FINAL PUBLISHABLE REPORT

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Project short name	KTOC
Project full title	Knowledge Transfer for Optical Communications

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Internal Funded Partners: 1. NPL, UK	External Funded Partners: 2. RP, UK	Unfunded Partners: 3. SAC, UK

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1 Overview

This project has successfully delivered methods for the characterisation of high-density optical connector functional performance developed in EMRP project IND51 MORSE to component manufacturers, network engineers, and fibre installers within the expanding data centre industry. Interactions with the IEC TC86, have created impact through the development and contributions to standards that provide confidence in the uptake of high-density optical interconnects in the communications sector. In addition, the use of Error Vector Magnitude measurements as an efficient measurement tool for monitoring high-speed optical network performance employing multilevel modulation schemes such as QPSK and 64-QAM have been promoted to a wide stakeholder audience via large international conferences, publications and an exhibition.

2 Need

The IND51 MORSE results were extremely relevant for the wider high-speed data comms community and to the IEC standards committee as the global telecom infrastructure equipment market was expected to grow at 7 % annually and reach $504.56 billion by 2023. Serving the expanding needs of 5G fibre-optic connectivity required the development of next generation optical equipment for deployment in data centres, banking, and the semiconductor industry. Therefore, transceiver vendors, such as the Primary Supporter, SENKO Advanced Components Euro Ltd, needed to expand their manufacturing capacity to keep pace with increasing demands for 200 Gbit/s modules and faster, but a requirement for traceable high-speed measurements was hampering the progress.

The key output of EMRP project IND51 was the establishment of NMI-level traceability for measurements of high-speed optical communication systems. Extensive research was undertaken into measurements at 200 Gbit/s, and knowledge about precise connectivity calibration was obtained. Recent standard developments (IEC 62496-4-3/Ed1: Optical circuit boards - Part 4-3: Interface standards - Terminated waveguide OCB assembly using a single-row thirty-two-channel PMT connector intermateable with 250 μm pitch MPO 16), have worked towards terminated waveguide assembly using single-row 32-channel connectors with the aim of harmonising measurements. Modification of this standard was important for the provision of up-to-date information on connectivity as technology evolves. This was a requirement for enabling positional repeatability of +/- 1 μm and insertion losses of 2 dB complementing the standard IEC 61300-3-34: *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Attenuation of random mated connectors*. The KTOC project contributed to the refinement and wider adoption of international standards for the measurements of advanced coupling interfaces for photonic integrated circuits and expanded fibre arrays, which addressed the emerging needs from the hyperscale industry for system embedded optics including co-packaged optical assembly. The project 20SIP05 KTOC helped to strengthen European competitiveness which will increase its total turnover through the development of state-of-the-art connectivity with inexpensive pluggable transceivers and integrated photonics.

For the research findings in EMRP project IND51 to be more widely adopted and to accelerate industrial uptake, more communication was required through conference engagement, standards contribution, publications and exhibition events. By presenting the research outputs from EMRP project IND51 MORSE through transferring the relevant knowledge of high-speed optical interconnect measurements and characterisation to normative standardisation committees IEC TC86, this project has enabled the committee members of GEL86/2 to exploit the fact that polymer waveguide cores share a common cladding and can be arranged far closer together than glass fibre cores. This enabled MT connectors with far smaller inter-channel pitches. In the proposed standard from this project a single row of 32 waveguides can be arranged over the same length as a single row of 16 glass fibre channels for high-density connectivity.

There was also a need for manufacturers of advanced optical components, represented in this project by Resolute Photonics UK LTD and SENKO Advanced Components Euro Limited, as the Primary Supporter, to develop metrology techniques to evaluate the performance of optical communication systems. The requirements for EVM measurements have been demonstrated as a promising figure-of-merit to quantify the impact of performance degradation in high-seed optical networks employing multilevel modulation schemes such as 64-QAM. This will enable greater uptake of EVM measurements by suppliers to have greater confidence in optical performance monitoring.

3 Objectives

The overall goal of this project is to disseminate the results of EMRP project IND51 MORSE to photonic component manufacturers and standards bodies, in order to harmonise metrological best practice, maximise efficiency and provide knowledge transfer. The specific objectives of this project are:

1. To disseminate the research outputs from EMRP project IND51 MORSE by transferring the relevant knowledge of high-speed optical interconnect measurements/characterisation to normative standardisation committees such as IEC TC86 for potential inclusion into a revision of IEC 62496-4-1:2019.
2. To promote and improve adoption of a traceable Error Vector Magnitude metrological tool developed in EMRP project IND51 MORSE by writing and presenting papers and/or posters at events such as the IEEE British and Irish Conference on Optics and Photonics (BICOP) and exhibition through the European Conference on Optical Communications (ECOC) conference.

4 Results

The project's aim was to maximise uptake of the EMRP project IND51 MORSE outputs by disseminating the characterisation results of high-density optical connector functional to component manufacturers, network engineers, and fibre installers within the expanding data centre industry and also through interactions with the IEC standards committee. In addition, the use of Error Vector Magnitude measurements as an efficient metrology tool for monitoring high-speed optical network performance employing multilevel modulation schemes such as QPSK, 16-QAM and 64-QAM was promoted to a wide stakeholder audience via large international conferences, publications and an exhibition at ECOC conference in Switzerland.

The Primary Supporter, Senko Advanced Components, recognised the necessity for the refinement and wider adoption of international standards regarding metrology techniques to evaluate the performance of optical communication systems. Accurate determinations of optical performance were needed to maintain compatibility of coupling interfaces with the rest of the installed fibre and network switch infrastructure. The partners in this project have facilititated the transfer of the results and the technology developed in the EMRP project IND51 into industrial use via their membership and interactions with IEC TC86 SC86B. Resolute Photonics, together with the project team, contributed towards future standards developed by the Internal Electrotechnical Commission (IEC). This boosted confidence in the usage of interface standards (terminated waveguide OCB assembly using a single-row thirty-two-channel Planar Multi-Terminal (PMT) connector intermateable with 250 µm pitch MPO 16) which allowed a single row of 32 waveguides to enable high-speed connectivity.

This project also successfully demonstrated the benefits of advanced metrology techniques to evaluate the performance of optical communication systems. The results derived in the EMRP project IND51 provided optical performance monitoring techniques which were disseminated through project members participation at conferences and exhibition to the wider photonic user community, in addition to standards contributions. Error Vector Magnitude (EVM) measurement results were published demonstrating that EVM is a promising figure-of-merit to quantify the impact of performance degradation in high-seed optical networks employing higher-order modulation formats such as QPSK, 16-QAM and 64-QAM. Greater uptake of EVM measurements by the user community enabled both users and suppliers to have greater confidence in optical performance monitoring. Specifically, the outputs for the 2 objectives for the project are discussed below:

Objective 1: To disseminate the research outputs from EMRP project IND51 MORSE by transferring the relevant knowledge of high-speed optical interconnect measurements/characterisation to normative standardisation committees such as IEC TC86 for potential inclusion into a revision of IEC 62496-4-1:2019

The consortium partners, Resolute Photonics, Senko Advanced Components and NPL, had close interactions with the BSI and IEC TC86 Standards committees including 5 working groups: SC86C/WG4, JWG9, SC86B/WG6, GEL86/2, SC86B/WG6. This includes presentation of consortium activities and general participation in committees' meetings. Higher interface densities are possible with polymer waveguides to enable smaller centre-to-centre pitches than would be possible with glass fibres. New standards were therefore required for PMTs with higher channel densities. To this end, the consortium fully supported and contributed to a new standard: IEC 62496-4-3/Ed1: (Optical circuit boards - Part 4-3: Interface standards - Terminated waveguide OCB assembly using a single-row thirty-two-channel PMT connector intermateable with 250 μm pitch MPO 16), which allowed a single row of 32 waveguides thereby increasing the data capacity by a factor > 2 compared to 12 channels.

The results of EMPR project IND51 MORSE were disseminated to the photonic component manufacturers and standards bodies, in order to harmonise metrological best practice, maximise efficiency and provide knowledge transfer (20SIP05 Deliverable D1). The international standards landscape covering optical communication is substantial involving all mainstream international standards bodies including the IEC. The key standard currently in progress in JWG9 is "IEC 62496-4-3 ED1: Optical circuit boards - Part 4-3: Interface standards - Terminated waveguide OCB assembly using a single-row thirty-two-channel PMT connector intermateable with 250 μm pitch MPO 16". This standard exploits the fact that polymer waveguide cores sharing a common cladding can be arranged far closer together than glass fibre cores. This enables MT connectors with far smaller inter-channel pitches. In this standard a single row of 32 waveguides can be arranged over the same length as a single row of 16 glass fibre channels. However, in theory this pitch can be substantially reduced through the introduction of cross-talk suppression features. This in turn would provide a useful means of coupling to photonic integrated circuits (PICs) with high "Shoreline densities" i.e. high port numbers arranged over short edges of the PIC. Due to higher absorption losses in conventional optical polymers at communication wavelengths in the O-band (around 1310 nm) compared to singlemode glass fibre, the distance over which optical signals in this wavelength range is conveyed over polymer waveguides would need to be minimised. Figure 1 shows a special high-density polymer waveguide connector called PMT (planar MT) designed to support the high connectivity requirements developed in EMPR project IND51 MORSE.

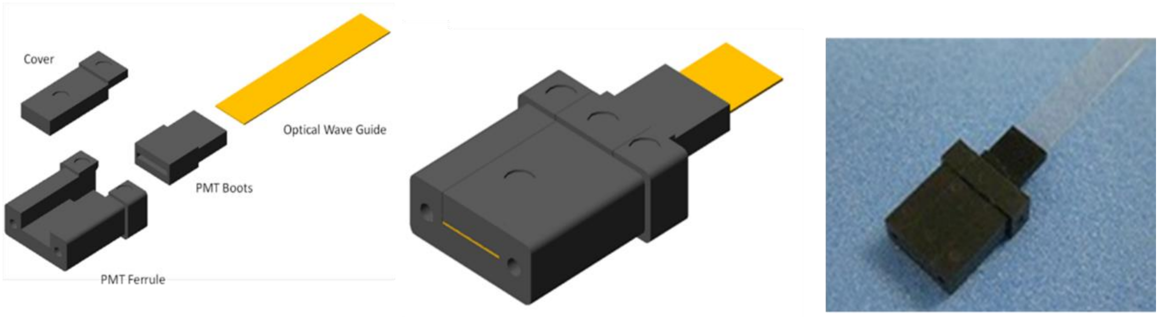

Figure 1: PMT multi-waveguide optical connector for polymer waveguides

One suitable application for such intermediary complex polymer waveguide circuits to support the high data rates connectivity developed in EMPR project IND51 MORSE would be as part of an advanced co-packaged optical (CPO) or near-packaged optical (NPO) solution for hyperscale data centre system enclosures, in which the polymer waveguide circuit would form a local intermediary between the interfaces of densely arranged PICs (micro-transceiver chiplets) within the CPO or NPO assemblies and an external fibre-optic circuit mounted on the main host board in the target system enclosure. The geometry of such an intermediary in-plane polymer waveguide circuit would, depending on the application, be expected to vary in complexity from a simple fan-out to a more meticulous circuit configuration. Given the expected tight space constraints within CPO or NPO assemblies, such a circuit would almost certainly need to include compact routing elements such as in-plane bends with very small radii of curvature and cross-overs, as well as potentially more advanced elements, such as actively tuned micro-ring resonators for wavelength filtering and routing for monitoring or sensing purposes. As part of KTOC dissemination activity, Resolute Photonics invited Professor Lin Ma from Shanghai Jiao Tong University to present two new proposals, which go beyond "IEC 62496-4-3/Ed1: Optical circuit boards - Part 4-3: Interface standards - Terminated waveguide OCB assembly using a single-row thirty-two-channel PMT connector intermateable with 250 μm pitch MPO 16":

(i) "IEC 62496-4-Y NP proposal of OPTICAL CIRCUIT BOARDS –Part 4-4: Interface standards – Terminated waveguide OCB assembly using two-row sixteen-, twenty- or twenty-four-channel PMT connectors" and

(ii) "IEC 62496-4-Z NP proposal of OPTICAL CIRCUIT BOARDS –Part 4-1: Interface standards – Terminated waveguide OCB assembly using two-row thirty-two-channel PMT connectors".

Senko has subsequently developed a new grade of optical fibre connector ("QuPC") that surpasses even the most stringent IEC connector grades, with recent results showing insertion losses within the margin of measurement uncertainty (<0.02 dB) and return losses over 80 dB as presented at the IEEE 71st Electronic Components and Technology Conference (ECTC) in June 2021.

Finally, as part of this objective, the project consortium also initiated discussions on a new standard, which further doubled the channel density IEC 62496-4-3 to a single row 64 channel PMT, which cannot be matched by optical fibres and truly showcased the fundamental benefit of polymer waveguides over multi-fibre ferrules. This proposal will be developed over the coming years to build on the results disseminated in this project for the single row of 32 waveguides.

This objective was completely met.

Objective 2: To promote and improve adoption of a traceable Error Vector Magnitude metrological tool developed in EMRP project IND51 MORSE by writing and presenting papers and/or posters at events such as the IEEE British and Irish Conference on Optics and Photonics (BICOP) and exhibition through the European Conference on Optical Communications (ECOC) conference

The project partners, Resolute Photonics, Senko Advanced Components and NPL, disseminated the optical performance monitoring results from the EMRP IND51 MORSE project as an important aspect in the design of the next generation of optical communication systems. Accurate measurement analysis was developed to quantify the novel modulation schemes and to reliably predict the performance of optical coherent systems encoding information on both the amplitude and phase of the optical carrier for M-ary quadrature amplitude modulation (QAM). Preparation and delivery of a conference paper on the technology transfer from IND51 MORSE was presented at the 7th Laser and Optoelectronics Conference (LOC 2021). The paper entitled 'Metrology of Optical Communication Systems Using Error Vector Magnitude' has been published as an Open Access peer-reviewed paper in Journal of Applied Mathematics and Physics. The consortium has further disseminated the results at the International European Conference on Optical Communications (ECOC) conference in Basel, Switzerland. An exhibition was attended at ECOC conference (September 2022) in collaboration with the project partners, Senko Advanced components and Resolute Photonics, to disseminate IND51 MORSE results through 3 posters presentation on (i) Optical performance monitoring using error vector magnitude, (ii) Knowledge transfer for optical communications – metrology for high-speed data interconnects, and (iii) Knowledge transfer for optical communications – metrology and standardization high density pluggable optical interconnects. EVM was demonstrated as an efficient metrological tool for characterising the performance of high-speed connectivity in optical communications as developed in the EMRP project IND51 MORSE. Figure 2 shows the deviation of the EVM estimated for nondata-aided from data-aided reception for QPSK, 16-QAM, and 64-QAM in the presence of additive white Gaussian noise.

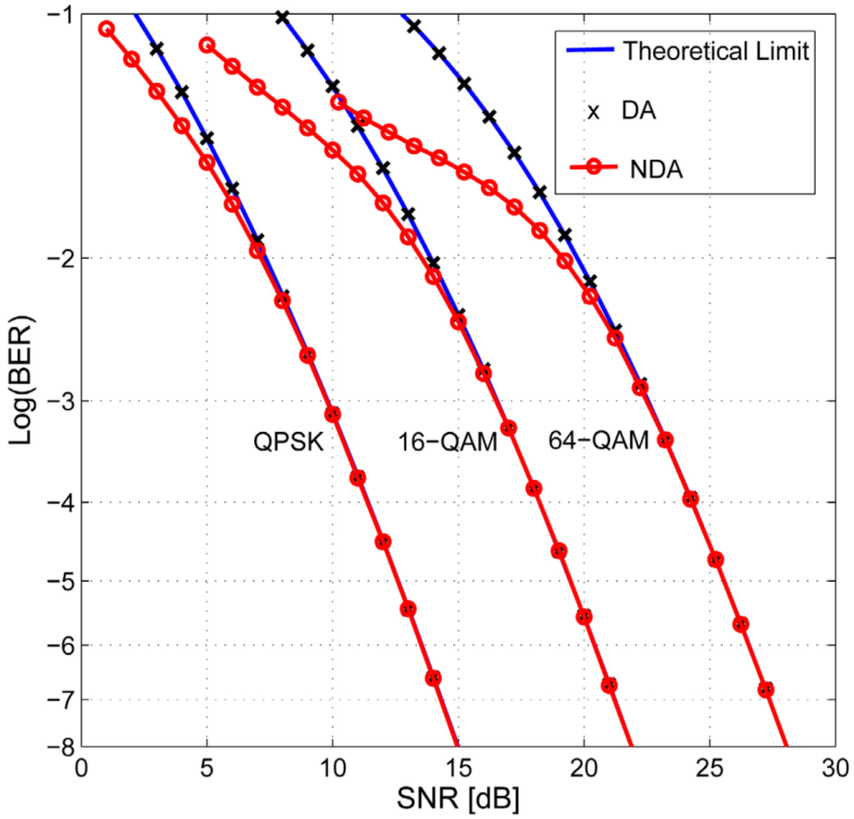

Figure 2. BER estimation from EVM analysis for data-aided (DA) and nondata-aided (NDA) reception for QPSK, 16-QAM, and 64-QAM.

The above results from IND51 MORSE showed that the EVM for nondata-aided reception was under-estimated at lower SNR values for the different modulation formats. The performance for data-aided reception was found to be in perfect agreement with the theoretical limit in the presence of ASE noise. At a target BER of 10^{-3}, the BER can also be estimated from EVM without significant deviation from the expected value for nondata-aided reception. However, the deviation can be seen to increase at a BER of 10^{-2} for the higher-order modulation formats. For lower SNR, the EVM and, hence, the BER were under-estimated as the decision-directed symbols are mapped to the wrong constellation points for nondata-aided reception. A calibration of the estimated BER was developed in IND51 MORSE as shown below in Figure 3 with a correction factor to reliably predict the performance of optical coherent systems with EVM analysis.

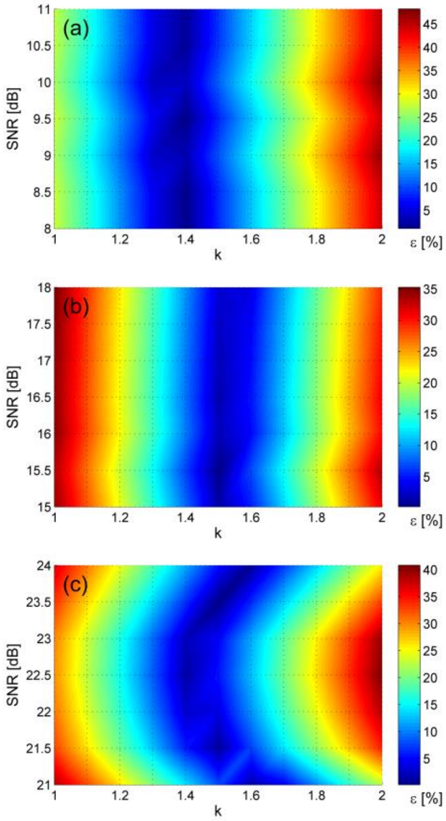

Figure 3. Correction factor, k, for (a) QPSK, (b) 16-QAM, and (c) 64-QAM.

The impact on the number of symbols used to estimate the BER from EVM analysis was also presented through paper and poster presentations and compared to the BER obtained by error counting from IND51 MORSE results. It was shown that an estimate with lower uncertainty can be achieved from EVM analysis compared to error counting, in particular, for low number of symbols. Thus, the calibrated BER can potentially be a useful figure of merit to reliably estimate the performance of optical coherent systems with EVM analysis as opposed to the large number of symbols that may be required for error counting to compute the actual BER. Moreover, the BER estimated from EVM analysis has the additional benefit that it can still be recovered for unknown symbol sequences transmitted over the optical network with low implementation complexity to evaluate the quality of advanced modulation formats.

Moreover, a paper on ‘Characterization of Quantum Grade Interconnects’ was also presented by the project partners to disseminate the metrology results from IND51 MORSE. It was demonstrated that high end classical systems such as those at National Measurement Institutes (NMI), can also be used to more fully characterise commercial quantum grade fibre as well as innovative hollow core fibre (HCF) which have up till now, been measured at much lower uncertainties or lack traceability altogether. The results showed that active involvement is needed in National and International standards bodies to harmonise the global approach towards standards thereby supporting industry and future research and development of emerging technologies. This showed that the established expertise developed in IND51 for optical communication technologies can be used as a basis to extend existing or develop new traceable systems.

In conclusion, this project ‘Knowledge Transfer for Optical Communications’ disseminated valuable research outputs from the EMRP project IND51 MORSE by transferring the relevant technology through national and European organised events. The consortium also promoted result findings from project IND51 MORSE to demonstrate Error vector magnitude (EVM) as a performance metric for multilevel modulation formats in optical coherent systems. We showcased the results at conferences and through publications demonstrating that the calibrated BER, which would otherwise be under-estimated without the correction factor, can reliably monitor the performance of optical coherent systems for various modulation formats: QPSK, 16-QAM, and 64-QAM employing carrier phase recovery with differential decoding to compensate for laser phase noise. The results on the number of symbols required to estimate the BER from EVM analysis were also disseminated and compared to the BER obtained by error counting showing that the EVM tool developed in IND51 MORSE is a powerful metrology tool for the next-generation of optical communication systems.

This objective was completely met.

5 Impact

The overall aim of 20SPI05 KTOC was to create additional impact from the work carried out in the EMRP project IND51 MORSE. The KTOC consortium participated actively with the BSI and IEC TC86 Standards committees including 5 working groups: SC86C/WG4, JWG9, SC86B/WG6, GEL86/2, SC86B/WG6. This included presentation of consortium activities and general participation in committees' meetings. In addition, the paper entitled 'Metrology of Optical Communication Systems Using Error Vector Magnitude' has been presented at the 7th Laser and Optoelectronics Conference (LOC 2021). A total of 4 open access journal papers have been generated in this project (see list below). Furthermore, 10 presentations were made at national and international conferences creating additional impact from the work carried out in EMRP project IND51 MORSE. This had relevance to optical networks directly, and also to wider general use of photonic components in other industries such as connectivity in data centres. Error Vector Magnitude (EVM) measurement results were published demonstrating that EVM is a promising figure-of-merit to quantify the impact of performance degradation in high-seed optical networks employing higher-order modulation formats such as QPSK, 16-QAM and 64-QAM. Greater uptake of EVM measurements by the user community enabled both users and suppliers to have greater confidence in optical performance monitoring.

With continuous pressure to be faster and more cost effective, the focus on optics was to overcome the limitation of copper in every aspect including speed and power dissipation. This encouraged the development of optical interconnects for different applications with the potential to replace certain functionality of electronics such as optical switching, optical storage, and also optical signal processing to address future challenges. The research results related to photonic interconnects were disseminated to transfer this knowledge to industry and academia and therefore gave potential for new improved products and innovations across Europe. The project also promoted new methodologies for more accurate measurements of optical communication systems such as error vector magnitude and bit error ratio measurements. Dissemination of the EMRP project IND51 project results has enhanced understanding for the photonic industry and the researchers regarding the significance of traceability and uncertainty in monitoring optical networks through our interactions at conferences (e.g. at ECOC conference and the joint symposium on quantum technologies), exhibition, posters and publications. This project had demonstrable impact in providing improved and new calibration services for customers throughout the photonic communication industry in Europe and internationally through standardisation engagements. By promoting the findings of EMRP project IND51 to the IEC International committee, the IEC 62496-4-1 standards were able to evolve in harmony with the technological advances of the photonic industry. New proposals for high-speed connectors enabled vertical density reduction from photonic components manufacturers compared to traditional connectors. This allowed connectivity for quantum computing, optical switching, and optical storage to name a few applications. The results dissemination in this project facilitated wider continuous innovation in optical connectivity which will continue to impact future data centre networks and machine-to-machine communications for Industry 4.0.

The project's Primary Supporter, Senko Advanced Components, recognised the necessity for the refinement and wider adoption of international standards regarding metrology techniques to evaluate the performance of optical communication systems. Accurate determinations of optical performance were needed to maintain compatibility of coupling interfaces with the rest of the installed fibre and network switch infrastructure. The results obtained in the EMRP project IND51, with the support of partners in this project has facilititated the transfer of this measurement approach and technology into industrial use via their membership and interactions with IEC TC86 SC86B. Therefore, Resolute Photonics, 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 interface standards (terminated waveguide OCB assembly using a single-row thirty-two-channel PMT connector intermateable with 250 µm pitch MPO 16) which allowed a single row of 32 waveguides to enable high-speed connectivity.

Direct impact has been achieved by working with the Primary Supporter, SENKO, who manufacture advanced optical connectors for data centre interconnects. This project also had demonstrable impact across Europe and internationally through contributions to Standards documents with the support of Resolute Photonics, as an external partner in this project and chair of IEC subcommittee SC86B – *Fibre optic interconnecting devices* *and passive components*, to facilitate early adoption of advanced components from manufacturers such as SENKO and the stakeholder, Arden Photonics Ltd. The project partner, Dr Richard Pitwon from Resolute Photonics, has also been appointed as the new chair of GEL86/2 and ran the first meeting disseminating the results from 19SIP05 KTOC. The Primary Supporter, SENKO, has gained knowledge transfer in optical connectivity beyond that available in published papers. SENKO has manufactured the CS^{TM} and the SN^{TM} connectors e.g. the duplex LCTM connector constructed with a zirconia ferrule that is spring loaded to ensure that an adequate mating force was applied to get a reliable fibre connection with a consistent low insertion loss. The dissemination activities within this project based on the results from EMRP project IND51 led to bandwidth optimisation within high-speed optical networks enabling the Primary Supporter to demonstrate the performance and significance of their photonic components to the wider photonic community as a global manufacturer developing advanced photonic components, therefore playing a major role in the relevant standards. The work within this project has led to bandwidth optimisation to meet the exponential growth in data rates for the next generation of optical networks important for high-speed communications. The contributions to IEC 62496-4-3/Ed1 to define the standard interface dimensions for a terminated waveguide optical circuit board assembly using single-row 32-channel waveguides that can be interconnected with a terminated MT ferrule for high-speed connectivity has, for example, enabled the Primary Supporter to demonstrate high-speed connectivity to the wider photonics community. Since, SENKO are one of only a few global manufacturers for photonic connectivity components, their involvement in this project facilitated the uptake and exploitation of traceable measurements by the photonic industry across Europe and internationally through active participation with world-leading standardisation bodies. This supported the “Europe’s age of light! How photonics will power growth and innovation” Strategic Roadmap. Additionally, the project has facilitated the transfer of design specifications to the Primary Supporter’s customer base including to the KTOC stakeholder, Arden Photonics Ltd, to enable improvements in data infrastructure and future growth. This has enhanced the Primary Supporter’s and the stakeholder’s position as an early adopter of the innovative technology demonstrated in IND51 MORSE. It also enabled them to become a lead advocate for good measurement practice, such as the use of Error Vector Magnitude as an efficient metrological tool, for optical performance monitoring in high-speed communication systems.

Dissemination of EMRP project IND51 outcomes and the Primary Supporter’s involvement with the project, has through standardisation widened their customer base and raise their profile on an international level helping to promote and realise the methodologies associated with increasing the high-speed, high-bandwidth capabilities of optical networks across Europe. Knowledge obtained through the metrology of high-speed photonic components facilitated the development of next generation optical interconnects operating at higher transmission speeds than currently possible. The Primary Supporter directly benefitted from the development of the relevant standards for a terminated waveguide optical circuit board assembly for high-speed connectivity and from the detailed knowledge of the standards generated in this project, therefore ensuring the compliance of their commercial product line optimised for 400 Gbit/s new generation data centres and rack level optical interconnect migration. The knowledge transfer in this project also expedited replacement of existing optical splices thereby improving modularity in limited space applications through innovative interconnect technology with photonic components used throughout the data industry, serving as vital parts of modern communications. This project resulted in new products from the primary supporter SENKO, e.g. duplex LCTM connector constructed with a zirconia ferrule to support next generation of optical communications equipment, leading to potential financial savings and environmental benefits being realised by the communications industry. The developments undertaken in the project further enabled the deployment of novel fibre-optic infrastructures for intra-data centres and machine-to-machine communications. The work carried out has relevance not only to data centres directly, but also for wider general use of photonic components in other industries enabling them to expand their manufacturing capacity to keep pace with the demand for 200 Gbit/s modules and above.

Finally, the development of photonic interconnects and optical network performance monitoring in 20SIP05 KTOC directly benefitted the energy costs associated with data centres reducing energy consumption and carbon footprint through improved coupling efficiencies for high-speed communication links. The early establishment of relevant metrology services developed in EMRP project IND51 has supported this development e.g. the contributions to IEC standards and development of metrology tools such error vector magnitude for performance monitoring. Alongside this research into optical connectivity and performance monitoring, understanding and minimising coupling losses can lead to energy savings in excess of 30%, directly reducing the electricity consumption required for cooling through the development of a new generation of high-capacity energy-efficient optical connectivity to strengthen Europe’s leading position in integrated photonics. In terms of social impact, the project has improved bandwidth efficiencies associated with optical networks to enable high-speed, high-definition mobile streaming to consumers helping to meet the significant data growth. The project demonstrated that reliable characterisation of optical interconnects enabled more efficient production methods thereby driving component costs down and thus making precision engineered items available to a wider audience increasing societal impact by meeting the demand for higher network bandwidth for applications such the social media platforms, 4K video streaming, increased number of smartphone users and the emergence of High-Performance Computing (HPC) in data centres and Internet of Things (IoT).

6 List of publications

Fatadin, I. (2021) 'Metrology of Optical Communication Systems Using Error Vector Magnitude', Journal of Applied Mathematics and Physics, 9, 2918-2926. https://doi.org/10.4236/jamp.2021.911185

R Ferguson et al (2022) 'Characterization of Quantum Grade Interconnects' J. Phys.: Conf. Ser. 2416 012003. https://iopscience.iop.org/article/10.1088/1742-6596/2416/1/012003/pdf

Y Gui et al (2022) 'Metrology Challenges in Quantum Key Distribution' J. Phys.: Conf. Ser. 2416 012005. https://iopscience.iop.org/article/10.1088/1742-6596/2416/1/012005/pdf

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/