FINAL PUBLISHABLE REPORT

Grant Agreement number	17FUN01
Project short name	BeCOMe
Project full title	Light-matter interplay for optical metrology beyond the classical spatial resolution limits

<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>
</table>

TABLE OF CONTENTS

1 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.

2 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.

3 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.**

4 Results

Objective 1: To develop stable and reliable methods to achieve deep-sub-wavelength spatial resolution by exploiting higher-order (beyond Born's 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 λ/10 level and sub-nanometre uncertainty, with λ being the wavelength of the light probe

This 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 mechanism behind a measurement result than a brute force numerical approach. The advantage of a perturbation approach stems from the fact that each term of the series has a clear physical meaning and can unveil much more about the scattering process than a purely numerical approach. However, a perturbation approach is unpractical under so-called strong-scattering conditions because the corresponding Born series strongly diverges.

A major result obtained in this project was to show how to solve this problem using Padé approximants and how to treat electromagnetic problems well beyond the weak-scattering regime. Highly divergent solutions arising from perturbative methods can hamper the practical usefulness of the strong scatterers. Therefore, finding a solution to this problem would provide significant impact to both theoretical and practical experiments. This is because direct scattering problems are instrumental in addressing and solving inverse scattering problems, which were one of the main goals of the project.

Partners VSL and TU Delft were able to solve the problem of the divergence for wildly divergent Born series by means of Pade' approximants. The partners also proved the applicability of this method for 1-D and 2-D scattering problems. This important result from was published in Phys Rev. Research **2**, (2020),013308.

Partner ZIB also worked on the development of novel inverse methods which could provide better insights on the mechanism behind superresolution. In this work inverse electromagnetic problems were applied from a different viewpoint, namely by using Bayesian inversion methods. The potential of the Bayesian inversion method to provide better insights on the mechanism behind superresolution was proven by the project by benchmarking its performance with respect to other commonly used methods such as scatterometry and ellipsomety. The improvement of the Bayesian inversion methods was shown to be successful, and it was focused on exploring how pre-computed simulation results can be used to train the Gaussian process and to accelerate the optimisation.

Another important output from the project was the design and fabrication of metamaterial-based superlenses, which were developed in order to boost the spatial resolution of existing optical systems, such as optical scatterometers and microscopes, 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 metamaterial-based superlense devices were fabricated by the project and tested on direct bright field imaging. The improvement of the different metamaterials-based superlenses on the quality and resolution of the images was clearly visible from the performed tests. Moreover, the project's newly designed resolution enhancers increased the spatial resolution to deep-subwavelength level.

In addition to this, multiple far-field illumination far-field detection methods were developed by partners VSL, CMI, DFM, NPL, PTB, Aalto, TUBS, FSU Jena, TU Delft and ZIB. The results from these new far-field illumination far-field detection methods showed significant improvements in Pade' resummation when applied to a Born series. The far-field illumination far-field detection methods included Hyperspectral Coherent Fourier Scatterometer (CFS), Solid Immersion Lens (SIL)-based far-field illumination far-field detection, improved Deep Ultraviolet (DUV) setups, enhanced Alternative Gracing Incidence Dark (AGID) field microscopy and Substrate-enhanced label free bright field microscopy. In particular the project developed a SIL-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. 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.

Further to this, by combining a multiple scattering with a ptychographic reconstruction the project demonstrated superresolution effects below the wavelength of the illumination source. The subwavelength ptychographic reconstruction of 3D objects at visible wavelengths was also completed by VSL. The design and experimental validation of superresolution enhancers by the project made it possible to resolve lines separated by 55 nm by using 632 nm light source. The glass substrate is covered with a thin layer (50 nm) of TiO_2 and on top of it, double lines of chromium were deposited. For comparison, the same structures were also deposited on a bare glass substrate and measurements were performed on both opaque and transparent surfaces. This is the first time that such resolution has been achieved by CFS and is a significant improvement to the previous state of the art which was lower than λ/10.

Moreover, the collaboration between the project partners was strengthened by staff exchange from a Research mobility grant (RMG) between DFM and VSL. During the RMG, research on the metrological potential of Fourier scatterometry using small sphere lenses was performed and the resolution enhancement using half sphere over no sphere has been demonstrated. The RMG also tested a full inversion model for obtaining information on geometrical parameters from a measured scatterometric signal. Further to this, the dependency of the half sphere resolution enhancement on the focal position of the light was also demonstrated and it was found that the best image quality was obtained with the focal position in the grating plane. The dependency of the sphere resolution enhancement on the focal position of the light has also been demonstrated and it was found that the best image quality was obtained with the focal position on top of the sphere. Finally, the RMG demonstrated that an enhanced scatterometry system with a sub-micrometer sized beam width was able to measure local variations beyond the limits of current optical technologies.

Summary

In summary the project achieved objective 1. Firstly, the consortium designed metamaterial-based structures that can enhance the light-sample interaction and bring it to detectable levels for a large class of targets, not only strong scatterers.

Secondly, the project developed stable and reliable methods such as SIL-based far-field illumination far-field detection, improved DUV setups, enhanced AGID field microscopy, Substrate-enhanced label free bright field microscopy and performed successful experiments with Hyperspectral CFS for sub-wavelength structures. By exploiting higher-orders (beyond Born's regime) and solving the scattering problem with Pade' approximants the project has made a big step forward towards achieving deep-sub-wavelength spatial resolution with probe-target interactions.

The project's goal for objective 1 was 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 λ/10 level and sub-nanometre uncertainty, with λ being the wavelength of the light probe. The project achieved these by resolving features (lines) separated by 55 nm by using 632 nm light source by developing novel and improved CFS and DUV setups.

Objective 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

Partners ICFO and VSL investigated different approaches to probe the specific spatial features of objects by using a spatial mode decomposition of a light field. One of the chosen approaches evaluated the maximum sensitivity that can be obtained in a given experiment using the results from quantum Fisher information theory. Another approach was chosen for probing the specific spatial features of objects using a formalism developed within quantum estimation theory and the approach was predominantly aimed at understanding what are the fundamental limitations of the amount of information that can be extracted from the optical wavefield. This important work has highlighted the impact that the evaluation of the quantum Fisher information of particular measurement schemes can have on the limitations and possibilities of optical metrology.

The project also determined that for phase objects, (where losses can be neglected and the object introduces a spatially-dependent phase shift to the illumination beam), the quantum Fisher information matrix yields the most informative resolution bound. Thus it can provide the ultimate resolution limit for any experiment for a given light-matter interaction protocol. Preliminary tests by ICFO on the experimental system showed that spatial spectrosocopy allows the estimation of a set of parameters of a phase object with the ultimate resolution given by the type of light-matter interaction used. Therefore, spatial spectroscopy can be used to provide a route towards optimal multiparameter estimation of phase objects. Another benefit of this 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 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 to estimate the effect of sub-wavelength structures (such as diffraction gratings) on the spatial channels used to describe the field. This was addressed by the partners ICFO, VSL and TU Delft, who used complementary approaches, such as, Helmholtz Natural Modes' (HNMs) 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. partners ICFO and VSL implemented experimental setups based on different imaging methods in order to tailor and detect the amplitude and phase of the wavefields and measure how they transform after interaction with objects of reference. Beam shaping and phase/amplitude separation were achieved by the project by combining spatial light modulation and CFS. Preliminary experimental results have shown that this technique (i.e. combining spatial light modulation with CFS) can be used to determine the geometrical parameters of subwavelength nanostructures.

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. Analysis of another method - spatial spectroscopy – also demonstrated that the spatial modes projected by designed spatial spectroscopy setup were optimal for the parameter estimation of phase objects and that by selecting appropriate spatial modes one can achieve the best resolution possible for a particular light-matter interaction. In addition, theoretical/numerical studies after phase mapping suggest that certain HNMs depending on the nanostructure geometry can influence the signal in the far field.

Further to this, partner CMI investigated white light interferometry (WLI) experiments using a Nanopositioning machine and a resolution standard (i.e. a sample fabricated by NPL which consisted of several fixed period gratings and two chirped gratings fabricated). This investigation was done in order to characterise surfaces with a reflectivity of at least 3 %. The experiments also showed that the lateral resolution achievable was below 600 nm and the fitting of atomic step height determined the z axis resolution was below 400 pm.

Summary

In summary the project achieved objective 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 for objective 2 was to implement spectroscopy-like measurement concepts, leading to robust and high-precision dimensional and physical measurement results. The project achieved this by designing a spatial spectroscopy setup and modifying CFS in order to explore phase and amplitude via beam shaping. The mapping of the electromagnetic field properties after the interaction with the sample was done using numerical simulations, HNMs and other beam shapes. WLI was also successfully used by the project to measure nanostructures and map the field of view containing the value of the nano-structure's height in each pixel.

Objective 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-field methods to far-field optical methods of specific applied interest.

Partners DFM, DTU, NPL, PTB and SwanU achieved significant progress in developing near field techniques. This included numerical simulations (calculations) of the near field of a grating SIL (Solid Immersion Lens) or photonic nanojet lens system performed alongside the development of a program for calculating the photonic nanojet (PNJ) field with a ball lens using Mie theory. The numerical simulations were then extended to circularly polarised light. Subsequently the developed near field numerical simulations was used to investigate the polarisation properties of photonic nanojet(s).

Transverse Electric (TE), Transverse Magnetic (TM) and radial polarisations were also investigated with respect to their spatial resolution and intensity. The results of the investigation showed that it was possible to select the best polarisation for an experiment. CMI has provided traceable scanning probe microscopy (SPM) which was used for comparison with PTB's ellipsometric measurements. The partners CMI, NPL and PTB then used this to carry out traceable dimensional measurements in order to validate the measurements from prototype artefacts i.e., resolution enhancers and measurement artefacts.

In addition to this, a numerical simulation method for control of the position of a PNJ was developed and successfully tested. A PNJ lens makes it possible to create a focused beam, outside the PNJ lens, with a width less than the incident wavelength. PNJ lenses have been observed in both large spheres (with an incident wavelength much smaller than radius of the sphere) and in small spheres (with an incident wavelength larger or similar to the sphere radius). A semi-analytical PNJ control technique was developed by the project and successfully validated numerically for circular cross-section and half-circular cross section 2D lenses. A proof of concept for a 3D version of the PNJ control method was also developed by partners DFM and DTU.

Furthermore, the project has established tip-enhanced Raman spectroscopy (TERS) using a sharp metal or metal-coated tip as a sensitive and enabling technique for nanoscale surface chemical characterisation. The TERS method using a sharp metal or metal-coated tip overcomes the diffraction limit of confocal optical microscopy by using the localised surface plasmon resonance (LSPR) at the metal tip-apex, which enhances the electromagnetic field of the incident laser light to an area comparable to the size of the tip-apex. The transition from an indirect bandgap to a direct bandgap then gives rise to a strong photoluminescence (PL) in single-layer Molybdenum disulphide (MoS_2) through excitonic processes. The PL signal can be used in tip- enhanced PL (TEPL) very effectively to measure the spatial resolution of an optical probe. High resolution imaging using PL can also be effectively used to locate defects, edges and contamination. The project's results revealed that TEPL imaging of a single-layer MoS_2 flake could achieve 20 nm spatial resolution, which is more than 15 times better than confocal resolution and 25 times less than the excitation wavelength (< /25). Using this method, the project also achieved its target of measuring deep subwavelength gratings down to << λ/10.

CMI developed and set up a novel spectroscopic Scanning Near Field Optical Microscopy (SNOM) tool. SNOM is a special near field technique from the Scanning Probe Microscopy (SPM) family. The key concept in SNOM is to use a small light source for scanning very close to the sample surface. New SNOM probes were cut using focused ion beams and then the sample was characterised and successfully tested with measurements of SNOM to illustrate that the probe-sample distance still plays a significant role in the contrast formation. A spectroscopic set-up was successfully, experimentally tested using multiple samples, including deep subwavelength gratings, fabricated by project partners FSU Jena and NPL. The resolution of the SNOM measurements ranged between 1 and 11 times smaller than the wavelength and could be reduced further using sharper probes (down to 50 nm aperture). However, when measuring fluorescence signals the sharper probes provided less signal, therefore there is a trade-off between the fluorescence sensitivity and spatial resolution.

Further to this, a spectroscopic set-up was realised and tested by the partner CMI. 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).

The project used different approaches to explore the link between the near-field and far-field optical methods. The different approaches included (i) the application of plasmonic lenses, (ii) the creation of subwavelength structured illumination using the fractional Talbot effect and (iii) resonance enhancement either by quasi-bound states in the continuum or by LSPR. As a result, the concepts for the characterisation of the form of nanostructures using polarisation information were investigated as well as far-field sensing concepts for sub-wavelength sized nanostructures based on support structures.

Metallic plasmonic lens structures were also investigated for their use to create deep-subwavelength focal spots. The original design of the metallic plasmonic lens showed severe manufacturing issues, therefore an alternative inverted lens design was developed instead. The optimisation of the inverted design was successfully completed using Finite Element Modelling (FEM) simulations and a particle swarm algorithm. The result showed a good compromise between performance and manufacturing ability for the inverted lens. Subsequently, the inverted lens was successfully fabricated and investigated (Meas. Sci. Technol. **31** (2020), 074013). Further investigations on the optical performance of this inverted lens are on-going.

The project investigated the enhancement of the sensitivity in scatterometry by using different types of resonances. The results demonstrated structure-induced resonance enhancement (Opt.Express **28** (2020), 23132).

A systematic numerical study based on rigorous coupled-wave analysis (RCWA) modelling was performed in order to investigate the parameter dependencies of LSPR in silicon gratings observed in the DUV (l = 266.3 nm). The results demonstrate 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 sensitivity capability of approx. 1 nm for pitch measurements for sub-diffraction periods between 50 nm and 250 nm, (which are not accessible without exploiting the LSPR).

Further to this, the project investigated the use of polarisation degrees of freedom to retrieve dimensional and optical information on nanoscale objects. Metamaterial nanostructures were developed by partners PTB, TUBS, FSU Jena and ZIB and then used to characterise polarisation features in the far field using adapted Mueller matrix ellipsometry. The adapted imaging Mueller matrix ellipsometry system (for visible wavelength range) was used to characterise the roundness of the metamaterial nanostructures using Mueller matrix polarimetry.

Summary

In summary, the project achieved objective 3; to realise and demonstrate near-field techniques to measure deep sub-wavelength gratings down to the regime << λ/10 which allows accurate and traceable optical procedures to characterise nanostructured optical components and to measure effective optical material parameters. In addition, the project used different approaches to explore the link between the near-field and far-field optical methods. The different approaches included (i) the application of plasmonic lenses, (ii) the creation of subwavelength structured illumination using the fractional Talbot effect and (iii) resonance enhancement either by quasi-bound states in the continuum or by LSPR. As a result, the concepts for the characterisation of the form of nanostructures using polarisation information were investigated as well as far-field sensing concepts for sub-wavelength sized nanostructures based on support structures

In order to achieve the best possible results, the project's research for objective 3 was focused on structured illumination using plasmonic lenses. An inverted plasmonic lens was designed and its characterisation begun.

Objective 4. The application of sub-shot noise quantum technologies to optical systems, addressing both low and high NA systems. To realise input fields with spatially entangled optical channels and to map their coupling with the geometry of nano-targets. To explore the potential of quantum metrology optical schemes based on spatial mode entanglement and its integration into existing optical systems. The aim is to find a natural link with the exploitation of topology information in classical fields, as discussed hereinabove.

The project developed a new protocol for low-noise imaging schemes. The new protocol was demonstrated experimentally to have improved resolution-sensitivity trade off in sub-shot noise imaging (SSNI) of weak transmitting masks (Appl. Phys. Lett. 116, (2020), 214001) as well as an increased signal to noise ratio in quantum ghost imaging (Phys. Rev. A 100 (2019), 063818).

The application of sub-shot noise quantum technologies to optical systems was also investigated by INRIM and UNITO, and a scheme was identified 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 for low and high NA systems, just using different optics. The developed experimental system at the moment is realised using low NA.

Partners INRIM and UNITO realised and detected structured light from single photon emitters by using a spatial resolving detector at the single photon level and investigated superresolution with structured light coming from single photon emitters and the use of high order correlation functions measured in wide field. It was realised with the high NA (NA = 1), 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.

Partners INRIM, UNITO and TU Delft collaborated on developing techniques for SSNI and classical phase retrieval. The investigated technique was based on the multi-mode pair-wise intensity squeezing obtained by photons emission from travelling wave spontaneous parametric down conversion. The main challenge was to develop a method that allowed phase retrieval while preserving the quantum correlations. In order to overcome this, INRIM, UNITO and TU Delft developed a technique which measures the 'shadow' left by the sample in a slightly defocused plane. This technique was implemented through the development of a specific setup combined with theoretical analysis and realistic simulations. As part of the technique to measure the 'shadow' left by the sample in a slightly defocused plane, partners INRIM and UNITO used the transport of intensity equation (TIE). The TIE was used to recover the phase whilst an ancillary system was used for noise reduction and resulted in an improvement in the quality of the phase recovery up to a factor 1.4 taking into account current experimental capabilities.

Important progress was also made by the project on the realisation of new sources of squeezed light and their application. Partner DFM built a new Optical parametric oscillator (OPO) system for generating squeezing in high-order modes. The result of this work (Opt. Express 29, (2021), 29828-29840) demonstrated the 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 (Optica 7 (2020), 470-475).

Further to this, partner IFCO investigated the potential of quantum metrology optical schemes. The investigations led to the analysis of Weak Value Amplification (WVA) which is mainly used for (i) estimating extremely tiny changes of parameters of interest (e.g., temperature, angle of deflection, frequency, position, temporal delay, etc.) and (ii) the Hong-Ou-Mandel (HOM) effect.

i. WVA is useful for parameter sensing as it allows the measurement of tiny changes in a parameter that otherwise cannot be determined due to technical limitations.

ii. The HOM effect is a two-photon interference effect.

Using both of the above, ICFO investigated subwavelength gratings and cliff-like nanostructures. It was demonstrated that by using frequency entanglement in combination with a HOM configuration a temporal sensitivity of 9 could be reached, which corresponds to a longitudinal sensitivity of 2.7 nm (NPJ Quantum Information 5, (2019), 43). This important result means that large bandwidth signals do not necessarily need to be considered, only two frequencies well separated (by few hundreds of nanometers) are needed. HOM was also investigated as a quantum version of Differential Interference Contrast (DIC) microscopy using sub-wavelength and cliff-like structures.

Summary

In summary the project achieved objective 4; to apply sub-shot noise quantum technologies to optical systems, addressing both low and high NA systems, as well as to realise input fields with spatially-entangled optical channels and to map their coupling with the geometry of nano-targets. The project also explored the potential of quantum metrology in optical systems through spatial modes entanglement and its integration into existing optical systems.

The project's goal for objetcive 4 was to find a natural link with the exploitation of topologic information in classical fields. The project achieved this through the application of sub-shot noise quantum technologies to optical systems, by building a new OPO system for generating squeezing in high-order modes and by investigating the potential of quantum metrology optical schemes.

5 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.

6 List of publications

[1]. Equivalence regimes for geometric quantum discord and local quantum uncertainty. Cordero, O., Villegas, A., Alvarez, J.R., Leon Montiel, R. de J., Passos, M.H.M. and P. Torres, Juan. 2021, Phys. Rev. A 104 (2021), 042401. https://doi.org/10.1103/PhysRevA.104.042401

[2]. Spectral features of Pb-related color centers in diamond – a systematic photoluminescence characterization. Ditalia Tchernij, S., Corte, E., Lühmann, T., Traina, P., Pezzagna, S., Degiovanni, I.P., Provatas, G., Moreva, E., Meijer, J., Olivero, P., Genovese, M. and Forneris, J. 2021, New Journal of Physics 23 (2021) , 063032. https://doi.org/10.1088/1367-2630/ac038a

[3]. Creation of pure non-crystalline diamond nanostructures via room-temperature ion irradiation and subsequent thermal annealing. Picollo, F. Battiato, A., Bosia, F., Scaffidi Muta, F., Olivero, P., Rigato, V. and Rubanov, S. 2021, Nanoscale Advances 3 (2021), 4156-4165. https://doi.org/10.1039/d1na00136a

[4]. Quasi-bound states in the continuum for deep subwavelength structural information retrieval for DUV nano-optical polarizers. Bodermann, B., Burger, S., Zeitner, U., Meyer, J., Käseberg, T., Siefke, T., Dickmann, W., Hurtado, C.B.R., Dickmann, J. and Kroker, S. 2020, Optics Express 28 (2020), 23122. https://doi.org/10.1364/OE.396044

[5]. Superresolution effect due to a thin dielectric slab for imaging with radially polarized light. Meng, P., Pereira, S.F., Dou, X. and Urbach, H.P. 2020, Optics Express 28 (2020), 20660-20668. https://doi.org/10.1364/OE.390602

[6]. Twin beam quantum-enhanced correlated interferometry for testing fundamental physics. Pradyumna, S. T., Losero, E., Ruo-Berchera, I., Traina, P., Zucco, M., Jacobsen, C. S., Andersen, U. L., Degiovanni, I. P., Genovese, M. and Gehring, T. 2020, Communications Physics 3 (2020), 104. https://doi.org/10.1038/s42005-020-0368-5

[7]. Single-phase and correlated-phase estimation with multiphoton annihilated squeezed vacuum states: An energy-balancing scenario. Samantaray, N., Ruo-Berchera, I. and Degiovani, P. I. 2020, Physical Review A 101 (2020), 063810. https://doi.org/10.1103/PhysRevA.101.063810

[8]. Improving resolution-sensitivity trade off in sub-shot noise quantum imaging. Ruo-Berchera, I., Meda, A., Losero, E., Avella, A., Samantaray, N. and Genovese, M.2020, Applied Physics Letters 116 (2020), 214001. https://doi.org/10.1103/PhysRevA.101.063810

[9]. Special Issue on Quantum Optics for Fundamental Quantum Mechanics. Genovese, Marco and Gramegna, Marco. 2020, Applied Sciences 10 (2020), 3655. https://doi.org/10.3390/app10103655

[10]. Inverted plasmonic lens design for nanometrology applications. Käseberg, T., Siefke, T., Kroker, S. and Bodermann, B. 2020, Measurement Science and Technology 31 (2020), 074013. https://doi.org/10.1088/1361-6501/ab7e6b

[11]. Demonstration of lateral resolution enhancement by focusing amplitude modulated radially polarized light in a confocal imaging system. Meng, P., Pham, H-L., Pereira, S.F. and Urbach, H.P. 2020, Journal of Optics 22 (2020), 045605. https://doi.org/10.1088/2040-8986/ab7aeb

[12]. Electromagnetic scattering beyond the weak regime: Solving the problem of divergent Born perturbation series by Padé approximants. van der Sijs, T. A., El Gawhary, O. and Urbach, H. P. 2020, Physical Review Research 2 (2020), 013308. https://doi.org/10.1103/PhysRevResearch.2.013308

[13]. Quasinormal mode expansion of optical far-field quantities. Binkowski, F., Betz, F., Colom, R., Hammerschmidt, M., Zschiedrich, L. and Burger, S. 2020, Physical Review B 102 (2020), 035432. http://dx.doi.org/10.1103/PhysRevB.102.035432

[14]. Quantum Correlations and Quantum Non-Locality: A Review and a Few New Ideas. Genovese, Marco and Gramegna, Marco. 2019, Applied Sciences 9 (2019), 5406. https://doi.org/10.3390/app9245406

[15]. Quantum differential ghost microscopy. Losero, E., Ruo-Berchera, I., Meda, A., Avella, A., Sambataro, O. and Genovese, M. 2019, Physical Review A 100 (2019), 063818. https://doi.org/10.1103/PhysRevA.100.063818

[16]. Quantum enhanced imaging of nonuniform refractive profiles. Ortolano, Giuseppe, Ruo-Berchera, Ivano and Predazzi, Enrico. 2019, International Journal of Quantum Information 17 (2019), 1941010. https://doi.org/10.1142/S0219749919410107

[17]. Dual-metasurface superlens: A comprehensive study. Mollaei, M.S.M. and Simovski, C. 2019, Physical Review B 100 (2019), 205426. https://doi.org/10.1103/PhysRevB.100.205426

[18]. Modal analysis for nanoplasmonics with nonlocal material properties. Binkowski, F., Zschiedrich, L., Hammerschmidt, M. and Burger, S. 2019, Physical Review B 100 (2019), 155406. http://dx.doi.org/10.1103/PhysRevB.100.155406

[19]. Benchmarking Five Global Optimization Approaches for Nano-optical Shape Optimization and Parameter Reconstruction. Schneider, P.I., Garcia Santiago, X., Soltwisch, Vi., Hammerschmidt, M., Burger, S. and Rockstuhl, C. 2019, ACS Photonics 6 (2019), 2726-2733. http://dx.doi.org/10.1021/acsphotonics.9b00706

[20]. Sub-Wavelength Features in Spectroscopic Mueller Matrix Ellipsometry. Kroker, Stefanie, Wurm, Matthias, Siefke, Thomas, Käseberg, Tim and Bodermann, Bernd. 2019, Deutsche Gesellschaft für angewandte Optik Proceedings 2019 120 (2019). ISSN: 1614-8436 https://www.dgao-proceedings.de/download/120/120_p9.pdf

[21]. Mueller matrix ellipsometry for enhanced optical form metrology of sub-lambda structures. Käseberg, T., Dickmann, J., Siefke, T., Wurm, M., Kroker, S. and Bodermann, B. 2019, Modeling Aspects in Optical Metrology VII 11057 (2019), 155-165. https://doi.org/10.1117/12.2527419

[22]. Hong-Ou-Mandel interferometry on a biphoton beat note. Chen, Y., Fink, M., Steinlechner, F., Torres, J.P. and Ursin, R. 2019, npj Quantum Information 5 (2019). https://doi.org/10.1038/s41534-019-0161-z

[23]. Quantum Micro–Nano Devices Fabricated in Diamond by Femtosecond Laser and Ion Irradiation. Eaton, S.M., Hadden, J.P., Bharadwaj, V., Forneris, J., Picollo, F, Bosia, F., Sotillo, B., Giakoumaki, A.N., Jedrkiewicz, O., Chiappini, A., Ferrari, M., Osellame, R., Barclay, P.E., Olivero, P.

and Ramponi, R. 2019, Advanced Quantum Technologies 2 (2019), 1900006. https://doi.org/10.1002/qute.201900006

[24]. An auxiliary field approach for computing optical resonances in dispersive media. Binkowski, F., Zschiedrich, L. and Burger, S. 2019, Journal of the European Optical Society-Rapid Publications 15 (2019), 3. https://doi.org/10.1186/s41476-019-0098-z

[25]. Using Gaussian process regression for efficient parameter reconstruction. Schneider, P-I., Hammerschmidt, M., Zschiedrich, L. and Burger, S. 2019, Metrology, Inspection, and Process Control for Microlithography XXXIII 10959 (2019), 1095911. http://dx.doi.org/10.1117/12.2513268

[26]. Optimal estimation of entanglement and discord in two-qubit states. Virzì, S., Rebufello, E., Avella, A., Piacentini, F., Gramegna, M., Ruo Berchera, I., Degiovanni, I.P. and Genovese, M. 2019, Scientific Reports 9 (2019), 1-9. https://doi.org/10.1038/s41598-019-39334-8

[27]. Towards a standard procedure for the measurement of the multi-photon component in a CW telecom heralded single-photon source. Rebufello, E., Piacentini, F., López, M., Kirkwood, R.A., Ruo Berchera, I., Gramegna, M., Brida, G., Kück, S., Chunnilall, C.J., Genovese, M. and Degiovanni, I.P. 2019, Metrologia 56 (2019), 025004. https://doi.org/10.1088/1681-7575/ab022e

[28]. Numerical Investigation of Light Emission from Quantum Dots Embedded into On-Chip, Low-Index-Contrast Optical Waveguides. Hoehne, T., Schnauber, P., Rodt, S., Reitzenstein, S. and Burger, S. 2019, physica status solidi (b) 256 (2019), 1800437. https://doi.org/10.1002/pssb.201800437

[29]. Correlation of circular differential optical absorption with geometric chirality in plasmonic meta-atoms. Wilson, J.C., Gutsche, P., Herrmann, S., Burger, S. and McPeak, K.M. 2019, Optics Express 27 (2019), 5097. http://dx.doi.org/10.1364/OE.27.005097

[30]. Quantum imaging with sub-Poissonian light: challenges and perspectives in optical metrology Berchera, I.R. and Degiovanni, I.P. 2019, Metrologia 56 (2019), 024001. https://doi.org/10.1088/1681-7575/aaf7b2

[31]. Theoretical description and experimental simulation of quantum entanglement near open time-like curves via pseudo-density operators. Marletto, C., Vedral, V., Virzì, S., Rebufello, E., Avella, A., Piacentini, F., Gramegna, M., Degiovanni, I.P. and Genovese, M. 2019, Nature Communications 10 (2019), 1-7. https://doi.org/10.1038/s41467-018-08100-1

[32]. Decomposition of scattered electromagnetic fields into vector spherical wave functions on surfaces with general shapes. Garcia Santiago, X., Hammerschmidt, M., Burger, S., Rockstuhl, C., Fernandez-Corbaton, I. and Zschiedrich, L. 2019, Physical Review B 99 (2019), 045406. http://dx.doi.org/10.1103/PhysRevB.99.045406

[33]. Feasibility study towards comparison of the g (2)(0) measurement in the visible range. Moreva, E., Traina, P., Kirkwood, R.A., López, M., Brida, G., Gramegna, M., Ruo-Berchera, I., Forneris, J., Ditalia Tchernij, S., Olivero, P., Chunnilall, C.J., Kück, S., Genovese, M. and Degiovanni, I.P. 2019, Metrologia 56 (2019), 015016. https://doi.org/10.1088/1681-7575/aaf6c8

[34]. Temperature-Controlled Entangled-Photon Absorption Spectroscopy. Torres, J., Svozilik, J., Leon-Montiels, R. and U'Ren, A. 2019, ArXiv quantum physics arxiv1902. (2019), 1-8. https://doi.org/10.1103/PhysRevLett.123.023601

[35]. Single-Photon Emitters in Lead-Implanted Single-Crystal Diamond. Ditalia Tchernij, S., Lühmann, T., Herzig, T., Küpper, J., Damin, A., Santonocito, S., Signorile, M., Traina, P., Moreva, E., Celegato, F., Pezzagna, S., Degiovanni, I. P., Olivero, P., Jakšić, M., Meijer, J., Genovese, P. M. and Forneris, J. 2018, ACS Photonics 5 (2018) , 4864-4871. https://doi.org/10.1021/acsphotonics.8b01013

[36]. Color centres in diamond from single photon sources to ODMR in cells. Genovese, M., Moreva, E., Traina, P., Forneris, J., Ditalia Tchernij, S., Picollo, F., Degiovanni, I.P., Carabelli, V. and Olivero, P. 2018, Quantum Photonic Devices 2018 10733 (2018), 1073304. https://doi.org/10.1117/12.2323102

[37]. Mapping the Local Spatial Charge in Defective Diamond by Means of NV Sensors - A Self-Diagnostic Concept. Forneris, J., Ditalia Tchernij, S., Traina, P., Moreva, E., Skukan, N., Jakšić, M, Grilj, V., Bosia, F., Enrico, E., Amato, G., Degiovanni, I.P., Naydenov, B., Jelezko, F., Genovese, M. and Olivero, P. 2018, Physical Review Applied 10 (2018). https://doi.org/10.1103/PhysRevApplied.10.014024

[38]. Investigating the Effects of the Interaction Intensity in a Weak Measurement. Piacentini, F., Avella, A., Gramegna, M., Lussana, R., Villa, F., Tosi, A., Brida, G., Degiovanni, I.P. and Genovese, M. 2018, Scientific Reports 8 (2018). https://doi.org/10.1103/PhysRevApplied.10.014024

[39]. GSvit — An open source FDTD solver for realistic nanoscale optics simulations. Klapetek, P., Grolich, P., Nezval, D., Valtr, M., Šlesinger, R. and Nečas, D.,2021, Computer Physics Communications 265 (2021), 108025. https://doi.org/10.1016/j.cpc.2021.108025

[40]. Practical Applications of Quantum Sensing: A Simple Method to Enhance the Sensitivity of Nitrogen-Vacancy-Based Temperature Sensors. Moreva, E., Bernardi, E., Traina, P., Sosso, A., Tchernij, S.D., Forneris, J., Picollo, F.), Brida, G., Pastuović, Ž., Degiovanni, I. P., Olivero, P. and Genovese, M. 2020, Physical Review Applied 13 (2020), 054057. https://doi.org/10.1103/PhysRevApplied.13.054057

[41]. A biocompatible technique for magnetic field sensing at (sub)cellular scale using Nitrogen-Vacancy centersBernardi, E., Moreva, E., Traina, P., Petrini, G., Ditalia Tchernij, S., Forneris, J., Pastuović, Ž., Degiovanni, I.P. (Istituto Nazionale di Ricerca Metrologica (INRiM), Torino, Italy), Olivero, P. and Genovese, M.2020, EPJ Quantum Technology 7 (2020), 13. https://doi.org/10.1140/epjqt/s40507-020-00088-2

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

7 Contact details

Lauryna Siaudinyte
Thijsseweg 11,
2629 JA Delft,
The Netherlands
T: +31 631 119 909
e-mail: lsiaudinyte@vsl.nl

Omar El Gawhary
Lorentzweg 1,
2628 CJ Delft,
The Netherlands
T: +31 152 787 132
e-mail: o.elgawhary@tudelft.nl

Bernd Bodermann
Physikalisch-Technische Bundesanstalt
Bundesallee 100
38116 Braunschweig,
Germany
T: +49 531 592-4222
e-mail: bernd.bodermann@ptb.de