Publishable Summary for 14IND13 PhotInd
Metrology for the photonics industry – optical fibres, waveguides and applications

Overview

This aim of the project is to develop online and offline measurement techniques for dimensional and optical characterisation of advanced photonic components and devices in fibre and waveguide optics as well as the necessary calibration techniques and artefacts to enable calibration of the newest generation of measuring instruments.

Need

The huge potential of photonics and fibre optics is evident from the Photonics21 Strategic Roadmap listing the major photonic research and innovation challenges. One challenge has been that modern photonic systems utilise novel components, whose dimensional and optical properties cannot be reliably measured using current techniques: commercial instruments are often uncalibrated, provide insufficient accuracy and are available only for some of the required characteristics. Thus, new traceable and improved measurements and calibration methods are needed to make photonic measurement technology an enabling technology that will allow technological breakthroughs as well as commercialisation of sophisticated fibre optic components.

- Improving online measurements of dimensional parameters (diameters and concentricity) during fabrication will benefit manufacturing of special fibres and capillaries.
- Evaluation of the performance of photonic components in optical interconnects and the next-generation of microwave or THz transmission links, traceable measurements of key parameters (dynamic range, insertion loss, bandwidth, etc.) as well as industry standards is necessary.
- The development of traceable measurement techniques to study environmental effects on the boards such as temperature cycling, ageing, humidity variation, etc. will help the data communications industry to understand the performance of optical printed circuit boards within their working environments.
- Coupling light without losses from fibres into optical circuits presents a challenge due to the large mode mismatch. Efficient solutions for matching conventional fibre-coupled systems to nanophotonic devices are needed.
- The metrology for measuring modal distribution in step index multimode optical fibres used in high bitrate multi-purpose optical networks is still not sufficient, leading to inconsistent measurement results that have a negative impact on the deployment of these systems.
- Novel optical fibre measuring instruments, like the high-resolution optical time-domain reflectometer, offer performances which cannot be adequately evaluated because of the lack of suitable calibration artefacts and procedures.

Optical communications, biophotonics, avionics, and automotive industries are examples of fields that will benefit from the improved measuring capabilities.

Objectives

The objectives of the project are:

- To develop traceable online and offline metrology techniques for characterisation of advanced optical fibres and photonic components – by developing measurement setups, procedures and numerical tools. Especially, the project will develop methods for thickness and concentricity measurements of different fibre layers with target accuracies of 0.5 µm and 1 µm, respectively, and for dispersion and optical parameter measurements in high power applications. The goal is to measure the relative content of light in the core with an accuracy of ±5 %.

- To develop metrology for improved traceability of fibre optic measuring instruments – by developing calibration techniques and artefacts. The main goal is to develop a traceable measuring system for encircled angular flux, which is a key parameter allowing characterisation of modal distribution in step index multimode fibres and components. Artefacts will be developed for the calibration of the attenuation scale and the distance scale of multimode optical time domain reflectometers (OTDR). Additionally, a novel portable absolute standard detector based on carbon nanotubes at cryogenic temperatures will be developed to solve the issues inherent to existing transfer standard detectors, like spectral dependence and temporal drift, and shorten the traceability chain of optical power measurements. This will result in a lower measurement uncertainty (target accuracy better than 0.5 %).
- To develop metrology for terahertz transmission links – by developing traceable measurement standards and measurement procedures for key parameters (dynamic range, insertion loss, SNR, bit error ratio (BER) for various modulation formats, free spectral range and bandwidth) of THz transmission links. The target accuracy for dynamic range and insertion loss measurements is 5 %.
- To establish the metrology tools for performance characterisation of polymer waveguides mounted on electronic circuit backplanes used in high-speed data links – by developing measurement systems that can characterise the functional performance of waveguides incorporated onto short range interconnect boards. The systems will assess the key parameters of attenuation, isolation and BER. The usability of typical fibre-to-fibre connectors at high average powers will be investigated by monitoring transmission as well as the heating of the components (target accuracy: ±5 %). Measurement strategies to characterise evaluation boards will be developed with accuracy levels within ~ 1 dB for attenuation.
- To engage with the European photonics industry and photonics equipment manufacturers – to facilitate the take up of the technology and measurement techniques developed by the project, and to recommend what further actions are required to ensure uptake.

Progress beyond the state of the art

Current measurement technologies are mostly adapted to standard telecommunication and thus are not suited for characterisation of advanced optical fibres with different core and cladding dimensions and power range.

The accuracy (~5 µm) of today's online measurement methods for concentricity of fibre coating is inadequate for modern production and the methods are not applicable to different fibre types. The project will develop measurement tools with target uncertainties below 1µm, which will be based on the measurement and numerical analysis of laser scattering from transversely illuminated fibres. The scattered pattern was modelled with finite-element and Fourier-modal methods, and showed a good match to the measured data. The developed method will be sensitive enough to measure deviations in diameter or concentricity of the coating below 1 µm for the common fibre geometries.

Dispersion is one of the most critical parameters in new and existing fibre-optic devices and deployments, affecting the link distance attainable, the data rate and channel cross-talk. The project will develop non-destructive and novel methods to measure dispersion and group velocities. The target is to measure optical dispersion with a relative uncertainty of 1×10^{-3} for dispersion slope and zero dispersion wavelength for 100 m of silica fibre. High power fibre lasers are often based on fibres consisting of an inner and outer core guiding the signal and pump light. Measurements of total transmission losses do not accurately reflect the losses of usable optical power, because the power transfer from signal core to cladding is neglected. A novel set-up for high power fibre characterization has been set-up for Watt-level optical power. In addition a new method for cladding light content measurement has been developed. The outcome of this work will include guidelines for measurement procedures for high power fibre optics.

To assess the performance of the photonics components used in THz transmission links, new metrology tools need to be developed. This project will study methods for measuring dynamic range and insertion loss and spectrally efficient modulation formats for the future THz links. A high resolution CW THz spectroscopy system and a new Lamellar mirror interferometer has been implemented.

The development of high bitrate multimode communication systems has made control of the modal distribution a key issue. The project will establish traceability for angular encircled flux (EAF) for the very first time and thus contribute to a proper implementation of these multimode systems. Two separate EAF set-ups have been constructed and have already been fully validated through a series of inter-comparisons.

The project will develop traceable calibration methods for the distance scale of high spatial resolution OTDR and for the attenuation scale of multimode reflectometers, which currently are lacking. A series of integrated recirculating delay lines for the calibration of the distance scale of Optical Low Coherence Reflectometers has been fabricated and fibre-based micro-recirculating delay lines are under evaluation.

A first prototype of a fibre coupled absolute cryogenic radiometer based on carbon nanotube absorbers was developed and is almost ready for first evaluations.

The EMRP project IND51 (MORSE) focused on development of high-level metrological tools for *complete transmission systems*. In contrast, this project is devoted to *component characterisation* underpinning the functionality of transmission links. The two projects are complementary, providing a comprehensive suite of metrological tools for quantifying performance of photonic communication systems.

Results

Develop traceable online and offline metrology techniques for dimensional and optical characterisation of advanced optical fibres and photonic components

The project will provide non-destructive and novel methods to measure dispersion and group velocities in optical fibres, measurement procedures for high power fibre optics, and online techniques for dimensional measurement of optical fibres. Construction of two novel set-ups for dispersion measurement of optical fibres has been partly completed. One utilises frequency comb with a pulse picker and white rabbit time synchronization, and the other is based on a SEA TADPOLE type white light spatial-spectral interferometer. For the high power characterisation at Watt level a metrological set-up for the measurement of fibre connector transmission has been build, and dependency of the connector performance on optical power has been investigated. A setup for the evaluation of cladding light content at up to 400 W has also been implemented and been successfully tested, reaching the target for repeatability and allowing for the cladding light measurement in multi-clad fibre geometries. OFDR technique has been adapted for evaluation of fibre core temperature in active high power fibres with large mode area. Guidelines for high power measurement are under development. For on-line characterisation of the dimensional properties of the fibre, a set-up has been designed and built for measurement of scattering from transversely illuminated fibres, and a portable set-up for testing in the production environment is under construction. Finite Element Method (FEM) and Fourier Modal Method (FMM) simulations are performed to find out sensitivity coefficients of scattering pattern to dimensional properties to support experimental results.

Develop metrology for improved traceability of fibre-optic measuring instruments

The project will provide a fully traceable measuring instrument for the calibration of the angular resolved modal properties of multimode systems, and will also fabricate artefacts for the calibration of the latest generation of high-resolution single-mode and multimode optical time-domain reflectometers.

Two different systems for Encircled Angular Flux (EAF) measurements have been constructed. The linearity and uniformity of two different types of IR-cameras have been characterised, and two independent analysis software for the calculation of the EAF have been developed, as well as a full uncertainty budget. The performance of EAF measurements have been validated by an inter-comparison, which showed excellent results. First discussions have been carried out with the technical committee IEC/SC86B, which is in charge of developing the relevant standards for EAF measurements and need to be further investigated. An artefact for the calibration of the distance scale of high resolution optical time domain reflectometers (OTDR) is under development. Waveguide-based recirculating delay lines for the calibration of Low Coherence Reflectometers (OLCR) have been built and are currently under test. An attenuation reference fibre with controlled modal distribution for the calibration of the attenuation scale of multimode OTDR has been successfully built and is ready for further inter-comparisons. First important steps towards the development of a fibre-coupled cryogenic radiometer have been successfully made.

Develop metrology of terahertz transmission links

The project will provide measurement standards and standard measurement procedures for terahertz transmission systems. A THz transmission link has been set up in collaboration with UCL and is currently being used to explore different modulation schemes. A paper describing this work in detail has been submitted for publication. In addition, a lamellar interferometer has been implemented. These systems will be used to characterise components employed in THz communication systems which would be obtained from UCL.

Establish metrology tools for performance characterisation of polymer waveguides mounted on

electronic circuit backplanes used in high-speed data links

The project will establish metrology for and will contribute towards standardisation of key parameters, such as coupling loss, attenuation, crosstalk and BER, of short range interconnects. Novel fibre-to-chip couplers will be developed to overcome existing barriers in conventional technologies.

A Novel grating coupling devices to optical fibres have been designed, measured and fabricated using nanofabrication procedures. Transparent silica substrates have been used for wavelengths in the near-infrared wavelength range. Insertion loss of -1.67 dB per input coupler has been measured on target with the plan. Devices have been characterized using pairs of grating couplers connected via waveguides. The device footprint is below 200 μm^2 and thus compact. A temperature chamber system is being used to characterise novel optical waveguides provided by other partners. The performance is currently being evaluated under different environmental conditions. A BER measurement set up using an arbitrary waveform generator and a SFP+ module have been implemented for investigation of the thermal impact on data transmission. NPL is also contributing to the following IEC standards: GEL/86/2, GEL/86/3.

Engage with the European photonics industry and photonics equipment manufacturers

The project will facilitate the take up of the novel technology and measurement techniques, and recommend what further actions are required to ensure uptake. The artefacts, protocols and measurement technologies developed will provide a basis for future standards and innovative products.

Project partners have been working to communicate with relevant international and national standardisation committees. The partners have after just 27 months published or submitted 9 open access peer reviewed papers and taken part or submitted abstract to 31 different national or international conferences. These include occasion organised by EOS, EPIC, BIPM and SPIE. Also first uptake actions of the project outcomes already came through: Two patent applications related to fibre characterisation and one patent application related to waveguide components have been submitted for examinations.

Impact

The project addresses the urgent metrology needs of photonics industry manufacturing and innovation. The European photonics industry would significantly benefit from the online and offline characterisation techniques for advanced optical fibres and photonic components as well as from the calibration techniques and artefacts to be developed in the project. The new metrological tools will support development and manufacturing of completely new products, which will be a competitive factor. The co-operation with European Photonics Industry Consortium, EOSAM and national photonics organisations guarantees effective dissemination.

The project partners have already submitted 9 manuscripts to peer reviewed scientific journals, 8 of them have already been published, had 31 talks or posters in international conferences, and had 12 different training events both for project partners and wider audience.

Impact on relevant standards

This project will have an impact on the work of IEC standardisation groups together with metrology committees of CCPR and EURAMET TC-PR. This far project partners have taken part to 16 different technical committee meetings. Project partners provide advice for the updating of existing standards and contribute to new standards related to the calibration of fibre optics measuring instruments (IEC TC86, WG4) and to the functional performance of short range interconnects (IEC TC86/TC91, JWG9). The project partners will provide advice for the improvement of calibration techniques to CCPR task groups on fibre optics (TG6) and on OTDR length calibration (TG9). Also EURAMET Technical committee for photo and radiometry is and will be informed about the results of the project.

Impact on industrial and other user communities

The manufacturers of advanced optical fibres will benefit from the project through the availability of novel tools for high-level characterisation of dimensional and optical properties. The development of techniques for online monitoring and control of the fabrication process will have a significant impact on the fibre industry, which would improve the quality of the production, increase the yield of the processes and reduce costs.

The development of new calibration techniques for the latest generation fibre optics will benefit industrial applications in the field of sensors. High-resolution spatial measurements of distance and attenuation scale calibrations would improve the accuracy of sensors. The develop EAF measuring instrument is planned to be for sale by one of the project partners. This will allow industry to better characterise output properties of different fibres. Several new calibration services are to be started-up by NMIs.

Developments in optical fibres and fibre connections, polymer waveguides, and THz interconnects enable more economic and faster data connections with optical Fibre-To-The-Home. Manufacturers of microwave photonics components including THz communications equipment would benefit from the project by having the means and procedures for characterising their equipment performance.

The coupling components developed in this project will provide a flexible architecture for multi-port access to integrated optical devices. This is of relevance for manufacturers of integrated optical circuits, as well as for the production of nanoscale photonic systems with macroscopic fibre connectors. The establishment of hybrid planar-3D photonic systems will satisfy the need to move beyond traditional optical designs and provide possibilities to transfer knowledge from free-space optics to on-chip circuits. This will be important for the manufacturers of 3D lithography equipment.

More reliable characterisation methods for high-power fibre lasers and components will reduce the effort required for the developers of these devices. By having reliably characterised high-power fibre connectors readily available, the spread of modular systems could also be increased, leading to more flexibility for companies using lasers.

The developed finite-element based numerical methods for simulating different photonics components will be available later as part of a commercial software package.

The project partners collaborate closely with companies interested in targets and results of the project. Several companies have already applied position in stakeholder committee of the project.

Impact on the metrological and scientific communities

A better understanding of the optical properties of advanced optical fibres will benefit the fibre optic community. Especially, new techniques for EAF and OTDR high resolution measurements requires a deep analysis of optics, optical detection and image processing; the outcomes of which will be beneficial for the scientific communities. Results from inter-comparisons of OTDR measurements and comparisons between modal distribution simulations and measurements will be shared with the metrological community.

In particular, the advances in fibre-to-chip light coupling and photonic metrology provided by this project will be used in many areas of integrated photonic circuits. By simplifying light coupling and providing a better waveguide characterisation, scientific communities will be able to focus their effort on the actual chip functionalities, increasing research efficiency and impact.

Terahertz communications is now at the research stage, focusing significant attention from the scientific community. Given its novelty, metrological communities still need to develop appropriate characterisation systems and standards. The results of the project will therefore greatly benefit all the aforementioned parties.

Establishing traceability will be a key part in the development of the new measurement techniques. The project results and outcomes have already been disseminated by 8 publications and 31 conference presentations.. The project results have been presented at EOSAM 2016 conference and at BIPM workshop on the metrology needs in the fiber optics. In spring 2018 the project will have a joint session with SPIE photonics west conference were the results of the project are more widely communicated for industrial and scientific community.

List of publications

I. Fatadin, Estimation of BER from Error Vector Magnitude for Optical Coherent Systems, Photonics (2016) 3(2) 21. doi:10.3390/photonics3020021

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H. Podmore, A. Scott, P. Cheben, A.V. Velasco, J. H. Schmid, M. Vachon, and R. Lee, A compressive-sensing Fourier-transform spectrometer chip using subwavelength grating waveguides, Optics Letters Vol. 2, pp. 1440-1443 (2017), https://doi.org/10.1364/OL.42.001440

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M. Hammerschmidt, M. Weiser, X. Garcia Santiago, L. Zschiedrich, B. Bodermann, S. Burger Quantifying parameter uncertainties in optical scatterometry using Bayesian inversion, Proceedings Volume 10330, Modeling Aspects in Optical Metrology VI; 1033004 (2017); doi: 10.1117/12.2270596

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