Final Program

Monday, September 12

All talks will be held in the Zuiten (East) room

11:00-14:00 Technical WS: Power saturation in LDs

Organizers:

Dr. Eugene Avrutin
(Univ. of York, UK)

Dr. Victor Rossin
(Lumentum Operations LLC)

High power diode lasers provide the optical energy for the majority of high performance laser systems, and are the most efficient technology for converting electrical energy into useful light. Solid-state and fiber laser systems that make use of such diode lasers as pump sources are progressing rapidly, driven by improvements to the diode lasers. As their power, efficiency and brightness improve, diode lasers have been increasingly deployed directly in material processing applications. For future systems, further enhanced diode lasers are needed, with ever-increasing output power per device, for cost reduction and for better system performance. However, the limits to peak power remain unclear, with various non-linear effects coming into play at high bias, driven by a combination of high optical intensity, current density, and temperature, whose relative importance is challenging to robustly diagnose, especially in these large area structures where spatial non-uniformity can also play a large role.
This workshop of invited speakers will discuss the efforts underway by various groups to enhance the peak achievable power in high-power semiconductor lasers, with a special focus on measures to diagnose and understand the limiting mechanisms. The workshop forum is meant to stimulate discussion and interaction with the audience to encourage feedback and consensus building among high-power laser researchers. The workshop will conclude with a panel discussion on how to sustain continual power scaling for the next generation of diode lasers.

Workshop Chair/Panel Discussion Moderator: **Paul Crump** *(Ferdinand-Braun-Institut)*

11:00 WS1 – "High Power Laser Diodes: Motivation and Hurdles"

V. Rossin
Lumentum Operations LLC, USA

11:15 WS2 – "The Role of Carrier Accumulation in the Optical Confinement Layer in Output Efficiency Deterioration of Laser Diodes"

Eugene A. Avrutin[1], Boris S. Ryvkin[2]
[1]University of York, UK, [2]A.F.Ioffe Physico-Technical Institute, Russia

Analytical and semi-analytical theory of the effects of carriers in the Optical Confinement Layer on the output efficiency degradation of high-power diode lasers is summarized. The main sources of carrier accumulation and the implications for laser design are discussed.

11:30 WS3 – "Linear and Non-linear Loss Mechanisms in High-Power Semiconductor Lasers and Optical Amplifiers"

Toby J. Garrod, J. J. Plant, D. F. Siriani, P. W. Juodawlkis
Massachusetts Institute of Technology, USA

As the intra-cavity and emitted power in optical emitters continues to rise, both linear and non-linear loss mechanisms contribute to the saturation of emitted power. This paper will discuss the physical mechanisms that constitute loss in semiconductor emitters, and offer insight into how these mechanisms can be mitigated.

11:45 WS4 – "Experimental and Theoretical Studies into the Limits to Peak Power in GaAs-Based Diode Lasers"

Paul Crump, Hans Wenzel, Thorben Kaul, Goetz Erbert, Guenther Traenkle
Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Germany

An overview is presented of progress in studies to diagnose and address limits to peak power in high power diode lasers. Key terms in advanced structures include carrier losses in the p-side waveguide, self-heating effects in the quantum well, and longitudinal spatial hole-burning.

12:00 WS5 – "Power Saturation in Standard and Double-AR Unfolded Laser Diode Cavities"

Matthew Peters[1], Arnaud Fily[1], Victor Rossin[1], Abdullah Demir[2]
[1]Lumentum Inc., USA, [2]Bilkent Univ., Turkey

We report modeling and experimental results that demonstrate mechanisms limiting the output power of broad area semiconductor lasers. The modeling comprises numerical simulations with evolution of non-uniform carrier density, photon density, temperature and index. We measure unfolded laser cavities to validate simulation methods and parameters.

12:15 WS6 – "Record-Breaking High-Power InGaN-Based Laser-Diodes Using Novel Thick-Waveguide Structure"

Masao Kawaguchi, Osamu Imafuji, Shinichiro Nozaki, Hiroyuki Hagino, Koshi Nakamura, Shinichi Takigawa, Takuma Katayama, Tsuyoshi Tanaka
Panasonic Corporation, Japan

High-power operation over 7W in InGaN laser-diodes is achieved by an undoped-thick-waveguide-structure where an optical-loss is suppressed by reduced light-leakage to the absorbing p-cladding. Operating voltage increase due to the high-resistive undoped-layer is successfully eliminated by utilizing the potential-flattening-effect of electrons reflected from electron-overflow-suppression-layer.

12:30 WS7 – "VCSELs for High Power Applications"

Ulrich Weichmann[1], Ralf Conrads[1], Carsten Deppe[1], Guenther Derra[1], Philipp Gerlach[1], Stephan Gronenborn[1], Xi Gu[2], Johanna Kolb[1], Michael Miller[1], Holger Moench[1], Pavel Pekarski[1], Jens Pollmann-Retsch[1], Armand Pruijmboom[2]
[1]Philips Photonics, Germany, [2]Philips Photonics, The Netherlands

High power VCSEL systems are novel laser sources, offering a unique combination of efficiency, compactness and robustness. Wide scalability of these systems in power makes them attractive for applications in industrial manufacturing. Basic properties and first applications of high power VCSEL systems are presented here.

12:45 WS8 – "Improvement of High Power Operation in 9××nm Broad Area Laser Diodes"

Yuji Yamagata[1], Yumi Yamada[1], Yoshikazu Kaifuchi[2], Ryozaburo Nogawa[2], Rintaro Morohashi[2], Masayuki Yamaguchi[2]
[1]Optoenergy, Inc., Japan, [2]Fujikura Ltd., Japan

Improvement of high power and high efficiency operation 9xx-nm broad area laser diodes are discussed. For the output power maximization, power saturation phenomenon is experimentally investigated. Power saturation is found to be governed by not only junction temperature but also by thermal lensing effect.

13:00-14:00 Panel Discussion (Lunch box is served)

14:00-14:20 Break

14:20-16:20 Anniversary WS 1

Session Co-Chairs: **Yuichi Tohmori** *(Tsurugi Photonics Foundation)*
Kent Choquette *(Univ. of Illinois)*

In the Anniversary Workshop, twelve invited speakers will review the progress of the technology leading to the now in their research fields, and more will speak about the future possibilities in this field. Anniversary Workshop will be held in Sept. 12 and 14.

14:20 AWS1 (Invited) – "Diode Laser Active Region Evolution"

Peter Zory
Univ. of Florida, USA

Laser beams generated in the p-n junction (active) regions of forward biased GaAs diode chips were first observed in September 1962. The active region width ‘d’ in these Zn-diffused chips was about 2 microns. By 1966, the diffusion technique had been replaced by a liquid phase epitaxy (LPE) growth technique. The higher quality LPE material led to chips capable of pulsed operation at room temperature (300 K) and commercialization.
At the first International Semiconductor Laser Conference (ISLC-1) held in Las Vegas in 1967, it was reported that forward-biased diode chips made from LPE-grown AlGaAs lased when immersed in liquid nitrogen (77 K). By 1968 this breakthrough had given birth to the single heterojunction (SH) laser; by 1969, the double heterojunction (DH) laser and by 1970, continuous wave (CW) operation at 300 K. With the advent of the DH structure, the active region concept crystalized to that of a gain layer of thickness ‘d’ enclosed in a waveguide that determined the spatial aspect of the laser beam. For the next 20 years or so, new material growth and processing techniques led to ‘d’ values decreasing from about 100 nm to a few nanometers and waveguides evolving from simple to complex. In this talk, highlights from the twelve ISLCs held between 1967 and 1990 will be selected to illustrate this active region evolution.

14:50 AWS2 (Invited) – "The History of Laser Emission on Silicon"

John E. Bowers
Univ. of California, Santa Barbara, USA

Fifty years ago the birth of the laser started a scientific and technological revolution. Two years later diode lasers were demonstrated in III-V compound semiconductors while Si-based transistor radios achieved mass popularity. In an effort to join the laser and transistor revolutions together, many scientists have researched lasing on silicon substrates. Recently, rapid advances in silicon photonics are being driven by a combination of a need for more complex, higher functionality and lower cost photonics integrated circuits, but also by pin count and power limits for communications. Electronics giants, including Intel, IBM, HPE, Oracle, ST Microelectronics, AIM Photonics, IMEC and Alcatel-Thales, have teamed up with research institutes around the world to drive progress in silicon photonics. The momentum to make a useful laser in or on silicon is significant. We describe research on lasers in or on silicon, including efforts to grow III-V on silicon, bond III-V on silicon, nanostructure silicon, use the Raman or Brillouin gain in silicon, and to use Ge and other group IV elements to make lasers on silicon. This research should lead to low-cost, terabit-level optical data pipes inside computers and data centers.

15:20 AWS3 (Invited) – "Progress in Quantum Well and Dot Lasers"

Yasuhiko Arakawa
The Univ. of Tokyo, Japan

In the history of semiconductor lasers, the quantum-size effect is one of important physics which gave a great impact on enhancement of lasing characteristics. For the period of more than 10 years from late 1970's, quantum well lasers were intensively investigated both theoretically and experimentally [1,2]. Nowadays, almost all active layers of semiconductor lasers including blue GaN lasers consist of the quantum wells.
In 1982, the concept of quantum dot lasers was proposed with theoretical prediction of temperature insensitivity of threshold current by Arakawa and Sakaki [3]. The temperature insensitivity was successfully demonstrated in a self-assembled InAs/GaAs quantum dot laser in 2006 by Fujitsu and the Univ. of Tokyo [4]. This achievement was led to launch of a venture company named QD Laser Inc.. The quantum dot lasers have a variety of superior performance to conventional lasers such as high temperature operation, low-power consumption, and low-cost productivity. Silicon photonics is a promising application for the quantum dot lasers.
In this presentation, we overview historical progress and the current state of the art of the quantum dot lasers. Future prospects of quantum dot photonics are also discussed.

References
[1] 1. P. van der Ziel, R. Dingle, R. C. Miller, W. Wiegmann, and W. A. Nordland Jr., Appl. Phys. Lett.. 26, 463 (1975)
[2] Y. Arakawa and A. Yariv, IEEE J. of Quant. Electron. 22 1887 (1986)
[3] Y. Arakawa and H. Sakaki, Appl. Phys. Lett. 40, 939 (1982)

15:50 AWS4 (Invited) – "Progress and Future Prospects of Photonic Crystal Lasers"

Susumu Noda
Kyoto Univ., Japan

The band-edge of two-dimensional (2D) photonic-crystal (PC), at which a group velocity of light becomes zero, can be utilized to realize a broad-area coherent 2D cavity mode, which enables a stable single longitudinal & lateral 2D lasing oscillation for semiconductor lasers. The 2D cavity mode can be coupled out to the direction normal to the PC plane by PC itself, which enables 2D surface-emitting operation. The first semiconductor laser based on this principle was realized in 1999, and very recently, watt-class high-power, high-beam-quality, surface-emitting lasing oscillation has been successfully achieved under room temperature (RT), continuous-wave (CW) condition. This laser possesses unique properties including generation of unique beams with controlled polarization and patterns ranging from circular to ring-shapes with very narrow divergence angles. Moreover, an extension of lasing wavelength to a blue-violet regime has been achieved, and even electronically-driven 1D and 2D beam-steering operation can be realized. In this conference, I will review the progress and future prospects of such photonic crystal lasers.

16:20-16:40 Coffee Break

16:40-18:40 Anniversary WS 2

Session Co-Chairs: **Luke J. Mawst** *(Univ. of Wisconsin)*
Akihiko Kasukawa *(Furukawa Electric Co., Ltd.)*

16:40 AWS5 (Invited) – "VCSEL Odyssey ++ -The Conception and Research of Vertical Cavity Surface Emitting Laser- "

Kenichi Iga
Tokyo Institute of Technology, Japan

The author obtained the conception of Vertical Cavity Surface Emitting Laser (VCSEL) in March 22, 1977. The first presentation of idea was in 1978 and the initial device came out in 1979 operating at 77K by GaInAsP/InP material. The primary innovation was 6-micron cavity VCSEL demonstrating clear VCSEL mode even at 77K in 1982; i.e., single mode, circular beam, linear polarization, and so on. The first room temperature CW operation was achieved in 1988 by GaAs system with F. Koyama exhibiting a possibly engineered semiconductor laser. Also, we achieved a first room temperature CW in a 1,300 nm VCSEL in 1992. The other important event in 1990 was the demonstration of a continuously tunable VCSEL by the use of mechanically changing the cavity length. Later, this concept led to a MEMS tunable VCSEL Since the beginning of 1990's, a lot of research sectors started the development of VCSEL and very low threshold devices reaching several micro-Amperes were reported. From 1999, VCSELs were applied to high speed LANs such as Gigabit Ethernet. Until now VCSELs have been applied to multi-Gigabit LANs, SANs, computer mice, optical interconnects in super computers, arrayed-laser printers, sensors, engine igniters, and various green IOT fields. The market size of production is postulated to be 2,500 M$ in 2020. The future of VCSELs may be opened to very low power consumption applications such as laser eye glasses, very high power photonics like laser manufacturing, laser displays, laser radars, and so on.

17:10 AWS6 (Invited) – "Long-Wavelength VCSELs: Devices and Applications"

Markus C. Amann
Technical Univ. Munich, Germany

Vertical-Cavity Surface-Emitting Lasers (VCSELs) exhibit attractive device features such as sub-milliamp threshold currents, low beam divergence, simple fiber-coupling, high slope efficiencies and low power consumption. Differing from their rather mature 850-950 nm counterparts, longwavelength (····1.3 µm) VCSELs only have become application-suited in recent years. Today, InPbased VCSELs based on the buried tunnel junction technology show excellent device performance.
These MBE-grown devices access the entire near-infrared wavelength range from 1.3 to 2.6 µm. They yield stable polarization, single-mode operation, high-speed modulation exceeding 20 GHz and simple electro-thermal tuning over several nanometers. Digital transmission systems with data rates exceeding 50 Gb/s at 1.55 µm were demonstrated and numerous trace gas species have been measured with sensing systems based on these lasers. While the InP-based laser diodes are limited to an upper wavelength of about 2.6µm, application of GaSb-based heterostructures opens the 2-4µm wavelength range. First GaSb-VCSELs for the wavelength range from 2.3 to 3 µm have been realized so far.
These early devices already show continuous-wave operation and stable single-mode emission. The electro-thermal tuning is about a factor of two stronger than for their InP-based counterparts and tuning ranges of the order of 10 nm have been achieved.

17:40 AWS7 (Invited) – "A 1989 Event in VCSEL Development"

Jack L. Jewell
USA

Prior to mid-1989, essentially all reported VCSELs had active regions a micron or more thick (one had 0.6um). Then a Bell Labs / Bellcore group (Jewell, et al., Electronics Letters, vol. 25, p. 1123, 1989), reported VCSELs with 3 (and subsequently 1) quantum wells (QWs) confined to a single standing-wave intensity peak (~40X reduction in thickness). Not long after that publication, essentially all VCSELs had similar active regions comprising ~1-4 QWs. With active regions similar to those of edge-emitters, VCSELs then showed promise for high efficiency and reliability. R&D funding increased sharply by industry and government. The use of such thin active regions in VCSELs required another innovation: having both mirror reflectivities well above 99%. Such mirrors comprised GaAs/AlAs layers grown by molecular beam epitaxy. To activate the VCSELs, electrical current was injected into a top gold contact, through the top mirror, into the active p-n junction, and through the bottom mirror into the substrate. To overcome electrical resistance at the GaAs/AlAs interfaces, graded superlattices were used. The features described here were mostly new at the time, and are still used most commercial VCSELs today. Factors leading to this transformative event in VCSEL development will be described.

18:10 AWS8 (Invited) – "25 Years of VCSEL Research and Development at Ulm University and Philips Photonics"

Karl J. Ebeling
Univ. of Ulm, Germany

Ulm University appeared in the semiconductor laser arena in the nineties of last century demonstrating efficient vertical-cavity surface-emitting laser diodes (VCSELs) and early 10 Gbit/s optical data transmission with these devices. The University start-up U-L-M Photonics founded in 2000 and now part of Philips has boosted VCSEL development at Ulm by meanwhile producing some 100 million high-performance VCSELs per year. The privilege of hosting the most memorable ISLC 2002 held at Garmisch, South Germany, has inspired various important hot-topic VCSEL research activities at the University and Philips Photonics like for example extended single-mode operation or mass fabrication of polarization-stable devices. From an application point of view we have focused our efforts to explore VCSELs and arrays for high-speed data communication and routing, surface sensing in computer mice, oxygen absorption spectroscopy, miniaturized Cs-based atomic clocks, distance measurements in smartphones, or materials processing using high power devices. We expect that in the future a novel mass market for VCSELs will arise in the context of 3-D imaging and 3-D video where brilliant high-power narrow-band VCSEL arrays will provide an almost ideal light source for time-of-flight scene illumination. Some topics will be highlighted in more detail.

18:40-19:00 Break

19:00- Welcome Reception (Zuiten (West) room)