Semiconductors, 2024, Vol. 58, No. 6

Optical amplification in InGaAs quantum well-dot waveguide heterostructures in spectral range of 1010–1075 nm

© A.A. Kharchenko[1], A.M. Nadtochiy[1,2], Yu.M. Shernyakov[3], N.Yu. Gordeev[3], A.S. Payusov[3], A.A. Beckman[3], G.O. Kornyshov[3], O.I. Simchuk[1], Yu.A. Salii[3], M.M. Kulagina[3], S.A. Mintairov[3], N.A. Kalyuzhnyy[3], M.V. Maximov[1]

[1] Alferov Federal State Budgetary Institution of Higher Education and Science
Saint Petersburg National Research Academic University of the Russian Academy of Sciences,
194021 St. Petersburg, Russia
[2] National Research University „Higher School of Economics“,
190008 St. Petersburg, Russia
[3] Ioffe Institute,
194021 St. Petersburg, Russia
E-mail: antoshkerrr@gmail.com

Received July 29, 2024
Revised August 9, 2024
Accepted August 15, 2024

The optical amplification of radiation from an external source was studied for the first time in waveguide heterostructures with an active region based on quantum well-dots. The dependence of outgoing radiation power on the pumping current was obtained in the spectral range of 990–1075 nm. Considering the spectral dependence of the transparency current, the optical gain coefficient was calculated depending on the current and wavelength. The optical gain in the structures under study reaches 22 dB at the pumping current of 57 mA at a wavelength of 1040 nm, while in the 1010–1075 nm band, the gain exceeds 10 dB.

Keywords: quantum well-dots, semiconductor optical amplifiers, transparency current.

DOI: 10.61011/SC.2024.06.59452.6937

1. Introduction

Semiconductor optical amplifiers (SOAs) of the 900–1100 nm spectral range are currently used widely in practice. A tunable laser with an external cavity [1] for spectroscopic applications may be constructed based on SOAs. This spectral range is also relevant to medical applications. Since radiation in this range penetrates the choroid deeper than radiation in the 800–900 nm band, it finds use in ophthalmological tomography (high-resolution retinal imaging) [2]. In addition, unlike free radicals, healthy biological tissues do not luminesce in this spectral range, enabling its use for optical diagnostics of tumors [3].

SOAs based on InGaAs quantum wells (QWs) with typical maximum gain of 15–30 dB in a 30–40 nm band at pump current values of 150–200 mA have already been studied [1,4]. One way to expand the spectral gain range of such devices is to produce structures with a multilayer active region with the emission spectra of individual layers shifted relative to each other. However, the use of more than three InGaAs QWs requires the application of a complex strain compensation technique [5]. Quantum well-dots (QWDs) constitute a new class of quantum-dimensional InGaAs heterostructures that has been developed relatively recently [6]. The advantage of QWDs over QWs is the possibility of epitaxial growth of more than 15 layers without the formation of dislocations, which made it possible to create superluminescent diodes with a broad (80–120 nm) emission spectrum [7,8]. Such QWDs have already demonstrated a modal absorption (gain) of 70 cm^{-1} that is considered high for a standard laser design [6,9]. These results suggest that QWDs should also perform fine as active regions of SOAs. The present study is the first to investigate the amplification of external radiation by a semiconductor optical amplifier based on quantum well-dots.

2. Experiment

The studied waveguide $p-i-n$ AlGaAs/GaAs heterostructure was grown by metalorganic vapor-phase epitaxy on an n^+-GaAs substrate misoriented by 6° in the [111] direction. The active region consisted of seven QWD layers separated by 40-nm-thick GaAs spacers. The QWD layers were formed by deposition of 2, 3, 4, 5, 6, 7, and 9 monolayers of $In_{0.4}Ga_{0.6}As$. The maxima of photoluminescence spectra of the QWD layers corresponded to wavelengths of 925, 950, 985, 1015, 1040, 1060, and 1075 nm [8]. The specifics of epitaxial synthesis and fabrication of strip waveguides and the optical and laser properties of QWDs were discussed in detail in [6,7]. Samples with a narrow ridge waveguide with a width of 5 μm and a length of 1 mm were formed from the grown structure.

The diagram of the experimental setup for studying optical amplification is shown in Figure 1. Continuous radiation from a tunable semiconductor laser operating in

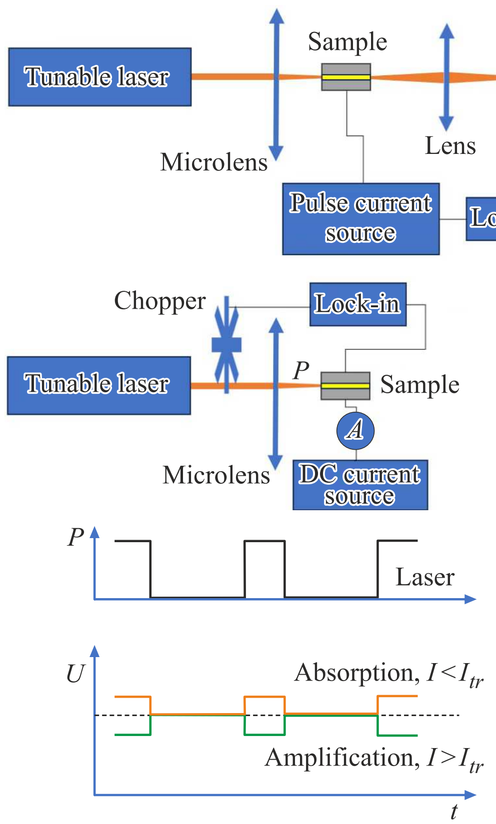

Figure 1. *a* — Diagram of the experimental setup for studying optical amplification in waveguide structures with QWDs; *b* — diagram of the experimental setup for measuring the transparency current; *c* — diagrams illustrating the variation of voltage across the sample synchronous with laser radiation pulses.

the spectral range of 990–1075 nm was introduced into the waveguide under study. This radiation had TE polarization, a maximum power of 6 mW, and a spectral line width of 0.3 nm and was focused onto the front face of the sample with a 20×/0.40 microlens. Pump current pulses with a duration of 50 μs were supplied to the sample at a frequency of 1033 Hz. The pump current did not exceed 63 mA, since the sample entered the lasing mode, which is undesirable for an SOA, at high pump currents due to the lack of antireflective coatings on mirrors. Radiation output from the back face and collected by a high-aperture lens onto a photodetector consisting of an InGaAs photodiode and a transimpedance amplifier, which converts input current into output voltage, may be split into three components: laser radiation that has passed through the waveguide; intrinsic electroluminescence of the sample; and laser radiation that was scattered and/or propagated outside the waveguide. Since measurements were carried out in the lock-in mode of detection of the photodetector signal at the frequency of pump current pulses, the last radiation component produced no contribution to the detected signal due to the lack of frequency modulation. It was also verified that the photodetector operated within the linear light-voltage dependence region and did not reach saturation within the entire range of laser output power.

Laser radiation entering the waveguide between pump current pulses is absorbed almost completely, since the sample operates in the short-circuit mode without pumping. Given that waveguide structures with QWDs have a modal absorption as high as 70 cm^{-1} [9], the radiation intensity should decrease by more than 3 orders of magnitude over a waveguide length of 1 mm. In view of this, it may be assumed that the power of laser radiation passing through the waveguide differs from zero only within the bounds of a pump current pulse. Thus, the voltage measured at the photodetector in the lock-in detection mode is directly proportional to power P_{out}, which includes the power of laser radiation passing through the waveguide within a pump pulse and the power of intrinsic electroluminescence. In the present study, the measured radiation power is expressed in arbitrary units and is numerically equal to the photodetector voltage in millivolts.

Power $P_{out}(I)$ was measured at different wavelengths within a sample pump current I range of 0–63 mA. Power $P_0(I)$ of intrinsic electroluminescence of the sample was measured separately without laser irradiation.

3. Results and discussion

Examples of the $P_{out}(I)$ dependences obtained at certain wavelengths and $P_0(I)$ are shown in Figure 2, *a*. The power of radiation output P_{out} from the waveguide exceeds the power of intrinsic electroluminescence P_0, and this difference increases with increasing pump current. These data are not sufficient to proof the fact of optical amplification in the waveguide, since the input optical power is unknown. In the general case, optical gain k is calculated

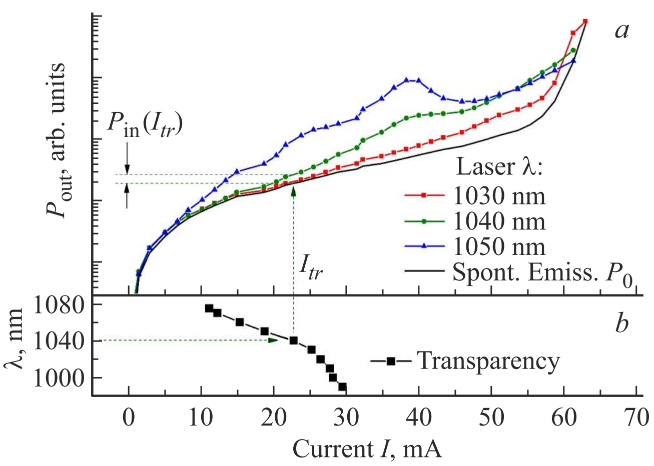

Figure 2. *a* — Dependence of the radiation power output from the waveguide with input laser radiation with a wavelength of 1030, 1040, and 1050 nm and intrinsic electroluminescence on the pump current; *b* — dependence of the waveguide transparency wavelength on the pump current. An example of estimating the value of P_{in} for a wavelength of 1040 nm is illustrated with arrows.

as $k = (P_{out} - P_0)/P_{in}$, where P_{in} is the radiation power introduced into the waveguide. Direct measurements of gain require data on the absolute value of power P_{in} and are typically performed for packaged devices with the use of polarization-maintaining optical fiber [1], since the coefficient of coupling and outcoupling of radiation may be controlled in this case.

It is difficult to measure P_{in} precisely in the discussed experimental setup, since the dimensions of the light spot focused by the microlens exceed the vertical dimensions of the waveguide (0.44 μm), and only a fraction of laser radiation enters the waveguide. We used a method for estimating the gain factor that takes into account the specifics of operation of the examined waveguide under pumping corresponding to the transparency current (I_{tr}). Being in a transparent state, the waveguide does not amplify or absorb incident external radiation; therefore, output power $P_{out}(I_{tr})$ is the sum of intrinsic electroluminescence power $P_0(I_{tr})$ of the waveguide and power P_{in} of laser radiation captured by it. The values of $P_0(I_{tr})$ and $P_{out}(I_{tr})$ may be measured, allowing one to calculate the power of laser radiation introduced into the waveguide, $P_{in} = P_{out}(I_{tr}) - P_0(I_{tr})$, where the geometric coefficients of laser radiation coupling to the waveguide and collection of output radiation by the lens at the photodiode are taken into account automatically. An example of estimating input power P_{in} at a laser radiation wavelength of 1040 nm is illustrated in Figure 2 with arrows. When the sample pump current exceeds (falls below) the transparency current, the input laser power remains unchanged, but radiation is amplified (absorbed). To summarize, gain k at pump current I may be calculated as

$$k(I)[\text{dB}] = 10 \lg \frac{P_{out}(I) - P_0(I)}{P_{out}(I_{tr}) - P_0(I_{tr})}. \quad (1)$$

The transparency current at each of the examined wavelengths was measured using a method similar to the one detailed in [10]. In these measurements (Figure 1, b), modulated laser radiation with power P is introduced into a sample pumped with variable direct current I. When the sample is pumped with a current lower than the transparency current ($I < I_{tr}$), laser radiation entering the waveguide is absorbed, which leads to an increase in voltage U across the sample (Figure 1, c). When pumped above the transparency current ($I > I_{tr}$), the waveguide operates in the amplification mode. Laser radiation entering the waveguide then stimulates radiative recombination of carriers in the active region, reducing the degree of population inversion and, consequently, voltage U across the sample. Thus, transparency current I_{tr} for a given wavelength was determined as sample pump current I at which the voltage across the sample measured by the lock-in detection method at the modulation frequency is zero. The results of measurement of the transparency current for wavelengths within the 990–1075 nm range are presented in Figure 2, b. The wavelength at which the waveguide

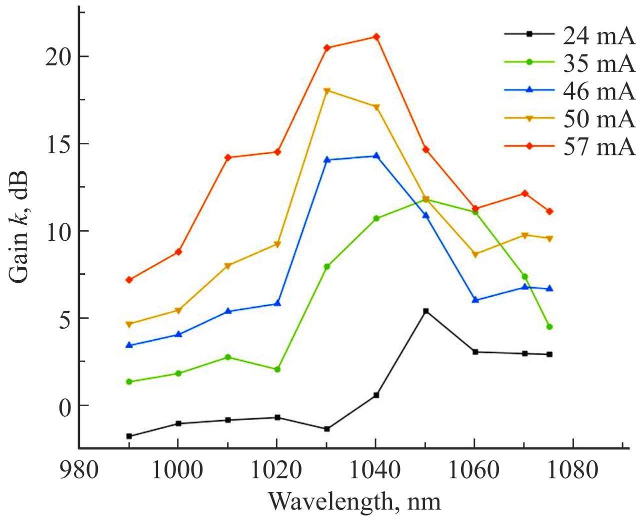

Figure 3. Optical gain spectra of waveguide structures with QWDs at different pump currents.

becomes transparent predictably decreases with current, since stronger pumping is required at higher energy levels.

The results of measurement of output power $P_{out}(I)$, power $P_0(I)$ of intrinsic electroluminescence of the waveguide, and the transparency current at different wavelengths (Figure 2, b) and calculations by formula (1) were used to plot the optical gain spectra within the pump current range of 24–57 mA at several different wavelengths (Figure 3).

It follows from Figure 3 that the gain increases with pump current, while the maximum shifts toward shorter wavelengths in the process, which is indicative of sequential filling of levels of different QWD layers. The maximum optical gain of 22 dB was achieved at a pump current of 57 mA, and the width of the band with a gain above 10 dB was 65 nm (1010–1075 nm). If one takes into account the data on position of the emission peaks of different QWD layers used in the structure [8], it may be concluded that only the four longest-wavelength QWD layers contribute to gain in the studied range of pump currents. We believe that the application of techniques for feedback suppression in the cavity, such as the use of inclined or j-shaped strip waveguides and antireflection coatings on the input/output faces [1,11], should help suppress parasitic lasing in SOAs and, consequently, expand the gain band and raise the maximum gain value. Note that the 10-dB gain band width in [1] was 55 nm; therefore, the values obtained even in non-optimized structures indicate that QWDs hold much promise for use in SOAs.

Let us point out certain limitations of the approaches used. Firstly, the intrinsic electroluminescence of the waveguide was measured without laser irradiation. The introduction of radiation into an SOA in the amplification mode at a fixed pump current should lead to an increase in the rate of optical recombination of carriers at the radiation wavelength and to a corresponding decrease in the population of QWD levels, which implies a reduction in the intrinsic electroluminescence power. Spectral selection of the amplified radiation is therefore necessary for accurate measurement. Note, however, that the electroluminescence power was relatively small compared to the peak amplified radiation power. In addition, the values of intrinsic electroluminescence power are overestimated in the discussed method, and this translates into underestimation of the gain factor.

The second limitation is related to the detection of radiation output from the waveguide with a lens. The used optical circuit did not ensure complete collection of radiation that diverges upon leaving the waveguide. The presented method is valid if the detected fraction of radiation does not change with the magnitude of SOA pump current pulses and the coefficient of collection of output radiation is, consequently, taken into account automatically in normalization to the magnitude of output radiation at the transparency current. However, the P_{out} bursts observed at certain pump current values in Figure 2, *a* may indicate a certain redistribution of the output power over different optical modes and a corresponding change in the collection coefficient. A more correct method for output radiation measurement may involve the use of an integrating sphere. We believe that the gain estimate obtained above is relatively reliable, since the redistribution of intensity between lateral modes should be insignificant and the fraction of output radiation collected in the used optical circuit is rather high.

4. Conclusion

The amplification of radiation in an SOA with several layers of QWDs within the range of 990−1075 nm has been investigated for the first time. An original method, which does not require data on the coefficient of radiation coupling and outcoupling and relies on conversion of the values of power of amplified radiation with account for measurements under the condition of transparency at a given wavelength, was used to calculate the gain factor. A maximum gain of 22 dB at a wavelength of 1040 nm and a 10-dB gain band width of 65 nm at a current of 57 mA were obtained for a non-optimized structure with straight cleaved facets, where the range of operating currents is limited by the emergence of parasitic lasing.

Funding

This study was supported by grant No. 23-72-00038 from the Russian Science Foundation (https://rscf.ru/project/23-72-00038/). A.A. Kharchenko and O.I. Simchuk express their gratitude to the Ministry of Science and Higher Education of the Russian Federation (project FSRM-2023-0010) for supporting experimental research with a tunable laser. A.M. Nadtochiy wishes to thank the Fundamental Research Program of the HSE University for supporting his work on processing the experimental data.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.A. Lobintsov, M.V. Shramenko, S.D. Yakubovich. Quantum Electron., **38**, 661 (2008).
[2] K.K. Bizheva, B. Povazay, A.A. Apolonski, A. Unterhuber, B. Hermann, H. Sattmann, P.S.J. Russell, F. Krausz, A.F. Fercher, W. Drexler. Coherence Domain Optical Methods in Biomedical Science and Clinical Applications VI: V.V. Tuchin, J.A. Izatt, J.G. Fujimoto (eds). SPIE, **4619**, 249 (2002).
[3] I.P. Shilov, G.L. Danielyan, S.V. Marechek, S.V. Kochmarev, L.Yu. Novichikhin. J. Commun. Technol. Electron., **67** (4), 463 (2022).
[4] M. Tang, X. Tian, X. Lu, S. Fu, P.P. Shum, Z. Zhang, M. Liu, Y. Cheng, J. Liu. Optics Lett., **34**, 2204 (2009).
[5] N.V. Baidus, V.Y. Aleshkin, A.A. Dubinov, Z.F. Krasilnik, K.E. Kudryavtsev, S.M. Nekorkin, A.V. Novikov, A.V. Rykov, D.G. Reunov, M.V. Shaleev, P.A. Yunin, D.V. Yurasov. Semiconductors, **52**, 1547 (2018).
[6] M.V. Maximov, A.M. Nadtochiy, S.A. Mintairov, N.A. Kalyuzhnyy, N.V. Kryzhanovskaya, E.I. Moiseev, N.Yu. Gordeev, Y.M. Shernyakov, A.S. Payusov, F.I. Zubov, V.N. Nevedomskiy, S.S. Rouvimov, A.E. Zhukov. Appl. Sci., **10** (3), 1038 (2020).
[7] M.V. Maximov, Yu.M. Shernyakov, G.O. Kornyshov, O.I. Simchuk, N.Yu. Gordeev, A.A. Beckman, A.S. Payusov, S.A. Mintairov, N.A. Kalyuzhnyy, M.M. Kulagina, A.E. Zhukov. Semiconductors, **57** (4), 294 (2023).
[8] M.V. Maximov, N.Y. Gordeev, Y.M. Shernyakov, G.O. Kornyshov, A.A. Beckman, A.S. Payusov, S.A. Mintairov, N.A. Kalyuzhnyy, M.M. Kulagina, A.E. Zhukov. Photonics (MDPI), **10** (10), 1090 (2023).
[9] A.A. Kharchenko, A.M. Nadtochiy, S.A. Mintairov, Y.M. Shernyakov, A.A. Serin, N.Y. Gordeev, M.V. Maximov, A.E. Zhukov. Nano-Struct. Nano-Objects, **25**, 100628 (2021).
[10] P.A. Andrekson, N.A. Olsson, T. Tanbun-Ek, R.A. Logan, D. Coblentz, H. Temkin. Electron. Lett., **28** (2), 171 (1992).
[11] S.H. Chang. Appl. Sci., **10** (4), 1552 (2020).

Translated by D.Safin