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Microlasers based on $Al_{0.2}Ga_{0.8}As/Al_{0.9}Ga_{0.1}As$ distributed Bragg reflectors

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TThe results of implementing lasing at elevated temperatures in lasers based on a vertical microcavity with a wavelength of 980 nm and using mirrors that do not absorb light at the optical pump wavelength are presented. The minimum threshold pump power was ~ 0.8 mW and corresponded to a temperature of 150 K. The microcavity quality factor, determined at the lasing threshold, exceeded 13000. The maximum operating temperature of the microlaser was 195 K. Increasing the temperature to 195 K led to an increase in the threshold power to 1.7 mW.

Keywords: microlasers, vertical microcavity, quantum dots, Stranski–Krastanov mechanism, optical reservoir computing.

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Introduction

Arrays of spectrally homogeneous lasers based on a vertical microresonator can be used to implement the scheme of photonic reservoir computing (RC) [1–4]. Vertical-cavity surface-emitting laser (VCSEL) [5,6] can also provide diffraction coupling (DC) of lasers in the array and, as a result, can be used to implement photonic RC [7–12], however, the maximum number of lasers in the array providing DC does not exceed 24 [11], due to the significant placement step of VCSEL in the array ($80-100\,\mu$m [1]). The use of lasers based on an optical pumped vertical microresonator makes it possible to create arrays of densely spaced elements, with an order of magnitude smaller, in comparison with VCSEL ($8-10\,\mu$m [1,13]). The main disadvantages of implementing an RC circuit based on vertical-cavity surface-emitting lasers are low operating temperatures and significant pumping power thresholds. The maximum temperature for microlasers with semiconductor distributed Bragg reflectors based on alternating quarter-wave layers $Al_{0.9}Ga_{0.1}As/GaAs$, at which laser generation is demonstrated, is 130 K, and the threshold pumping power at this temperature does not exceed 1.2 mW [3]. The use of semiconductor mirrors that are non-absorbing at the pumping wavelength (based on $Al_{0.9}Ga_{0.1}As/Al_{0.2}Ga_{0.8}As$) allowed the authors to significantly reduce the generation threshold, but the maximum operating temperature of the laser was 77 K [4], due to insufficient amplification of active regions based on a single InGaAs CT layer.

This paper presents the first results on the implementation of generation at elevated temperatures (up to 195 K) in microlasers with semiconductor distributed Bragg reflector based on $Al_{0.9}Ga_{0.1}As/Al_{0.2}Ga_{0.8}As$ layers.

Experiment details

The heterostructure of the vertical microresonator was grown by molecular beam epitaxy on a semi-insulating GaAs substrate with a crystallographic orientation (100). In comparison with the previously presented results for the construction of a microresonator with non-absorbing DBR, which were epitaxed using the gas-phase epitaxy method from organometallic compounds [4], the number of quantum dot (QD) layers was increased in order to increase the gain of the active region and realize generation at elevated temperatures. Previously, QD scans were used in vertical microresonator heterostructures, the self-organization of which occurred from the layer $In_{0.33}Ga_{0.67}As$ [14] or $In_{0.37}Ga_{0.63}As$ [4,15]. The QD composition was changed to achieve a zero mismatch between the position of the maximum in the photoluminescence spectrum of the QD and the resonant wavelength of the microresonator at elevated temperatures (130 K). Three QD layers, which self-organized according to the Stransky-Krastanov method [16], were formed from a layer of $In_{0.5}Ga_{0.5}As$ with a thickness of ~ 1.9 nm. The QD layers are placed in the center of the GaAs layer forming a vertical microresonator. In comparison with the results in Ref. [3,4,15], the thickness of the microresonator (value L_g) with a length of λ/n, where λ is the wavelength, n is the refractive index, is reduced to 210 nm. The lower and upper DBR were formed on the basis of quarter-wave ($\lambda/4n$) alternating

layers of $Al_{0.2}Ga_{0.8}As/Al_{0.9}Ga_{0.1}As$. A detailed description of the heterostructure and a study of its structural quality is presented in Ref. [17]. Microlazers with a diameter of $5\,\mu$m are formed by dry etching. A „tanned" photoresist was used as a mask to form the etching profile. The slope of the side wall of the microlaserwas less than 1°.

The microphotoluminescence (microPL) spectra of microlasers at various temperatures were studied in an optical cryostat Cryostation s50 (Montana Instruments Corp.). A semiconductor laser with a pumping wavelength of 808 nm operating in continuous pumping mode is used for optical pumping. The laser radiation used for pumping was focused into a spot with a diameter of $1-2\,\mu$m using a micro lens M Plan Apo NIR (Mitutoyo Corp.) with 100 x magnification. The luminescence spectra were recorded using a Shamrock 500i monochromator (Oxford Instruments Andor Ltd) with a diffraction grating based on 1200 strokes per mm, providing a spectral resolution of 0.05 nm.

Results and discussion thereof

MicroPL spectra were measured in the course of the study at various levels of optical pumping in the temperature range of $77-195$ K. It is shown that the luminescence line near 980 nm (see the inserts to Fig. 1) demonstrates an ultra-linear increase in the integral radiation intensity with an increase in the optical pumping level, which, along with a narrowing of the luminescence line, indicates the presence of generation in the studied microlaser [4]. Based on the Gaussian distribution [1], the shape of this line is approximated in the luminescence spectra measured at various optical pumping levels and temperatures (Fig. 1). The *S*-shaped (on a double logarithmic scale) dependence of the integral radiation intensity (optical output power, P_{out}) on the optical pumping power (P_{pump}) can be approximated based on the result of solving the velocity equations [4,18] and described using the expression:

$$P_{\text{pump}} = \kappa\gamma q\Big(bP_{\text{out}}(1+\xi)(1+\beta bP_{\text{out}})/ (1+bP_{\text{out}}) - \xi\beta bP_{\text{out}}\Big)\Big/\delta\beta, \quad (1)$$

where κ is the coefficient characterizing the efficiency of optical pumping of QDs and taking into account the absorption of radiation in the layers of the upper DBR and microresonator, q is the electron charge, b is the coefficient relating the average number of photons in the optical mode and the optical output power, ξ is the parameter characterizing the number of photons in the laser mode when the transparency threshold is reached, δ is the efficiency of converting absorbed power into the number of excitons, γ is the reverse lifetime of photons in the microresonator and β is a factor determining the proportion of spontaneous emission in the laser mode. The value of $\kappa(\lambda)$ can be determined based on the expression [3]:

$$\kappa(\lambda) = T_{\text{DBR}}(\lambda)\Big[\big(1-\exp(-\alpha_{\text{GaAs}}(\lambda,T)L_g)\big) + \big(1-\exp(-\alpha_{\text{WL}}(\lambda,T)L_{\text{WL}})\big)\Big], \quad (2)$$

where $T_{\text{DBR}}(\lambda)$ is the transmittance coefficient of the upper DBR at a given wavelength, $\alpha_{\text{GaAs}}(\lambda,T)$ is the absorption coefficient of GaAs at a given wavelength and at a fixed temperature T, $\alpha_{\text{WL}}(\lambda,T)$ is the absorption coefficient of the wetting layer ($In_{0.5}Ga_{0.5}As$) at a given wavelength at a fixed temperature T. The value of $T_{\text{DBR}}(\lambda)$ is described using the expression [3]:

$$T_{\text{DBR}}(\lambda) = \big(1-R_{\text{DBR}}(\lambda)\big)\exp\big(-\alpha_{\text{AlGaAs}}(\lambda,T)L_{\text{DBR}}\big), \quad (3)$$

where R_{DBR} is the reflection coefficient of the upper DBR at a given wavelength, α_{AlGaAs} is the absorption coefficient of the AlGaAs layers forming the upper DBR, and L_{DBR} is the total thickness of these layers of the upper DBR. Taking into account absorption data (Al)GaAs and InGaAs, presented in Ref. [3,19–22], and calculated reflection spectra of the upper DBR (calculated using the transfer matrix method at various temperatures), the coefficient κ, characterizing the pumping efficiency of the active region, which was 13.5 % at 77 K. An increase in temperature to 195 K led to an increase in pumping efficiency to 15.0%. The value of γ is described based on the expression [3]:

$$\gamma = 2\pi E/hQ, \quad (4)$$

where E is the quantum energy, Q is the Q factor of the microresonator, h is the Planck constant expressed in eV·s. The value δ is determined based on the analysis of pre-threshold power characteristics [3]. The $P_{\text{out}}(P_{\text{pump}})$dependencies shown in Fig. 1 are plotted taking these values into account.

The threshold value of the P_{th} pumping power can be determined provided that the average number of photons at the generation threshold is one ($bP_{\text{out}} = 1$) and is described based on the expression [18]:

$$P_{\text{th}} = \kappa\gamma q[1+\beta+\xi(1-\beta)]/2\delta\beta. \quad (5)$$

The dependence $P_{\text{th}}(T)$ is shown in Fig. 2, upper panel. It is shown that the minimum temperature dependence of the generation threshold correlates with the temperature corresponding to the zero mismatch between the position of the maximum of the photoluminescence spectrum of the QD and the resonant wavelength of the microresonator. The lowest experimental value of the pumping threshold power is $\sim 760\,\mu$ W and corresponds to a temperature of 150 K. The threshold absorbed power, defined as the product of $\kappa(\lambda)$ and P_{th}, reduced to the QD layer, was $\sim 40\,\mu$ W, which corresponds to the previously presented results at a lower temperature ($P_{\text{th}} \sim 40\,\mu$ W for $5.4\,\mu$ m microlaser at 77 K [4]). The maximum value of the β factor corresponded to the minimum temperature of the pumping threshold (150 K) and was equal to (0.7 ± 0.2) %. This

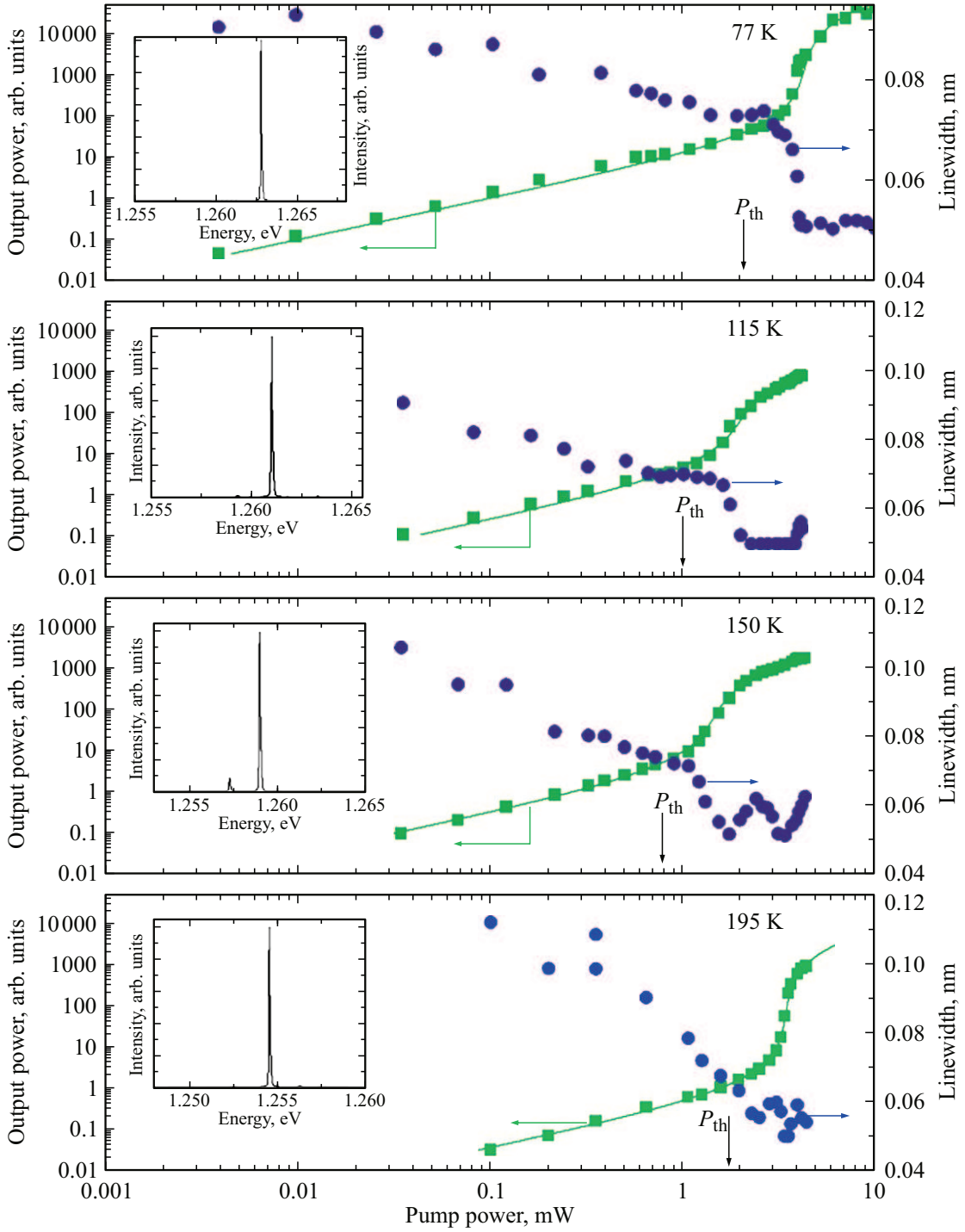


Figure 1. The dependences of the integral radiation intensity (left axis Y) and the half-width of the 980 nm generation line (right axis Y) on the pumping power. Panels (top to bottom) — at temperatures of 77 K, 115 K, 150 K and 195 K. The inserts correspond to the generation spectra at a fixed optical pumping power of 4.3 mW.

value is comparable to those previously discussed for high-Q microresonators ($\beta = 1.0 \pm 0.3\,\%$ for 5.4 μm microlaser at 77 K [4]). The Q-factor of the microresonator, determined at the generation threshold (Q_{thr}), was 13300. The high values of Q_{thr} (15000 for the 5.4 μm microlaser [4]) were discussed earlier, however, these results correspond to a temperature of 77 K and, as a result, a lower heating of the laser.

The maximum temperature at which the transition to laser generation was observed, confirmed by the S-shaped power characteristic, was 195 K. The threshold power value at a given temperature (~ 1.7 mW) is less than the same

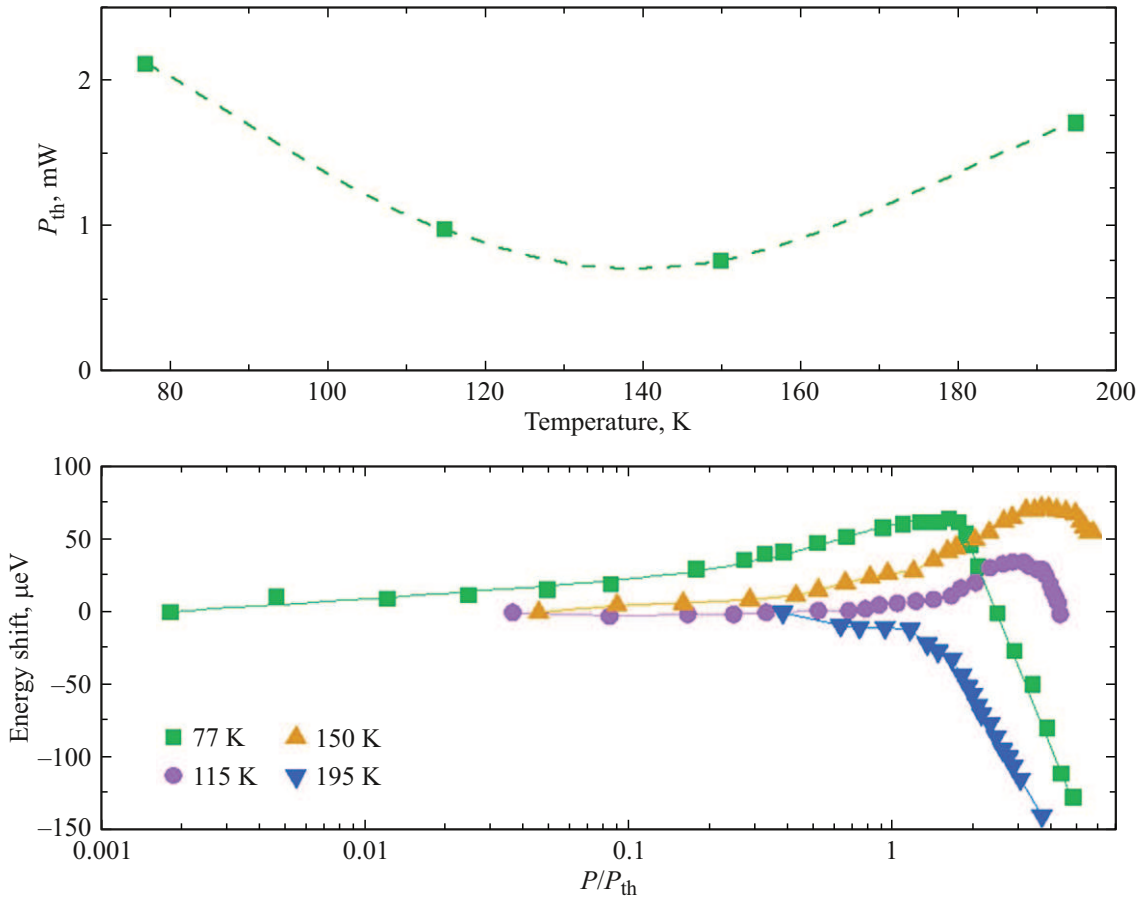


Figure 2. Upper panel: the dependence of the threshold power of optical pumping on the temperature of the microlaser. Bottom panel: dependences of the shift of the position of the generation line (quantum energy) on the level of optical pumping, corresponding to temperatures of 77 K, 115 K, 150 K and 195 K.

value (2.6 mW) for planar microlasers with generation in the defective mode [14]. For microlasers with DBR based on $Al_{0.2}Ga_{0.8}As/Al_{0.9}Ga_{0.1}As$, epitaxy of which was performed by gas-phase epitaxy, the maximum temperature at which generation was observed was 200 K, and the generation threshold was 1.9 mW [23].

It was previously shown in Ref. [4,14,24], that the use of $GaAs/Al_{0.9}Ga_{0.1}As$-based DBR absorbing at the pump wavelength (in the GaAs layers forming DBR) leads to additional heating of the microlaser, which is expressed in a long-wave shift of the generation wavelength with an increase in the pump level and a broadening of the generation line [4]. In turn, the use of mirrors that are non-absorbing at the pumping wavelength (switching to using $Al_{0.2}Ga_{0.8}As$ instead of GaAs) minimizes thermal effects. As a result, the broadening of the generation line and a significant shift in its wavelength have not been demonstrated for both the case of generation in the vertical mode [4,14] and the whispering gallery mode [15,25]. No significant broadening of the generation line is also observed in the studied microlasers, with an increase in the pumping level (Fig. 1). The position of the generation line in the luminescence spectra of the microlaser, measured at various temperatures, is shown in Fig. 2, lower panel. A shift of the PL line to the short-wavelength region of the spectrum ($\sim 60\,\mu$eV) is observed at a temperature of 77 K, in the pre-threshold mode, followed by a predominance of thermal effects due to high pumping power thresholds at this temperature, which results in a long-wavelength shift of the line position by $16\,\mu$eV (up to $+44\,\mu$eV) with a two-fold increase in the pumping power threshold. An increase in temperature to 115 K leads to a more pronounced short-wave shift of the generation line ($35\,\mu$eV), which corresponds to a three-fold excess of the pumping threshold, followed by a predominance of thermal effects. At a temperature corresponding to the minimum threshold pumping power (150 K), the short-wave shift in the position of the generation line is $70\,\mu$eV, which is due to the predominance of plasma effects [4] caused by an increase in the number of injected carriers over thermal effects due to sample heating. An increase in temperature to 195 K leads to a long-wave shift of the generation line in the pre-threshold mode, which indicates the predominance of sample heating over the entire range of pumping levels.

Conclusion

This paper presents the results on the implementation of generation at elevated temperatures in microlasers with semiconductor DBRs. The use of mirrors that are non-absorbing at the pumping wavelength made it possible to increase the efficiency of optical pumping by 5 times, which amounted to 15% at 195 K. The minimum pumping threshold power ($\sim 40\,\mu$W at 150 K) corresponds to the temperature of zero mismatch between the position of the QD luminescence and the resonant wavelength of the microresonator and correlates with the previously presented results obtained at lower temperatures ($P_{\text{th}} \sim 40\,\mu$W at 77 K [4]). The maximum estimated value of the β-factor was $(0.7 \pm 0.2)\,\%$. The use of mirrors that are non-absorbing at the pumping wavelength made it possible to increase the temperature stability of the laser and realize generation in microlasers with a vertical microresonator at 195 K with a pumping threshold power of less than 2 mW. Similar output characteristics were demonstrated for microlasers grown by gas-phase epitaxy [23]. These results open up the possibility of implementing a reservoir computing scheme based on optical pumped microlasers at a temperature more than 2 times higher than the previously discussed [1].

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] T. Heuser, J. Grose, S. Holzinger, M.M. Sommer, S. Reitzenstein. IEEE J. Sel. Top. Quantum Electron., **26** (1), 1 (2020). DOI: 10.1109/JSTQE.2019.2925968
[2] T. Heuser, J. Große, A. Kaganskiy, D. Brunner, S. Reitzenstein. APL Photonics, **3** (11), 116103 (2018). DOI: 10.1063/1.5050669
[3] L. Andreoli, X. Porte, T. Heuser, J. Große, B. Moeglen-Paget, L. Furfaro, S. Reitzenstein, D. Brunner. Opt. Express, **29** (6), 9084 (2021). DOI: 10.1364/OE.417063
[4] C.-W. Shih, I. Limame, S. Krüger, C.C. Palekar, A. Koulas-Simos, D. Brunner, S. Reitzenstein. Appl. Phys. Lett., **122** (15), 151111 (2023). DOI: 10.1063/5.0143236
[5] S.A. Blokhin, A.V. Babichev, A.G. Gladyshev, I.I. Novikov, A.A. Blokhin, M.A. Bobrov, N.A. Maleev, V.V. Andryushkin, D.V. Denisov, K.O. Voropaev, V.M. Ustinov, V.E. Bougrov, A.Y. Egorov, L.Y. Karachinsky. Opt. Eng., **61** (9), 096109 (2022). DOI: 10.1117/1.OE.61.9.096109
[6] A. Babichev, S. Blokhin, A. Gladyshev, L. Karachinsky, I. Novikov, A. Blokhin, M. Bobrov, Y. Kovach, A. Kuzmenkov, V. Nevedomsky, N. Maleev, E. Kolodeznyi, K. Voropaev, A. Vasilyev, V. Ustinov, A. Egorov, S. Han, S.-C. Tian, D. Bimberg. Photonics, **10** (6), 660 (2023). DOI: 10.3390/photonics10060660
[7] A. Skalli, J. Robertson, D. Owen-Newns, M. Hejda, X. Porte, S. Reitzenstein, A. Hurtado, D. Brunner. Opt. Mater. Express, **12** (6), 2395 (2022). DOI: 10.1364/OME.450926
[8] Z. Chen, A. Sludds, R. Davis, I. Christen, L. Bernstein, L. Ateshian, T. Heuser, N. Heermeier, J.A. Lott, S. Reitzenstein, R. Hamerly, D. Englund. Nat. Photon., **17**, 723 (2023). DOI: 10.1038/s41566-023-01233-w
[9] T. Heuser, M. Pflüger, I. Fischer, J.A. Lott, D. Brunner, S. Reitzenstein. J. Phys. Photonics, **2** (4), 044002 (2020). DOI: 10.1088/2515-7647/aba671
[10] A. Skalli, X. Porte, N. Haghighi, S. Reitzenstein, J.A. Lott, D. Brunner. Opt. Mater. Express, **12** (7), 2793 (2022). DOI: 10.1364/OME.451524
[11] M. Pflüger, D. Brunner, T. Heuser, J.A. Lott, S. Reitzenstein, I. Fischer. Opt. Lett., **49** (9), 2285 (2024). DOI: 10.1364/ol.518946
[12] A. Skalli, M. Goldmann, N. Haghighi, S. Reitzenstein, J.A. Lott, D. Brunner. Commun. Phys., **8** (1), 68 (2025). DOI: 10.1038/s42005-025-01972-y
[13] A. Babichev, I. Makhov, N. Kryzhanovskaya, A. Blokhin, Y. Zadiranov, Y. Salii, M. Kulagina, M. Bobrov, A. Vasil'ev, S. Blokhin, N. Maleev, M. Tchernycheva, L. Karachinsky, I. Novikov, A. Egorov. IEEE J. Sel. Top. Quantum Electron., **31** (5), 1900208 (2024). DOI: 10.1109/JSTQE.2024.3494245
[14] K. Gaur, C.-W. Shih, I. Limame, A. Koulas-Simos, N. Heermeier, C.C. Palekar, S. Tripathi, S. Rodt, S. Reitzenstein. Appl. Phys. Lett., **124** (4), 041104 (2024). DOI: 10.1063/5.0177393
[15] I. Limame, C.-W. Shih, A. Koulas-Simos, J. Pietsch, L.J. Roche, M. Plattner, A. Koltchanov, S. Rodt, S. Reitzenstein. Opt. Express, **32** (18), 31819 (2024). DOI: 10.1364/OE.529679
[16] A.V. Babichev, S.D. Komarov, Y.S. Tkach, V.N. Nevedomskiy, S.A. Blokhin, N.V. Kryzhanovskaya, A.G. Gladyshev, L.Ya. Karachinsky, I.I. Novikov. Semiconductors, **57**, 93 (2023). DOI: 10.1134/S1063782623040012.
[17] A.V. Babichev, A.M. Nadtochiy, S.A. Blokhin, V.N. Nevedsky, N.V. Kryzhanovskaya, M.A. Bobrov, A.P. Vasiliev, N.A. Maleev, L.Ya. Karachinsky, I.I. Novikov, A.Yu. Egorov. FTP, **58** (6), 318 (2024) (in Russian). DOI: 10.61011/FTP.2024.06.58946.6287
[18] G. Bjork, Y. Yamamoto. IEEE J. Sel. Top. Quantum Electron., **27** (11), 2386 (1991). DOI: 10.1109/3.100877
[19] B. Monemar, K.K. Shih, G.D. Pettit. J. Appl. Phys., **47** (6), 2604 (1976). DOI: 10.1063/1.322979
[20] D.E. Aspnes, S.M. Kelso, R.A. Logan, R.J. Bhat. Appl. Phys., **60** (2), 754 (1986). DOI: 10.1063/1.337426
[21] M. Sturge. Phys. Rev., **127** (3), 768 (1962). DOI: 10.1103/physrev.127.768

[22] S. Adachi. *Physical properties of III-V semiconductor compounds* (John Wiley & Sons., Hoboken, NJ, U.S., 1992). DOI: 10.1002/352760281x
[23] K. Gaur, S. Tripathi, F. Laudani, A. Barua, I. Limame, A. Koulas-Simos, S. Rodt, S. Reitzenstein. Laser Photonics Rev., **19** (18), e00533 (2025), DOI: 10.1002/lpor.202500533
[24] N. Heermeier, T. Heuser, J. Große, N. Jung, A. Kaganskiy, M. Lindemann, N.C. Gerhardt, M.R. Hofmann, S. Reitzenstein. Laser Photonics Rev., **16** (4), 2100585 (2022). DOI: 10.1002/lpor.202100585
[25] A. Babichev, I. Makhov, N. Kryzhanovskaya, S. Troshkov, Y. Zadiranov, Y. Salii, M. Kulagina, M. Bobrov, A. Vasil'ev, S. Blokhin, N. Maleev, L. Karachinsky, I. Novikov, A. Egorov. IEEE J. Sel. Top. Quantum Electron., **31** (2), 1502808 (2024). DOI: 10.1109/JSTQE.2024.3503724

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