COST Action
Final Achievement Report

MP1302: NanoSpectroscopy

(15/11/2013 to 14/11/2017)

The Action was approved by the Committee of Senior Officials (CSO) on 16-5-2013 and has the MoU reference COST 032/13.

This report was submitted on 26-01-2018 by the Action Chair on behalf of the Management Committee in fulfilment of the requirements of the rules for COST Action Management, Monitoring and Final Assessment.

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Action leadership and participants

Leadership positions

Position	Name	Contact details	Country of work affiliation
Chair	Prof Monika Fleischer	monika.fleischer@uni-tuebingen.de +4970712976336	Germany

Position	Name	Contact details	Country of Nomination
Vice Chair	Prof Pierre-Michel Adam	pierre_michel.adam@utt.fr +33325715661	France

Working groups

#	WG Title	# of participants	WG Leader	Country of nomination
1	Management	232	Prof Monika Fleischer monika.fleischer@uni-tuebingen.de	n/a
2	System design and nanofabrication	120	Prof Ronen Rapaport ronenr@phys.huji.ac.il	Israel
3	Physical processes and modelling	137	Dr Johannes Gierschner johannes.gierschner@imdea.org	Spain
4	Improving spectroscopic techniques	134	Dr Antonio Cricenti antonio.cricenti@artov.ism.cnr.it	Italy
5	Preparation of a coherent textbook on optical nanospectroscopy	57	Dr Norman McMillan McMillan@itcarlow.ie	Ireland

Other key leadership positions

Position	Name	Contact details	Country of work affiliation
STSM Coordinator	Dr Teresa I. Madeira	teresa.madeira@physik.tu-chemnitz.de	Germany

Participants

COST members having accepted the MoU

AT	21/10/2013	**BE**	23/07/2013	**BA**	13/05/2014	**BG**	31/07/2014	**HR**	12/07/2013
CZ	25/09/2013	**DK**	09/07/2013	**EE**	26/09/2013	**FI**	10/09/2013	**FR**	02/07/2013
DE	13/06/2013	**EL**	28/11/2013	**HU**	24/03/2014	**IE**	02/07/2013	**IL**	26/06/2013
IT	11/07/2013	**LV**	09/11/2014	**LT**	15/11/2013	**LU**	30/03/2016	**MT**	20/09/2013
NL	31/07/2014	**PL**	12/06/2013	**PT**	20/09/2013	**RO**	01/11/2013	**RS**	27/09/2013
SI	25/08/2013	**ES**	04/06/2013	**SE**	03/10/2013	**CH**	05/09/2013	**TR**	05/08/2013
UK	03/06/2013								

Other participants

Institution Name	Country
V.Lashkarev Institute of Semiconductor Physics of the NAS of Ukraine	Ukraine
University of Sfax	Tunisia
Kyiv Taras Shevchenko National University	Ukraine
State Engineering University of Armenia	Armenia
Institute of Applied Physics, Academy of Sciences of Moldova	Republic of Moldova

Summary

Main aim/ objective

The main objective of the Action is to gather European expertise to further develop UV/Vis/NIR/Raman nanospectroscopy techniques, their application to novel hybrid (in)organic nanomaterials, and the modelling of light-matter-interaction and energy flow at the nanoscale.

The Action addressed this as described below

The COST Action MP1302 succeeded in creating an interdisciplinary international network on aspects of Nanospectroscopy, joining over 230 groups from 35 countries. The member profiles were collected in a database on the Action website. All activities of the COST Action took place as scheduled in the working plan. The Action created a stand-alone conference series Optical Nanospectroscopy I-IV that reserved sufficient time for WG meetings and served as a place for networking. The abstract books showcase a cross-section through European nanospectroscopy activities. In between, combined WGs and MC meetings were organized to discuss open issues and identify focus areas for the Action. Many bilateral discussions, proposals, and ideas for STSMs originated from these events. The meetings also served the objective of overcoming community barriers and bringing together researchers from nanostructure synthesis and fabrication, spectroscopic methodology, fundamental processes investigation, and biomedical applications. At the WG1 meetings a Capability Map for nanomaterials and nanofabrication was created. WG2 identified three focus areas in which many members were involved, i.e. plasmonics, conjugated organic materials, and life sciences / medical applications. Focused topical meetings on Medical Applications, Nonlinear Plasmonics, Food Safety, Nanoparticles, and Chiral Sensing explored the possibility of joint project proposals. Nearly 200 predominantly high-ranking journal articles were published in the course of the Action. In the WG3 meetings, a list of instrumentation issues was drafted from the input of the present experts, and circulated in the minutes and the website. Representatives from industry added their valuable perspective. Amongst others, the improvement of tip-enhanced Raman spectroscopy was targeted as a joint Action activity. Standard samples were developed and shared in a round robin together with a TERS quality checklist. Seven Training Schools for ECIs (one jointly with COST Action MP1403) offering lectures and hands-on experience were very well received. The Schools served the objective of interdisciplinarily training the next generation of nanospectroscopists in relevant skills. As an output, training material was created. ECIs were involved at all levels of the Action, including two conferences specifically organized by ECIs for ECIs. A total of 75 STSMs were granted, offering excellent opportunities for starting new collaborations and training ECIs. Detailed reports and collaborative publications were generated as an output. WG4 has extended the original objective of a comprehensive textbook on Optical Nanospectroscopy to a three-volumes approach. Over 1000 pages of contents were submitted to the publisher for editing, to be published in 2018. On the way a literature meta-survey on nanospectroscopy was conducted. The methodology is being published in an article co-authored by 11 Action members. Possible tutorial approaches for complementing the textbook with interactive material were explored, and an introductory video was produced. The Action has fulfilled the objectives of improving spectroscopic techniques, developing and analysing nanoscale objects, training a new generation, and widening the circle of nanospectroscopy. In the process, the Action increasingly focused on dissemination, interacting with industry, and exploring nanospectroscopy for areas of broader societal interest such as optoelectronics, energy applications, food safety, or sensing and medical diagnostics.

Action website

www.cost-nanospectroscopy.eu

Achievement of MoU objectives, deliverables and additional outputs/ achievements

MoU objectives

The Action had the following specific objectives:

MoU objective	Level of achievement	Further information (hyperlink or other)
improving spectroscopic techniques and instrumentation towards (ultra-)high resolution and sensitivity as well as user-friendly (turn-key) techniques	76 - 100%	First it should be noted that Nanospectroscopy covers a wide range of subtopics. The specific subtopics addressed by this COST Action directly depend on the expertise of the >230 members who joined the Action over its running time. All scientific MoU objectives were addressed by many groups. This report can therefore only shine a spotlight, since the overall activities are too extensive to fully detail here. A general overview over the addressed topics as well as key publications and STSMs will be given. For the objective "improving spectroscopic techniques and instrumentation", the Action aimed at improving existing techniques towards higher sensitivity, spatial, temporal and spectral resolution. To make them more user-friendly, compact, robust designs and improved data handling were targeted. Also approaches for the development of novel techniques, instrumentation and components were pursued. Improving spectroscopic techniques was especially the focus of WG3 (http://cost-nanospectroscopy.eu/wg3.html). To start a dialogue between academia and industry, a WG3 meeting with >40 participants was held. A list of existing techniques was compiled. Open issues in terms of equipment, standards and protocols, performance, interpretation of results, and scanning probe tip fabrication were discussed. The resulting list is available on the WG3 webpage. As a particular focus of WG3, the standardization of procedures and the tip fabrication for tip-enhanced Raman spectroscopy (TERS) and scanning near-field optical microscopy (SNOM) was identified. A checklist for the standardization of TERS measurements and standardized test samples were developed. A round robin was started where 8 research groups and 2 companies agreed to perform measurements on these samples for a comparative study (see separate documents). The round robin is ongoing and will be finalized & published in 2018. Developments in the Action that fall in the field of

		instrumentation development: Improvement of early cancer detection by combined infrared SNOM and atomic force microscopy Development of several types of TERS probes and their commercialization in collaboration with companies Newly developed thermal probe technique Development of surface enhanced Raman spectroscopy with optical tweezers and for nanomaterial cytotoxicity assessment Development of optical trapping for hypothermia processes Preparation, quantitative description and imaging of harmonic nanoparticles for bioimaging, localized therapy and nonlinear optics Development of instrumentation and method for optical coherent correlation spectroscopy and optical coherent microscopy Setup for phase-detection of gold particles for chemical sensing Setup for automated position, shape and size determination of single crystal gold flakes Setup for nano-optofluidic detection and size determination of nanoparticles Development of microresonator spectroscopy Development of plasmon-based optical nanosensors and their miniaturization by gradient index lenses Further improved sensitivity of nonlinear microscopy through the use of laser beams with inhomogeneous states of polarization / spatially phase-shaped beams Development of time-resolved ultrafast spectroscopy with pump-probe method to study ultrafast processes in nano-objects Development of a novel nano-UV-vis technique Commercially available novel Raman spectrometer for rapid measurement of micro litre liquid samples & software See also http://cost-nanospectroscopy.eu/publications.html and STSMs number 2014(1,2,3,4,6,7,8,10), 2015(8,9,13,19,22), 2016(3,6,7) and 2017(13) on http://cost-nanospectroscopy.eu/stsm.html.
engineering molecular structures or nanoparticles, applying them for gaining basic knowledge on light-	76 - 100%	This objective was pursued by research projects, laboratory exchanges and STSMs. The topic was

matter-interaction and for improving optical applications/devices, and theoretical modelling

covered at the annual conferences Optical Nanospectroscopy I to IV (http://cost-nanospectroscopy.eu/conferences-meetings.html), which each delivered a comprehensive book of abstracts.

In particular, this objective was addressed in WG1: System design and nanofabrication (http://cost-nanospectroscopy.eu/wg1.html). At the beginning of the COST Action, an overview over all relevant techniques in nanostructure fabrication and synthesis was compiled in WG1 meetings. Experts who could offer these methods within the Action were identified, and requests by members looking for specific expertise were collected. The list of methods is available on the WG1 webpage. In further WG1 meetings new developments in member groups were disseminated in short presentations, and the results of recent STSMs on the topic were shown. The WG minutes were collected by the Chair.

Over the course of the Action, particularly shaped plasmonic nanoantennas were crafted from noble metals for near-field enhancement, surface-enhanced Raman spectroscopy and nonlinear optical effects. Colloidal synthesis was employed to create metal and semiconducting nanoparticles or nanowires, as well as core-shell particles. Their scattering, phase-shifting properties etc. were investigated. Specific shapes such as nano-dumbbells were created. Novel metal nanoclusters were fabricated in polymers using direct laser writing and shaping techniques. The nonlinear optical effects were engineered in single and arrangements of plasmonic nanoparticles (e.g. tilted nanocones, ordered arrays of nanoparticles, plasmonic oligomers, plasmonic nano-apertures). The ultrafast processes in light-matter interaction, in particular plasmonic responses and charge dynamics, were analysed by the time-resolved pump-probe technique. Nanoantennas were designed and fabricated as improved tip-enhanced Raman spectroscopy probes. Harmonic nanoparticles were optimized for biosensing and as multiphoton imaging nano-probes for cancer-cell-specific labeling. Plasmonic nanostructures were integrated in microfluidic environments for sensitive plasmon resonance shift sensing. The interaction between light and metallic nanostructures was modelled using different methods such as the finite element method, finite boundary method or finite-difference time-domain modelling.

For detailed results, see publications (http://cost-nanospectroscopy.eu/publications.html).

A targeted Topical Meeting on Nanoparticle Preparation, Assembly, Characterization and Applications was organized in Poland

		(https://cost-nanospectroscopy.eu/nanoparticles.html). A second Topical Meeting on Single Quantum Emitters followed in Portugal (http://cost-nanospectroscopy.eu/final-meeting.html), each with abstract books delivered. At the international conference on Surface Plasmons and Photonics (SPP7) in Israel, the COST Action organized a special session on Plasmonic Nanospectroscopy, which was attended by over 100 participants. 12 travel grants for ECIs were distributed, and the ECIs presented their results at the conference (http://cost-nanospectroscopy.eu/spp7.html). In addition, two Training Schools contributed to this objective: The Training School on Nanomaterials Characterization in Italy (http://cost-nanospectroscopy.eu/nano-characterization.html), where all presentations by the trainers were collected by the chair as deliverables, and the Training School on Raman and Correlative Surface Analytics on Carbon Nanomaterials in Germany (http://cost-nanospectroscopy.eu/training-raman.html), where the contents of the School were delivered as a book of abstracts. Dedicated STSM were performed to address this objective (http://cost-nanospectrsocopy.eu/stsm.html), e.g. STSMs 2014(1,4,6,7,12,14,15,18), 2015(2,6,8,9,17,21,23,25), 2016(6,7,9,10,11,16), 2017(4,5). The results of the STSMs were reported, and one-page summaries for all STSMs were collected in a book of abstracts (see separate document).
organic layers and molecules with novel properties will be created by molecular engineering	76 - 100%	This objective was pursued by research projects, laboratory exchanges and STSMs. The topic was covered at the annual conferences Optical Nanospectroscopy I to IV (http://cost-nanospectroscopy.eu/conferences-meetings.html), which each delivered a comprehensive book of abstracts. In particular, this objective was addressed in WG1: System design and nanofabrication (http://cost-nanospectroscopy.eu/wg1.html), see also objective 2. Over the course of the Action, novel photochromic materials were developed. The spectroscopic properties of supramolecular conjugated organic materials were investigated. Color stabilization in

		natural compounds by copigmentation was demonstrated. The properties of J-aggregation in dyes were analyzed in-depth. Organic photovoltaic systems, e.g. small molecule solar cells, and organic single crystal lasers were investigated and improved. For detailed results, see publications (http://cost-nanospectroscopy.eu/publications.html). A targeted Training School on Organic Semiconductors in Spain addressed this Objective. The school focused on the electronic, optical and photo-physical properties of organic semiconductors, discussed by means of optical spectroscopy and theoretical/computational approaches, with hands-on courses in quantum chemistry. The interdisciplinary Training School brought together ECIs and trainers from chemistry, physics and materials science (http://cost-nanospectroscopy.eu/trainingschool-organics.html). For example the following STSMs exchanged knowledge on this topic (http://cost-nanospectrsocopy.eu/stsm.html): STSMs 2015(1,7,15) and 2017(16). Each STSM contributed a report and a 1-page summary, which were collected in a book of abstracts.
novel hybrid nanosystems (organic-inorganic, semiconducting-metallic, metallic-metallic) will be fabricated using nanotechnology	76 - 100%	This objective was pursued by research projects, laboratory exchanges and STSMs. The topic was covered at the annual conferences Optical Nanospectroscopy I to IV (http://cost-nanospectroscopy.eu/conferences-meetings.html), which each delivered a comprehensive book of abstracts. In particular, this objective was addressed in WG1: System design and nanofabrication (http://cost-nanospectroscopy.eu/wg1.html), see also objective 2. Over the course of the Action, hybrid nanoparticles (core-shell, doped, alloyed, Janus particles) were synthesized, which combine different functionalities within one particle. Layered nanostructures (metal-insulator-metal, magneto-optic structures) were prepared using top-down nanofabrication. Laser patterning was used to create novel nanoparticle-polymer composites. Metal nanoparticles were integrated in organic layers for added functionality, e.g. to increase absorption or fluorescence for opto-

electronic devices. Silver and gold particles were deposited on porous silicon for SERS applications. The mechanisms of J-aggregation of dyes on metal nanoparticles were illustrated. Optical nanoantennas were coupled to organic thin films for energy transfer studies and absorption enhancement. Single semiconductor quantum dots were coupled to metallic nanoantennas. The resulting hybrid system showed a strongly enhanced emission intensity, a two-level system behavior of the quantum dots acting as single photon emission sources, and a drastic decrease of the lifetime of the quantum dot states. Also, it was shown that the emission directionality of quantum dots can be strongly influenced and sharpened to a small-angle emission by coupling to bullseye antennas. The nonlinear properties of plasmonic grating structures were harnessed for lipid membrane imaging. By bringing together metal nanostructures and analyte molecules (toxins, antibodies, pollutants, pesticides,…), highly sensitive optical sensing was demonstrated by surface-enhanced Raman spectroscopy as well as by plasmon resonance shift sensing. Optical switches were developed based on a novel photochromic material and DNA-gold colloidal particles.

For detailed results, see publications (http://cost-nanospectroscopy.eu/publications.html).

A Symposium on Nanospectroscopy was organized by the COST Action at the Conference Nanometrology France (without financial contribution by COST). The symposium with invited speakers from among the Action members gave insights in UV/vis/NIR spectroscopy, absorption and scattering spectroscopies, enhanced Raman scattering, fluorescence and non-linear spectroscopies of novel hybrid (in)organic nanomaterials and their applications. (http://www.setcor.org/conferences/NanoMetrology-2016/conference-workshops/17).

In addition, the dedicated Winter School on Photophysics of Hybrid Interfaces in Slovenia contributed to this topic (http://cost-nanospectroscopy.eu/hybrid-interfaces.html). At the School the role of complex multi-component hybrid structures that combine organic semiconductors with other organic or inorganic semiconductors or metals (metal/dyes, inorganic/organic semiconductors, organic/organic and organic carbons) was illuminated. The interdisciplinary School addressed ECIs from physics, chemistry, materials science and engineering and included hands-on training in

		advanced data analysis. The presentations given by the Trainers were collected as an additional deliverable. Dedicated STSM (http://cost-nanospectrsocopy.eu/stsm.html): STSMs 2014(4,9,15,16,17,18), 2015(1,5,9,15,24), 2016(2,5,6,9,11,12,15), and 2017(1,4,5,7,11,13,15,16).
analyzing energy and charge flow and light harvesting at the nanoscale, to improve materials for applications e.g. in photovoltaics or sensing/medical diagnostics	76 - 100%	This objective was pursued by research projects, laboratory exchanges and STSMs. The topic was covered at the annual conferences Optical Nanospectroscopy I to IV (http://cost-nanospectroscopy.eu/conferences-meetings.html). In particular, this objective was addressed in WG2: Physical processes and modelling (http://cost-nanospectroscopy.eu/wg2.html). The WG2 Leaders first defined the scope of WG2 in terms of physical processes, materials, methods, modelling, and applications, giving keywords for added specificity. A collaboration matrix was drafted of the WG members, their available instrumentation, and their research focus. The members were grouped according to different fields of expertise to facilitate looking for project partners. Three main focus areas were identified: 1) Photo-physics of Conjugated Organic Materials, 2) Plasmonics, and 3) Applications for Life Sciences. Discussion groups were formed where specific research questions were formulated to be addressed throughout the Action, which were checked up upon at the following meetings. These subtopics also triggered several Topical Meetings and Schools: Topical Meeting Nanospectroscopy for Medical Applications (http://cost-nanospectroscopy.eu/workshop-medapps.html) Topical Meeting Nonlinear Plasmonics and its Applications (http://cost-nanospectroscopy.eu/nonlinear.html) Topical Meeting on Specific Methods for Food Safety and Quality (http://cost-nanospectroscopy.eu/food-safety.html) Topical Meeting on Chiral Plasmonics and Chiral Sensing (http://cost-nanospectroscopy.eu/chiral.html) Conference by ECIs for ECIs on Nanospectroscopy for 2D Materials (http://cost-nanospectroscopy.eu/esr-2015.html)

Conference by ECIs for ECIs on Laser Applications in Plasmonics (http://cost-nanospectroscopy.eu/esr-2017.html)

Additionally two Training Schools contributed to this objective:

Winter School on Photophysics of Hybrid Interfaces (http://cost-nanospectroscopy.eu/hybrid-interfaces.html)

Training School on Multi-Dimensional Spectroscopy (http://cost-nanospectroscopy.eu/training-multidim.html) (a joint Training School with the COST Action MP1403 Nanoscale Quantum Optics)

During the Action, energy and charge flow at the nanoscale was investigated e.g. by extinction spectroscopy, Raman spectroscopy, time-resolved spectroscopic studies and photoluminescence, pump-probe measurements, polarization effects, electron energy loss spectroscopy and theoretical calculations. As an example, the photo-physical phenomena related to relaxation mechanism occurring after photoexcitation in semiconductor nanoparticles and metallic nanostructures were investigated. The carrier dynamics and the plasmonic response were studied with sub-picosecond time resolution. Modelling of the processes by numerical simulations was established. The understanding of these processes is crucial for photovoltaics applications and for sensing. A better understanding of nonlinear optical effects and chiral effects at nanoantennas was developed, which can be harnessed for nano-light sources, bio-imaging and sensing purposes. Charge photo-generation was demonstrated in few-layer MoS_2, and the response of silicon/organic hybrid photodetectors was enhanced. Enhanced Raman sensing was further developed for the detection of single amino acid molecules, single cells, spin-waves in nanoparticles, plant material, biomolecules, nanomaterial cytotoxicity studies on living cells, designer drugs, and dye molecules. By tuning optical properties of nanostructures via mechanical changes, plasmonic strain sensors were demonstrated.

Nanospectroscopy has proved highly promising for new photonic technologies such as quantum systems / single photon devices; (e.g. organic or perovskite) photovoltaics; light-emitting diodes; photo-detection; medical applications such as hyper-thermal treatment, analysing orthopaedic implants, following cellular uptake / dynamics at soft-matter interfaces on the nanoscale, or early

		cancer detection; analytical and material science such as food authenticity and provenance analysis, toxicity studies, cultural heritage / analysing and dating works of art; and sensing of toxins, pollutants, antibodies, etc. For detailed results, see publications (http://cost-nanospectroscopy.eu/publications.html). Dedicated STSM (http://cost-nanospectrsocopy.eu/stsm.html): STSMs 2014(5,8,9,11,13), 2015(5,6,7,8,9,11,14,16,18,20,21,24), 2016(2,3,4,6,7,8,9,10,12,13,16), 2017(1,2,4,5,7,8,9,11,13,14,15,16).
Outreach activities will make the new developments accessible to a wider audience	76 - 100%	Various outreach activities were pursued. The biggest outreach activity of the Action is the 3-volume textbook on Optical Nanospectroscopy. This coherent textbook broadly covers the basics of nanospectroscopy and continues up to state-of-the-art research results. It is split into the volumes Fundamentals, Methods and Applications. Fundamentals takes a look at the basics of light-matter-interaction, at optical spectroscopies in general, and at nanospectroscopy in particular. Methods gives insight into the instrumentation required for nanospectroscopy, simulation approaches in the field, and nanomaterials for nanospectroscopy. In Applications, individual members of the Action are highlighting specific application areas in photonics, sensing, life sciences and material science. The textbook aims at the level of advanced students in the natural sciences or life sciences, or professionals newly entering the field. It will at least partly be made available by open access (http://cost-nanospectroscopy.eu/wg4.html and separate table of contents / book draft). As part of the textbook considerations, intensive research was done on possible tutorial material to complement the book. Different formats were explored, links to existing material and sample exercises collected. Web-tutorials may be implemented as a second step once the textbook is published. The respective resources can be implemented with the publishers. In a collaboration between Lisbon, Dublin and Chemnitz a 12-minute video-tutorial on nanospectroscopy was prepared. It gives a nice illustrated scientific introduction to the field and was professionally produced at the Institute of Technology Carlow. This video will be very useful as teaching material in nanospectroscopy classes and as a first introduction on the Action website. Before it can be made widely accessible, all copyrights need to be attained. The Action website acts as an important dissemination source. It gives a database of

		nanospectroscopy activities and experts across Europe and beyond, compilations of relevant capabilities and techniques and open issues, a list of publications, and an overview over all the actions events and activities. Nearly 200 journal articles in peer-reviewed, mostly high-impact journals were published by the Action so far (mostly with COST acknowledgement), with more in preparation. The Action members engaged in conference talks, lecture series, book chapters and articles written for the general public, podcasts, hosting pupils and many more individual activities (http://cost-nanospectroscopy.eu/publications.html). A regular newsletter was sent to the Action members. In preparation for the textbook, an extensive meta-survey was conducted by members of WG4. This served to highlight existing literature in the field, show the publication history of the subtopics and their interrelations, and make sure that all relevant subtopics were covered in the textbook. An article on this meta-survey from the methodical point of view co-authored by 11 Action members was submitted to the library journal Liber. It received favorable reviews, and will be published shortly. A second article from the scientific point of view is under preparation. Likewise, a Roadmap for Optical Nanospectroscopy is currently under preparation to be shared with European stakeholders. A checklist for tip-enhanced Raman spectroscopy (TERS) and reference samples for TERS imaging were developed by WG3 to serve the standardization of this technique beyond the Action's reach.
developing joint proposals, from bilateral collaborations to European projects	76 - 100%	Many collaborations between groups that had not worked together before were initiated through the COST Action Nanospectroscopy across different countries and disciplines. Sharing an STSM is an excellent initiator for such collaborations, where other groups can be visited, samples can be exchanged and new methods tested. Developing joint proposals requires an in-depth knowledge on each other's capabilities, as well as some preliminary work to be documented in the proposal. A large number of such seeds for future collaborations were planted with the help of this COST Action. A most immediate outcome was the development of a follow-up COST Action proposal to further advance the now-formed network with a different updated research focus. This proposal was prepared in a dedicated meeting (Madrid 2017) between Action members from six COST Countries with 60% female participation and a designated Chair from an ITC. The proposal was submitted in the 2017 call and will be resubmitted in a revised version in the 2018 call.

Many more bi- and multi-lateral proposals were submitted. Some were granted, some rejected, especially in view of low EU acceptance rates. Because of the rather long time scales involved for meeting new groups in the COST Action, establishing communication and exchange, preparing preliminary results e.g. in an STSM, establishing a consortium, proposal writing, and the review process, many joint proposals resulting from this COST Action are still either in preparation or under review.

Here are some examples for joint proposals that directly resulted from the COST Action (for a more comprehensive list, see "Additional outputs" below):

3 Horizon 2020 Applications (FET Open 2015 & 2016 and Call H2020-ICT-2016-2017) (rejected)

FET-Open proposal 2016-2017, submitted (including Action members from academia and industry)

ITN proposal on Active plasmonic systems currently in preparation between Action Members from France, German, Italy and UK

ITN proposal on Metasystems including members from Germany and Finland will be submitted in 2018

ERA-NET proposal between members from Italy and Tunisia

ERA-NET proposal on PhotonicSensing

Italy-England: Bilateral project granted

Germany-France: Two bilateral DAAD projects for personnel exchange and a BWS plus project granted

Ukraine-France: Bilateral project on ellipsometry

Ukraine-Austria: Bilateral project on tip-enhanced Raman scattering

Ukraine-Poland: Bilateral project between Ministry of Education and Researches of Poland and Ministry of Education and Sciences of Ukraine (submitted)

Ukraine-Germany: A joint DFG-SFFRU proposal and a BMBF proposal submitted by partners who met through the COST Action

Luxembourg-France: bilateral project

Bilateral proposal between members from Serbia and Portugal granted

Bilateral proposal between members from Serbia and Croatia granted

		Proposal between members from Serbia and Germany submitted Proposal between Serbia and Slovenia submitted Bilateral proposal Italy-Russia (former Action members from Germany) National proposals submitted to the Academy of Finland that include letters of intent and funding for exchange with German Action members Again, this is just an excerpt to highlight the more extensive overall proposal activities.
Early Stage Researchers (ESRs) will be trained in joint research projects, Short-Term Scientific Missions (STSMs), hands-on training, and training schools organized by ESRs for ESRs	76 - 100%	The Action had a strong focus on involving ECIs at all levels. About 32% of the Action members were ECIs. Additionally, for all principal investigators who joined as Action members, their whole research groups were considered as members by affiliation, and thus eligible for participation in Action events. Feedback from ECIs showed that for this group the COST Action was particularly beneficial, since it allowed them to participate in a large number of nanospectroscopy events, to expand their international scientific network, to gain access to methods that may not be available in their own laboratories, and to add to their visibility in the community. At the beginning of the COST Action the Action Chair herself was an ECI. Further ECIs joined as WG Leaders and thus were included in the organizational structure of the Action. ECIs also took active roles in the textbook project and writing. As a specific tool to support the independence of ECIs, two conferences organized by ECIs for ECIs were held in years 2 and 4 of the Action. Teams of postdocs from the University of Chemnitz (DE) and the University of Szeged (HU) agreed to take on the time-intensive, but also rewarding tasks of organizing these two events. This included independently choosing and addressing invited speakers, developing a program, finding the locations and infrastructure, communicating with the participants, and handling the finances. The conferences were well attended by international postdocs and PhD students. http://cost-nanospectroscopy.eu/esr-2015.html http://cost-nanospectroscopy.eu/esr-2017.html Travel support was granted to 12 ECIs who actively participated in the special COST Action session at the international conference SPP7 (http://cost-nanospectroscopy.eu/spp7.html). Since Nanospectroscopy is a highly interdisciplinary topic at the intersection between physics, chemistry, biology, medicine, and material science, it is especially important that a future generation of young scientist receives

		suitable training across the boundaries of the traditional fields. It is also a strongly method-based topic, where advanced techniques and instrumentation need to be mastered and further developed to achieve progress. For this reason the Action made it a priority to offer Training Schools by renowned experts in the field, including extensive hands-on capabilities that were mostly targeted at ECIs. The following Training Schools were held: Training School on Scanning Tunneling Microscopy, Atomic Force Microscopy, and Scanning Near-field Optical Microscopy, Rome (IT) 2014, http://cost-nanospectrosocpy.eu/trainingschool-spm.html Training School on Organic Semiconductors, Imdea Nanoscience Madrid (ES) 2015, http://cost-nanospectroscopy.eu/trainingschool-organics.html Training School on Raman Spectroscopy of Molecules and Crystals and SERS, Zagreb (HR) 2015, http://cost-nanospectrosocpy.eu/trainingschool-raman.html Training School on Nanomaterials Characterization, University of Bialystok (PL) 2016, http://cost-nanospectroscopy.eu/nano-characterization.html Training School on Raman Spectroscopy and Surface Analytics (DE) 2016, http://cost-nanospectroscopy.eu/training-raman.htm Training School on Photophysics of Hybrid Interfaces, Ambroz pod Krvavcem (SL) 2017, http://cost-nanospectroscopy.eu/hybrid-interfaces.html Joint Training School on Multi-dimensional Spectroscopy with COST Action MP1403 Nanoscale Quantum Optics, Prague (CZ) 2017, http://cost-nanospectroscopy.eu/training-multidim.html One of the most important tools for the advancement of ECIs however was found to be the opportunity to visit international partner groups in STSMs. Altogether 75 STSMs in the area of nanospectroscopy were supported over the Action’s running time, and the results were reported by the participants, honing their scientific writing skills.
Stronger links between industry and academia are expected to trigger joint instrumentation development	76 - 100%	Nanospectroscopy strongly depends on the availability of highly specialized instrumentation, including microscopes, light sources and lasers, detectors/spectrometers, and optical components, together with the relevant data analysis capabilities and numerical simulation tools, as well as instruments for synthesis and nanofabrication. It is therefore mandatory that good communication

is established between research and industry to maximize the possible research output, to enable the technology transfer of developments from the research labs to the marketplace, and to jointly work on the improvement of existing instrumentation.

The COST Action therefore attempted to solicit a strong industry presence both among the Action members and at the Action events. It is a common experience that motivating companies to join research networks that do not involve any direct financial interest can be challenging. Still, over 10 representatives of companies and technology transfer institutions actively participated in the Action. In addition the German National Metrology Institute PTB was actively involved and contributed to several conferences. This added a valuable exchange on standardization and metrology issues.

Dedicated exhibitions for companies to showcase their products and communicate with the Action members were held at all four annual conferences Optical Nanospectroscopy I-IV. Slots for contributed talks from industry were reserved at the conferences (http://cost-nanospectroscopy.eu/conferences-meetings.html).

At the conference Optical Nanospectroscopy I, the WG3 meeting was dedicated to an open exchange between researchers and industry on open issues in instrumentation that were collected in a list as a deliverable, see also MoU objective 10.

In 2016, a joint Training School was organized between the Natural and Medical Sciences Institute in Reutlingen, Germany, which is a technology transfer institute with very strong contacts to industry, and the Core Facility LISA$^+$ of the University of Tübingen, Germany, which is a shared scientific instrumentation facility. The School consisted of a workshop with 50% participants each from academia and industry giving oral presentations on methods and applications, and an exhibition with demos where users could bring their own samples. These were followed by two days of shared hands-on training for the Action participants on method training (http://cost-nanospectroscopy.eu/training-raman.html).

Altogether, the full value chain of technology transfer was represented in the COST Action, from basic research over applied research to research and technology transfer institutes all the way to industry and to the end users.

Some specific spotlights on industry collaboration within the COST Action:

		Service measurements using nanospectroscopy were performed for a large semiconductor company and for small and medium enterprises. New scanning probes for tip-enhanced Raman spectroscopy were developed and commercialized with different companies. Commercial measurement setups were made available to Action groups for a limited time to test their capability. Action members were invited to give talks at workshops organized by spectroscopy companies.
A list of current open issues in nanospectroscopic instrumentation and data analysis development will be drafted in communication with industry and disseminated via the Action's public website	76 - 100%	The Action aimed at improving nanospectroscopic instrumentation and data analysis by performing relevant fundamental method development in the participating research groups, by fostering exchange between research and industry to gain a better mutual understanding of the respective issues, and by collecting a list of open issues from both stakeholders that should be addressed in the near future in order to boost the field of nanospectroscopy. During the first annual conference Optical Nanospectroscopy I a dedicated session was held in which open issues in nanospectroscopic instrumentation and data analysis development were discussed between over 40 participants representing research and companies specializing in spectroscopy. A list of open issues was drafted from the results, which is openly accessible on the Action's website: http://cost-nanospectrosocpy.eu/wg3.html. The list was further refined in later conferences joined by industry.

Deliverables

The Action reported the following deliverables:

Deliverable	Timing of deliverable	Further information (hyperlink or other)
Dedicated COST Action Nanospectroscopy Website with references to member publications and information on optical nanospectroscopy and Action events, database on nanospectroscopy activities	Delivered	http://cost-nanospectroscopy.eu
Annual conferences Optical Nanospectroscopy I, II III and IV with Working Group Minutes, Management Committee Minutes and Books of Abstracts as deliverables	Delivered	http://cost-nanospectroscopy.eu/conferences-meetings.html
1st and 2nd conference organized by ESRs for ESRs, books of abstracts as deliverables	Delivered	http://cost-nanospectroscopy.eu/conferences-meetings.html
3-volume textbook on Optical Nanospectroscopy	Not delivered, but foreseen within 2 years	
Lists of instrumentation issues and Action competences	Delivered	http://cost-nanospectroscopy.eu/wg3.html
Discussions, summaries of state-of-the-art and open questions on specific topics in Working Groups and Topical Meetings, evidenced by minutes, abstract books or summary slides	Delivered	http://cost-nanospectroscopy.eu and restricted documents
Hands-on Training for ESRs in basics and techniques relevant to the field of nanospectroscopy, evidenced by training material	Delivered	http://cost-nanospectroscopy.eu/training-mobility.html
Scientific results from bilateral and networking activities, evidenced by STSM reports, publications and highlights	Delivered	http://cost-nanospectroscopy.eu/publications.html and STSM Book of Abstracts

Additional outputs/ achievements

N/A

Projects

N/A

Other outputs / achievements

N/A

Impacts

The Action reported the following impact(s):

Description of the impact, i.e. what will change, and for whom, as a result of what the Action achieved	**Type of impact**	**Timing of impact**
Advances in nanosystem design and nanofabrication, physical processes and modelling of nanospectroscopy, and improving spectroscopic techniques, as evidenced by publications http://www.cost-nanospectroscopy.eu/publications.html	• Scientific / Technological	Achieved
Less well-known and less visited locations, e.g. in ITCs, gained visibility by organizing COST events, with participants spreading the news and possibly returning in future, and the events contributing to local businesses (accomodation, restaurants, transportation, sights).	• Economic • Societal	Achieved
ECIs will have improved job chances due to additional skills, international experience, and higher visibility	• Scientific / Technological • Economic • Societal	Foreseen within two years
A new generation of interdisciplinarily trained ECIs will enter the field of nanospectroscopy to advance it further	• Scientific / Technological • Economic • Societal	Foreseen within two years
New generations in the interdisciplinary field of optical nanospectroscopy will be taught the relevant fundamentals, methods and applications using a coherent 3-volume textbook (where no such full coverage of the topic existed before this Action) http://www.cost-nanospectroscopy.eu/wg4.html	• Scientific / Technological	Foreseen within two years
Researchers, including ECIs, will submit joint project proposals and perform joint projects, bridging geographical and disciplinary boundaries	• Scientific / Technological	Foreseen within two years
The community of this COST Action will dynamically continue via a joint conference series, mailing list, linkedin group, mutual invitations to give presentations, exchange of group members, and scientific projects.	• Scientific / Technological • Economic	Foreseen within two years
The limits and differences in signal recording using different tip-enhanced Raman spectroscopy (TERS) setups will be demonstrated in a comparative study (round robin), giving a best-practice example of providing metadata (of signal collection) together with the measurement data using a unified quality checklist. The results will help towards further standardization of TERS applications.	• Scientific / Technological • Economic • Societal	Foreseen within two years
Mobility of European researchers within the Action has been and will further be increased through collaborations and research visits with contacts developed in the Action, supporting cultural exchange, inclusion of ITC, and global understanding.	• Scientific / Technological • Economic • Societal	Foreseen within two years
Training materials developed in the frame of the COST Action (presentations, introductory texts, introductory video, practical instruction manuals, podcasts, ...) will be distributed and used for training future ECIs.	• Scientific / Technological • Economic • Societal	Foreseen within two years
Collaboration at the European level is strengthened, generating cross-links across the European scientific community, triggering projects within European frameworks, and encouraging participants to look for further possibilities of interaction, e.g. in other COST Actions or ITNs after the end of this COST Action.	• Scientific / Technological • Economic • Societal	Foreseen within two years

The research area of nanospectroscopy will further advance and mature based on the Actions's research findings as evidenced by publications	• Scientific / Technological	Foreseen two-to-five years
The high-resolution optical techniqes of scanning near-field optical microscopy and tip-enhanced Raman spectroscopy will profit from novel scanning probes designed, developed and commercialized within this Action, for more robust, high resolution, and reproducible measurements, to tackle questions of nanoscale structure elucidation.	• Scientific / Technological • Economic • Societal	Foreseen two-to-five years
New substrates and standards for surface-enhanced Raman spectroscopy will be developed and commercialized, keeping in mind a standardization of the measurement data through high reproducibility and highly homogeneous enhancement platforms. The technique will be applied for sensing in medicine, environmental monitoring, food safety, contamination and explosives testing, etc.	• Scientific / Technological • Economic • Societal	Foreseen two-to-five years
Commercial instruments will be developed based on patents submitted during the Action's running time.	• Scientific / Technological • Economic • Societal	Foreseen two-to-five years
Optical nanospectrosocpy techniques will find broader and less obvious applications in different areas of societal interest, from the medical sector over safety and security, sensing and trace detection, food sciences / authentification / contamination / food packaging to energy applications or data processing, all the way to cultural heritage / artefact dating, and to as yet unidentified fields of application.	• Scientific / Technological • Economic • Societal	Foreseen five-to-ten years
Novel and improved techniques and instrumentation for nanospectroscopy will be widely made available to address societal questions. Examples include high-throughput Raman and SERS sensing machines, correlative setups for high-resolution topographic, electronic and optical structure determination, infrared AFM-TERS for early cancer detection, thermal probe imaging, nonlinear nanoparticles as biomarkers, nonlinear microscopy / confocal second harmonic scanning microscopy, label-free (noninvasive) spectroscopic techniques for medically relevant samples offering an alternative to hisopathology, in-situ imaging using fully tailorable spatio-temporal optical fields, ...	• Scientific / Technological • Economic • Societal	Foreseen five-to-ten years
The performance of optoelectronical devices will be improved based on the determination of energy flow, absorption or emission enhancement, and failure mechanisms using nanospectroscopy.	• Scientific / Technological • Economic • Societal	Foreseen ten years or more
Nanospectroscopy will enter even more strongly into the field of medicine, being applied for early cancer detection, early ostheoporosis detection, non-invasise sub-cutaneous Raman spectroscopy, identifying implant failure mechanisms, resolving biological / cellular processes on the nanoscale, etc.	• Scientific / Technological • Economic • Societal	Foreseen ten years or more
Nanospectroscopy will enable broad access to sensing down to single molecule sensitivity for pollutants and contaminants, explosives, antibodies, cancer markers, viruses, and more.	• Scientific / Technological • Economic • Societal	Foreseen ten years or more

Dissemination and exploitation of Action results

Dissemination and exploitation approach of the Action

The Action's dissemination and exploitation approach as well as all activities undertaken to ensure dissemination and exploitation of Action results and the outcomes of these activities are described below.

Dissemination and exploitation of the Action results was approached on several levels, i.e.: 1) Dissemination of information to Action members; 2) Dissemination of results to the scientific community beyond the COST Action; 3) Dissemination of results to persons new to the field or the general public; 4) Dissemination of results to EU stakeholders or policy makers; 5) Exploitation of Action results, e.g. in terms of commercialization. Different measures were pursued for the different stakeholders: 1) Dissemination to Action members took place via the Working Group Meetings, presentations at the Action events, publications in scientific journals, the Action website, and the regular Action Newsletter, which included input and information from all the member groups. Dissemination of specific techniques or skills was directly achieved by the Action's hands-on training schools and STSMs. These measures proved very effective. The ECIs trained by the Action will further disseminate the knowledge in their future careers. Following the end of the COST Action, a mailing list is now being introduced for additional information exchange. Looking back, a mailing list might have been introduced at an earlier point, but this was voted against by the MC to avoid spamming. The Action developed standards for tip-enhanced Raman spectroscopy, which were disseminated to the members via a round robin, and will be disseminated beyond the Action when the results of the round robin are published. 2) Dissemination to the scientific community can be most effectively achieved by peer-reviewed journal publications and conference contributions. Nearly 200 publications, mostly including a COST acknowledgement, as well as two Editorials and a collection of Action conference proceedings were published within the Action's running time. All Action members are active members of the scientific community, who were also highly visible at non-COST events. Additionally, Action results such as the capability lists of the member groups, collections of techniques and instrumentation issues, an overview over nanofabrication methods, or abstract books of the Action events were made publicly accessible on the Action website. 3) In terms of dissemination of results to persons new to the field and the general public, the Action's biggest achievement is the 3-volume coherent textbook on Optical Nanospectroscopy, which will be published shortly. It will be made at least partly freely accessible to the public via open access through the Final Action Dissemination grant. The books give a comprehensive overview over the field of nanospectroscopy, from the fundamentals to the state-of-the-art, and is aiming at a student level. This should be very effective in training the next generation on nanospectroscopy. Added to this, a 12 min introductory video to nanospectroscopy was produced. Additional information can be gained from the public website, or by joining the Nanospectroscopy linkedin group. 4) Dissemination to EU stakeholders or policy makers mostly took place via COST events (Annual Progress Conference of the DC, COST Connect event, networking with other Actions). Currently a Roadmap on Nanospectroscopy is being prepared for further dissemination. 5) A key point in the exploitation of the Action results was to involve technology transfer institutes and companies in the Action from the beginning. Industry participation was organized at all Action conferences, and a dialogue was started from the first WG3 meeting, where a list of instrumentation issues was jointly developed. Several proposals with industry and academia involvement were submitted to bridge the gap between fundamental research and commercial exploitation (e.g. Horizon 2020 FET, ITN). Individual patents were filed. Action members offered their analytical services to industry in order to prove the potential of the nanospectroscopy techniques to various end users. Several member groups work closely with industry or with hospitals in view of bringing their developments to the market place and/or the end user. This has successfully led to the commercialization of TERS probes and a novel Raman spectrometer, and to the successive implementation of novel biomarkers and diagnostic approaches.

Dissemination meetings funded by the Action

The Action funded Dissemination Meetings as shown below:

Title	Textbook meeting

Date	14-12-2015 to 15-12-2015	**Country**	Germany
Event	Textbook Meeting - Meeting of the Editors and Section Leaders of the textbooks Optical Nanospectroscopy 1-3.		

Other dissemination activities

The Action also undertook the following dissemination activities:

Activity	Introductory Video to Nanospectroscopy
Target	Interested public and people starting in the field.
Outcome	12 min illustrated video, commentated by the Action Member T. Madeira, giving an introduction to nanotechnology, nanoscience and nanospectroscopy.
Link	Restricted content, available from Chair

Activity	Editorial to the topical collection Nanospectroscopy of the Journal Analytical and Bioanalytical Chemistry
Target	Scientific community working in analytics
Outcome	The MC Substitute M. Culha was the guest editor for the topical collection Nanospectroscopy in the journal Anal. Bioanal. Chem.. In his Editorial he gives a broad introduction to the topic and gives special mention of the COST Action MP1302 Nanospectroscopy.
Link	https://link.springer.com/article/10.1007/s00216-015-9033-3

Activity	Editorial to the special issue on Biophotonics in Europe in the journal Frontiers in Optoelectronics
Target	Research community in optoelectronics and biophotonics
Outcome	The MC Member E. Borisova was one of the guest editors for the special issue Biophotonics in Europe in the journal Front. Optoelecton.. In her Editorial she gives a broad introduction to the topic and gives special mention of the COST Action MP1302 Nanospectroscopy.
Link	https://link.springer.com/article/10.1007/s12200-017-0757-x

Activity	Conference Proceedings in the Open Access journal Nanospectroscopy (de Gruyter)
Target	Scientific community
Outcome	The open access journal Nanospectroscopy by deGruyter was newly established in 2015 and is edited by the Action's Vice Chair, P.-M. Adam. Selected papers from the Action's annual conference Optical Nanospectroscopy I to IV were published in this journal as conference proceedings.
Link	https://www.degruyter.com/view/j/nansp#

Activity	Invited presentation in the COST Action Nanoscale Quantum Optics Conference and MC Meeting
Target	Membership of COST Action MP1403 NQO
Outcome	The Chair was invited to give a presentation on the activities, results and outputs of the COST Action MP1302 Nanospectroscopy at the conference of the COST Action MP1403 Nanoscale Quantum Optics, along with representatives of other COST related Actions, to share experiences and further connect the Actions.
Link	http://www.cost-nqo.eu/event/nanoscale-quantum-optics-conference-mc-meeting-prague-czech-republik/

Activity	Participation in the COST Connect event Quantum: Where will the next jump go?
Target	COST Association, Action Chairs, representatives from the Quantum sector and EU stakeholders

Outcome	The Chair will take part in the COST Connect event Quantum: Where will the next jump go? in Warsaw (March 2018) to engage in a Discussion round between Action representatives and the COST Scientific Committee, and to enter into conversation with other Actions and with stakeholders in the field (e.g. DG CONNECT, Quantum Flagship, QUANTERA, ESA, JRC etc.).
Link	http://www.cost.eu/events/cost_connect_quantum

Activity	Participation in the Annual Progress Conference of the COST Domain Committee Materials, Physics and Nanosciences 2014
Target	COST Domain Committee, Action Chairs of the Domain
Outcome	Presentation slides by the Chair on the status of the COST Action after Year 1, Poster on the COST Action Nanospectroscopy
Link	https://e-services.cost.eu/action/MP1302/overview

Activity	3-volume textbook Optical Nanospectroscopy
Target	Students and ECIs in the field, and researchers / company members newly entering the field of Nanospectroscopy
Outcome	Publication of the 3-volume coherent textbook on Optical Nanospectroscopy with deGruyter in 2018
Link	http://cost-nanospectroscopy.eu/wg4.html

Activity	Roadmap on Nanospectroscopy
Target	European policy makers, nanospectroscopy community
Outcome	A Roadmap on optical nanospectroscopy is currently in preparation
Link	N.A.

Activity	Unveiling of a commemorative Plaque for Edward Hutchinson Synge (1890-1957)
Target	European public
Outcome	The WG4 Leader N. McMillan is a member of the National Committee for Commemorative Plaques in Science and Technology in Ireland. With his support the Committee decided to dedicate a plaque to E.H. Synge, who amongst others was the pioneer of scanning near-field optical microscopy, describing the theoretical concept long before it was realized. The inscription for the plaque was discussed in WG4. The plaque will be put up in the County Dublin. The unveiling is envisaged for 2018, with the participation of the Action Chair and general media coverage.
Link	http://www.askaboutireland.ie/reading-room/life-society/science-technology/irish-scientists/index.xml

Activity	Organization of and participation in non-Action meetings
Target	Scientific community
Outcome	All of the Action members regularly participated in scientific non-Action meetings, and numerous conferences and workshops were organized by Action members as non-Action events. At these events results from the COST Action were publicized. Through acknowledgements of the COST Action, news on the COST Action was spread further.
Link	e.g. * https://www.tu-chemnitz.de/physik/ICSFS18/committees.php * http://www.acp.uni-jena.de/News/Jena+hosts+International+Conference+on+Raman+Spectroscopy+%28ICORS2014%29.html * http://www.ices2017.cup.uni-muenchen.de/committee/ * http://ices2015.its.me.cnr.it/ * http://www.ism.cnr.it/en/workshop/epioptics-14/ * http://www.frontiers.ethz.ch/ * https://www.grc.org/plasmonics-and-nanophotonics-conference/2016/

Activity	linkedin group Nanospectroscopy

Target	interested community
Outcome	A linkedin group on the topic of Nanospectroscopy was created by the MC Member P. Gucciardi (currently 157 members)
Link	https://www.linkedin.com/groups/5183347/profile

Exploitation activities

The Action undertook the following activities to ensure exploitation (use, in particular in a commercial context) of the Action's achievements:

Activity	Further development and commercial distribution of tip-enhanced Raman spectroscopy probes
Target	AFM and TERS users
Outcome	Tips have been made commercially available, both by Action members directly and in collaboration with known companies.

Activity	Joint meetings, conferences and exhibitions with industry
Target	Companies in the area of nanospectroscopy
Outcome	Close contacts have been established between academia and companies working in the area of nanospectroscopy. The companies gave talks and presented their products at Action events and made them avaible to the Action members for sample testing. Feedback by the Action members helps to improve the instrumentation capabilities and the software development.

Activity	TERS round robin
Target	Raman community
Outcome	Standard samples for testing TERS functionality were developed by the Action. They were distributed to 8 groups from academia and 2 groups from industry. All participants are currently evaluating these standards with their setups, using the same standardized quality checklist to provide the metadata for their measurements. About 50% feedback have been collected so far, to be concluded in 2018. The efforts help the standardization and commercialization of TERS applications.

Activity	Development of a novel Raman spectrometer designed to rapidly measure microlitre liquid samples
Target	Nanospectroscopy users
Outcome	A novel Raman spectrometer designed to rapidly measure microlitre liquid samples was developed by a start-up company that is an active Action member. The spectrometer will be introduced to the market in 2018. An industry-driven project was submitted in the Horizon2020 framework to further expand the instrument's capabilities.

Activity	Analytical measurements for industry
Target	R&D in industry
Outcome	Nanospectroscopy analytics on samples for real-life applications were performed in cooperation with technology transfer institutions and industry, e.g. the semiconductor and biomedical industry. Showing the potential that these techniques provide in the area of e.g. material development or improving optoelectonic devices is an important step towards their dissemination and commercializations. Example: X. Wang et al., Morphology related Photo-degradations of Low Band-gap Polymer Blends, Adv. Energy Mater. 4 (2014) 14000497 I. Ibrahim et al., Confirming the Dual Role of Etchants during the Enrichment of Semiconducting Single Wall Carbon Nanotubes by Chemical Vapor Deposition, Chem. Mater. 27 (2015) 5964 K. Fuchsberger et al., Electrochemical etching of micro-pores in medical grade cobalt–chromium alloy as reservoirs for drug eluting stents, Journal of Materials Science: Materials in Medicine 27(3) (2016) 1

Activity	Harmonic nanoparticles developed for biolabeling in a joint effort between academia and industry
Target	Biomedical sector
Outcome	In the light of their prospective use as biological and clinical markers, harmonic nanoparticles were assessed with respect to their biocompatibility on human healthy and cancerous cell lines. The potential for cell imaging of these inherently nonlinear probes in terms of optical contrast, wavelength flexibility, and signal photostability was demonstrated. The studies are performed jointly by academic partners and optical companies, e.g. C. Staedler et al., Harmonic Nanocrystals for Biolabeling: A Survey of Optical Properties and Biocompatibility, ACS Nano, 2012, 6 (3), 2542 (http://pubs.acs.org/doi/10.1021/nn204990n)

Activity	Collaboration between research and hospitals for early cancer detection
Target	Medicine / diagnostics
Outcome	Members from academia work closely together with hospitals in order to advance nanospectroscopic techniques for early cancer detection, e.g. using SNOM for cervical cytology, D.E. Halliwell et al., An imaging dataset of cervical cells using scanning near-field optical microscopy coupled to an infrared free electron laser, Scientific Data 4 (2017) 170084 (https://www.nature.com/articles/sdata201784); D.E. Halliwell et al., Imaging cervical cytology with scanning near-field optical microscopy (SNOM) coupled with an IR-FEL, Sci. Rep. 6 (2016) 29494 (https://www.nature.com/articles/srep29494) or e.g. using fluorescence spectroscopy for tumor evaluation and cancer diagnostics, e.g. E. Borisova et al., Synchronous autofluorescence spectroscopy of gastrointestinal tumours - tool for endogenous fluorophores evaluation, Optoelectronics and advanced materials 9(9-10) (2015) 1234 (https://oam-rc.inoe.ro/index.php?option=magazine&op=view&idu=2698&catid=92); E. Borisova et al., Endogenous synchronous fluorescence spectroscopy (SFS) of basal cell carcinoma-initial study, Optics and Spectroscopy 120(1) (2016), 38 (https://link.springer.com/article/10.1134%2FS0030400X16010057); E. Borisova et al., Excitation-emission matrices (EEMs) of colorectal tumors — tool for spectroscopic diagnostics of gastrointestinal neoplasia, Frontiers of Optoelectronics 10(3) (2017) 292 (https://link.springer.com/article/10.1007%2Fs12200-017-0720-x)

Activity	Collaboration between nanospectroscopy and hospitals for implants, bone analysis and scaffolds
Target	Medicine
Outcome	e.g. bone-mimicking collagen/hydroxyapatite composites were investigated with FTIR spectroscopy, e.g. J. Wang and C. Liu, Biomimetic Collagen/Hydroxyapatite Composite Scaffolds: Fabrication and Characterizations, J. Bionic Eng. 11 (2014) 600 (https://www.sciencedirect.com/science/article/pii/S1672652914600718?via%3Dihub)

Activity	Patents
Target	Potential commercialization
Outcome	Several patents were filed in the context of this COST Action

Activity	Enhancing solar cell efficienc and understanding organic solar cell mechanisms and degradation
Target	Solar cell industry
Outcome	Organic solar cell degragation has e.g. been investigated in the EU FP7-People project Revolutionizing Understanding of Organic Solar Cell Degradation to Design Novel Stable Materials (SolarRevolution) involving academia and industry. A study on Designing high performance all-small-molecule solar cells with non-fullerene acceptors was recently published as a result of an STSM; J. Shi et al., Energy Environ. Sci. 11 (2018) 211 (http://pubs.rsc.org/en/content/articlelanding/2018/ee/c7ee02967e#!divAbstract). Quantum dot engineering for photoelectrochemical solar energy conversion was shown in L. Jin et al., Nano Energy 30 (2016) 531 (https://www.sciencedirect.com/science/article/pii/S2211285516304475?via%3Dihub); ZnO-based dye-sensitized solar cells were investigated between a materials engineering institute and an R&D laboratory in S. Akin et al., Electrochimica Acta 225 (2017) 243 (https://www.sciencedirect.com/science/article/pii/S0013468616326810)

Activity	Joint academia/industry proposals
Target	R&D
Outcome	Several proposals with the participation of both academia and industry have been submitted, particularly in the frame of Horizon2020 (e.g. FETs or ITNs), to bridge the gap between fundamental studies and their commercial exploitation, see Additional Outputs - Proposals/Projects.

Activity	Training of Nanospectroscopists
Target	Future generation of R&D departments
Outcome	A number of PhD students and ECIs that were comprehensively trained in Nanospectroscopy in this COST Action have over the Action's running time found jobs in nanospectroscopy-related companies and will help to disseminate the techniques they experienced first-hand before.

Action Success(es)

The Action's two most significant successes were the following:

- 1) First success: science dissemination *** The 3-volume textbook Optical Nanospectroscopy in considered a significant successes of the Action in terms of dissemination of knowledge, training of a new generation of researchers, and impact on the international community. The textbook as far as possible covers the whole field of Nanospectroscopy (from fundamentals over methods to applications). The basic idea to create a coherent textbook with a consistent table of contents like a monograph, but written by a large pool of authors, who each are renowned experts on certain aspects of the topic, is rather unique. Such a pool of contributors, together with the organizational structure of regular face-to-face progress meetings, was only made possible because of the COST Action. The books will address a broad readership, in particular targeting ECIs, and will at least partly be made open access. Over 1000 book pages have been collected. Publication is expected in 2018. *** This COST Action allowed for networking between international experts with a strong participation of scientists from ITCs, which often had no other means of funding to attend international meetings, and ECIs, who otherwise may have had much less visibility in the community. This provided the basis for future European projects, and has boosted new developments. It also clearly bridged the separate communities of physics, chemistry, biology, material science and medicine, and the worlds of academia and industry, in an integrative approach. *** The COST Action Nanospectroscopy had a strong basic research focus. Significant publications have resulted from it, including many very high impact papers (Nat. Nanotechnol., Nano Energy, Adv. Energy Mater., Adv. Funct. Mater., Adv. Mater., J. Am. Chem. Soc., ACS Nano, Nano Lett., ...)
- 2) Second success: technique development including industry involvement *** Another significant success of this COST Action is the development of new nanospectroscopic techniques and instrumentation. These developments open new opportunities towards applications of nanospectroscopy with societal impact. *** As a special focus tip-enhanced Raman spectroscopy (TERS) was chosen. This technique strongly depends on the quality of the scanning probes and the particular setup. It therefore suffers intensity and resolution losses from non-optimal tips, and comparability between different measurements is difficult. For this reason, novel scanning probes were developed in the COST Action and partly commercialized. Intense discussions were conducted to find suitable test samples and standardization protocols. A quality checklist was drafted, in which all relevant measurement parameters are collected. This initiative is also in the spirit of the ongoing global discussion on publishing meaningful metadata together with experimental results. A TERS round robin was started, where the participants collect data with their setups on the same test samples, and results are compared. The time-consuming measurements are still ongoing and will be finalized and evaluated in 2018. *** Further techniques that were developed or advanced in this Action include thermal probe imaging, IR-AFM-TERS for cancer research, SERS, nonlinear microscopy using laser beams with inhomogeneous states of polarization, bioimaging and localized therapy with harmonic nanoparticles, plasmon-based optical nanosensors and their miniaturization by gradient index lenses, ultrafast pump-probe spectroscopy, and more.

Action Expenditure

The table below shows the budget allocated to the Action for each Grant Period:

#	Grant Period	Start Date	End Date	Budget allocated to Action (EUR)
1	MP1302-20131211	1-1-2014	30-11-2014	0.00 (EUR)
2	CGA-MP1302-2	2-12-2014	31-8-2015	81,816.89 (EUR)
3	CGA-MP1302-2B	1-9-2015	30-4-2016	163,183.11 (EUR)
4	AGA-MP1302-4	1-5-2016	30-4-2017	141,000.01 (EUR)
5	AGA-MP1302-5	1-5-2017	14-11-2017	86,200.01 (EUR)