FINAL PUBLISHABLE REPORT

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Internal Funded Partners: 1. NPL, United Kingdom	External Funded Partners: -	Unfunded Partners: 2. Arden, United Kingdom 3. RP, United Kingdom

TABLE OF CONTENTS

1 Overview

The purpose of this project was to maximise uptake of the EMPIR project 14IND13 PhotInd outputs by characterising functional performance of photonic waveguides among end-users (e.g. Electro Optical Circuit Board (EOCB) manufacturers, network engineers, installers and commercial instrumentation manufacturers). The project demonstrated that highlighting the measurement criteria and design limits enables further improvements and support future growth in the expanding data centre thereby benefiting the wider communications sector.

The project's Primary Supporter, Arden Photonics Ltd, recognised the necessity for the refinement and wider adoption of international standards regarding metrology of EOCBs, intended for data centres. Therefore, Arden Photonics Ltd, together with the project team, contributed towards future standards developed by standardisation bodies such as the Internal Electrotechnical Commission (IEC). This boosted confidence in the usage of EOCBs and photonic waveguides and created worldwide impact.

This project demonstrated that an increase in thermal load caused a subtle shift in the Encircled Flux (EF) profiles with this progressive shift becoming significant as it exceeds the limits of the EF templates defined in IEC 61280-4-1/Ed3/CD:2015. This is particularly relevant at the elevated temperatures of 60-80°C which is crucial within the operating range for data centres. The project also showed that the Bit Error Ratio (BER), which is the conclusive figure of merit, degraded with the increased thermal load on the EOCB.

2 Need

For the research findings in 14IND13 PhotInd to be more widely adopted and to accelerate industrial uptake, more communication was required through conference engagement, standards contribution and trade events. Presenting the findings of key EOCB parameters such as: attenuation, EF and BER, was of extremely high value to end users who need to know whether a product will fulfil its function and compliance with current standards. Given that the above key parameters revealed excellent correlation in 14IND13 PhotInd, these compelling results were extremely relevant for dissemination to the wider high-speed data comms community and to future data centre technologies.

Understanding attenuation and controlling the launch condition within a waveguide and the modal energy distribution in terms of EF enabled optimisation of the network bandwidth through efficient use of mode filling. This need becomes more pertinent when we consider the ever-growing complexity of EOCB designs incorporating radii, crossovers and splitters as well as the integration of on-board components such as transceivers and CPUs. EF sets the limits for optical power included within a specified radius of the circular fibre core thereby fully characterising the launch condition. In addition, Encircled Angular Flux (EAF) was the key parameter of choice when characterising the output of a non-circular waveguide. Therefore, the wider adoption of the emerging EAF measurements in addition to EF is a preferable means of characterising EOCB output. Moreover, network loss budgets are becoming increasingly smaller and more precise methods of defining mode fill for bandwidth simulation and loss testing are now required. The same criteria for link loss and modal distribution apply to waveguides embedded on short range interconnects in data centres and, given the very high speeds of these links, it was essential to understand and maximise mode fill through EF/EAF metrology.

Another important need was improving and maintaining compliance with standards for photonic waveguides operating over a wide temperature range. The EMPIR project 14IND13 PhotInd demonstrated that an increase in thermal load caused a subtle shift in the EF profiles. This progressive shift becomes significant as it exceeds the limits of the EF templates defined in IEC 61280-4-1/Ed3/CD:2015. This was particularly relevant near the elevated temperature of 80°C which was within the operating range for data centres. Subsequent measurements at these elevated temperatures could potentially fail specified criteria required by IEC standards and incorporating this unpublished temperature-dependent data within standards will bring it in line with current research.There was a severe lack of commonality regarding measurement definitions for a testing process leading to wide variations in results between different locations and establishments on reference test samples. Recent standard developments led by Richard Pitwon under TC86 JW9 have worked towards integrating a measurement identification system with the aim of harmonising measurements to within 5% variation. The subsequent standard IEC 62496-2:2017 (E) has now been released as a full standard. The standard proposes the adoption of a Measurement Identification Code (MIC) to specify sufficiently the measurement conditions for the optical channel under test. The measurements from the 14IND13 PhotInd have adopted this coding system and RP will provide further guidance in this proposal on its experimental validation for wider dissemination. Furthermore, the findings should be incorporated within IEC 62496-3:2011 as they provide

functional design limitations of EOCBs operating across a thermal range. Modification of this standard is highly important to provide up-to-date information as this technology evolves.

The work undertaken in 14IND13 PhotInd was an important step in understanding functional performance of these emerging polymer waveguides within application environments where the propagating channels were expected to be in very close proximity to other thermally generating components. Testing a waveguide's integrity had been carried out in the past with the subsequent performance assessed in terms of attenuation and BER but not EF/EAF. Moreover, these experiments were specifically carried out under ambient lab conditions. Our investigation over a wide temperature range in 14IND13 PhotInd has had far reaching consequences for board designers, manufacturers and standards bodies. Unavoidable increase in board complexity and hybridization, in the drive to accommodate higher data rates, will need to consider these performance and functional limitations. Dissemination of these findings will maximise network bandwidth through greater awareness and wider adoption. In addition, this will enable uptake of improved metrology by network installers and engineers. This growth will be underpinned by improved and harmonised standards and improved sales of relevant measurement instrumentation such as the MPX Modal Explorer and ModCon Modal Conditioning artefacts as evidenced by the letter of support from the Primary Supporter, Arden Photonics.

3 Objectives

The overall goal was to disseminate the results of the EMPIR project 14IND13 PhotInd to those utilising photonic waveguides in data centres in order to harmonise metrological practice, maximise efficiency and provide knowledge transfer. The specific objectives of this project were:

1. To disseminate valuable research outputs from the EMPIR project 14IND13 PhotInd by transferring the relevant technology through national and European organised events.
2. To promote and improve adoption and use of the standards on the impact of the functional performance and design of EOCBs as per standards requirements for data centres.

4 Results

The project's aim was to maximise uptake of the EMPIR project 14IND13 PhotInd outputs by disseminating the characterisation results of the functional performance of photonic waveguides among end-users (e.g. Electro Optical Circuit Board (EOCB) manufacturers, network engineers, installers and commercial instrumentation manufacturers). The project demonstrated that highlighting the measurement criteria and design limits enables further improvements and support future growth in the expanding data centre thereby benefiting the wider communications sector.

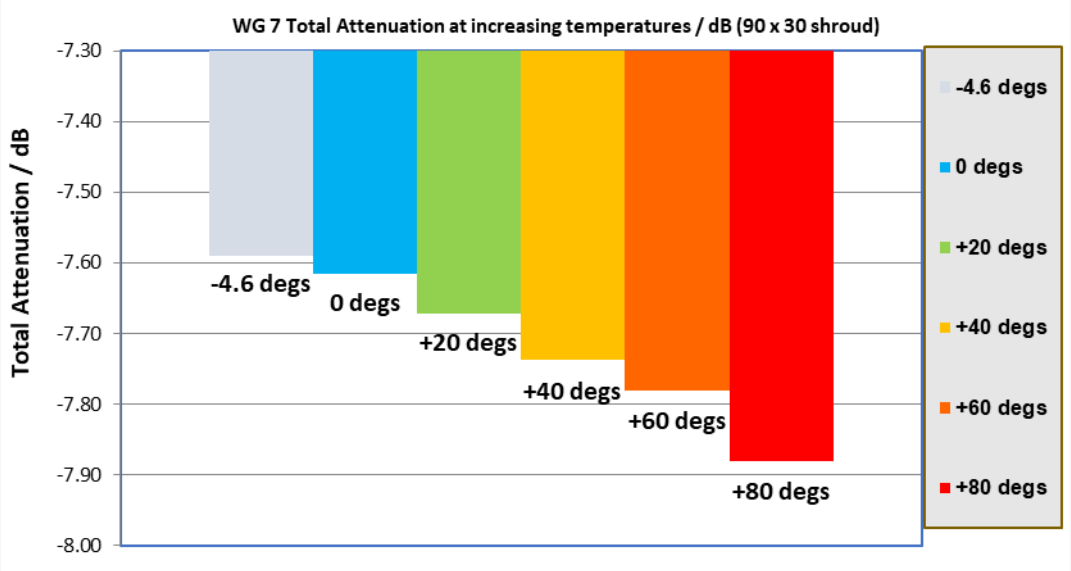
The project 19SIP05 Primary Supporter, Arden Photonics Ltd, recognised the necessity for the refinement and wider adoption of international standards regarding metrology of EOCBs, intended for data centres. Therefore, Arden Photonics Ltd, together with the project team, NPL and Resolute Photonics, contributed towards future standards developed by standardisation bodies such as the Internal Electrotechnical Commission (IEC). This boosted confidence in the usage of EOCBs and photonic waveguides to create worldwide impact.

This project demonstrated that an increase in thermal load caused a subtle shift in the Encircled Flux (EF) profiles with this progressive shift becoming significant as it exceeds the limits of the EF templates defined in IEC 61280-4-1/Ed3/CD:2015. This is particularly relevant at the elevated temperatures of 60-80°C which is crucial within the operating range for data centres. The project also showed that the Bit Error Ratio (BER), which is the conclusive figure of merit, degraded with the increased thermal load on the EOCB. Specifically, the outputs for the 2 objectives for the project are discussed below.

Objective 1: To disseminate valuable research outputs from the EMPIR project 14IND13 PhotInd

Based on the research findings from 14IND13 PhotInd, three posters were prepared and presented at the European Conference on Optical Communication (ECOC) 2020, in collaboration with the primary supporter. These posters were designed to disseminate and promote relevance to standards bodies, the importance of emerging key parameters and the implication for design limits as a consequence of the research findings to the commercial photonics sector. NPL presented the posters based on the findings of EMPIR project 14IND13 PhotInd and the technology transfer to the photonic industry in collaboration with Arden Photonics and Resolute Photonics. Research findings to provide international harmonisation through the activities of

standards bodies establishing reliable measurement definition systems for optical interconnects were disseminated. The project raised awareness that the key prerequisite for future commercial adoption of Electro Optic Circuit Boards (EOCBs) technology is through metrology and specific design limits. The posters also disseminated a clear understanding of the measurement condition that goes hand in hand with an understanding of functional performance of EOCBs. Effects upon changes in refractive index as well as combined stresses on the board structure were presented to be important areas of investigation that need to be understood as specifications and standards develop and board technology improves and becomes more complex. The consortium also presented the 14IND13 PhotInd research showing the results have far reaching consequences for board designers, manufacturers and standards bodies. The unavoidable increase in board complexity and hybridisation, in the drive to accommodate higher and higher data rates, will need to account for performance and functional limitations imposed by the application of thermal loading. The project partners thus presented the results from 14IND13 PhotInd demonstrating that as the technology develops, modal energy distribution in terms of encircled flux (EF) can maximise potential bandwidth of networks through efficient use of mode filling. In 14IND13 PhotInd, the project partners observed that an increase in the applied thermal load showed an observable increase in total attenuation values. This has potentially a significant effect on board performance. The attenuation result disseminated in the project is shown below at different temperatures:

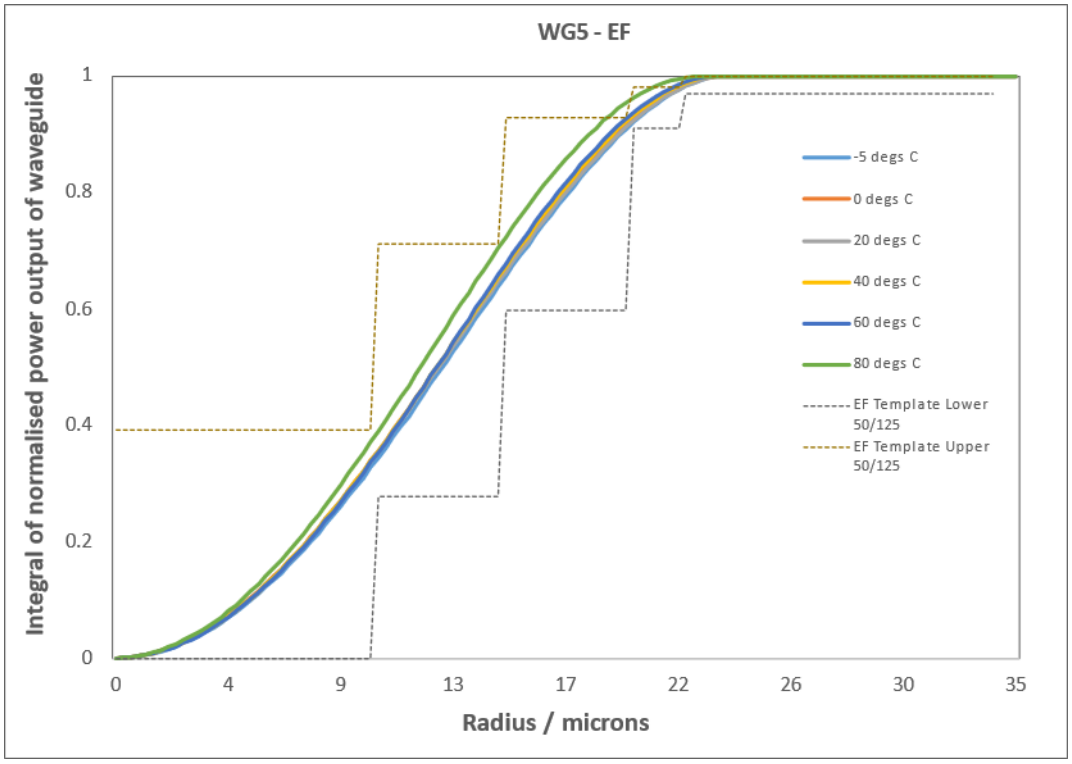


Total attenuation against temperature for the optical waveguide

A peer-reviewed paper ‘Metrology and Standardization of High Speed Pluggable Optical Interconnects’ was published at the PHOTOPTICS conference 2021. An oral presentation on the paper was successfully delivered virtually to the conference audience in February 2021. The target audience was manufacturers and the high-speed telecom community. The consortium presented the severe lack of commonality regarding measurement definitions for a particular testing process. This led to wide variations in results between different establishments on reference test samples as identified from the results in 14IND13 PhotInd. The consortium also presented how recent standard developments have worked toward integrating a measurement identification system with the aim of harmonizing measurements to within 5 % variation.

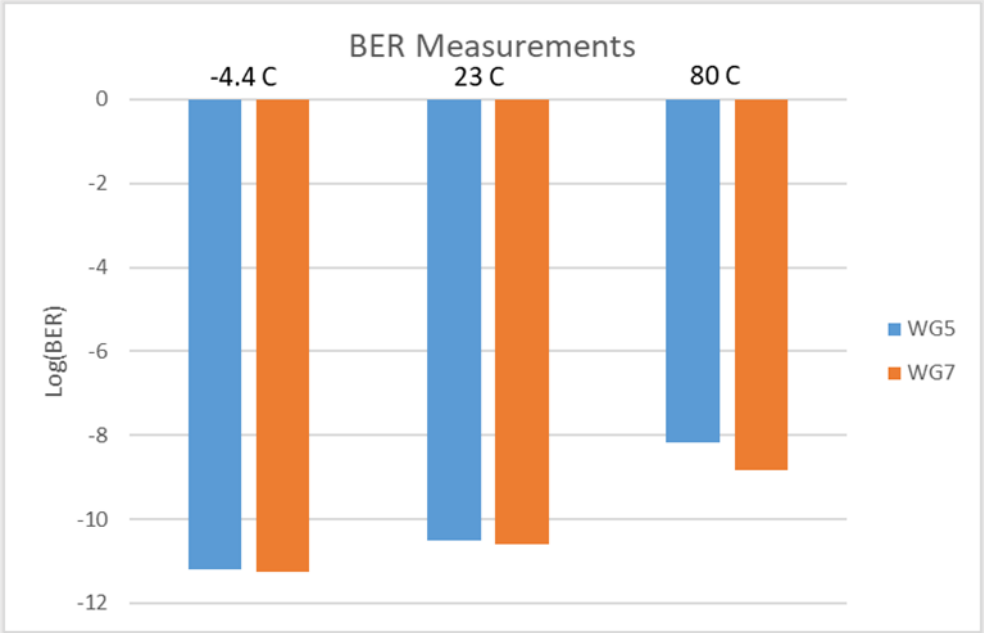
An open-access paper entitled ‘Variable Launch System for the Metrology of EOCBs’, has also been published on total attenuation, where an increase in the applied thermal load show an observable increase in total attenuation values. The results in the paper aimed at improving awareness of the technical issues involved and the necessity of evolving standards for the commercial sector. The consortium disseminated valuable research outputs from the EMPIR project 14IND13 PhotInd by transferring the relevant technology through this publication. In particular, the consortium presented the signal degradation observed for the transmitted data correlates with the increased total attenuation over the temperature range. Moreover, Encircled Flux results were also disseminated in the paper where an increase in applied thermal load indicates an observable shift in the Encircled Flux profiles, consistent with higher order modes being decoupled from the guide due to

associated changes in the core cladding refractive index ratio. The project partners provided characterisation for Encircled Flux, defined as a fraction of the cumulative near-field power to the total output power as a function of radial distance from the optical centre. An observable effect was found as the thermal load was increased which was an important observation to disseminate as part of this project. This is consistent with that of higher-order modes being decoupled from the waveguide, due to changes in the core-cladding refractive index ratio. The consortium found that under exceptional thermal stress the resulting performance shift exceeds that of templates recommended by current IEC standards. This Encircled Flux shift exceeded the template limits defined in current standards and was an important dissemination of the results obtained in 14IND13 PhotInd as shown below:



Normalised power output and waveguide radius.

Finally, as a conclusive figure of merit, the project partners presented how bit error ratio (BER) was affected by the application of thermal loads in our posters, oral presentation and publication. The measurements made in 14IND13 PhotInd employed a Thermostream chamber to emulate thermal hotspots on the waveguides. An arbitrary waveform generator was used to generate a pseudo-random binary sequences electrical signal to drive an SFP+ transceiver module to launch the intensity modulated signal onto the waveguides. The results disseminated in this project were based on the launch configuration complied with restricted launch EF requirements IEC 61300-1/IEC 61280-4-1. The project's findings for the two waveguides are shown below at 3 different temperatures:



Bit error ratio at three temperatures showing the impact of thermal stress on EOCBs

The consortium found that BER rose with increased thermal stress, consistent with performance expectations based on the results for total attenuation and the shift in EF profiles shifting. Signal degradation was observed for the transmitted data at the extreme temperature of 80 ºC for both waveguides. As BER is a particularly critical parameter and a key metric for data channel performance and has been previously characterised at room temperature, this work highlighted the significant impact localised temperature variation can have for EOCB utilisation. Management of heat alongside carefully controlled launch conditions as prescribed by practical metrology standards is therefore needed to maintain industry-required performance and was an important dissemination of the findings from 14IND13 PhotInd.

Objective 2: To promote and improve adoption and use of the standards for ECOB design and performance

European standards bodies such as IEC recognise the need for good metrological technique across the industry. There is a pressing need to transfer the research findings to the industrial end-user and to disseminate it among the wider community. Dissemination of the results from 14IND13 PhotInd was an opportunity that could be exploited to achieve successful uptake by photonic industry. By promoting the findings to the National and International committees, the standards are able to evolve in harmony with the technological advances of the industry. The work undertaken in 14IND13 PhotInd has been an important step in understanding functional performance of these emerging polymer waveguides within application environments where the propagating channels are expected to be in very close proximity to other thermally generating components. Testing a waveguide's integrity has been carried out in the past with the subsequent performance assessed in terms of attenuation and BER, but not EF/EAF. Moreover, these experiments were specifically carried out under ambient lab conditions. Our investigation over a wide temperature range in 14IND13 PhotInd has far reaching consequences for board designers, manufacturers and standards bodies. Unavoidable increase in board complexity and hybridisation, in the drive to accommodate higher data rates, need to consider these performance and functional limitations. There was also a requirement to ensure performance falls within the templates defined by Standards documents for board compatibility from different manufacturers. It was important for the measurement findings and the technology developed in the EMPIR project 14IND13 PhotInd to be transferred to the industrial research and manufacturing environment.

The Primary Supporter, Arden Photonics, required technology transfer in EF and EAF measurements beyond that available in published papers as direct impact will be achieved for them as a manufacturer of EF measurement instrumentation and controlled Modal Conditioners used to provide IEC compliant controlled launch conditions. Based on discussions with the Primary Supporter, presentations on Encircled Flux and thermal effects on EOCBs, have been made: to committee members and Chair of BSI GEL/86/2 and 3 (on 29th September 2020) and to 50+ industrial participants and the committee members and Chair of International IEC

committee TC86 JWG9 meeting (on 15th October 2020). In these presentations, the case was outlined for the inclusion of the functional specification design limits into relevant EOCB standards such as IEC to 62496-3:2011 and the importance of adopting the metrological practices outlined in IEC 62496-2:2017 (E), taking into account current standards specifications. The project partner, Resolute Photonics, reviewed and advised on IEC 62496-2:2017 (E), with respect to the use and implementation of the coding system for characterising EOCBs. NPL measurements from 14IND13 PhotInd followed the Measurement Identification Coding (MIC) system defined for the source characteristics, launch conditions, input coupling, output coupling and capturing conditions. These parameters were presented to the BSI and IEC committees as part of this project to outline the importance of adopting these metrological practices in the standards to establish reliable measurement definition systems for optical interconnects with a clear understanding of measurement conditions required at operational temperatures. This dissemination was necessary to understand the functional performance of electro optical circuit boards. In addition, the project partners raised awareness in the committees' meetings on the results from 14IND13 PhotInd showing an increase in applied thermal load led to an observable shift in the EF profiles, consistent with higher order modes being decoupled from the guide. This progressive shift is significant as it can exceed limits defined by the EF templates as specified in IEC 61280-4-1/Ed3/CD:2015 especially at the elevated temperature of 80 °C. This finding will lead to more intensive measurements to be performed on different types of waveguides and their adoption in future standards.

In conclusion, this project 'Technology Transfer of Photonic Waveguide Characterisation' disseminated valuable research outputs from the EMPIR project 14IND13 PhotInd by transferring the relevant technology through national and European organised events. The consortium also promoted result findings from project 14IND13 PhotInd to improve adoption and use of the standards on the impact of the functional performance and design of EOCBs as per standards requirements for data centres. Dissemination of these findings will maximise network bandwidth through greater awareness and wider adoption. In addition, this will enable uptake of improved metrology by network installers and engineers. This growth will be underpinned by improved and harmonised standards and improved sales of relevant measurement instrumentation such as the MPX Modal Explorer and ModCon Modal Conditioning artefacts by the Primary Supporter, Arden Photonics. Dissemination of their involvement with the project through paper and poster presentations as well standardisation activities will widen their customer base and raise their profile on an international level helping to promote and realise the methodologies associated with high-speed, high-bandwidth capabilities of optical networks across Europe.

5 Impact

A conference paper has been published by PHOTOPTICS on metrology and standardisation of high speed pluggable optical interconnects. Furthermore, the project partners have actively engaged with key national and international standardisation committees: BSI and IEC to disseminate 14IND13 PhotInd results in relation to functional performance of EOCBs and raise awareness of the need to include temperature effects on key parameters in relevant IEC standards. As such, two presentations have been given to committee members and industrial partners. Three posters have been presented virtually at the ECOC 2020 conference along with participation in its virtual exhibition. Furthermore, this project will have a demonstrable wider impact across Europe and internationally through contributions to relevant IEC standards, with the support from project partner, Resolute Photonics UK Ltd, which will facilitate the early adoption of EF and EAF metrological tools in the near future.

Photonic waveguides such as EOCBs are used throughout the data industry, serving as vital parts of modern communications. Improvement in photonic waveguide standards and characterisation affects industries such as data centres, banking and the semiconductor industry as well as deliver direct social impact. The overall aim of this project was to create additional impact from the work carried out under wok package 2 of the 14IND13 PhotInd. The work carried out has relevance to data centres directly, but also to wider general use of photonic waveguides in other industries. Dissemination of the Primary Supporter, Arden Photonics, involvement with the project through THE PHOTOPTICS 2021 paper and ECOC 2020 posters presentations has widened their customer base and raised their profile on an international level helping to promote and realise the methodologies associated with high-speed, high-bandwidth capabilities of optical networks across Europe. They have benefited from the technology transfer in EF/EAF measurements beyond that available in published papers. The work within this project has enabled the Primary Supporter to exploit the performance and significance of their instruments and components to benefit the wider photonic community. Direct impact was thus achieved for the Primary Supporter who are manufacturers of EF measurement instrumentation and controlled Modal Conditioners used to provide IEC compliant controlled launch conditions.

The involvement of Arden Photonics in this project has facilitated the uptake and exploitation of traceable measurements by the photonic industry across Europe and internationally through active participation with world-leading standardisation bodies in line with the “Europe’s age of light! How photonics will power growth and innovation” Strategic Roadmap 2021-2027. Additionally, the project has enabled the transfer of design limits to the Primary Supporter’s customer base, enabling improvements in data infrastructure and future growth. The work within this project has led to bandwidth optimisation within high speed optical networks enabling the Primary Supporter to demonstrate the performance and significance of their instruments and components to the wider photonic community.

European standards bodies such as IEC recognise the need for good metrological technique across the industry. There was a pressing need to transfer the research findings to the industrial end-user and to disseminate it among the wider community. Dissemination of the results from 14IND13 PhotInd was exploited to achieve successful uptake by photonic industry. By promoting the findings to the National and International committees, the standards were able to evolve in harmony with the technological advances of the industry. As a current active committee member, the Primary Supporter will directly gain from the development of the relevant standards and benefit from the detailed knowledge of the standards ensuring compliance with their commercial product line. The research findings from 14IND13 PhotInd will provide international harmonisation through the activities of standards bodies establishing reliable measurement definition systems for optical interconnects for the primary supporter.

In terms of wider impact, the research related to photonic interconnects and waveguides has improved knowledge of industry and academia and has therefore given potential for new improved products and innovations across Europe. The project has also promoted the new methodologies for more accurate simulations related to interconnects and waveguides. In general, dissemination of the project results has enhanced understanding for the photonic industry and the researcher regarding the significance of traceability and uncertainty in waveguide measurements. The project enabled demonstrable impact in providing improved and new calibration services for customers throughout the photonic industry in Europe and internationally. This impact was primarily achieved through the open access peer-reviewed paper on ‘Variable Launch System for the Metrology of EOCBs’ that was published. It detailed the transfer of functional performance of EOCBs from 14IND13 PhotInd to end-users, standardisation bodies and the wider high-speed data communications community. Waveguides support many modes and the light entering the waveguide determines the modal and energy distribution exiting the guide. Ideal launch conditions should occur if the light is distributed through the whole fibre core. Knowing and controlling the launch conditions was found to be important in 14IND13 PhotInd to ensure reliable measurements for key parameters. These results were presented in the paper and will have an impact on the way these key parameters are measured for novel photonic waveguides.

In terms of economic impact, the development of optical waveguide characterisation techniques, efficient photonic interconnects and metrology instruments in this project has benefited the ever-growing photonic industry including the laser industry. In addition, the project has strengthened European competitiveness and will increase its total turnover through the development of state-of-the-art instrumentations for the metrology of data centre interconnects.

The development of photonic interconnects and waveguides will directly benefit the energy costs associated with data centres reducing energy consumption and carbon footprint through improved coupling efficiencies for high-speed communication links. Input to relevant metrology services developed in 14IND13 PhotInd has therefore supported this development. Alongside this research into on-board waveguide propagation efficiencies, understanding and reducing coupling losses can provide estimated propagation energy savings in excess of 30%, directly reducing the electricity consumption required for cooling. Establishing EF/EAF measurement standards documents would further enable the development of a new generation of high-capacity energy-efficient optical interconnects to strengthen Europe’s leading position in integrated photonics.

In terms of social impact, the improved bandwidth efficiencies associated with optical networks will enable high-speed, high-definition mobile streaming to consumers helping to meet the exponential data growth. The performance of Electro Optical Circuit Boards (EOCBs) operating within data centres was characterised in 14IND13 PhotInd for key operational parameters: Total Attenuation, Encircled Flux and Bit Error Ratio. Reliable characterisation of optical waveguides for these parameters were presented at conference, exhibition and standards committee meetings to enable more reliable production methods. This will lead to reduced costs and thus make precision engineered items available to a wider audience.

6 List of publications

Ferguson, R.; Fatadin, I.; Liu, K.; Barbeito, I.; Hart, C.; Pitwon, R. and Robinson, D. (2021). Metrology and Standardization of High Speed Pluggable Optical Interconnects. In Proceedings of the 9th International Conference on Photonics, Optics and Laser Technology, ISBN 978-989-758-492-3, ISSN 2184-4364, pages 63-67. DOI: 10.5220/0010171900630067; https://zenodo.org/record/5777190

Ferguson R, Fatadin I, Liu K (2021) Variable Launch System for the Metrology of EOCBs. Int J Opt Photonic Eng 6:037. DOI: 10.35840/2631-5092/4537; https://vibgyorpublishers.org/content/ijope/ijope-6-037.pdf

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