PhD on Controlling light emission by dielectric nanoantennas

Nanoantennas provide an efficient link between optical near- and far-fields. They have the ability to strongly enhance the interaction of light with nanoscale matter and, in particular, they provide a tool for controlling the emission of light and its properties from localized sources. Most nanoantennas to date are composed of metallic nanoparticles. Metal nanoparticles can support localized surface plasmons, namely collective oscillations of the free electrons of a small metal particle, which can be harnessed to achieve the antenna functionality. However, unlike at radio frequencies, at optical frequencies metals exhibit strong intrinsic absorption losses, which reduces their radiation efficiency, which can be a problem for basic research as well as real-world applications. A new route to overcome this problem is offered by nanoantennas composed of dielectric nanoparticles instead of metallic nanoparticles. Dielectric nanoparticles support strong Mie-type resonances and can have very low losses at optical frequencies. In the last few years several dielectric nanoantenna design proposals have been presented, showing their potential for spontaneous emission control with high radiation efficiency. However, low losses are not the only motivation to investigate dielectric nanoantennas: in addition, high index dielectric nanoparticles support not only the commonly used electric dipolar resonances, but also higher multipolar resonances, such as magnetic dipole and electric quadrupole resonances. These multipolar resonances have a vast potential to control the emission from exotic emitters supporting electromagnetic transitions of higher order, and they offer a natural platform, which can be well defined by modern nanotechnology, to study new, unexplored multipolar interactions at optical frequencies.

The objective of this doctoral project is the experimental realization of coupled photonic systems consisting of nanoscale emitters and dielectric nanoantennas.

In this doctoral project the following techniques will be applied and developed further:

- Photoluminescence spectroscopy and time-resolved photoluminescence
- Back focal plane imaging of emission
- Characterization of exotic emitters
- Numerical simulations for dielectric nanoantenna design and optimization
- Precise positioning of nanoscale light emitters

Required qualification: Master or Diploma in physics, photonics, electrical engineering, or comparable

PhD supervisor: Prof. Isabelle STAUDE (isabelle.staude@uni-jena.de)
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PhD on Machine learning-based design of metamaterials & Metamaterial-based machine learning systems

The research project will be centered in the rapidly evolving field of nano-optics and metamaterials. It will involve the use of Maxwell's Theory in order to describe the interaction between light and various arrangements of nano-particles. Due to the complexity of the underlying physics, numerical methods and simulations on high-performance computers will be employed. In combination with an intuitive analytical framework the PhD-candidate will learn to develop semi-analytic models to both understand the physical processes of metamaterials and engineer application driven solutions.

The focus of the project will be on the implementation of neural networks (NN) to improve and simplify our physical models of metamaterials and nano-optical interaction. Specifically, the task will be to develop models and suitable neural networks for so called stacked metasurfaces. These are a subclass of metamaterials that consists of multiple layers of nano-structured surfaces. They allow to achieve complex optical behavior while being intuitive to model and realize experimentally.

The project will be based on existing Python and MatLab code. This can be used as a starting point for future work as well as to learn the basics of nano-optical modelling in combination with neural networks.

If the candidate is interested in fundamental physics, has a talent for programming and appreciates the possibility for novel applications, this project will be ideally suited. He or she will do programming mostly in Python or Matlab and gets the opportunity to run vast simulations on a powerful computer cluster. Furthermore, the candidate will learn how to elegantly use physical approximations in order to develop semi-analytic models. The results of the work will directly impact the scientific community as the application of neural networks to stacked metasurfaces is just at the beginning.

Depending on the abilities and preferences of the PhD candidate the following subjects would be covered

- Machine learning algorithms and neural networks
- Numerical simulations of nanostructured surfaces
- Analytical modelling of complex physical systems

Required qualification: Master or Diploma in physics, photonics, electrical engineering, or comparable

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PhD on Quantum light 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 tailor 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.

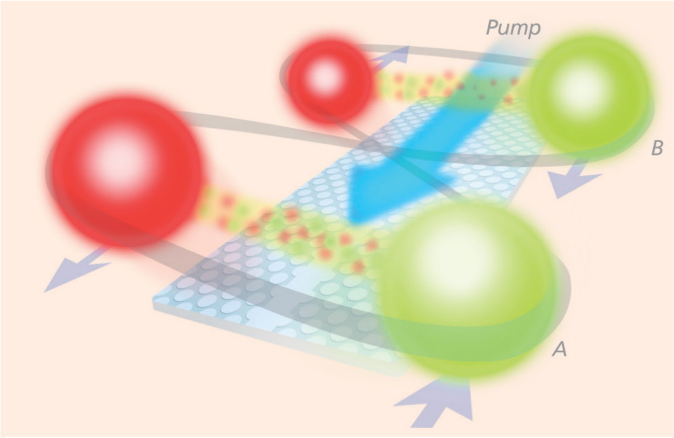
One mechanism to generate such photon pairs is spontaneous parametric down-conversion, a nonlinear optical process in which one photon splits spontaneously into a pair of two photon. Due to energy conservation, each of the generated photons has a longer wavelength, i.e. smaller energy, than the original 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.

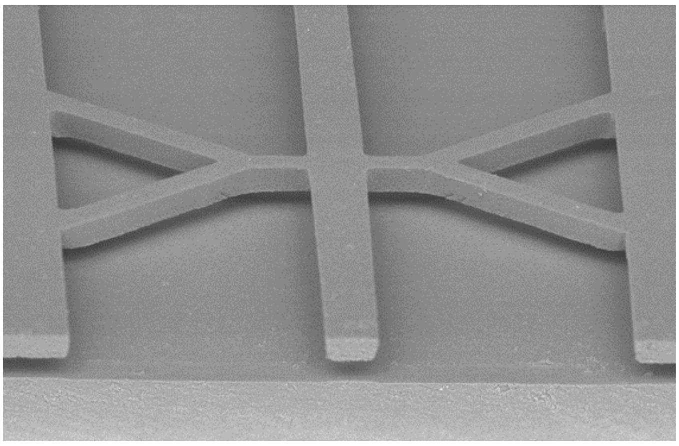
In our research, we investigate different platforms for photon-pair generation, ranging from bulk nonlinear crystals, e.g. lithium niobate, over waveguides, e.g. PPLN, all the way to nanostructured surfaces, e.g. AlGaAs, and two-dimensional materials, e.g. MoS_2. Furthermore, technologies to fabricate nanostructured photon-pair sources as well as experimental approaches for their characterization need to be developed and implemented. The targets of our research are set by the specific application fields of the photon sources. For quantum imaging applications, we are searching for massively parallelized sources, where the many modal degrees of freedom of high-resolution imaging systems can be filled. For quantum communication and quantum sensing however, we aim for high photon rates and fewer mode numbers. In all cases, the degrees of entanglement of the generated photon pairs must be controlled precisely to lessen the demand of post processing.

Depending on the abilities and preferences of the PhD candidate the following subjects would be covered

- Theoretical quantum optics and numerical simulations
- Nonlinear nanooptics including, waveguides and nanostructured surfaces
- Experimental characterization and nanostructuring technology

Required qualification: Master or Diploma in physics, photonics, electrical engineering, or comparable





References

M. Gilaberte Basset, F. Setzpfandt, F. Steinlechner, E. Beckert, T. Pertsch, and M. Gräfe, "Perspectives for applications of quantum imaging," Laser & Photonics Reviews, DOI: 10.1002/lpor.201900097 (2019).

S. Saravi, T. Pertsch, and F. Setzpfandt, "Photonic crystal waveguides as sources of counterpropagating factorizable biphoton states," Opt. Lett. 44, 69-72 (2019).

A. Solntsev, P. Kumar, T. Pertsch, A. Sukhorukov, and F. Setzpfandt, "LiNbO3 waveguides for integrated quantum spectroscopy," APL Photonics 3, DOI: 10.1063/1.5009766 (2018).

S. Saravi, T. Pertsch, and F. Setzpfandt, "Generation of counter-propagating path-entangled photon-pairs in a single periodic waveguide," Phys. Rev. Lett. 118, 183603 (2017).

F. Setzpfandt, A. S. Solntsev, J. Titchener, C. W. Wu, C. Xiong, R. Schiek, T. Pertsch, D. N. Neshev, and A. A. Sukhorukov, "Tunable generation of entangled photons in a nonlinear directional coupler," Laser & Photonics Reviews 10, 131-136 (2015).

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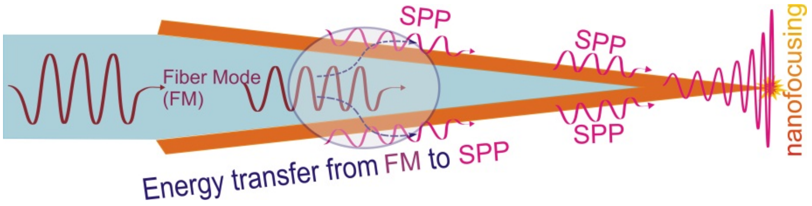
PhD in Control and characterization of the optical nearfield by next generation nearfield optical microscopy

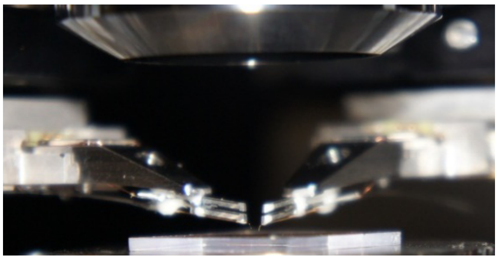
Scanning near-field optical microscopy (SNOM) is a powerful technique to measure and study simultaneously the architecture of nanostructures and electromagnetic near-fields emitted by them, where both are otherwise not resolvable with classical microscopy. Among different types of SNOMs, the scattering pseudo-heterodyne SNOM (ps-het SNOM) offers two main advantages: high resolution in topographical and optical images by employing sharp cantilever tips and simultaneous detection of field intensity and phase by exploiting the lock-in detection method and interferometry. Furthermore, the principle and performance of such SNOM measurements strongly depend on the tip design and the tip's apex size. With the aim to improve the performance of SNOM-based near-field detection and control we develop a new generation of high-performance plasmonic tips, which provide unprecedented performance parameters and at the same time are easy to apply to many applications in different environments. Thus, besides applying SNOM in our research on nanostructured light emitters, we are aiming to improve substantially the applicability and performance of near-field optical microscopy in these investigations.

In this PhD project, the ps-het SNOM technique will be used to map electromagnetic near-field distribution of not only complex nano-antennas and plasmonic structures but also single emitters like defect centers in 2D materials, vacancy centers, and quantum dots. Furthermore, new technologies can be developed to increase the performance of the SNOM tips. As a first step, their performance parameters are to be evaluated by exploring the tip's interaction with different quantum systems, as e.g. single fluorescent molecules, quantum dots, lanthanide nanoparticles, and emission centers in atomically thin membranes of MoS_2. To explore the spectral and temporal characteristics of the quantum systems, a superfocusing SNOM setup will be combined with a time correlated single photon counting system and a single photon sensitive optical spectrometer. After establishing stable measurement methods and skills, we want to apply this tool to the in depths investigation of the interaction of the nano-sized quantum systems with plasmonic and dielectric nano-antennas. Besides experimental characterization, analytical and computational modeling shall be carried out to understand the complex behavior of the quantum emitters and their interaction with the tips.

Required qualification: Master or Diploma in physics, photonics, electrical engineering, or comparable

Applicant should have experimental experience as well as the motivation to develop and run complex experiments. Basic knowledge and experience in programming, nanotechnology, and electromagnetic simulation software and process control software (e.g. LabView) are helpful.





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.

References

N. Abbasirad, J. Berzins, K. Kollin, S. Saravi, N. Janunts, F. Setzpfandt, and T. Pertsch, "A fully automated dual-tip scanning near-field optical microscope for localized optical excitation and detection in the visible and near-infrared," Review of Scientific Instruments 90, 053705 (2019).

B. N. Tugchin, N. Janunts, M. Steinert, K. Dietrich, E.-B. Kley, A. Tünnermann, and T. Pertsch, "Quasi-linearly polarized hybrid modes in tapered and metal-coated tips with circular apertures: understanding the functionality of aperture tips," New J. Phys. 19, 063024 (2017).

B. N. Tugchin, N. Janunts, M. Steinert, K. Dietrich, D. Sivun, S. Ramachandran, K. V. Nerkararyan, A. Tünnermann, and T. Pertsch, "Controlling the excitation of radially polarized conical plasmons in plasmonic tips in liquids," RSC Adv. 6, 53273-53281 (2016).

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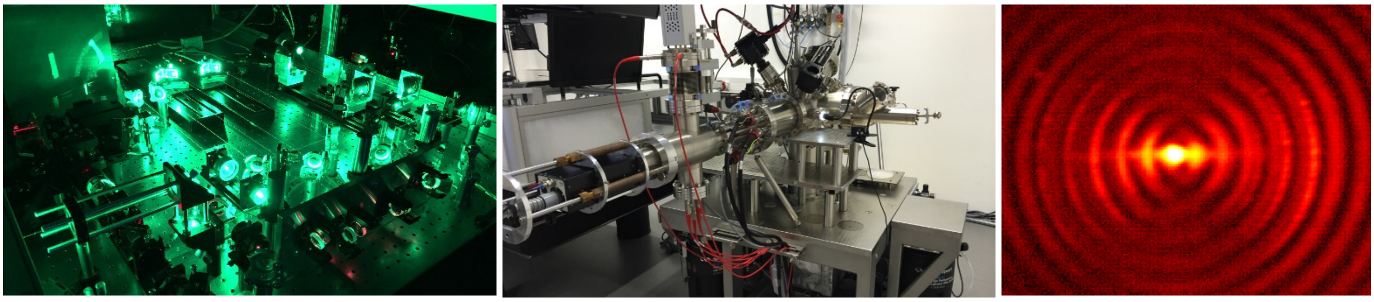
PhD in Spatiotemporal dynamics of nano-scale light-matter interactions in metasurfaces and atomic membranes

The control and characterization of light on length scales shorter than the diffraction limit (~0.5 λ) requires shaping or probing of the photonic states by nano-scale matter. Therefore, basically all nanooptical effects are coupled states of light and excited matter. Hence, the exploration of optics down to the nan-scale requires detailed knowledge about strong light-matter interaction at these ultrashort length scales. This interaction typically concerns the electronic states and happens on ultrashort time scales of a few femtoseconds. The experimental observation of such effects hence requires tools probing simultaneously the electronic matter states and the photonic states with nanometer spatial and femtosecond temporal resolution. While scanning nearfield optical microscopy (SNOM) is a versatile tool to explore photonic states beyond the diffraction limit, it does not provide insight into matter's excitation. Hence, in addition to SNOM we are developing novel techniques based on laser driven photoemission electron microscopy (PEEM), which probe directly the electronic excitation of matter with the spatial resolution of an electron microscope. Temporal resolution is obtained by triggering the photoemission by few-cycle laser pulses (~6 fs). These ultra-short laser pulses give access to events, which are inaccessible to electronic measurement systems. They allow resolving processes in physical, chemical or biological samples with femtosecond resolution in real time. They are thus an ideal probe to study the photo-induced electron dynamics in the building blocks of photonic nanosystems, as e.g. plasmonic antennas and nanowaveguides, nanostructured semiconductor surfaces, nanowires, carbon nanotubes, as well as atomic membranes like graphene or MoS_2. A typical PhD project will combine advanced instrumentation of fs lasers and ultra-high vacuum systems for electron microscopy with the physics of several novel quantum systems.

Possible covered subjects

- Experimental investigation of the ultrafast dynamics of laser-excited solid state nanosystems
- Nanotechnologies for the realization of hybrid nonlinear photonic nanosystems and metasurfaces
- 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 material models

Required qualification: Master or Diploma in physics, photonics, electrical engineering, or comparable



Left: Dual channel OPCPA system for the generation of ultrashort laser pulses in a pump-probe configuration. Center: PhotoEmission Electron Microscope - PEEM. Right: Electron-photon wavepackets on a ring-type nanoantenna.

References

F. J. F. Löchner, R. Mupparapu, M. Steinert, A. George, Z. Tang, A. Turchanin, T. Pertsch, I. Staude, and F. Setzpfandt, "Controlling second-harmonic diffraction by nano-patterning MoS_2 monolayers," Opt. Express 27, 35475-35484 (2019).

I. Staude, T. Pertsch, and Y. S. Kivshar, "All-dielectric resonant meta-optics lightens up," ACS Photonics 6, 802-814 (2019)

G. K. Tadesse et al., "Wavelength-scale ptychographic coherent diffractive imaging using a high-order harmonic source," Scientific Reports 9, 1735 (2019).

A. Rahimzadegan, D. Arslan, R. N. S. Suryadharma, S. Fasold, M. Falkner, T. Pertsch, I. Staude, and C. Rockstuhl, "Disorder-induced phase transitions in the transmission of dielectric metasurfaces," Phys. Rev. Lett. 122, 015702 (2019).

S. Liu et al. , "Light-emitting metasurfaces: simultaneous control of spontaneous emission and far-field radiation," Nano Lett. 18, 6906-6914 (2018).

F. Löchner, A. Fedotova, S. Liu, G. Keeler, G. Peake, S. Saravi, M. Shcherbakov, S. Burger, A. Fedyanin, I. Brener, T. Pertsch, F. Setzpfandt, and I. Staude, "Polarization-dependent second harmonic diffraction from resonant GaAs metasurfaces", ACS Photonics 5, 1786-1793 (2018).

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