Electrically injected InP microdisk lasers integrated with nanophotonic SOI circuits

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[4]Tracit Technologies, France

ABSTRACT

We have achieved continuous-wave electrically-injected lasing operation at room-temperature in InP-based microdisks heterogeneously integrated on a SOI nanophotonic circuit. The microdisks were evanescently coupled with sub-micron SOI wire waveguides, resulting in up to 10 µW waveguide-coupled unidirectional output power, with a measured slope efficiency up to 20 µW/mA. A tunnel junction was used for efficient electrical injection with low optical absorption. The measured laser performance agrees well with calculations based on a standard laser model. This model suggests that considerable improvement in laser performance is possible.

Keywords: microdisk laser, heterogeneous integration, silicon photonics

1. INTRODUCTION

Silicon-on-insulator (SOI) has emerged as a promising platform to achieve compact nanophotonic ICs, due to the transparency of silicon at telecom wavelengths, its high refractive index contrast and the fact that CMOS processing infrastructure can be used for fabrication [1]. A major obstacle for large-scale silicon-based electronic-photonic integration is the absence of a compact and efficient silicon-based light source, due to the indirect band gap of silicon. Despite some recent encouraging results, compact and efficient electrically pumped silicon-based lasers don't seem feasible in the short term. An alternative approach to add efficient active photonic functionality to the SOI platform is through heterogeneous integration of a thin III-V epitaxial film using bonding technology. Since the processing of the III-V layers can be done after bonding, the critical alignment to the underlying SOI waveguides is obtained through lithography, as opposed to flip-chip approaches. Over the last twenty years, microdisk lasers have shown good potential as compact and coherent light sources for large-scale photonic integrated circuits [2,3]. These microdisk structures support whispering-gallery resonances that enable ultra-compact and low-threshold laser operation. Electrically-injected microdisk lasers have been demonstrated on InP substrates with threshold currents as low as 40 µA [4]. In this work, we have used heterogeneous bonding technology to integrate electrically-injected InP microdisk lasers on a SOI nanophotonic waveguide platform.

2. MICRODISK LASER DESIGN

A schematic drawing of the laser structure is shown in figure 1. A microdisk is etched in the InP-based layer, leaving a thin lateral bottom layer. The fundamental optical resonances in such a structure are whispering gallery modes (WGMs), which are confined to the edges of the microdisk. Therefore, a top metal contact can be placed in the center of the microdisk, without adding extra optical losses. The bottom contact is positioned on a thin lateral contact layer: this layer will cause no substantial additional optical losses, provided it is sufficiently thin. The laser resonance is evanescently coupled to the underlying SOI waveguide, which is vertically aligned with the edge of microdisk.

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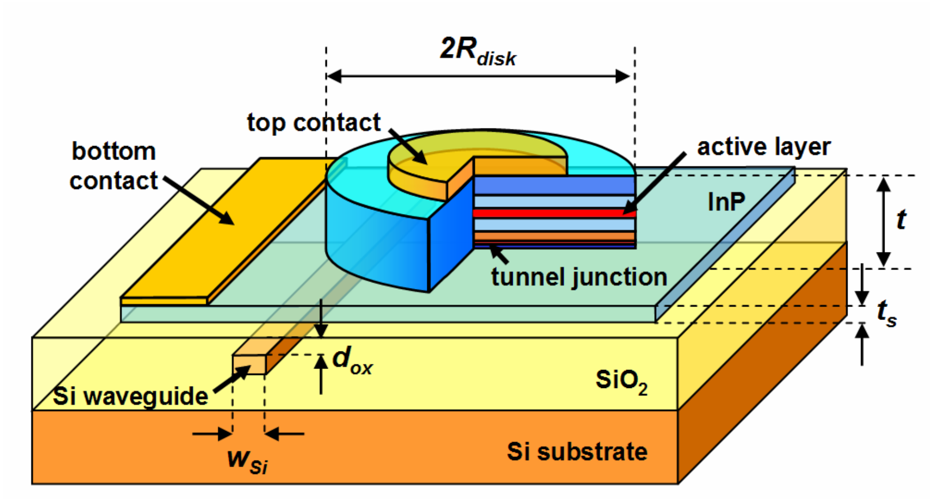

Figure 1. Schematic representation of the heterogeneously integrated microdisk laser

An important design aspect is the composition of the bonded InP-based film. It should enable efficient current injection, while preserving the optical resonance quality. The epitaxial layer should also be as thin as possible, since optical coupling to the underlying SOI waveguide is expected to be less efficient for thicker InP films. Thicker devices are also more difficult to etch with low surface roughness and to planarize, thus making integration more difficult. The major challenge in the epitaxial design lies in the requirement for low-voltage operation and high injection efficiency together with low internal optical loss. A major bottleneck for the electrical current could occur at the p-type contact. It is known that it is much more difficult to achieve low-resistance metal contacts to p-type InP as compared to n-type InP. In traditional InP-substrate based lasers, this is solved by using heavily p-type doped, low bandgap contact layers such as p++ InGaAs. These layers have large optical absorption, due to band-to-band absorption and/or free-carrier absorption (FCA), as highly p-type doped layers have large intervalence band absorption (IVBA). In classic substrate lasers, relatively thick (> 1 µm) cladding layers provide optical isolation between the waveguide core and these very absorptive contact layers. In our approach, a tunnel junction is incorporated to efficiently contact the p-type diode layer, with low optical loss. As has been shown in the case of long-wavelength vertical-cavity surface-emitting lasers (VCSELs), TJs with a bandgap wavelength above the emission wavelength exhibit relatively low electrical resistance with only a minor optical loss penalty, provided that the TJ is well-positioned at a minimum of the optical field intensity and has adequate doping levels [5]. In our design, we have used a Q1.2 tunnel junction. While this approach outperforms a design based on a ternary p++ InGaAs contact layer, the major contribution to the internal loss is still due to free-carrier related losses in the heavily doped TJ layers. Therefore, the doping level of the TJ layers is an important design parameter, which allows for a trade-off between low optical losses and low electrical resistance.

Further contributions to the optical loss in the resonator are bending losses, scattering losses and coupling loss to the SOI wire waveguide. Numerical simulations indicate that the microdisk - including the bottom contact layer – can be as small as 4.5 µm in diameter before bending losses become important. Scattering losses arise due to sidewall roughness, and can thus be strongly reduced by optimizing the dry etch processes used for obtaining the microdisk shape. Finally, the coupling loss to the SOI wire depends strongly on the thickness of the bonding layer, and should be optimized for obtaining optimum laser performance. A useful rule of thumb is to make the coupling loss equal to the parasitic loss. Numerical simulations (3-D FDTD) indicate that this can be achieved by bonding layer thicknesses in the range 100-200nm, for microdisk thicknesses in the range 1 - 0.5µm. For further details on the modeling, we refer to [6]

3. EXPERIMENTAL RESULTS

We have fabricated SOI-integrated microdisk lasers, both in 0.55-µm thick and 1-µm thick bonded epitaxial structures., as illustrated in . For fabrication details, we refer to [7]. The microdisk diameters were 5 µm, 7.5 µm and 10 µm. Before

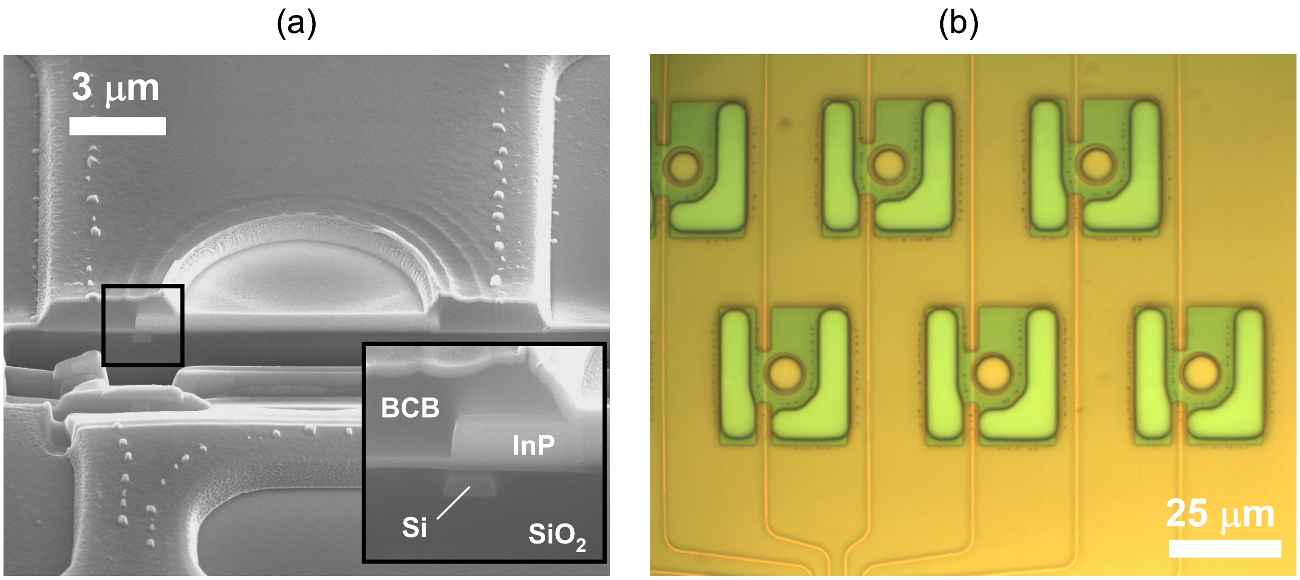

Figure 2. (a) FIB/SEM image in cross section of microdisk laser before metallization. (b) Top down microscope image of 6 microdisk lasers on SOI.

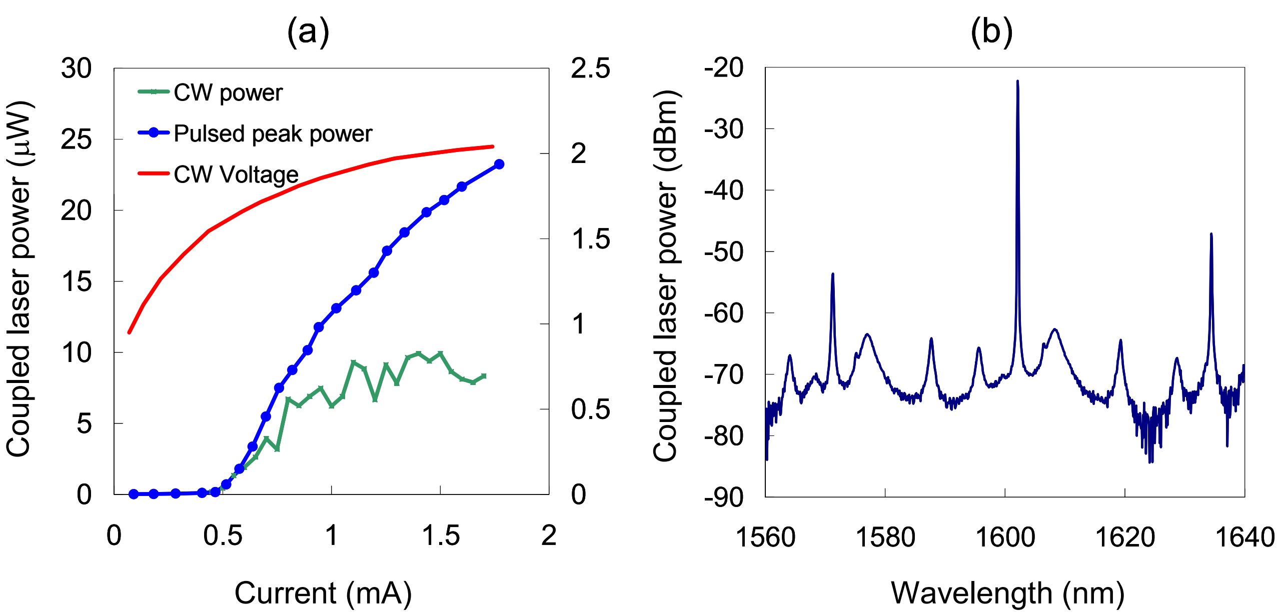

Figure 3. (a) L-V-I data measured for a 7.5-mm microdisk laser. (b) Lasing spectrum for 1.4mA current injection.

metallization, the microdisk lasers were tested under optical pumping, and all devices exhibited lasing with sub-mW threshold powers and substantial coupling into the SOI waveguide. After BCB processing and metallization and a burn-in treatment, electrically pumped characterization was performed. Devices with variable top contact size (0.7−0.84R) were available, and lasing performance was found to depend strongly on the size and position of the top contact. During fabrication, the top contact was misaligned by 400 nm. As a result, lasing from 5 μm-diameter microdisks was generally poor. The measured lasing characteristics for a 7.5-μm microdisk are shown in fig. 3. Lasing was obtained at room temperature both in pulsed and continuous wave (CW) regime. The best lasers had a threshold current of 0.5mA and a differential efficiency of about 30μW/mA in pulsed regime, with up to 100mW peak output power. In CW, the output

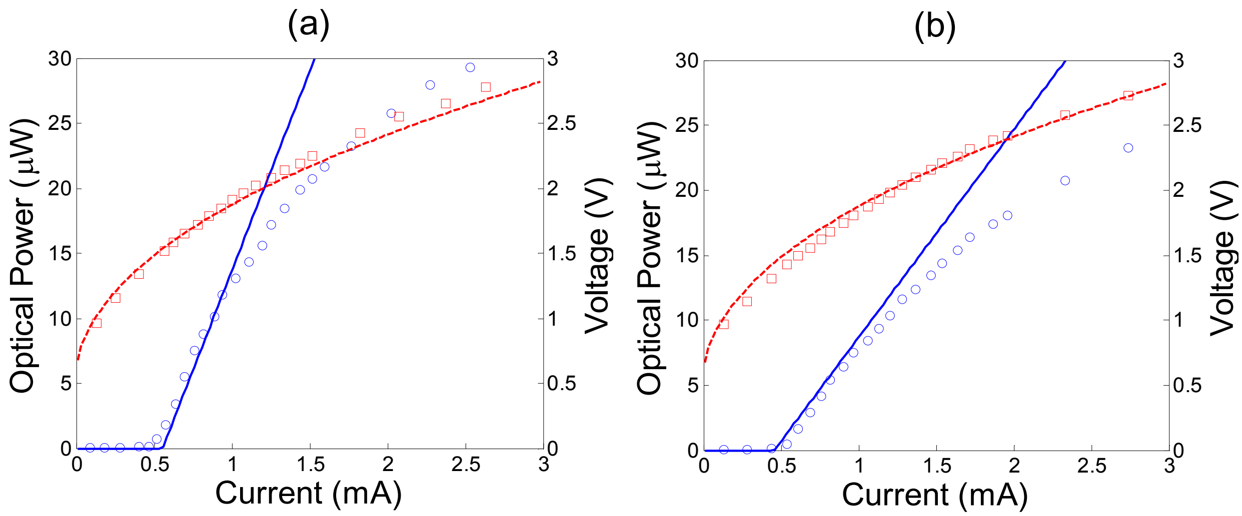

Figure 4. Measured (markers) and fitted (lines) lasing performance in pulsed regime for two 7.5-µm microdisk lasers with different coupling loss.

power was limited to about 10µW due to early thermal roll-over. The device voltage was below 2V. The lasing spectrum, as shown in fig 3. (b) exhibited a clear single lasing peak at 1.6µm, with a linewidth that was equal to or smaller than the resolution of our measurement setup (60pm).

4. DEVICE OPTIMIZATION

A theoretical lasing model, based on classical laser theory applied to the microdisk laser configuration, and including a theoretical electrical TJ model from literature, was used for the interpretation of the measurement results (in pulsed regime). A good fit could be obtained using model parameter values obtained from simulations as discussed in section 2, and assuming reasonable values for parameters that couldn't be estimated through simulation. This is illustrated in fig. 4, where the experimental data is compared with the theoretical fit, for two 7.5-µm microdisk lasers with different lateral waveguide-disk offsets. Good agreement was obtained both for the output power as for the device voltage, except for the saturation of the output power at higher pumping levels.

To estimate the performance of a fully optimized microdisk structure, the theoretical model was used to find the optimum values for the dominant design parameters, which were identified as the microdisk radius, p-type doping of the TJ and the coupling loss. These calculations indicate that a fully optimized microdisk laser could reach a wall-plug efficiency of more than 10%.

5. CONCLUSION

We have developed an electrically-injected InP-based microdisk laser, integrated on and coupled to a nanophotonic SOI platform. Electrically injected lasing in continuous-wave regime was obtained at room temperature, with lasing thresholds around 0.5mA, device voltages below 2V, and slope efficiencies up to 30µW/mA. The measured lasing performance could be fitted by a theoretical model using model parameter values obtained from simulation. This model predicts a wall-plug efficiency of over 10% for a fully optimized microdisk structure.

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SESSION 5

Room: Conv. Ctr. A1 . . . . Tues. 1:30 to 3:30 pm

Silicon Photonics I

Session Chair: **Philippe M. Fauchet,** Univ. of Rochester

Joint session with Conference 6909: Novel In-Plane Semiconductor Lasers VII

1:30 pm: **A monolithic integrated low-threshold Raman silicon laser** *(Invited Paper)*, Haisheng Rong, Shengbo Xu, Intel Corp.; Oded Cohen, Omri Raday, Intel Corp. (Israel); Mario J. Paniccia, Intel Corp. . . . . [6898-15]

2:00 pm: **Silicon nanocrystals and Er coupled to silicon nanocrystals for lasers and amplifiers** *(Invited Paper)*, Nicola Daldosso, Lorenzo Pavesi, Zeno Gaburro, Univ. degli Studi di Trento (Italy) . . . . [6898-16]

2:30 pm: **Monolithically integrated III-Sb diode lasers on miscut Si substrates** *(Invited Paper)*, Diana L. Huffaker, Ganesh Balakrishnan, Univ. of California/Los Angeles; A. Jallipalli, M. N. Kutty, S. Huang, Larry R. Dawson, The Univ. of New Mexico . . . . [6909-21]

3:00 pm: **On-chip integration of quantum dot lasers with waveguides and modulators on Si** *(Invited Paper)*, Pallab K. Bhattacharya, Jun Yang, Univ. of Michigan . . . . [6909-22]

Coffee Break . . . . 3:30 to 4:00 pm

SESSION 6

Room: Conv. Ctr. A1 . . . . Tues. 4:00 to 5:30 pm

Silicon Photonics II

Session Chair: **Mario J. Paniccia,** Intel Corp.

Joint session with Conference 6909: Novel In-Plane Semiconductor Lasers VII

4:00 pm: **Electrically injected InP microdisk lasers integrated with nanophotonic SOI circuits** *(Invited Paper)*, Joris Van Campenhout, Univ. Gent (Belgium); Pedro Rojo-Romeo, Philippe Regreny, Christian Seassal, Ecole Centrale de Lyon (France); Dries Van Thourhout, Univ. Gent (Belgium); Léa Di Cioccio, Commissariat à l'Energie Atomique (France); Chrystelle Lagahe-Blanchard, TRACIT Technologies (France); Jean-Marc Fedeli, Commissariat à l'Energie Atomique (France); Roel G. Baets, Univ. Gent (Belgium) . . . . [6898-17]

4:30 pm: **Recess integration of micro-cleaved laser diode platelets with dielectric waveguides on silicon** *(Invited Paper)*, Clifton G. Fonstad, Jr., Joseph Rumpler, Edward Barkley, Shaya Famenini, James Perkins, Massachusetts Institute of Technology. . . . . [6909-23]

5:00 pm: **Integrated AlGaInAs-silicon evanescent racetrack laser and photodetector** *(Invited Paper)*, Alexander W. Fang, Univ. of California/Santa Barbara; Richard Jones, Intel Corp.; Hyundai Park, Univ. of California/Santa Barbara; Oded Cohen, Omri Raday, Intel Corp. (Israel); Mario J. Paniccia, Intel Corp.; John E. Bowers, Univ. of California/Santa Barbara . . . . [6898-18]

Wednesday 23 January

SESSION 7

Room: Conv. Ctr. A1 . . . . .Wed. 8:10 to 10:10 am

Waveguides I

Session Chair: **Andrew W. Poon,** Hong Kong Univ. of Science and Technology (Hong Kong China)

8:10 am: **Strategies for realization of strong-confinement microphotonic devices** *(Invited Paper)*, Tymon Barwicz, Massachusetts Institute of Technology and IBM Thomas J. Watson Research Ctr.; Milos A. Popovic, Michael R. Watts, Peter T. Rakich, Charles W. Holzwarth, Franz X. Kärtner, Erich I. Ippen, Henry I. Smith, Massachusetts Institute of Technology . . . . [6898-19]

8:50 am: **Segmented and slotted waveguides for high-speed electro-optic modulation**, Guangxi Wang, Tom W. Baehr-Jones, Michael Hochberg, Jingqing Huang, Axel Scherer, California Institute of Technology. . . . . [6898-20]

9:10 am: **Photon confinement in multislot waveguides**, Yijing Fu, Dan Railey, Han G. Yoo, Philippe M. Fauchet, Univ. of Rochester . . . . [6898-21]

9:30 am: **Proton beam writing of waveguides in bulk silicon**, Ee Jin Teo, Andrew A. Bettiol, National Univ. of Singapore (Singapore); Pengyuan Yang, Graham T. Reed, Univ. of Surrey (United Kingdom); Mark B. H.Breese, National Univ. of Singapore (Singapore) . . . . [6898-22]

9:50 am: **Sub-micron optical waveguides for silicon photonics formed via the local oxidation of silicon (LOCOS)**, Frederic Y. Gardes, Graham T. Reed, Univ. of Surrey (United Kingdom); Andrew P. Knights, McMaster Univ. (Canada); Goran Z. Mashanovich, David Thomson, Univ. of Surrey (United Kingdom); Paul E. Jessop, McMaster Univ. (Canada); Lynda K. Rowe, Carleton Univ. (Canada); Sarah M. McFaul, Doug M. Bruce, McMaster Univ. (Canada); N. Garry Tarr, Carleton Univ. (Canada) . . . . [6898-23]

Coffee Break . . . . 10:10 to 10:30 am

SESSION 8

Room: Conv. Ctr. A1 . . . . Wed. 10:30 am to 12:10 pm

Waveguides II

Session Chair: **Andrew W. Poon,** Hong Kong Univ. of Science and Technology (Hong Kong China)

10:30 am: **Fiber on a chip: nonlinear optics for data communication via silicon photonic wires** *(Invited Paper)*, Richard M. Osgood, Jr., Xiaogang Chen, Iwei Hsieh, Jerry I. Dadap, Jr., Nicolae C. Panoiu, Columbia Univ.; William M. J.Green, Yurii G. A.Vlasov, IBM Thomas J. Watson Research Ctr. . . . [6898-24]

11:10 am: **Silicon waveguides for the mid-infrared wavelength region**, Goran Z. Mashanovich, Pengyuan Yang, Univ. of Surrey (United Kingdom); Stevan Stankovic, Univ. of Belgrade (Serbia and Montenegro); Ee Jin Teo, National Univ. of Singapore (Singapore); Jasna V. Crnjanski, Univ. of Belgrade (Serbia and Montenegro); Georg Pucker, Fondazione Bruno Kessler (Italy); William R. Headley III, Univ. of Surrey (United Kingdom); Andrew A. Bettiol, Mark B. H.Breese, National Univ. of Singapore (Singapore); Graham T. Reed, Univ. of Surrey (United Kingdom) . . . . [6898-25]

11:30 am: **Leakage studies on SOI slot waveguide structures**, Paul Müllner, Norman Finger, Rainer Hainberger, ARC Seibersdorf Research GmbH (Austria) . . . . [6898-26]

11:50 am: **Low-temperature amorphous silicon based photonic crystal technology**, Khadijeh Bayat, Sujeet K. Chaudhuri, Saffiedin Safavi-Naeini, Univ. of Waterloo (Canada). . . . . [6898-27]

Lunch/Exhibition Break . . . . 12:10 to 1:30 pm

SESSION 9

Room: Conv. Ctr. A1 . . . . .Wed. 1:30 to 3:10 pm

Waveguides III

Session Chair: **L. W. Cahill,** La Trobe Univ. (Australia)

1:30 pm: **Silicon microsphere photonics**, Ali Serpengüzel, Koç Univ. (Turkey) . . . . [6898-28]

1:50 pm: **Optical solitons in a silicon waveguide**, Jidong Zhang, Qiang Lin, Giovanni Piredda, Robert W. Boyd, Govind P. Agrawal, Philippe M. Fauchet, Univ. of Rochester. . . . . [6898-29]

2:10 pm: **Nonlinear optics in silicon-polymer systems**, Michael Hochberg, California Institute of Technology and Univ. of Washington; Tom W. Baehr-Jones, Guangxi Wang, Axel Scherer, California Institute of Technology[6898-30]

2:30 pm: **Vertically integrated multimode interferometers for 3D photonic circuits in SOI**, Chris J. Brooks, Andrew P. Knights, Paul E. Jessop, McMaster Univ. (Canada). . . . . [6898-31]

2:50 pm: **Experimental demonstration of waveguide-coupled corner-cut square resonators**, Elton Marchena, Shouyuan Shi, Dennis W. Prather, Univ. of Delaware . . . . [6898-32]

Coffee Break . . . . 3:10 to 3:30 pm

Tuesday 22 January

OPTO 2008 Plenary Session

Session Chairs: **Ali Adibi,** Georgia Institute of Technology; **James G. Grote,** Air Force Research Lab.

Room: Conv. Ctr. A7/A8 · 8:30 to 10:00 am

8:30 am: **Introduction and Opening Remarks**

8:40 am: **Nanophotonics: from Photonic Crystals to Plasmonics** *(Presentation Only)*, Eli Yablonovitch, Univ. of California/Berkeley

9:20 am: **Organic "Plastic" Optoelectronic Devices** *(Presentation Only)*, Niyazi Serdar Sariciftci, Johannes Kepler Univ. Linz (Austria)

See p. 28 for details.

Coffee Break . . . . 10:00 to 10:30 am

SESSION 5

Room: Conv. Ctr. B4 . . . . Tues. 10:30 am to 12:20 pm

THz Lasers

Session Chair: **Dan Botez,** Univ. of Wisconsin/Madison

10:30 am: **High-temperature and high-power operation of terahertz quantum-cascade lasers** *(Invited Paper)*, Sushil Kumar, Alan W. Lee, Qi Qin, Massachusetts Institute of Technology; Benjamin S. Williams, Univ. of California/Los Angeles; Qing Hu, Massachusetts Institute of Technology; John L. Reno, Sandia National Labs. . . . . [6909-17]

11:00 am: **Progress in quantum cascade lasers** *(Invited Paper)*, Jerome Faist, ETH Zürich (Switzerland). . . . . [6909-18]

11:30 am: **Terahertz source based on intracavity difference-frequency generation in quantum cascade lasers** *(Invited Paper)*, Mikhail A. Belkin, Harvard Univ.; Alexey A. Belyanin, Texas A&M Univ.; Federico Capasso, Harvard Univ.. . . . . [6909-19]

12:00 pm: **Time-resolved investigation of heat-transport dynamics in THz quantum-cascade lasers**, Miriam Serena Vitiello, Vincenzo Spagnolo, Gaetano Scamarcio, Cinzia Di Franco, Univ. degli Studi di Bari (Italy) . . . . [6909-20]

Lunch/Exhibition Break . . . . 12:20 to 1:30 pm

SESSION 6

Room: Conv. Ctr. A1 . . . . Tues. 1:30 to 3:30 pm

Silicon Photonics I

Joint Session with Conference 6898: Silicon Photonics III

1:30 pm: **A monolithic integrated low-threshold Raman silicon laser** *(Invited Paper)*, Haisheng Rong, Shengbo Xu, Intel Corp.; Oded Cohen, Omri Raday, Intel Corp. (Israel); Mario J. Paniccia, Intel Corp. . . . . [6898-15]

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Coffee Break . . . . 3:30 to 4:00 pm

SESSION 7

Room: Conv. Ctr. A1 . . . . Tues. 4:00 to 5:30 pm

Silicon Photonics II

Joint Session with Conference 6898: Silicon Photonics III

4:00 pm: **Electrically injected InP microdisk lasers integrated with nanophotonic SOI circuits** *(Invited Paper)*, Joris Van Campenhout, Univ. Gent (Belgium); Pedro Rojo-Romeo, Philippe Regreny, Christian Seassal, Ecole Centrale de Lyon (France); Dries Van Thourhout, Univ. Gent (Belgium); Léa Di Cioccio, Commissariat à l'Energie Atomique (France); Chrystelle Lagahe-Blanchard, TRACIT Technologies (France); Jean-Marc Fedeli, Commissariat à l'Energie Atomique (France); Roel G. Baets, Univ. Gent (Belgium). . . . [6898-17]

4:30 pm: **Recess integration of micro-cleaved laser diode platelets with dielectric waveguides on silicon** *(Invited Paper)*, Clifton G. Fonstad, Jr., Joseph Rumpler, Edward Barkley, Shaya Famenini, James Perkins, Massachusetts Institute of Technology. . . . . [6909-23]

5:00 pm: **Integrated AlGaInAs-silicon evanescent racetrack laser and photodetector** *(Invited Paper)*, Alexander W. Fang, Univ. of California/Santa Barbara; Richard Jones, Intel Corp.; Hyundai Park, Univ. of California/Santa Barbara; Oded Cohen, Omri Raday, Intel Corp. (Israel); Mario J. Paniccia, Intel Corp.; John E. Bowers, Univ. of California/Santa Barbara . . . . [6898-18]

Wednesday 23 January

SESSION 8

Room: Conv. Ctr. B4 . . . . .Wed. 8:10 to 10:00 am

High Brightness

Session Chair: **Gary A. Evans,** Photodigm Inc.

8:10 am: **High-brightness diode lasers with very narrow divergence** *(Invited Paper)*, Götz Erbert, Frank Bugge, Joerg Fricke, Karl-Heinz Hasler, Hans Wenzel, Guenther Traenkle, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany) . . . . [6909-24]

8:40 am: **Highly reliable, high-brightness 915-nm laser diodes for fiber laser applications**, Zuntu Xu, Wei Gao, Lisen Cheng, Kejian Luo, Kun Shen, Andre Mastrovito, Axcel Photonics, Inc. . . . . [6909-25]

9:00 am: **Asymmetric Al-free active-region laser structure for high-brightness tapered lasers at 975 nm**, Nicolas Michel, Michel Lecomte, Olivier Parillaud, Michel M. Krakowski, Thales Research & Technology (France); Jose-Manuel Garcia-Tijero, Ignacio Esquivias, Univ. Politécnica de Madrid (Spain) . . . . [6909-26]

9:20 am: **High-reliability, high-power arrays of 808-nm single-mode diode-lasers employing various quantum well structures**, Bocang Qiu, Olek P. Kowalski, Stewart D. McDougall, Xuefeng Liu, John H. Marsh, Intense Ltd. (United Kingdom). . . . . [6909-27]

9:40 am: **Grazing incidence slab semiconductor laser (GRISSL)**, Anish K. Goyal, Robin K. Huang, Leo J. Missaggia, MIT Lincoln Lab. . . . . [6909-28]

Coffee Break . . . . 10:00 to 10:30 am

SESSION 9

Room: Conv. Ctr. B4 . . . . Wed. 10:30 am to 12:20 pm

Mid-IR Lasers

Session Chair: **Claire F. Gmachl,** Princeton Univ.

10:30 am: **InAs-based quantum-cascade lasers** *(Invited Paper)*, Alexei N. Baranov, Roland Teissier, Jan Devenson, Olivier Cathabard, Univ. Montpellier II (France) . . . . [6909-29]

11:00 am: **Short-wavelength quantum cascade lasers** *(Invited Paper)*, John W. Cockburn, Dmitri Revin, The Univ. of Sheffield (United Kingdom). . [6909-30]

11:30 am: **Fiber-coupled, GaSb-based diode-laser modules for the 2.X Î1/4m wavelength range**, Christian Mann, Marcel Rattunde, Eva Geerlings, Johannes Schmitz, Gudrun Kaufel, Joachim Wagner, Fraunhofer-Institut fÃ1/4r Angewandte FestkÃ¶rperphysik (Germany) . . . . [6909-31]

11:50 am: **Interband cascade laser progress** *(Invited Paper)*, William W. Bewley, Chad L. Canedy, Mijin Kim, Chul Soo Kim, Jill A. Nolde, Diane C. Larrabee, J. R. Lindle, Igor Vurgaftman, Jerry R. Meyer, Naval Research Lab. . . . . [6909-32]

Lunch/Exhibition Break . . . . 12:20 to 1:30 pm

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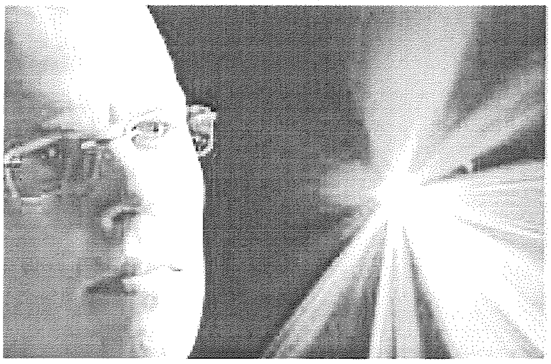
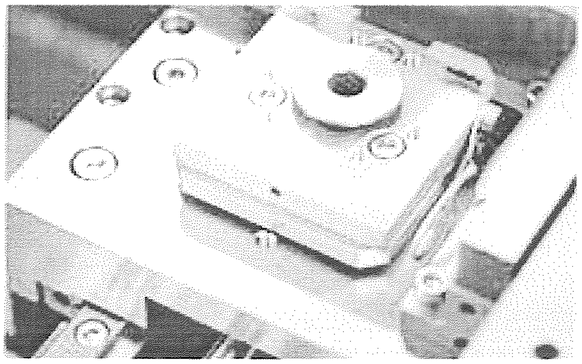


SPIE
Connecting minds. Advancing light.