Overview of available research topics in the Nano & Quantum Optics group of the Institute of Applied Physics

The Nano & Quantum Optics group of the Institute of Applied Physics is looking permanently for talented and enthusiastic new students who would like to contribute to cutting edge research projects on photonics and quantum optics at the nano scale.

The group covers a broad range of research fields in experiment and theory:

– ultrafast light-matter interactions and optical quantum phenomena in nanostructured matter, as e.g. photonic nanomaterials, metamaterials, photonic crystals, and 2D-materials (TMDCs)
– nonlinear spatio-temporal dynamics, plasmonics, near field optics, high-Q nonlinear optical microresonators, opto-optical processes in integrated optics, and all-optical signal processing
– integrated quantum optics, quantum imaging, and quantum sensing
– photonics in 2D-materials for imaging and quantum light sources, integration of 2D-materials in optical systems
– multi-tip scanning nearfield optical microscopy (SNOM), photoemission electron microscopy (PEEM)
– application of photonic nanomaterials for multi-functional diffractive optical elements
– application of optical nanostructures for efficiency enhancement of photovoltaic elements
– application of advanced photonic concepts for astronomical instruments

The topics listed in the following document are just a selection of ongoing research projects, which students could join during their studies. Further topics could be identified by individual discussions. Most topics can be adjusted for short-term research periods during the BSc and MSc studies and can be expanded into Bachelor thesis projects, Master thesis projects and even doctoral projects. An overview of our current research can be found at our webpage www.iap.uni-jena.de/nano+quantum_optics.

If you are interested in our research and could imagine joining our group, please contact one of the following scientists preferably by an email, in which you describe your interest and already obtained qualifications:

– Falk Eilenberger (falk.eilenberger@uni-jena.de, +49 3641 947990)
– Thomas Pertsch (thomas.pertsch@uni-jena.de, +49 3641 947560)
– Frank Setzpfandt (f.setzpfandt@uni-jena.de, +49 3641 947569)
– Isabelle Staude (isabelle.staude@uni-jena.de, +49 3641 947566)

List of topics described in this document

Institute of Applied Physics – Nano & Quantum Optics
Research project / Master Thesis on

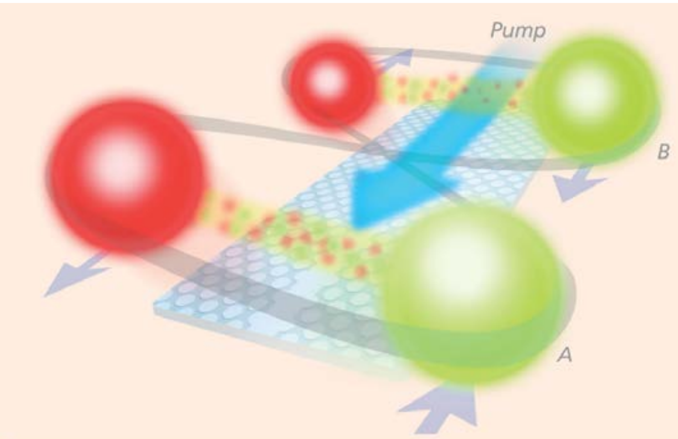
Sources for entangled photon pairs

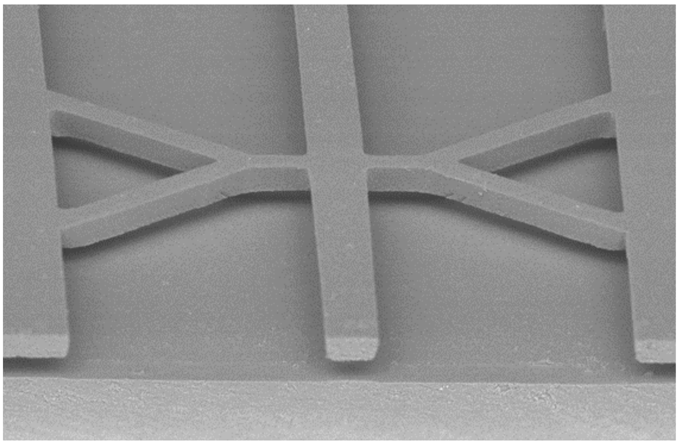
Entangled photon pairs, quantum states of light with exactly two photons, are an important resource for applications of quantum optics. To fully use the potential of quantum optics for applications e.g. in computing, sensing, and cryptography, it is important to optimize the properties of the used photon pairs with respect to the targeted application. This means, their spectral, spatial, and polarization features have to be tailored in a wide range.

The most common mechanism to generate such photon pairs is by using spontaneous parametric down-conversion, a nonlinear optical process in which one photon is spontaneously split into a photon pair, where each of the generated photons has a longer wavelength than the original one. This process, and thereby also the state of the generated photons, depends sensitively on the properties of the nonlinear system that is used for the down conversion. In our research, we investigate different platforms for photon-pair generation, ranging from bulk nonlinear crystals over waveguides all the way to nanostructured surfaces and two-dimensional materials. Furthermore, technologies to fabricate nanostructured photon-pair sources as well as experimental approaches for their characterization need to be developed and implemented. Depending on the specific topic, one or several of the following subjects will be covered.

Covered subjects

- Experimental and theoretical quantum optics
- Nonlinear optics
- Waveguides and nanostructured surfaces
- Numerical simulations
- Programming in MatLab and LabView
- Nanostructuring technology





Contact for further information and application **https://www.iap.uni-jena.de/setzpfandt**

Dr. Frank SETZPFANDT (f.setzpfandt@uni-jena.de)

Institute of Applied Physics – Nano & Quantum Optics
Research project / Master Thesis on

Quantum Imaging and Sensing

Entangled photon pairs enable new modalities for optical sensing and imaging. They can help to surpass classical noise limits, image through turbulent media, and image in spectral domains where no cameras are accessible. We are investigating several quantum imaging and sensing approaches, aiming to fundamentally understand, optimize, and implement them.

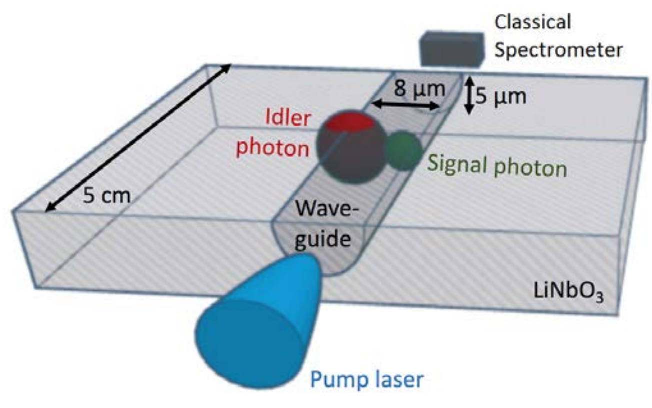
One example for studied imaging methods is quantum ghost imaging. Here, only one of the two photons of a photon pair is interacting with the sample and is afterwards detected with a single detector without spatial resolution. The second photon, which did not see the object, is spatially characterized using a single-photon sensitive camera. None of the individual detection events is able to generate an image, however, by correlating both measurements such image can be obtained. We are striving to implement quantum ghost imaging with high spatial resolution and in technically hardly accessible wavelength regions like the mid-infrared with the aim of applying it in real-world measurement scenarios.

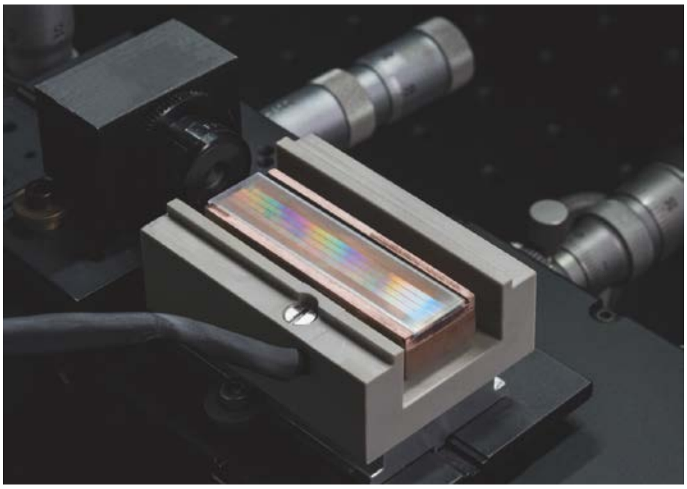
Another research topic is SPDC spectroscopy in waveguide platforms. Using the quantum interference of several sources of photon pairs, which characteristics depends on the properties of the sources and media between them, information about the optical properties of these media can be obtained by measuring only one of the two photons of a photon pair. Utilizing photon pair sources that generate pairs of different wavelength, e.g. in the mid-infrared and the visible, this enables the measurement of the spectral properties of analytes in the mid-infrared by simply characterizing the second photon in the visible. Our goal is to fundamentally understand this measurement principle and its properties, as well as to design, implement, and test suitable optical structures realizing it.

Depending on the specific topic, one or several of the following subjects will be covered.

Covered subjects

- Waveguide and nonlinear optics
- Quantum optics
- Optical Imaging
- Numerical simulations
- Programming in MatLab and LabView
- Correlation measurements





Contact for further information and application **https://www.iap.uni-jena.de/setzpfandt**

Dr. Frank SETZPFANDT (f.setzpfandt@uni-jena.de)

Institute of Applied Physics – Nano Optics
Research project / Master Thesis on

Nanostructured photonic metamaterials

Photonic metamaterials represent a novel class of artificial matter consisting of periodically or randomly arranged unit cells, having a size smaller than the wavelength of light. Metamaterials promise to obtain complete control over all properties characterizing light propagation. By designing the metamaterials´ unit cells one can tailor light propagation in such media beyond the limits given by natural occurring materials. The envisioned achievements range from a dramatic enhancement of optical effects like polarization rotation by several orders of magnitude to the overall spatial and spectral shaping of light by appropriately designed and spatially distributed nanoparticles. Recent advances in fabrication technology have allowed for the realization of optical structures with sub-wavelength dimensions. Modern nanostructure technologies enable the creation of photonic nanomaterials in order to examine them experimentally.

Our group has a firm experience in the fabrication and characterization of photonic metamaterials. The student's projects range from the usage and optimization of available experimental setups for characterization, to the design and numerical optimization of novel photonic metamaterials and advanced investigations like the characterization of nonlinear optical properties or even quantum state control.

The candidate should ideally have high interest in new types of physics, basic lab and computational experience. Depending on the chosen task good experimental skills or advanced Matlab / Comsol knowledge is appreciated.

Covered subjects

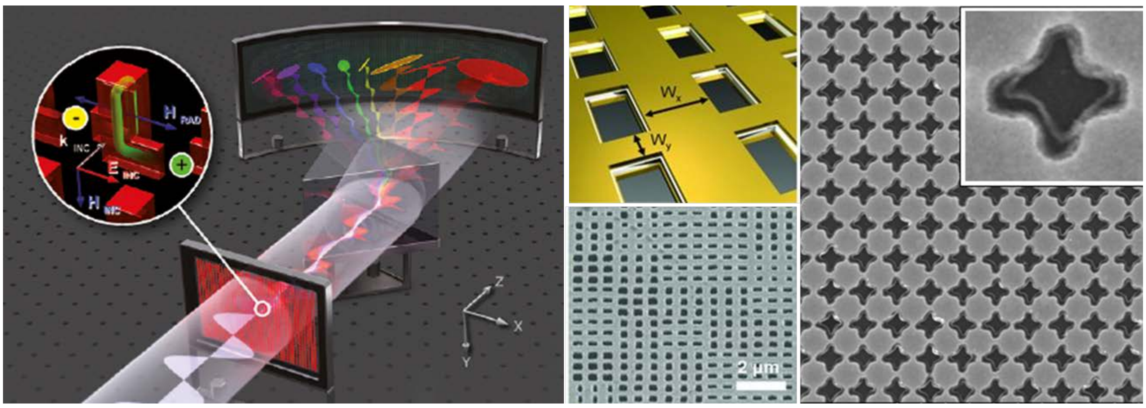
- structural characterization and nanofabrication (FIB, SEM, AFM, SNOM …)
- resonant excitation of plasmonic or dielectric eigenmodes in artificial structures with spectral & angular resolution
- spectral data processing and physical interpretation

Experimental activities

- characterization and optimization of existing experimental setups for the band structure measurement of highly dispersive nanomaterials
- computer controlled automation of an experimental procedure for parameter optimization and precise measurement procedures

Theoretical activities

- numerical modeling of single and periodic nanostructures based on rigorous solutions of Maxwell's equations on parallel cluster computers
- analytical modeling by simplified toy models and semi-analytical computer-supported calculations
- comparing experimental results to rigorous numerical simulations to extract basic physical phenomena



Contact for further information and application **www.iap.uni-jena.de/nano+quantum_optics**

Prof. Thomas PERTSCH (thomas.pertsch@uni-jena.de)

Institute of Applied Physics – Nano & Quantum Optics

Research project / Master Thesis on

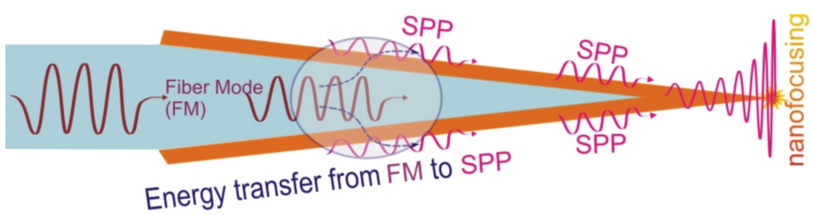
Control of the optical nearfield by plasmonic nanostructures and SNOM investigation

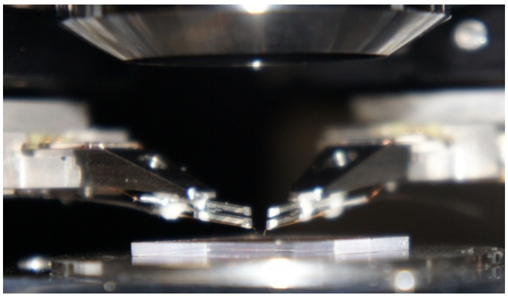
The emerging field of nano-plasmonics addresses the study of the interaction between electromagnetic waves and electron plasmas on metal surfaces and in metallic nanostructures, i.e. the hybrid states of plasmon-polaritons. It has received much attention in the last decade due to the high potential of new applications ranging from subwavelength photonic circuits to high-resolution microscopy. Plasmonic devices are capable of efficiently confining and enhancing optical fields, serving as a bridge between diffraction-limited optics and the nanoscale. One of the main research tools in nano-plasmonics to observe plasmon-polaritons beyond the optical diffraction limit is scanning near-field optical microscopy (SNOM) targeted to obtain ultimate topographic and optical resolution for nano-imaging. To break the diffraction limit, a plasmonic superfocusing SNOM (PS-SNOM) has been proposed in which a nano-sized plasmonic tip (metallic probe) scans the sample surface to form topography and optical image with extremely high spatial resolution. The principle of PS-SNOM is based on the excitation of localized modes of surface plasmon polaritons (SPP) at the metallic tip with far-field illumination, which generates a nano-sized spot of light at the apex of the nano-tip.

The goal is to develop and to operate different nearfield microscopy setups to address different purposes, such as plasmonic waves propagating on noble metal surfaces, locally excited plasmon-polariton eigenmodes in metal-dielectric nanomaterials and metamaterials, or chemically synthesized nanostructures such as semiconductor nanowires, and the generation of non-diffracting surface waves, so called plasmonic Airy beams. Another goal is the development of new SNOM techniques using two SNOM tips simultaneously on the same sample. Here, one tip is fed by an input signal exciting the probe at one local spot of the sample while the other tip collects the information on the field distribution from a different spot, disclosing the nearfield optical Green's function.

Covered subjects

- fundamentals of surface plasmon-polaritons at metal nanostructures
- theoretical modeling and numerical simulation of the spatio-temporal dynamics of light on the nano-scale below the diffraction limit based on rigorous solutions of Maxwell's equations
- design and realization of complex experimental setups for the control of scanning tips with nanometer precision and phase sensitive detection of scattered near fields
- experimental investigation of new functionalities of plasmonic nanostructures, as e.g. strong coupling of nano-antennas to quantum systems, as e.g. quantum dots for enhanced light-matter interaction





Left: Schematic for the excitation of a superfocusing surface plasmon-polariton at a metalized fiber tip by resonant coupling to a propagating fiber mode. Right: Two-tip nearfield scanning optical microscope for direct measurement of the optical nearfield Green's function of photonic nanostructures.

Contact for further information and application **www.iap.uni-jena.de/nano+quantum_optics**

Prof. Thomas PERTSCH (thomas.pertsch@uni-jena.de)

Dr. Bayarjargal NARANTSATSRALT (n.bayarjargal@uni-jena.de)

Institute of Applied Physics – Nano & Quantum Optics
Research project / Master Thesis on

Ultrafast multidimensional, spatiotemporal pulse measurement techniques

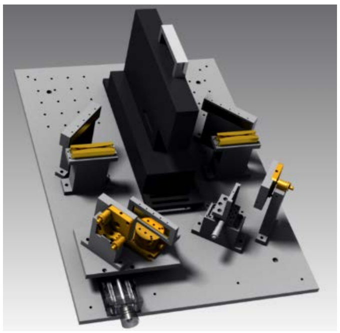
Ultrashort laser pulses give access to events, which are inherently inaccessible to electronics. They can resolve processes such in physical, chemical or biological samples with femtosecond resolution in realtime. They are thus an ideal probe to study the motion of electrons and other fundamental particles, which are the building blocks of nature. The complex nature of their interaction with matter can, however, only be leveraged, if the pulses themselves can be measured precisely and reproducibly in space and time, which is a highly active research topic in its own right.

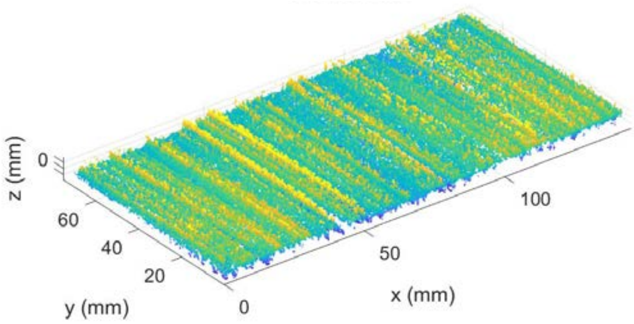
Our group is using ultrashort laser pulses to understand the complex physical systems in a multidimensional manner. We combine ultrashort pulses with electron microscopy to understand the motion of electrons in nanoplasmonic systems on a scale of femtoseconds and nanometers. We also combine ultrashort laser pulses with state-of-the-art 3D-measurement techniques to visualize highly dynamic events in 3D with unpreceded temporal resolution and spatial precision. We also develop techniques and devices to analyze spatiotemporal highly-complex light fields with femtosecond and nanometer resolution.

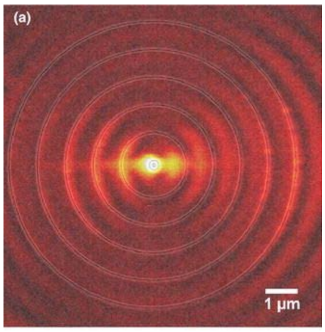
This field offers many opportunities for research projects: one opportunity would be the development of a real-time 3D-measurement fringe-projection based scheme with micrometer precision, which is capable to visualize highly dynamic effects, such as the propagation of high frequency photons in crystalline materials or the development and propagation of cracks. A second opportunity for project is in the development of devices, methods and algorithms for the spatiotemporal characterization of ultrashort laser pulses. A third area are projects in real-time analysis of the dynamics of electrons in plasmonic nanoresonatores under the excitation of light and the ensuing interaction of light waves and matter waves in bound plasmons.

Covered subjects

- fundamentals of surface plasmon polaritons at metallic nanostructures
- theoretical modeling and numerical simulation of the spatio-temporal dynamics of light and electrons on the nano-scale below the diffraction limit based on rigorous solutions of Maxwell's equations coupled to materials models
- design and realization of complex experimental setups for the three ultrafast three dimensional measurements and spatiotemporal pulse reconstruction
- experimental investigation of the ultrafast dynamics of laser-excited solid state systems







Left: Schematic of a femtosecond pulse shaping device. Center: A planar surface measured with an ultrafast 3D-camera. Right: Measured electron wavepackets excited by a laser beam incident on a ring-type nanoantenna.

Contact for further information and application **www.iap.uni-jena.de/nano+quantum_optics**

Dr. Falk Eilenberger (falk.eilenberger@uni-jena.de)

Institute of Applied Physics – Nano & Quantum Optics
Research project / Master Thesis on

Resonant Interaction of Light with 2D-Materials

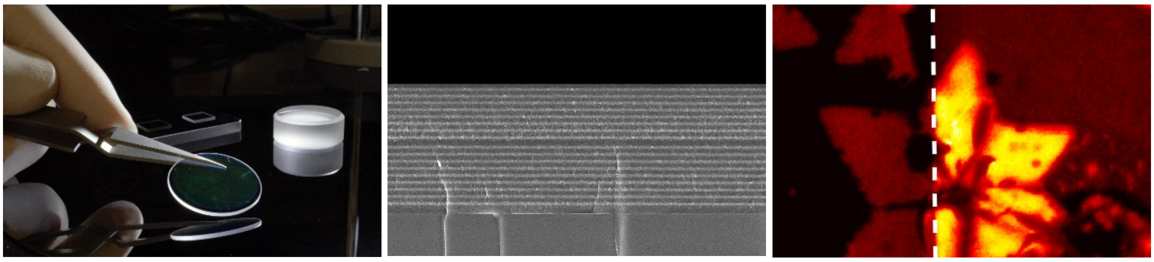
Two-dimensional semiconductors are the first class of atomic layer materials with a high degree of optical activity. Due to their unusual geometry, they exhibit extremely strong and highly unexpected light-matter interaction. In comparison to bulk semiconductors they have superior linear and nonlinear coefficients, extended excitonic lifetimes, spin-valley coupling and fluorescence. They are a highly attractive platform for fundamental experiments related to effects induced by dimensionality and also suitable for applications, e.g. sources for entangle photon pairs and novel imaging modalities.

We specialize on integrating two-dimensional semiconductors with optically resonant structures such as monolithic and optical fiber based cavities as well as nanoresonatores to further enhance and tailor their interaction with light. This gives access to experiments in fundamental physics of light-matter-interaction 2D-semiconductors, including experiments in strong coupling of exciton-polaritons, spin-valley coupling and the defect-state-based single photon emitters. The integration with optical systems also allows for the efficient and robust integration with optical systems, with applications in the development of atomic scale lasers, new light sources for entangled photons, highly sensitive sensing and new microscopic imaging modalities based on the unique fluorescence properties of these materials.

This field offers many possibilities for research projects. We offer projects in the light-based fabrication of the materials themselves, their growth on and integration with micro- and nanooptical systems and the characterization of their properties. We also offer projects on fundamental questions on their light-matter interaction, such as their interaction with near-field active nanostructures and the ensuing effects on single-photon emitters and spin-valley coupling. A third class of projects deals with the development of 2D-materials-enabled applications for lasing, sensing, imaging and quantum photonics.

Covered subjects

- fabrication, transfer, integration and growth of 2D-materials on photonics structures and with photonic methods
- characterization and theoretical modelling of light-matter-interaction of 2D-materials with micro- and nanooptical systems, using rigorous solutions of Maxwell's equations coupled to materials models
- design and realization of complex of experimental setups for 2D-materials-based applications in lasing, sensing, microscopy and quantum light sources



Left: A monolithic optical cavity loaded with 2D-materials. Center: Cross-Section through a cavity loaded with 2D-materials. Right: Fluorescence of a 2D-material, partially enhanced by underlying nanoresonators.

Contact for further information and application **www.iap.uni-jena.de/nano+quantum_optics**

Dr. Falk Eilenberger (falk.eilenberger@uni-jena.de)

Jun.-Prof. Isabelle Staude (isabelle.staude@uni-jena.de)

Dr. Frank Setzpfandt (f.setzpfandt@uni-jena.de)

Institute of Applied Physics – Nano & Quantum Optics
Research project / Master Thesis on

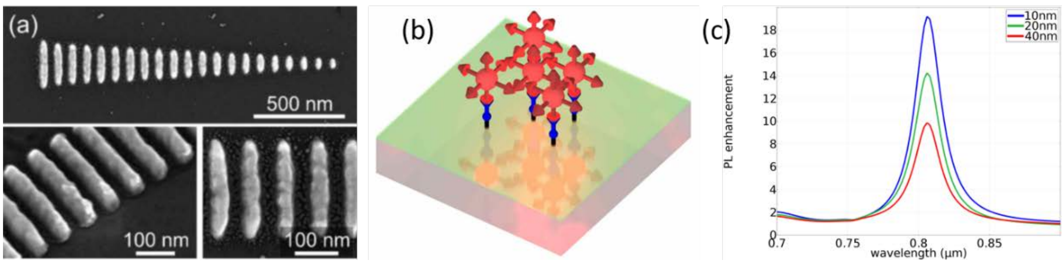
Actively tunable nanoantennas

Nanoantennas are able to efficiently link propagating light waves with tightly confined optical near fields, thereby strongly enhancing the interaction of light with nanoscale matter. Based on this principle nanoantennas offer unique opportunities for key applications like efficient quantum light sources, transmitting and receiving devices for integrated nanophotonic circuitry, photovoltaics, nonlinear optics, single-molecule detection, and display technology. Research into nanoantennas is furthermore strongly connected with ongoing research activities in quantum plasmonics and functional metasurfaces. Nanoantennas share many characteristics with their classical radio frequency (RF) counterparts - they are usually made of metal and are used to create electromagnetic waves with a well-defined radiation pattern, or, by reciprocity, to receive electromagnetic waves from a remote source. However, to date nanoantennas remain drastically underutilized compared to their radiofrequency and GHz counterparts. This is mainly caused by their small dimensions, by strong material dispersion at optical frequencies, and by the occurrence of particle plasmons in subwavelength metallic particles. Despite continuously growing efforts to improve nanoantenna performance over the past few years there are several important challenges remaining. In particular, almost all nanoantennas realized so far were static, i.e. their functionality was encoded into the structure during fabrication, and it was impossible to tune or switch it later on, which would be crucial for many of the mentioned applications.

In our group, we aim to obtain dynamic control of spontaneous emission by nanoantennas and metasurfaces using temperature, applied voltage, or the pH value of their surroundings as external control parameters. In this interdisciplinary research project, which will be performed in collaboration with a research group from the chemistry department, we aim to decorate optical nanoantennas with nanoscale emitters, which are chemically bound to the nanoantennas via a dynamic linker molecule. Depending on the value of the control parameters, this linker molecule can stretch or fold up, thereby changing the distance between the nanoantenna and the nanoemitter, and thus inducing a strong change in the emission strength, pattern or polarization of the coupled system.

Covered subjects

- photoluminescence mapping and time-resolved photoluminescence measurements on active nanoantennas for a systematic variation of the control parameters using an existing optical setup
- functionalization of nanoantenna samples with nanoemitters using functional linkers
- design of a new generation of functional active nanoantennas using numerical Maxwell solvers



(a*) Scanning-electron micrographs of various fabricated nanoantennas able to enhance and direct the emission from a nanoemitter. (b) Sketch of nanomeitters (red spheres) bound to a surface by functional linker molecules (blue). (c) Expected change of the photoluminescence (PL) enhancement experienced by a nanoemitter bound to the nanoantenna as a function from the distance between the two nano-objects, which can be changed by controlling temperature or pH value.*

Contact for further information and application **www.iap.uni-jena.de/nano+quantum_optics**

Jun.-Prof. Isabelle Staude (isabelle.staude@uni-jena.de)

Guidelines for the selection of projects

Guidelines for MSc Photonics students

Student enrolled in the program MSc Photonics have to do the following research projects as part of their studies:

- Module "Internship" during the 2nd semester
- Module "Research Labworks" during the 3rd semester
- Module "Master Thesis" during the 4th semester

In these modules the students have the opportunity to work in optical research laboratories at the Friedrich-Schiller-Universität Jena, the Fraunhofer Institute of Applied Optics, and the Institute of Photonic Technology or in the research labs of the companies associated to the Abbe School of Photonics.

The aim of the Internship (2nd semester) is to get first research experience and to use this opportunity to acquire some orientation in the broad variety of different fields in photonics. The aim of the Research Labwork (3rd semester) and Master Thesis (4th semester) is to apply the knowledge obtained during the lectures to a state-of-the-art research problem. Hence, the topic of the Research Labwork should be directly connected to the topic of the Master Thesis project of the 4th semester and should be performed in the same research group. Hence, students should choose this topic carefully since they will spend a full year on it.

Guidelines for MSc Physics students

Student enrolled in the program MSc Physics have to do the following research projects as part of their studies:

- Module "Einführung in das wissenschaftliche Arbeiten" during the 3rd semester
- Module "Projektplanung zur Masterarbeit" during the 3rd semester
- Module "Masterarbeit" during the 4th semester

In these modules the students have the opportunity to work in optical research laboratories at the Friedrich-Schiller-Universität Jena, the Fraunhofer Institute of Applied Optics, and the Institute of Photonic Technology.

The topics of the modules "Einführung in das wissenschaftliche Arbeiten" (3rd semester) and "Projektplanung zur Masterarbeit" in the 3rd semester should be directly connected to the topic of the Master Thesis project of the 4th semester and should be performed in the same research group. Hence, students should choose this topic carefully since they will spend a full year on it. The students should contact the professors or lecturers directly and ask for appropriate topics.

The list above contains a collection of research projects, which are offered at the Nano & Quantum Optics group of the Institute of Applied Physics. Students can always contact professors directly in their lectures and ask for other appropriate topics.