glasgow.ac.uk/ucet

eng-UCET@glasgow.ac.uk

UK-China Emerging Technologies Conference

UCET

2018 3rd UK-China Emerging Technologies (UCET) Conference

21st and 22nd August 2018
Room 375, James Watt South Building, University of Glasgow

Sponsored by the University of Glasgow, UK
University of Electronic Science and Technology of China
Institute of Semiconductors, Chinese Academy of Sciences
Nanjing University of Science and Technology (NUST)
Northwest University (NWU), China
Peking University, China

University of Glasgow

电子科技大学
University of Electronic Science and Technology of China

UCET 2018 conference Programme

Tuesday, 21 August 2018			
1	09:30	UCET-Glasgow welcome/Opening	Prof John Marsh (Dean of University of Glasgow, UESTC)
1.1	09:40	Plenary lecture	Plenary lecture: Prof Jonathan Cooper (Vice principal of University of Glasgow), **“Technologies for Medical Diagnostics and Precision Therapy”**
1.2	10:30	Lecture 1-3 Chair: Prof John Marsh	Tea/Coffee break
1.3	10:50		Lecturer 1: Prof Song Liang (Institute of Semiconductors, Chinese Academy of Sciences), **“Design and Fabrication of InP Based Long Wavelength Transistor Lasers”**
			Lecturer 2: Dr Martin Lavery (University of Glasgow),”**Sustainable Photonics for Bridging the Digital Divide”**
			Lecture 3: Dr Neil Martin (CST Global)
1.4	11:50	Lunch	Poster presentation
1.5	13.00	Lecture 4-9 Chair: Prof Muhammad Imran	Lecture 4: Prof David Cumming (University of Glasgow), **“Terahertz imaging using focal plane arrays”**
			Lecture 5: Prof Guangzhao Ran (Peking University), **“III-V/Si hybrid laser array with DBR on Si waveguide”**
			Lecture 6: Prof Dan Lu (Institute of semiconductors, Chinese academic of Sciences), **“Photonic microwave generation based on monolithically integrated multi-section semiconductor lasers”**
			Lecturer 7: Prof Nikolaj Gadegaard (University of Glasgow), “**Informed design for nanostructured biomaterials**”
			Lecture 8: Miss Hao Wang (Institute of Semiconductors, Chinese Academy of Sciences), **“Fabrication of 1.55-μm high power InGaAsP/InP ridge waveguide distributed feedback lasers”**
			Lecture 9: Prof Shangjian Zhang (University of Electronic Science and Technology of China), “**Self-calibrated Microwave Characterization of High-speed Optoelectronic Devices”**
1.6	15:00	Tea/coffee break	Tea/coffee break
1.7	15:30	Plenary lecture	Plenary lecture: Prof Miles Padgett (Vice principal of University of Glasgow) “**How many pixels does your camera have? Ours has only one!”**
1.8	16:20	Lecture 10-14 Chair: Dr Hadi Heidari	Lecture 10: Dr Zhiyao Zhang (University of Electronic Science and Technology of China), “**Photonic undersampling and its application in broadband microwave measurement”**
			Lecturer 11: Dr Daibing Zhou (Institute of Semiconductors, Chinese Academy of Sciences), **“High-speed directly modulated widely tunable two-section InGaAlAs DBR lasers”**
			Lecture 12: Dr Arthur Smith (University of Glasgow), “**An Introduction to the James Watt Nanofabrication Centre”**
			Lecture 13：Mr Yunlong Liu (Institute of Semiconductors, Chinese Academy of Sciences), “**Dual mode DBR laser integrated with high speed EAM for THz communications**”
			Lecture 14: Prof Ying Ding (Northwest University, China), **“High-power quantum dot tunable ultrafast laser source”**
1.9	18:00	Banquet	Chinese restaurant – Sichuan House

Wednesday, 22 August 2018			
2.1	09:30	Lecture 15- 20 Chair: Dr Keliang Zhou	Lecture 15: Dr Da Mu (Changchun University of Science & Technology), "**Contemporary Optical System Design"**
			Lecture 16: Prof Anthony Kelly (University of Glasgow), "**InGaN/GaN Laser Diodes and their Applications"**
2.2	10:10		Tea/Coffee break
2.3	10:40		Lecture 17: Prof Edward Wasige (University of Glasgow), **"Mm-wave/THz Multi-Gigabit Wireless Links"**
			Lecturer 18: Prof Richard Hogg (University of Glasgow), "**Photonic Crystal Surface Emitting Lasers"**
			Lecture 19: Prof Xuefeng Liu (Nanjing University of Science and Technology), **"In Situ Finger Prints of Photon Status Parameters in Limited Space Scattering for Biomacromolecule Imaging and Structural Characterization"**
			Lecture 20: Dr Rongguo Lu (University of Electronic Science and Technology of China), **"Graphene-assisted polarization-insensitive electro-absorption optical modulator"**
2.4	12:00	Lunch	Poster presentation
2.5	13:00	Lecture 21-23 Chair: Prof Marc Sorel	Lecture 21: Prof John Marsh (University of Glasgow), **"Terahertz Photonics – Opportunities for Photonic Integrated Circuits"**
			Lecture 22: Prof Marc Sorel (University of Glasgow), **"Integration technologies for complex photonic circuits"**
			Lecture 23: Prof Yong Ma (Chongqing University of Posts and Telecommunications), **"A Terahertz Metasurface Based on Electromagnetically Induced Transparency Effect and its applications on chemical sensing"**
2.6	14:00	Feedback and good Bye Prof Muhammad Imran	
2.7	14:30	Whisky tour	Auchentoshan Whisky distillery

Plenary lecture I

Technologies for Medical Diagnostics and Precision Therapy

Professor Jonathan M. Cooper
University of Glasgow
Tel:0141 330 4931, Email: Jon.Cooper@glasgow.ac.uk

ABSTRACT

The global challenges around provision of care within ever-increasing populations has put severe pressures on the delivery of health systems. For example, the increasing burden of infectious diseases, coupled with the threat of antimicrobial resistance makes the case for the need for faster and cheaper diagnostic sensors, that are able to deliver improved information "at the point of need". The ability to provide low cost sensors that can inform correct treatment to a patient, either in a clinic or in the field is now seen as critical to the delivery of healthcare. In this talk I will explore the use of low cost, disposable manufacturing methods in order to produce advanced medical sensors and show how these devices can be translated into clinical practice.

BIOGRAPHY

Professor Jon Cooper holds The Wolfson Chair in Biomedical Engineering and is Vice Principal leading the University's strategy in Knowledge Exchange and Innovation. He is an EPSRC Leadership Research Fellow and holds a European Research Council Advanced Programme Grant. His major research interests are in medical diagnostics and imaging, with a track record of spin-out and translation of devices into industry and practice.

In one example, he is working with colleagues in UCLA on combining ultrasonics with computational photonics to produce ultra-high resolution mobile microscopes for biological imaging, resolving objects at sub-micron resolutions on a phone camera (e.g. differentiating viruses and bacteria). In a second strand of his current work, rapid, zero-cost multiplexed "origami paper" diagnostics are being trialled in rural East Africa as species-specific DNA sensors to identify the cause of infectious disease and inform treatment amongst under-served rural communities. Further examples of translation of his research include bathroom diagnostics, sold as a bowel cancer test on the high street (e.g. Boots the Chemist), and a new venture-funded product for sexual health testing in the clinic. He was elected as a Fellow of the Royal Academy of Engineering (UK's national academy of engineering) as well as a Fellow of the Royal Society of Edinburgh (Scotland's national academy of arts, humanities and sciences). He has published over 260 papers, 18 books and book chapters and has an H-index of 48.

Plenary lecture II

How many pixels does your camera have? Ours has only one!

Professor Miles Padgett
Kelvin Chair of Natural Philosophy at the University of Glasgow
Email: Miles.Padgett@glasgow.ac.uk

ABSTRACT

Cameras are often marketed in terms of the number of pixels they have – the more pixels the "better" the camera. Rather than increasing the number of pixels we ask the question "how can a camera work when it only has a single pixel?" This talk will link the field of computational ghost imaging to that of single-pixel cameras explaining how components found within a standard data projector, more commonly used for projecting films and the like, can be used to create both still and video cameras using a single photodiode.

These single pixel approaches are particularly useful for imaging at wavelengths where detector arrays are either very expensive or even unobtainable. The ability to image at unusual wavelengths means that one can make cameras that can see through fog or smoke or even image invisible gases as they leak from pipes.

Beyond imaging at these unusual wavelengths, by using pulsed illumination and adding time resolution to the camera it is possible to see in 3D, perhaps useful for autonomous vehicles and other robotic applications.

A full colour image recorded using data from a single photo-diode

BIOGRAPHY

Miles Padgett, plenary speaker CLEO 2015

Miles Padgett holds the Kelvin Chair of Natural Philosophy at the University of Glasgow. He is interested in all things optical both classical and quantum. In 2001 he was elected a Fellow of the Royal Society of Edinburgh (RSE) and in 2014 a Fellow of the Royal Society, the UK's National Academy. In 2009, with Les Allen, he won the Institute of Physics Young Medal, in 2014 the RSE Kelvin Medal, in 2015 the Science of Light Prize from the European Physical Society and in 2017 the Max Born Award of the Optical Society (OSA).

He is lead scientist in QuantIC, a £30M investment and one of the UKs four Quantum Technology Hubs. QuantIC links over 100 world-leading quantum scientists/technologists from six UK Universities with global industry leaders to transform imaging across instrumentation, security and industrial sectors.

Lecture 1

Design and Fabrication of InP Based Long Wavelength Transistor Lasers

Professor Song Liang

Key Laboratory of Semiconductor Material Sciences, Institute of Semiconductors,
Chinese Academy of Sciences, P. O. Box 912, Beijing 100083, P. R. China
Tel: +86-10-82304121 Email: liangsong@semi.ac.cn

ABSTRACT

A transistor laser (TL) has the structure of a transistor, but having multi-quantum wells (MQWs) near its base region. From a TL, an electrical signal can be obtained simultaneously with a light signal by inputting one electrical signal. We design and fabricate deep ridge InP Based longwavelength transistor lasers. Because MQWs are inserted in between the emitter and the base in the structure, both the diffusion of p type dopant into the MQWs and the optical absorption of the p type base material can be reduced noticeably. CW operation up to 20 ^{o}C of 1.5-µm wavelength deep ridge npn-InGaAsP/InP MQW TL has been realized. The effects of doping in MQW active region on the properties of InP base TLs are studied numerically. It is found that the doped MOWs lead to a decrease of the slope efficiency and a notable increase of the current gain of the TLs. Further, we propose a novel design of TLs, which have an n-doped InP layer inserted in the emitter ridge. Numerical studies show that the common emitter current gain can be significantly enlarged.

BIOGRAPHY

Song Liang received the B.S. degree and the M.S. degree from the Department of Material Physics, Beijing University of Science and Technology, China, in 1999 and 2002, respectively, and the Ph. D degree from the Institute of Semiconductors, Chinese Academy of Sciences, Beijing, in 2006. He is currently working as a Professor at Institute of Semiconductor, Chinese Academy of Sciences. His current research includes the MOCVD growth of semiconductor materials and the fabrication of optoelectronics devices.

Lecture 2

Sustainable Photonics for Bridging the Digital Divide

Dr Martin P.J. Lavery

Rankine Building, University of Glasgow, UK.
Email: martin.lavery@glasgow.ac.uk

ABSTRACT

Sustainable photonic communication systems can resolve the global digital divide. Free-space optical (FSO) systems offer the ability to distribute high speed digital links into remote and rural communities where terrain, installation cost or infrastructure security pose critical hurdles to deployment. We will discuss the development of a low-cost FSO system prototype that could allow for out of the box self-aligning optical systems that require no specialist engineer for installation. Utilising off-the-shelf consumer electrical components and a bespoke alignment algorithm we demonstrate a spatially multiplexing link with a loss of 15 dB over a 200 m FSO channel.

BIOGRAPHY

Dr. Martin Lavery currently holds a Royal Academy of Engineering Research Fellowship, is an Senior Lecturer in the School of Engineering at the University of Glasgow (UoG) and leads the Structure Photonics Research Group. His research team at the UoG investigates fundamental developments in Physics, and applies them to industry inspired engineering challenges. In 2013, he completed his PhD in Physics under supervision of Prof. Miles J. Padgett FRS and subsequent secured an EPSRC Doctoral Prize Fellowship. In 2015, Dr. Lavery formed the Structured Photonics Research Group that has rapidly grown to include 2 PhD Students and 2 RAs, situated in two dedicated labs focusing on a broad range of research challenges including free-space and fibre optical communications, ultrasonics and solar power.

Lecture 3

Dr Neil Martin (CST Global)

Lecture 4

Terahertz imaging using focal plane arrays

Professor David Cumming
Head of School of Engineering and Chair of Electronic Systems, University of Glasgow
Email: David.Cumming.2@glasgow.ac.uk

ABSTRACT

We present the monolithic integration of two types of Terahertz (THz) focal plane arrays (FPAs) created in a standard 180 nm CMOS process. The imagers are composed of THz metamaterial (MM) absorbers, fabricated in the metal and dielectric layers of the CMOS process, coupled to a microbolometer, either vanadium oxide (VOx) or silicon pn diode. Both imagers are integrated with their readout electronics to form high-resolution 64 x 64 CMOS FPAs. The suitability of THz imagers for stand-off imaging of concealed objects was demonstrated in transmission and reflection mode by capturing images of metallic objects hidden in a manila envelope. A lensless holographic imaging system is also demonstrated with the potential to obtain THz images at video rates. The system is comprised of a gas laser and microbolometer FPA for high-speed reflection imaging of metallic objects.

BIOGRAPHY

David Cumming is the Professor of Electronic Systems at the University of Glasgow. He completed his B.Eng in EEE at Glasgow University in 1989 and his Ph.D. in microelectronics at Cambridge University in 1993. He subsequently worked as a VLSI design engineer with ST Microelectronics in Bristol, UK, and carried out post-doctoral research at Glasgow University. He was a lecturer at the University of Canterbury, NZ, and has been at Glasgow University since 1999 where he is now the Head of the School of Engineering. His research interests are focused on semiconductor devices and microsystems for sensing applications. He has published over 300 papers on sensor and photonic technologies, mainly with an emphasis on integration of technologies. He was a founder of medical diagnostics company Mode DX and his research on CMOS ion sensor arrays enabled the development of the Ion Torrent gene sequencing system. He has held 1851 and EPSRC research fellowships, a Chinese Academy of Science Distinguished Fellowship, a Royal Society Wolfson Merit Award, and is FIEEE, FRSE, FREng.

Lecture 5

III-V/Si hybrid laser array with DBR on Si waveguide

Professor Guangzhao Ran (冉广照)
State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, China
Email: rangz@pku.edu.cn

ABSTRACT

We report an eight-channel silicon evanescent laser array operating at continuous wave and room temperature conditions using selective-area metal bonding technique. The laser array is realized by evanescently coupling the optical gain of InGaAsP multi-quantum wells to the silicon waveguides of varying widths and patterned with distributed Bragg reflector (DBR) gratings. The lasers have emission peak wavelengths in a range of 1537 and 1543 nm with a wavelength spacing of about 1.0 nm. The thermal impedances ZT of these hybrid lasers are evidently lower than those DFB counterparts
OCIS Codes: (250.0250) Optoelectronics; (250.5300) Photonic integrated circuits; (250.5960) Semiconductor lasers.

BIOGRAPHY

Guangzhao Ran, Professor of School of Physics, Peking University. He received his PhD from Peking University in 2001. His interests cover semiconductor photonics, including silicon light sources, molecule semiconductor and so on. He has published about 100 scientific papers and gained the State Natural Science Award (the second prize).

*** Related paper to this lecture has been attached at the end of this booklet.**

Lecture 6

Photonic microwave generation based on monolithically integrated multi-section semiconductor lasers

Professor Dan Lu
Key Laboratory of Semiconductor Material Sciences, Institute of Semiconductors,
Chinese Academy of Sciences, P. O. Box 912, Beijing 100083, P. R. China
Email: ludan@semi.ac.cn

ABSTRACT

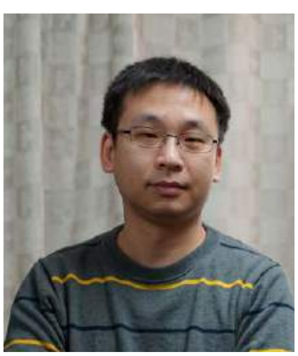
Photonic integration provides a new possibility to bring together many functional components into a single chip to deliver multipurpose optical or microwave carriers or signals. In this talk, we will present our recent work on photonic microwave generation using monolithically integrated multi-section semiconductor lasers, with emphasis on amplified feedback lasers (AFL). Rich dynamics including single mode, dual mode, period oscillation and chaos can be obtained by controlling the injection currents on the different sections of the AFL.

Using different cavity design, AFLs with dual-mode separation ranging from 6 GHz to 109 GHz are manufactured. Frequency tunable photonic microwave covering C, X, Ku, K, Ka, U, V and W microwave bands have been demonstrated. High-quality microwave signals tunable from 28 GHz to 41 GHz with phase noise below -106 dBc/Hz @10kHz offset from the carrier are demonstrated. The frequency tunable feature of the AFLs can also be used to generate linearly chirped microwave. By applying a sweeping signal to the AFL, a linearly chirped microwave waveform with a pulse duration of 1 μs, a bandwidth of 3.3 GHz (ranging from 31.5 to 34.8 GHz) are realized.

In the chaos state, the optical spectrum and the heterodyning microwave spectrum are considerably broadened and flattened, enabling a chaos output covering a frequency range over 40 GHz, with a standard bandwidth over 16 GHz and flatness of 13 dB. With an external delayed feedback loop and proper choice of the route into chaos, chaos signal with frequency range extended to over 50 GH, standard bandwidth over 32 GHz, flatness better than 6.3 dB is demonstrated.

The AFL's applications in high-speed all-optical clock recovery, high-resolution correlation optical time-domain reflectometry, and ultra-fast physical random number generation are also discussed.

BIOGRAPHY



Dan Lu received the B.A. degree from the Beijing University of Aeronautics and Astronautics, Beijing, China in 2000, the M.Sc. degree in optics from Sichuan University, Sichuan, China in 2004, and the Ph.D. degree in electrical engineering from the Beijing University of Posts and Telecommunications, Beijing, China in 2009. From 2009 to 2011, he was a postdoctoral research fellow with the Department of Electrical Engineering, Tsinghua University, Beijing, China, with research focus on high-speed fiber optical systems and devices. In 2011, he joined the Institute of Semiconductor, Chinese Academy of Sciences, where he is currently a Full professor at the Key Laboratory of Semiconductor Materials Science. His current research interests include the development and application of semiconductor lasers, photonic integrated circuits, and microwave photonics. Dr. Lu is a member of the IEEE Photonics Society, and the SPIE Society.

Lecturer 7

Informed design for nanostructured biomaterials

Professor Nikolaj Gadegaard
University of Glasgow
Email: Nikolaj.Gadegaard@glasgow.ac.uk

ABSTRACT

Our expectations to well-being and healthcare is ever increasing. This puts a continuous demand on new or smarter materials used in health and medical applications. Although new materials are constantly developed, "re-engineering" of existing materials is an attractive solution as the approval process is faster. In this talk we will discuss how modern engineering methods can be applied to firstly understand the biological requirements for a given biomedical application, and secondly how we can specifically engineer existing materials to meet those needs. Our approach has been the use of nanoscale fabrication to elicit the required biological responses such as cell type selection or stem cell differentiation. We use semiconductor techniques such as electron beam lithography and reactive ion etching to design specific and precise nanoscale structures. The advantage behind this approach is the ability to specifically design at a length scale comparable to the building blocks of life: cells and proteins. To date most discoveries are serendipitous and designs are often guesstimates which is a slow and unpredictable route of discovery of new materials. Thus our current approach is to develop a framework which will identify the blueprint required for new biomaterials with specific functionalities. To that length we have developed a range a libraries of nanopatterned materials and are using high content imaging to quantify the interaction of cells with these libraries. These results are then used to develop a computational model which allows us to predict the biological response of new materials.

BIOGRAPHY

Nikolaj Gadegaard has a broad educational background from the University of Copenhagen where he graduated with a dual degree in Physics and Chemistry in 1998. His PhD in Biophysics was carried out at Risø national laboratory in Denmark where he developed methods for injection moulding of nanostructures for biological applications. After completion of his PhD in 2002 he moved to Glasgow to take up a post doc position at the Centre for Cell Engineering and in 2003 was awarded a Royal Society of Edinburgh personal fellowship. In 2006 he was appointed lecturer in Bioelectronics at University of Glasgow and promoted to professor of Biomedical Engineering in 2014. Gadegaard currently holds an ERC Consolidator Award (2015-2020) and is co-PI on a Centre for Excellence at Oslo University (2018-2027). He has published more than 150 papers in journals such as Nature (and its sister journals), Advanced Materials, Nano Letters and ACS Nano and have amassed more than 10.000 citations for his work.

Lecture 8

Fabrication of 1.55-µm high power InGaAsP/InP ridge waveguide distributed feedback lasers

Miss Hao Wang
Key Laboratory of Semiconductor Material Sciences, Institute of Semiconductors,
Chinese Academy of Sciences, P. O. Box 912, Beijing 100083, P. R. China
Email: haowang@semi.ac.cn

ABSTRACT

The design and fabrication of high power InGaAsP/InP quantum-well lasers which have single lateral mode double trench ridge waveguide structures are studied. The influence of an effective lateral refractive index step on the maximum output power are investigated. The lasers have asymmetrical optical confinement layers to obtain a high output optical power at 1.55 µm emission wavelength. With the optimized thicknesses of the optical confinement layers and coupling coefficient κ of the DFB gratings, single mode CW output power of 275 mW can be obtained for a 1.5-mm-long ridge waveguide device at an injection current of 1 A, with a slop efficiency of 0.38 W/A.

BIOGRAPHY

Hao WANG received the B. E. degree from the department of Electronic Information Engineering, Xi'an University of Posts and Telecommunications, China, in 2010, the M. E. degree from the University of Chinese Academy of Sciences, in 2013. She was awarded the National Scholarship in 2012. She is currently working as an assistant Professor at Institute of Semiconductor, Chinese Academy of Sciences. Her current research interests include high-speed DFB lasers based on InP , high power DFB lasers based on both GaAs and InP.

Lecture 9

Self-calibrated Microwave Characterization of High-speed Optoelectronic Devices

Prof. Shangjian Zhang
School of Optoelectronic Science and Engineering
University of Electronic Science and Technology of China
Email: sjzhang@uestc.edu.cn

ABSTRACT

We discuss a self-calibrated method for independent frequency response measurement for discrete optical modulators and photodetectors based on frequency-shifted heterodyne. We also show on-wafer probing-kit for RF characterization of silicon photonic integrated transceivers based on heterodyne mixing.

BIOGRAPHY

Shangjian Zhang received his Phd from Institute of Semiconductors, Chinese Academy of Sciences. Now he is with School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China (UESTC), Chengdu, China, as a Full Professor. He was ever with City University of Hong Kong, Eindhoven University of Technology (TU/e), the Netherlands, University of Electro-Communications (UEC), Tokyo, Japan, and University of California, Santa Barbara (UCSB), as a visiting scientist.

Research interests: High-speed microwave photonic devices and ultrafast optical signal processing

Lecture 10

Photonic undersampling and its application in broadband microwave measurement

Dr. Zhiyao Zhang
School of Optoelectronic Science and Engineering
University of Electronic Science and Technology of China, Chengdu, 610054, P. R. China
Email: zhangzhiyao@uestc.edu.cn

ABSTRACT

Photonic undersampling is a techinique that can directly transfer a high-frequency microwave signal to a low-frequency replica in the first Nyquist zone, thanks to the large bandwidth of the electro-optic modulator and the passively mode-locked laser. In this talk, I will present two application examples of photonic undersampling in microwave measurement. The first one is about broadband high-resolution microwave frequency measurement based on low-speed photonic sampling. The second one is about calibration-free microwave characterization measurement of broadband Mach-Zehnder electro-optic modulator employing low-speed photonic sampling and low-frequency detection.

BIOGRAPHY

Dr. Zhiyao Zhang received his PhD degree in Optical Engineering from University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2010. He was a visiting scholar in University of Ottawa in 2017. He is now an associate professor in UESTC.

Research interests: Microwave photonics; Nonlinear optics

Lecturer 11

High-speed directly modulated widely tunable two-section InGaAlAs DBR lasers

Daibing Zhou, Song Liang, Lingjuan Zhao and Wei Wang
Key Laboratory of Semiconductor Material Sciences, Institute of Semiconductors,
Chinese Academy of Sciences, P. O. Box 912, Beijing 100083, P. R. China
Email: dbzhou@semi.ac.cn

ABSTRACT

Widely tunable two-section distributed Bragg reflector (DBR) lasers, which have InGaAlAs multiple quantum wells (MQWs) as the gain material, have been fabricated. By butt-jointing InGaAsP, which has a photoluminescence wavelength of 1.4 μm as the material of the DBR section, a wavelength tuning range of 12 nm can be obtained by current injection into the DBR section. The direct modulation bandwidth of the lasers is greater than 10 GHz over the entire wavelength tuning range up to 40 ^{o}C. Compared with InGaAsP DBR lasers having the same structure, the InGaAlAs lasers have smaller variations in both the threshold current and slope efficiency with the temperature because of the better electron confinement in the InGaAlAs MQWs. Moreover, the DBR-current-induced decreases in the modulation bandwidth and side mode suppression ratio (SMSR) of the optical spectra are notably smaller for the InGaAlAs lasers than for the InGaAsP lasers. 10 Gb/s data transmissions are performed at up to 15-km distance and different wavelength emissions.

BIOGRAPHY

Daibing Zhou received the B. E. degree from the department of Electrical Engineering, Zheng Zhou University, China, in 2002, the M. E. degree from the department of Optical Engineering, Beijing Institute of Technology, in 2005, and the Ph. D degree from the Institute of Semiconductors, Chinese Academy of Sciences, in 2016. He is currently working as an assistant Professor at Institute of Semiconductor, Chinese Academy of Sciences. His current research includes the fabrication of InP based widely tunbale DBR lasers and electro absorption modulated DFB lasers (EMLs).

Lecturer 12

An Introduction to the James Watt Nanofabrication Centre

Dr. Arthur Smith
JWNC, James Watt (South), The University of Glasgow, Glasgow, G12 8QQ, Scotland
Email: Arthur.smith@glasgow.ac.uk

BIOGRAPHY

Arthur Smith is currently a Director at the University of Glasgow's James Watt Nanofabrication Centre where he has responsibility for the operation of the facility. Dr. Smith has over 30 years of professional experience in the areas of semiconductor technologies and telecom/data networking equipment. Prior to joining the University of Glasgow in 2015, Dr. Smith held a number of senior executive roles in the telecom/data networking industry – as Chief Executive Officer of Intune Networks (Ireland) and previously as Chief Operating Officer of Ciena (USA) where he spent 13 years helping to grow the company from a start-up to a publicly traded company with more than $1bn in revenue. Earlier in his career, Dr. Smith was employed for a number of years with Bell Northern Research (Canada and England) as a research engineer in optoelectronic device fabrication and device reliability assessment. Dr. Smith holds both a B.Sc. in Electrical Engineering and a Ph.D. from the University of Glasgow, Scotland.

Lecture 13

Dual mode DBR laser integrated with high speed EAM for THz communications

Yunlong Liu and Song Liang
Key Laboratory of Semiconductor Material Sciences, Institute of Semiconductors,
Chinese Academy of Sciences, P. O. Box 912, Beijing 100083, P. R. China
Email: liuyl@semi.ac.cn

ABSTRACT

We have fabricated distributed Bragg reflector (DBR) lasers which have one DBR grating section on each side of the gain section. Dual mode emissions have been achieved from the device because of the presence of the two gratings. By varying the inject current of one of the DBR sections, different mode separations ranging from 100 GHz to over 400 GHz can be obtained. An electro absorption modulator (EAM) is integrated with the dual mode DBR laser monolithically by using selective area growth (SAG) technique. The EAM has an over 20 dB static extinction ratio at - 5 V reverse bias. The 3 dB small signal modulation bandwith of the EAM is over 10 GHz. At 10 Gb/s data modulation, clearly opened eyediagrams can be obtained with over 8 dB dynamic extinction ratio. A semiconductor optical amplifier (SOA) is also integrated and can be used to equalize the intensity between the two modes besides enhancing the output power. The integrated dual mode DBR laser is a promising light source for THz communication system, in which a photomixer is used to convert the light emission to THz waves.

BIOGRAPHY

Yunlong Liu received the B. S. degree from the department of physic, Huazhong University of science and technology, China, in 2015. He is now working toward his Ph. D degree in the Institute of Semiconductors, CAS. He is currently focusing on the fabrication of InP based electro absorption modulated widely tunbale DBR lasers for WDM-PON applications.

Lecture 14

High-power quantum dot tunable ultrafast laser source

Professor Ying Ding
Institute of Photonics & Photonic Technology, Northwest University,
Xi'an, 710069, China
Email: yingding@nwu.edu.cn

ABSTRACT

High-power all-semiconductor ultrafast master-oscillator-power-amplifier (MOPA) systems with wavelength and repetition rate tunability are one of the key elements for the development of cutting-edge biomedical imaging applications for replacing the classic but expensive and bulky ultrashort pulsed Ti: sapphire (Ti:s) laser source. Ultrafast semiconductor lasers operating with widely tunable wavelengths and repetition rates, together with high-power semiconductor optical amplifiers (SOAs), are of great interest for different nonlinear microscopy (NLM) applications. Quantum dot (QD) materials offer a broad gain bandwidth, high saturable output power and ultrafast recovery time of the absorber making them ideal candidates for the generation of ultrashort pulses. In this talk, a high-peak-power all-QD MOPA system and repetition rate tunability will be presented. Our recent progress on optimization of high-quality QD growth will also be introduced.

BIOGRAPHY

Dr. Ying Ding is Professor with Institute of Photonics & Photonic Tech., Northwest University and Chief Scientist of Hike Information Technology (Shanghai) Co., Ltd. He has over eighteen years' experience in photonic microchip design, materials epitaxial growth, device fabrication, characterization and nano-photonic study. He was awarded the Ph.D. degree from the Institute of Semiconductors, Chinese Academy of Sciences. He and his colleagues in Japan were the first to present microcavity modes and sub-wavelength waveguides and optical coupling in InP nanowires in the world. He and his partners in Europe are the world-record holders for the highest peak power, the broadest wavelength tunability as well as the narrowest RF linewidth to be achieved from chip-size quantum dot mode-locking ultrafast lasers at the 1.3-μm waveband.

Research interests: Quantum dot lasers; Ultrafast optics; Integrated optics; Mid-infrared photonic devices.

Lecture 15

Contemporary Optical System Design

Dr Da Mu
School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK
School of Opto-electronic Engineering, Changchun University of Science and Technology, China

Email: Da.Mu@glasgow.ac.uk

ABSTRACT

"Optical design" is an ancient and dynamic subject; the development of contemporary optical system design tends to be miniaturized, multi-band, and co-aperture. In this talk, I will present that some typical contemporary optical system design: infrared optical system design, ultraviolet optical system design, THz optical system design etc.

BIOGRAPHY

Dr. Da Mu received her doctor degree from Changchun Institute Optics Fine Mechanics and Physics, Chinese Academy of Science in 2007. She is an associate professor teaching in School of Opto-electronic Engineering, Changchun University of Science and Technology. Now she is visiting to School of Engineering, University of Glasgow as an honorary research fellow from March 2018 to March 2019.

Research interests: Optical Design; Optical test; THz transmission enhancement; THz signal test

Lecture 16

InGaN/GaN Laser Diodes and their Applications

Professor Anthony Kelly
University of Glasgow
Email: Anthony.kelly@glasgow.ac.uk

ABSTRACT

Gallium nitride (GaN) laser diodes are becoming popular sources not only for lighting but for applications ranging from communications to quantum. This paper presents the use of a commercial, off-the-shelf laser diode, with an emission wavelength of 450 nm, for visible light communication, both in free space and for underwater scenarios. Data rates up to 15 Gbit/s have been achieved by making use of orthogonal frequency division multiplexing (OFDM). In addition, distributed feedback (DFB) lasers have been realised emitting at a single wavelength which lend themselves towards applications where high spectral purity is crucial such as atomic clocks or filtered free space transmission systems. Etched sidewall 3rd and higher order gratings have resulted in successful single frequency operation. This talk will discuss current device performance and applications.

BIOGRAPHY

Anthony E Kelly (male) has spent over 20 years in industry and academia. He spent 7 years at BT Laboratories and Corning and co-founded Kamelian Ltd and Amphotonix Ltd, raising more than $30M in venture finance in the process. He joined the University of Glasgow in 2004. He has published over 200 journal and conference papers on a range of optoelectronic devices and systems and holds a number of patents. His current research is concerned with SOA and related technologies in passive optical networks, 25Gbit/s devices for 100G Ethernet, and GaN laser diodes and LEDs. His current funding is associated with high speed optoelectronic wireless interfaces, GaN lasers for Quantum Cooling, and advanced InP etching for laser manufacturing.

Lecture 17

Mm-wave/THz Multi-Gigabit Wireless Links

Prof Edward Wasige
University of Glasgow
Email: Edward.Wasige@glasgow.ac.uk

ABSTRACT

The demand for broadband content and services worldwide is growing at a tremendous pace. Soon, traffic from wireless devices will exceed that of wired setups. Currently, high-resolution videos account for about 69 % of all data viewed on mobile devices and are expected to reach 79 % by 2020. At this pace, short-range wireless communication will soon require data transfer speeds of tens of gigabits per second (Gbps), which current wireless technology cannot support. A host of technologies are being actively researched to meet this challenge. In this talk, we will describe our research on the resonant tunnelling diode (RTD) technology to create ultra-broadband wireless communications. RTDs are compact, high-speed semiconductor devices that can function as transmitters and receivers. They can be modulated using electronic or optical signals and can also be used to modulate lasers. This makes them potentially valuable as a link between fibre and wireless domains. We will report on short range wireless links with data rates of over 10 Gbps using new RTD transmitters developed for the 100 GHz and 300 GHz regions of the radio spectrum. These speeds are over 1 000 times faster than the rates available at the moment.

BIOGRAPHY

Edward Wasige is a Professor and leads the High Frequency Electronics Group, School of Engineering, University of Glasgow. Prior to joining the University of Glasgow in 2002, he held a UNESCO postdoctoral fellowship at The Technion (Israel Institute of Technology) where he worked on compound semiconductor electronics. His current research covers gallium nitride (GaN) device technologies for power electronics and for microwave electronics, and indium phosphide (InP) based device and integrated circuit (IC) technologies for microwave, millimetre-wave (mm-wave) and terahertz (THz) electronics. He leads a number of projects on these topics with funding by the European Commission under the Horizon 2020 Programme and by the Engineering and Physical Sciences Research Council (EPSRC).

Lecturer 18

Photonic Crystal Surface Emitting Lasers

Professor Richard Hogg
University of Glasgow
Email: Richard.hogg@gla.ac.uk

ABSTRACT

Photonic crystal surface emitting lasers (PCSELs) have recently become a commercial offering, due to their ability to deliver high power, single frequency, with almost perfect collimated beams. I will briefly discuss the operating principles, and the state-of-the-art. I will outline: our development of epitaxially re-grown all-semiconductor PCSELs; the realization of coherently coupled 2D PCSEL arrays; and the effect of external in-plane feedback. I will then describe new simulation methods for such devices, and outline possible future opportunities for this new type of semiconductor laser.

BIOGRAPHY

Richard A. Hogg received the Ph.D. degree in 1995 from the Department of Physics and Astronomy, The University of Sheffield, Sheffield, U.K., and then spent two years as a postdoctoral researcher at NTT Basic Research Laboratories in Atsugi, Japan. He was then awarded an EU-Japan fellowship as a visiting researcher in Professor Arakawa's Laboratory at the University of Tokyo, Tokyo, Japan. He subsequently spent three years at Toshiba Research Europe's Cambridge Laboratory, before moving to Agilent Technologies Fibre-Optic Component Operation in Ipswich, U.K., in 2000. In 2003 he joined the Electronic and Electrical Engineering Department, The University of Sheffield, Sheffield, U.K. Since 2015 he has been a Professor of Electronic and Nanoscale Engineering at the University of Glasgow, Glasgow, U.K.

Research interests: His research group is active in developing the understanding of device physics and engineering, epitaxial processes, fabrication technologies and applications of various semiconductor light sources such as lasers, amplifiers, superluminescent diodes, and resonant tunneling diodes.

Lecturer 19

In Situ Finger Prints of Photon Status Parameters in Limited Space Scattering for Biomacromolecule Imaging and Structural Characterization

Prof. Xuefeng Liu
Research Institute of Nano-Resolution Optics, School of Electronic and Optical Engineering
Nanjing University of Science and Technology
Email: liuxf1956@163.com

ABSTRACT

Biomacromolecules play significant roles in cells in tissues. In order to observe the structural characteristics at molecular level with the morphological context of tissues, new methods must be explored which can achieve an additional level of information, such as spatially resolution. We apply previously reported method, namely, Parametric Indirect Microscopic Imaging (PIMI) to fulfill this task, and extending it to the level of biomacromolecule structure analysis, including in situ RNA sequencing using limited space scattering. We however limit our discussion in this paper in the fundamental properties of a wave preclude it from being localized to subwavelength distances. In this report, we propose a polarization modulation method that employs a reconstruction method to map the subwavelength scattering field distributions in the form of polarization parameters. The spatial signature of these indirect parameters delivered an extra scattering information that helps us to resolve scattering modes information such as an amplicon from the cDNA originated in the RNA reverse transcription. We apply this method to single fluorophore and multiple of them in amplicon particles, and we successfully resolve their scattering spatial distribution. In particular, we explore the use of subwavelength scattering modes information provided by the spatial signature of these polarization parameters to intensify the measurement signals and increase the SNR of RNA in situ sequencing. The scattering finger print method for biomacromolecule structure characterization has also been parallelly verified by in vitro single molecule particle scattering experiments and also by Mie theory and finite difference time domain (FDTD) simulation method.

BIOGRAPHY

Xuefeng Liu, Member of National 1000 Talents Recruitment Plan, CAS 100 Talent Recruitment Plan, Director of Research Institute of Nano-Resolution Optics (RINRO), Chair in Nano Photonic Science and Technologies, Full Professor in School of Electronic and Optical Engineering, Nanjing University of Science and Technology (NUJST). Research Field: Photon and Optical Wave Parameters Indirect Imaging (PIMI), Optical Super Resolution Technologies and Systems.

Xuefeng Liu, PhD in the University of Sheffield, in Optical Materials and Instrumentation, had taken various senior technical roles in world renown research and development centers including professorship engineer in the modern lithographic system development center in ASML, department head and consulting member in nano-scale optical measurement system engineering in Oxford Cryosystems and the UK division of Nanometrics Inc. and a Core Member and product owner in telecom components and system development company Bookham Technology (renamed Oclaro). Out from his long working titles and holding position lists, *Xuefeng Liu has built more than 15 significant optical systems including Me*triPol, Anisoscope, Pupmas, Polmas and PupILIAS and so on for wanefront, wavevectors and polarization parametric indirect microscopic imaging (PIMI), a new super resolution research field generated by him and his team. In addition, Xuefeng Liu has made more than 60 journal publications and more than 15 innovation patents.

Research interests: super resolution optical theories and system engineering.

Lecture 20

Graphene-assisted polarization-insensitive electro-absorption optical modulator

Dr. Rongguo Lu
School of Optoelectronic Science and Engineering
University of Electronic Science and Technology of China, Chengdu, 610054, China
Email: lurongguo@uestc.edu.cn

ABSTRACT

The conventional modulator is always polarization-sensitive, which results in very large polarization-sensitive loss. In this talk, I will present a broadband polarization independent graphene-based electro-absorption optical modulator.

BIOGRAPHY

Dr. Rongguo Lu received his M.Sc. and Ph.D. degree in optical engineering in 2006 and 2009, respectively, both from University of Electronic Science and Technology of China, Chengdu, China.

Research interests: integrated optics and microwave photonics.

Lecture 21

Terahertz Photonics – Opportunities for Photonic Integrated Circuits

Professor John H. Marsh and Dr Lianping Hou
School of Engineering, James Watt South Building, University of Glasgow, Glasgow, G12 8QQ, UK.
Email: john.marsh@glasgow.ac.uk

ABSTRACT

Many applications of THz radiation require sources that are compact, low-cost, and operate at room temperature.

In this paper we will describe three optoelectronic sources of THz radiation:

- A dual mode DFB semiconductor laser;
- A mode-locked semiconductor laser using a DBR grating; and
- A PIC that use mode-beating of light from separate integrated lasers.

Looking to the future, we are now working on a novel 'system on a chip', integrating a thin film antenna array, photodiode array, semiconductor optical amplifier (SOA) array and optical beam forming network. The advantages of this THz emitter system include a high peak intensity due to radiation from the antennas combining coherently, room temperature operation, continuous-wave operation, compact form factor, and a narrow steerable beam.

BIOGRAPHY

John Marsh is Professor of Optoelectronic Systems at the University of Glasgow, and Dean of University of Glasgow, UESTC. His experience of semiconductor laser technology and integrated optics ranges from epitaxial growth through to the design and development of integrated laser modules for applications including advanced printing and imaging. His research covers fundamental electrical and optical properties of semiconductors, development of novel optoelectronic devices, processes for creating photonic integrated circuits, integrated mode-locked lasers for ultra-short pulse generation, and development and manufacturing of high-power laser array products.

A graduate of the universities of Cambridge (BA), Liverpool (MEng) and Sheffield (PhD), Professor Marsh is a Fellow of the Royal Academy of Engineering, Royal Society of Edinburgh, IEEE, OSA, IET, Institute of Physics and Royal Society of Arts. He was awarded the 2006 IEEE/LEOS Engineering Achievement Award with Catrina Bryce '*for extensive development and commercialization of quantum well intermixing for photonic devices*', as well as the 2006 LEOS Distinguished Service Award. He was the elected President of the IEEE Photonics Society in 2008 and 2009. He co-founded Intense Ltd in 2000 to exploit his research in high power lasers; the company was sold in 2011 and continues to operate from a base in New Jersey. He is the Glasgow PI of the EPSRC Centre for Doctoral Training in Photonic Integration and Advanced Data Storage, a £8M collaboration with Queen's University, Belfast. He is a Visiting Professor at Queen's University Belfast and at Northwest University, Xi'an, China, and is the Chief Foreign Master of a Project 111 Programme on 'Advanced Optoelectronic Imaging Theory and Technology Base' at Nanjing University of Science and Technology. He was a recipient of the Chengdu Jinsha Friendship Award in 2017.

Research interests:

Semiconductor lasers, Terahertz photonics, Photonic Integrated Circuits (PICs), Novel imaging systems, High power semiconductor laser.

Lecture 22

Integration technologies for complex photonic circuits

Prof Marc Sorel (University of Glasgow)
Email: Marc.sorel@glasgow.ac.uk

ABSTRACT

Integrated photonics is currently regarded as one of the most promising solutions for the development of complex circuits, thanks to its unique potential for integration, volume production, energy efficiency and scalability. In the last few years, the establishment of generic and accessible foundry models has propelled a phenomenal growth in silicon photonic research activities, with the demonstration of several circuits with unprecedented level of functionality. However, such increase in chip complexity can only be sustained with a shift from today's "device" level to a full "system-on-a-chip" that will require the development of adequate tools to reliably control the manufacture and operation of the circuits, as well as approaches for efficient chip integration. In this talk, we will discuss recent progress in post-fabrication trimming through local laser annealing and robust integration of non-linear waveguides and III-V devices on silicon chips.

BIOGRAPHY

Marc Sorel (MS) received a laurea degree cum laude in Electrical and Electronics Engineering and a Ph.D. degree in Electronics and Computer Science from Università di Pavia in 1995 and 1999, respectively. He joined the Optoelectronics Research Group at the University of Glasgow in 1998 with a Rotary Foundation fellowship and was awarded a personal Marie-Curie fellowship in 1999. He was appointed Lecturer in 2002, Senior Lecturer in 2008 and Professor in 2015. MS has been active in research related to integrated photonic devices and optoelectronics for over 20 years, supported by several funding bodies such as EU, EPSRC, Royal Society, DSTL and Innovate UK. His main research interests include silicon photonics, III-V semiconductor lasers, photonic integration and midIR LEDs for sensing. MS has also been involved through several Knowledge Transfer initiatives in the exploitation of mid-infrared sensing technologies. He has authored or co-authored more than 150 papers in peer-reviewed journals including in Science, Physical Review Letters, Optica and Nature Communications and has made numerous presentations at major international conferences.

Lecture 23

A Terahertz Metasurface Based on Electromagnetically Induced Transparency Effect and its applications on chemical sensing

Wu Pan, Yanjun Yan, Dajun Shen, Yong Ma*
School of Optoelectronic Engineering, Chongqing University of Posts and Telecommunications, Chongqing, 400065, P.R.China
* Corresponding author: mayong@cqupt.edu.cn

Recently, metasurfaces based on Electromagnetically induced transparency (EIT) effect has been widely studied over a wide spectral range [1-4]. They also have attracted an increasing attention in many aspects, such as modulators, low-loss slow-light devices and chemical/biological sensors. The advantages of using EIT is due to its intrinsic properties: destructive interference between the bright and dark mode resonances leading to extremely narrowband transparency window over a wide absorption spectrum.

Several types of EIT based metasurfaces have been reported. Driscoll et al. [1] reported a SRRs metasurface which consists of resonances sensitive to the dielectric properties of the surrounding environment. However its sensitivity is quite limited due to the internal LC resonances. A metasurface based on asymmetrically coupled SRRs was proposed to provide high sensitivity for the application of label-free bio-sensors via EIT-like effect [2] [3]. He et al. [4] reported a highly sensitive metasurface consisting of two complementary nanoscale metal film in a uniform surface.

In this paper, we designed, fabricated and characterized a metasurface device based on EIT-like effect which can be used for the applications of chemical and biological sensing. The structure consists of two resonance parts: “bright” CSRR and “dark” SSRR allowing us to maximize the EIT effect and the sensitivity of the devices. Finite-difference time-domain modeling is used to design the structure of the metasurface device. The characteristics of the fabricated device have been examined by using a terahertz time-domain spectrometer (THz-TDS). The experiment shows a sharp resonance peak with refractive sensitivity of 96.2 and figure of merit (FOM) of 7.6, which are in good agreement of with the simulations.

[1] Driscoll T, et al. Applied Physics Letters. 91 (2007) 062511.
[2] Chen C Y, et al. Optics Express. 17 (2009) 15372–15380.
[3] Meng F Y, et al. IEEE Transactions on Microwave Theory & Techniques. 60 (2012) 3031–3022.
[4] He X J, etal. Journal of Physics D Applied Physics. 46 (2013) 365302.

Biography

Dr Yong Ma is an associate Professor at School of Optoelectronic Engineering, Chongqing University of Posts and Telecommunications (CQUPT), China. He obtained a BSc in optoelectronics from Beijing Institute of Technology and a PhD from University of Essex. He was a research assistant at the Micro System Technology group, School of Engineering, University of Glasgow from 2008-2011, research associate at Heriot-Watt University from 2011-2015 and associate Professor at Chinese Academy of Sciences from 2015-2017. He has been an associate Professor at CQUPT since 2017.

He has authored/co-authored over 50 scientific research publications, and presented research at national and international conferences. Over 750 total citations and Three authored/co-authored papers are highly cited paper as reported by web of knowledge (over 150 citations). Has achieved H factor 11, and made 20 invited research talks. His main research interests include Terahertz photonic devices, metamaterials, metasurfaces as well as Interdisciplinary research on quantum and THz photonic sciences and technologies.

III-V/Si hybrid laser array with DBR on Si waveguide

Guangzhao Ran (冉广照)[1*],Lijun Yuan (袁丽君)[2], Li Tao (陶利)[1], Yanping Li (李艳平)[1], , Weixi Chen (陈娓兮)[1], Baojun Wang (王宝军)[2], Qiang Kan (阚强)[2], Hongyan Yu (于红艳)[2],and Jiaoqing Pan (潘教青)[2]**

[1]State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, China
[2]The Key Laboratory of Semiconductor Materials Science, Institute of Semiconductor, Chinese Academy of Science, Beijing 100083, China
**Corresponding author: rangz@pku.edu.cn; jqpan@semi.ac.cn*

We report an eight-channel silicon evanescent laser array operating at continuous wave and room temperature conditions using selective-area metal bonding technique. The laser array is realized by evanescently coupling the optical gain of InGaAsP multi-quantum wells to the silicon waveguides of varying widths and patterned with distributed Bragg reflector (DBR) gratings. The lasers have emission peak wavelengths in a range of 1537 and 1543 nm with a wavelength spacing of about 1.0 nm. The thermal impedances Z_T of these hybrid lasers are evidently lower than those DFB counterparts

OCIS Codes: (250.0250) Optoelectronics; (250.5300) Photonic integrated circuits; (250.5960) Semiconductor lasers.

Silicon integrated photonics rapidly expands for supporting ever increasing data rates in internet, parallel many-core computations and wireless communications etc [1-5]. In silicon integrated photonic circuit, the most important active component perhaps is silicon light source, which is the most challenging to realize due to the poor spontaneous emission ability of silicon stemming from its indirect energy bandgap [4]. But, the past few years have seen quite a few exciting successes [7-11]. Among them, bonding III-V compound semiconductors to silicon platform and evanescently coupling the optical gain of III-V part to silicon waveguide is a low cost and practical approach [12-16].

Based on the existing hybrid integration technology, the recent research focus shifts to the multi-wavelength and wavelength tunable silicon lasers for wavelength division multiplexing (WDM), which is the largest advantage of silicon optical interconnects. In multi wavelength laser array, each channel must operate with a single longitudinal mode and its wavelength is different to adjacent one with uniform spacing. The distributed Bragg reflector (DBR) or distributed feedback (DFB) laser is stable and highly reliable single-mode laser [17-21], and by changing the grating period in each channel, the different lasing wavelength can be realized. Unfortunately, according to the gating equation, $2n_{eff}\Lambda=\lambda$, a 1 nm deviation of the grating period (Λ) will cause a wavelength (λ) error of ~5-8 nm due to the high effective refractive index (n_{eff}), thus the reported 4 channel arrayed silicon lasers defined a wide wavelength spacing of 20 nm [22]. By careful use of electron-beam lithography (EBL), the grating with different periods can narrow the wavelength spacing to 5 nm [23, 24], but EBL suffers from high costs and low yields and so is not CMOS compatible. Could the channel wavelength spacing be as narrow as ~1 nm similar to the ITU standard by ordinary technique? Here, we fix the grating period on silicon passive waveguide but vary the width of silicon waveguide to realize the wavelength varying laser array. By computations and experiments [25, 26], the variation (~10%) in the ridge width leads to a slight effective index difference (1‰) and then to a lasing wavelength difference (~1nm, nonlinearly). This is a simple, low cost and highly-stable method [25-26] suitable for mass production, and these width-varying grating waveguides can be fabricated simply by use of standard photolithography and holographic lithography. Recently, we reported an InGaAsP-Si distributed feedback (DFB) evanescent laser array previously [27]. However, the surface corrugated gratings bonded directly to the III-V gain region causes higher thermal impedance; the rough surface of the sidewall of the DFB gratings usually causes a scattering loss and then a higher lasing threshold. On the other hand, distributed Bragg reflector (DBR) lasers putting the grating at the ends of the gain region can overcome the both shortcomings. This work reports an 8-λ DBR InGaAsP-Si hybrid laser array based on selective area metal bonding to overcome the disadvantage of DFB ones. The bonding step follows both the whole silicon components and III-V ones are finished separately, avoiding the crossover of the silicon and III-V process flow. This 8-λ laser array can support an 8×25 GHz silicon photonic transceiver.

The transverse cross-section of the InGaAsP-Si hybrid laser is shown in Fig. 1(a). A buried ridge (BRS) InGaAsP quantum well epitaxial structure is flip-chip bonded onto a patterned SOI wafer with SAMB method. The III-V material has the same epitaxial structure as in [16].

In the SOI region, the gratings of 244 nm period are formed on an undoped SOI substrate by conventional holographic exposure combined with the optical photolithography [28] and $HBr/He/O_2$ based inductively coupled plasma (ICP) etching. Then the silicon waveguide with a hight of 0.5 μm and width of (2.0, 2.1, 2.2, 2.3, 2.4, 2.6, 2.8, 3.0) μm is formed using photolithography and a second ICP dry etching. Then metal lift-off technology is adopted to selectively deposit the bonding metal on each side of the silicon waveguide. The bonding metal is indium, which is widely used in metal bonding and packing due to its low melting point and good fluidness. Finally, the III-V wafer is diced into bars with a length of 300 μm and flip-chip bonded onto the SOI wafer by a bonder with alignment accuracy ± 0.5 μm. The bonding process is done at 170 °C for 5 mins under a pressure of about 2 MPa. The 45 degree angle view of the hybrid laser is shown in Fig. 1(b). The effective refractive indicies of the unetched and the etched regions are estimated using the finite differential in time domain (FDTD) solutions (Lumerical Solution Inc., Canada), resulting in a coupling constant κ of ~ 67 cm^{-1}. The lengths of the front and back gratings are 150 and 300 μm, resulting in power reflectivities of 48.3 % and 93.1 % for the back and front mirrors, respectively.

The chip with the fabricated laser is mounted on a thermo electric cooler which allows the operating temperature of the laser varying from 0 to 70 °C. The laser output from the waveguide facet of the front mirror is collected by a lensed multi-mode fiber and then characterized by using a spectrum analyzer or optical power meter.

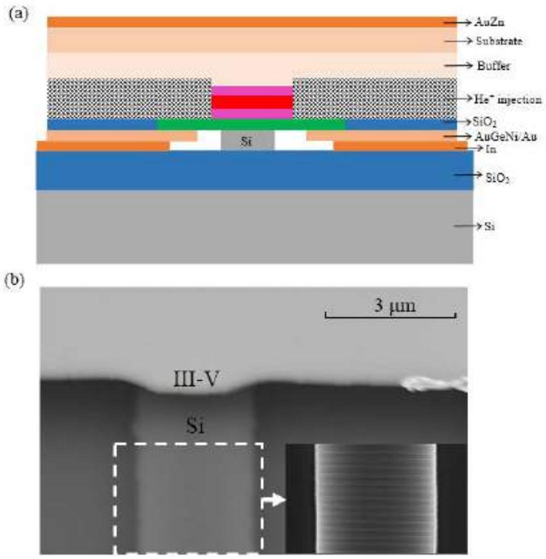


Fig. 1. (a) The transverse cross-section of the hybrid laser. (b) Scanning electronic microscopic image of 45-degree angle view of the fabricated laser. Inset is the SEM image of the DBR silicon waveguide

Figure 2(a) shows the measured continuous wave output power from one facet as a function of injected current at operating temperatures ranging from 10 to 35 ^{o}C. As can be seen, the threshold current is 20 mA with an output power of 60 μW at 70 mA. The coupling efficiency from waveguide to fiber is about 30%. Figure 2(b) shows the measured lasing spectrum of the silicon evanescent laser driven slightly above the threshold at 20 mA at room temperature. The spectrum was measured with an Agilent 86142B spectrum analyzer. The used wavelength resolution is 0.3 nm, so the measured linewidth is slightly larger. The lasing wavelength is around 1544 nm with a side-mode suppression ratio (SMSR) of ~25dB. Furthermore, the lasing wavelength is shifted to longer wavelength at higher injection currents due to device heating(temperature rise). The wavelength shift is about 0.018 nm/mA.

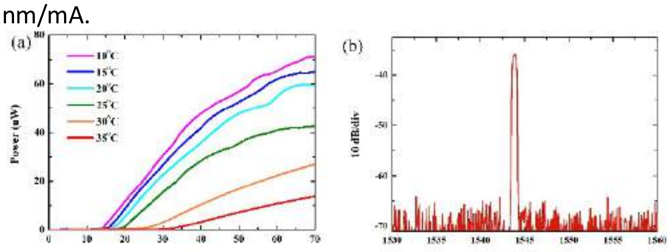


Fig. 2. (a) Curves of light output power versus injection current for stage temperature of 10 to 35 ^{o}C. (b) The lasing spectrum with 30 dB side mode extinction ratio at 20 mA at room temperature.

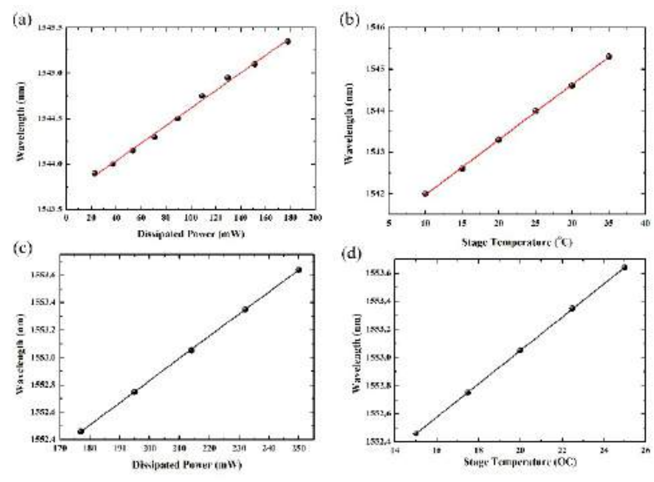


Fig. 3. (a) Lasing wavelength versus electrical dissipated power of DBR laser. (b) Lasing wavelength versus stage temperature of DBR laser. (c) Lasing wavelength versus electrical dissipated power of DFB laser. (b) Lasing wavelength versus stage temperature of DFB laser.

The thermal impedance Z_T of the hybrid laser is determined by the peak emission wavelength shifts with the increase of the input electrical power (P) and the corresponding temperature (T) rise of the device, that is $Z_T = (d\lambda/dT)^{-1}(d\lambda/dP)$. Figure 3(a) shows the plot of wavelength versus dissipated electrical power; Figure 3(b) shows the changes in lasing wavelength as a function of temperature of the stage (controlled using a Peltier element). By using linear fit, we measure the wavelength shift with the increase of dissipated power of $\Delta\lambda/\Delta P$ = 9.68 nm/W, while the wavelength shift with the increase of the temperature of the stage is Δλ/ΔT = 0.133 nm/°C. Dividing these values yields a thermal impedance of 72.8 K/W. It is much better than that of our reported DFB [27] laser 137.3 K/W which can be calculated from figure 3(c) and figure 3(d). This thermal impedance can be improved by optimizing the bonding condition or changing the bonding metal.

Table 1 Effective refractive index and the lasing wavelength of the eight Si waveguide Vs waveguide width

	Ch.1	Ch.2	Ch.3	Ch.4	Ch.5	Ch.6	Ch.7	Ch.8
w(μm)	2.0	2.1	2.2	2.3	2.4	2.6	2.8	3.0
n_{eff}	3.14576	3.14793	3.14983	3.15149	3.15295	3.15536	3.15728	3.15883
λ (nm)	1535.1	1536.2	1537.1	1537.9	1538.6	1539.8	1540.8	1541.3

To demonstrate the scalability of this hybrid laser method for WDM optical system, we achieve an eight channel laser array by varying the width of silicon waveguide. To guarantee the coupling efficiency, the eight widths of the silicon waveguide are chosen between 2.0 and 3.0 μm, which are 2.0, 2.1, 2.2, 2.3, 2.4, 2.6, 2.8, and 3.0 μm, respectively. The effective refractive index of each Si waveguide is shown in Table 1 calculated by FDTD. The effective refractive index increases with the silicon waveguide width exponentially, and increases more rapidly below 2.5 μm. The refractive index of passive waveguide as a function of silicon waveguide width can generally be described by the following empirical formula fitted from the computation data:

$$n_{eff} = 3.1643 - 0.238e^{-1.269w},$$

where n_{eff} is the effective refractive index of the passive waveguide, *w* is the width of the silicon waveguide. The wavelength spacing is around 0.8 nm estimated by $\Delta\lambda=2(\Delta\eta_{eff}\Lambda)$, where Λ=244 nm is the Bragg gratings period. The lasing spectrum of each device driven slightly above its own threshold is shown in Fig. 4(a). The lasing wavelengths are shown in Table 1 and Fig. 4 with an SMSR around 25 dB. There is some difference in wavelength between the measured values and the calculated values because there exists fabrication and calculation errors. The fabrication tolerance of the silicon waveguide width and grating constant are 10 and 0.2 nm respectively, which leads to a wavelength shift of 1 nm in total. Because the effective refractive index of the hybrid waveguide varies nonlinearly with the silicon waveguide width, fixed wavelength spacing can be obtained by nonlinearly varying the silicon waveguide width. Furthermore, narrower wavelength spacing can be achieved by reducing the silicon waveguide width interval. Figure 4(b) shows the imaged output facet of the InGaAsP/Si evanescent laser array operating simultaneously. The devices are driven with a common pulsed current 250 mA at a repetition rate of 1 kHz and 0.2 % duty cycle. More channel hybrid lasers with different silicon waveguide width can be fabricated to meet the needs of dense wavelength division multiplexing (DWDM) systems using this approach. Furthermore, if the eight channel outputs are guided into a single silicon nanowire waveguide, a considerably high optical power density can be achieved, which is needed for on-chip silicon nonlinear photonics and microwave photonics. A different optical communication band can be met by just tuning the grating period. During the revision of this paper, 8-λ hybrid silicon μ-disk laser array was also reported [29].

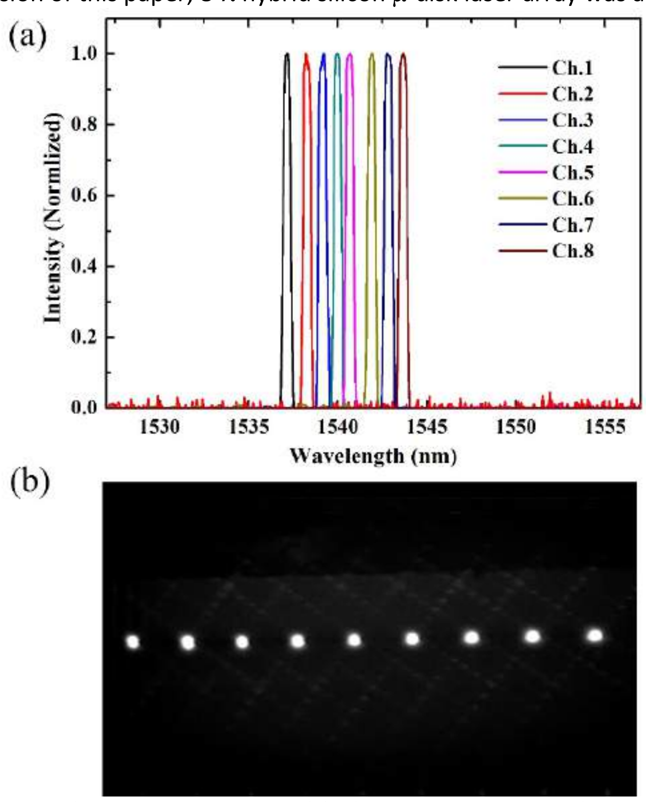


Fig. 4. (a) Spectra of the eight lasing channels. (b) Infrared microscopeimage of the lasing array.

Eight-channel InGaAsP-Si DBR array lasers fabricated with this technique can be easily scaled up to more channels by increasing the silicon waveguide width range and reducing the silicon waveguide width interval. Only photolithography and holographic lithography are used for the fabrication of silicon waveguides, which are CMOS technology compatible. These DBR lasers have better thermal properties than those DFB counterparts, which can be easily used in silicon optical interconnects.

This work is supported by the National 973 program (No. 2013CB632105) the National 863 project (Grant No. 2012AA012203) the National Natural Science Foundations of China (No. 11174018, 61404003).

References

1. D. A. B. Miller, "Optical interconnects to silicon", IEEE J. Sel. Top. Quantum Electron. **6**, 1312 (2000).
2. R. S. Jacobsen, K. N. Andersen, P. I. Borel, J. F. Pedersen, L. H. Frandsen, O. Hansen, M. Kristensen, A. V. Lavrinenko, G. Moulin, H. Ou, C. Peucheret, B. Zsigri, A. Bjaklev, "Strained silicon as a new electro-optic material", Nature **441**, 199 (2006).
3. V. R. Almeida, C. A. Barrios, R. R. Panepucci, and M. Lipson, "All-optical control of light on a silicon chip", Nature **431**, 1081 (2004).
4. D. Liang and J. E. Bowers, "Recent progress in lasers on silicon", Nat. photonics **4**, 511 (2010).
5. A. Melikyan, L. Alloatt, A. Muslija, D. Hillerkuss, P. C. Schindler, J. Li, R. Palmer, D. Korn, S. Muehlbrandt, D. Van Thourhout, B. Chen, R. Dinu, M. Sommer, C. Koos, M. Kohl, W. Freude, and J. Leuthold, "High-speed plasmonic phase modulators", Nat. photon. **8**, 229 (2014).
6. H. Rong, R. Jones, A. Liu, O. Cohen, D. Hak, A. Fang, and M. Paniccia, "A continuous-wave Raman silicon laser", Nature **433**, 725 (2005).
7. S. G. Cloutier, P. A. Kossyrev, and J. Xu, "Optical gain and stimulated emission in periodic nanopatterned crystalline silicon", Nat. Mater. **4**, 887 (2005).
8. Y. H. Kuo, Y. K. Lee, Y. Ge, S. Ren, J. E. Roth, T. I. Kamins, D. A. B. Miller, and J. S. Harris, "Strong quantum-confined Stark effect in germanium quantum well structures on silicon", Nature **437**, 1334 (2005).
9. K. Tanabe, K. Watanbe, and Y. Arakawa, "III-V/Si hybrid photonic devices by direct fusion bonding", Sci. Rep. **2**, 349 (2012).
10. M. Tang, S. Chen, J. Wu, Q. Jiang, V. G. Dorogan, M. Benamara, Y. I. Mazur, G. J. Salamo, A. Seeds, and H. Liu, "1.3-µm InAs/GaAs quantum-dot lasers monolithically grown on Si substrates using InAlAs/GaAs dislocation filter layers", Opt. Express **22**, 11528 (2014).
11. I. J. Luxmoore, R. Toro, O. Del Pozo-Zamudio, N. A. Wasley, E. A. Chekhovich, A. M. Sanchez, R. Beanland, A. M. Fox, M. S. Skolnick, H. Y. Liu, and A. I. Tartakovskii, "III-V quantum light source and cavity-QED on silicon", Sci. Rep. **3**, 1239 (2013).
12. A. W. Fang, H. Park, O. Cohen, R. Jones, M. J. Paniccia, and J. E. Bowers, "Electrically pumped hybrid AlGaInAs-silicon evanescent laser", Opt. Express **14**, 9203 (2006).
13. S. Stankovic, R. Jones, M. N. Sysak, J. M. Heck, G. Roelkens, and D. V. Thourhout, "1310-nm Hybrid III-V/Si Fabry-Perot Laser Based on Adhesive Bonding", IEEE Photon. Technol. Lett. **23**, 1781 (2011).
14. T. Hong, G. Z. Ran, T. Chen, J. Q. Pan, W. X. Chen, Y. wang, Y. B. Cheng, S. Liang, L. J. Zhao, L. Q .Yin, J. H. Zhang, W. Wang, and G. G. Qin, "A selective-Area Metal Bonding InGaASP-Si Laser", IEEE Photon. Technol. Lett. **22**, 1141 (2010).
15. T. Hong, Y. P. Li., W. X. Chen, G. Z. Ran, G. G. Qin, H. L. Zhu, S. liang, Y. Wang, J. J. Pan, and W. Wang, "Bonding InGaAsP/ITO/Si hybrid laser with ITO as cathode and light-coupling material", IEEE Photon. Technol. Lett. **24**, 712 (2012).
16. L. J. Yuan, L. Tao, W. X. Chen, Y. P. Li, S Liang, H. Y .Yu, G. Z. Ran, J. Q. Pan, and W. Wang, "A buried ridge stripe structure InGaAsP-Si hybrid laser", IEEE Photon. Technol. Lett. **27**, 352 (2015).
17. S. Keyvaninia, S. Verstuyft, L. Van Landschoot, F. Lelarge, G.-H Duan, S. Messaoudene, J. M. Fedeli, T. De Vries, B. Smalbrugge, E. J. Geluk, J. Bolk, M. Smit, G. Morthier, D. Van Thourhout, and G. Roelkens, "Heterogeneously integrated III-V/silicon distributed feedback lasers", Opt. Lett. **38**, 5434 (2013).
18. A. W. Fang, B. R. Koch, R. Jones, E. Lively, D. Liang, Y. H. Kuo, and J. E. Bowers, "A distributed Bragg reflector silicon evanescent laser", IEEE Photon. Technol. Lett. **20**, 1667 (2008).
19. S. Keyvaninia, G. Roelkens, D. V. Thourhout, C. Jany, M. Lamponi, A. L. Liepvre, F. Lelarge, D. Make, G. Duan, D. Bordel, and J. M. Fedeli, "Demonstration of a heterogeneously integrated III-V/SOI single wavelength tunable laser", Opt. Express **21**, 3784 (2013).
20. Y. Zhang, H. Qu, H. Wang, S. Zhang, L. Liu, S. Ma, and W. Zheng, "A hybrid silicon single mode laser with a slotted feedback structure", Opt. Express **21**, 877 (2013).
21. Y. Konink, F. Raineri, A. Bazin, R. Raj, G. Roelkens, and R. Baets, "Experimental demonstration of a hybrid III-V-on-silicon microlaser based on resonator grating cavity mirrors", Opt. Lett. **38**, 2496 (2013).
22. M. Paniccia, "Integrating silicon photonics", Nat. photonics **8**, 498 (2010).
23. S. Kanazawa, T. Fujisawa, A. Ohki, H. Ishii, N. Nunoya, Y. Kawaguchi, N. Fujiwara, K. Takahata, R. Iga, F. Kano, and H. Oohashi, "A compact EADFB laser array module for a future 100-Gb/s Ethernet transceiver", IEEE J. Sel. Top. Quantum Electron. **17**, 1191 (2011).
24. T. Fujisawa, T. Itoh, S. Kanazawa, K. Takahata, Y. Ueda, R. Iga, T. Yamanaka, M. Kotoku, and H. Ishii, "Ultracompact, 160-Gbit/s transmitter optical subassembly based on 40-Gbit/s × 4 monolithically integrated light source", Opt. Express **21**, 182 (2013).
25. Y. Nakano, and Kunio Tada, "Analysis, Design, and Fabrication of GaAlAs/GaAs DFB lasers with Modulated Stripe Width Structure for Complete Single Longitudinal Mode Oscillation", IEEE J. Quant. Electronics **24**, 2017 (1988).
26. J. Hong, W. P. Huang, T. Makino, and G. Pakulski, "Static and Dynamic Characteristic of MQW DFB lasers with Varying Ridge Width", IEEE Proc., Optoelectron. **141**, 303 (1994).
27. L. Tao, L. J. Yuan, Y. P. Li, H. Y. Yu, B. J. Wang, Q. Kan, W. X. Chen, J. Q. Pan, G. Z. Ran, and W. Wang, "4-λ InGaAsP-Si distributed feedback evanescent lasers with varying silicon waveguide width", Opt. Express **22**, 5448 (2014).

Posters from IOS, UESTC, UOG

Authors	Poster Title	Presenter (*) Title
Wang Jiankun, Yongguang Huang*	Modulation Response of Directly Modulated DFB Laser on Co-planar Waveguide with Defected-ground Plane	Associate professor
Zhaosong Li, Fangyuan Meng*, Dan Lu**, YimingHe, XuliangZhou, LingjuanZhao, JiaoqingPan	A monolithic integrated InP-based few-mode transmitter	PhD Student
Qiufang Deng, Qiang Tang*, Hongliang Zhu, Song Liang and Wei Wang	Low chirp EMLs Fabricated by Combining SAG And Double Stack Active Layer Techniques	PhD Student
Songtao Liu, Mengdie Sun, Dan Lu, Ruikang Zhang* and Chen Ji	Arrayed Waveguide Grating Based Monolithic Multi-wavelength Mode-locked Semiconductor Laser	Associate professor
Hongliang Zhu*	Some progress in the fabrication technology of side emitting lasers	Professor
Zhao Liu*, Yong Liu	Graphene with pin Germanium photodetector integrated on SOI	PhD Student
Lingjie Zhang*, Zhiyao Zhang**, Shangjian Zhang, Fei Yuan, Yong Liu	Intrinsic phase response retrieval of optical filters based on magnitude response only measurement	PhD Student
Zhen Zeng*, Zhiyao Zhang**, Yangxue Ma, Shangjian Zhang, Yong Liu	Optically Tunable Microwave Frequency Down-conversion Based on an Optoelectronic Oscillator Employing a Phase-Shifted Fiber Bragg Grating	PhD Student
Wenxiong Du*, Heping Li, Junwen Li, Pinghe Wang, Shangjian Zhang, and Yong Liu	Mechanism of dissipative-soliton-resonance generation in fiber laser mode-locked by real saturable absorber	PhD Student
Yujia Zhang*, Shengwei Ye, Rongguo Lu, Zhiyao Zhang, Yong Liu	Polarization-Independent Electro-Absorptive Modulator Based on Slanted Graphene Buried in a Silicon-on-Insulator Waveguide	PhD Student
Xuyan Zhang*, Zhiyao Zhang**, Heping Li, Yong Liu	Bi-directional Comb-fiber Architecture for Resolution Improvement of Optical Quantization Employing Soliton Self-frequency Shift and Spectral Compression	PhD Student
Mengke Wang*, Shangjian Zhang**, Heng Wang, Xinhai Zou, Yali Zhang, Yong Liu	Accurate time-delay measurement of optical delay components based on frequency-shifted self-heterodyne spectrum	PhD Student
Di Peng, Yuan Ling*, Zhiyao Zhang, Yong Liu	Single-shot photonic time-stretch digitizer using a dissipative soliton-based passively mode-locked fiber laser	PhD Student
Lianping Hou[1**], Bin Hou[1*], Song Tang[1], Song Liang[2], Dejun Chen[3], John H. Marsh[1]	Generation of THz Radiation by Sampled Grating DBR Mode Locked Laser Diodes	PhD student
Song Tang*, Bin Hou, Song Liang, Dejun Chen, Lianping Hou, John H. Marsh[1]**	Terahertz Signal Generation Based on Dual-Mode 1.5 µm DFB Diode Lasers	PhD students

Modulation Response of Directly Modulated DFB Laser on Co-planar Waveguide with Defected-ground Plane

Wang Jiankun, Yongguang Huang*

Key Laboratory of Semiconductor Materials Science, , Institute of Semiconductors,
Chinese Academy of Sciences, P. O. Box 912，Beijing 100083, China
(e-mail: yghuang@semi.ac.cn).

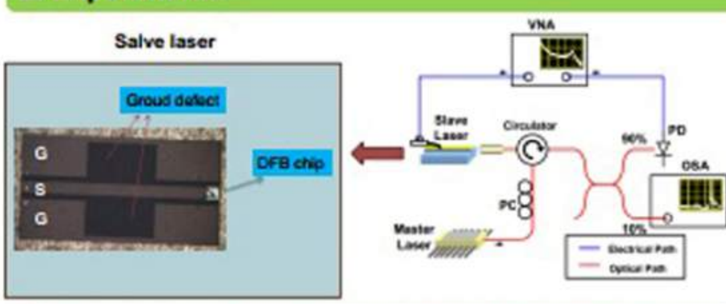
Absrtact: When small signal direct modulation response of a DFB laser is measured on a coplanar waveguide carrier with ground defects, the S21 or S11 curve of the DFB laser would be effected by micro-cavity reflection caused by the defects. This is expected to flatten the small signal response curve or lead to special band filtering during direct modulation. Small signal modulation experiments on a DFB laser with external feedback cavity show that the peak of electron-photon response can be lowered effecttively by the ground defects, without effecting the photon-photon oscillation notably.

1.Introduction

- For high-speed semiconductor lasers, the design and fabrication of packaging carrier are very important, which greatly affect the high-speed modulation performance of the devices. Since the carrier itself is an equivalent L-R-C circuit, the design of the carrier can be combined with the equivalent circuit of the laser to jointly adjust some modulation response characteristics of the laser. In this study, the frequency response characteristics of carriers with and without ground defects and the direct modulation response of a DFB laser with external feedback cavity soldered on the defected carriers are studied. It is found that the peak of electron-photon response can be lowered effecttively by the ground defects of the carriers, without effecting the photon-photon oscillation notably.

2. Experiments

Salve laser



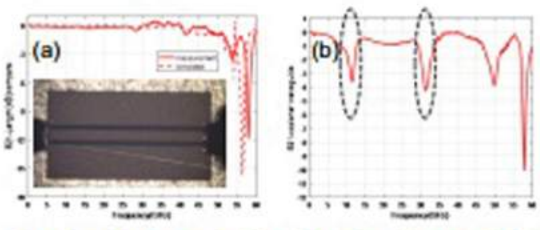
Carrier: AlN , Ground Signal Ground structure, DFB chip are soldered on AlN submount.

Measurements: vector network analyzer(VNA), a ground signal ground (GSG) microwave probe provides small signal modulation and dc biasing for the DFB lasers.

Injection feedback DFB experiments : DFB bandwidth can be enhanced by a master laser optical injection

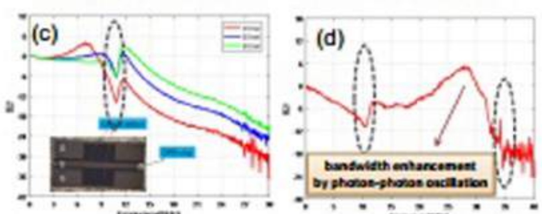
3. Device Characterizations

Small signal modulation responses curve S21 of carrier



(a) carrier without ground-defect, (b) carrier with ground-defect

Small signal modulation responses curve S21 of laser



(c) DFB laser without optical injection at different bias current (30mA,60mA,90mA) on carrier with ground-defects , (d) Injection feedback DFB laser on carrier with ground-defects (injection condition: maser laser power 21.5dBm, and slave laser bias is 92mA, wavelength is 1312.5nm)

4.Conclusion

- Ground defects induce micro-cavity reflection mode, resulting in periodic valley distribution on the transmission curve S21 of small signal modulation
- The peak of electron-photon response is obviously lowered by ground defects, but the effects on the response of photon-photon oscillation is much weaker

Acknowledgment: This work was supported in part by the National Natural Science Foundation of China (Grant No. 61574137)

Jiankun Wang received the B. S. degree from the department of physic, Beijing University of Technology, China, in 2014. He is now working toward his Ph. D degree in the Institute of Semiconductors, CAS. He is currently focusing on. His current research includes the high speed DFB laser and its application.
Yongguang Huang is an associate Professor atInstitute of Semiconductor, Chinese Academy of Sciences, China. He obtained the B.S. degree from Minzu University of China and the Ph. D degree from Beijing University of Technology. His current research includes the high-speed and high power DFB lasers .

A monolithic integrated InP-based few-mode transmitter

Zhaosong Li[1,2], Fangyuan Meng[1,2], Dan Lu[1*], Yiming He[1,2], Xuliang Zhou[1], Lingjuan Zhao[1,2], Jiaoqing Pan[1,2]

1. Key Laboratory of Semiconductor Materials Science, Beijing Key Laboratory of Low Dimensional Semiconductor Materials and Devices, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China.
2. College of Materials Science and Opto-Electronic Technology, University of Chinese Academy of Sciences, Beijing 100049, China.
Corresponding author: ludan@semi.ac.cn

➢ Introduction:

A monolithic integrated InP-based few-mode transmitter comprising of two directly modulated lasers and a mode converter-multiplexer based on multimode interference coupler was designed and demonstrated. 2×10 Gbps two modes generation and modulation was realized.

➢ Device design and simulations

This device consists of two DMLs as light sources and a 3×3 MMI coupler as the mode converter/multiplexer with 66% mode conversion efficiency ($TE_0 \rightarrow TE_1$) as shown in Fig.1. The optical distributions of the mode converter-multiplexer in the X-Z plane and X-Y plane are simulated by 3D BPM as shown in Fig.2. The parameters of the few-mode transmitter are shown in Table 1.

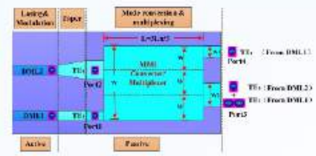


Fig.1. Schematic diagram of the few-mode transmitter

Table 1 The parameters of the few-mode transmitter

Type	Width/ μm	Length/ μm
MMI	13	500
Input Port	2.7	/
Output Port	4.5	/
DFB-LD	3	250

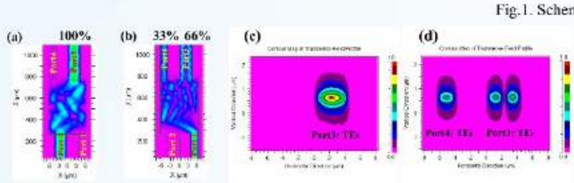


Fig.2. Optical field distributions of the device in (a) X-Z plane, (b) X-Y plane.

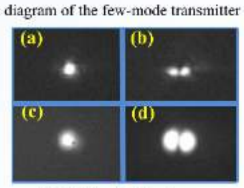


Fig.3. Near field patterns.

➢ Experimental results

Butt-joint technology was used to integrate the DFB-LDs with MMI-based mode converter/multiplexer on InP substrate. Fig.3 (a) and (b) demonstrate the near field patterns of the fundamental TE_0 mode and the first order TE_1 mode at the output Port3, respectively, corresponding to the separate operation of DML2 and DML1. The generated two modes were then coupled into a 200-meter two-mode few mode fiber to excite the fiber modes. Fig.3 (c) and (d) show the LP_{01} and LP_{11} modes excited by the TE_0 and TE_1 mode, respectively. Clear optical fiber mode patterns can be excited by the few-mode transmitter. The PIV curves, optical spectrum, frequency response and eye diagram characteristics of the transmitter are shown in Fig.4 and Fig.5 for fundamental mode and first order mode, respectively. The -3 dB small signal bandwidth for DFB-LD 1 and DFB-LD 2 were 17.4 GHz and 14.7 GHz, respectively, as shown in Fig.4 (c) and Fig.5 (c). Then the DFB-LDs were directly modulated at a bit rate of 10 Gbps. Clear eye diagrams were obtained for both TE_0 and TE_1 mode, as shown in Fig.4 (d) and Fig.5 (d).

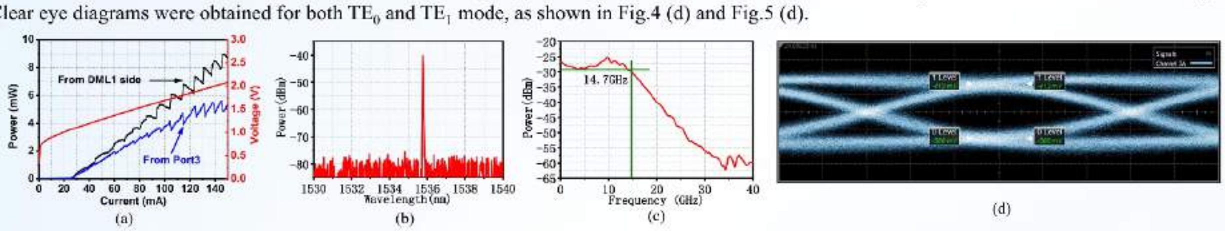


Fig.4. (a) PIV curves, (b) Optical spectrum, (c) frequency response, (d) 10 Gbps eye diagram for DML 1.

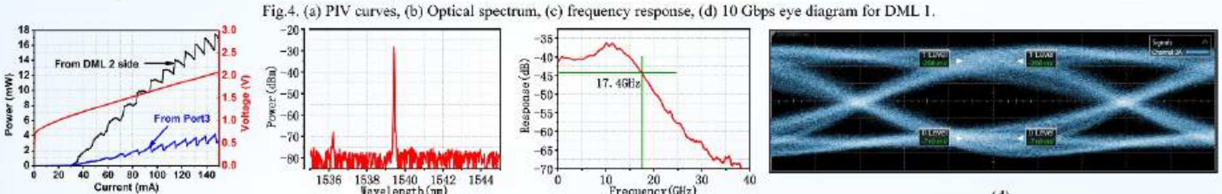


Fig.5. (a) PIV curves, (b) Optical spectrum, (c) frequency response, (d) 10 Gbps eye diagram for DML 2.

➢ Conclusion

An InP-based few-mode transmitter was designed and demonstrated. Fundamental TE_0 and first order TE_1 mode were generated and modulated from single-mode DMLs. The -3 dB small signal bandwidth of 17.4 GHz and 14.7 GHz were obtained for the two mode channels, respectively. Clear opened 2×10 Gbps eye diagrams were demonstrated. The directly modulated monolithic integrated few-mode transmitter may find potential applications in short range or on-chip MDM systems where intensity modulation with direct detection (IM/DD) is preferred.

[1] J. Leuthold, et al. J. Light. Technol., vol. 16, no. 7, pp. 1228–1239, 1998.
[2] Zhaosong Li, in Asia Communication and Photonics Conference, 2016. AF3B.6
[3] Zhaosong Li, et al. in Conference on Lasers and Electro-Optic, 2016. JW2A.123.
[4] Y. Chaen, et al. in Microoptics Conference, 2013, pp. 2–3.
[5] Fei Guo, et al. Photonics Journal, vol. 8, no. 1. 2700608. Feb. 2016.

The work is supported by the National Science Foundation of China (NSFC) (Grant No. 61674134) and the National 973 Program (Grant No. 2014CB340102)

Photonic Integrated Circuit Group

Low chirp EMLs Fabricated By Combining SAG And Double Stack Active Layer Techniques

Qiufang Deng, Qiang Tang, Hongliang Zhu, Song Liang and Wei Wang

Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

College of Materials Science and Opto-Electronic Technology, University of Chinese Academy of Sciences, Beijing 100083, China

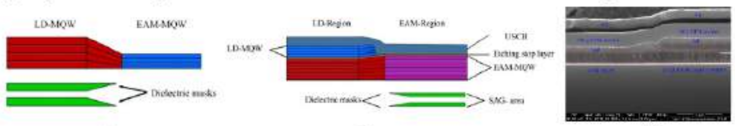
Beijing Key Laboratory of Low Dimensional Semiconductor Materials and Devices, Beijing 100083, China.

Abstract

We present electroabsorption modulators integrated with DFB lasers (EMLs) fabricated by a simple method which combines the advantages of the selective area growth (SAG) and double stack active layer techniques. The device proves to be a promising candidate for cost effective and energy-efficient transmitters used in long distance.

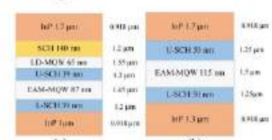
Device Structure

Pairs of dielectric masks are formed in the EAM areas in the process, which is contrary to the usual SAG method. The EAM MQWs and the LD MQWs are grown successively in a single MOCVD growth on the patterned substrate. After the growth, the LD MQWs in the EAM areas are selectively etched off by the usual photolithography and wet etching, leaving only the EAM MQWs in the EAM section. The length of the total device is 500 μm, which consist of a 300-μm laser section and a 150-μm EAM. A 50-μm isolation trench is inserted between the two parts to avoid electrical crosstalk. A 3-μm ridge waveguide is adopted for both the DFB laser and the EAM. Before testing, dielectric high reflection (>70%) coating and anti-reflection (<1%) coating layers are deposited on the laser facet and modulator output facet, respectively.



(a) (b) (c)

Figure 1. The schematic material structures of DFB section (a) and EAM section (b) and the SEM image of the grown material (c)



(a) (b)

Figure 2. The schematic material structures of DFB section (a) and EAM section (b)

Experimental Results

The device is sintered on an AlN heat sink and the temperature is controlled at 20 oC by a thermoelectric cooler (TEC). The threshold current of the device is 16 mA. The output power is larger than 10 mW at an injection current of 85 mA. When the injection current of the laser is set at 64 mA, the wavelength of the light is 1552.28 nm.

A larger than 30 dB static extinction ratio can be obtained at -5 V EAM bias.The small signal 3 dB bandwidth increases from 6 to 10 GHz when the bias voltage is increased gradually from 0.4 to 2 V.Negative chirp parameters can be obtained when the reverse voltage is larger than 0.5 V at all cases. Open eye diagrams are demonstrated from the EML at both 10 and 20 Gb/s modulations with a driving voltage of only 0.65 V.

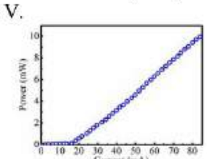


Figure 3. The power vs. injection current characteristics of the device

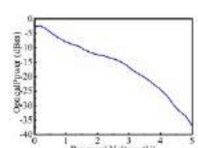


Figure 4. Fiber coupled output power vs. reverse bias of the EML device

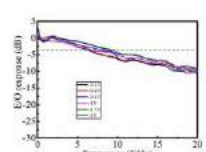


Figure 5. Electro-optic small signal response of the fabricated EML under different bias voltages

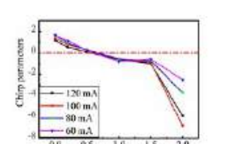


Figure 6. Measured reverse bias voltage dependence of the α parameter when the current of the DFB laser ranges from 60 mA to 120 mA

(a) (b) (c) (d)

Figure 7. Large signal eye diagrams (a) 10 Gb/s back-to-back configuration, (b) 10 Gb/s after 25 km transmission through SMF, (c)20 Gb/s back-to-back configuration, (d) 20 Gb/s after 25 km transmission through SMF.

More references:

1. J. Xu, S. Liang, Z. Zhang, J. An, H. Zhu, and W. Wang, "EML Array fabricated by SAG technique monolithically integrated with a buried ridge AWG multiplexer," Opt. Laser Technol., vol. 91, no. November 2016, pp. 46–50, Jun. 2017.
2. C. Zhang, S. Liang, H. Zhu, L. Han, and W. Wang, "Multichannel DFB Laser Arrays Fabricated by Upper SCH Layer SAG Technique," IEEE J. Quantum Electron., vol. 50, no. 2, pp. 92–97, Feb. 2014.

Institute of Semiconductors

Chinese Academy of Sciences

Arrayed Waveguide Grating Based Monolithic Multi-wavelength Mode-locked Semiconductor Laser

Songtao Liu, Mengdie Sun, Dan Lu, Ruikang Zhang and Chen Ji

Key Laboratory of Semiconductor Materials Science, , Institute of Semiconductors,
Chinese Academy of Sciences, P. O. Box 912， Beijing 100083, China

1.Introduction

Multi-wavelength mode-locked lasers are ideal candidates for high speed optical sampling, photonic microwave systems and next generation optical communication systems[1,2,3]. Using monolithic photonic integration approaches, multiple channels of mode locked lasers can be realized on a semiconductor chip, leading to a robust, compact, low cost and reliable design compatible with standard semiconductor manufacturing technologies, making them highly attractive in commercial markets.

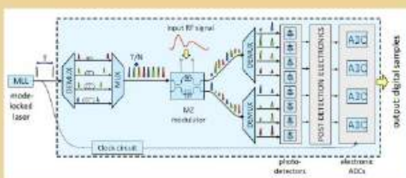


Fig. 1 Layout of a photonic ADC with Multi-channel mode lock laser[2].

2. Device Structure and fabrication process

Fig. 2(a). Optical microscope image of the fabricated AWG-based synchronized multichannel mode-locked semiconductor laser. The device operated under both passive and hybrid mode-locking conditions. The RF ground contact (GND) was fabricated right next to the saturable absorber contact for direct on chip RF probing.

Fig. 3(a). SEM cross-sectional image of the active-passive interface using the bundle waveguide integration approach. Fig. 3(b). SEM cross-sectional image of the passive waveguide section.

- Integrate a semiconductor optical amplifier array, an AWG and a common saturable absorber on a single InP substrate.
- Layer structure is epitaxial grown by LP-MOCVD.
- Using a bundle active-passive photonic integration technique, only one regrowth step is required.
- A shallow ridge waveguide structure is used for both active and passive section , which is formed in a single dry etching process.

3. Characterization of Devices

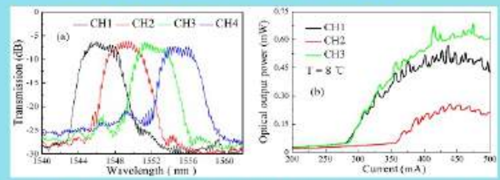


Fig. 4 TE transmission spectra of the 1 × 4 AWG in a test wafer, (b) CW L-I curves of the three consecutive channels of the chip with the common SA section zero biased and the SOA section forward biased at a stage temperature of 8 °C.

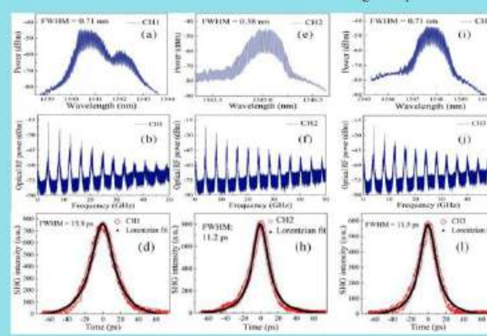


Fig. 5 PML operation characterizations of each individual mode-locked channels respectively. (a,e,i) optical spectrum, (b,f,j) full-span RF spectrum, (d,h,l) time domain autocorrelation trace with Lorentzian fit.

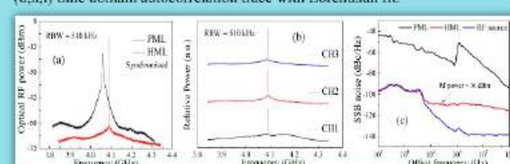


Fig 6. Multi-channel simultaneous mode locking operation measured through the common output waveguide (a) fundamental RF spectral peak under PML and HML conditions, (b) HML RF power spectra, individual mode-locked channels filtered with a tunable bandpass filter, (c) Single sideband phase noise plots (1 kHz – 100 MHz) comparing the PML and HML conditions, also RF clock source .

4.Conclusion

- An AWG-based multichannel ultrashort optical pulse source was presented. The pulse repetition frequencies are near of 4.1 GHz, and the pulse width of each individually channels ranged from 11.2 ps to 15.9 ps.
- Synchronous multichannel mode-locking operation was realized with timing jitter as low as 1 ps.
- Simplified and low cost manufacturing, A promising candidate for cost-effective photonic analog-to-digital converter systems.

[1] George C. Valley, "Photonic analog-to-digital converters," Opt. Express, vol.15, no. 5, pp.1955-1982, 2007.
[2] Anatol Khilo,1 Steven J. Spector, "Photonic ADC: overcoming the bottleneck of electronic jitter," Opt. Express, vol.20, no. 4, pp.4454-4469, 2012.
[3] M. Mielke, G. A. Alphonse and P. J. Delfyett, "168 channels x 6 GHz from a multiwavelength mode-locked semiconductor laser," IEEE Photon. Technol. Lett., vol. 15, no. 4, pp. 501-503, April 2003.

Some progress in the fabrication technology of side emitting lasers

Hongliang Zhu

Institute of Semiconductors, *Chinese Academy of Sciences, P. O. Box 912，Beijing, China*
Henan Shijia photons Technology Co., LTD. Henan, China(e-mail: zhuhl@semi.ac.cn).

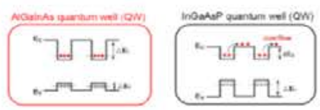
Absrtact: In the paper, the progress of in material design, fabrication development, wide spectrum tuning technology, and whole-wafer testing method for edge-emitting lasers is briefly described.

Introduction

With the rapid development of optical fiber communication, novel fabrication technology of optoelectronic devices have been developed, particularly for edge-emitting lasers. In this paper, the progress of edge-emitting lasers in material design, fabrication technology, wide spectrum tuning and whole-wafer testing in the past decade is briefly described, which can be used as reference for researchers in the same field.

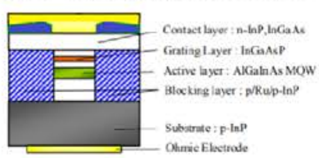
Ⅰ. Material system

1). The AlGaInAs/InP is used to replace the InGaAsP/InP MQW material system to improve the temperature and transmission characteristics [1].



Energy band containing Al and non Al MQW

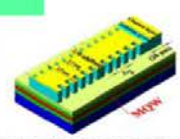
2). A buried heterojunction (BH) is fabricated by substituting Ru for Fe and growing semi-insulating (SI) InP material [2]. The interdiffusion between metal dopants and Zn at the interface can be avoided.



Cross section with Ru doped BH Structure[2]

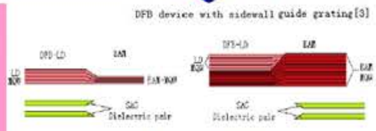
Ⅱ. Simplified process steps

1) Fabrication of DFB using side-wall gratings instead of buried gratings [3]. Simplify the epitaxy and fabrication processes.



DFB device with sidewall guide grating[3]

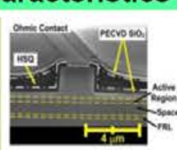
2) Exchanging the Position of SiO_2 pair in the manu-facturing EML with selec-tive area growth (SAG) to grow the double stacked active layer (SAG-DSAL) [4]. The thickness and composition of laser and modulator MQW can be optimized by a single epitaxy.



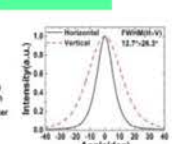
EML active area produced by traditional SAG method　　EML stacked active area produced by SAG-DSAL method

Ⅲ. Improving device characteristics

1) A far-field reduction layer (FRL) is inserted underneath MQW to replace the tapered spot-size converter(SSC) to reduce the far-field diver-gence angle of the laser [5], improving the coupling efficiency with the single mode fiber.

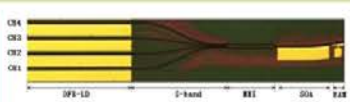


laser with FRL [5]



far-field divergence angle

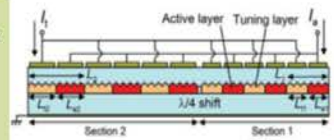
2) A bending waveguide is used to replace the guide-free diffuse reflector to reduce the facet light reflection [6].



monolithic integrated DFB laser array with curved waveguide[6]

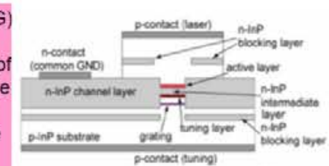
Ⅳ. Wide range spectral tuning

1) Using cross distri-buted active and tuning segments to keep Bragg reflection peak and longitudinal mode spectrum of the device synchronized, tunable distributed amplification (TDA) DFB laser[7] can avoid mode-hopping and achieve 7.5 nm wavelength tuning .



TDA-DFB laser structure [7]

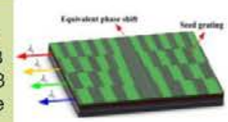
2) The tunable twin-guide (TTG) DFB laser use longitudinal doublejunc-tion guide instead of transverse single-junction guide [8]. The upper pn MQW guide layer provides stable gain. The lower pn grating and the tuning guide layer perform wavelength tuning. which can realize a continuously 8.0 nm no mode-hopping wavelength continuously tuning.



TTG-DFB laser structure [8]

Ⅴ. Multi-wavelength integration

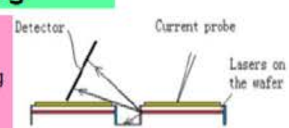
The ±1 order peaks of Bragg grating were used to replace the 0-order peak to design the lasing wavelength of DFB laser. The different wavelengths of DFB lasers can be obtained by changing the period of sampling grating . The phase shift can be easily introduced by using the reconstruction equivalent chirp (REC) Technology [9] to realize the integration of multi-wavelength DFB laser array.



DFB grating array by REC

Ⅵ. Whole-wafer testing

Edge-emitting lasers need to be cleaved into bars, facets coating, then cleavage into chips for testing and packaging, which is very complicated. The MACOM company has developed the whole-wafer coating and testing method by using etched facet technology (EFT) [10].



schematic diagram of MACOM's whole-wafer test

Acknowledgment: This work was supported by the National Natural Science Foundation of China (Grant No. 61320106013)

References [1] Solid-State Electronics，Vol.51,P.925,(2007) [2] Phys. Status Solidi C 9(2), P.342,（2012） [3] IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 25(12),P.1169,(2013) [4] Chinese Science Bulletin , Vol. 54(20),P.3627,(2009) [5] OPTICS LETTERS，Vol.36（6），P.966, (2011) [6] IEEE J.of Quantum electronics, VOL.48(2),P.137,(2012) [7]IEEE J.of Selected Topics in Quant.Electr., Vol.17，P.1505，(2011) [8] Lasers and Electro-Optics, CLEO/Pacific Rim,P. 628,（2005） [9] Opt. Lett., vol.37（16）, P.3315,（2012） [10]. US patent: US 2012 0142123A1, (2012)

Graphene with pin Germanium photodetector integrated on SOI

Zhao Liu, Yong Liu*

State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Information, University of Electronic Science and Technology of China, Chengdu, 610054
Author e-mail address: 1434227613@qq.com

Graphene photodetector attracts a lot of attention for years and the bandwidth and responsivity are the key issues. Graphene has ultrafast carrier mobility approaching 20,000cm^{2}V^{-1}s^{-1}, however, the extremely low efficiency of photoelectric conversion and light absorption especially limit its application.

We design a structure combine Ge with graphene. Pin Ge-Si photodetector has impressive performance due to the ability of light absorption and electron transmission of Ge. But N-doped Si seriously impact the bandwidth and current. This problem will be improved in this structure when we add graphene on it.

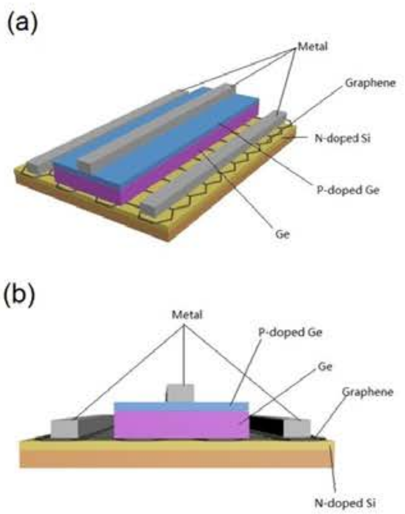


Fig.1 (a) Schematic views of pin graphene-Ge photodetector integrated in SOI waveguide. (b) Cross section of the pin diode.

Electrons generated from Ge will transmit through N-doped Si to positive electrodes. The velocity in N-doped Si is much lower because it is diffusion velocity compared to drift velocity in Ge. Simultaneously, a huge number of electrons in N-doped Si result in strong scattering which is also badly effected to bandwidth and responsivity. A monolayer graphene on N-doped Si will lead electrons to positive electrodes directly rather than diffuse through N-doped Si.

Simulation results

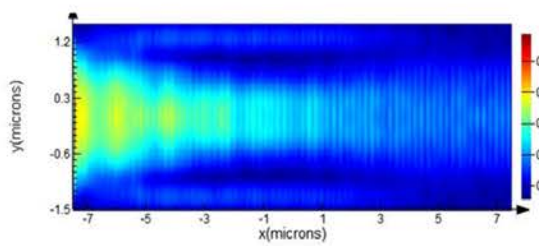


Fig. 2 Beam propagation simulation results of the device. Almost 100% light was absorbed by Ge material.

Almost all of the light from waveguide was absorbed by Ge till nearly 7um. If monolayer graphene is used as absorbing material, only 3% of light can be absorbed.

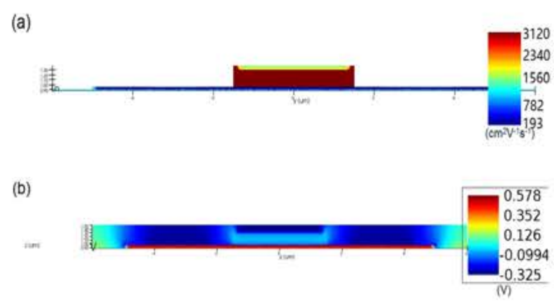


Fig. 3 (a) Mobility of all the materials. The mobility of N-doped Si is much smaller than that of others. (b) Inner field of this pin photodetector.

Figure 3 exhibits the mobility of N-doped Si is almost 193cm^{2}V^{-1}s^{-1} which is not large enough compared to graphene. The realistic velocity will much lower owing to that is diffusion velocity instead of drift velocity.

Conclusion

This device combine the advantages of graphene and pin Ge, and avoid the problems of both at the same time. It will have better performance when it is applied to photodetector.

Intrinsic phase response retrieval of optical filters based on magnitude response only measurement

Lingjie Zhang, Zhiyao Zhang*, Shangjian Zhang, Fei Yuan, Yong Liu

State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China

E-mail: zhangzhiyao@uestc.edu.cn

Introduction

We demonstrate an approach to retrieve the intrinsic phase response of an optical filter based on magnitude response only measurement.

Motivation:

- Simplify the measurement setup.
- Obtain the intrinsic phase response of optical filters without the influence of other devices (e.g. fiber pigtail).

Principle

- The minimum phase response $\phi_{\min}(\omega)$ and the logarithm of the magnitude response $\ln|H(\omega)|$ are related by the well-known Kramers-Krönig relation, given by

$$\phi_{\min}(\omega)=\frac{\omega}{\pi}\left[P.V.\int_{-\infty}^{+\infty}\frac{\ln|H(\Omega)|}{\Omega^2-\omega^2}d\Omega\right]$$

where *P.V.* represents the Cauchy principal value.

- Using the Wiener-Lee transform and trigonometric expansion, $\phi_{\min}(\omega)$ and $\ln|H(\omega)|$ can be expressed as

$$\ln|H(\omega)|=\sum_{n=0}^{+\infty}a_n\cos(n\omega)$$

$$\phi_{\min}(\omega)=\sum_{n=1}^{+\infty}b_n\sin(n\omega)$$

$$b_n=-a_n \qquad (n\geq 1)$$

- Not all kinds of optical filters can meet the requirement that the magnitude response is an even function. The flow chart of the phase retrieval algorithm is given in Fig. 1.

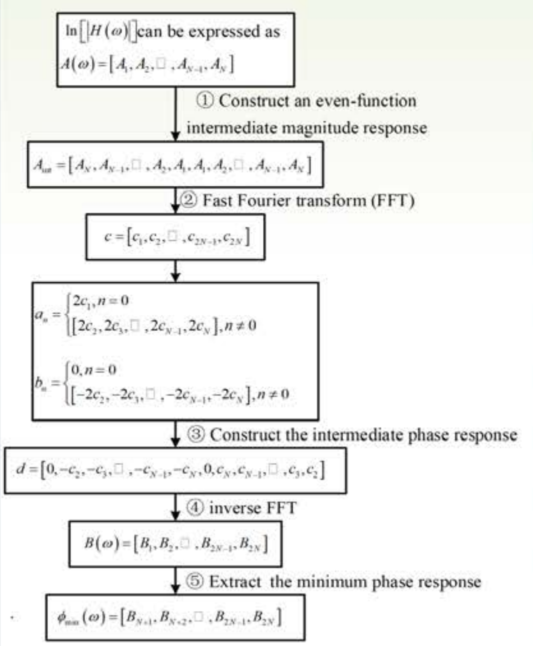


Fig. 1 Flow chart of the phase retrieval algorithm.

Experimental results

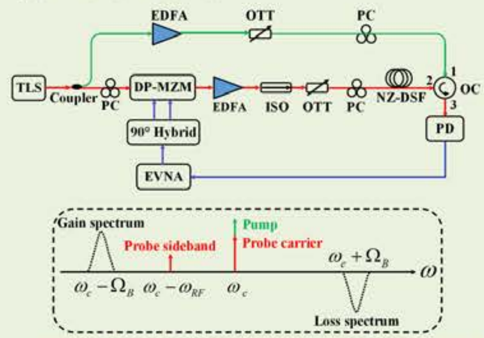


Fig. 2 Schematic diagram of the experimental setup to measure both the magnitude and the phase response of an active SBS-based optical filter.

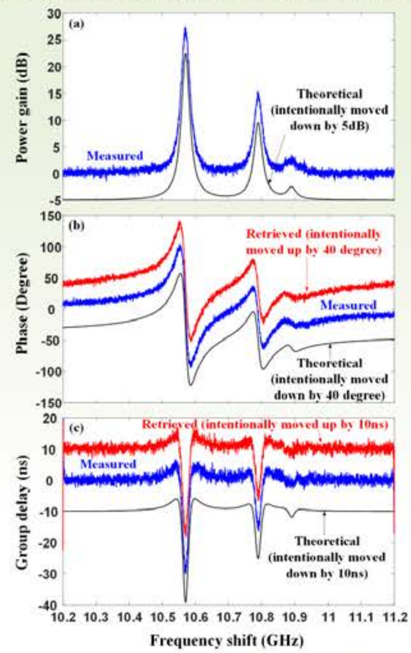


Fig. 3 Experimental results for an active SBS-based optical filters. (a) Power gain. (b) Phase response. (c) Group delay response. Blue lines: the measured results using the electrical VNA, red lines: the retrieved results using the proposed method; black lines: the theoretical results.

Summary

- Optical filters with a minimum phase response includes a uniform or apodized fiber Bragg grating (FBG), a PS-FBG, a Fabry-Perot filter, a WGM resonator, a microring resonator etc.
- This method is not suitable for a chirped fiber Bragg grating.
- This method can be used for not only optical devices but also electrical devices, where the only requirement is that the devices should have a minimum phase response.

University of Glasgow

电子科技大学

University of Electronic Science and Technology of China

UK-China Emerging Technologies Conference

Optically Tunable Microwave Frequency Down-conversion Based on an Optoelectronic Oscillator Employing a Phase-Shifted Fiber Bragg Grating

Zhen Zeng, Zhiyao Zhang*, Yangxue Ma, Shangjian Zhang, Yong Liu
State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China
E-mail: zhangzhiyao@uestc.edu.cn

Introduction

We demonstrate an approach to achieve optically tunable microwave frequency down-conversion based on an optoelectronic oscillator (OEO) incorporating a tunable microwave photonic filter (MPF).

Features:

◆ Wideband optically tunable local oscillation（LO）, which can be extended beyond 40 GHz.

◆ RF signal and LO signal are mixed by a single modulator in the OEO loop.

Principle

The operation principle can be briefly described as follows:

- CW light from TLS is split by an OC1 into two paths. The lower path is used to recover optical carrier in the OEO loop, and the other is modulated by the LO and RF signal.
- One modulation sideband of the LO falls into the reflection notch, and transmits through the PS-FBG.
- The other modulation sideband of the LO together with the two RF modulation sidebands and the optical carrier are reflected back to port 2 of the optical circulator, and output from port 3 into PD2 for realizing down-conversion.
- The optical carrier is combined with the filtered LO modulation sideband via OC2, and both of them are photo-detected by PD1 in the OEO loop to recover the electrical LO signal.
- By tuning the wavelength of the TLS (thus the frequency difference between TLS and PS-FBG reflection notch changes), the LO frequency can be varied.

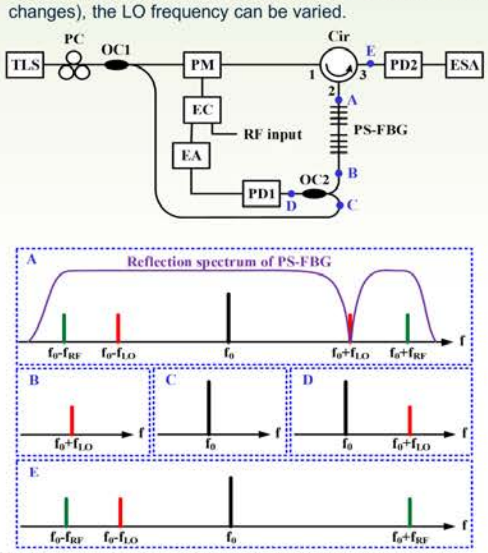


Fig.1 Schematic diagram of the OEO-based optically tunable microwave downconverter.

Experimental Results

□ Fig. 2(a) presents the superimposed open loop responses of the OEO, and Fig. 2(b) shows the superimposed spectra of the generated LOs in the frequency range of 6 GHz to 15 GHz.

□ In Fig. 3, RF signals with frequencies of 7 GHz to 16 GHz are successfully downconverted to IF band around 1 GHz.

□ Fig. 4(a) gives the measured conversion efficiency versus input RF frequency, and Fig. 4(b) exhibits the SFDR of downconverter which is tested by applying two RF tones at 9 GHz and 9.010 GHz with identical power.

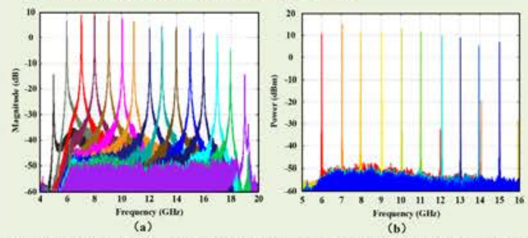


Fig.2 (a) Superimposed open loop responses of the OEO; (b) Superimposed spectra of the generated Los in the OEO.

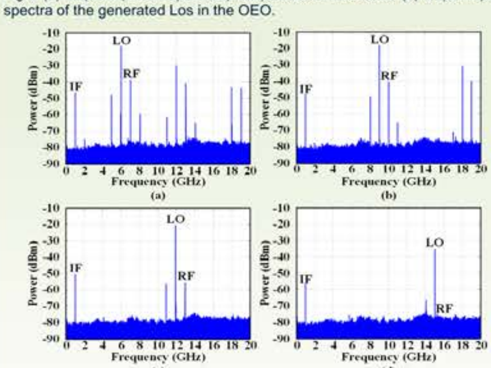


Fig. 3 Measured electrical spectra at the output of PD2 (RBW=100 kHz). (a) RF: 7 GHz, LO: 6 GHz. (b) RF: 10 GHz, LO: 9 GHz. (c) RF: 13 GHz, LO: 12 GHz. (b) RF: 16 GHz, LO: 15 GHz.

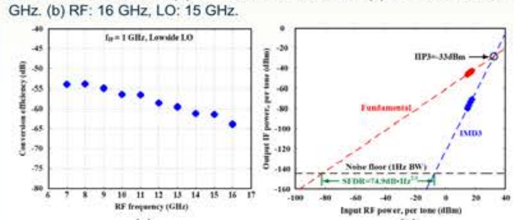


Fig.4 (a) Conversion efficiency versus input RF frequency; (b) SFDR of OEO-based downconverter.

Outlook

✓ Operation bandwidth can be extended by increasing the reflection bandwidth of the PS-FBG（>1.28 nm to cover >40 GHz bandwidth）and using devices (i.e., PM, EC, EA, PD1) with a broader bandwidth.

✓ Conversion efficiency and SFDR can be improved by using carrier-suppressed double-sideband modulation scheme, utilizing a high-power TLS (or adding optical amplifier) and employing PDs with a higher saturation power（or adding a LNA after PD2）.

University of Glasgow

电子科技大学

University of Electronic Science and Technology of China

Mechanism of dissipative-soliton-resonance generation in fiber laser mode-locked by real saturable absorber

Wenxiong Du, Heping Li, Junwen Li, Pinghe Wang, Shangjian Zhang, and Yong Liu

State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China

E-mail: wenxiong_du@163.com

Generation of dissipative soliton resonance (DSR) is numerically investigated in an all-normal-dispersion (ANDi) Yb-doped fiber laser mode-locked by a real saturable absorber (SA). Our simulation results will offer insight into the underlying mechanism of DSR generation in mode-locked fiber lasers by means of real SAs.

Introduction

High-energy fiber lasers have widespread applications as practical alternatives to solid-state lasers. In our simulation model, both the saturable absorption and reverse saturable absorption (RSA) effects are included in the SA. It is found that the RSA effect induced by the SA material itself is required for achieving the DSR pulses in the cavity. Understanding the mechanism of the DSR generation could be useful for generating optical pulses with the highest possible energy.

Numerical model

The proposed ANDi Yb-doped fiber ring laser is schematically shown in Fig. 1. The cavity consists of a piece of 1-m ytterbium-doped fiber (YDF), two pieces of single mode fiber (SMF) with a total length of 5 m, a Gaussian-shaped spectral filter with a bandwidth of 6 nm, a 20% output coupler (OC) and a real SA. The real SA is used as a mode locker. The YDF and SMF have dispersion parameters of about 36 and 23 ps^2/km at 1060 nm, respectively. The net cavity dispersion is 0.151 ps^2. It has been found that some SA materials exhibit different nonlinear absorption properties depending on the input pulse power. With increase of the pulse power, a changeover from saturable absorption to RSA can be observed.

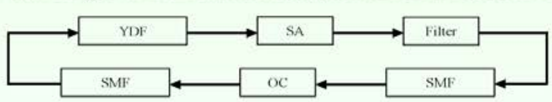


Fig. 1. Schematic of an ANDi Yb-doped fiber laser.

We numerically simulated the pulse formation and evolution in the laser cavity based on a cavity round-trip model. Briefly, the action of each cavity component on the optical pulses was taken into account. The simulation started from an arbitrary weak pulse, and eventually converged into a stable solution with appropriate parameter settings after a limited number of circulations in the cavity. The SA used in our simulation includes both the saturable absorption and RSA effects. The total power-dependent transmission coefficient can be expressed by:

$$T = 1 - \frac{\alpha_0}{1 + I(t)/I_{sat}} - \alpha_{ns} - \beta I(t)$$

where α_0 represents the modulation depth; α_{ns} denotes the non-saturable absorption; $I(t)$ is the instantaneous pulse power and I_{sat} is saturation power; β refers to the RSA coefficient.

Simulation results

The numerical model was solved by using the split-step Fourier method. We firstly simulated the intra-cavity pulse evolution in the absence of RSA effect in the SA. The SA parameters were set as $\alpha_0 = 0.25$, $\alpha_{ns} = 0.3$, $\beta = 0$ W^{-1} and $I_{sat} = 20$ W. The transmissivity of SA increases monotonically with the input pulse power. With increasing pump, the stable dissipative soliton (DS) is generated in the cavity, as observed from Figs. 2(a) and 2(b). Further increasing the pump E_{sat} to 6 nJ, the noise-like pulse (NLP) state occurs in the cavity. The corresponding calculated autocorrelation trace has a narrow spike riding on a broad shoulder, which is a unique characteristic of the NLP. No DSR operation state can be achieved in this case as is evident from the numerical results.

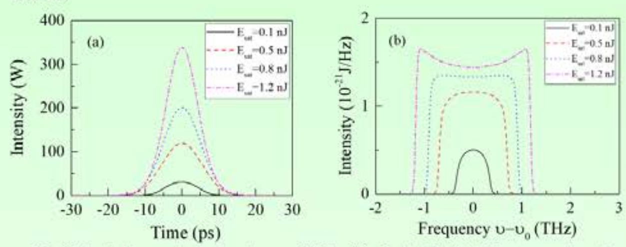


Fig. 2. Simulation results in the absence of RSA effect in the SA. (a) Pulse temporal profiles with the increasing E_{sat}. (b) Pulse spectral profiles with the increasing E_{sat}.

We also simulated the mode-locked pulse evolution in the cavity when both the saturable absorption and RSA effects are included in the SA. For the sake of comparing with the aforementioned case, we only altered the value of β from 0 kW^{-1} to 3 kW^{-1}. In this case, when the pump power is high enough, the RSA effect is activated, namely the transmissivity of SA decreases as the pulse peak power increases. As presented in Fig. 3(a), when the pump E_{sat} is increased from 0.1 nJ to 1.6 nJ, the pulse peak power initially increases and then clamps at a certain value while its temporal profile transfers from a Gaussian shape to a rectangular one. Figure 3(b) shows the change in the corresponding pulse spectra. The intensity in the central region of pulse spectrum increases continuously while the 3-dB bandwidth is significantly narrowed at first and then keeps almost constant. The evolution process from the DS to the rectangular pulse is in agreement with the DSR theory, indicating that stable DSR pulses are generated in the cavity.

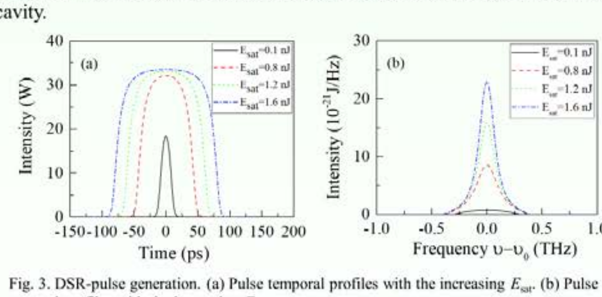


Fig. 3. DSR-pulse generation. (a) Pulse temporal profiles with the increasing E_{sat}. (b) Pulse spectral profiles with the increasing E_{sat}.

Conclusion

We have numerically demonstrated DSR-pulse generation in an ANDi Yb-doped fiber laser mode-locked by a real SA. The SA includes both the saturable absorption and RSA effects. Theoretical analysis shows that the RSA effect induced by the SA material itself plays a dominant role in generating the DSR pulses, which will be conducive to understanding the mechanism of DSR generation in passively mode-locked fiber lasers.

Polarization-Independent Electro-Absorptive Modulator Based on Slanted Graphene Buried in a Silicon-on-Insulator Waveguide

Yujia Zhang, Shengwei Ye, Rongguo Lu, Zhiyao Zhang, Yong Liu

State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China

E-mail: zhangyujiauestc@126.com

An electro-absorptive modulator (EAM), which is employed to impose electrical signal onto the intensity of light wave, is widely used in the fields such as optical communication, optical sensing and microwave photonics. In this paper, a polarization-insensitive EAM scheme is presented based on using slanted graphene which covers the silica-on-silicon waveguide both vertically and horizontally, and eliminates the polarization-dependent loss problem.

Background

Currently, most of the commercially-available EAMs are polarization-dependent, which means that they can only load signal onto either TE or TM mode in the waveguide.When these EAMs are used in the optical fiber transmission systems, polarization-dependent loss is a headache in the system design process, since the polarization state of light wave is random during its propagation in the optical fiber. Therefore, polarizations-insensitive EAMs, which can equally load signal onto both TE and TM modes, have attracted intensive attention in recent years.

The most commonly used scheme to realize a polarization-insensitive modulator is based on subtle waveguide structure design, in which a small waveguide fabrication error may generally lead to failure of eliminating polarization-dependent loss. In recent years, graphene is demonstrated to be a promising two-dimension (2D) material to realize high-speed electro-optic modulator. However, polarization-dependent problem still exsits in the previously reported schemes due to the unidirectional placement of graphene in the waveguide.

Proposed structure

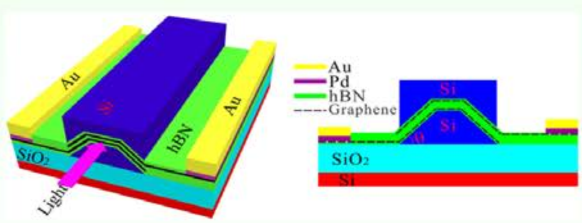


Fig.1. (a) 3D view of the EAM structure. (b) 2D cross section of the waveguide

Fig. 1 exhibits the geometrical structure of the proposed graphene-based EAM, where Fig. 1(a) and (b) present the three-dimension (3D) view of the modulator structure and the 2D cross section of the waveguide, respectively. The fabrication process of the EAM can be described as follows. Firstly, a silicon waveguide with a width of 500nm and a thickness of 300nm is epitaxially grown on a silica-on-silicon substrate. Then, the silicon waveguide with angled sidewalls (θ=55°) is fabricated by using SiO2 hard mask and fluorine-based dry etching technique, after which two CVD-grown graphene flakes are transferred upon it. Whereafter, silicon is further grown on the surface, forming a rectangular silicon-graphene waveguide with a cross sectional area of $500\times400nm^2$. The two graphene flakes are separated by an hBN isolation layer with a thickness of 40nm, which forms a capacitor. Besides, both the lower and upper graphene flakes are isolated from the silicon by an hBN isolation layer with a thickness of 5nm to prevent potential carrier injections from the graphene flakes into the silicon. In addition, the two flakes are extended out from both sides of the slanted silicon waveguide for metallization. Since the contact resistance between the graphene and Pd is low at room temperature, the metal palladium is deposited on the flakes followed by the Au which acts as the electrodes. Fig. 2 shows the calculated electric field distribution of TE and TM modes, respectively. It can be seen from Fig. 2 that the electric fields of both TE and TM modes are tightly confined in the slanted graphene layer, which is favorable for substantial electro-absorption.

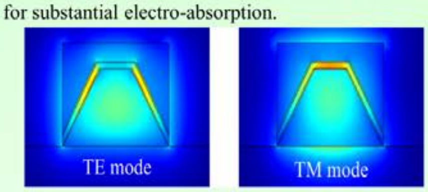


Fig.2Electric field distribution of TE and TM modes

Simulation Results

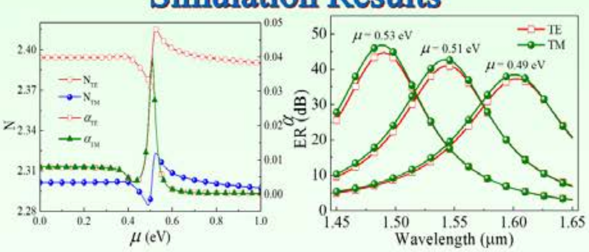


Fig.3. Calculated (a) effective refractive index and extinction coefficient under various chemical potential. (b) ER versus wavelength under three different chemical potential

Fig. 3(a) presents the effective refractive index and the extinction coefficient under various chemical potentials . It can be seen from Fig. 3(a) that the extinction coefficient of both TE and TM modes is nearly identical, which implies that the proposed scheme fulfills the requirement of a polarization-independent EAM. Fig. 3(b) shows the calculated extinction ratio (ER) versus wavelength under three different chemical potential , i.e., 0.53eV , 0.51eV and 0.49eV. It is obvious that the ER variation for both modes are almost synchronized, and ER over 40dB is achieved at 1550 nm for both modes.

Conclusion

We present a concept of a broadband polarization independent graphene-based electro-absorption optical modulator. Under different graphene chemical potentials and different wavelengths, the graphene induced EMI variations for TE and TM modes are investigated. The results show that TE and TM modes have most identical EMI variation, both the real and imaginary parts, which fulfills the requirement of polarization independent modulation. The ER gap between TE and TM modes is always kept at an acceptable level, and the polarization dependency for "ON" state is less than 0.1dB, even if the angle the slanted silicon stripe varies from 52° to 60° .

UK-China Emerging Technologies Workshop

21st – 22th August 2018, Glasgow, UK

Bi-directional Comb-fiber Architecture for Resolution Improvement of Optical Quantization Employing Soliton Self-frequency Shift and Spectral Compression

Xuyan Zhang, Zhiyao Zhang,* Heping Li, Yong Liu

State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Information, University of Electronic Science and Technology of China, Chengdu, China, 61005

Author e-mail address: xyzhang1921@126.com

INTRODUCTION

We demonstrate a high-resolution quantization scheme based on soliton self-frequency shift (SSFS) and spectral compression in a bi-directional comb-fiber architecture.

Advantages:

- ✓ Two sections of interleaved SMFs and HNLFs comb-like combination to achieve single-stage SSFS and three-stage spectral compression.
- ✓ Higher quantization resolution compared with its unidirection counterpart.
- ✓ Small volume and low cost.

OPERATING PRINCIPLE

☐ The operation principle can be briefly introduced as follows.

- Sampled optical pulses with various intensity, which are injected into port one of the optical circulator, output from port two and propagate in the forward direction (i.e., towards the right in Fig. 1) through HNLF_1 with an anomalous group-velocity dispersion to induce SSFS.
- Then, the wavelength-shifted optical pulses propagate in the forward direction through SMF_1 cascading HNLF_2 to achieve 1st-stage spectral compression.
- The output optical pulses from HNLF_2 are reflected by a Sagnac loop formed by connecting two output ports of a 2×2 3-dB optical coupler with SMF_2, and propagate again in the backward direction (i.e., towards the left in Fig. 1) through HNLF_2 for 2nd-stage compression.
- The further compressed optical pulses pass through SMF_1 cascading HNLF_1 for 3rd-stage compression.
- Finally, the quantized pulses output from port three of the optical circulator.

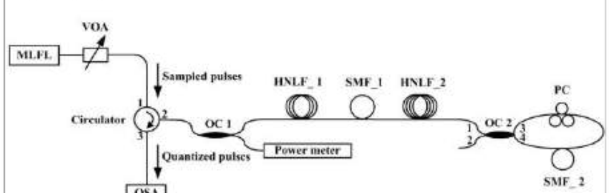


Fig. 1 Experimental setup of the proposed all-optical quantization.

☐ The resolution (i.e., number of quantization bits) of the proposed optical quantization scheme can be calculated

$$N = \log_2\left(\frac{\lambda_{shift} + \Delta\lambda_{FWHM}}{\Delta\lambda_{FWHM}}\right)$$

where λ_{shift} and $\Delta\lambda_{FWHM}$ are the maximum central wavelength shift and the spectral width of the optical pulses after quantization, respectively.

CONCLUSION

- ◆ A high-resolution optical quantization scheme based on SSFS and spectral compression in a bi-directional comb-fiber architecture is proposed and demonstrated.
- ◆ The resolution can be further improved if the number of sections of interleaved SMFs and HNLFs comb-like combination is increased.

EXPERIMENT & RESULTS

- ➢ The Sagnac loop is formed by a 2×2 3-dB optical coupler, a polarization controller and SMF_2.
- ➢ Fig. 2 shows the optical spectra after SSFS, which are measured at the end of HNLF_1.
- ➢ Fig. 3(a) and Fig. 3(b) show the output optical spectra of the proposed bi-directional scheme and its uni-directional counterpart, respectively.
- ➢ Fig. 4(a) and Fig. 4(b) present the relationship between central wavelength shift and input average power and the spectral width of the output optical pulse using both schemes, respectively.
- ➢ The results reveal that during the range of 1580.0 nm to 1672.2 nm, the output spectral width using the bi-directional scheme is approximately 1.3 nm and the resolution is calculated to be 6.2 bits which is 1.2-bit larger than that of its uni-directional counterpart

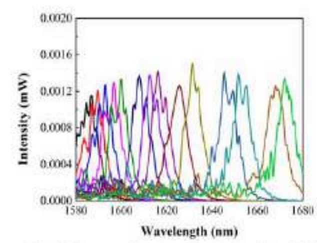


Fig. 2 Measured output spectra after SSFS.

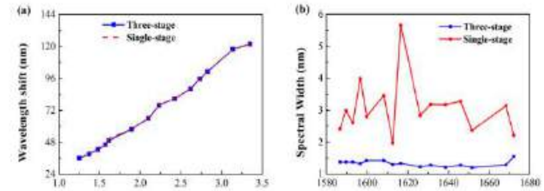


Fig. 3 Measured output optical spectra of (a) the proposed bi-directional optical quantization scheme, and (b) its uni-directional counterpart.

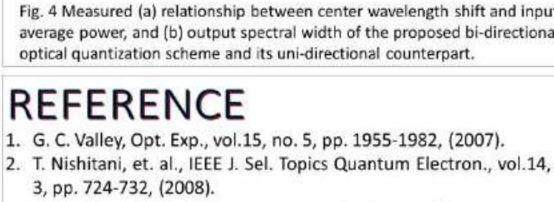


Fig. 4 Measured (a) relationship between center wavelength shift and input average power, and (b) output spectral width of the proposed bi-directional optical quantization scheme and its uni-directional counterpart.

REFERENCE

1. G. C. Valley, Opt. Exp., vol.15, no. 5, pp. 1955-1982, (2007).
2. T. Nishitani, et. al., IEEE J. Sel. Topics Quantum Electron., vol.14, no. 3, pp. 724-732, (2008).
3. X. Y. Zhang, et. al., Opt. Communications, vol. 410, pp. 571-576,(2018).

Accurate time-delay measurement of optical delay components based on frequency-shifted self-heterodyne spectrum

Mengke Wang, Shangjian Zhang*, Heng Wang, Xinhai Zou, Yali Zhang, Yong Liu

State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Information, University of Electronic Science and Technology of China, Chengdu, 610054
Author e-mail address: mkwanguestc@163.com

INTRODUCTION

The absolute time-delay is key parameter of optical delay components.

There are traditional optical and electrical methods, such as optical time-domain reflectometry, optical frequency-domain reflectometry, and electrical swept frequency methods for measuring the time-delay of optical delay components. The optical methods are limited by the adjustment resolution of the optical path, while the electrical methods require complicated de-embedding to avoid the ambiguity resulted by the phase periodicity. In this work, an electrical method is proposed for characterizing the time-delay of optical delay components based on the frequency-shifted self-heterodyne spectrum.

OPERATING PRINCIPLE

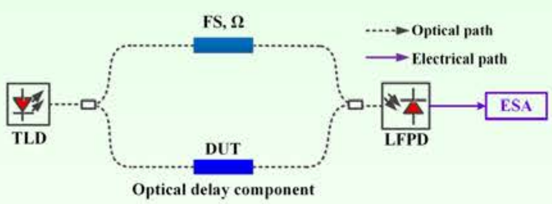


Fig. 1. Schematic diagram of the frequency-shifted self-heterodyne spectrum analysis method, TLD: tunable laser diode, FS: frequency shifter, LFPD: low-frequency photodetector, ESA: electrical spectrum analyzer.

The output power spectral density of the photocurrent can be summarized as the following equation

$$S(\omega)=\frac{P_0^2}{2}\cdot\frac{\alpha\cdot\tau_1}{\alpha^2+\theta^2}\cdot\left\{1-e^{-\alpha}\left[\cos\theta+\frac{\alpha}{\theta}\sin\theta\right]\right\}+\frac{\pi P_0^2}{2}\cdot e^{-\alpha}\cdot\delta(\omega-\Omega) \quad (1)$$

From Eq. (1), we can quantify the different θ values (m=1,2) corresponding to the first and the second troughs of the power spectral density, which can be expressed by

$$\theta=2m\pi+\frac{2e^{\alpha}-2+\alpha}{2m\pi},|m|\geq 1 \quad (2)$$

We set m=1,2. In this case, the time delay of one path with respect to the other path with and without DUT can be obtained, which are given by

$$\tau_i=\frac{3}{2f_{2i}-f_{1i}-f_0} \quad (3)$$

Where f_{1i} and f_{2i} (i=1,2) are the notch frequencies corresponding to the first and the second troughs on the same side of output power spectral density, respectively and f_0 is the FS frequency shift. So the absolute time-delay of optical delay components can be extracted by the following equation, given by

$$\tau=\tau_1-\tau_0 \quad (4)$$

EXPERIMENTAL RESULTS

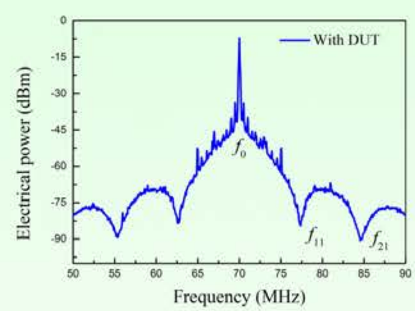


Fig. 2. Measured low-frequency electrical spectra in the case of f_0=70 MHz with DUT.

From Fig. 2, we can see that f_{11} and f_{21} are 77.3397 MHz and 84.6154 MHz, respectively. Based on Eq. (3), the τ_1 is calculated to be 1.3704×10^{-7} s.

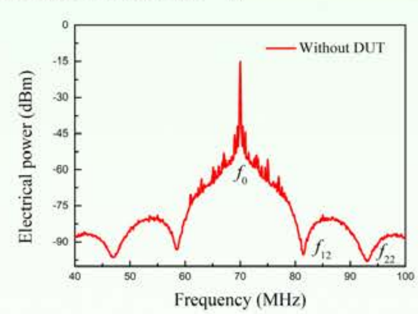


Fig.3. Measured low-frequency electrical spectra in the case of f_0=70 MHz without DUT.

Fig. 3 shows that f_{12} and f_{22} are 81.4423 MHz and 92.9808 MHz, respectively. Based on Eq. (3), the τ_0 is calculated to be 8.6908×10^{-8} s. So, the absolute time-delay of optical delay component is determined to be 5.0132×10^{-8} s.

CONCLUSION

In this work, the time delay can be accurately determined from the notch frequencies of the spectrum, enabling high-resolution and wide measurement range with low-frequency electrical spectrum analysis.

Single-shot photonic time-stretch digitizer using a dissipative soliton-based passively mode-locked fiber laser

Di Peng, Yuan Ling, Zhiyao Zhang, Yong Liu

State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Information, University of Electronic Science and Technology of China, Chengdu, China, 61005

Author e-mail address: dzllxpzp@163.com

INTRODUCTION

We demonstrate a single-shot photonic time-stretch digitizer using a dissipative soliton-based passively mode-locked fiber laser.

Motivation:

- ✓ Reducing pulse envelope-induced signal distortion with its flat spectrum.
- ✓ Increasing time-bandwidth product with its broadband optical spectrum.
- ✓ Improving SNR with its high energy spectral density or even avoiding using optical amplifier.
- ✓ Eliminating overlapping between neighboring pulses with its sharp spectrum edge.

OPERATION PRINCIPLE

☐ The operation principle can be briefly introduced as follows.

- Dissipative soliton is produced by the homemade passively mode-locked erbium-doped fiber laser (with net normal dispersion in the cavity) shown in Fig. 1.
- Dissipative soliton propagates through the first spool of dispersion compensation fiber (DCF1 in Fig. 2).
- Then, RF signal is loaded on the flat envelope of the optical pulse via a push-pull Mach-Zehnder modulator (MZM) biased at its quadrature point.
- The modulated signal propagates through the second spool of dispersion compensation fiber (DCF2 in Fig. 2).
- Finally, the slowed-down RF signal is converted back to the electrical domain by a photodetector, and digitized by a real-time digital oscilloscope.

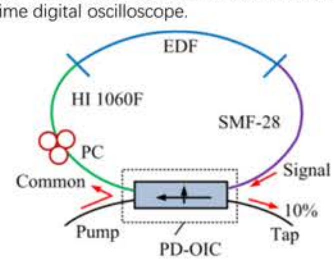


Fig. 1 Schematic diagram of the proposed dissipative soliton-based passively mode-locked erbium-doped fiber laser

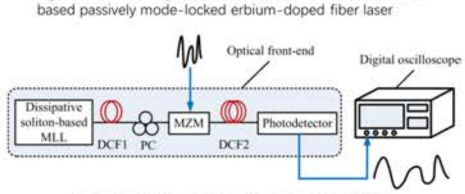


Fig. 2 Schematic diagram of the proposed digitizer.

CONCLUSION

- ◆ A dissipative soliton-based passively mode-locked erbium-doped fiber laser is produced, which has a relatively flat spectrum and an energy spectral density 50 times higher than that of the conventional one.
- ◆ By employing this home-made dissipative soliton-based optical source in a single-shot photonic time-stretch digitizer, an ENOB of 4.11 bits under an effective sampling rate of 100 GS/s is experimentally achieved.

EXPERIMENTAI RESULTS

- ➢ The net normal dispersion in the laser cavity is 0.205 ps^2, and the pump power is 196 mW.
- ➢ Table 1 shows the parameters of the DCFs used in the time stretch process.
- ➢ Fig. 3(a) and Fig. 3(b) present the output spectra of the proposed dissipative soliton fiber laser and a conventional soliton fiber laser, respectively.
- ➢ Fig. 4(a) and Fig. 4(b) exhibit the output waveform and Fourier spectrum of the dissipative soliton-based photonic time-stretch digitizer, respectively.
- ➢ Fig. 5(a) and Fig. 5(b) give the output waveform and Fourier spectrum of the conventional soliton-based photonic time-stretch digitizer, respectively.
- ➢ Through using dissipative soliton, ENOB of 4.11 bits is obtained without optical amplifying and removing the pulse envelope

Table 1. Parameters of the DCFs

Physical quantity	Values and Units
GVD coefficient (D)	-130ps/nm/km
Length of DCF1 (L1)	1.3km
Length of DCF2 (L2)	11.7km

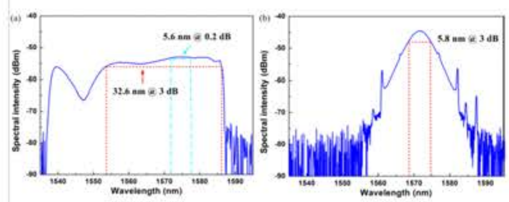


Fig. 3 Output spectra of (a) the dissipative soliton and (b) the conventional soliton.

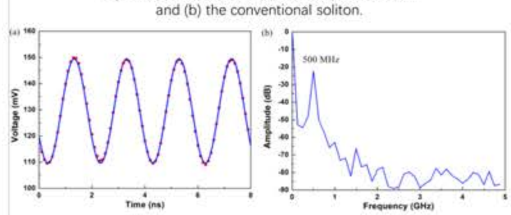


Fig. 4 Output of the dissipative soliton-based photonic time-stretch digitizer. (a) Waveform and (b) Fourier spectrum.

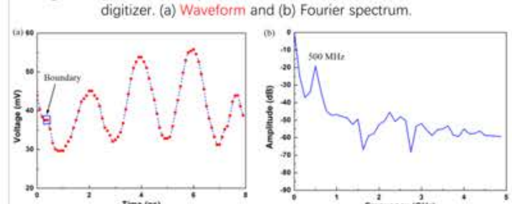


Fig. 5 Output of the conventional soliton-based photonic time-stretch digitizer. (a) Waveform and (b) Fourier spectrum.

REFERENCE

1. R. H. Walden, IEEE Journal on Selected Areas in Communications. 17(4), 539-550(1999).
2. Y. Han and B. Jalali, J. Lightwave Technol. 21(12), 3085–3103 (2003).
3. A. Mahjoubfar, et. al. Nat. Photonics 11(6), 341–351 (2017).

Generation of THz Radiation by Sampled Grating DBR Mode Locked Laser Diodes

Lianping Hou[1*], Bin Hou[1], Song Tang[1], Song Liang[2], Dejun Chen[3], John H. Marsh[1]

1. School of Engineering, University of Glasgow;
2. Institute of Semiconductors, Chinese Academy of Sciences;
3. School of Optoelectronic Information, University of Electronic Science and Technology of China

Abstract: 640 GHz THz signals were generated based on 1.55 μm operating wavelength sampled grating distributed-Bragg-reflector mode locked laser diodes and photomixing techniques which will pave a way to provide compact low-cost, robust THz sources.

1. Sampled grating DBR semiconductor mode locked laser diode structure and its mode locking performances

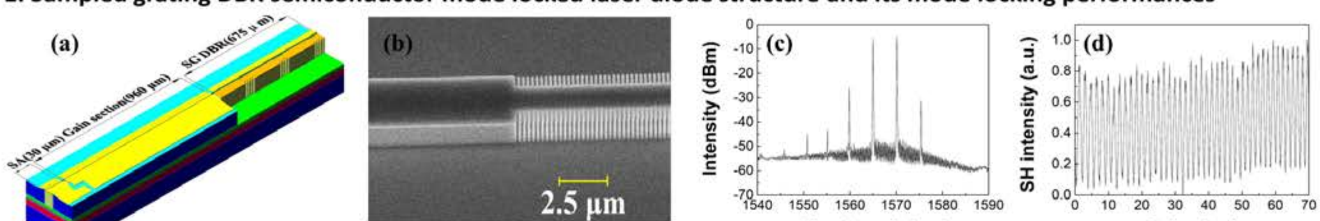


Fig. 1. (a) Schematic diagram of the 1.55 μm side-wall SGDBR SMLLD, (b) the SEM picture of first-order side-wall grating, (c) measured optical spectrum and (d) autocorrelaton traces of the 640 GHz SGDBR SMLLDs under $V_{SA} = -3$ V, $I_{Gain} = 204$ mA, $I_{SGDBR} = 0$ mA.

2. THz signals generation using a PCA which is directly modulated by a pulse generator

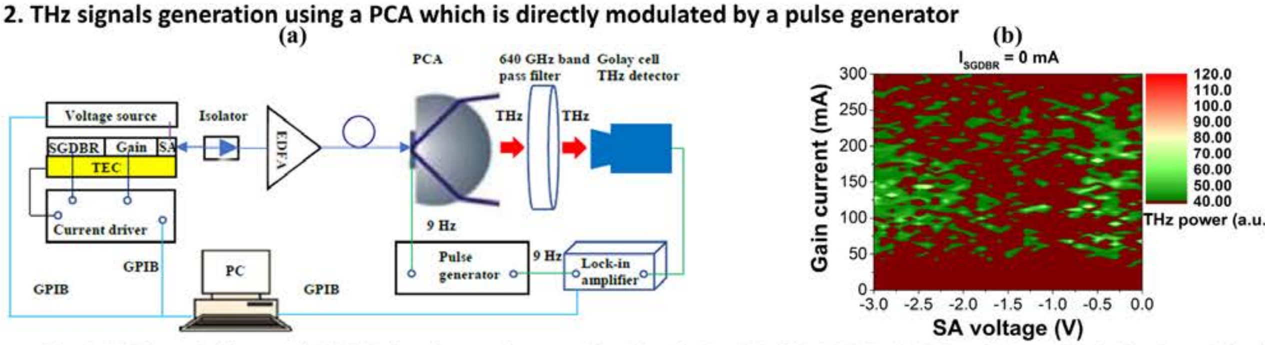


Fig. 2. (a) Schematic diagram of 640 THz signal generation system based on the $F_r = 640$ GHz SGDBR SMLLD and PCA which is directly modulated by a pulse generator; (b) measured THz signal power as a function of the gain current and the SA reverse voltage at $I_{SGDBR} = 0$ mA.

3. THz signals generation using a PCA which is external modulated by a an optical chopper

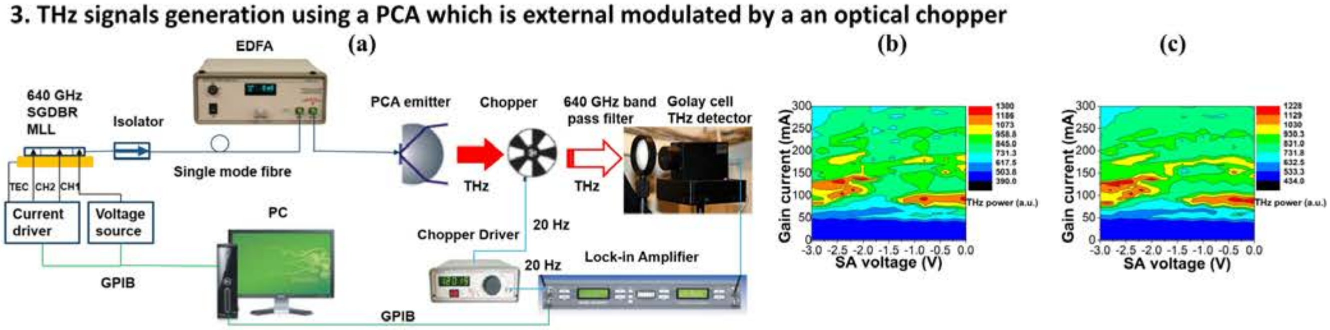


Fig. 3. (a) THz signal generation system based on a SGDBR SMLLD and a PCA which is external modulated by an optical chopper, (b) measured 2-D THz signal power as a function of the gain current and the SA reverse voltage at $I_{SGDBR} = 0$ mA without a white paper in front of the 640 GHz band pass filter and (C) when there is a white paper with a thickness of 80 g/m² ahead of the 640 GHz band pass filter.

4. Summary –A THz signal of 640 GHz was generated based on a 1.55 μm SGDBR SMLLD, EDFA amplification and photomixing in a photoconductive antenna(PCA). The system is a compact low-cost and robust source of narrow-band THz radiation, with all components operating at room temperature. This approach is expected to open new applications of THz technology.

University of Glasgow

The James Watt Nanofabrication Centre

Terahertz Signal Generation Based on Dual-Mode 1.5 µm DFB Diode Lasers

Song Tang[1], Bin Hou[1], Song Liang[2], Dejun Chen[3], Lianping Hou[1], John H. Marsh[1*]

1. School of Engineering, University of Glasgow; 2. Institute of Semiconductors, Chinese Academy of Sciences; 3. School of Optoelectronic Information, University of Electronic Science and Technology of China

Abstract: A novel dual-mode DFB semiconductor diode laser has been demonstrated. Using photomixing techniques, a terahertz signal at ~560 GHz has been generated. The terahertz (THz) signal shows power fluctuations related to mode competition in the laser.

1. Sampled Bragg grating design and device structure

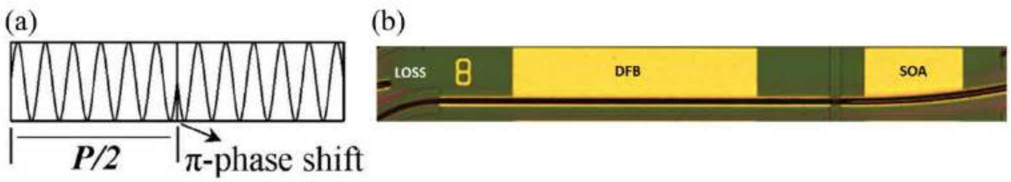


Fig. 1. (a) An sampled Bragg grating with two phase-shifted sections (2PS-SBG), P is the sampling period, (b) the micrograph of the fabricated device.

2. Optical spectrums and autocorrelation traces

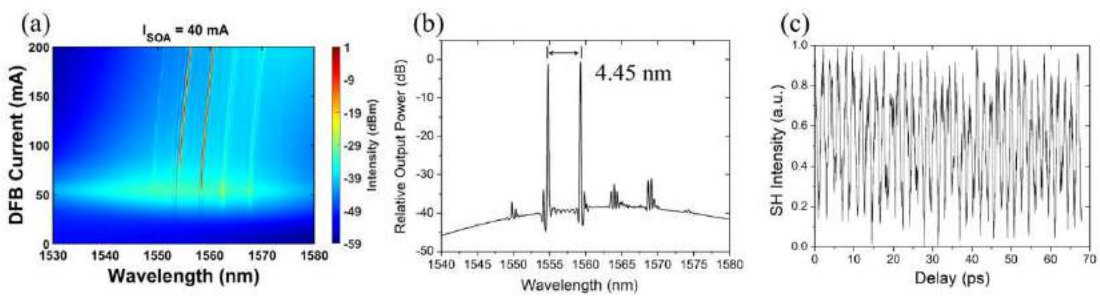


Fig. 2. (a) 2D-wavelength map at an SOA current of 40 mA, (b) the optical spectrum at an SOA current of 40 mA and DFB current of 120 mA, (c) corresponding autocorrelation traces showing mode beating frequency of 560 GHz.

3. THz signals generation and detection

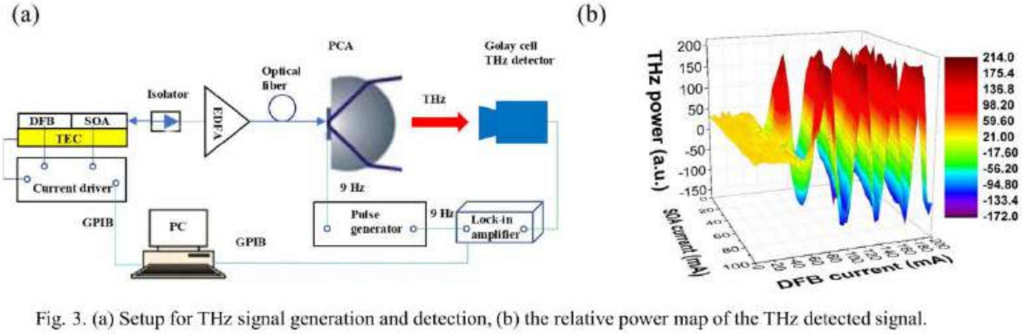


Fig. 3. (a) Setup for THz signal generation and detection, (b) the relative power map of the THz detected signal.

Summary – Novel dual-mode lasers have been applied to produce THz waves successfully based on photomixing