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Wideband Optical Networks [WON]

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WP5 – Innovative personal career training

Deliverable D5.4 Graduation of all ESRs with PhDs

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WON Consortium and Acronyms

Consortium member	Legal Entity Short Name
Aston University	Aston
Danmarks Tekniske Universitet	DTU
VPIphotonics GmbH	VPI
Infinera Portugal	INF PT
Fraunhofer HHI	HHI
Politecnico di Torino	POLITO
Technische Universiteit Eidhoven	TUE
Universiteit Gent	UG
Keysight Technologies	Keysight
Finisar Germany GmnH	Finisar
Orange SA	Orange
Technische Universitaet Berlin	TUB
Instituto Superior Tecnico, University of Lisboa	IST

CONTENTS

EXECUTIVE SUMMARY

The deliverable D5.4 titled 'Graduation of all ESRs with PhDs', is part of Work Package 5, which focuses on 'Innovative personal career training' within the European Training Network 'Wideband Optical Networks (ETN WON).' This project is funded through the Horizon 2020 Marie Skłodowska-Curie scheme under Grant Agreement (GA) 814276.

The purpose of this document is to provide details about the graduation of recruited ESRs within the WON project, their enrollment in PhD programs and the progress of their respective PhD theses as of the submission date of this deliverable. In summary, four PhD theses have been successfully completed and defended (see Section 2), while eight PhD theses are currently in preparation (see Section 3.). It is important to note that the information provided for the ongoing PhD theses, including titles, abstracts, and submission dates, may be subject to modifications and amendments based on the evolving progress.

It should be noted that, as a deviation from the initial plan outlined in the GA, two out of the fourteen ESRs recruited by the project consortium did not complete their PhD studies due to personal circumstances, despite finishing their research projects and employment contracts with the hiring beneficiaries (See Section 4).

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1 RECRUITED ESR COHORT

ERS N	Name	Recruiting Beneficiary	Contract start date	Contract end date	PhD Enrolment
ESR 1	Rasoul Sadeghi Yamchi	Politecnico di Torino	01/09/2019	31/08/2022	Politecnico di Torino
ESR 2	Thyago Monteiro Sá Pinto	Technical University of Denmark	1/09/2019	31/08/2022	Technical University of Denmark
ESR 3	André Luiz Nunes de Souza	Infinera Portugal	18/01/2021	30/06/2023	IST
ESR 4	Bruno Vinicius de Araujo Correia	Politecnico di Torino	01/12/2019	30/11/2022	Politecnico di Torino
ESR 5	Elliot Peter London	Politecnico di Torino	01/09/2019	30/11/2022	Politecnico di Torino
ESR 6	Gabriele Di Rosa	VPIphotonics GmbH	01/05/2019	30/04/2022	Technical University of Berlin
ESR 7	Caio Marciano Santos	Fraunhofer HHI	16/09/2021	30/06/2023	Not registered in PhD program
ESR 8	Pratim Hazarika	Aston University	01/112019	31/10/2022	Aston University
ESR 9	Yu Wang	Eindhoven University of Technology	15/11/2019	14/11/2022	Eindhoven University of Technology
ESR 10	Rafael Magalhães Gomes Kraemer	Eindhoven University of Technology	01/12/2019	08/09/2022	Eindhoven University of Technology
ESR 11	Aleksandr Donodin	Aston University	16/09/2019	15/09/2022	Aston University
ESR 12	Matheus Sena	Fraunhofer HHI	10/06/2019	09/06/2022	Technical University of Berlin
ESR 13	Yaonian Cui	Fraunhofer HHI	01/08/2019	31/07/2022	Not registered in PhD program
ESR 14	Emadreza Soltanian	Ghent University	19/08/2019	18/08/2022	Ghent University

2 PHD THESES COMPLETION AND DEFENCE

2.1 Thyago Monteiro Sà Pinto

Host beneficiary:	Technical University of Denmark (DTU)
PhD Enrolment:	Technical University of Denmark (DTU)
Supervisor:	Professor Darko Zibar
PhD thesis title:	**Spectral Shaping of Electro-Optical frequency Combs using Machine Learning Techniques**
PhD defence date:	4 November 2022
Access to Full Text (Open Access)	DTU Findit (DTU library) https://findit.dtu.dk/en/catalog/63c6559db88e571c23e8b245

PhD Thesis Abstract

Electro-Optical frequency combs (EOFC)s are widely applied in areas such as metrology, spectroscopy, light detection and ranging, detection of exoplanets, and optical communications systems. Among their advantages, EOFCs offer high stability in the frequency spacing, coherence in the phases, and the possibility to replace an array of lasers with one single optical source. In contrast, EOFCs require strict control over the power distribution per carrier (or line), constituting an essential parameter for efficient EOFC applications. The EOFC power profile is mainly represented by the flatness which is the difference between the maximum to minimum peak power in a frequency window.

In this work, machine learning (ML) algorithms are demonstrated to improve the characteristics of EOFCs in terms of flatness, carrier-to-noise ratio (CNR), and the number of carriers. The laser is driven by optimized bias current and RF driving signal composed of multiple harmonics. The bias current, amplitude, and relative phases of the harmonics in the laser RF driving signal are optimized using inverse system design, reinforcement learning, and gradient-free optimizers such as particle swarm optimization (PSO) and differential evolutionary (DE) algorithms. The methods presented in this work support contributions for developing an optimization benchmark for EOFCs, automation of setups including EOFC combs, and use of harmonic composition to improve flatness in combs. The contributions are demonstrated numerically and experimentally using EOFCs based on GS-lasers, Mach-Zehnder modulators, and silicon ring resonator modulators. The optimization techniques yield to improve performance of state-of-art EOFCs, and the results in this work show how ML techniques support the increase of capabilities applications of EOFCs.

2.2 Aleksandr Donodin

Host beneficiary	Aston University, United Kingdom
PhD Enrolment	Aston University, United Kingdom
Supervisors	Professor Sergei Turitsyn
PhD thesis title	**Bismuth-doped fibre amplifiers for multi-band optical networks**
PhD defence date	14 December 2022
Access to Full Text (Open Access)	Aston Research Explorer https://research.aston.ac.uk/en/studentTheses/bismuth-doped-fibre-amplifiers-for-multi-band-optical-networks

PhD Thesis Abstract

Fibre-optic networks are the backbone of the global communications infrastructure that made possible modern Internet, providing a multitude of online services and a digital economy. The development of novel approaches for further increasing capacity of optical communication systems is in the focus of research around the world due to the constantly growing data traffic and the corresponding bandwidth demand. Arguably, the most practical technique is multi-band transmission which utilises a huge spectral bandwidth of the existing fibre base that has not previously been used. Unlike spatial division multiplexing, multi-band transmission does not require a new fibre deployment. However, it involves a significant upgrade of current networks with novel amplifiers in the O-, E-, S-, and U- optical bands that are yet to be developed and optimised.

In this thesis, E- and S-band bismuth-doped fibre amplifiers (BDFAs) are demonstrated. The following record characteristics of BDFAs are achieved: 40 dB gain, 4.5 dB noise figure, and 38% power conversion efficiency. In total, three BDFAs have been developed, characterised and optimised using pump laser diodes at different wavelengths. Two modelling techniques of BDFAs are proposed: one based on conventional rate equations, and another one based on a neural network "black box" approach. Both of these methods are analysed and their challenges are discussed. A big part of the thesis is devoted to data transmission demonstrations supported by developed BDFAs in E- and S-bands. The experiments include both IM/DD and coherent signal transmissions through various lengths of single mode fibre including record E-band transmission through 160 km of single mode fibre. In addition, a multi-band transmission experiment in E-, S-, C-, and L-band is performed with an in-line amplifier based on combined bismuth-doped fibre and discrete Raman amplification. The total signal bandwidth is 195 nm and the total number of transmitted channels is 143. The obtained results pave the way towards commercial implementation of multi-band transmission enabled by BDFAs in E- and S- optical communication bands.

2.3 Pratim Hazarika

Host beneficiary	Aston University, United Kingdom
PhD Enrolment	Aston University, United Kingdom
Supervisor	Professor Wladek Forysiak
PhD thesis title	**Performance Evaluation of Raman Amplifiers in Fibre Optic Communication Systems**
PhD defence date	24 March 2023
Access to Full Text (Open Access)	Aston Research Explorer https://research.aston.ac.uk/en/studentTheses/

PhD Thesis Abstract

This thesis presents an overview of Raman amplifiers in fibre optic transmission systems. Detailed analysis of the nonlinear accumulated noise and relative intensity noise (RIN) induced penalties are evaluated in discrete and distributed Raman amplifiers. In addition to these the thesis also includes different architectures of Raman amplifiers enabling multiband transmission. The parametric dependency of fibre chromatic dispersion (CD) on the accumulated nonlinear noise in discrete Raman amplifiers (DRAs) was studied both theoretically and experimentally. Analytical modelling was performed over different fibre types that are widely used as a gain medium in DRAs. It was found that systems using Raman gain fibres with a positive value of CD induce lower accumulated nonlinear noise in comparison to systems using Raman gain fibres with a negative value of CD. The results obtained from the analytical model were then validated experimentally over a long-haul transmission system with DRAs as an inline amplifier using a recirculation loop.
RIN-induced penalties in distributed Raman amplifiers (DiRAs) were experimentally studied in two standard single-mode fibre (SSMF) G.654.E©TXF and G.652.D with different pumping schemes. Signal RIN for G.654.E© TXF was found to be lower in comparison to its counterpart G.652.D. The impact of RIN on the short-haul system was validated using both the test fibres pumped in a forward-pumped distributed Raman. Similarly, backward and bidirectional pumping was performed over a long-haul transmission system using a recirculation loop. It was experimentally observed that RIN-induced transmission penalties for G.654.E are lower in comparison to G.652.D making it a better choice of SSMF type for distributed amplification.

Experiments on novel architectures such as cascaded dual-stage and dual-band designs were demonstrated over a coherent transmission system with S-, C- and L-band signals. It was observed that the dual-stage design requires a guard band of ~10 nm to prevent overlapping of the pumps and signal, reducing the overall transmission capacity. In contrast, for dual-band design, no such guard band was required, but this benefit comes at a cost of the additional pump requirement increasing the overall amplifier power consumption. The performances of novel multistage Raman amplifier structures were also evaluated over the E-, S-, C- and L-band. Experimental studies were performed independently using DRAs only, hybrid bismuth-DRA and hybrid distributed-DRA. The E- and S-band signals were seen to have higher performance penalties in comparison to C- and L-band signals in the case of DRAs only and hybrid bismuth-DRA. In contrast, for the hybrid distributed-discrete design, the E-band signals were seen to have a similar penalty as C- and L-band signals.

2.4 Gabriele di Rosa

Host beneficiary	VPIphotonics GmbH, Germany
PhD Enrolment	Technical University of Berlin (TUB), Germany
Academic Supervisor	Professor Ronald Freund
Host supervisor/ Industrial Mentor	Dr André Richter
PhD thesis title	**Digital Optimization Techniques for Multi-Band Optical Communication Systems**
PhD defence date	15 May 2023
Access to Full Text (Open Access)	Deposit Once, TUB Repository for Research Data and Publications https://depositonce.tu-berlin.de/home

PhD Thesis Abstract

The ever-increasing data load on the fiber-optic network infrastructure rapidly encourages next-generation communication systems to operate in a larger optical transmission window extending beyond the C-band. This approach increases the channel capacity while not requiring the deployment of additional fiber-optical cables, enabling the effective reuse of this valuable asset. This unique feature of multi-band systems is a strong driver for the techno-economic assessment of techniques for next-generation higher-capacity optical networks. Following this strategy, a relatively smooth transition from the legacy C-band systems to commercial solutions extending the wavelength range of operation to the C-L-band was witnessed in the past years. The next natural step in exploiting the optical fiber low attenuation window is the development of S-C-L-band systems. However, this transition poses considerably more complex challenges than the previous network upgrade due to the surge of peculiar multi-band effects and the lack of established transceiver and amplification technologies in this range of wavelengths. The first part of the thesis reviews standard coherent optical communication systems and outlines some additional challenges arising when extending operation to the S-C-L-band from the system design perspective. On the physical level, particular emphasis is given to coherent transceivers' operation, channel modeling, and multi-band amplification techniques, with original results concerning the modeling of multi-band Raman amplifiers. Finally, digital modulation and digital signal processing (DSP) for optical coherent communication systems are reviewed, and the benefits of constellation shaping for capacity maximization over a wavelength-dependent channel are presented. In the second part of the thesis, the wavelength-dependency of imbalances between the in-phase (I) and quadrature (Q) components of the signals in off-the-shelf C-band coherent transceivers operating in the S-C-L-band is characterized. The results obtained verify the effectiveness of operating the commercially available devices considered with no clear penalties in a multi-band scenario without increasing the DSP complexity or the device characterization effort. The third part of the thesis presents novel improved DSP algorithms that adapt over variable signal characteristics and local channel conditions. First, a low-complexity carrier phase recovery (CPR) which improves the algorithm performance for probabilistically shaped signals by adapting the decision regions to the signal and noise statistics is described. Next, a blind update rule for amplitude-based multiple-input-multiple-output (MIMO) equalization that improves the convergence and tracking ability of the algorithm for static and dynamic channel conditions is presented. The improved update is based on the likelihood of the received samples being correctly assigned. The main result is a larger tolerance in differential group delay (DGD) for the blind operation of the equalizer and improved tracking ability of the rapidly-varying state of polarization (SOP) for an equalization scheme supported by periodically inserted pilot symbols. The final part of the thesis presents a statistical method to separate nonlinear interference noise (NLIN) into a Gaussian noise and a nonlinear phase noise (NLPN) component.

The generation of NLIN when using shaped constellations and its interaction with the receiver-side DSP is analyzed by considering the amount of correlation of the NLPN under different channel conditions. In this way, it is possible to predict the achievable post-DSP transmission performance for transmission over the nonlinear fiber channel.

3 ONGOING RESEARCH: PHD THESES IN PREPARATION

3.1 Rasoul Sadeghi Yamchi

Host beneficiary	Politecnico di Torino, Italy
PhD Enrolment	Politecnico di Torino, Italy
Supervisor	Professor Vittorio Curri
Industrial Mentor	Dr Nelson Costa, Infinera Portugal
PhD thesis title	**Multi-Band Optical Networks Capacity, Energy, and Techno-Economic Assessmen**
PhD defence date	Expected: Autumn 2023
Access to Full Text (Open Access)	Politecnico di Torino Libraries https://iris.polito.it/

PhD Thesis Abstract

As the use of 5G/6G services, video applications on the internet, and cloud services and data centers becomes more popular, network traffic is constantly increasing. This means that there is a continuous need for expanding the capacity of optical networks. In the past, efforts were made to increase fiber capacity by improving spectral efficiency through techniques like high-order modulation and constellation shaping. However, the Shannon limit sets a limit on spectral efficiency at a specific transmission distance, which means that there is a greater reliance on utilizing the optical spectrum from either the same optical fiber or other optical fibers. This can be achieved through extending to more wavelength bands or deploying more fibers, or through spatial division multiplexing. These methods will need to be increasingly utilized to keep up with growing network traffic. In this thesis, Multi-band optical fiber transmission is generally proposed and investigated for capacity upgrades in optical transport networks. To comprehensively assess the potential of ulti-band transmission, key metrics such as the potential capacity increase, energy consumption, and the number of required interfaces must be evaluated for different transmission scenarios. Thus, first of all, it has been considered progressive spectral exploitation, starting from the C-band only and up to C+L+S+U-band transmission, for both transparent and translucent solutions that exploit optical signal regeneration. By considering accurate state-of-the-art physical layer models for each investigated multi-band configuration, networking performance metric that enables the comparison of different solutions in terms of capacity allocation and energy consumption have been driven. For a translucent network design, different regenerator placement algorithms are compared, with the aim of minimizing energy consumption and costs.

The proposed network-wide numerical analysis shows that, for spectral occupations exceeding the C+L-band, translucent solutions can significantly increase network capacity, while leading to a similar energy consumption per transmitted bit as in the transparent design case, but they require the deployment of additional line interfaces. Significantly these results provide evidence that the transparent exploitation of an additional transmission band produces a capacity increment that is at least comparable to that of a translucent solution based on already-in-use bands. Since this is attained at the expense of fewer line interfaces, it is a key finding suggesting that extending the number of bands supported is a cost-effective approach to scaling the capacity of existing fiber infrastructures. Moreover, it has been compared and
analyzes comprehensively the network capacity, along with the required number of interfaces and amplifiers for different network topologies, for both regular and extended bandwidth (super) bands which recently proposed to efficiently use of already installed devices. Thus, two multi-

band transmission (MBT) scenarios: first, the regular configurations, consisting of the C+L-band and C+L+S1-band – being S1 half of the standard S-band, with total bandwidths of 9.6 and 14.4 THz, respectively, and second, extended bandwidth configurations for the C- and C+L-band, with total bandwidths of 6 and 12 THz, respectively have been investigated in this thesis. Both transparent and translucent network design scenarios are applied. Numerical network assessment process assisted by an accurate physical layer model, for all MBT configurations in this part performed as well. It has been shown that compared to regular bands, super bands significantly increase network capacity for both uniform and nonuniform traffic distributions. Crucially, super bands require fewer line interfaces, suggesting that extending the bandwidth of already deployed bands is a cost-effective approach when up-scaling existing fiber infrastructures, in comparison to add extra bands.

3.2 André Luiz Nunes de Souza

Host beneficiary	Infinera Unipessoal Lda – Infinera Portugal
PhD Enrolment	Instituto Superior Tecnico, Lisbon University, Portugal
Host supervisor Industrial Mentor	Dr João Pedro. Dr Nelson Costa
Academin supervisor	Professor João Pires
PhD thesis title	**Power Optimization and Techno-Economic Aspects of Multiband Optical Networks**
PhD defence date	Expected date of submission: December 2023, Expected date for defence: May 2024
Access to Full Text (Open Access)	Scientfic Repository https://repositorio.ul.pt/
PhD Thesis Abstract	

3.3 Bruno Correia

Host beneficiary	Bruno Vinicius De Araujo Correia
PhD Enrolment	Politecnico di Torino, Italy
Supervisor	Professor Vittorio Curri
Industrial Mentor	Dr Antonio Napoli, Infinera Germany
PhD thesis title	**Optical Line Systems Power Optimization and Optical Network Design for Multi-band Transmission**
PhD defence date	Expected: Autumn 2023
Access to Full Text (Open Access)	Politecnico di Torino Libraries https://iris.polito.it/
PhD Thesis Abstract	

Not ready at the date of the submission.

3.4 Elliot London

Host beneficiary	Elliot London
PhD Enrolment	Politecnico di Torino, Italy
Supervisor	Professor Vittorio Curri
Industrial Mentor	Dr Antonio Napoli, Infinera Germany
PhD thesis title	**Nonlinear Interference Generation in Wideband and Disaggregated Optical Network Architectures**
PhD defence date	Expected: Autumn 2023
Access to Full Text (Open Access)	Politecnico di Torino Libraries https://iris.polito.it/

PhD Thesis Abstract
To account for unprecedented rises in capacity and throughput, network operators are seeking to exploit network components and structures in the most cost-effective way possible. One of the most promising methods to achieve this is the expansion of coherent transmission into currently-unused wideband frequencies, which would permit significant capacity increases, and goes hand-in-hand with advances in network structures towards open and multi-vendor approaches, corresponding to increasing levels of network disaggregation. Practical implementation of wideband transmission is currently hindered by a lack of maturity in both modelling and component technologies, with frequency-dependent effects such as stimulated Raman scattering (SRS) and nonlinear interference (NLI) requiring consideration for the former, and reliable and scalable devices required for the latter. The creation of an accurate wideband NLI model that also supports disaggregated architectures is therefore a desirable required to handle advancements in network technology. In this framework, all wavelengths and fiber spans must be modelled independently, across the entire wideband spectrum. Within this thesis a wideband and disaggregated NLI model is introduced, and subsequently validated using numerical simulation tools, most notably an implementation of the split-step Fourier method (SSFM) that permits wideband and disaggregated transmission. A wide variety of network configurations are investigated, including non-uniform disaggregated and dispersion-managed network segments, and experimental transmission through a single fiber span across the L-, C-, S-, and E-bands. The intricacies of power optimization, wideband amplification, and quantification of coherent and nonlinear contributors to quality of transmission are then discussed, and optimised approaches to wideband and disaggregated transmission are presented.

3.5 Yu Wang

Host beneficiary	Eindhoven University of Technology (TU/e), The Netherlands
PhD Enrolment	Eindhoven University of Technology (TU/e), The Netherlands
Supervisor	Assistant Professor Nicola Calabretta
Industrial Mentor	Dr Antonio Napoli, Infinera Germany

PhD thesis title	**Wideband optical filters and switches**
PhD defence date	Expected: November 2023
Access to Full Text (Open Access)	TU/e Open Access Repository https://research.tue.nl/en/studentTheses/

PhD Thesis Abstract

To efficiently switching the large heterogeneous data traffic in wideband optical network (WON), wideband wavelength selective switch (WSS) is one of the key subsystem components to implement a programmable network by dynamically routing wavelengths from any inputs to any outputs of an optical switching node without electric-optic conversion. At present, commercial WSSs are based on liquid crystal, free space optics and micro-electro-mechanical technologies. Such technologies could be used to in WON by wavelength extension operation to cover multi-band beyond the C-band. However, they have disadvantages of bulky size, complex assembly, high cost and low switching speed. Meanwhile, the WSS based on photonic integrated circuit (PIC) technologies is the attractive option for managing data traffic in WON as PICs could potentially provide compact footprint, high stability, mass productivity, potentially low cost, fast switching speed and wavelength and polarization insensitive operation. Typical configuration of PIC-WSSs consists of passive demultiplexer/multiplexer (Demux/Mux) for wavelengths separation/combining and active photonic switching units for wavelengths bypass/blocking.
To realize the PIC-WSS for WON application, the Demux/Mux are required to have ideal performance of low insertion loss (< 2 dB), narrow channel spacing (100 GHz), low polarization dependent loss (PDL < 0.5 dB), low polarization dependent wavelength shift (PDWS < 0.1 nm), low crosstalk level (< -30 dB) and large operation wavelength range (O- band to L- band). The challenges in meeting these requirements lie in enabling the same design working for WON with similar performance. Meanwhile, the PIC Demux/Mux should be compact enough and have negligible wavelength mismatching. For the switching unit, the desired features should have nanosecond switching speed, < 1.5 dB insertion loss, 20 dB extinction ratio, < 2 dB PDL and wideband operation. The difficulty in achieving this goal is to simultaneously implement these functions (especially for low PDL and ultrafast switching) on the same PIC platform.
Investigation of hybrid PIC configuration using optimized passive components and active components in different PIC technologies is currently gaining a lot of attention as this allows optimal performance that might be not achieved in a single PIC platform.

The research described in the thesis aims to provide solutions for developing novel wideband PIC-WSSs with the Demux/Mux and the switch matrix, and addresses three interrelated aspects:
1) Wideband PIC Demux/Mux based on Arrayed waveguide grating (AWG) and planar Echelle grating (PEG) on 3-μm silicon photonics (SiPh) platform.
2) Wideband and PI switch matrix on polymer and 3-μm photonic platform.
3) Monolithic and hybrid integrated WSS.

3.6 Rafael Kraemer

Host beneficiary	Eindhoven University of Technology (TU/e), The Netherlands
PhD Enrolment	Eindhoven University of Technology (TU/e), The Netherlands
Supervisor	Assistant Professor Nicola Calabretta
Industrial Mentor	Dr. Antonio Napoli, Infinera Germany
PhD thesis title	**Wavelength Selective Switching for Wideband Optical Networks**
PhD defence date	Expected: December 2023
Access to Full Text (Open Access)	TU/e Open Access Repository https://research.tue.nl/en/studentTheses/ https://research.tue.nl/en/persons/rafael-kraemer
PhD Thesis Abstract	
Not ready at the date of the submission.	

3.7 Matheus Ribeiro Sena

Host beneficiary	Fraunhofer HHI, Germany
PhD Enrolment	Technische Universität Berlin (TUB), Germany
Supervisors	Dr Johannes Fisher
Academic Supervisor	Professor Ronald Freund
Industrial Mentor	Dr Andre Richter
PhD thesis title	**Analysis and Application of Digital Signal Processing Algorithms for Intelligent Optical Coherent Transceivers in Multiband Systems**
PhD defence date	Expected: November 2023
Access to Full Text (Open Access)	Deposit Once, TUB Repository for Research Data and Publications https://depositonce.tu-berlin.de/home

PhD Thesis Abstract

Over the past decades, the world has experienced an increasing reliance on Internet for communication, entertainment, and e-commerce. And with billions of users spread across the globe, the necessity for enhanced network infrastructures capable to support the ever growing high-bandwidth services has become an important aspect that will determine the survivability of the Internet in the future. As most of today's data traffic is transferred over of optical fiber cables, the realization of innovative approaches to increase capacity of optical networks is a vital step to tackle the challenges that may undermine Internet's future. One alternative to explore the capacity of the already deployed optical fiber cables is by means of utilizing multiple optical bands of the telecom spectrum, i.e., the so-called multiband (MB) technology. Yet, a successful implementation of the MB approach in optical networks still requires the solution of a series of questions, such as the development of MB-capable devices, the creation of mechanisms that can estimate and cope with component wavelength- dependent distortions, and how to efficiently monitor MB networks. This thesis discusses two applications for optical MB networks using optical coherent transceivers, or more specifically, transmitter (Tx) and receiver (Rx) based digital signal processing (DSP). Since modern coherent transceivers are embedded with powerful Tx- and Rx-DSP modules, algorithms can be implemented such to fulfill a wide range of functions that are crucial for the realization of MB systems. In that context, this work starts debating the influence of wavelength-based component-induced distortions on the design specifications for MB optical transmitters based on Indium Phosphide (InP) technology, which later justifies the development of Tx-DSP algorithms. In this discussion, a significant focus is given to the modeling of optical dual-polarization (DP) in-phase (I) quadrature (Q) modulators, which are built from InP multi-mode interference (MMI) couplers. Some simulative analysis are utilized to quantify the impact of wavelength-dependent component-induced distortions in optical coherent transmitters. In this study, it is observed that the optimization of MMI design can lead to optical modulators yielding optical signal-to-noise ratio (OSNR) penalties under 0.5 dB (back-to-back) in approximately 95% of the optical spectrum from 1260 – 1620 nm(O+E+S+C+L-band).

When operated in nonlinear regime, the performance of optical coherent transmitters can be further improved with the utilization of Volterra-based nonlinear digital pre-distortion (DPD) schemes. Yet, the design of DPD filters is a challenging task and since MB effects are expected to be wavelength-dependent, additional features must be developed such to offer adaptability to the Tx-DSP. Then, the Tx-DSP can self-tune its operation to account for distortions in multiple optical bands. In this sense, a Tx-DSP approach based on using Bayesian optimization (BO) to

optimize the design of Volterra DPD filters is used and verified in several transmission scenarios. In this approach, the BO tunes the length of memory taps in a Volterra series used for the the synthetization of DPD filters. One of the benefits observed after utilizing the BO is the reduction of 46% in the convergence speed of the system identification, when this method is compared against a benchmarked approach. Additionally, in conjunction with the use of memory polynomials filters, the BO-based DPD can lead to a filter complexity reduction of approximately 75% in comparison to Volterra DPD filters without any significant performance loss in an optical back-to-back setup. Finally, this scheme is tested to improve performance of a traditional C-band transmitter in S+C+L-band, where the optimization of the memory tap distribution for the DPD filter via BO yields a gain of approximately 0.4 dB in Q-factor over 40 km of single mode fiber. Thisapplication, then, covers the first proposed scope, which is the development of Tx-DSP for MB systems.

At last, the second proposed scope, i.e., a Rx-DSP for MB optical communication, is achieved with the demonstration of a spatially-resolved and wavelength-wise monitoring scheme to estimate MB properties of C+L-band optical amplifiers and identify faults that may occur in MB operation. In this analysis, a link tomography, i.e., an estimation of the channel's optical power with respect to distance and wavelength, is constructed and used in an extensive experimental investigation where the spectral gain profile of optical amplifiers deployed over 280 km of optical fiber can be predicted from the Rx-DSP. The results reported in this work show that sub-dB errors (maximum 0.6 dB) can be achieved when comparing the gain extraction from the link tomography against a back-to-back characterization realized through an optical spectrum analyzer. At last, the link tomography is employed in a novel manner by delivering a visualization of common amplification anomalies such as gain tilts and narrowband gain compressions caused by spectral hole burning effect. This complements the second proposed application for this thesis, which intends to offer a practical use of the Rx-DSP for MB systems.

3.8 Emadreza Soltanian

Host beneficiary	Ghent University, Belgium
PhD Enrolment	Ghent University, Belgium
Supervisors	Professor Gunther Roelkens
Academic Supervisor	Professor Ronald Freund
Industrial Mentor	Dr. Andreas Steffan, II-VI Incorporated (Finisar)
PhD thesis title	**Micro-Transfer Printing III-V on Si Amplifiers and Ultra-Wide Tunable Narrow Linewidth Lasers**
PhD defence date	December 2023
Access to Full Text (Open Access)	Online library https://biblio.ugent.be/type/dissertation

PhD Thesis Abstract

Silicon photonics (SiPh) has developed at a rapid rate by leveraging the extremely mature silicon manufacturing ecosystem as a result of decades of CMOS development. In addition to the availability of mature process technology, large wafer sizes of 200 mm or 300 mm make SiPh the leading candidate for high volume production of photonic integrated circuits (PICs) with high uniformity and yield. The high index contrast of the silicon-on-insulator (SOI) platform results in compact low-loss bends in waveguides and extremely compact components, which makes it possible to have thousand of photonic elements in a PIC. Since silicon does not provide optical

gain, as it is an indirect bandgap material, having integrated light sources and optical amplifiers is still a stumbling block which limits the functionality of PICs on SiPh. Therefore, it is essential for SiPh to be combined with III-V materials as a gain medium, in order to e.g. provide integrated widely tunable lasers to make SiPh's foothold firm in a wide variety of applications and markets such as coherent optical communication and datacenters, sensing and spectroscopy, LiDAR, deep learning and quantum applications. A proper external cavity design can provide both wavelength tunability and linewidth reduction for semiconductor lasers. Therefore, there have been great efforts in recent years in assembling a gain chip with a passive SiPh chip as an external cavity as hybrid and heterogeneous approaches. Heterogeneous integration of III-V semiconductors on SiPh, such as flip-chip integration, wafer-to-wafer/die-to-wafer bonding, and even hetero-epitaxial growth provides a solution to combine the best of both worlds. Although the flip-chip integration comes with the advantage of being able to test the III-V devices in advance, it suffers from limited throughput due to its sequential assembly using active or passive alignment. In contrast, the die-to-wafer bonding approach has the advantage of high throughput, since the unpatterned wafers do not need accurate alignment. However, it also faces some challenges as the SiPh back-end flow needs to be modified and it needs a dedicated III-V process implemented on 200 mm and 300 mm wafers as well. The hetero-epitaxial growth, while allowing for the highest integration density, has drawbacks in terms of III-V material quality. Here, we use micro-transfer-printing (µTP) for the integration of pre-fabricated InP-based SOAs as the gain section in a SiPh cavity to realize narrow-linewidth widely tunable lasers (WTL), which results for the first time into a narrow-linewidth III-V-on-Si double laser structure with more than a 110 nm wavelength tuning range. Two types of pre-fabricated III-V semiconductor optical amplifiers (SOAs) with a photoluminescence (PL) peak around 1500 nm and 1550 nm are micro-transfer printed on two silicon laser cavities. The laser cavities are fabricated in imec's silicon photonics (SiPh) pilot line on 200 mm silicon-on-insulator (SOI) wafers with a 400 nm thick silicon device layer. By combining the outputs of the two laser cavities on chip, wavelength tunability over S+C+L-bands is achieved. Moreover, We demonstrated a high-saturation power III-V-on-Si SOA with a tapered design realized using (µTP) technology. The SOA provides a 9 dB small-signal gain and an output saturation power of 15 dBm at the wavelength of 1573 nm.

4 RESEARCH PROJECTS WITHOUT PHD THESIS COMPLETION

This section addresses the case of two researchers, Yaonian Cui (ESR 13) and Caio Mariano Santos (ESR7), who were recruited by the beneficiary Fraunhofer HHI, and did not complete their PhD theses due to personal circumstances. This deviation from the project's original Grant Agreement (GA) did not adversely affect the overall implementation, project results, or the future careers of the researchers. Both researchers successfully finished their research projects and fulfilled their employment contracts, contributing positively to the project's objectives and outcomes.