

INFORMATION

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Symposium on the coherent optical radiation of semiconductor compounds and structures (Zvenigorod, 27 – 29 November 2007)

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***Abstract*. A review of papers devoted to high-power heterostructure semiconductor lasers, optically and electron-pumped semiconductor lasers, unipolar semiconductor lasers, promising directions in the development of optical coherent sources, the physics of damage and degradation of emitting semiconductor structures, etc is presented.**

Keywords: *coherence, semiconductor lasers, light-emitting diodes, nanostructures.*

The symposium on the coherent optical radiation of semiconductor compounds and structures was held 27 – 29 November, 2007 in Zvenigorod, Moscow region. The symposium was organised by P.N. Lebedev Physic Institute, RAS (FIAN), the Department of Physical Sciences of RAS, the Russian Foundation for Basic Research, and Quantum Electronics journal. The chairman of the organising committee was academician O.N. Krokhin.

Scientists from Moscow, St. Petersburg, Samara, Vladivostok, Nizhnii Novgotrod, and other cities of Russia participated in the Symposium. Twenty-five plenary reports were presented and the round table was organised.

The Symposium program included papers encompassing all modern directions of fundamental studies in the field of coherent optical radiation of semiconductor compounds and structures.

The main attention was devoted to the generation of coherent radiation by widely used injection (diode) lasers. This topic was presented in several reports and was separately actively discussed at the round table. Russian scientists have made a considerable contribution to the development and fabrication of semiconductor lasers. The idea of an injection laser was proposed at FIAN in 1961, the first cw room-temperature heterolasers were created at A.F. Ioffe Physico-Technical Institute (FTI) in 1970. The studies on semiconductor lasers being performed at present at these institutes determine their leadership in the successful development of this important field in quantum electronics in Russia.

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I.S. Tarasov (FTI) presented a review of papers on diode lasers performed at FTI, in particular, studies devoted to high-power diode lasers. The reduction of the intracavity optical loss down to 0.3 – 0.5 cm^{-1} made it possible to increase the laser cavity length up to 5 mm and to increase the output power up to 16 – 20 W in the cw regime with the emitting stripe of width 100 μm and the 'in-plug' efficiency more than 70 % and up to 120 – 150 W in the pulsed regime. The output energy density of a pulsed fibre pigtail laser array provides the efficient cutting of steel sheets a few millimetres in thickness, the cutting cost being considerably lower than that for diode-pumped fibre lasers. The problem of laser end-face coatings determining the maximum output power to a great extent, which still exists, was discussed. The use of aluminium-free laser heterostructure solid solutions can help to some extent to solve this problem. Unfortunately, the cost of one watt of radiation from high-power diode lasers still remains high.

V.V. Bezotosnyi (FIAN) pointed out in his report that the quality of the connection of a laser crystal (chip) with a heat sink element is one of the main factors determining the achievement of high output powers and high lasing efficiency, as well as the required operating life of diode lasers. It is necessary to provide the planarity and coplanarity of the operation and base surfaces of the heat sink element. For a crystal of length 3 mm and a solder thickness of 2 – 3 μm, the required coplanarity parameter should be 1 μm on a base of length 3 mm, which can be provided by using diamond sharpening. The quality of surface processing is also important (it is desirable to have the roughness $\sim$5 nm). Metal films of thickness 4 – 8 μm were deposited in vacuum on copper heat sinks by a magnetron source. Crystals were mounted on a Lambda A6 setup (Finetech) under the conditions of the locally pure zone of class 100. The heat removal efficiency was enhanced by processing films with a scanning laser beam to reduce the porosity and roughness of the film surface and to purify it from oxides and organic contaminations. The short-time output power up to 7 W was achieved; however, the cw power in the operation regime corresponding to service characteristics achieves only 4 W. The rapid degradation is caused by a strong heat release due to the imperfection of technologies used for processing of heat-sink elements and deposition of metal films and a solder. A Nd : YAG crystal was pumped by three laser diodes. The cw output power obtained in the single-mode regime was 5 W at a wavelength of 1060 m and 2 W at 530 nm.

A.P. Bogatov (FIAN) presented in his report the method of expanding the laser beam in the direction perpendicular to heterolayers, which reduces the radiation load at output mirrors and decreases the angular divergence of radiation. Calculations were performed to optimise the optical beam width in a passive waveguide layer taking into account the possibility of obtaining both the high output power and the undesirable decrease in the optical confinement factor and the reduction of the mode amplification. The calculations and experimental data obtained for a ridge waveguide laser diode showed that the laser beam was expanded by five times, the output power achieved 500 mW, and the divergence in the transverse single-mode regime was reduced to $11^{\circ}-12^{\circ}$ (instead of usual 30°).

V.I. Kozlovskii (FIAN) presented the recent results of studies devoted to the improvement of the parameters of longitudinally optically and electron-pumped semiconductor lasers based on the II – VI and III – V heterostructures emitting in the visible region. The tunable lasers based on the GaInP/AlGaInP heterostructure with one or two AlAs/AlGaAs Bragg mirrors emitting 7 – 8 W in the range between 620 and 660 nm were fabricated. Due to the improved quality of the ZnSe/ZnMgSSe structures, the output power of the laser at 460 nm was increased up to 2.5 W. The studies on the development of diode-pumped mid-IR lasers (2 – 5 μm) based on the II – VI single crystals doped with transition metals are being continued. Continuous wave lasing was achieved for the first time in a Cr : CdSe crystal (1 W at 2.6 μm) and laser tuning was performed in the range between 2.26 and 3.62 μm.

The results of investigations of the low-frequency power noise and the radiation pattern of a spectrally selective-external cavity AlGaAs/GaAs diode laser performed at Moscow State University were reported by V.V. Bruevich. The spectral power density of the low-frequency intensity noise (down to 1 kHz) and radiation patterns were studied. Measurements were performed upon lasing at a single longitudinal mode of the external cavity. It was found that the noise level in this frequency range could depend (within the measurement accuracy) on the presence or absence of the feedback.

Yu.P. Yakovlev (FTI) presented the results of studies of lasers based on the InAsSbP/InAsSb/InAsSbP double heterostructure grown by the method of liquid-phase epitaxy on a p-InAs substrate. Continuous wave lasing was obtained in the spectral range between 2.7 and 3.8 μm in the temperature range from 30 to 120 K, and in the pulsed regime – up to 200 K. The laser linewidth was 18 MHz. The rapid tuning of the laser was performed by using nonlinear-optical effects inside a waveguide and the absorption spectra of OCS, NH_3, H_2O, and CH_3Cl gases were recorded.

One of the urgent problems of modern solid-state electronics is the development of ultrafast devices and advancement to the ultrahigh frequencies, and the development of new radiation sources, in particular, based on principles of lasing.

New prospects in this direction are related to the development of the physics and technology of nanostructures. The research in this field is developed in two main directions, one of which is related to increasing the operation frequency of traditional semiconductor electronic devices by using complicated nanoheterostructures and also to the possible increase in the lasing frequency due to its multiplication by means of nonlinear nanostructure elements. The other direction involves the development of terahertz semiconductor lasers based on optical transitions between the dimensional quantisation subbands and shallow impurity levels in nanostructures.

The generation of terahertz radiation was discussed in reports of V.V. Kocharovskii [Institute of Applied Physics, RAS (Nizhnii Novgorod)] and V.N. Shastin [Institute of Physics of Microstructures, RAS (Nizhnii Novgorod)]. V.V. Kocharovskii proposed to obtain coherent terahertz radiation by mixing laser radiation produced simultaneously at two frequencies in one cavity. It is also possible to mix the modes of the two current-independent p – n junctions with slightly different quantum wells (QWs), but having two mutually coupled waveguides or to use an interband two-cascade laser with the tunnelling p – n junction separating the active regions of two QWs located in the same waveguide. It can be expected that a two-frequency laser with a low threshold current will generate microwatt terahertz radiation at room temperature. The output power in the pulsed regime can be considerably increased.

V.N. Shastin discussed the problem of generating terahertz radiation in the case of the inverse population of the levels of impurity donors of the fifth group in silicone. Note that this variant of lasing was proposed by N.G. Basov, B.M. Vul, and Yu.M. Popov even in 1958. Great difficulties involved in obtaining inversion are related to the short excited-state relaxation times due to a strong interaction with phonons of different types and to the absence of pumping methods for such lasers. The calculations of the relaxation times of excited states interacting with phonons of different types show that they do not exceed, as a rule, 1 ns.

The studies of the picosecond dynamics of nanoheterostructure lasers were reported by E.L. Portnoi (FTI). The principles of fabrication of integrated optical circuits were analysed and the scheme of lasers based on waveguide nanoheterostructures with quantum dots containing monolithic integrated amplification and absorption sections was developed. These schemes were used to generate short light pulses in passive *Q*-switching and passive mode-locking regimes.

The emission of quantum dot (QD) InAs/InGaAs laser diodes in the region between 1.15 and 1.3 μm was reported by A.E. Zhukov (FTI). This spectral range (the O range), in which the optical loss is only 2 – 3 times larger than the absolute minimum for silica fibres and the group velocity dispersion is small, is of obvious interest for optical communications. The laser wavelength can be changed within a narrow range by using different effective thicknesses of InAs deposited on a GaAs substrate by the method of molecular beam epitaxy. The closure of the InAs QD array by a $In_xGa_{1-x}As$ layer ($x = 10\,\% - 20\,\%$) of thickness 4-12 nm allows the laser wavelength to be varied from 1.1 to 1.3 μm. The inhomogeneous broadening is 40 meV. There exists the optimal density of the QD array at which the threshold current density achieves the minimum value corresponding to the specified level of optical losses. In the case of typical losses, it is possible to obtain threshold current densities ~ 100 A cm^{-2} for the array density $(3-5)\times 10^{10}$ cm^{-2}, which corresponds to 6 – 10 QD rows. The extremely low threshold current (1.4 mA) was obtained in a short 600-μm cavity ridge laser with two QD rows and highly reflecting facets. The high output power (800 mW) was achieved in a laser (with 10 QD rows) of length 7 mm with the AR-coated output facet and the ridge width of 6 μm. By introducing the disorder to the QD distribution, a very broad lasing spectrum of width up to 75 nm was obtained. By using the external modulation of the spectrally selected mode of the laser, signals were transferred at a rate of 10 Gb s^{-1} with the bit error rate (BER) less than 10^{-13}. According to estimates, the operation life of lasers under normal operation conditions (40 °C) was 1.2×10^6 h.

The studies of quantum well InSb/InAsSb heterostructures for 3 – 5-μm IR lasers were presented by A.N. Semenov (FTI). The author reported the main results of investigations of the properties of formation and physical properties of InSb QD semiconductor heterostructures in the InAsSb matrix obtained by the method of molecular beam epitaxy and used as active regions in the mid-IR injection lasers.

Yu.A. Aleshchenko (FIAN) presented the results of the study (together with Yu.V.Kopaev) devoted to the development of unipolar semiconductor lasers based on heterostructures with the variable dimensionality of electronic states. The original design of the active element of a $GaAs/Al_xGa_{1-x}As$ QW unipolar semiconductor laser with strongly asymmetric (in height) barriers was proposed. The optimisation of the active element of the unipolar laser gave the numerical values of QW widths and barriers providing good laser parameters.

The report of V.N. Murzin (FIAN) was devoted to analysis of the results of fundamental studies of nonlinear and nonequilibrium properties of semiconductor quantum-well resonance-tunnelling structures. The possibilities of using these structures for the development of lasers and subterahertz and terahertz converters of a new type were investigated. It was shown that inverted distributions could be formed in the lower quantum-well subbands in structures with broad QWs. The energy gap between the lower subbands in them is smaller than the optical phonon energy. The principal possibility of the creation of a solid-state resonance-tunnelling terahertz laser on intersubband electronic transitions was shown.

The development of subterahertz and terahertz generators and converters is of current interest for mastering these spectral ranges and opens up possibilities for various applications in electronics, microelectronics, informatics, communication systems, radio imaging, introscopy, molecular spectroscopy, astrophysics, medicine, biology, and other fields of science and technology.

The studies of nonlinear optics of magnetic structures and magnetophotonic crystals performed at Moscow State University were presented in the report of T.V. Murzina. The results of the investigation of the nonlinear-optical magnetic response of magnetic nanostructures (nanolayers and nanoparticles) and magnetophotonic crystals were reported. It was shown experimentally that the magnetic nonlinear-optical response in these structures was at least one – two orders of magnitude greater than the linear magnetooptical response. This suggests that nonlinear-optical methods, first of all the method of magnetically induced second optical harmonic, can be widely used for diagnostics of magnetic structures. It was found that magnetically induced contributions to SHG in magnetophotonic crystals and microcavities exceeded nonmagnetic contributions. The interrelation between ferroelectric and magnetic properties of nanostructured ferromagnetics was established, which is manifested in the characteristic type of the temperature dependence of the second harmonic intensity.

The studies of the properties of laser radiation, the possibilities of its formation and conversion received much attention. The collinear interaction of light fluxes at different wavelengths in a heterophase liquid nanocomposite was discussed in the report of Yu.N. Kul'chin (Institute of Automatics and Control Systems, Far Eastern Branch, RAS, Vladivostok). The dependences of the transmission

Figure 1. Participants of the Symposium in the Winter Garden at the Zvenigorodskii holiday hotel.

of light by the nanocomposite on the intensity of radiation at wavelengths 532 and 633 nm were investigated both separately for these beams and in the case of their collinear interaction. It was found that after the propagation of radiation through the nanocomposite, due to its interaction with a complex of Al_2O_3 – liquid-phase matrix nanoparticles, variations in the refractive index and absorption coefficient of the composite medium were observed, which depended on the radiation wavelength and intensity, as well as on the parameters of the matrix material, the chemical composition, size, and concentration of nanoparticles.

V.S. Lebedev (FIAN) presented in his report the studies of the conversion of optical radiation to the subwave-scale fields in tapered semiconductor waveguides. The high conversion efficiency of optical radiation to the fields of the nanometre extension (30 – 100 nm) was demonstrated in semiconductor (GaAs, GaP, GaN, Si) near-field optical probes of length a few micrometres. It was found that the use of highly refractive semiconductor materials with a small extinction coefficient instead of glass fibres or crystalline quartz resulted in the increase in the near-field radiation energy density at the optical probe output in the short-wavelength region of the visible spectrum by a few orders of magnitude. The possibility of using these results in the optical study of nanostructures and in problems related to the local photoinduced action on materials was discussed.

The papers devoted to the formation of radiation fields of semiconductor lasers were discussed in the report of S.P. Kotova (Samara Branch, FIAN). The formation and propagation of complicated transverse spatiotemporal fields (optical vortices with the nonzero angular momentum) is of fundamental interest in optics and can be used in various fields, in particular, for laser manipulating microscopic object, the capture and confinement of atoms. Due to their high efficiency, compactness and convenient control of radiation parameters by varying the pump current, diode lasers are most commonly used among other lasers. This determines the urgency of the search for efficient methods of formation of vortex fields with the specified radiation intensity distribution of semiconductor lasers. The author considered two approaches for solving this problem.

New tunable radiation sources based on microstructure fibres for femtosecond microspectroscopy of semiconductor materials were considered in the report of A.B. Fedotov and co-authors (Moscow State University). Microstructure fibres are a new type of optical fibres with a cladding consisting of a set of hollow glass capillaries drawn at a high temperature. They have a number of unique properties opening up new possibilities for the transfer of the electromagnetic radiation and nonlinear-optical conversion of laser pulses.

The reliability of semiconductor lasers was discussed in two reports. I.N. Zavestovskaya (FIAN) presented the results of simulation of processes producing the degradation of the active region of gallium nitride semiconductor lasers. The laser-induced damage threshold was studied by irradiating gallium nitride by femtosecond laser pulses at a wavelength of 400 nm, at which these semiconductor lasers emit. The damage threshold was 34 TW cm^{-2} upon irradiation by 130-fs pulses, which provides the large resource of gallium nitride semiconductor lasers.

The experimental studies of the degradation of semiconductor light-emitting diodes (LEDs) were considered in the report of A.N. Turkin (Moscow State University). The limiting characteristics of LEDs based on wide-gap gallium nitride semiconductors and degradation mechanisms of semiconductor structures were determined by studying the degradation of semiconductor heterostructures at temperatures close to the critical operating temperature of the p – n junction and under the recommended operating conditions. The aim of these investigations was to determine the mechanisms and properties of degradation processes in semiconductor gallium nitride heterostructures upon injecting the direct or pulsed current. Crystal samples based on InGaN heterostructures emitting in the blue and green regions were studied.

It was pointed out at the final meeting on 29 November 2007 that the Symposium on the coherent optical radiation of semiconductor compounds and structures was successful both in the scientific and organisation aspects. The Symposium program represented by reports at the high scientific level was completely fulfilled. It was emphasised that the Symposium made up for the deficiency of scientific contacts and broad discussions of the problems of development of coherent optical radiation of semiconductor compounds and structures. The decision was accepted to hold the Symposium on the coherent optical radiation of semiconductor compounds and structures at least every two years.