Publishable Summary for 17FUN01 BeCOMe
Light-matter interplay for optical metrology beyond the classical spatial resolution limits

Overview

The EU wants to hold a dominant global position in nanotechnology, micro-nanoelectronics, photonics and advanced materials: four of the six Key Enabling Technologies (KETs) identified by the European Commission. However, such a dominant position strongly depends on the availability of proper tools that can serve the metrology needs of those KETs in terms of speed, non-invasiveness, reliability and integrability. This project addressed these needs by exploring (i) novel metrology paradigms exploiting light-matter interplay, (ii) the topological information encoded in optical fields and (iii) the most recent accomplishments in the areas of quantum optics and inverse problems to achieve disruptive advances in optical metrology. The project has achieved the realisation of the next generation of optical metrology systems, with unprecedented performances in terms of spatial resolution, traceability, reliability, robustness. These next generation of optical metrology systems include higher order ptycographic reconstruction, solid immersion lens (SIL) -based far-field illumination and detection, alternating grazing incidence dark (AGID) microscopy, designing and fabricating superlenses as resolution enhancers, enhancement of Tip-enhanced photoluminescence, scanning near-field optical microscopy (SNOM), application of sub-shot noise quantum technologies to optical systems and spatial spectroscopy.

Need

The EU formally identified six KETs, which were given the highest priority within the EU strategic research agenda. KETs have a *"…significant impact on how Europeans will live and work, and on how European industries and economies will grow to provide sustainable employment for its citizens*". KETs represent the *technology building blocks* for advanced products and their manufacture, and they form the backbone of the European competitiveness on the global market. Research efforts meant to strengthen the position of Europe in these KET areas are of uppermost importance, since "*once the manufacturing base is lost, it never comes back*".

Metrology runs side by side with such scientific and technologic progress. Manipulating matter at the nanoscale, in a scientifically reliable and predictable way, urges the metrology community to provide the appropriate metrology solutions. Such novel or improved metrology solutions then, in turn, stimulate the next technological and scientific developments.

In this context, optical measurement methods play an instrumental role in the development in four out of the six KETs (Nanotechnology, Micro-nanoelectronics, Photonics and Advanced materials) as this development is underpinned by optics-based measurement methods. The importance of holding a dominant scientific and technologic position in these sectors is clear considering that (prior to the start of this project) they were worth more than € 800 billion on the global market and that the Photonics and Micro-nanoelectronics areas employed more than 400,000 people in Europe.

Despite the many advantages of optical systems (speed, non-invasiveness, high-precision, moderate investments involved, integrability) the operational spatial resolution attainable in classical optical metrology prior to the start of this project was still essentially limited by the wavelength used for the optical probe. Therefore, novel and robust metrology solutions were needed that could maintain the recognised benefits of optical methods while substantially overcoming the limitations at that time.

Objectives

The overall goal of this project was to set the basis for the realisation of the next generation of optical metrology systems, with unprecedented performances in terms of spatial resolution, traceability, reliability, robustness. The specific objectives of the project were:

1. **To develop stable and reliable methods to achieve deep sub-wavelength spatial resolution by exploiting higher-order (beyond Born regime) probe-target interactions**. To design metamaterials-based structures that can enhance such interaction and bring it to detectable levels for a large class of targets, not only strong scatterers. The goal is to reach, for a well-defined class of samples (e.g. diffraction gratings on silicon substrates, isolated nanoparticles on both opaque and transparent substrates), a traceable spatial resolution at the $\lambda/10$ level and sub-nanometre uncertainty, with λ being the wavelength of the light probe
2. **To exploit invariant topological structures in electromagnetic fields,** in their polarisation, amplitude and phase distributions**, and map how such topological information transforms after interacting with matter**, especially in the case of nanostructured materials endowed with specific geometric symmetries (e.g. diffraction gratings, spiral geometries, bio-inspired circularly-symmetric objects). The ultimate goal is to implement spectroscopy-like measurement concepts, leading to robust and high-precision dimensional and physical measurement results
3. **To realise and demonstrate near-field techniques to measure deep sub-wavelength gratings down to the regime << λ/10** which allow accurate and traceable optical procedures to characterise nanostructured optical components and to measure effective optical material parameters. In addition to link such near-fields methods to far-field optical methods of specific applied interest
4. **To apply sub-shot noise quantum technologies to optical systems, addressing both low and high Numerical Aperture (NA) systems**. To realise input fields with spatially-entangled optical channels and to map their coupling with the geometry of nano-targets. The potential of quantum metrology in optical systems will be explored through spatial modes entanglement and its integration into existing optical systems. The aim is to find a natural link with the exploitation of topologic information in classical fields, as discussed hereinabove
5. **To facilitate the take up of the technology developed in the project by the end users.**

Progress beyond the state of the art

Rayleigh's criterion for assessing the resolution limit of optical systems, no matter how complex and which wavelength λ they employ, states that the smallest detail that can be resolved in an object is of the order of 0.6 λ/NA, where NA is the numerical aperture of the system. For systems operating in air, NA is a positive number smaller than 1, which results in a resolution of about half of the wavelength. Prior to the start of this project different criteria could be adopted to quantify such limit, however they all agreed on the fact that the wavelength is the limiting factor.

This was a severe limitation for optical methods, especially in view of the growing impact of nanostructured devices and materials in technological developments. For specific applications, smart alternatives were found e.g. for the imaging of biological samples, they can be stained by fluorophores, and hence time-resolved fluorescent methods (such as Stimulated Emission Depletion (STED), Stochastic Optical Reconstruction Microscopy (STORM), Photo Activated Localisation Microscopy (PALM) etc.) flourished in the few years before this project began, with proven resolutions at few tens of nanometres level. But unfortunately, such techniques were of no use for inorganic materials in the semiconductor sector, where no natural fluorescent response existed, and contamination with external markers was not allowed. Additionally, the quantification of the measurements results was complex and rarely addressed.

One way to approach the issue was by progressively moving to smaller wavelengths and/or is to make use of all the prior information available on the target. However, moving towards smaller wavelengths does not completely solve the problem because shorter wavelengths have a short (around 100 nm) penetration depth and for some applications no prior information on the target is available.

This project intended to go beyond the state of the art by developing novel methods to improve the spatial resolution limit of far-field optical systems well beyond the classical resolution limit. Specifically, the project investigated ways to exploit higher-order interactions between the probe and sample of interest. This enabled the implementation of multiple scattering models into imaging systems to account for strong spatial light-matter interaction regimes. For weak scatterers, where such interaction can be too feeble to be detected, amplification of sub-wavelength information, such as evanescent wave amplification, were realised through the design of specially engineered nanodevices and structures. The targeted resolution, for systems working in far field illumination-far-field detection mode, was one tenth of the wavelength, with targeted sub-nanometre uncertainty.

The project also investigated the existence of invariant modal information in vectorial optical fields and how that information can be transformed after interacting with matter. The goal was to identify robust information channels that can be used to establish a direct mapping between the light probe and scattered field and to setup the basis for the new field of spatial spectroscopy. In addition, the project aimed to link the performance of methods developed with the project to near-field techniques in use at NMIs, in order to validate the novel solutions investigated in the project.

Further to this, the project developed sub-shot noise quantum technologies, quantum-based metrology schemes and novel spatial entanglement-based measurement concepts that could be implemented in existing metrology systems, such as optical scatterometers, atomic force microscopes (AFM) and optical ptychographic systems.

Results

To develop stable and reliable methods to achieve deep sub-wavelength spatial resolution by exploiting higher-order (beyond Born regime) probe-target interactions

The project investigated ways to solve direct strong scattering problems using perturbative methods. Perturbative methods are semi-analytical and can provide more insights on the physical mechanisms behind a measurement result than a brute force numerical approach. However, it is known that for strong scatterers (i.e. those with a strong scattering regime), perturbative methods can lead to highly divergent solutions, which can hamper their practical usefulness. Providing a solution to this problem should give high theoretical and practical impact because direct scattering problems are instrumental to addressing and solving inverse scattering problems, which were key goals for the project. The project was able to solve the problem of the divergence for wildly divergent Born series as well as proving the method for 1-D and 2-D scattering problems. Development and implementation of the higher order ptycographic reconstruction in combination with coherent Fourier scatterometry provided deep sub-wavelength spatial resolution.

The project also investigated the application of this theory for creating novel inverse methods where more insights on the mechanism behind superresolution can be gained. In addition, inverse electromagnetic problems were approached from a different viewpoint, namely by using Bayesian inversion methods. Subsequently the project proved the potential of Bayesian inversion by benchmarking its performances with respect to other commonly used methods.

Another output of the project has been the design and fabrication of metamaterials-based superlenses. These metamaterials-based superlenses were designed to boost the spatial resolution of existing optical systems, such as optical scatterometers, in the visible range of the electromagnetic spectrum. Five different designs of metamaterials-based superlens artefacts for novel far-field illumination far-field detection super-resolving optical metrology systems were developed by consortium. Some of the designed devices were fabricated and tested on direct bright field imaging, where the positive impact of the different metamaterials-based superlenses on the quality and resolution of the images was clearly visible. Moreover, the project's newly designed resolution enhancers increased the spatial resolution to deep-subwavelength level.

SIL (solid immersion lens)-based far-field illumination far-field detection microscope, with a target resolution of λ/10 (55 nm, if visible light is used) and sub-nanometre uncertainty was also developed during the project. A microscope setup was modified so that it was possible to perform multi-wavelength scatterometry microscopy. Another noteworthy achievement for the project was the measurement of the line structures down to 75 nm using AGID microscopy at a wavelength of 405 nm. The project has also demonstrated AGID measurement capability down to as low as 30 nm line features using simulations. Thus, the target deep sub-wavelength resolution of λ/10 has been successfully demonstrated by the project for AGID microscopy.

To exploit invariant topological structures in electromagnetic fields and map how such topological information transforms after interacting with matter

The project developed different aproaches to probe the specific spatial features of objects, using a spatial mode decompositin of a light field. The goal was to develop an approach that could be used as a general procedure and applied to a wide range of objects of interest. The approach chosen uses results from quantum Fisher information theory to evaluate the maximum sensitivity one can obtain in a given experiment. The approach also uses a formalism developed within quantum estimation theory and is predominantly aimed at understanding what are the fundamental limitations of the amount of information that can be extracted from an optical wavefield. This important work highlights the impact that the evaluation of the quantum Fisher information of particular measurement schemes should have on the limitations and possibilities of optical metrology. Another benefit of the project's chosen approach was the identification of an ideal measurement setup and procedure that consists of projecting the wavefield reflected or transmitted by the object in the spatial modes already selected. Experimental demonstration of this is currently on-going.

The project also investigated the mapping of the spatial degrees of freedom carried by an optical field. The project did this using two different methods:

1. theoretical/numerical studies were carried out to estimate the effect of sub-wavelength structures (such as diffraction gratings) on the spatial channels used to describe the field. The project partners involved in this used complementary approaches, such as HNMs decomposition, decomposition in spatial modes containing orbital angular momentum and spatial modes with radial or azimuthal polarisation, or the use of quantum Fisher information to estimate resolution limits.
2. the development of experimental setups based on different imaging methods to tailor and detect the amplitude and phase of the wavefields and measure how they transform after interaction with some objects of reference.

Both methods provided beneficial results for further research and the development of the experimental setups enabled the project to separate the phase and the amplitude. The project found that the designed spatial spectroscopy setup was optimal for the resolution enhancement and parameter estimation of phase objects by selecting appropriate spatial modes for a certain light-matter interaction. Furthermore, theoretical/numerical studies after phase mapping suggested that certain HNMs depending on the nanostructure geometry can influence the signal in the far field.

To realise and demonstrate near-field techniques to measure deep sub-wavelength gratings down to the regime << λ/10

First calculations of the near field of a grating SIL (Solid Immersion Lens) or photonic nanojet lens system were performed together with the realisation of a program for calculating the photonic nanojet field after a ball lens using Mie theory. The project's numerical simulations were subsequently extended to circularly polarised light. Additionally, a numerical method for the substantial control of the position of a photonic nanojet was developed and successfully tested. The method currently works in the 2D setting was also successfully generalised to 3D settings.

The project achieved significant progress in setting up of a novel spectroscopic SNOM tool. New SNOM probes were fabricated using a focused ion beam and were then characterised and successfully tested with measurements.

Further to this, a spectroscopic set-up was realised and tested by the project partners. First test measurements showed unexpected discrepancies between measured and expected intensity distribution in the reflected spectra. Therefore, rigorous Finite-difference time-domain (FDTD) simulations were undertaken to clarify the observed discrepancies. These FDTD simulations were successful and confirmed that the multiple reflections between the probe apex and the sample can lead to the results in a wrong scale (i.e. the source of the observed discrepancies).

Tip-enhanced photoluminescence (TEPL) is another advanced technique which was enhanced by the project for use with high resolution imaging. The project performed a comparison of the enhancement of photoluminescence yield by localised surface plasmon resonances (LSPR) in single - layer and multiple-layers of MoS_2 and demonstrated that TEPL mapping can be used to locate nanoscale adsorbates on a single-layer

MoS_2 flake. The results also demonstrated that spatial resolution achieved by TEPL imaging of a single - layer MoS_2 flake can be more than 20 times smaller than the excitation wavelength (< /25).

To explore the link between the near-field and far-field optical methods, the project investigated a variety of different approaches, such as (i) the application of plasmonic lenses, and (ii) the ability to create subwavelength structured illumination using the fractional Talbot effect and resonance enhancement either by quasi-bound states in the continuum or by LSPR. The investigations on Structured Illumination Microscopy included N-SIM, P-SIM Design and Finite Element Modelling (FEM) simulations of metallic plasmonic lens structures. The original design of the plasmonic lens demonstrated severe manufacturing issues and therefore an alternative design, an inverted lens design, was developed by the project to prevent this. The optimisation of the inverted lens design was successfully completed using a particle swarm algorithm. The resulting inverted design was investigated, and the results showed a good compromise between performance and manufacturing ability. An inverted lens based on this designed has since been produced and investigations on its optical performances are ongoing.

Additionally, the project developed a method for enhanced sensitivity in scatterometry by analysing structure-induced resonances, which was also experimentally proven. A systematic numerical study based on rigorous RCWA modelling was also performed by the project in order to investigate the parameter dependencies of LSPR in silicon gratings observed in the Deep Ultraviolet (DUV) (l = 266.3 nm). The results demonstrated not only a significantly enhanced sensitivity of structure width and hight of < 0.2 nm and < 0.5 nm, respectively, for goniometric DUV scatterometry, but also a measurement capability with a sensitivity of about 1 nm for pitch measurements for sub-diffraction periods between 50 nm and 250 nm, which were not accessible without exploiting the LSPR.

To apply sub-shot noise quantum technologies to optical systems, addressing both low and high NA systems

The project's work on low-noise imaging schemes included the development of a new protocol for improving resolution-sensitivity trade off in sub-shot noise imaging (SSNI) of weak transmitting masks. The effectiveness of this protocol was demonstrated experimentally, and the results showed an increased signal to noise ratio in quantum ghost imaging.

The application of sub-shot noise quantum technologies to optical systems was also investigated by the project. The project identified an approach that is suitable for the phase retrieval of an unknown object, using spatially multimode entangled light sources (Noise Reduction Factor (NRF) < 0.3). The quantum correlation enhanced phase retrieval method and can be applied with both low and high NA systems, using different optics. However, the developed experimental system was currently realised using low NA.

The project realised and detected structured light from single photon emitters by using a spatial resolving detector at the single photon level. It also investigated superresolution with structured light coming from single photon emitters and the use of high order correlation functions measured in wide field. This was done with the high numerical aperture (NA=1), and by using single photon emitters, which are sub-Poissonian (sub-shot-noise) quantum sources. The measurement of this sub-shot-noise feature was achieved with a high NA wide field single-photon microscope and further work is on-going to exploit this signal for obtaining superresolution.

In addition, important progress was made on the realisation of new sources of squeezed light and their application. As part of this the project developed a new optical parametric oscillator (OPO) system for generating squeezing in high-order modes, which was then used to demonstrate quantum frequency conversion of vacuum squeezed light to bright tunable blue squeezed light and higher-order spatial modes.

Another novel and important application of the squeezed sources developed in the project, is quantum enhanced stimulated Raman imaging. Furthermore, investigations on the potential of quantum metrology optical schemes led to the analysis of Weak Value Amplification (WVA) which is typically used for estimating extremely tiny changes in parameters of interest (e.g., temperature, angle of deflection, frequency, position, temporal delay, etc.) as well as the Hong-Ou-Mandel (HOM) effect.

Impact

Over the project has produced 47 open access publications (either published or waiting to be published) and been presented 76 times at conferences. The project has also hosted a large number of events for scientific end users and the general public. These have included:

- The "QUILT Autumn School 2018 - Quantum-Enhanced Imaging and Spectroscopy" organised by the Fraunhofer Gesellschaft (IOF/IPM) in Bad Honnef, Germany. The School was aimed at providing participants with first-hand information on current trends in quantum imaging and to discuss fundamental and applied aspects in the area of research. The audience consisted of about 70 attendees, mainly PhD students but also experts and scientists working on different field of classical and quantum physics.
- 21-23 October 2019, at the Face2Phase conference the project organised a workshop focused on Phase retrieval and its applications to metrology. Four lectures were provided by recognised experts in the field and more than thirty participants attended.
- 29 May 2019, a special section dedicated to this project and entitled " *BeCOMe - Current and future trends in Quantum Optics-based measurements methods*" was organised as part of the workshop "*From Foundations of Quantum Mechanics to Quantum Information and Quantum Metrology & Sensing"* (Quantum2019), held at the University of Torino (Italy), with more than 250 attendees.
- The consortium organised conference sessions dedicated to Optical Metrology and Nanometrology, at the SPIE conference Modelling Aspects in Optical Metrology (June 2019, Munich, Germany, partly combined with CLEO/EQEC) and the Nanoscale (October 2019, PTB Braunschweig, Germany).
- The consortium organised a school of physics on optical metrology as part of the European Optical Society (EOS) Annual Meeting (EOSAM2020, 07-11 September 2020). Although originally planned in Porto, Portugal, it was hosted online due to the COVID-19 pandemic. The focus of the school was on innovation and how fundamental research into metrology can underpin the scientific and industrial role of Europe in optical metrology. More information can be found here. The School successfully attracted >200 attendees from all other the world.
- June 1st, 2021, the consortium organised an online conference "Applications of field topology and non-trivial symmetries in optical metrology", which was targeted towards at scientific end-users interested in developments within the BeCOMe project. The online conference attracted over 200 attendees from European universities and the scientific community.
- September 25th and October 14th, 2021 the consortium organised two seminars for the general public during the 2021 European Researchers night and the 2021 Festival of innovation and science in Italy. The seminars attracted over 150 attendees from Italy.

The project has also produced two press releases, by the University of Torino, on the "UNITONews" and "Frida" portals. These press releases showed the first achievements of the project on a new class of single photon emitters, with potential applications to high-resolution imaging.

Finally the project has supported 9 Masters and 1 PhD theses in physiscs based on the BeCOMe project at the University of Torino, Technical University of Denmark and Delft University of Technology.

Impact on industrial and other user communities

This project performed innovative research that can be used to benefit high-intensity technologies such as software, biotechnology and computer electronics. The project investigated optical measurement instruments and methods which were relevant for these applications, such as optical scatterometers and high-contrast phase sensitive systems (Objectives 1, 2 & 3). The project's method based on the extension of the standard ptychographic algorithm beyond the Born approximation regime (Objective 1), in instruments such as scatterometers is also relevant to end-users. Further to this, the adoption of the partner's DFM developed software (Objectives 1 & 3) has helped grating manufacturing company "Ibsen Photonics" to move towards developing a more advanced system for grating measurement. In addition, partner DFM has developed software for improving the spectrophotometer devices based on the work in Objective 1 for SME company "Copenhagen Nanosystems".

The project has developed valuable tools and improved metrology for end-users. Two important stakeholders (a leading company in the field of optical lithography and a leading manufacturer of precision measuring equipment) were invited to and attended the project's meetings to discuss possible uptake of the project's results and to provide end-user feedback. The project has also provided consultancy to one of these companies on optical methods for metrology.

Finally, to support user uptake the open source software linked to the FDTD calculations performed by CMI has been made publicly available at http://gsvit.net/. The software code was adapted for modelling of scattering on sub-wavelength gratings and its performance was compared to results obtained by FEM modelling by partner ZIB. Notes on the comparison are available at http://gsvit.net/wiki/doku.php/docs:become.

Impact on the metrology and scientific communities

This project provided new solutions for optics-based dimensional metrology by demonstrating the possibility of integrating modern field theories and material science into classical measurement schemes, in order to progress beyond the current-state-of-the-art. Examples of this include development of the resolution enhancers and improvement in Pade' resummation when applied to a Born series (Objective 1).

Metrology systems, such as optical scatterometers, bright-field microscopes and similar contact-less metrology tools, also had their spatial resolution extended through new methods ranging from the implementation of new super-resolution models (Objective 1) to classical experimental data (Objective 1) and the integration of metamaterials-based superlenses (resolution enhancer devices), into existing systems (Objective 1). In this way, end-users from the metrology and the scientific community should now be able to boost the performances of tools already at their disposal without resorting to major investment and technology shifts.

One distinctive feature of most of optics-based metrology systems is their reliance on physical models for the extraction of desired information on a measurement target from acquired data. This often means rigorously solving Maxwell equations, using subtle inversion models and regularisation methods. The spatial spectroscopy (Objectives 3 & 4) directly mapped the measured data to the measurand in a more straightforward way. Thus, facilitating the adoption of optical measurements techniques by the scientific communities by reducing the need for complex data post-processing and analysis.

The project's results also highlighted a need for higher-throughput, larger-scan-range reference metrology for nanoscale resolution standards, which accumulate defects during normal use that are not reliably captured by sparse, local checks. Partner NPL developed a metrological high-speed (HS) AFM, by increasing its XY scan range. This enhanced, metrological HS-AFM features scanning speeds of several millimetres per second with a data acquisition rate of 1 megapixel per second and has been successfully demonstrated on the 1D and 2D resolution standards developed by NPL within the project. Both the enhanced measurement capability and the characterised standards can now be used to provide improved traceability for the metrology and scientific communities for the evaluation of resolving power (Objectives 1 & 3).

Further to this, the project's integration of quantum-enhanced methods, such as spatial modes entanglements and sub-shot noise shadow imaging, into optical systems (Objectives 2 & 4) should further promote the integration of quantum technologies and classical optical systems and help to increase uptake in the field of non-invasive optical metrology. To support this, the consortium worked with the collaborator fom University of Purdue (USA) on the integration of quantum theories into optical metrology.

The impact of the project on metrology is also linked to the definition of standards for the measurement of new quantities related to the quantum phenomena. For example the first informal comparison of the g(2) measurement in the visible range is related to the project's work on quantum-based super-resolution imaging (Objective 4), and was highlighted in "Nature Communications", https://www.nature.com/articles/s41467-018-08100-1.

Impact on relevant standards

The project is fundamental research by nature, hence significant impact on standards was not foreseen. However the project was disseminated within EURAMET TC-Length (TC-L), the BIPM Consultative Committee for Length (CCL) Working Group on Dimensional Nanometrology (CCL-WG-N) and Versailles Project on Advanced Materials and Standards (VAMAS) Technical Work Area (TWA) 42 on Raman and microscopy.The work done within the BeCOMe project on the measurements artefacts, for assessment of the spatial resolution of optical systems, was also presented to ISO/TC 213 “Dimensional and geometrical product specifications and verification” at a working group meeting in October 2019.

Longer-term economic, social and environmental impacts

According to the European commission the expected impact of advances on nanotechnology are, amongst others, “*supporting European competitiveness through accelerated market uptake of nano-enabled products, improving in existing manufacturing processes and industrial productivity, contribution to improved technical knowledge, promoting safe-by-design approaches and contributing towards the framework of EU nanosafety and regulatory strategies (including standardisation)*“. This is particularly true for Europe's photonics industry, (e.g. in laser-based manufacturing, medical photonics, sensing, lighting, high-end fabrication of optical components) which has the possibility to exploit new emerging market opportunities, particularly by using the novel opportunities provided by functional nano-optical materials.

This project supported the long-term goal of collaborative research in materials science, classical and quantum optics by stimulating the interaction of specialists in optical systems and metrology, experts in materials fabrication and metamaterial engineering. An example of this is the work in Objective 1, where the design of resolution enhancers (such as metamaterials-based superlenses), requires input from different experts with knowledge of the main features of optical and imaging systems, the limitations of material production and innovative design concepts and models for such spatial resolution enhancers that can work on a broad range of wavelengths.

Prior to the start of this project, the scientific communities working on classical and quantum optics had little interaction with each other. Scientists from classical optics worked in close contact with industry and addressed issues as they emerged from the applications. Whereas, quantum optics communities, in particular dimensional metrology, have focused on key aspects of quantum physics, such as entanglement. The uptake of such fundamental research often encountered resistance from end-users, due to the complexity of its implementation and, sometimes, the arguable added value offered. Therefore, this project provided a unique environment where both communities could unite to advance optical metrology and in order to provide long-term benefits to end users.

List of publications

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<table>
<tr><td colspan="2">Project start date and duration:</td><td>June 2018, 40 months</td></tr>
<tr><td colspan="3">Coordinator: Lauryna Siaudinyte, VSL   Tel: +31(0)631 119 909   E-mail: lsiaudinyte@vsl.nl
Project website address: https://www.ptb.de/empir2018/BeCOMe</td></tr>
<tr><td>Internal Funded Partners:
1 VSL, Netherlands
2 CMI, Czech Republic
3 DFM, Denmark
4 INRIM, Italy
5 NPL, United Kingdom
6 PTB, Germany</td><td>External Funded Partners:
7 Aalto, Finland
8 FSU Jena, Germany
9 ICFO, Spain
10 SwanU, United Kingdom
11 TU Delft, Netherlands
12 TUBS, Germany
13 UNITO, Italy
14 ZIB, Germany</td><td>Unfunded Partners:
15 DTU, Denmark</td></tr>
<tr><td colspan="3">RMG1: DFM, Denmark (Employing organisation); VSL, Netherlands (Guestworking organisation)</td></tr>
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