Conference materials
UDC 621.373.826
DOI: https://doi.org/10.18721/JPM.173.242

Mode leakage into substrate in microdisk lasers

I.A. Melnichenko[1,2]✉, E.I. Moiseev[1], K.A. Ivanov[1], N.V. Kryzhanovskaya[1], A.G. Vainilovich[3], A.V. Nahorny[3], E.V. Lutsenko[3], A.E. Zhukov[1]

[1] National Research University Higher School of Economics, St. Petersburg branch, St. Petersburg, Russia;

[2] Alferov University, St. Petersburg, Russia;

[3] Institute of Physics of the NAS of Belarus, Minsk, Belarus

✉ imelnichenko@hse.ru

Abstract. The propagation of whispering gallery modes of a quantum-dot injection disk laser into a GaAs substrate has been investigated experimentally and using simulation. For a 50 μm diameter microlaser with 1.5-μm-thick $Al_{0.4}Ga_{0.6}As$ claddings, the intensity of the mode leaking into the substrate can be up to 10^{-3} of the intensity of the laser mode in the waveguide.

Keywords: InGaAs quantum well-dots, whispering gallery mode microlasers, mode leakage

Funding: The article was prepared within the framework of the project "International academic cooperation" HSE University.

Citation: Melnichenko I.A., Moiseev E.I., Ivanov K.A., Kryzhanovskaya N.V., Vainilovich A.G., Nahorny A.V., Lutsenko E.V., Zhukov A.E., Mode leakage into substrate in microdisk lasers, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 17 (3.2) (2024) 212–216. DOI: https://doi.org/10.18721/JPM.173.242

Материалы конференции
УДК 621.373.826
DOI: https://doi.org/10.18721/JPM.173.242

Утечка мод в подложку в микродисковых лазерах

И.А. Мельниченко[1,2]✉, Э.И. Моисеев[1], К.А. Иванов[1], Н.В. Крыжановская[1], А.Г. Войнилович[3], А.В. Нагорный[3], Е.В. Луценко[3], А.Е. Жуков[1]

[1] Национальный исследовательский университет «Высшая школа экономики», Санкт-Петербургский филиал, Санкт-Петербург, Россия;

[2] Академический университет им. Ж.И. Алфёрова РАН, Санкт-Петербург, Россия;

[3] Институт физики НАН Беларуси, Минск, Беларусь

✉ imelnichenko@hse.ru

Аннотация. Экспериментально и с помощью моделирования исследовано распространение мод шепчущей галереи дискового лазера с квантово-точечной инжекцией в подложке GaAs. Для микролазера диаметром 50 мкм с облицовками из $Al_{0.4}Ga_{0.6}As$ толщиной 1,5 мкм интенсивность моды, просачивающейся в подложку, может составлять до 10^{-3} от интенсивности лазерной моды в волноводе.

Ключевые слова: квантовые точки InGaAs, микролазеры с модами шепчущей галереи, утечка мод

Финансирование: Статья подготовлена в ходе проведения исследования в рамках проекта «Международное академическое сотрудничество» НИУ ВШЭ.

Ссылка при цитировании: Мельниченко И.А., Моисеев Э.И., Иванов К.А., Крыжановская Н.В., Войнилович А.Г., Нагорный А.В., Луценко Е.В., Жуков А.Е. Исследование утечки мод в подложку в микродисковых лазерах // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2024. Т. 3.2 № .17. С. 212–216. DOI: https://doi.org/10.18721/JPM.173.242

Introduction

Microlasers based on whispering gallery modes (WGMs) are promising light emitters for photonic integrated circuits [1]. Such microlasers have high *Q*-factor, which allows to achieve low lasing thresholds and offer high power efficiency [2]. In addition, the emission of such lasers propagates in the plane of a substrate, which simplifies their integration with other optical components on the chip.

One advantage of WGM lasers over other types of microlasers is that the epitaxial structure is very similar to that typically used for stripe edge-emitters [3–5] and does not require high precision thickness and/or composition in growth of its components. However, the thickness of the cladding layers of about 1.5–2 μm may be insufficient for effective localization of the mode in a cylindrical microcavity.

To investigate this problem, we analyzed the propagation of WGMs of an injection disk microresonator based on InGaAs/GaAs quantum well-dots into a GaAs substrate. The leakage of the microdisk laser mode into the substrate and the magnitude of this type of losses was determined.

Materials and Methods

The epitaxial structure was prepared by MOVPE epitaxy on a 6°-disoriented GaAs substrate. The structure comprises an *n*+-GaAs buffer, a 1.5-μm-thick *n*-$Al_{0.4}Ga_{0.6}As$ bottom-side cladding layer, a 0.78-μm-thick GaAs waveguiding layer, a 1.5-μm-thick *p*-$Al_{0.4}Ga_{0.6}As$ top cladding layer, and a 0.35-μm-thick p^{++}-GaAs contact layer. The active layer consisted of five layers of $In_{0.4}Ga_{0.6}As$ quantum dots placed evenly inside 800 nm GaAs matrix. Using photolithography and dry etching, microdisk lasers with a diameter of 50 μm were formed on the surface of the epitaxial structure. To investigate the mode leakage, the sample was cliffed so that the substrate edge was in close proximity to the microdisk under study (not more than 5 μm). After that, the structure was mounted on the heat sink due to more convenient heat dissipation and vertical orientation of sample. Next, the contacts to one of 50 μm microdisks were welded.

The study of the intensity distribution of the electromagnetic field propagating from the laser waveguiding layer into the substrate was carried out using the technique of fiber near-field microscopy. For this purpose, a room temperature NT-MDT Integra Spectra microscope-based fiber probe head was used, which is a Nufern 980-HP single-mode optical fiber attached to a fork-shaped quartz resonator. The end of the fiber is tapered by chemical etching and coated with a layer of aluminum (70nm) with a formed aperture of 100 nm at the end. The signal from the fiber probe was collected in noncontact regime (distance between fiber tip and surface was approximately 30–40 nm). Then it was transferred into a Sol Instruments MS5204i monochromator and detection was performed using a cooled InGaAs CCD array. Also, to investigate the processes of WGM spreading, a numerical model of the disk was developed in the COMSOL Multiphysics environment using the finite element method.

Results and Discussion

Fig. 1, *a* shows the electroluminescence (EL) spectrum obtained by near-field fiber microscopy from the GaAs substrate under the microdisk laser. In the investigated wavelength range, two WGMs were identified (at wavelengths 1082.8 nm and 1099.1 nm), the radiation leakage of which was localized under the periphery of the microdisk laser. The scheme in Fig. 1, *b* demonstrates the

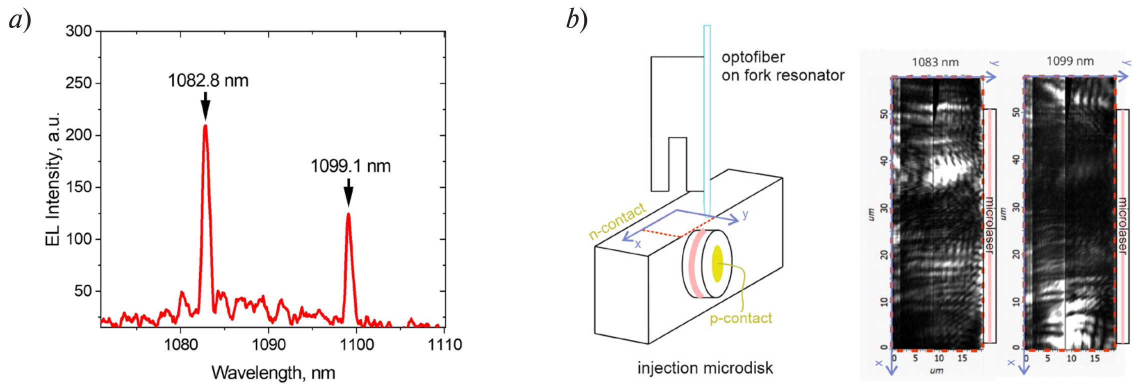

Fig. 1. EL spectrum obtained by near-field fiber acquisition from the substrate under the microdisk (*a*). Schematic of the near-field fiber microscopy experiment and electroluminescence intensity distribution maps of the 1082.8 and 1099.1 nm modes (*b*)
The vertical line on both maps is due to a measurement imperfection (due to the substrate cleaved surface curvature, the near-field fiber moved away from the surface during scanning)

process of scanning the GaAs substrate cliff with a fiber near-field probe, the red rectangle highlights the approximate region where the experimental maps of the EL intensity distribution were obtained. The observed electromagnetic intensity distribution is concentrated under the peripheral parts of the microdisk laser, as expected for WGMs. However, the distribution in the substrate is different for different WGM modes.

From the experimental results it can be also seen that the EL intensity modulations obtained on the maps have a large number of modulations that we associate with interference of laser emission in GaAs substrate. To investigate the interference into the GaAs substrate, intensity distribution deeper inside the substrate was calculated. To avoid too long calculation times, the thickness was limited to 6 μm. The results are presented in Fig. 2 for two modes of which has $q = 20$, and the other $q = 1$. For both numerical and experimental distributions, the maximum of the electromagnetic field intensity is observed under the disk edges. The simulations also show that the mode with higher radial order shows more intense mode leakage into the GaAs substrate than the $q = 1$ mode.

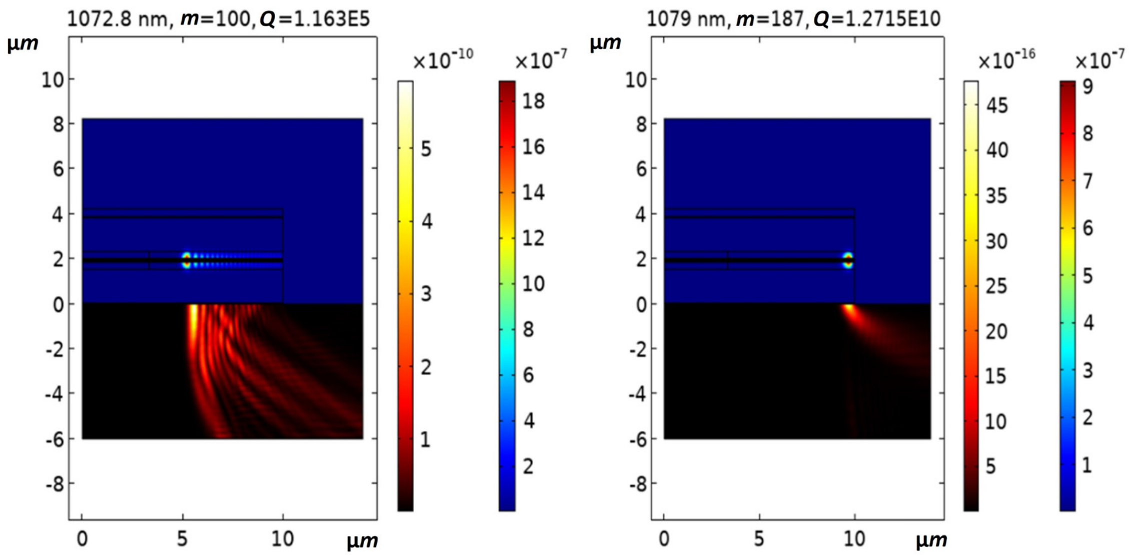

Fig. 2. Electromagnetic energy distribution in 50 μm microlaser for $m = 100$, $q = 20$ and m = 187, $q = 1$ azimuthal and radial orders WGMs in GaAs substrate

The amount of mode leakage into the GaAs substrate was calculated as the ratio of the EL intensity maxima in the GaAs substrate to the EL intensity maximum in the microdisk waveguide (for the results of numerical modeling, the intensity value was estimated using expression $I \sim E^2$). The calculation data are shown in Table 1; the maximum values of the radiation intensity on the surface of the waveguide part of the microdisk and on the cleaved plane of the GaAs substrate were taken for the $I_{substrate}/I_{waveguide}$ ratio. For the experimental data, this value of maximum amount of mode leakage was estimated as ~$3 \cdot 10^{-4}$ for the 1082.8 nm mode wavelength, and for the theoretical simulations show a maximum amount of mode leakage ~10^{-5} for the third radial order mode. Q-factor of leaking mode also decreases significantly with radial order raise from $q = 1$ to $q = 3$ approximately from $1.24 \cdot 10^{10}$ to $3.1 \cdot 10^6$.

Table 1

Calculation of magnitude of mode leakage into substrate for theoretical and experimental cases

Experimental data		Numerical calculations	
λ	$I_{substrate}/I_{waveguide}$	λ	$I_{substrate}/I_{waveguide}$
1082–1083 nm	~$3 \cdot 10^{-4}$	$q = 1$, 1076.1 nm	~$5.01 \cdot 10^{-9}$
1098–1099 nm	~$2.2 \cdot 10^{-3}$	$q = 3$, 1078.1 nm	~$1.26 \cdot 10^{-5}$

It was also observed that for different WGMs, the propagation in the GaAs substrate occurs at different angles. It can be assumed in Fig. 2 that for low radial order WGM with $q = 1$ and $m = 187$, the angle to the GaAs substrate surface at which the WGM scatters is larger than the same angle for high radial order WGM of $q = 20$ and $m = 100$. The same inversed dependency can be observed for Q-factor: the smaller the mode Q-factor, the larger will be the angle to the GaAs substrate surface. Despite the fact that there is no absorption in the GaAs substrate, for models with finite GaAs substrate thickness, scattering is observed as one moves away from the disk. It should be mentioned that the experimentally observed intensity distribution can be additionally affected by the other effects, such as surface bumps of the cleaved GaAs substrate and the parasitic absorption of microdisk radiation due to noncontact near-field experimental setup.

Conclusion

In this study, a new method was developed to experimentally investigate the leakage of WGM from a microdisk laser using fiber near-field optical microscopy. This methodology allowed us to demonstrate that for microdisk lasers based on AlGaAs/GaAs waveguide structure, the mode leakage into the substrate is quite significant for modes with high radial number, which is confirmed by both experimental and modeling data. It can be also assumed that the smaller the mode Q-factor, the larger the angle to the GaAs substrate surface at which the WGM scatters. The results obtained indicate the necessity to take into account factor of WGMs leakage into the GaAs substrate.

Acknowledgments

The work was carried out using the large-scale research facility #2087168 “Complex optoelectronic stand”.

REFERENCES

1. **Yang S., Wang Y., & Sun H.,** Advances and prospects for whispering gallery mode microcavities. Advanced Optical Materials. 3 (9) (2015) 1136–1162.
2. **McCall S.L., Levi A.F. J., Slusher R.E., et al.,** Whispering-gallery mode microdisk lasers. Applied physics letters. 60 (3) (1992) 289–291.
3. **Munsch M., Claudon J., Malik N.S., et al.,** Room temperature, continuous wave lasing in microcylinder and microring quantum dot laser diodes. Applied Physics Letters. (100) (2012) 031111.
4. **Moiseev E., Kryzhanovskaya N., Maximov M., et al.,** Highly efficient injection microdisk lasers based on quantum well-dots. Optics Letters. 43 (19) (2018) 4554–4557.
5. **Kryzhanovskaya N., Zhukov A., Moiseev E., Maximov M.** III–V microdisk/microring resonators and injection microlasers. Journal of Physics D: Applied Physics. 54 (45) (2021) 453001.

THE AUTHORS

MELNICHENKO Ivan A.
imelnichenko@hse.ru
ORCID: 0000-0003-3542-6776

MOISEEV Eduard I.
emoiseev@hse.ru
ORCID: 0000-0003-3686-935X

IVANOV Konstantin A.
kivanov1992@gmail.com
ORCID: 0000-0003-2165-1067

KRYZHANOVSKAYA Natalia V.
nkryzhanovskaya@hse.ru
ORCID: 0000-0002-4945-9803

VAINILOVICH Alexey G.
a.vainilovich@ifanbel.bas-net.by

NAHORNY Alexey V.
a.nahorny@ifanbel.bas-net.by

LUTSENKO Eugeniy V.
e.lutsenko@ifanbel.bas-net.by

ZHUKOV Alexey E.
zhukale@gmail.com
ORCID: 0000-0002-4579-0718

Received 26.07.2024. Approved after reviewing 29.07.2024. Accepted 30.07.2024.