Rev. Adv. Mater. Technol., 2022, vol. 4, no. 1, pp. 9–13 DOI: 10.17586/2687-0568-2022-4-1-9-13

Polarization Instabilities in Vertical-Cavity Surface-Emitting Lasers

A.V. Apanasevich, A.A. Petrenko*, V.E. Bougrov

Institute of Advanced Data Transfer Systems, ITMO University, Kronverksky Pr. 49, bldg. A, St. Petersburg, 197101, Russia

Article history

Received February 28, 2022
Received in revised form
March 25, 2022
Accepted March 25, 2022
Available online March 30, 2022

Abstract

We report on experimental investigation of short-period InGaAs/InGaAlAs superlattice vertical cavity surface emitting lasers characteristics (VCSEL), including light-current-voltage characteristics, optical and radiofrequency spectra and polarization mode hopping between orthogonal modes. The observed polarization switching features is similar to what is observed in quantum well VCSEL. Future investigations will consider polarization-resolved optical and radiofrequency spectra, total intensity noise analysis of VCSEL biased near the polarization switching point.

Keywords: Long-wavelength vertical cavity surface-emitting lasers; Short-period superlattices; Polarization switching; Orthogonal polarization modes; Information-telecommunication systems

1. INTRODUCTION

Long-wavelength vertical cavity surface-emitting lasers (VCSELs) are promising radiation sources for radiophotonics devices design, utilized in information-telecommunication and computer systems for high-speed data transmission, and are widely used in the quantum random number generators [1–5]. One of the factors explaining the VCSELs popularity in telecommunication devices is the rich variety of polarization phenomena (unstable polarization behavior), suitable for improving the randomness of generated bit sequences and increasing security for high-speed chaos multiplexing [6]. For free-running (no external forcing, feedback or modulation) VCSELs a low-dimensional polarization chaos in laser output has been previously identified. The VCSELs polarization instability appears in the form of a polarization switch: for example, flip of laser output dominant polarization between two orthogonally polarized modes with increasing current or active region temperature [7].

The research results of the dynamics of polarization switching for VCSELs based on quantum wells (QWs) for solitary VCSELs were previously analyzed in Refs. [8–11]. In Ref. [8], the average dwell time of the polarization state was experimentally investigated. For QW VCSELs it has been established that the average dwell time between hops is determined by the height of the potential barrier between the wells corresponding to different polarization states, by the spontaneous emission noise that initiates switching. Abrupt polarization mode hopping occurs at pump current values in the vicinity of polarization switching current (different for different devices) based on the thermal and nonthermal origins [12]. Similar behavior of QW VCSELs, observed in numerous experiments, is in good agreement with Kramers hopping in a double-well potential model [6,7].

Meanwhile, a promising research area in the field of VCSELs design is the development of VCSEL with active regions based on short-period superlattices (SLs) containing QWs, which leads to the mode gain, output power magnification and energy consumption reduction [13]. However, current SL VCSELs polarization characteristics have not been fully investigated and require additional study. SL based VCSELs polarization mode hopping features, dynamics and origins still remain important research area.

This paper presents the results of experimental observation of SL VCSELs characteristics and investigation of polarization instabilities dependence on pump current.

2. EXPERIMENTAL SETUP

The design of the SL VCSEL (see Fig. 1) under study is a vertical microcavity with a current confinement based on buried tunnel junction (BTJ). Optical 3λ InAlGaAs cavity consists of active region based on the short-period

* Corresponding author: A.A. Petrenko, e-mail: aapetrenko@itmo.ru

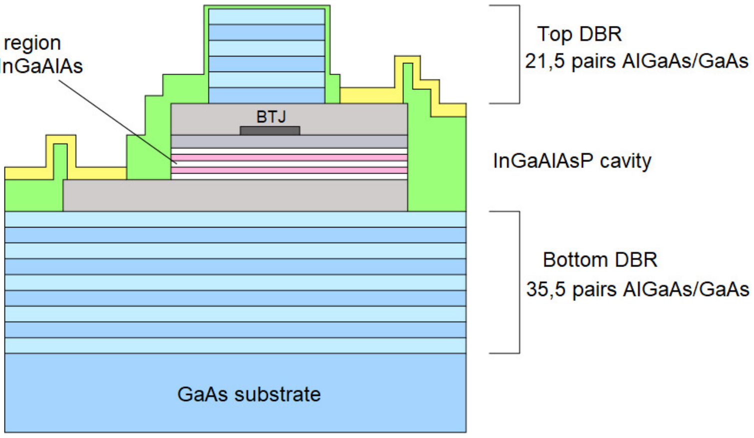

Fig. 1. The investigated SL based VCSEL design.

superlattice made of 24 successive layers of 0.8 nm $In_{0.57}Ga_{0.43}As$ QW and 2 nm $In_{0.53}Ga_{0.27}Al_{0.2}As$ barriers, n^{++}-InGaAs/p^{++}-InGaAs/p^{++}-InGaAlAs tunnel junction with 5 µm BTJ. Top and bottom distributed Bragg reflectors (DBR) are 21.5 and 35.5 $Al_{0.9}Ga_{0.1}As$/GaAs pairs, respectively. The VCSEL heterostructure was fabricated by double wafer-fusion technique as described in Ref. [14]. The structure and composition of a short-period superlattice InGaAs/InGaAlAs VCSEL utilized in our experiment are described in detail in Ref. [15].

The investigated VCSEL module additionally contains a crystal holder, SMA connector and optical fiber with FC/PC connector.

3. RESULTS AND DISCUSSION

Fig. 2. shows the light-current-voltage (L-I-V) characteristics of the investigated VCSELs obtained in the continuous-wave (CW) mode for pump currents up to 17 mA. When analyzing the watt-ampere characteristic, a significant increase in the output power is observed when the lasing threshold is exceeded, followed by a smooth decrease at high pump levels, which occurs due to the self-heating of the laser structure. The maximum output optical power achieved is 1.157 mW at a pump current of 14.5 mA, the threshold current is about 1.5 mA.

The optical spectra captured with Aragon Photonics BOSA 100 O spectrum analyzer near threshold and far from it are shown in Fig. 3. The long-wavelength shift of the VCSEL emission spectrum is observed with an increase in the pump current. The current-induced shift does not exceed 0.37 nm/mA. For a peak full width at a half maximum (FWHM) there is a significant decrease with increasing current (see Figs. 3 and 4).

Laser output radiofrequency spectra were obtained from time sequences acquired using a Keysight UXR0204A real-time oscilloscope and a 20 GHz bandwidth optoelectronic converter by fast Fourier transform with 1 MHz resolution bandwidth (see Fig. 5). In Fig. 6 the relaxation oscillation frequency as a function of the square root of the pump current above threshold is shown. With an increase in the pump level, a gradual increase in the relaxation oscillations frequency is observed, which is clearly seen from Fig 6. The maximum small-signal

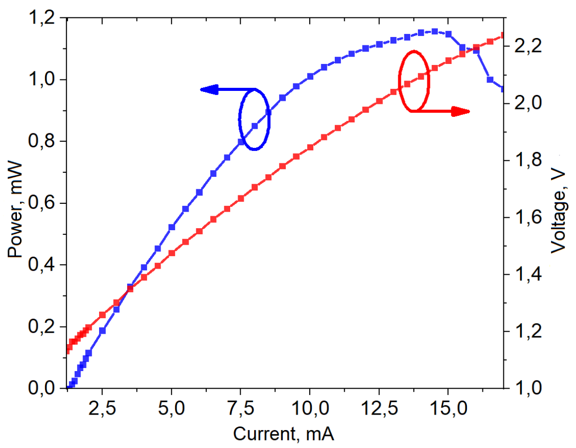

Fig. 2. L-I-V characteristics measured in CW mode.

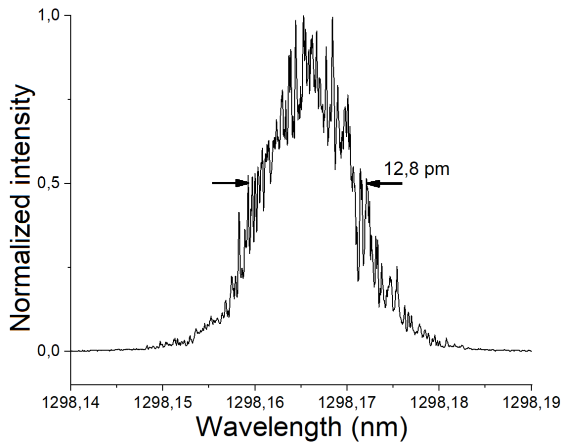

Fig. 3. Optical spectrum near threshold (at pump current of 1.5 mA). Arrows indicate the achieved FWHM.

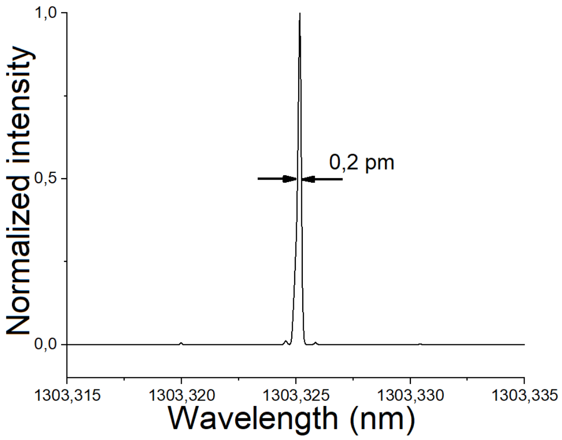

Fig. 4. Optical spectrum at pump current 17 mA. Arrows indicate the achieved FWHM.

modulation frequency obtained through analytical evaluation is 12.75 GHz. Examples of recorded radio frequency spectra are shown in Fig. 5.

The emitted light passes through a polarizer to analyze its polarization properties. The polarization-resolved curve of the normalized laser output power versus the pump current for two different positions of the polarizer is demonstrated at Fig. 7. As follows from the figure, the solitary VCSEL is linearly polarized (polarization mode is denoted as LP1) in the range from the 1.5 (threshold current) to 9.8 mA. At a current of 9.8 mA the polarization switches to LP2 orthogonal mode, the power of which gradually increases over the wide range of currents. In this case, the power of LP2 mode, that is suppressed below the threshold of 9.8 mA, gradually increases, while the power of LP1 mode decreases, up to the point of 10.5 mA, where they become equal. Then the gradual growth of LP2 mode power continues with further current increase, and LP1 mode after reaching the pump current of 11.5 mA is suppressed. The solitary VCSEL operates in the fundamental mode regime from threshold and up to 9.8 mA, then from 11.5 mA till 17 mA. In our experiment at pump current from 9.8 mA to 11.5 mA VCSEL operates with different transverse modes.

Polarization mode hopping features demonstrated for SL based VCSEL are similar to QW VCSELs in case of switching between the two orthogonal modes [8–12], but in contrast there is no abrupt polarization switching point — power of LP1 mode gradually decreases after passing a fixed current value. In polarization mode hopping dynamics gradual LP1 mode suppression is observed for 9.8–11 mA current region.

In order to get a better insight into polarization mode hopping features subsequent investigations will consider polarization-resolved optical and radiofrequency spectra analysis of VCSEL biased near the polarization switching point and experimental observation of the polarization instabilities dependence on the SL based VCSEL total intensity noise.

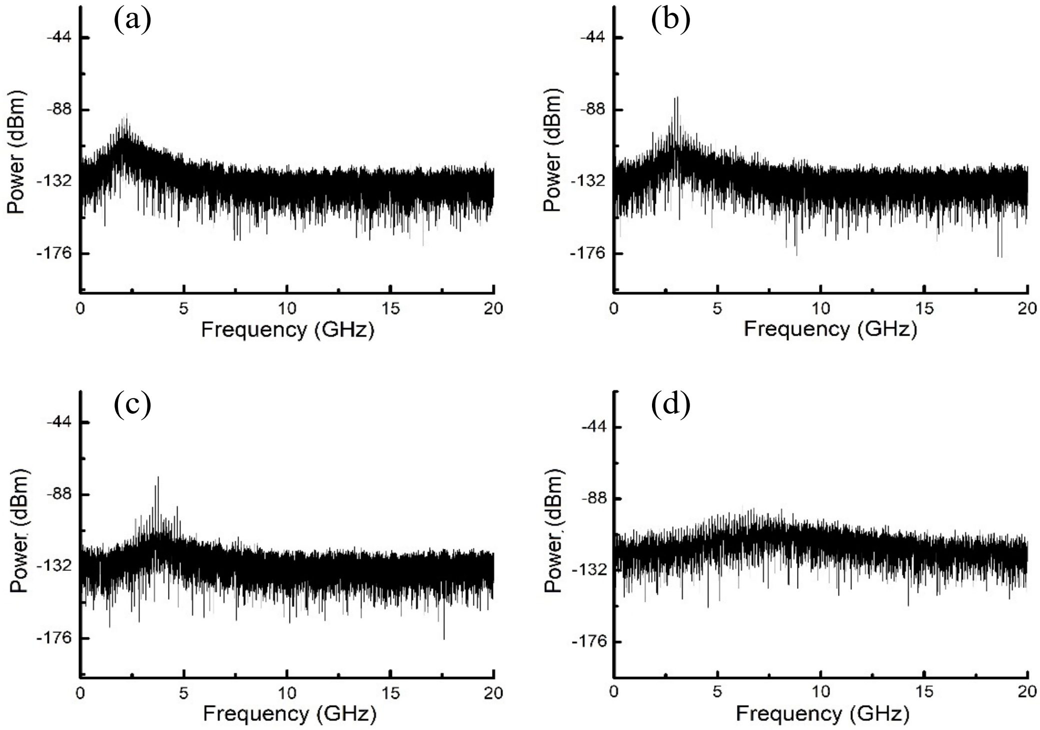

Fig. 5. SL VCSEL radiofrequency spectra at pump currents of 5 (a), 6 (b), 7 (c), 8 (d) mA. The corresponding relaxation oscillation frequencies are 2.1, 3.1, 3.8, 6.2 GHz.

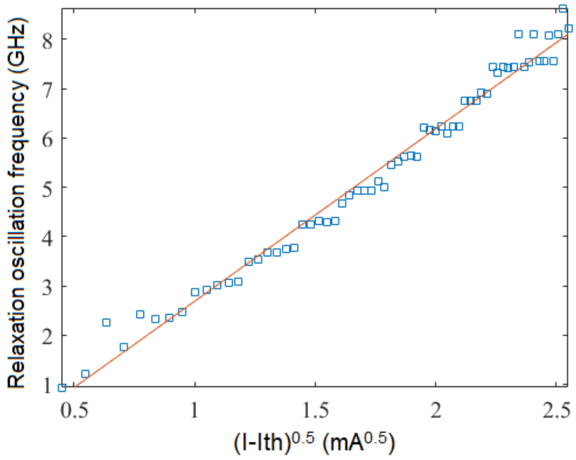

Fig. 6. Relaxation oscillation frequency (squares) as a function of the square root of the pump current above threshold; the solid red curve is a linear fitting.

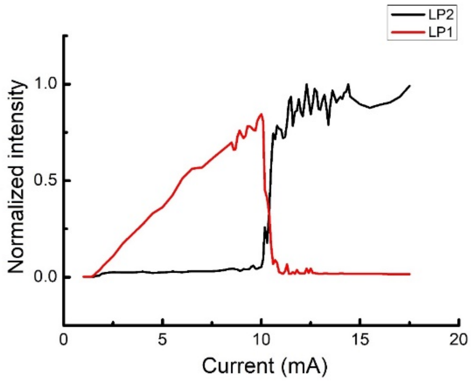

Fig. 7. Polarization-resolved VCSEL optical power dependence on pump current demonstrating polarization instabilities. LP1 and LP2 are indicated with red and black curve, respectively.

4. SUMMARY AND CONCLUSIONS

In this paper we show experimental characterization of polarization instabilities in short-period superlattice InGaAs/InGaAlAs VCSEL. The observed dynamics of polarization switching is similar to what is observed in QW VCSEL, however no abrupt polarization switching point is currently established. The reported polarization dynamic is important for SL VCSEL optical telecom and datacom applications due to its defining role in system bit-error-rate degradation. At the same time, the observed instabilities may be utilized to develop systems based on semiconductor lasers optical chaos, such as random bit generators and cryptosystems.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Science and Higher Education of Russian Federation, research project no. 2019-1442.

REFERENCES

[1] S.A. Blokhin, M.A. Bobrov, N.A. Maleev, A.A. Blokhin, A.G. Kuz'menkov, A.P. Vasil'ev, S.S. Rochas, A.G. Gladyshev, A.V. Babichev, I.I. Novikov, L.Ya. Karachinsky, D.V. Denisov, K.O. Voropaev, A.S. Ionov, A.Yu. Egorov, V.M. Ustinov, *A vertical-cavity surface-emitting laser for the 1.55-μm spectral range with tunnel junction based on n^{++}-InGaAs/p^{++}-InGaAs/p^{++}-InAlGaAs layers*, Tech. Phys. Lett., 2020, vol. 46, pp. 854–858.

[2] N.N. Ledentsov, V.A. Shchukin, V.P. Kalosha, N.N. Ledentsov Jr., J.R. Kropp, M. Agustin, S.A. Blokhin, A.A. Blokhin, M.A. Bobrov, M.M. Kulagina, Yu.M. Zadiranov, N.A. Maleev, *A design and new functionality of antiwaveguiding vertical-cavity surface-emitting lasers for a wavelength of 850 nm*, Tech. Phys. Lett., 2018, vol. 44, pp. 36–39.

[3] S.A. Blokhin, M.A. Bobrov, A.A. Blokhin, A.G. Kuzmenkov, N.A. Maleev, V.M. Ustinov, E.S. Kolodeznyi, S.S. Rochas, A.V. Babichev, I.I. Novikov, A.G. Gladyshev, L.Ya. Karachinsky, D.V. Denisov, K.O. Voropaev, A.S. Ionov, A.Yu. Egorov, *Influence of output optical losses on the dynamic characteristics of 1.55-μm waferfused vertical-cavity surface-emitting lasers*, Semiconductors, 2019, vol. 53, pp. 1104–1109.

[4] M. Sciamanna, K.A. Shore, *Physics and applications of laser diode chaos*, Nat. Photonics, 2015, vol. 9, pp. 151–162.

[5] A.A. Petrenko, S.S. Rochas, L.Ya. Karachinsky, A.V. Babichev, I.I. Novikov, A.G. Gladyshev, E.S. Kolodeznyi, P.E. Kopytov, V.E. Bougrov, S.A. Blokhin, A.A. Blokhin, K.O. Voropaev, A.Yu. Egorov, *Characterization of lasing regimes in 1.3 μm vertical cavity surface emitting lasers based on the InGaAs/InGaAlAs superlattice*, J. Opt. Technol., 2021, vol. 88, pp. 11–16.

[6] M. Virte, K. Panajotov, H. Thienpont, M. Sciamanna, *Deterministic polarization chaos from a laser diode*, Nat. Photonics, 2013, vol. 7, pp. 60–65.

[7] L. Olejniczak, K. Panajotov, H. Thienpont, M. Sciamanna, A. Mutig, F. Hopfer, D. Bimberg, *Polarization switching and polarization mode hopping in quantum dot vertical-cavity surface-emitting lasers*, Opt. Express, 2011, vol. 19, no. 3, pp. 2476–2484.

[8] B. Nagler, M. Peeters, J. Albert, G. Verschaffelt, K. Panajotov, H. Thienpont, I. Veretennicoff, J. Danckaert, S. Barbay, G. Giacomelli, F. Marin, *Polarization-mode hopping in single-mode vertical-cavity surface-emitting lasers: Theory and experiment*, Phys. Rev. A, 2003, vol. 68, no. 1, art. no. 013813.

[9] K. Panajotov, M. Sciamanna, A. Tabaka, P. Megret, M. Blondel, G. Giacomelli, F. Marin, H. Thienpont, I. Veretennicoff, *Residence time distribution and coherence resonance of optical-feedback-induced polarization mode hopping in vertical-cavity surface-emitting lasers*, Phys. Rev. A, 2004, vol. 69, no. 1, art. no. 011801.

[10] I. Gatare, M. Triginer, H. Thienpont, K. Panajotov, M. Sciamanna, *Experimental study of polarization switching and polarization mode hopping induced by optical injection in VCSELs*, Proc. Symp. IEEE/LEOS Benelux Chapter, Ghent, 2004, pp. 143–146.

[11] T. Zhang, Z. Jia, A. Wang, Y. Hong, L. Wang, Y. Guo, Y. Wang, *Experimental observation of dynamic-state*

switching in VCSELs with optical feedback, IEEE Photonics Technol. Lett., 2021, vol. 33, pp. 335–338.

[12] M. Virte, E. Mirisola, M. Sciamanna, K. Panajotov, *Asymmetric dwell-time statistics of polarization chaos from free-running VCSEL*, Opt. Lett., 2015, vol. 40, no. 8, pp. 1865–1868.

[13] L.Ya. Karachinsky, I I. Novikov, A.V. Babichev, A.G. Gladyshev, E.S. Kolodeznyi, S.S. Rochas, A.S. Kurochkin, Yu.K. Bobretsova, A.A. Klimov, D.V. Denisov, K.O. Voropaev, A.S. Ionov, V.E. Bougrov, A.Yu. Egorov, *Optical gain in laser heterostructures with an active area based on an InGaAs/InGaAlAs superlattice*, Opt. Spectrosc., 2019, vol. 127, pp. 1053–1056.

[14] S. Blokhin, A. Babichev, A. Gladyshev, L. Karachinsky, I. Novikov, A. Blokhin, S. Rochas, D. Denisov, K. Voropaev, A. Ionov, N. Ledentsov, A. Egorov, *Wafer-fused 1300 nm VCSELs with an active region based on superlattice*, Electron. Lett., 2021, vol. 57, no. 18, pp. 697–698.

[15] S.A. Blokhin, A.V. Babichev, A.G. Gladyshev, L.Ya. Karachinsky, I.I. Novikov, A.A. Blokhin, M.A. Bobrov, N.A. Maleev, A.G. Kuzmenkov, A.M. Nadtochii, V.N. Nevedomsky, V.V. Andryushkin, S.S. Rochas, D.V. Denisov, K.O. Voropaev, I.O. Zhumaeva, V.M. Ustinov, A.Yu. Egorov, V.E. Bougrov, *Investigation of properties of InGaAs/InAlGaAs superlattice for vertical-cavity surface-emitting lasers in the spectral range of 1300 nm*, Zh. Tekh. Fiz., 2021, vol. 91, no. 12, pp. 2008–2017 (in Russian).

УДК 621.373.826

Переключение поляризации излучения в вертикально-излучающих лазерах

А.В. Апанасевич, А.А. Петренко, В.Е. Бугров

Институт перспективных систем передачи данных, Университет ИТМО, Кронверкский пр., 49, литер А, Санкт-Петербург, 197101, Россия

Аннотация. В статье представлены результаты экспериментальных исследований характеристик вертикально-излучающих лазеров на основе короткопериодных сверхрешеток InGaAs/InGaAlAs, включая вольтамперные характеристики, оптические и радиочастотные спектры. Приведены ватт-амперные характеристики, свидетельствующие о переключениях поляризации излучения между ортогональными модами. Наблюдаемые особенности переключения поляризации аналогичны наблюдаемым особенностям для вертикально-излучающих лазеров на квантовых ямах. В ходе будущих исследований будут рассмотрены оптические и радиочастотные спектры, анализ шума интенсивности излучения вертикально-излучающего лазера на основе короткопериодной сверхрешетки InGaAs/InGaAlAs, смещенного вблизи точки переключения поляризации.

Ключевые слова: длинноволновые вертикально-излучающие лазеры; короткопериодные сверхрешетки; поляризационные переключения; ортогональные поляризационные моды; информационно-телекоммуникационные системы