# Tuesday, September 13

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

## 8:00-10:15 Opening Ceremony
## Plenary Lecture

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

**8:00** TuA1 (Plenary) – "What does it Take to Make The Semiconductor Laser a High Coherence Laser"

Amnon Yariv
*California Institute of Technology, USA*

The Semiconductor laser (SCL) is, arguably, the most important player in the optoelectronic field. It is hard to imagine a modern communications measurement, or a sensing system without it. It owes this distinction principally to its monolithic semiconductor character, which is responsible for a long list of crucial attributes. These include small size, efficiency, natural compatibility with electronic driving circuitry, speed, structural and chemical control of key features. Another feature of the SCL, which is mentioned less often is its intellectual elegance. Its theoretical underpinnings, design and fabrication require an intricate interweaving of solid state physics, quantum field theory, semiconductor device theory, material science, and laser theory. The chemical and fabrication control enables us to vary the active medium from that of a bulk semiconductor to that of atom-like quantum dots. The incorporation of spatial modulation, of the structure, modulated gratings, photonic crystals, for example, enables a spatial control that would be analogous, to the ability to design crystals with varying size of atoms and of periodicities. The noise, and the resulting degraded coherence, of the semiconductor laser is an example of the Dissipation-Fluctuation theorem. Which links losses with noise. This is manifested in the SCL by following chain of causally related events: high optical losses (dissipation) --> large compensatory gain provided by the inverted population of electrons and holes --> high rate of spontaneous recombination emission into the laser mode --> low coherence. This chain can, however, be snapped by taking advantage of the new flexibility afforded us by the Si photonic platform. This is achieved by redesigning the laser mode so that the overwhelming majority (~ 99%) of optical energy is moved away from the lossy III-V material into the, essentially lossless, Si. The residual, about 1% in our case, of the optical energy remaining in the III-V is just sufficient to provide the now reduced, threshold gain. Applying these ideas results in new lasers in which the fundamental quantum noise is some three orders of magnitude below that of high-performance commercial Distributed Feedback SCLS. Some thoughts of future directions for improved coherence in SCLs will conclude the talk.

**8:45** TuA2 (Plenary) – "In-plane Semiconductor Membrane Lasers for Photonic Integrated Circuits"

Shigehisa Arai
*Tokyo Institute of Technology, Japan*

Lasing properties of in-plane semiconductor membrane lasers required for ultra-low power-consumption and high-speed operation are explained from aspects of output power and direct modulation bandwidth. Recent results on GaInAsP/InP long wavelength membrane lasers are reviewed and remaining issues for this application will be discussed.

**9:30** TuA3 (Plenary) – "Quantum Dot Lasers for Integrated Photonics"

Peter M. Smowton[1], Sam Shutts[1], Robert Thomas[1], Stella Elliott[1], Angela Sobiesierski[1], Ivan Karomi[1], Sara Gillgrass[1], Andrey Krysa[2]
[1]*Cardiff Univ., UK,* [2]*The Univ. of Sheffield, UK*

We review progress in the operating performance and the underlying physical mechanisms of InP quantum dot lasers and demonstrate applications in dual wavelength sources and monolithically integrated optoelectronics and microfluidics for cell sensing.

## 10:15-10:35 Coffee Break

## 10:35-12:50 Session: Mid IR Laser

Session Co-Chairs: **Gary Evans** *(Southern Methodist Univ.)*
**Chung-en Zah** *(Focuslight)*

**10:35** TuB1 (Invited) – "Interband Cascade Lasers Emitting at 4.6-6.1 µm"

C. L. Canedy[1], M. V. Warren[1], C. D. Merritt[1], W. W. Bewley[1], M. Kim[2], C. S. Kim[1], I. Vurgaftman[1], J. R. Meyer[1], M. Fradet[3], C. F. Fradet[3], R. M. Briggs[3], S. Forouhar[3]
*[1]Naval Research Laboratory, USA, [2]Sotera Defense Solutions, Inc., USA, [3]Jet Propulsion Laboratory, USA*

We report interband cascade lasers exhibiting improved performance in the λ = 4.6-6.1 µm spectral range. For pulsed operation at 300 K, the threshold current density of a broad area device emitting at λ ≈ 4.8 µm is 220 A/cm$^2$, while its external differential quantum efficiency per stage is 33%.

**11:05** TuB2 – "4.7 mm-Emitting Leaky-Wave-Coupled Quantum Cascade Laser Phase-Locked Array"

C. Sigler[1], C. Boyle[1], J. D. Kirch[1], D. Lindberg III[2], T. Earles[2], J. Myers[3], R. Bedford[3], D. Botez[1], Luke J. Mawst[1]
*[1]Univ. of Wisconsin-Madison, USA, [2]Intraband LLC, USA, [3]Air Force Research Laboratory, Sensors Directorate, Wright-Patterson AFB, USA*

Phase-locking, via leaky-wave coupling, of five 4.7 µm-emitting quantum cascade lasers is demonstrated. Non-resonant devices fabricated by two-step MOCVD operate in mixtures of in-phase and out-of-phase modes to 3.85 W peak pulsed output power. Design analysis shows in-phase-mode operation under resonant-coupling occurs for optimized devices.

**11:20** TuB3 – "Distributed Feedback Quantum Cascade Lasers on Silicon"

Alexander Spott[1], Jon Peters[1], Michael Davenport[1], Eric Stanton[1], Chong Zhang[1], William Bewley[2], Charles Merritt[2], Igor Vurgaftman[2], Chul Soo Kim[2], Jerry Meyer[2], Jeremy Kirch[3], Luke Mawst[3], Dan Botez[3], John Bowers[1]
*[1]Univ. of California, Santa Barbara, USA, [2]Naval Research Laboratory, USA, [3]Univ. of Wisconsin-Madison, USA*

Here we demonstrate distributed feedback (DFB) quantum cascade lasers (QCLs) which are heterogeneously integrated on silicon. These lasers emit over 200 mW of pulsed power at room temperature and operate at up to 100 °C.

**11:35** TuB4 – "First Demonstration of 2 µm Wavelength Tunable Distributed Bragg Reflector Laser Diode"

Takuya Kanai, Naoki Fujiwara, Yoshitaka Ohiso, Hiroyuki Ishii, Mikitaka Itoh
*NTT Corporation, Japan*

We have developed the first 2 µm wavelength tunable distributed Bragg reflector (DBR) laser diode. The 2 µm DBR laser enables us to obtain a continuous wavelength tuning range of 5.6 nm with a single tuning current.

**11:50** TuB5 – "Mid-Infrared Quantum Cascade Laser Integrated with λ/4-thick Distributed Bragg Reflector (DBR)"

Hiroyuki Yoshinaga, Jun-ichi Hashimoto, Hiroki Mori, Yukihiro Tsuji, Manabu Shiozaki, Makoto Murata, Mitsuru Ekawa, Yasuhiro Iguchi, Tsukuru Katsuyama
*Sumitomo Electric Industries, LTD., Japan*

We report a first successful operation of a distributed Bragg reflector (DBR) integrated InP-based QCL. The DBR facet (λ/4-thick semiconductor-wall and λ/4-thick air-gap, 2 pairs) shows a high reflectivity of 91%, leading to a significant threshold current reduction of QCL in 7 µm wavelength region.

**12:05** TuB6 – "Realization of Unexplored Frequency Terahertz Quantum-Cascade Lasers by Using III Nitride Semiconductors"

Wataru Terashima[1], Norihiko Kamata[2], Hideki Hirayama[1]
*[1]RIKEN, Japan, [2]Saitama Univ., Japan*

III Nitride semiconductor is a material having a potential for realizing wide frequency range of quantum cascade lasers (QCLs) including unexplored frequency from 5 to 12 THz. We fabricated GaN/AlGaN THz-QCLs with novel pure-3-level design active regions and achieved lasing at frequency between 5.4-7 THz.

**12:20** TuB7 – "Single-Mode Interband Cascade Lasers Emitting beyond 5.2 µm for Sensing Applications"

Steffen Becker[1], Julian Scheuermann[1], Michael Von Edlinger[1], Lars Nähle[1], Marc Fischer[1], Robert Weih[1], Johannes Koeth[1], Sven Höfling[2], Martin Kamp[2]
*[1]nanoplus Nanosystems and Technologies GmbH, Germany, [2]Universität Würzburg, Germany*

We present single-mode distributed feedback interband cascade lasers with record long wavelength emission beyond 5.2 µm. The devices show continuous wave operation at room temperature, threshold currents of 66 mA and side mode suppression ratios >28 dB with more than 5 nm tuning range.

**12:35** TuB8 – "Wavelength Dependence of Efficiency Limiting Mechanisms in Type I GaInAsSb/GaSb Lasers Emitting in the Mid-Infrared"

Timothy Eales[1], Igor P. Marko[1], Barnabas A. Ikyo[1], Alf R. Adams[1], Shamsul Arafin[2], Stephan Sprengel[2], Markus C. Amann[2], Stephen Sweeney[1]
*[1]Univ. of Surrey, UK, [2]Technische Universität München, Germany*

Type-I GaInAsSb lasers, emitting between 2-3 µm are investigated using temperature and high pressure. A model of the Auger processes is used to fit the non-radiative component of the threshold current at room temperature, identifying the dominance of different Auger losses across the wavelength range.

## 12:50-13:50 Lunch (Lunch box is served)

## 13:50-16:05 Session: Novel Communication Lasers

Session Co-Chairs: **Peter Smowton** *(Cardiff Univ.)*
**Milan Mashanovitch** *(Freedom Photonics)*

**13:50** TuC1 (Invited) – "Monolithic Laser Integrated Mach-Zehnder Modulator InP PICs for High-Speed Optical Networks"

Sophie Lange, Ronald Kaiser, Marko Gruner, Norman Wolf, Lei Yan, Wolfgang Rehbein, Martin Schell
*Fraunhofer Heinrich Hertz Institute, Germany*

We present our recent advances in InP-based optical transmitter photonic integrated circuits, developed for compact size, power efficiency and high-speed modulation. The transmitters have low switching voltages of 2 V. Excellent BER performance is achieved up to 64 Gb/s QPSK and 107.4 Gb/s

PAM8 operation.

**14:20** TuC2 (Invited) – "Narrow Linewidth Tunable DBR Lasers"

Michael C. Larson
*Lumentum Operations LLC, USA*

Thermally tuned sampled-grating distributed Bragg reflector lasers achieve <100kHz spectral linewidth, >50dB side-mode-suppression ratio, and >17dBm fiber-coupled output power over the full C-band to meet the demands of flex-grid wavelength-division-multiplexed coherent transmission systems.

**14:50** TuC3 – "Tunable DFB Laser Array Combined by Monolithically Integrated AWG Counpler"

Toshihito Suzuki, Kazuaki Kiyota, Maiko Ariga, Yusuke Inaba, Shunsuke Okuyama, Tatsuro Kurobe
*Furukawa Electric Co., Ltd., Japan*

We proposed an AWG integrated tunable DFB laser array for digital coherent systems. The insertion loss of AWG coupler optimized for 16 lasers was less than 6 dB. After SOA amplification, 100 mW output power was obtained under SOA current of 450 mA.

**15:05** TuC4 – "High Modulated Output Power of +9.0 dBm Transmitted over 80 km with L-band SOA Assisted Extended Reach EADFB Laser (AXEL)"

Takahiko Shindo, Wataru Kobayashi, Naoki Fujiwara, Yoshitaka Ohiso, Koichi Hasebe, Hiroyuki Ishii, Mikitaka Itoh
*NTT Corporation, Japan*

We successfully transmitted a high modulated output power exceeding 9 dBm over 80 km of SMF by using an L-band extended reach EADFB laser (AXEL) without increasing the power consumption and number of electrical input ports compared with an EADFB laser.

**15:20** TuC5 – "Monolithically Integrated Widely Tunable Narrow-Linewidth Light Source for the C+ Band Based on Quantum Dot Laser Material"

Annette Becker, Vitalii Sichkovskyi, Anna Rippien, Florian Schnabel, Johann Peter Reithmaier
*Univ. of Kassel, Germany*

A monolithically integrated narrow-linewidth light source was realized on InP-based quantum dot laser material, which can be tuned over the whole C+ communication band and utilizes the low linewidth enhancement factor as well as the broad gain bandwidth of quasi-zero dimensional gain material.

**15:35** TuC6 – "Phase Noise Study of Laser Diodes with External Optical Feedback for Digital Coherent Communications"

Toshimitsu Kaneko, Masaaki Okamoto, Katsumi Uesaka
*Sumitomo Electric Industries, LTD., Japan*

We evaluated external optical feedback effect for TDA-CSG-DR tunable laser by real-time phase variation measurements. The phase variation slower than feedback delay was significantly reduced without imperiling laser stability and the noise level for 50-100 MHz was ~17 kHz2/kHz, as an equivalent FP laser explaining.

**15:50** TuC7 – "Optical Gain in GaAsBi/GaAs Quantum Well Diode Lasers"

Igor P. Marko[1], Christopher A. Broderick[2], Shirong Jin[1], Peter Ludewig[3], Wolfgang Stolz[3], Kerstin Volz[3], Judy Rorison[2], Eoin P. O'Reilly[4], Stephen J. Sweeney[1]
*[1]Univ. of Surrey, UK, [2]Univ. of Bristol, UK, [3]Philipps-Universität Marburg, Germany, [4]Tyndall National Institute, Ireland*

Optical gain, absorption, spontaneous emission spectra for GaAs0.978Bi0.022/GaAs laser diodes are studied experimentally and theoretically. Internal optical losses of 10-15cm$^{-1}$ and peak modal gain of

$24cm^{-1}$ are measured at threshold. The results of calculations showed excellent agreement with the experiment, key for future laser design.

## 16:05-16:25 Coffee Break

## 16:25-18:40 Session: Advanced VCSELs

Session Co-Chairs: **Kazuhisa Uomi** *(Oclaro Japan, Inc.)*
**Tsuyoshi Yamamoto** *(Fujitsu Laboratories Ltd.)*

**16:25** TuD1 (Invited) – "Continuous Wavelength-Swept MEMS-VCSEL"

C. J. Chang-Hasnain[1], P. Qiao[1], K. Li[1], C. Chase[2], Y. Rao[2], M. C.Y. Huang[2]
*[1]Univ. of California, Berkeley, USA, [2]Bandwidth10 Inc., USA*

In this talk, we review recent progress of monolithic, wavelength-swept vertical-cavity surface-emitting lasers (VCSELs) and their applications. A typical electrically-pumped VCSEL consists of two oppositely doped distributed Bragg reflectors (DBRs) with a cavity layer in between. In the center of the cavity layer resides an active region, consisting of multiple quantum wells. Due to the short cavity length which results in a very large longitudinal mode spacing, there is only one longitudinal mode that lases. Lasing wavelength can be continuously swept with continuously varied cavity length. The first generation of sweptable tunable VCSELs were demonstrated with part or entire top DBR be held by a micro-electro-mechanical structure (MEMS) and the lasing wavelength is varied by moving the MEMS with an electric bias. Electrically-pumped, tunable VCSELs emitting at 850-nm, 940-nm, 1060-nm, 1300-nm and 1550-nm were all demonstrated. These VCSELs are demonstrated with high modulation rate and coherent lengths, well poised for optical communications applications in datacenters, fiber-to-the-home and metropolitan area networks. Recently, optically pumped tunable VCSEL has been demonstrated with an ultrawide tuning range. In addition, new applications in optical coherence tomography and LIDAR are particular interesting for continuously tunable VCSEL. Finally, replacing the movable top DBR mirror by an ultra-thin high-contrast grating (HCG), the sweep rate of the tunable VCSEL was reported to drastically increased to 1~10 MHz, which can enable many real-time 3D imaging applications. We will discuss the design criteria, characteristics, challenges, advances and prospects of wavelength-swept MEMS-VCSEs.

**16:55** TuD2 – "GaAs High-Contrast Gratings with InGaP Sacrificial Layer for Multi-Wavelength VCSEL Arrays"

Erik Haglund[1], Johan S. Gustavsson[1], Wayne V. Sorin[2], Jörgen Bengtsson[1], David Fattal[3], Åsa Haglund[1], Anders Larsson[1], Michael Tan[2]
*[1]Chalmers Univ. of Technology, Sweden, [2]Hewlett Packard Enterprise, USA, [3]LEIA Inc., USA*

We report on highly reflective suspended GaAs high-contrast gratings (HCGs) using an InGaP sacrificial layer. A high reflectivity approaching 100% was observed both in direct reflectivity measurement and by low threshold currents in fabricated multi-wavelength HCG-VCSEL arrays.

**17:10** TuD3 – "Temperature Dependence of Small Signal Response of 850 nm Transverse-Coupled-Cavity VCSELs"

Takashi Kondo[1], Junichiro Hayakawa[1], Naoki Jogan[1], Akemi Murakami[1], Jun Sakurai[1], Xiaodong Gu[2], Fumio Koyama[2]
*[1]Fuji Xerox Co., Ltd., Japan, [2]Tokyo institute of Technology, Japan*

We fabricated 850 nm transverse-coupled-cavity VCSELs using 3-inch full wafer process. The modulation bandwidth enhancement was observed in wide temperature range over 120K thanks to an optical feedback in coupled cavity. The result shows a possibility of high-speed VCSELs without any temperature and bias control.

**17:25** TuD4 – "New Perspectives on Coherent Vertical Cavity Laser Arrays"

Stewart Fryslie, Zihe Gao, Bradley Thompson, Kent Choquette
*Univ. of Illinois, USA*

Coherently coupled photonic crystal vertical cavity laser arrays have been developed and studied. Dynamic coupled mode theory is applied from the perspectives of monolithic injection locking or parity-time symmetry considerations. We find new predicted phenomena which agrees quantitatively with theory which may enable new applications.

**17:40** TuD5 – "VCSEL-Based High Resolution Wavelength Demultiplexer with Large Optical Gain"

Masanori Nakahama, Xiaodong Gu, Akihiro Matsutani, Takahiro Sakaguchi, Fumio Koyama
*Tokyo Institute of Technology, Japan*

We demonstrate a novel wavelength demultiplexer based on VCSEL amplifier structure, which offers demultiplexing and amplification functions simultaneously. Its high resolution beam steering enables a wavelength resolution of 0.07nm. Also, a 1mm-long device exhibited the maximum linear gain of 28dB and saturation power of 23dBm.

**17:55** TuD6 – "Strong Enhancements in Output Power and High-Speed Data Transmission Performances by Using Parallel Oxide-Relief/Zn-Diffusion 850 nm VCSELs"

Kai-Lun Chi[1], Xin-Nan Chen[1], Jye-Hong Chen[2], John E Bowers[3], Ying-Jay Yang[4]
*[1]National Central Univ., Taiwan, [2]National Chiao Tung Univ., Taiwan, [3]Univ. of California, Santa Barbara, USA, [4]National Taiwan Univ., Taiwan*

By using parallel two high-speed VCSELs, double increase in maximum output power (4 vs. 8mW), negligible degradation in 3-dB electrical-to-optical bandwidth (~25 GHz), and strong enhancement in 46 Gbit/sec data transmission through OM4 MMF is achieved compared with those of single reference.

**18:10** TuD7 – "980-nm Intra-Cavity Contacted VCSELs for Optical Interconnects"

Philip Moser[1], Marcin Gebski[2], Holger Schmeckebier[1], Patrycja Spiewak[2], Michal Wasiak[2], James A. Lott[1]
*[1]Technische Universität Berlin, Germany, [2]Lodz Univ. of Technology, Poland*

We present oxide-confined 980-nm VCSELs for optical interconnects that are processed into four different n-contact and p-contact configurations. The static and dynamic properties of the four top and bottom extra-DBR and intra-DBR contact configurations of VCSELs from the same epitaxial material are compared and evaluated.

**18:25** TuD8 – "Impact of Bonding Interface Thickness on the Performance of Silicon-Integrated Hybrid-Cavity VCSELs"

Emanuel P. Haglund[1], Sulakshna Kumari[2], Erik Haglund[1], Johan S. Gustavsson[1], Roel G. Baets[2], Gunther Roelkens[2], Anders Larsson[1]
*[1]Chalmers Univ. of Technology, Sweden, [2]Ghent Univ. – IMEC, Belgium*

The dependence of the performance of short-wavelength silicon-integrated hybrid-cavity VCSELs on the thickness of the bonding interface used for the heterogeneous integration has been studied. Performance measures investigated include the emission wavelength, thermal impedance, and variation of threshold current and output power with temperature.

## 18:40-20:00 Dinner Time (on your own)

## 20:00-22:00 Rump Session: Integrated Optoelectronics in next 50 years: light source, platform, scale

Organaizers:

**Dr. Di Liang**
*(Hewlett Packard Labs, Hewlett Packard Enterprise)*

**Prof. Nobuhiko Nishiyama**
*(Tokyo Institute of Technology)*

The information exploration in this Big Data era poses many great opportunities to tremendously lift up the volume of integrated optoelectronics. Behind this business driver, innovation in integration platform, scale and options to deploy the light source is likely to be a key technical driver to determine the new technology landscape in next 50 years. In this exciting venture, silicon photonics emerges to be a new platform to challenge the dominance of the traditional compound semiconductors. But:

1. What is the best venue to monolithically integrate the efficient and reliable light source(s) in the silicon substrate eventually? Should we continue perfecting the growth template to block the defects, developing lattice-matched direct bandgap materials or growing active materials with much better defect tolerance, e.g., quantum dot?

   1a: Lattice-matched III-V material growth on Si
   Professor Stephen Sweeney, University of Surrey (United Kingdom)
   Dr. Stephan Wirths, IBM Research – Zurich (Switzerland)

   1b: Novel/hybrid structures and growth template
   Prof. Kei May Lau, Hong Kong University of Science and Technology (China)

   1c: QD material, laser and commercial development
   Dr. Kenichi Nishi, QD laser Inc. (Japan)

2. Considering the distinct difference between electronics and photonics in materials, operations and control, should there be a "Moore's Law" to guide the photonics integrated circuits (PICs)? If yes what does it look like?

   2a: Large-scale integration in conventional InP platform
   Dr. Hideki Yagi, Sumitomo Electric. (Japan)

   2b: Large-scale integration in silicon
   Dr. Yu Tanaka, Fujitsu (Japan)

   2c: Innovative packaging technology
   Dr. Hiroshi Aruga, Mitsubishi Electric. (Japan)

3. When scaling up the PICs for more functionalities, we can integrate many nanolasers or just deploy a few master light sources and split the output into many channels. Which one is more power efficient?

   3a: Split one master laser power into multiple streams
   Dr. Nobuaki Hatori, PETRA (Japan)

   3b: Nanolasers (Plasmonic, nanowire)
   Prof. Constance Chang-Hasnain, UC-Berkeley (USA)