control [5], and the latter method decreases the quantum efficiency as κL increases, meanwhile reducing the side-mode suppression ratio (SMSR) cause by spatial hole burning (SHB) effects [3]. Other solutions include gain-coupled and complex-coupled DFB lasers. Periodic gain (loss) assures a lasing spectrum exactly at Bragg wavelength without any degeneracy problem, realizing single longitude mode, facet reflection immunity, wide temperature range of single-mode oscillation, low chirping, and reduced SHB [6–12]. However, the preparation process generally requires complex quadratic epitaxial growth technology and expensive electron beam lithography techniques to process the active layer, causing instability and increasing the cost. Thus, they are not suitable for commercial applications. DFB lasers based on high-order Bragg gratings (HOBG) [13–15] are therefore proposed to simplify the production process. These usually etch deep slots in complicated shapes (such as V-shaped slots using stepper lithography [15]) into the waveguide to increase κL for index coupling. Here, we propose a gain-coupled, broad-stripe DFB laser based on periodic surface anode canals (PSACs) prepared by simple i-line lithography. The device works at 1.2 A with 144.6 mW at each uncoated cleavage facet with single-longitude mode at 968.8 nm and offers the same level of lasing power, operating at single-longitude mode, as HOBG devices and ordinary DFB lasers when the power from both uncoated cleavage facets is counted together [16,17]. Measured spectrum linewidth is less than 0.04 nm and SMSR is greater than 29 dB. The processing technologies are low-cost and far simpler, as no quadratic epitaxial growth technology, electron beam lithography techniques, or stepper lithography techniques are needed.

2. DEVICE FABRICATION AND MEASUREMENT

The schematic structure of the PSAC on the proposed device is shown in Fig. 1(a). The chip structure for the laser is shown in Table 1 and fabricated by epitaxial growth using the Metal Organic Chemical Vapor Deposition (MOCVD) method. The active layer of the epitaxial structure consists of two AlGaInAs quantum wells with an emission peak around 970 nm. Figure 1(b) shows several periodicities of the canals under scanning electron microscopy.

First, broad stripes were defined by the photoresist layer using i-line lithography. The width of the broad stripes was

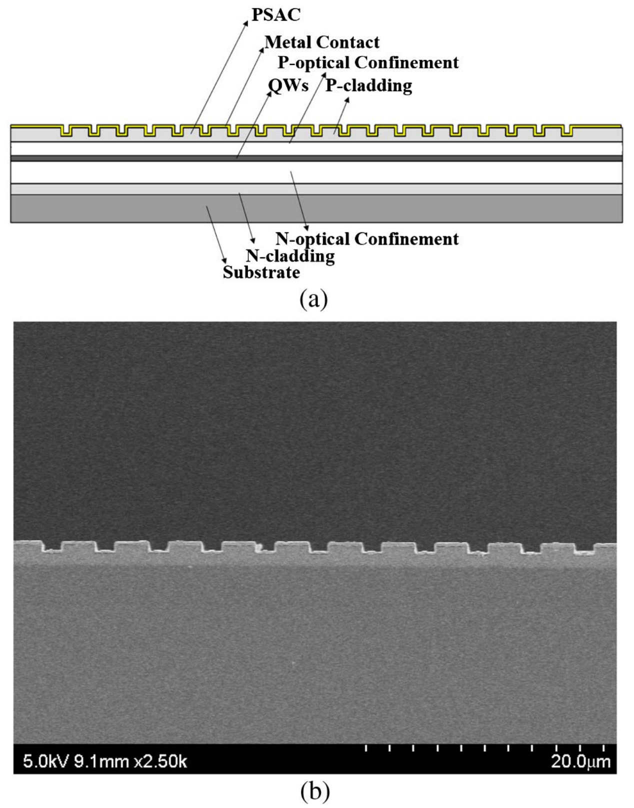

Fig. 1. (a) Schematic structure of PSAC gain-coupled DFB laser and (b) scanning electron microscope picture of HOBG.

100 μm. The broad stripes were then etched out at a depth of 1.4 μm using an inductively coupled plasma etcher. For the next step, i-line lithography was used again to pattern the periodic canals on the broad stripes and dry etching was used to form the periodic canal grooves with a depth of 0.67 μm and width of 1.67 μm at a periodicity of 4.45 μm along the whole 2 mm laser cavity. This etching depth exposed the bottom and side walls of the grooves with aluminum-doped layers to the air; then the grooves were partially oxidized. The chips were metal-contacted for 300 nm gold thereafter. Because of the oxidation, the groove region had larger resistance and current injection mainly came from the non-etched part of the chip, making surface periodic anodes injected from each canal available. Finally, the chips were cleavaged without coating. For comparison purposes, Fabry–Perot (FP) lasers with the same cavity length and width, also without facet coating, were placed on the wafer.

Table 1. Structure of the 970 nm Chip

Layer	Material	Thickness (nm)	Layer Name
1	$p+$-GaAs	120	Cap
2	p-Al0.2Ga0.8As	500	P-cladding
3	p-Al0.12Ga0.88As ~Al0.08Ga0.92As	1200	P-optical confinement
4	GaAs & InGaAs	32	QWs
5	n-Al0.08Ga0.92As ~Al0.12Ga0.88As	3000	N-optical confinement
6	n-Al0.15Ga0.85As	600	N-cladding
7	$n+$-GaAs	~350000	Substrate

Both the PSAC device and common FP laser were mounted p-side down on Cu c-mount heat sinks and placed on a water-cooling unit to maintain a stationary temperature of 20°C for testament under continuous-wave (CW) operation. The spectra were measured directly by coupling the output laser using a 10 μm core diameter fiber-linking YOKOGAWA AQ6370C optical spectrum analyzer with 0.02 nm resolution, meaning ±0.02 nm instrument error.

3. TEST RESULTS AND DISCUSSION

The CW power-voltage-current and spectrum characteristics of devices are shown in Figs. 2 and 3. Figure 2 shows that the threshold current of the FP laser is 0.39 A with a slope efficiency of 520 mW/A. Compared with the FP laser, the gain-coupled PSAC laser's threshold current increases to 0.7 A, and meanwhile the slope efficiency drops down to 274 mW/A. This is basically because the latter worked at single-longitude mode.

The PSAC actually coupled a small part of the waveguide power working as Bragg gratings. Since calculated effective index of the chip is 3.4817, this is a 32-order grating. The etching depth of 0.67 μm decreases the effective index n_{eff} from 3.4817 to 3.4815. The theoretical calculation for κL [18] is

$$\kappa L = \frac{L}{\Lambda}\left(\frac{\Delta n}{n_{\mathrm{eff}}}\right),$$

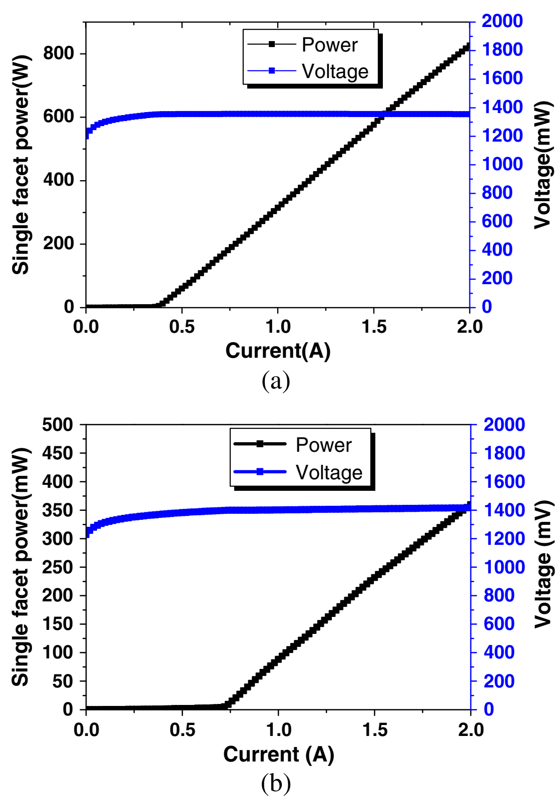

Fig. 2. CW power-voltage-current characteristics of (a) FP lasers and (b) gain-coupled PSAC lasers.

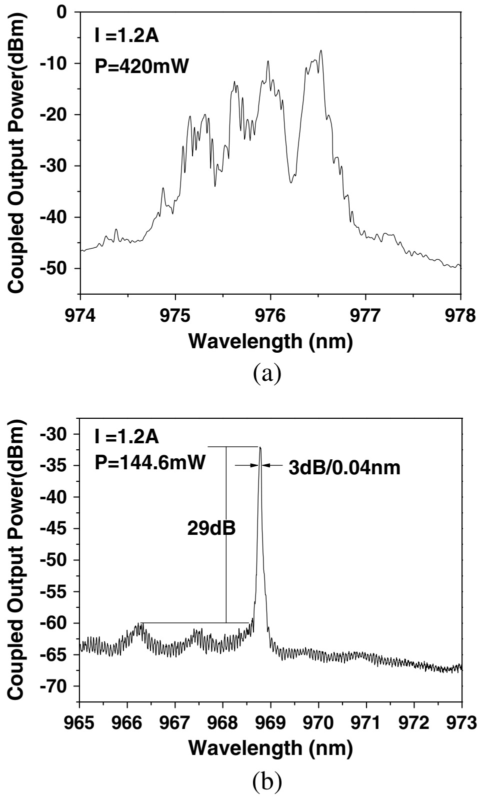

Fig. 3. CW spectrum characteristics of (a) FP lasers and (b) gain-coupled PSAC lasers at 1.2 A.

where L is the cavity length of 2 mm and Λ is 4.45 μm, the periodicity of the PSAC. The calculated κL for the PSAC cold cavity is only 0.026. This is because, compared with the Bragg grating DFB laser, Λ is much larger and Δn is smaller. This leads to a very weak index-coupled effect that can be neglected (κL is greater than 1 for ordinary DFB lasers and 0.3 for HOBG multiple-longitude-mode lasers [15]), assuring the device is gain-coupled.

At 1.2 A, the device still maintains single-longitude mode, with an output power of 144.6 mW from every cleavage facet. The linewidth is only 0.04 nm, already beyond our instrument error, and corresponding SMSR >29 dB. Considering both sides together, the total power level is 289.2 mW. This is the same as a single-longitude-mode ordinary second-order, index-coupled DFB laser [16,17], but no quadratic epitaxial growth technology or electron beam or stepper lithography techniques are needed, making the fabrication process easy and low-cost. The actual lasing wavelength is 968.8 nm at 1.2 A, which is very close to the Bragg wavelength of 968.3 nm. This small difference is probably caused by four factors. First, the periodicity of the PSAC defined by i-line lithography might have a 2 nm deviation from the original design, perhaps due to processing or fabrication error caused by the ±1 μm lithographic plate resolution: for a device with 2 mm cavity length, including 450 PSAC, each period with a 2 nm deviation only enlarges the total cavity length by 900 nm from the design. Second, the theoretical refractive index might be different with our chip, having been grown by MOCVD. Current injection

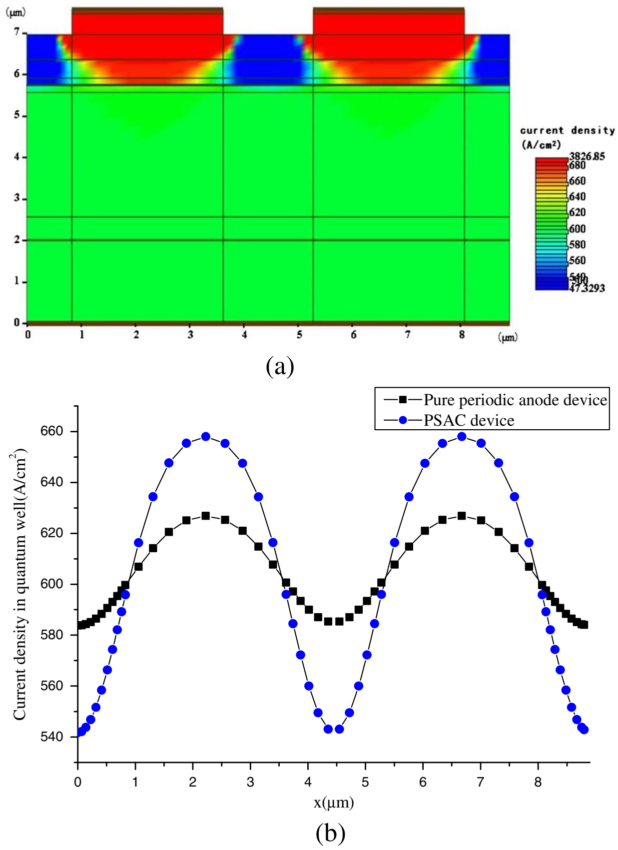

Fig. 4. (a) Two-dimensional current density distribution for two periodicities of the PSAC device. (b) One-dimensional current density distribution in the quantum well for the PSAC device and pure periodic anode device without etching grooves.

and heat accumulation are the third and fourth factors that may lead to fluctuations of the chip's refractive index.

To calculate the current density of the devices, simulation analysis was carried out using the commercial software PICS3D. Results for both the PSAC device and a model with pure periodic anodes without canals separated by etching grooves are given in Fig. 4. At 1.2 A, the whole device has an average current density of 600 A/cm^2. Figure 4(a) shows the PSAC device's two-dimensional current density distribution for two periodicities. Thanks to PSAC, the current was injected into the quantum wells periodically; this is caused by 1.67 μm separation between each anode canal. Figure 4(b) shows the differences of current density in the quantum well layer between the models with and without etching grooves. It can be seen that the PSAC device with etching grooves has a current density contrast of 115 A/cm^2, almost three times as 43 A/cm^2 for the pure periodic P-contact anode model without etching grooves. High electric current density contrast means high contrast of optical gain along the cavity; therefore, the PSAC device can operate in single-longitude mode at high power before gain saturation. Etching grooves increase the periodic current density contrast by inducing the injected current into the quantum well from periodic anode canals as deep as possible to reduce the current side drift while not bringing much optical coupling to scatter the photons in the waveguide, which often leads to high-order scattering loss or unwanted directional lasing attenuation.

4. CONCLUSION

To conclude, a single-longitude mode, gain-coupled DFB laser at 1.2 A based on PSACs with a power of 144.6 mW at every uncoated cleavage facet is demonstrated. Considering both sides together, its total power level is 289.2 mW, the same as an ordinary DFB laser. The measured lasing wavelength is 968.8 nm, linewidth is less than 0.04 nm, and SMSR >29 dB. The device is based on simple i-line lithography and is suitable for commercial production. Future work will include film coating on cleavage facets for single-facet emitting and making a device at an optical communication wavelength, such as 1550 nm.

Funding. National Natural Science Foundation of China (NSFC) (61234004, 11404327, 61176045, 61204055, 61306086, 61376070, 61434005); Natural Science Foundation of Jilin Province (Natural Science Foundation of Jilin Province of China) (0140101206JC-02, 20130206006GX, 20140101172JC, 20140520132JH).

REFERENCES

1. H. Kogelnik and C. V. Shank, "Coupled-wave theory of distributed feedback lasers," J. Appl. Phys. **43**, 2327–2335 (1972).
2. S. Chinn, "Effects of mirror reflectivity in a distributed-feedback laser," IEEE J. Quantum Electron. **9**, 574–580 (1973).
3. H. Soda, Y. Kotaki, H. Sudo, H. Ishikawa, S. Yamakoshi, and H. Imai, "Stability in single longitudinal mode operation in GaInAsP/InP phase-adjusted DFB lasers," IEEE J. Quantum Electron. **23**, 804–814 (1987).
4. J. E. A. Whiteaway, B. Garrett, G. H. B. Thompson, A. J. Collar, C. J. Armistead, and M. J. Fice, "The static and dynamic characteristics of single and multiple phase-shifted DFB laser structures," IEEE J. Quantum Electron. **28**, 1277–1293 (1992).
5. J. Buus, "Mode selectivity in DFB lasers with cleaved facets," Electron. Lett. **21**, 179–180 (1985).
6. N. Susa, "Fluctuations of the laser characteristics and the effect of the index-coupling component in the gain-coupled DFB laser," IEEE J. Quantum Electron. **33**, 2255–2265 (1997).
7. J. Hong, K. W. Leong, T. Makino, J. Evans, X. Li, and W. P. Huang, "Impact of random facet phases on modal properties of partly gain-coupled distributed-feedback lasers," IEEE J. Sel. Top. Quantum Electron. **3**, 555–568 (1997).
8. S. Kim and B. Kim, "Analysis of single-mode yields above threshold for complex-coupled distributed feedback lasers with asymmetric facet reflectivities," J. Opt. Soc. Am. B **22**, 1010–1015 (2005).
9. Y. Xi, X. Li, S. M. Sadeghi, and W. Huang, "Dispersive-grating distributed feedback lasers," Opt. Express **16**, 10809–10814 (2008).
10. Y. Xi, W. Huang, and X. Li, "A standing-wave model based on threshold hot-cavity modes for simulation of gain-coupled DFB lasers," IEEE J. Lightwave Technol. **27**, 3853–3860 (2009).
11. M. Aliannezhadi, F. Shahshahani, and V. Ahmadi, "Improved performance of complex gain-coupled DFB laser by using tapered grating structure," Opt. Quantum Electron. **44**, 1–16 (2012).
12. W. Feng, J. Q. Pan, L. Wang, Z. Y. Liao, Y. B. Cheng, D. B. Chen, L. J. Zhao, H. L. Zhu, and W. Wang, "1.3 μm gain coupled DFB laser with InGaAlAs MQW grown on absorptive InGaAsP corrugation," Semicond. Sci. Technol. **22**, 859–862 (2007).
13. A. M. Shams-Zadeh-Amiri, J. Hong, and X. Li, "Second- and higher order resonant gratings with gain or loss—Part I: green's function analysis," IEEE J. Quantum Electron. **36**, 1421–1430 (2000).
14. R. R. Millett, K. Hinzer, T. J. Hall, and H. Schriemer, "Simulation analysis of higher order laterally-coupled distributed feedback lasers," IEEE J. Quantum Electron. **44**, 1145–1151 (2008).
15. J. Decker, P. Crump, J. Fricke, A. Maassdorf, G. Erbert, and G. Tränkle, "Narrow stripe broad area lasers with high order distributed feedback surface gratings," IEEE Photon. Technol. Lett. **26**, 829–832 (2014).
16. W. Zeller, M. Kamp, J. Koeth, and L. Worschech, "High-power pulsed 976-nm DFB laser diodes," Proc. SPIE **7682**, 76820T (2010).
17. A. Klehr, H. Wenzel, O. Brox, F. Bugge, G. Erbert, T.-P. Nguyen, and G. Tränkle, "High-power 894 nm monolithic distributed-feedback laser," Opt. Express **15**, 11364–11369 (2007).
18. L. Coldren, S. Corzine, and M. Masanovic, *Diode Lasers and Photonic Integrated Circuits*, 2nd ed. (Wiley, 2012), pp. 113–121.