PhD topics in nano & quantum optics

The research of the laboratory for nano & quantum optics at the Abbe Center of Photonics is part of the recently established Max Planck School of Photonics (www.maxplanckschools.de). The group's research targets the control of light at the single photon level and at the nanoscale using nanostructured materials and ultrafast nonlinear optical effects. The lab, which is a part of the Faculty of Physics and Astronomy of the Friedrich Schiller University Jena (Germany), covers a broad range of research fields in experiment and theory to study interaction of light with microstructured and nanostructured matter, employing advanced methods for nanofabrication, experimental characterization and numerical modelling.

The laboratory is led by Prof. Dr. Thomas Pertsch, Jun.-Prof. Dr. Isabelle Staude, Dr. Frank Setzpfandt, and Dr. Falk Eilenberger. We are constantly looking for talented young scientists who would like to contribute to cutting edge research projects on quantum photonics at the nano scale. Currently there are openings for PhD projects on the topics described on the following pages:

- Quantum light sources for entangled photon pairs,
- Control and characterization of the optical nearfield by next generation nearfield optical microscopy,
- Spatiotemporal dynamics of nano-scale light-matter interactions,
- Manipulation of “forbidden transitions” with dielectric nanoantennas,
- Ultrafast wavefront control with semiconductor metasurfaces,
- Quantum imaging and sensing,
- Ultrafast multidimensional, spatiotemporal pulse measurement techniques,
- Resonant interaction of light with 2D materials.

Details about the laboratory for nano & quantum optics can be found at www.iap.uni-jena.de/nano+quantum+optics. If you are interested in joining our lab, please contact:

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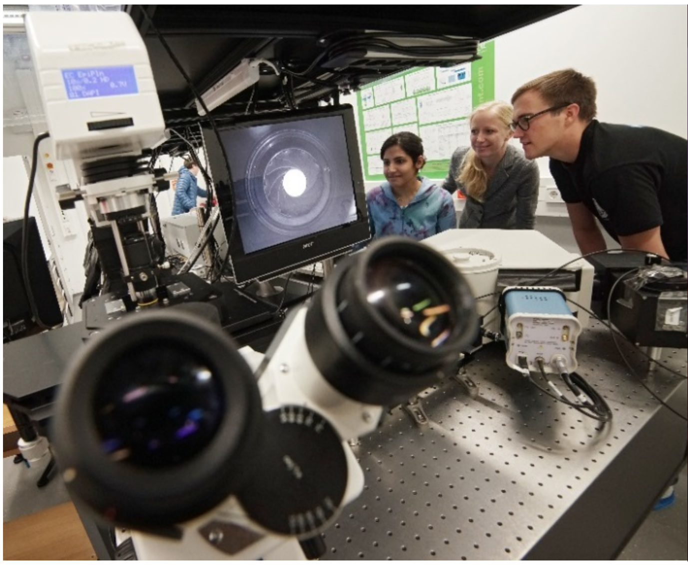

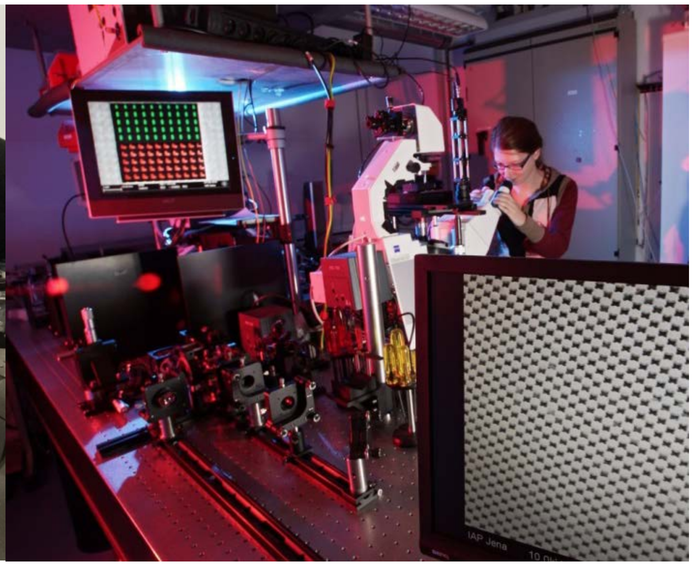

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Quantum light sources for entangled photon pairs

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.

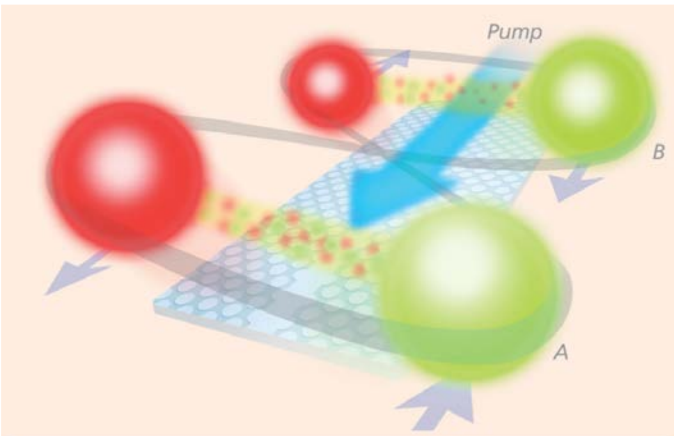
One mechanism to generate such photon pairs is spontaneous parametric down-conversion, a nonlinear optical process in which one photon splits spontaneously into a pair of two photon. Due to energy conservation, each of the generated photons has a longer wavelength, i.e. smaller energy, than the original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

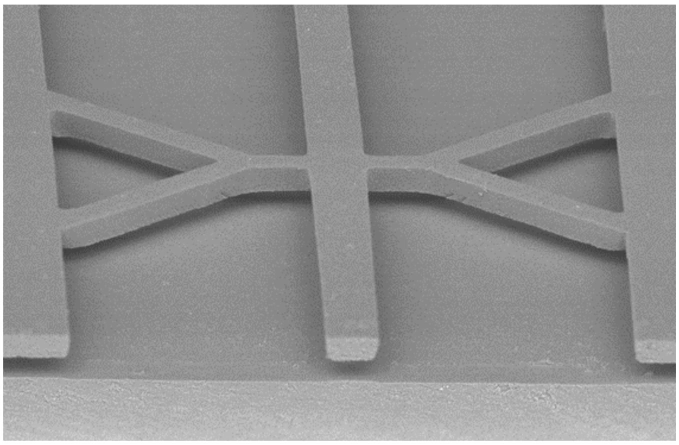
In our research, we investigate different platforms for photon-pair generation, ranging from bulk nonlinear crystals, e.g. lithium niobate, over waveguides, e.g. PPLN, all the way to nanostructured surfaces, e.g. AlGaAs, and two-dimensional materials, e.g. MoS_2. Furthermore, technologies to fabricate 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
- Waveguides and nanostructured surfaces
- Experimental characterization and nanostructuring technology

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





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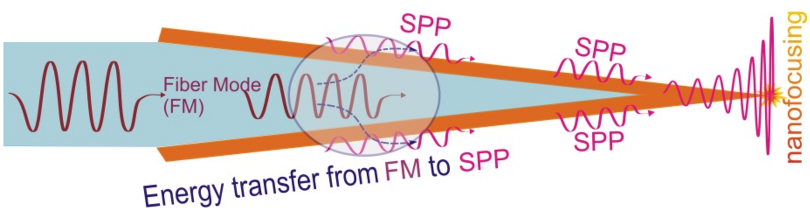
Control and characterization of the optical nearfield by next generation nearfield optical microscopy

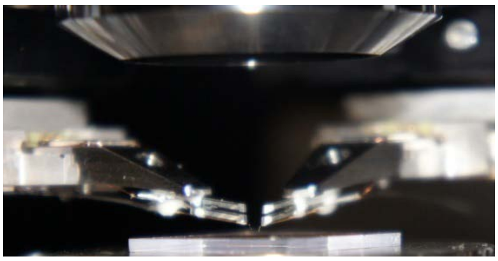
Scanning near-field optical microscopy (SNOM) is a powerful tool to studying optical characteristics of diffraction limited nanoparticles and molecules where the electromagnetic field is localized to the emitter's near-field region. The principle and performance of such SNOM measurements strongly depend 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, we are aiming to substantially improve the applicability and value of near-field optical microscopy. Generally, our tip concept relies on tapered and fully metal-coated fiber tips. These tips employ the radially polarized surface plasmon polariton mode and the plasmon superfocusing effect to improve the optical resolution, contrast, as well as signal to noise and background ratios. As the radially polarized plasmonic mode propagates toward the tip apex, the electromagnetic field is compressed longitudinally, due to the shrinking propagation constant, and transversally, due to the nature of the surface plasmons. Furthermore, the field amplitude increases enormously due to the in-phase field oscillation within the metal. These effects result in so-called plasmon superfocusing allowing us to achieve highly localized and strong electromagnetic fields at the tip's apex.

In the scope of the PhD project, initially, new technologies have to be developed to increase the sharpness of the plasmonic tips. As a next 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, the 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 further 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 also have good experimental experience and basic knowledge in programming skills. Experiences in 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.

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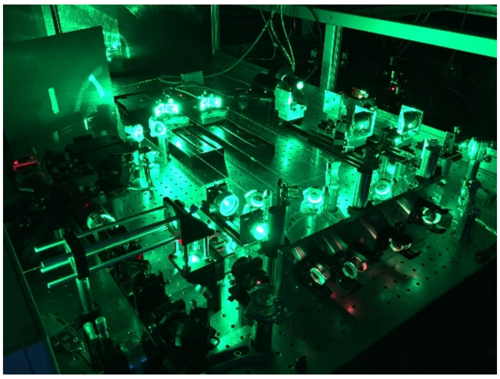
Spatiotemporal dynamics of nano-scale light-matter interactions

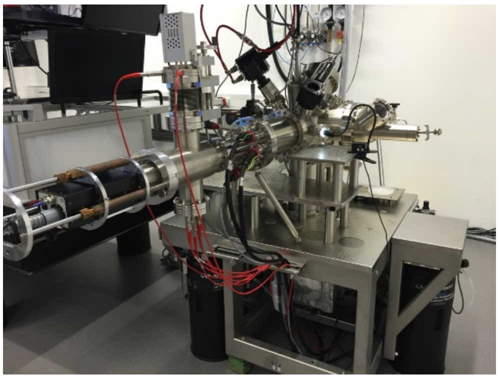
The control and characterization of light on length scales shorter than the diffraction limit (~0.5 λ) requires shaping or probing of the photonic states by nano-scale matter. Therefore, basically all nanooptical effects are coupled states of light and excited matter. Hence, the exploration of optics 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 ultrafast laser pulses as short as ~6 fs. These ultrashort 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 realtime. 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.

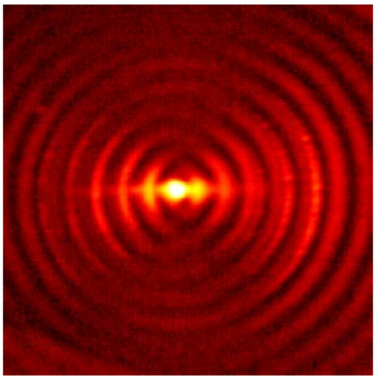
Covered subjects

- Fundamental excitation in metals and semiconductors at nanostructured surfaces
- 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
- Experimental investigation of the ultrafast dynamics of laser-excited solid state systems

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







Left: Dual channel OPCPA system for the generation of two independently tunable ultrashort laser pulses in a pump-probe configuration. Center: PhotoEmission Electron Microscope - PEEM. Right: PEEM-measured electron-photon wavepackets excited by a laser beam incident on a ring-type nanoantenna.

References

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Ultrafast wavefront control with semiconductor metasurfaces

Photonic metasurfaces are two-dimensional arrangements of designed nanoscopic building blocks, which can convert an incident light field into an outgoing light field with tailored spectrum, polarization, and wavefront. While most metasurfaces realized so far are made of metallic nanoresonators, all-dielectric or semiconductor metasurfaces offer the advantage of low absorption losses. A flurry of optical functionalities has been demonstrated using all-dielectric metasurfaces in the last few years, including reflectors, magnetic mirrors, beam deflection, beam shaping, focusing and holographic imaging (see Fig. 1 (a)), clearly demonstrating their potential for flat wavefront shaping devices. While so far, dielectric/semiconductor metasurfaces have been mainly studied in the regime of continuous light waves, the goal of this PhD project is to study the ultrafast interaction of high-refractive-index semiconductor metasurfaces with femto-second laser pulses. The influence of the shape, size, arrangement, and material properties of the constituent semiconductor building blocks on the ultrafast optical response of the metasurface shall be experimentally investigated, opening the door to all-optical wavefront modulation on a picosecond time scale. This could eventually lead to the realization of spatial light modulators with switching times reduced by several orders of magnitude as compared to current liquid-crystal based solutions, as well as to completely new approaches for pulse shaping and spatiotemporal light-field synthesis.

Covered subjects

- design and numerical simulation of ultrafast photonic metasurfaces
- involvement in the development of dedicated nanofabrication procedures for ultrafast metasurfaces
- building of an optical pump-probe measurement setup for ultrafast back-focal plane imaging
- optical characterization of the fabricated metasurfaces

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

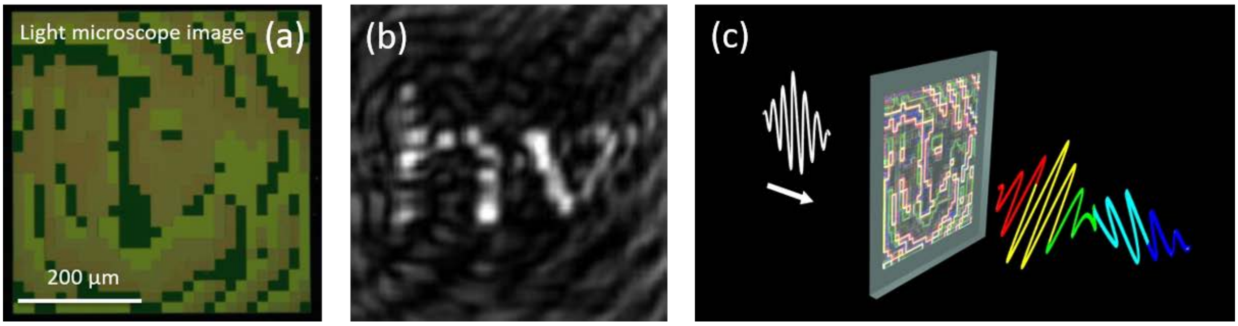

Fig. 1: (a) Light microscope image of a wavefront shaping semiconductor metasurface designed to interact with continuous light waves. (b) Image of the letters $h\nu$ produced behind the metasurface for illumination with an infrared laser. (c) An artist's impression of a photonic metasurface interacting with a femtosecond laser pulse

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Manipulation of “forbidden transitions” with dielectric nanoantennas

Antennas are all around in our modern wireless society: they are the front-ends in satellites, cell-phones, laptops and other devices establishing communication by sending and receiving electromagnetic waves. While all these devices typically operate at frequencies from 300 GHz to as low as 3 kHz, according to Maxwell’s equations the same principles of directing and receiving electromagnetic waves should work at various scales independently of the wavelength. Thus, one may naturally ask if an antenna can also send a beam of light. The answer is that this can indeed be accomplished using nanoscale antennas.

However, nanoantennas have even more to offer than this: They can concentrate light in ultra-small nanoscopic volumes, thereby strongly enhancing its interaction with nanoscale matter. Plus, they can efficiently link these spatially localized near fields with propagating optical fields and, by reciprocity, the other way round. Based on these principles nanoantennas are expected to play an important role in key applications like efficient quantum-light sources, photovoltaics, nonlinear optics, single-molecule detection, and as transmitting and receiving devices for on-chip optical networks. Yet, given the small dimensions of nanoantennas, their precision fabrication still remains a challenge and relies on state-of-the-art nanotechnology.

Even more severely, unlike at radio frequencies, metals exhibit strong absorption losses at optical frequencies, intrinsically limiting the nanoantenna performance. A route to overcome this problem is offered by dielectric nanoantennas, which can have very low losses at optical frequencies. However, low losses are by far not the only motivation to investigate dielectric nanoantennas. Recent studies indicate that their strong multipolar Mie-type resonances make them particularly interesting for enhancing dipole-forbidden electromagnetic transitions such as magnetic dipole transitions supported e.g. by trivalent lanthanide ions. Usually, these transitions are orders of magnitude weaker than electric dipole transitions.

The objective of this doctoral project is the design and experimental realization of coupled photonic systems consisting of emitters supporting higher-order transitions and dielectric nanoantennas, and the development of the optical setups for their characterization.

Covered subjects

- Photoluminescence spectroscopy and time-resolved photoluminescence
- Back focal plane imaging and momentum spectroscopy of emission
- Numerical simulations for dielectric nanoantenna design and optimization
- Nanofabrication of nanoantennas and hybridization of fabricated structures with magnetic emitters

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

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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.

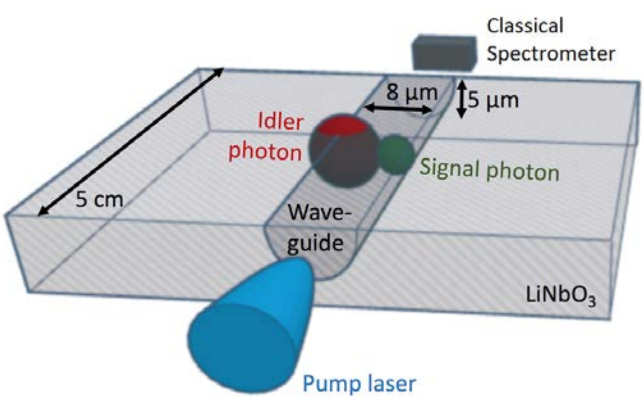
One example for studied imaging methods is quantum ghost imaging. Here, only one of the two photons of a photon pair is interacting with the sample and is afterwards detected with a single detector without spatial resolution. The second photon, which did not see the object, is spatially characterized 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.

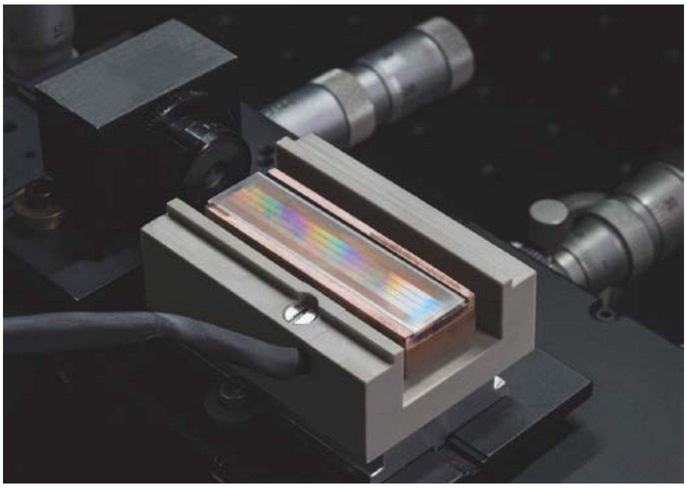
Another research topic is SPDC spectroscopy in waveguide platforms. Using the quantum interference of several sources of photon pairs, which characteristics depends on the properties of the sources and media between them, information about the optical properties of these media can be obtained by measuring 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.

The PhD project can cover one or more of the following subjects:

- Theoretical description of quantum imaging and spectroscopy
- Implementation of high-resolution and multimodal quantum imaging schemes
- Development of waveguide-based realizations of SPDC spectroscopy
- Application of quantum imaging in life science

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





References

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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.

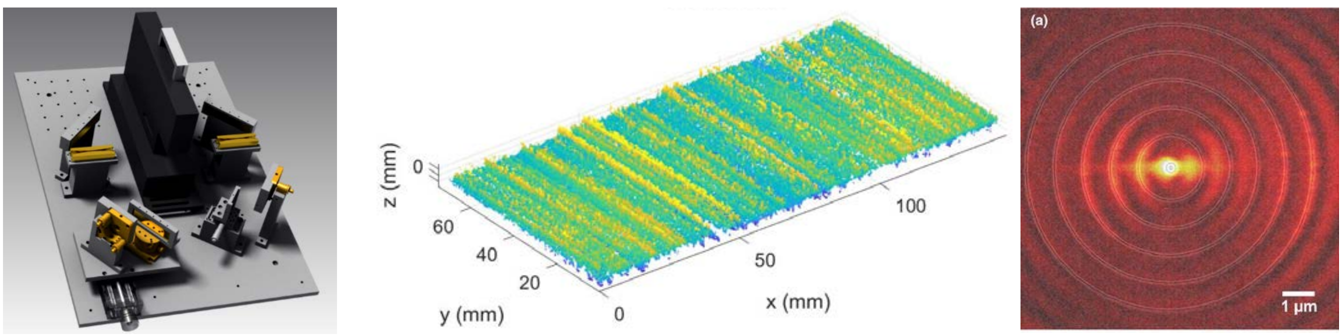
Our group is using ultrashort laser pulses to understand the complex physical systems in a multidimensional manner. We combine ultrashort pulses with electron microscopy to understand the motion of electrons in nanoplasmonic systems on a scale of femtoseconds and nanometers. We also combine ultrashort 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

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



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.

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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.

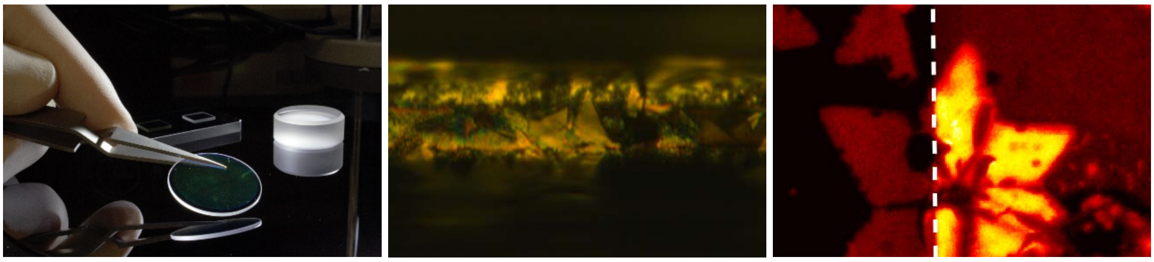
We specialize on integrating two-dimensional semiconductors with optically resonant structures such as monolithic and optical fiber based cavities as well as nanoresonatores to further enhance and tailor their interaction with light. This gives access to experiments in fundamental physics of light-matter-interaction 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

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



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

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