
ESLW 2023
European Semiconductor Laser Workshop
University of Glasgow, September 30th

Welcome to Glasgow and the European Semiconductor Laser Workshop!

We look forward to an exciting and packed schedule culminating in a Gala dinner at the Clydeside Distillery. The programme contains a broad range of talks and posters that capture the breadth of activity in semiconductor lasers and their increasingly wide range of applications. We are delighted to have excellent keynote and invited presentations which give an overview of some of the current key areas of activity in this field.

It is just over 60 years since the invention of the semiconductor laser and the origins of the European Semiconductor Workshop series go back 45 years. The workshop was last held in Scotland (in Glasgow) in 2005 and it is an honour for us to have the pleasure once again to host the workshop.

We are grateful to the sponsors of the workshop and to the many people that have helped us with its organisation. We thank you very much for your participation, wish you a successful workshop and hope that you enjoy your visit to Glasgow.

Scott Watson
Kevin Gallacher
Stephen Sweeney
Richard Hogg

Workshop Programme

Saturday 30th September

8:00-8:30am	Arrival with tea/coffee and pastries

8:30-8:40am	Welcome/introductions	Scott Watson	
8:40-9:10am	Keynote: Integration of Mid-IR lasers and Si photonics circuits	Eric Tournie	Chair: Stephen Sweeney
9:10-9:30am	Monolithic III-V/Si lasers and amplifiers integrated on the backside of advanced Silicon Photonics wafers	Sylvie Menezo	
9:30-9:50am	Limits to power in GaAs-based broad area lasers	Paul Crump	
9:50-10:10am	Highly stacked quantum dot lasers operating in the telecom band	Kouichi Akahane	

10:10-10:30am	Tea/coffee break

10:30-10:45am	Demonstration of high resolution FMCW LiDAR using fully photonic integrated widely tunable laser at 2 microns	Jannis Holzer	Chair: Paul Crump
10:45-11:00am	Ultra-stable 10 GHz optical clocks based on injection mode-locked semiconductor lasers	Mohanad Al-Rubaiee	
11:00-11:15am	Development of Mid-Infrared Light Emitting Diodes	Peter Carrington	
11:15-11:30am	1.3 µm optically pumped quantum dot photonic crystal laser designed at bounded states in the continuum	Danqi Lei	
11:30-11:35am	Short break		
11:35-11:50am	Eight-channel DFB laser array based on four phase-shifted sampled bragg gratings	Yiming Sun	Chair: Sylvie Menezo
11:50-12:05pm	Demonstration of a 200 GHz grid spacing 16-channel CW-WDM-MSA compliant DFB laser array with output power above 70 mW	Stuart Smyth	
12:05-12:20pm	Optically pumped edge-emitting lasers for photovoltaics at extreme concentrations	Brian Corbett	
12:20-12:35pm	Wide-band GaSb/Si tunable laser devices for 2.X µm biomedical spectroscopy	Kristijonas Vizbaras	

12:35-1:35pm	Lunch break/poster session*

1:35-1:55pm	Optical frequency combs for precision metrology	Dag Schmidt	Chair: Kevin Gallacher
1:55-2:15pm	Laser systems for quantum applications	Una Marvet	
2:15-2:30pm	kHz-level linewidth distributed feedback laser at 778.1, 780.24 and 795 nm emission wavelength for Rb quantum systems	Eugenio Di Gaetano	
2:30-2:45pm	Novel technique for measuring linewidth enhancement factor enabled by photonic integration	Julian Konig	
2:45-3:00pm	Implementation of an FPGA-based laser lock box with high-bandwidth and auto-relocking features: Application to sub-kHz external cavity diode lasers	Joachim Sacher	

3:00-3:15pm	Room temperature low threshold nanobeam lasers using InGaAs/GaAs nanowires on silicon-on-insulator grown by MOCVD	Bogdan Petrin Ratiu
3:15-3:35pm	Tea/coffee break	

3:35-3:50pm	Large-area semiconductor lasers for neural network computing	Xavier Porte	Chair: Richard Hogg
3:50-4:05pm	VCSEL-based photonic spiking neural network with highly efficient training	Joshua Robertson	
4:05-4:20pm	Lowering the coherence of vertical-cavity surface-emitting lasers using chaotic cavity designs	Boon S. Ooi	
4:20-4:35pm	Towards TAMSELs: Tamm-assisted meta-surface emitting lasers	Talal Alshammari	
4:35-4:40pm	Short break		
4:40-4:55pm	High temperature operating InAs/GaAs quantum dot lasers with co-doping technique	Mingchu Tang	Chair: Scott Watson
4:55-5:10pm	Beam quality improvement in broad area high power 970 nm diode lasers by modified current density profile	Shailesh Kumar Khamari	
5:10-5:25pm	Static and dynamic characterisation of 369 nm GaN Fabry-Perot laser diodes	Nicola Parry	
5:25-5:40pm	Novel photonic filter feedback method for time delay signature suppression of chaos generated in semiconductor lasers	Yanhua Hong	
5:40-5:55pm	Non-linear dynamics from a laser diode with both optical feedback and optical injection	Lucas Oliverio	
5:55-6:05pm	Closing remarks	Scott Watson	

6:30pm	Bus to Clydeside Distillery

7:00pm	Conference Dinner & Whisky Tasting at Clydeside Distillery

*Poster session:

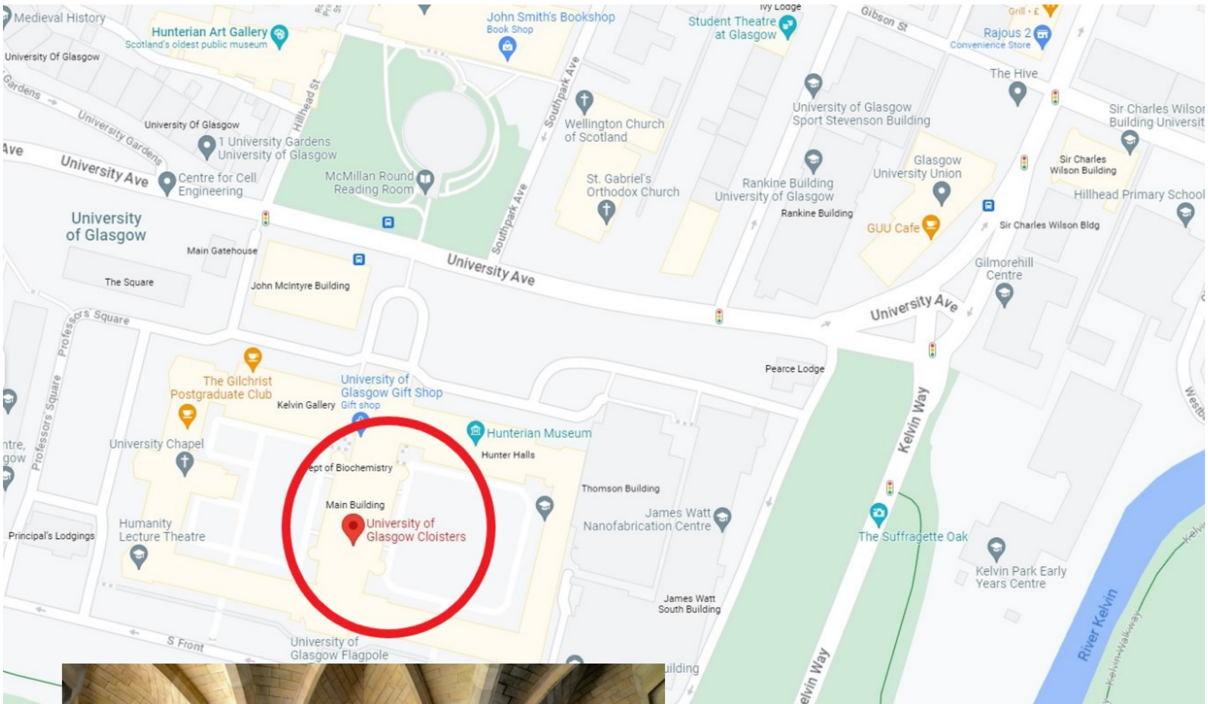
P1	Challenges for room temperature operation of electrically pumped GeSn lasers	Aneirin Ellis
P2	III-V semiconductor light emitters for active photonic thermometry	Anoma Yamsiri
P3	Advancing semiconductor material characterisation with compressed sensing time-resolved photoluminescence imaging	Aidas Baltusis
P4	Towards thermally stable type-II "W"-semiconductor lasers for telecoms applications	Dominic Duffy
P5	Advanced characterisation approaches for optimisation of semiconductor lasers	Igor Marko
P6	Probabilistic Markov chain modelling of photonic crystal surface emitting lasers and the characterisation of laser parameters	Jingzhao Liu

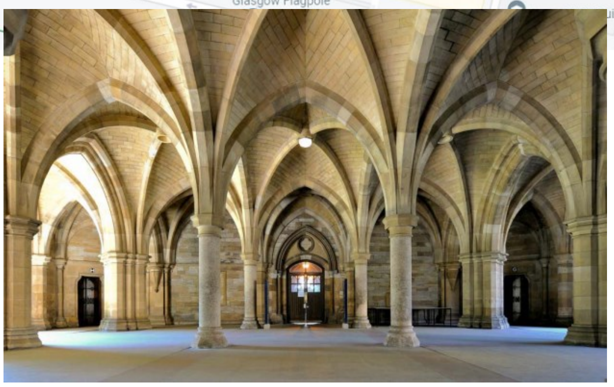
Conference Locations and Getting Around

Join us for a Welcome Drinks Reception in the Cloisters at the University of Glasgow from 7-9pm on Friday 29th September 2023. Drinks and canapes will be served in the amazing surroundings of the University main building where conference attendees can meet and chat and kick off the event in style.

Getting to the Cloisters:

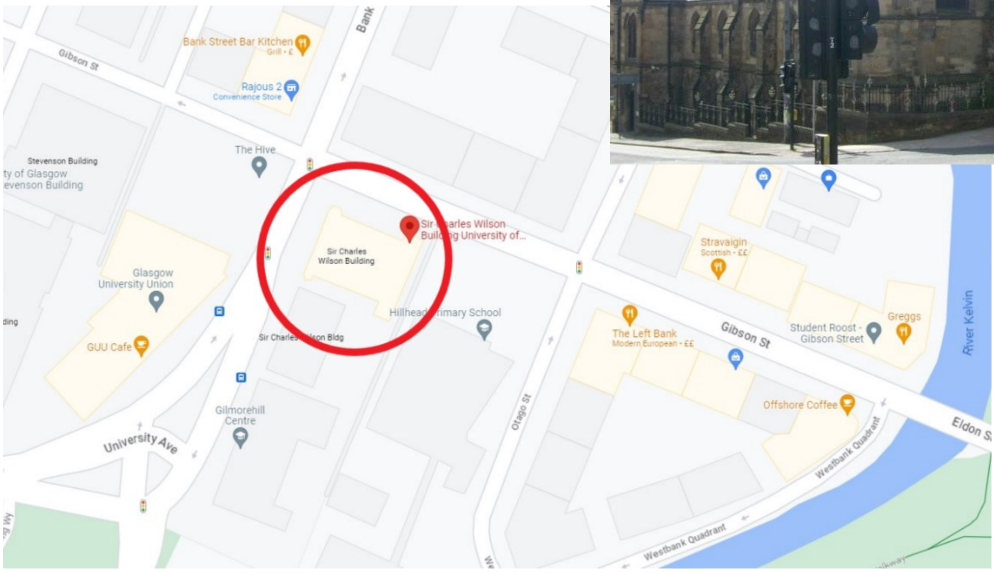
If you leave University Avenue at the Memorial Gates* and walk straight ahead, you can go up either staircase (or use the lift) and follow signs for the Cloisters – this is situated between the East and West Quadrangles [G12 8QQ].





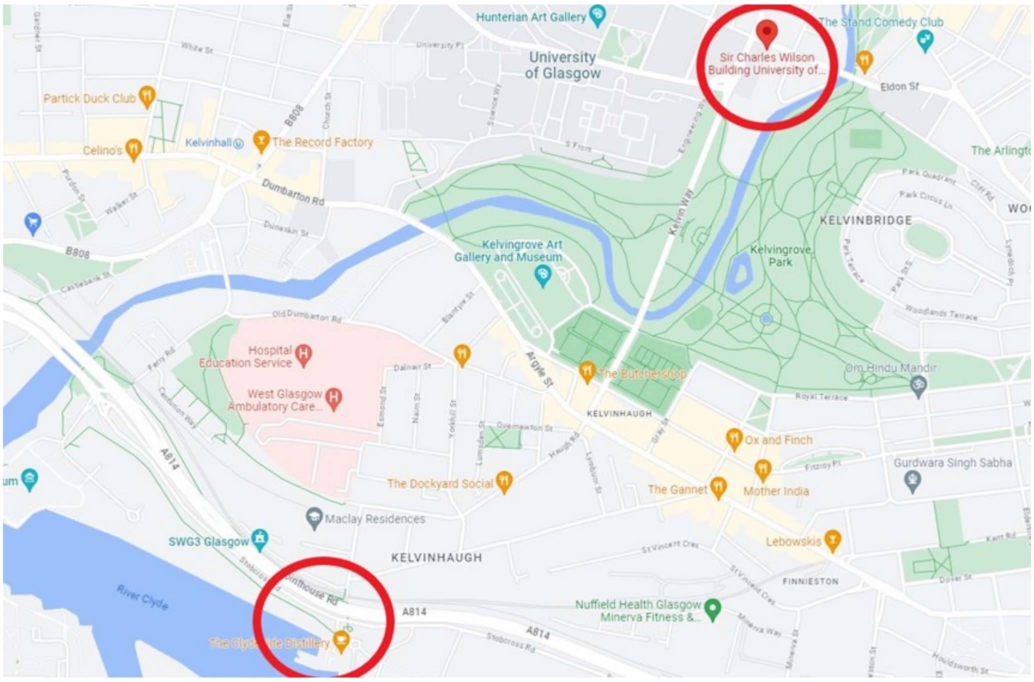
Getting to the Conference Venue:

The European Semiconductor Laser Workshop 2023 will take place in the Sir Charles Wilson building, situated on the corner of [University Avenue and Gibson Street [G12 8NN]](#).



Getting to the Conference Dinner:

The conference dinner and distillery tour will take place at the [Clydeside Distillery [G3 8QQ]](#). A bus is provided to take attendees to the venue directly after the conference (6:30pm) and is approximately 10 minutes. Delegates will have to make their own journey to their accommodation following the conference dinner.



Oral Presentations

Integration of Mid-IR lasers and Si photonics circuits

Eric Tournié[1], M. Paparella[1,2], A. Remis[1], A. Gilbert[1], M. Rio-Calvo[1], L. Monge-Bartolome[1], G. Boissier[1], M. Grande[2], L. Cerutti[1], A. Blake[4], L. O'Faolain[3,4], and J.-B. Rodriguez[1]

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The direct epitaxy of III-V lasers on Silicon (Si) substrates has been considered for decades as an important objective for the realization of integrated photonics chips. Major progress has been achieved recently thanks to the understanding of the defect generation mechanisms, and systematic studies of their suppression [1, 2], or at least the drastic reduction of their density into the active region of the device. In this presentation, we will discuss the challenges related to the growth of III-Vs on Si and present the current state-of-the-art of mid-IR lasers grown on Si [3]. In addition, we will present recent advances in the epitaxial integration of DLs on patterned Si photonics wafer equipped with SiN waveguides. Growth and device fabrication challenges arising from the template architecture were overcome to obtain DLs butt-coupled to the passive waveguides. We demonstrate several mW outpower of emitted light in continuous wave operation at room temperature from the DL grown on the patterned Si photonic wafer [4]. In addition, we will show that, in our configuration, around 10% of the laser light is coupled into the passive SiN waveguides, in good agreement with theoretical calculations [4]. These results open the route to active photonic integrated circuits operating in the mid-infrared for sensing applications. Part of this work was sponsored by the French program on "Investments for the Future" (EquipEx EXTRA, ANR-11-EQPX-0016), the French ANR (ANR-19-CE24-0002) and the H2020 program of the European Union (REDFINCH, GA 780240; OPTAPHI, GA 860808).

[1] M. Rio-Calvo *et al.*, Adv. Electron. Mater. 8, 202100777 (2022). doi: 10.1002/aelm.202100777
[2] A. Gilbert *et al.*, Adv. Opt. Mater. 11(15), 2203050 (2023). doi: 10.1002/adom.202203050
[3] For a review see E. Tournié et al., Light: Science & Applications 11, 165 (2022). doi: 10.1038/s41377-022-00850-4
[4] A. Remis *et al.*, Light: Science & Applications 12, 150 (2023). doi: 10.1038/s41377-023-01185-4

Monolithic III-V/Si lasers and amplifiers integrated on the backside of advanced Silicon Photonic wafers

Sylvie Menezo[1]

[1] SCINTIL Photonics

Silicon (Si) photonics technology has been produced in multiple commercial foundries for ~10 years now. Several vendors offer electrically pluggable transceivers for fibre transmissions within and between datacentres using this integrated technology. As an example, 'QSFP-DD 400GBASE-FR4 PAM4' transceiver modules, which offer 4 x 112 Gigabit per second (Gbps) can be made up of a single Si photonic circuit integrating 4 modulators and 4 photodetectors. 4 CWDM InP lasers are needed at 1271, 1291, 1311 and 1331nm, powering each of the 4 modulators. The lasers are assembled on, or edge-coupled to the Si chip. This assembly requires active alignment between the lasers and the Si chip and the use of isolators and lenses. It implies 2 to 4 dB coupling losses. With cloud bandwidth increasing by 50% every year, the next generation of transceivers should deliver 8 to 16 x 112 GBaud PAM4. This means more lasers to assemble, each delivering more power. Our monolithic laser integration on the back side of Si Photonic circuits has been developed to build on standard Si photonics technology available in commercial foundries. It offers fully integrated circuits with high parallelization. Multiple assembly steps are eliminated, as are the associated optical losses. In this talk, we will present our circuit technology and report on the performance of our integrated DFB lasers and amplifiers, as well as on the Si MZ modulators, germanium photodetectors and Si/SiN filters. A selection of integrated circuits and their performance will be presented.

Limits to power in GaAs-based broad area lasers

Paul Crump[1]

[1] *Ferdinand-Braun-Institut gGmbH*

GaAs-based diode laser edge emitters that lase in the 900-1000 nm wavelength range remain the most efficient and powerful source of optical emission, and have shown rapid improvement in conversion efficiency [1], output power [2] and beam quality [3] in the past 20 years. Single emitters now produce many 10s of Watts of optical output [4] and 1-cm wide bars deliver multiple kW of output power [5]. Although peak conversion efficiency at room temperature remains around 70%, the operating power at this high value has been steadily extended. An overview of current research is presented, with special focus on efforts in experimental diagnosis and device development to overcome limits to specific output power, i.e. to understand limits to and to increase the optical output power from (for example) devices with 100 µm apertures, as needed for high brightness applications. Here, carrier losses triggered by spatially non-uniform temperature profiles in these large area structures are seen to play an important role [6].

[1] https://doi.org/10.1109/JSTQE.2013.2239961
[2] https://doi.org/10.23919/ISLC52947.2022.9943301
[3] https://ieeexplore.ieee.org/document/9478231
[4] https://doi.org/10.1117/12.2647096
[5] https://doi.org/10.1109/JPHOT.2022.3165399
[6] https://doi.org/10.1063/5.0153210

Highly stacked quantum dot lasers operating in the telecom band

Kouichi Akahane[1]

[1] *National Institute of Information and Communications Technology*

Semiconductor quantum dot (QD) structures can confine carriers, such as electrons and holes, three-dimensionally, thereby improving the properties of devices such as semiconductor laser diodes and semiconductor optical amplifiers (SOAs). As a result, considerable research has been conducted in this field over the past three decades. The self-assembled growth technique has been widely used to fabricate QD structures capable of realizing lattice-mismatched material systems. Although the stacking process is used to increase the density of QDs, the accumulation of strain can often become problematic, causing the generation of defects and dislocations. To overcome this problem, we have developed a strain compensation technique to fabricate highly stacked QD structures and realize high-performance QD lasers and QD SOAs. In this paper, we introduce our recent activities on QD lasers. A mode-locked QD laser diode with a two-section structure was fabricated using highly stacked QDs. Each section in this case acts as either a gain or saturable absorber region. Therefore, high-density QDs are required to fabricate short-cavity mode-locked lasers to realize a high repetition rate. The fabricated mode-locked laser, with a cavity length of 500 µm, exhibited a low threshold current of 5 mA. A narrow optical pulse with a pulse width of ~500 fs and a repetition rate of 80 GHz were obtained. As the strain-compensation technique to fabricate highly stacked QDs is flexible in terms of changing the gain or absorption parameters, shorter pulse widths or higher repetition rates can be achieved by optimizing the QD parameters.

Demonstration of high-resolution FMCW LiDAR using fully photonic integrated widely tunable laser at 2 microns

S. Chin[1], J. Holzer[1], A. De Groote[2], D. Martens[2], G. Naujokaite[3], A. Vizbaras[3], K. Vizbaras[3], and C. Pache[1]

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[3] Brolis Sensor Technology UAB Moletu pl.73 LT-14259 Vilnius Lithuania

This paper reports on the experimental demonstration of a fully integrated frequency-modulated continuous wave (FMCW) LiDAR sensing system, operating at 2.0 µm. It makes use of a widely tunable hybrid external cavity laser based on the combination of GaSb gain chip and silicon waveguide circuits. The single-frequency laser operation over the full spectral bandwidth of the gain chip is secured using a frequency-selective filter, consisting of two sequential microring resonators in a Vernier configuration. To increase the mode-hop free wavelength tuning range while preserving the Schawlow-Townes linewidth of the laser, the heater of the phase section placed along the bus waveguide is synchronously controlled with two independent heaters placed on each microring resonator. This laser is then utilized for the development of FMCW LiDAR, consisting of all-optical fiber-based two independent unbalanced Mach-Zehnder interferometers: k-space interferometer for the linearization of continuously swept laser frequency and main interferometer for the measurement on the distributed back-reflection over distance. The optical frequency of the laser is continuously swept over a 117 GHz range (or Δλ=1.56 nm at the operating wavelength); hence, resulting in the LiDAR axial resolution of 1.3 mm in air. To the best of our knowledge, the achieved frequency-sweeping range is beyond the state-of-the-art. The measured sweeping range remains constant up to the frequency sweeping speed of 100 Hz and becomes gradually narrower due to the thermal constant of the whole structure. The measurement range of LiDAR is also evaluated to be <2m, limited by the laser coherence length.

Ultra-stable 10 GHz Optical Clocks Based on Injection Mode-Locked Semiconductor Lasers

Mohanad Al-Rubaiee[1,2], Shengwei Ye[1], Bocheng Yuan[1], Yizhe Fan[1], John H. Marsh[1], and Lianping Hou[1]

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[2] Renewable Energy Department Al-Karkh University of Science Baghdad 10003 Iraq

In the field of high-speed digital systems, there is a critical need to distribute fast and stable clock signals. This work demonstrates an ultra-stable 10 GHz optical clock based on a 1550 nm two-section passive semiconductor mode-locked laser (SMLL), which is injection-locked to a 10 GHz actively mode-locked fibre laser (Pritel). The passive SMLL is based on AlGaInAs/InP material with a three-quantum-well (3QW) active layer on a semi-insulating InP substrate. Using only 3 QWs reduces the optical overlap with the QWs leading to a reduction in self-phase modulation (SPM) effects in the gain section. A 160 nm thick 1.1 Q far-field reduction layer (FRL) was inserted in the lower n-cladding layer to increase the spot size, reduce the internal loss of the cavity and further reduce optical overlap with QWs while suppressing higher transverse mode lasing. Passive mode-locking (ML) was achieved by applying a forward current to the gain section and a reverse voltage to the saturable absorber (SA) section. Sech2 pulses of 1.8 ps duration were generated at a repetition rate of 10 GHz. Compared with a free-running SMLL, the RF linewidth of injected SMLLs was reduced from 46.5 kHz to subhertz. The FRL reduced the divergence angle from 34.7° × 35.1° to 18.3°×31.1°, which doubles the coupling efficiency to a flat cleaved single-mode fibre (SMF). The significant reduction in RF linewidth and timing jitter in our device proves injection locking is a promising technique for distributing ultra-stable optical clocks.

Development of Mid-Infrared Light Emitting Diodes

P. J. Carrington[1], M. Bentley[1], F. A. AL-Saymari[1], A.R Altayar[2], A. P. Craig[2], E. Delli[1], and A. R. J. Marshall[2]

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III-V semiconductor materials based on the '6.1 Å family' (InAs, AlSb, GaSb and their respective alloys) offer a wide variety of band gaps and alignments that can be used to produce a wide range of photonic devices operating in the technologically important mid-infrared (MIR) spectral range. This work will discuss the progress made in the development of GaSb based materials and devices directly grown onto silicon, to reduce manufacturing costs and open the possibility of new applications in lab-on-chip MIR photonic integrated circuits. It will also discuss the performance of new resonant cavity (RC) MIR LEDs which offer many attractive features such as high output power, narrow spectral linewidth, and superior temperature stability.

11:15-11:30am

1.3 µm Optically Pumped Quantum Dot Photonic Crystal Laser Designed at Bounded States in the Continuum

D. Lei[1], Jitong Wang[1], Nicolae C. Panoiu[1], Huiyun Liu[1], and Mingchu Tang[1]

[1] Department of Electronic and Electrical Engineering University College London Torrington Place London WC1E 7JE U.K

Photonic crystal (PC) laser is one of the best candidates as a light source for quantum computing and on-chip photonic integration applications, owning to its superior properties of compact structure, single mode property and narrow beam divergence. However, a low threshold PC laser with a compact structure is usually designed by a defect cavity that has a limited Q factor. In this study, a PC laser designed at bound states in the continuum (BICs) obtains a Q factor up to ~109 that is supported by the simulation result. BICs are different from traditional guided mode, which locates along Γ direction in a radiation band while out of the light cone shown in a band diagram, presents a special solution of wave equation. A vortex beam can be generated by BICs that is usually created by combining optical cavities with spiral waveguides. Thus this BICs PC laser potentially simplifies the structure of a compact vortex microlaser. Additionally, this study is developed on an InAs quantum dots wafer that delivers gain peaked at optical communication wavelength of 1.3µm. III-V quantum dots offer attractive alternatives to conventional quantum wells, such as lower pumping energy and temperature-insensitive operation above room temperature, and great separation of energy levels, which plays great active region role. Such BIC PC laser has potential to break the tradeoff between high Q factor and low threshold, which delivers insights on developing 1.3 µm vortex beam laser that is highly demanded by optical communication systems.

Eight-Channel DFB Laser Array Based on Four Phase-Shifted Sampled Bragg Gratings

Yiming Sun, Bocheng Yuan, Xiao Sun, John H. Marsh, and Lianping Hou

[1] *University of Glasgow*

Distributed feedback (DFB) semiconductor laser arrays are of substantial interest in dense wavelength division multiplexing (DWDM) networks for higher data capacity, especially for low-cost applications in data centres and access networks. It is highly desirable to precisely control the DWDM source channel spacing with simple technology. Here an eight-channel DFB laser array with integrated semiconductor optical amplifiers (SOAs) is demonstrated using four phase-shifted sampled Bragg gratings (4PS-SBGs). Compared with conventional sampled Bragg gratings (C-SBGs) and 2PS-SBGs, whose corresponding effective grating coupling coefficients (κ) are only 0.32 times and 0.64 times that of the continuous uniform gratings respectively, 4PS-SBGs configuration enhances the effective κ of approximately 0.9 times that of a uniform grating. The DFB laser cavity is only 600 µm long, while the channel spacing is precisely maintained at 0.8 ± 0.016 nm around the operational wavelength of 1565 nm. The single longitudinal mode (SLM) operation is maintained across a wide range of drive currents for both the DFB and SOA, with side-mode suppression ratios (SMSRs) surpassing 35 dB and output power of about 33 mW. Furthermore, the sidewall grating design needs only one MOVPE step and one dry etch of the III-V material, simplifying the whole device fabrication process, which is a highly desirable feature for DWDM sources in price-sensitive applications such as passive optical networks (PONs).

Demonstration of a 200Ghz grid spacing 16 channel CW-WDM-MSA compliant DFB laser array with output power above 70mW

Stuart Smyth, Andrew Mckee, and Josua Xiaoyang Lo

[1] *Sivers Photonics*

The demand for high-speed, high-bandwidth optical interconnects for use in artificial Intelligence (AI) and High-Performance Computing (HPC) workloads has prompted the need for high-power dense wavelength optical sources to enable the next generation of Co-Packaged Optics (CPO) and External Laser Source (ELS) solutions. This work presents the successful demonstration of a 200GHz grid spacing 16-channel distributed feedback (DFB) laser array, compliant with the Continuous-Wave Wavelength Division Multiplexing Multi-Source Agreement (CW-WDM MSA), capable of optical output powers exceeding 70mW per channel. The device was designed and fabricated on the Sivers Photonics InP100 manufacturing platform that allows the integration of distinct wavelength-emitting DFBs into a single footprint whilst retaining the high sidemode suppression ratio (SMSR) and output powers required for these applications.

Optically pumped edge-emitting lasers for photovoltaics at extreme concentrations

Meena Baskaran, Ava Carroll, Brendan Roycroft, and Brian Corbett

[1] *Tyndall National Institute University College Cork*

We show that an edge-emitting laser can act as an efficient power converter when pumped by a laser at higher energy. In contrast to conventional laser power converters, which are illuminated from the planar surface, the edge-illuminated power converter has the exceptional property that the open circuit voltage (Voc) can reach the bandgap voltage even under modest illumination intensities. This is due to high carrier density in the low number of quantum wells, which drives the open circuit voltage. An additional, initially somewhat surprising, result is that one laser can drive the other to lasing through edge coupling. The sharing of the voltage across the device with the contact metalisation facilitates this. We have investigated a variety of commercial laser pairs including 1480 nm to 1550 nm (Voc = 0.83 V), 850 nm to 980 nm (Voc = 1.27 V) and 980 nm to broad area 1060 nm (Voc = 1.07 V). The factors limiting the power conversion are the fill factor, which is dominated by the low internal electric field close to open circuit, and the absorption of light, which is polarization and coupling detendent . Custom designed devices are needed to address these limitations. Higher open circuit voltages can be obtained with multiple junction (nanostack) devices though these require equal illumination in each junction.

Wide-Band GaSb/Si Tunable Laser Devices for 2.X µm Biomedical Spectroscopy

Daan Martens, Andreas De Groote, Antonio Ribeiro, Gerda Klimaitė, Greta Naujokaitė, Valentinas Andrulis, Tomas Žukauskas, Augustinas Vizbaras, and Kristijonas Vizbaras

[1] *Brolis Sensor Technology*

The spectral range between 2 and 2.4 µm offers significant potential for biomedical spectroscopy due to the presence of various molecular absorption lines and low water absorption. However, its exploration has been limited by the scarcity of suitable light sources with adequate power and spectral coverage to detect the typically broad absorption peaks effectively. In this context, Brolis Sensor Technology presents a novel spectroscopic device based on GaSb type-I quantum well gain chips combined with silicon-on-insulator external cavity circuits. The latter employ a Vernier filter, consisting of two thermally tunable ring resonators, and a distributed Bragg reflector, enabling wide tunability within the 2.X µm wavelength range. In the latest version of this tunable laser, we have achieved a spectral bandwidth of 180 nm. By butt-coupling three gain chips to a single 4 mm^2 silicon chip containing a separate external cavity for each gain chip, we obtain a single device that spans a wavelength range from 2050 nm to 2400 nm. It furthermore offers a spectral resolution of 0.5 nm, output power ranging from 0.1 to 1 mW, and side mode suppression consistently above 25 dB. With its wide tuning range, ample power, and high spectral resolution, the device combines numerous merits as a spectroscopic sensor. Additionally, its compact size and cost-effectiveness make it highly suitable for various biomedical sensing applications. Further developments toward these sensing applications are currently underway to unlock the full potential of this device in biomedical spectroscopy.

Optical frequency combs for precision metrology

Dag Schmidt[1]

[1] *Menlo Systems Munich Germany*

Within two decades, the optical frequency comb has revolutionized numerous fields in physics: Precision spectroscopy, time and length-metrology, molecular fingerprinting, and ultra-low phase noise microwaves mark just a few application examples. Being the only device with the ability to directly link the optical with the radio frequency domain, the frequency comb has become an irreplaceable tool. Combined with advanced semiconductor-CW laser sources, the full system acts as a multi-color, sub-Hz linewidth laser source, ensuring to transfer the spectral purity of a high finesse optical reference to all CW lasers which are stabilized to the comb. This feature is exploited in clock comparisons or quantum experiments, where a long coherence time of the laser sources is mandatory. In this talk, Menlo Systems elaborates on the basic physics of frequency combs and their key benefits for different applications. Furthermore we present the FC1500-Quantum, a complete laser system for applications in optical (lattice) clocks and quantum technology. Applications examples from these research areas elucidate the demand in highest stability and accuracy of the involved semiconductor laser sources.

Laser Systems for Quantum Applications

Una Marvet[1]

[1] Alter Technology TUV Nord (UK) Ltd

Availability of compact, cost effective, robust laser sources is a major barrier to commercialisation of quantum technologies. There is significant research and development effort in this direction but the commercial availability of suitable sources is limited, especially for high performance applications. Alter is developing a range of laser systems suitable for a variety of quantum applications, notably cold atom trapping and entangled photon sources for QKD, with a view to enabling these markets. Developments of this type present significant technical and logistical problems stemming from the scarcity of component supply and uncertainty in end user requirements. This talk presents some of the work we’ve been doing including challenges and potential solutions and outlines future plans and requirements.

kHz-level linewidth distributed feedback laser at 778.1, 780.24 and 795 nm emission wavelength for Rb quantum systems

Eugenio Di Gaetano[1], Brendan Keliehor[2], Kevin Gallacher[1], Paul Griffin[2], Marc Sorel[1,3], Erling Riis[2], and Douglas J. Paul[1]

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Short-wavelength GaAs/AlGaAs-based semiconductor lasers are of interest for emerging quantum technologies such cold atom systems. However, such technologies require high-power, stable single-mode, and narrow linewidth sources at specific target wavelengths, e.g. 780.24 nm for D2 87Rb transitions. Several material properties, such as propagation losses, self-heating, and far-field emission pattern, are critical for laser performance, including power output before damage, coupling efficiency into optical components, and linewidth, following the Schawlow-Townes formula. In our work, an aluminum-free active area is designed with InGaAsP quaternary compounds and sandwiched between AlGaAs cladding layers. The presence of an asymmetrical mode expander into both p- and n-doped AlGaAs cladding shapes mode profile to achieve a Gaussian-like emission pattern. The asymmetrical mode expander configuration reduces propagation losses, modal confinement within the active region, and decrease the vertical beam divergency. A long phase-shifted laterally-coupled DFB lasers are fabricated by reactive ion etching with weakly coupled grating to narrow the laser linewidth. The AR/HR laser devices exhibit single-mode emission at the wavelength of 778.1, 780.24, and 795 nm with a tunability above 0.5 nm, power output of 48 mW, SMSRs exceeding 35dB, and vertical beam divergence of 20.5°. Instantaneous Lorentzian linewidth, measured by homodyne technique with automated noise characterisation tool, proved to be below 10 kHz, achieving 3.67 kHz for 778.nm wavelength. The 778.1 nm laser is employed to probe the 87Rb two-photon transitions employing a heated Rb cell in retroreflection configuration. Using an acousto-optical modulator for frequency scan, the laser resolved hyperfine levels for the 87Rb two-photon transition.

Novel technique for measuring linewidth enhancement factor enabled by photonic integration

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The linewidth enhancement factor (LEF) is a key parameter to describe the relation between gain and phase changes, which is essential in describing the various noise effects in semiconductor optical amplifiers, saturable absorbers, and semiconductor lasers. Different techniques for measuring the LEF of a material have been developed, but they are indirect and/or only work for forward bias. We propose a new, simple method to directly measure the LEF for both forward and reverse bias, using photonic integration. Our method uses an on-chip asymmetric Mach Zehnder interferometer to measure gain and phase change as a function of bias in a short piece of semiconductor material. The LEF of the material is calculated from the ratio between the gain and phase change. By integrating the material and the interferometer on a photonic chip, we can achieve very short sections of the material (down to 12 µm) and have high phase stability in the interferometer, which are both necessary for this technique. Time domain traveling wave simulations show that we can measure a LEF set beforehand with the measurement method. We demonstrate the measurement method on saturable absorbers of lengths between 12 µm and 42 µm, fabricated in indium phosphide. The measured LEF is bias dependent and approaches -1.1 for lower bias voltages.

Implementation of an FPGA-based Laser Lock Box with High-Bandwidth and Auto-relocking features: Application to Sub-kHz External Cavity Diode Lasers

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Narrow linewidth lasers with high stability are a key enabling technology in high-impact applications such as quantum technologies. The stability of such lasers requires the design of high-performance control electronics. Digital PID controllers for high-end applications mainly require high regulation bandwidth; relock function, easy-to-tune parameters and long-term stability. Satisfying all these requirements when designing the PID controller is a challenging task, mainly due to the phase lag in the negative feedback loop. In order to tackle this design challenge, we relied on the one hand, on high resolution and sampling rate converters and on the other hand we implemented the pipeline technique in the design of our PID controller. In order to cope with relocking features and easy to adjust parameters, we relied on FPGA technology because of its flexibility, parallelism and real-time execution. As an efficient means of validating frequency stabilization, we combined our PID controller with a miniaturized diode laser with external resonator (VBG). Stabilization is performed on a high-Q reference cavity to achieve linewidth reduction in the sub-kHz range. The high frequencies of the PID controller have been used to adjust the laser current via an FET type transistor while the lower frequencies are available as options for more flexibility according to different system configurations. External disturbances were also applied in order to cause the unlocking of the system and to check the correct operation of the automatic relocking. The proposed controller is flexible and can be customized to any other system with similar high bandwidth requirements.

Room temperature low threshold nanobeam lasers using InGaAs/GaAs nanowires on silicon-on-insulator grown by MOCVD

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Nanowire lasers have shown many favourable properties such as very low lasing threshold, high energy efficiency, small footprints. The ability to grow the laser directly onto an SOI substrate along with its favourable properties make this an ideal integrated light source for use in silicon photonics applications. The small footprint and flexible cavity shape can bring advantages for dense integration of lasers, spectrometers, and sensors. Here, we present a bottom-up epitaxially grown InGaAs/SOI nanowire nanobeam laser. The MOCVD growth conditions have been optimized to reach the high yield required for nanobeam photonic crystal lasers. Using a GaAs/InGaAs core-shell structure we were able to grow high yield arrays. Under pulsed optical pumping, the nanowire arrays lase with a low threshold of 127 $\mu J/cm^2$. The nanowire arrays are arranged to form a photonic crystal cavity. This is the first realization of a curved nanobeam photonic crystal using a bottom-up method. Using simulations, we show that the curve of the cavity does not lower the Q-factor. Moreover, the shape of the cavity dictates the emission direction. This leads the way to arbitrary laser cavity shapes with variable emission direction.

Large-area semiconductor lasers for neural network computing

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High-performance computing hardware is crucial for advanced neural network (NN) computing schemes. Photonics promises strong advantages in terms of parallelism, yet until now scalable and integrable concepts are scarce and partially rely on exotic substrates. Here, we implement a fully parallel and autonomous photonic reservoir computer based on the spatially distributed modes of an efficient and fast large-area vertical-cavity surface-emitting laser (LA-VCSEL).
As photonic neuron substrate we use the complex multimode field of an injection locked LA-VCSEL of ~20 mm diameter emitting around 920 nm. Our LA-VCSEL was fabricated via standard commercial technology and follows a minimalistic design principle boosting its small-signal modulation bandwidths beyond 20 GHz. Noteworthy, all the photonic NN connections to- and from- the LA-VCSEL are implemented in hardware: the injected information is Boolean encoded on a digital micro-mirror device (DMD). Intra-cavity fields and carrier diffusion intrinsic to LA-VCSELs recurrently couple the >100 photonic neurons, and trainable readout weights are encoded on a second DMD and photo-detected to directly provide the computational result. We online train the readout weights to perform n-bit header recognition, XOR and digital-to-analog conversion tasks. We operate our recurrent photonic NN in its steady state with bandwidths of several 100s inferences per second, only limited by the communications with external hardware. Finally, we discuss the strategies to unleash the full potential of LA-VCSELs for NN computing, scaling towards deep networks in excess of 100 neurons per layer and to bandwidths in excess of 20 GHz.

VCSEL-Based Photonic Spiking Neural Network with Highly Efficient Training

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We report a high-speed (GHz-rate), low optical power (<150 µW), Photonic Spiking Neural Network (PSNN) built with a single Vertical Cavity Surface Emitting Laser (VCSEL) for complex non-linearly separable data classification tasks. The hardware-friendly VCSEL system uses time-multiplexing to realise a virtual spiking network, with a programmable number of nodes, using commercially-available optical telecom components. We demonstrate that this PSNN can solve a complex data classification task (MADELON), while only requiring the calculation of output layer weights for highly-reduced training requirements. Specifically, we demonstrate that using a single VCSEL the PSNN is able to perform with high accuracies (up to 94%), despite the high number of distractor features present in the dataset. With a flexible architecture that allows the node count to be selected at will, we are able to optimise the task for either accuracy or processing rate via the pre-allocation of ultrafast nodes (250ps per node, 0.5/1 µs per datapoint for 2048/4096 network nodes). Additionally, to further demonstrate the power of the VCSEL-based Photonic SNN, we demonstrate a new training algorithm that was developed to take full advantage of the sparsity of the optical spiking output of the system. This novel training algorithm, that scores the 'significance' of a node's contribution to a successful classification, is used to eliminate non-spiking nodes and deliver high accuracy performance with even more efficient training requirements.

Lowering the coherence of vertical-cavity surface-emitting lasers using chaotic cavity designs

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Vertical-cavity surface-emitting lasers (VCSELs) have been used widely adopted in many technologies because of their unique features enabled by their surface-emitting configuration. In particular, single-mode emission from VCSELs is desirable in many applications. However, despite the benefits of the high coherence, it also results in poor performance in applications that are affected by the presence of speckles due to the constructive and destructive interference between coherent photons as they scatter. These applications include display and projection applications, as well as illumination and imaging. For these applications, incoherent or partially coherent light sources are preferred. Random lasers, broadband lasers, and superluminescent diodes (SLDs) are examples of devices that offer better performance, but with edge emission. In addition, other applications, such as optical coherence tomography and random number generation utilize these partially coherent sources. Nevertheless, the edge-emission configuration makes the formation of 2D arrays of emitters challenging and impractical. We demonstrated designing the transverse shape of VCSEL cavities using chaotic-cavity designs and studied their effects on the optical power and the coherence of the emitted light, without resorting to increasing the area of the aperture, which would result in a lower speed and efficiency. The number of transverse modes is shown to double as compared to VCSELs with conventional circular cavities. Moreover, we tested their performance in high-speed optical communication and showed that they can still maintain high data rates. A net data rate of >12 Gb/s is more than double the record data rate achieved using partially coherent light sources (SLDs).

Towards TAMSELs: Tamm-Assisted Meta-Surface Emitting Lasers

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Tamm Optical States (TOS), sometimes known as Tamm plasmons, are formed by confining light between vertically between a metal, and the bandgap of a distributed Bragg reflector. These are highly attractive as candidates for confining light: highly manufacturable, as they can be formed simple by deposition of a metal layer on top of the semiconductor; momentum matching is not necessary to excite them, unlike surface plasmons; and most of the mode remains in the lossless medium. Tamm Optical States have attracted great interest recently as a route to making a highly manufacturable nanolasers.

In this talk, we discuss combining TOS with metasurfaces to form highly compact, efficient, tunable and manufacturable surface emitting lasers. We illustrate the concept, present designs and discuss the pitfalls and challenges that must be overcome to realise TAMSELs: Tamm-Assisted Meta-Surface Emitting Lasers. We examine two types of metasurface: photonic molecules and gratings. In the first, a photonic molecule approach can be used to create a photonic structure that operates on two distinct modes. When two nanocavities are physically close enough, their optical modes interact with each other to form hybridized supermodes. This is intriguing for dual-mode lasing. The second is a 1D grating, used to form a Bragg lens and to shape the far field emission pattern of the laser.

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High temperature operating InAs/GaAs quantum dot lasers with co-doping technique

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High performance III-V quantum dot (QD) laser is an ideal component to be used in the data and telecommunication silicon-based photonic integrated circuits, due to its superior device properties of low threshold current, high operating temperature, and high optical feedback and crystal defect tolerance. To further increase the QD laser performance, P-type modulation technique and N-type doping technique are developed recently for the laser active region, which aims to promote the model gain and the output power, respectively. However, these two techniques could also bring higher free carrier absorption and higher inhomogeneous for QDs. In this paper, a combined co-doping strategy of N-type and P-type doping is investigated on InAs/GaAs QD lasers, which is also compared with undoped, N-type doped and P-type doped QD laser. The co-doped fabricated broad-area 8-layer QD laser with 2 mm cavity length and 50 µm width showing a threshold current density as low as 71 A/cm^2 and operating temperature as high as 130 °C in continuous-wave mode. The highest operating temperature under pulsed mode has reached 195 °C without any roll-over, which indicates a very possible of >200 °C operation. The laser device is without any facet coating. The co-doped QD laser indicates a outstanding performance compared with other three lasers with N-type, P-type and no doping strategy. This results prove the feasibility of using co-doped QD laser applied in the cooling-free data transmission environment.

Beam Quality Improvement in Broad Area High Power 970 nm Diode Lasers by Modified Current Density Profile

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Despite improvement in conversion efficiency and temperature sensitivity, GaAs-based diode lasers remain limited in continuous wave power to around 25W from 100µm apertures [1]. Recent studies show that the local temperature differences arising in the stripe at high bias are a likely cause, with the resulting lateral carrier accumulation observed at the stripe edges near the front facet leading to carrier losses [2]. The same effects also lead to broadening of the lateral far field [3]. Using a varied lateral current profile to flatten the lateral temperature recently successfully increased power and reduced far field [4]. Therefore, we here modify also the longitudinal current density profile, seeking improved performance. Segmented p-contact diode lasers at 970 nm wavelength with n-side windows were used, from [2], with a 6mm resonator divided into 12 addressable segments, and 90µm aperture. Measurements were conducted in three modes: uniform voltage (u-V), uniform current density, J (u-J), and systematically reduced J towards the front (v-J). Total current was limited to 10A (rollover studies will follow). The front-to-back local electrical input power I.V in each segment varied strongly, from 1.33 (u-V) to 0.40 (v-J) at 8.1A and the local temperature difference along the resonator drops by 1.8x from 6.1 K (u-V) to 3.4K (v-J) (inferred from spontaneous emission wavelength, via the substrate). As a result, for the v-J case, 2x lowered carrier accumulation at the front stripe edges is observed, and lateral far field angle reduces by 0.6° at 8.1A. Further analysis will be discussed in the presentation.

[1] https://doi.org/10.23919/ISLC52947.2022.9943301
[2] https://doi.org/10.1063/5.0153210
[3] https://doi.org/10.1063/5.0149986
[4] https://doi.org/10.1117/12.2648355

Static and dynamic characterisation of 369 nm GaN Fabry-Perot laser diodes

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Integration of GaN laser diodes with passive platforms in the UV to visible region has the potential to significantly impact a variety of fields such as quantum communication, precision metrology, and sensing. Photonic integrated circuits are also predicted to improve the cost, size, and robustness of atomic clocks which would be dependent on reliable, narrow-linewidth lasers capable of accessing specific atomic transitions. The development of such a laser diode operating at 369.5 nm to access a cooling transition in 171Yb+ is of particular interest as it could form the basis of a microwave atomic clock. We present our recent work in development of Fabry-Perot GaN laser diodes operating at ~ 369 nm for atomic timing applications which is being carried out in parallel with producing an accompanying passive platform appropriate for integration. Our results include verification of emission at the target wavelength and CW mode operation. We also report preliminary dynamic characterisation of these devices which has allowed for calculation of properties such as intrinsic device bandwidth, parasitic capacitance, and modulation efficiency. Some of these parameters are the first to be reported at this wavelength and are compared to those reported for laser diodes operating above 400 nm.

Novel Photonic Filter Feedback Method for Time Delay Signature Suppression of Chaos Generated in Semiconductor Lasers

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Chaos has emerged as a versatile phenomenon with diverse applications spanning secure optical communication, random number generation, chaos radar and fibre fault detection. Semiconductor lasers, when subjected to optical feedback, have proven to be effective chaos sources, but the presence of Time Delay Signature (TDS) hampers their potential applications. Various techniques have been explored to mitigate TDS, yet a straightforward and efficient method remains elusive. In this work, a novel approach utilising photonic filter feedback to suppress the TDS is explored. A comparison between the TDS of chaos generated by conventional optical feedback and photonic filter feedback is conducted. Furthermore, the effect of the coupling ratio in the photonic filter feedback configuration on the TDS has also been investigated. Experimental results demonstrated that, for higher optical feedback strength, the TDS of chaos generated by photonic filter feedback can be significantly suppressed compared to that produced by conventional optical feedback. The TDS becomes indistinguishable under optimum parameter settings using photonics filter feedback. The new technique not only effectively suppresses TDS but also simplifies the complexity associated with existing approaches. The breakthrough achieved in this study holds great promise for advancing chaos-based technologies towards practical implementation. The demonstrated simplicity and efficacy of the proposed method open avenues for the miniaturization of chaos sources through photonic integration. This advancement could potentially revolutionise the landscape of secure optical communication systems, enhance the quality of random number generation and increase the accuracy of chaos radar and fibre fault detection.

Non-linear Dynamics from a Laser Diode with both Optical Feedback and Optical Injection

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Recent years have witnessed extensive research on the dynamics of semiconductor lasers under both optical injection (OI) and optical feedback (OF). OI gives rise to diverse dynamical states, including periodic oscillations, chaos, and stable locking, which have been valuable in generating microwave signals, improving laser stability, and enhancing bandwidth. OF can result in various modes of operation, such as laser linewidth reduction and high-dimensional chaos generation for secure chaotic communications. Recent laser configurations, particularly for neuro-inspired computing, have combined OF for the onset of self-pulsing dynamics with OI for the input data injection. Still, the combined impact of OI and OF on the laser nonlinear dynamics remains scarcely explored.

In our simulation-based study, we have conducted a detailed analysis of the dynamics of a single-mode laser diode under OI, considering the influence of OF. We use a Lang-Kobayashi model with typical numerical values for the laser parameters found in the literature. Time-traces and optical spectra of the laser reveal distinct timescales related to the delay. We found from detailed maps of the laser dynamics that the locking boundaries resulting from OI shift to larger negative detuning due to OF and exhibit a structured pattern as the feedback strength increases. Along these new bifurcation tongues, the laser exhibits abrupt dynamic changes. We will discuss the earlier asymptotic studies' limits on locking boundaries with OI and OF. Our work provides novel insight into earlier coarsely-resolve experiments on the topological characteristics (shape & position) of the injection-locking boundaries with OF.

Poster Presentations

Challenges for Room Temperature Operation of Electrically Pumped GeSn Lasers

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CMOS compatible lasers based on group-IV materials are highly desirable for sensing applications, enabling fully monolithic optoelectronic circuits to be produced on chip in a scalable manner [1]. Whilst group-IV materials have indirect bandgaps, alloying Ge with Sn can produce direct material, making it attractive for use as an emitter. Since the production of the first GeSn laser in 2015 [2], significant process has been achieved in optically pumped devices resulting in room temperature operation through the use of high tensile strain or high Sn compositions. However, since the advent of the first electrically pumped laser in 2020 [3], the maximum operational temperature of the electrically pumped devices has remained below 140K. Gaining insight into the carrier dynamics within these devices is crucial for pushing operation towards room temperature.

In this work, high hydrostatic pressure measurements at low temperature are used to ascertain the dominant recombination pathways in first generation bulk Ge0.89Sn0.11 lasers. It is found that leakage of carriers to indirect valleys in the active region and large defect densities play key roles in determining device performance. A theoretical bulk gain study is therefore conducted as a function of injected carrier density and temperature for a number of different Sn fractions to understand how this leakage of carriers can be mitigated, leading to recommendations for future device designs.

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III-V Semiconductor Light Emitters for Active Photonic Thermometry

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Photonic thermometry uses the thermally induced change in refractive index of semiconductors resonant structure such as ring resonator or photonic crystal cavity as a means of measuring temperature. There has been good progress in using a silicon/SOI waveguide system for photonic thermometry [1], but the indirect bandgap of silicon means it is unable to generate an efficient light emitter and requires an external light emitter to be coupled to the resonator. This introduces mechanical issues due to the optical fibre attachment. To overcome this problem, the use of III-V direct bandgap light sources on chip are proposed as an alternative approach towards active photonic thermometry. This study aims to embed the InGaAsP/InP quantum well heterostructures on chip as the internal light source for photonic thermometry. As a first step, spectroscopic ellipsometry measurements of the complex refractive indices of the III-V binary compound semiconductors making up the alloys of interests between 800 nm and 1800 nm and 298 K and 573 K have been undertaken. These are used as source parameters for finite differential time domain (FDTD) modelling of the resonators to demonstrate the potential of using the III-V semiconductors in photonic thermometry.

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Advancing Semiconductor Material Characterisation with Compressed Sensing Time-Resolved Photoluminescence Imaging

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Spatial characterisation techniques and imaging methods are essential for advancing semiconductor materials and devices, especially in semiconductor laser applications. Time-resolved photoluminescence (TRPL) imaging is a powerful tool for understanding charge carrier dynamics in semiconductor materials, applicable throughout the semiconductor processing stages. However, traditional TRPL imaging, which involves point-by-point scanning, limits measurement speed and signal quality. In this work, we introduce a transformative approach that combines TRPL imaging with compressed sensing theory, significantly improving spatial resolution, measurement speed, and signal sensitivity, benefiting semiconductor laser technologies. Our innovative imaging system employs compressed sensing via digital light processing (DLP) to simultaneously illuminate the entire semiconductor sample with patterns. This eliminates the constraints of traditional scanning methods, allowing for more rapid measurements. Measurement resolution becomes determined by the scale and resolution of the selected excitation patterns, rather than beam spot size and translational movements. Through a sparse reconstruction algorithm, we extract a data-cube representing photoluminescence intensity at different spatial and temporal coordinates. This data enables the creation of a minority charge carrier lifetime map, given an appropriate decay model. Numerical simulations demonstrate an improvement in measurement speed, approximately one order of magnitude faster than point-by-point scanning. Experimental results with our DLP system validate the feasibility of compressed sensing TRPL measurements. This innovative approach promises to improve the characterisation method of semiconductor materials, enabling faster laser development and improved laser performance.

Towards Thermally Stable Type-II "W"-Semiconductor Lasers for Telecoms Applications

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With data-intensive applications playing an increasingly integral role in day-to-day life, there is significant interest in developing more efficient and thermally stable near-infrared semiconductor lasers for use in data communications networks. While devices based on type-I (Al)GaInAsP alloys grown on InP have been a mainstay in telecommunications, these systems suffer from thermal instability of their threshold current density and lasing emission wavelength [1] and so must be actively cooled during operation. A promising alternative approach is to utilise type-II "W"-quantum well heterostructures, in which electrons and holes are spatially separated in the active region, which provides greater design flexibility through independent control of both the material and carrier wavefunction overlap properties [2]. We have previously explored the device characteristics and gain in low threshold MOVPE-grown "W"-lasers targeting the O-band. In this work, we explore the impact of electrostatic interactions on the design space optimisation of near-infrared type-II "W"-systems, highlighting the importance of accounting for many-body effects when modelling optical gain in type-II structures. We show how this approach can be used to optimise the design of temperature stable communications lasers.

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Advanced Characterisation Approaches for Optimisation of Semiconductor Lasers

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Semiconductor lasers play a crucial role in a broad variety of modern technologies and applications, including telecommunications and sensing. However, even current state-of-the-art systems suffer from limited efficiency and temperature stability increasing their cost and overall energy consumption. To overcome existing performance limitations and develop new types of devices, there are various areas of research activity including developing new III-V and group-IV semiconductor alloys and heterostructures as well as new device concepts (e.g. photonic structures, nanocavities, quantum dots, cascade structures, etc.). To develop and optimise new materials and devices, it is essential to provide feedback both in the design and modelling stage as well as during growth optimisation. To enable this, we describe a series of experimental approaches to investigate fundamental material properties and efficiency limiting mechanisms in devices. In this work, we present an overview of several experimental techniques for characterisation of the optical and electronic properties of semiconductor materials and devices.

At the initial stage of material development and device design, various optical spectroscopy techniques like cryogenic testing of photoluminescence and modulated reflection spectroscopy can effectively probe the band structure and material quality [1]. To manipulate and control material and device properties we developed high hydrostatic pressure testing facilities, which allows reversible tuning of optical and electronic properties (e.g. an LED emitting in red can be tuned by applying pressure to provide green emission at room temperature, to tune a laser across a whole band, e.g. the O- or C-bands, or to modify the properties of Quantum Cascade Lasers) [2]. For device optimisation, we fabricate and characterise prototype devices to investigate their performance by studying laser properties and optical gain at different temperatures and investigate the contribution of radiative and non-radiative mechanisms as a function of temperature and band gap. This helps to identify and quantify performance limiting mechanisms (e.g. defect related recombination, Auger, recombination, thermal carrier leakage or interband carrier scattering processes) [2, 3]. An in-depth understanding of the fundamental recombination mechanisms and their resulting impact on device characteristics is critical and consequently used at the next iteration of design and growth optimisation, as shall be discussed.

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Probabilistic Markov Chain Modelling of Photonic Crystal Surface Emitting Lasers and The Characterisation of Laser Parameters

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Photonic crystal surface emitting lasers (PCSELs) are expected to benefit a variety of application fields due to their impressive characteristics in single-mode power scaling, and in opportunities for beam steering. Research is increasing world-wide in both industry and academia, and commercial offerings are emerging. However, the characterization of PCSELs to deduce intrinsic laser parameters has not been widely discussed. In this paper we describe probabilistic Markov chain (PMC) modelling of various laser structures and describe how key device engineering parameters may be deduced. PMC modelling incorporates microscopic input parameters (the in-plane scattering coefficients and those related to radiative and parasitic internal loss) derived from either simulation or experiment [1]. The simulator then determines macroscopic device level PCSEL parameters such as in-plane optical power loss (allowing threshold gain and slope efficiency to be deduced) and the near-field profile. This can be performed for a range of shapes, aspect ratios, and sizes of photonic crystal (PC) structure. The PMC simulator will be described in detail, in particular, details of the convergence criteria are explained and agreement with data in the literature will be demonstrated. The effect of in-plane coupling coefficients, perimeter reflectors, un-pumped PC perimeter, PC shape, and PCSEL device size on in-plane loss will then be described in detail. We go on to discuss how the characterisation of PCSELs with different lateral extent (radius of circle, side of square) may be used to unlock details of the various loss parameters.

[1] K. Sakai, E. Miyai, and S. Noda, Appl. Phys. Lett. 89, 021101 (2006).

VIA VERITAS VITA

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