Modal gain characteristics of a 2 μm InGaSb/AlGaAsSb passively mode-locked quantum well laser

Xiang Li,¹ Hong Wang,^{1,a)} Zhongliang Qiao,^{1,2} Xin Guo,¹ Geok Ing Ng,¹ Yu Zhang,³ Zhichuan Niu,^{3,a)} Cunzhu Tong,⁴ and Chongyang Liu¹

¹*School of Electrical and Electronic Engineering, Nanyang Technological University, 639798 Singapore*

²*The National Key Laboratory on High Power Semiconductor Lasers, Changchun University of Science and Technology, Changchun 130022, China*

³*State Key Lab for Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China*

⁴*State Key Lab of Luminescence and Applications, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China*

(Received 22 October 2017; accepted 5 December 2017; published online 18 December 2017)

Passive mode locking with a fundamental repetition rate at ~ 18.46 GHz is demonstrated in a two-section InGaSb/AlGaAsSb quantum well laser emitting at 2 μm . Modal gain characteristics of the laser are investigated by performing the Hakki-Paoli method to gain better insight into the impact of the absorber bias voltage (V_a) on the light output. The lasing action moves to longer wavelengths markedly with increasing negative V_a . The light output contains more longitudinal modes in the mode locking regime if the gain bandwidth is larger at a certain V_a . Our findings provide guidelines for output characteristics of the mode-locked laser. *Published by AIP Publishing.*

<https://doi.org/10.1063/1.5010015>

Ultrafast light sources operating in the 2 μm range are promising for many applications such as molecular spectroscopy, high resolution gas sensing, advanced telecommunications, and eye-safe light detection and ranging (LIDAR).^{1–3} For this type of light source, 2 μm mode-locked solid-state^{4,5} lasers, fiber lasers,⁶ as well as a semiconductor disk laser⁷ have been demonstrated using GaSb-based semiconductor saturable absorber mirrors (SESAMs) taking advantage of their very fast sub-ps absorption recovery time.^{8,9} Compared to these lasers, monolithic mode-locked semiconductor lasers have their specific advantages, such as small size and low power consumption. In addition, they are integratable with Si photonic devices and they can be pumped electrically.^{10,11} All these features make them very desirable. Regarding the architecture of semiconductor mode-locked lasers (MLLs), a two-section or multi-section waveguide is popularly used,^{12–15} and in a semiconductor laser, the absorber can just simply be a section of the device with reverse bias.

Recently, Merghem *et al.* reported passive mode locking in a monolithic 2 μm GaSb-based diode laser,¹⁵ which first proved the feasibility of the two-section architecture in the 2 μm range. In their work, a detailed investigation of the mode locking characteristics of the laser was given. However, the influence of the bias condition on the gain characteristics and how it thereby affects the light emission (e.g., wavelength, spectral content when working in the mode locking regime, and so on) remain unexplored. These issues are critical for the use of mode-locked diode lasers as light sources for practical applications. In this letter, we demonstrate a monolithic two-section passive MLL at 2 μm , and modal gain characteristics of the laser are first investigated using the Hakki-Paoli method^{10,16,17} to gain better knowledge of its bias-dependent output.

The laser structure was grown on a (100) n-GaSb substrate by molecular beam epitaxy (MBE). It comprises a 10 nm-thick $\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}$ single QW (SQW) with lattice-matched 270 nm-thick $\text{Al}_{0.25}\text{GaAsSb}$ barriers on both sides. Cladding layers with a thickness of 2000 nm were made of lattice-matched $\text{Al}_{0.5}\text{GaAsSb}$. A 130 nm-thick GaSb contact layer ended the structure. A very similar laser structure with high performance has been demonstrated by us previously.^{10,18} The schematic diagram of the two-section MLL is shown in Fig. 1. First, the grown wafer was processed into Fabry-Perot (FP) ridge waveguide lasers.¹⁹ Then, a 10 μm -wide electrical isolation was formed by removing the high-conductivity contact layer and part of the p-cladding layer. To avoid deep etching and thus make single spatial mode operation more achievable,¹⁵ only GaSb-based materials in the contact window region were etched away. A resistance of ~ 1.1 k Ω was achieved between the two sections with a etch depth of ~ 1.5 μm . For the tested laser in this study, the ridge width is ~ 5 μm , which provides single lateral mode

FIG. 1. Schematic diagram of the two-section passively mode-locked laser (not to scale). When working in the mode locking regime, the gain section is forward biased (I_g) while the absorber section needs to be reverse biased (V_a).

^{a)}Electronic addresses: ewanghong@ntu.edu.sg and zcniu@semi.ac.cn

operation. The lengths of the gain section (L_g) and the absorber section (L_a) are 1.89 mm and 0.23 mm, respectively. When working in the mode locking regime, the gain section is forward biased (I_g) while the absorber section needs to be reverse biased (V_a). During the measurements, the two-section laser was placed on a temperature electronic controller (TEC) with temperature fixed at 20 °C.

Figure 2 shows the light output power collected from the facet of the gain section as a function of the injection current (I) for the tested laser in the continuous wave (CW) mode at room temperature (RT). The bias voltage applied to the absorber section (V_a) was varied from a small forward value (+0.5 V) to -5 V, and I_g was increased from 0 to 200 mA at each V_a . The threshold current increases consistently with increasing negative V_a owing to the stronger absorption. Note that when the absorber is at small forward bias or left open ($V_a = 0$ V), the L - I curves exhibit a turn-on jump at lasing threshold, which is common for devices with a saturable absorber.^{12,20} This jump is attributed to a rapid increase of the carrier density in the absorber QW region caused by the photon density increase as the lasing action starts, and the electric field is not strong enough to sweep the carriers out of the QW region immediately. This process decreases the absorption of the absorber, which subsequently results in the output power jump.

Stable mode locking was achieved over a wide range of V_a (from -2 to -5 V). The RF spectra were measured using a high-speed photodetector followed by a 50 GHz RF spectrum analyzer (N9030A), while the strongest RF power was observed at $I_g = 150$ mA and $V_a = -4$ V as shown in Fig. 3(a). The fundamental repetition rate with more than 40 dB signal to noise ratio is at ~18.46 GHz, corresponding to the photon round-trip time in the 2.13 mm-long laser cavity. The second harmonic at 36.92 GHz is also marked in the figure. The RF peak at the fundamental repetition rate is shown in greater detail in the inset of Fig. 3(a). It has a linewidth as small as 30 kHz, which indicates an efficient mode locking mechanism. The RF signal from the high-speed photodetector was also fed into a 30 GHz real-time oscilloscope (DSO93004L). Figure 3(b) shows the pulse train observed on the oscilloscope. The time interval between two pulses is

FIG. 2. L - I curves of the laser at room temperature with the absorber section bias V_a varied from +0.5 to -5 V.

FIG. 3. (a) Electrical spectrum of the laser under the bias condition to get the strongest RF power ($I_g = 150$ mA, $V_a = -4$ V). The inset shows the RF peak at the fundamental repetition rate in greater detail. (b) Pulse train under the same bias condition.

~54.3 ps, corresponding well to the fundamental repetition rate at ~18.46 GHz.

Optical spectra of the tested laser were measured using an optical spectrum analyzer (AQ6375). Figure 4(a) shows the spectral evolution along with I_g towards the passive mode locking regime when the absorber was biased at -4 V. At $I_g = 113$ mA, when the laser is just about to lase, the wide spectrum corresponds to amplified spontaneous emission (ASE). At $I_g = 121$ mA, which is slightly beyond lasing threshold, the laser does not work in the mode locking regime. The spectrum is quite narrow, consisting of only a few longitudinal modes, just like a single-section QW laser. With a further increase in I_g to the mode locking optimum condition (~150 mA), more and more longitudinal modes are locked in phase, and the emission spectrum becomes wider [shown in Fig. 4(a), $I_g = 155$ mA]. Lorentz fit of the spectrum centering at ~1989 nm gives a full width at half maximum (FWHM) of ~3.4 nm as shown in Fig. 4(b), and more than 40 longitudinal modes spaced by ~0.238 nm are included. If sech² pulses are assumed which have a time-bandwidth product of ~0.315, a pulse width of ~1.2 ps is expected. Using the pulse width estimation method in Ref. 15 gives a similar result.

To obtain the gain characteristics of the laser and thus gain better insight into its bias-dependent output, the net modal gain (G_{net}) of the two-section laser was investigated using the Hakki-Paoli method. Figure 5 shows the net modal gain spectra for a range of I_g when V_a was fixed at -1 V.

FIG. 4. (a) Spectral evolution along with I_g towards the passive mode locking regime when the absorber was biased at -4 V. (b) Lorentz fit of the spectrum at $I_g = 155$ mA.

G_{net} was computed from the amplified spontaneous emission (ASE) spectra using the following equation:¹⁰

$$G_{net}(\lambda) = \Gamma g_{material}(\lambda) - \alpha_i$$

$$= \frac{1}{L} \ln \frac{\sqrt{S(\lambda)} - 1}{\sqrt{S(\lambda)} + 1} + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right), \quad (1)$$

where Γ is the confinement factor, $g_{material}$ is the material gain, α_i is the internal loss due to crystal defects and dopant atoms in the waveguide. S is the peak-to-valley ratio of the FP resonances which can be directly obtained from the ASE

FIG. 5. Net modal gain spectra of the laser for a range of I_g when V_a was fixed at -1 V. This figure also shows the lasing spectrum at $I_g = 93$ mA. The inset shows some of the FP modes in detail.

spectra,¹⁰ L is the cavity length (2.13 mm), and R_1 and R_2 are facet reflectivities ($R = 0.34$ is used for both facets). The ASE spectra were recorded with a step size of 0.01 nm and a spectral resolution of 0.05 nm. The spectral resolution in the measurement is considered very good compared to the adjacent longitudinal FP mode spacing in our laser, which is ~ 0.238 nm. The inset of Fig. 5 shows the FP modes in greater detail. It can be seen from Fig. 5 that with increasing current, the net modal gain becomes larger to compensate the mirror loss [$(1/2L)\ln(1/R_1 R_2) = \sim 5.0 \text{ cm}^{-1}$], which is the threshold value for lasing. The measured gain never reaches this value even at the lasing threshold (91 mA). This is owing to the difficulty in accurately measuring S in the limit $S \rightarrow \infty$ [the first term on the right-hand side of Eq. (1) $\rightarrow 0$].²¹ Figure 5 also shows the lasing spectrum at $I_g = 93$ mA. The laser lases exactly at the location of the net modal gain peak, and the same case was observed at all other V_a .

Figure 6 shows the V_a -dependent net modal gain spectra from -1 to -5 V, all of them were measured just below threshold. The net modal gain peak redshifts consistently by around 20 nm with increasing negative V_a , which can be mainly attributed to the absorption spectrum shift due to the quantum confined Stark effect (QCSE). The same phenomenon was reported in a GaAs-based multi-section laser,²² which implies the well known electric field-induced red shift of the absorption peak in these two material systems. At the same time, since the lasing actions start exactly at the locations of the net modal gain peaks for the laser under testing, it also implies a potential application for tunable operation. As expected, at all absorber biases, the peak net modal gain has a similar value which is mainly determined by the mirror loss.

Figure 7 shows the V_a - and I_g -dependent gain bandwidth of the tested laser. For each V_a , the gain bandwidths with I_g increased to threshold are shown. Basically, increasing I_g results in a broadening of the gain curve with all applied V_a . Regarding the gain bandwidth at threshold, it is large when $V_a = -1$ V and just slightly changes from -2 to -4 V. At $V_a = -5$ V, the gain bandwidth increases markedly again, which indicates that the laser is able to support more longitudinal modes to lase. The inset of Fig. 7 shows the lasing spectra when the laser works well in the mode locking regime at $V_a = -4$ V and -5 V. The spectrum at $V_a = -5$ V

FIG. 6. V_a -dependent net modal gain spectra of the laser from -1 to -5 V.

FIG. 7. V_a - and I_g -dependent gain bandwidth of the laser. The inset shows the lasing spectra at $V_a = -4$ and -5 V when the laser is working well in the mode locking regime.

is obviously wider than that at $V_a = -4$ V, which confirms the analysis on the gain bandwidth. The wider spectrum also indicates the potential to obtain shorter pulses and that more channels can be expected when the laser is used as a multiwavelength light source.²³

In conclusion, stable passive mode locking is achieved in a two-section InGaSb/AlGaAsSb SQW MLL emitting at 2 μ m. Bias-dependent modal gain characteristics of the laser are first investigated by performing the Hakki-Paoli method. The absorption of the saturable absorber increases consistently with increasing negative V_a , which results in an increasing threshold current and lower output power at the same I_g . The lasing action moves to longer wavelengths markedly with increasing negative V_a . This implies the possibility of tunable operation. Stable mode locking with a fundamental repetition rate at ~ 18.46 GHz can be achieved under a wide range of bias conditions. The highest RF power was obtained when the absorber is biased at a moderate negative voltage of $V_a = -4$ V, while shorter pulses as well as more channels for multiwavelength operation can be expected at a more negative V_a of -5 V. These findings provide guidelines for the use of GaSb-based QW MLLs as light sources for different applications.

This work was supported in part by the National Research Foundation of Singapore (NRF-CRP12-2013-04),

National Natural Science Foundation of China (61435012 and 61308051), and National Key Basic Research Program of China (2014CB643903 and 2013CB932904).

- ¹A. Schliesser, N. Picqué, and T. W. Hänsch, *Nat. Photonics* **6**, 440 (2012).
- ²J. Geng and S. Jiang, *Opt. Photonics News* **25**, 34 (2014).
- ³K. Scholle, S. Lamrini, P. Koopmann, and P. Fuhrberg, in *Frontiers in Guided Wave Optics and Optoelectronics*, edited by B. Pal (InTech, Rijeka, 2010), Chap. XXI.
- ⁴K. Yang, D. Heinecke, J. Pajaste, C. Kölbl, T. Dekorsy, S. Suomalainen, and M. Guina, *Opt. Express* **21**, 4311 (2013).
- ⁵A. A. Lagatsky, S. Calvez, J. A. Gupta, V. E. Kisel, N. V. Kuleshov, C. T. A. Brown, M. D. Dawson, and W. Sibbett, *Opt. Express* **19**, 9995 (2011).
- ⁶Q. Wang, J. Geng, Z. Jiang, T. Luo, and S. Jiang, *IEEE Photonics Technol. Lett.* **23**, 682 (2011).
- ⁷A. Härkönen, J. Pajaste, S. Suomalainen, J.-P. Alanko, C. Grebing, R. Koskinen, G. Steinmeyer, and M. Guina, *Opt. Lett.* **35**, 4090 (2010).
- ⁸A. Gluth, Y. Wang, V. Petrov, J. Pajaste, S. Suomalainen, A. Härkönen, M. Guina, G. Steinmeyer, X. Mateos, and S. Veronesi, *Opt. Express* **23**, 1361 (2015).
- ⁹J. Pajaste, S. Suomalainen, R. Koskinen, A. Härkönen, G. Steinmeyer, and M. Guina, *Phys. Status Solidi C* **9**, 294 (2012).
- ¹⁰X. Li, H. Wang, Z. Qiao, Y. Zhang, Z. Niu, C. Tong, and C. Liu, *IEEE J. Sel. Top. Quantum Electron.* **22**, 1500507 (2016).
- ¹¹A. Gassenq, N. Hattasan, L. Cerutti, J. B. Rodriguez, E. Tournié, and G. Roelkens, *Opt. Express* **20**, 11665 (2012).
- ¹²X. Huang, A. Stintz, H. Li, L. F. Lester, J. Cheng, and K. J. Malloy, *Appl. Phys. Lett.* **78**, 2825 (2001).
- ¹³W. G. Scheibenzuber, U. T. Schwarz, L. Sulmoni, J.-F. Carlin, A. Castiglia, and N. Grandjean, *Appl. Phys. Lett.* **97**, 181103 (2010).
- ¹⁴K. Holc, T. Weig, W. Pletschen, K. Köhler, J. Wagner, and U. T. Schwarz, *Proc. SPIE* **8625**, 862515 (2013).
- ¹⁵K. Merghem, R. Teissier, G. Aubin, A. M. Monakhov, A. Ramdane, and A. N. Baranov, *Appl. Phys. Lett.* **107**, 111109 (2015).
- ¹⁶B. W. Hakki and T. L. Paoli, *J. Appl. Phys.* **46**, 1299 (1975).
- ¹⁷D. Arsenijevic, C. Liu, A. Payusov, M. Stubenrauch, and D. Bimberg, *IEEE Photonics Technol. Lett.* **24**, 906 (2012).
- ¹⁸X. Li, H. Wang, Z. Qiao, Y. Liao, Y. Zhang, Y. Xu, Z. Niu, C. Tong, and C. Liu, *Jpn. J. Appl. Phys., Part 1* **56**, 050310 (2017).
- ¹⁹C. Liu, H. Wang, Q. Meng, B. Gao, and K. S. Ang, *Appl. Phys. Express* **6**, 102702 (2013).
- ²⁰L. Sulmoni, J.-M. Lamy, J. Dorsaz, A. Castiglia, J.-F. Carlin, W. G. Scheibenzuber, U. T. Schwarz, X. Zeng, D. L. Boiko, and N. Grandjean, *J. Appl. Phys.* **112**, 103112 (2012).
- ²¹L. Harris, A. D. Ashmore, D. J. Mowbray, M. S. Skolnick, M. Hopkinson, G. Hill, and J. Clark, *Appl. Phys. Lett.* **75**, 3512 (1999).
- ²²W. Knop, C. Harder, and W. Bachtold, *IEEE Photonics Technol. Lett.* **6**, 338 (1994).
- ²³M. Mielke, G. A. Alphonse, and P. J. Delfyett, *IEEE Photonics Technol. Lett.* **15**, 501 (2003).