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

The Nano Optics group of the Institute of Applied Physics is looking permanently for talented new students who would like to contribute to cutting edge research projects on photonics at the nano scale. The group covers a broad range of research fields in experiment and theory:

- interaction of light with microstructured and nanostructured matter
- optical metamaterials, photonic crystals, plasmonics, near field optics
- nonlinear light-matter interaction in microstructures and nanostructures, nonlinear spatio-temporal dynamics, quantum phenomena, high-Q nonlinear optical microresonators, opto-optical processes in integrated optics, all-optical signal processing
- scanning optical nearfield microscopy, photoemission electron microscopy
- 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 could be joined by students 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.

If you are interested in our research and could imagine joining our group, please contact Prof. Thomas Pertsch (thomas.pertsch@uni-jena.de).
Institute of Applied Physics – Nano Optics

Research project / Master Thesis on

Accelerating single photons

The phase velocity of light is determined by the refractive index of the medium the light is propagating in. However, the group velocity of light pulses can be influenced. This is true also for light pulses consisting of only a single photon, which has been shown recently using the geometric features of a Bessel-beam [1]. However, this experiment is limited to decelerating photons. Accelerating classical optical pulses was demonstrated by directly controlling the temporal profile of a pulse to shape it into an Airy-wavepacket [2].

The aim of this thesis is to use earlier demonstrated techniques to accelerate classical optical pulses for quantized light pulses consisting of single photons. To this end, a suitable source for single photons using spontaneous parametric down-conversion and a setup allowing to measure the arrival times of photons based on the Hong-Ou-Mandel effect have to be implemented. Furthermore, these components have to be integrated with an existing device for temporal pulse shaping, which can generate Airy-pulses.

Covered subjects
- Experimental and theoretical quantum optics
- Experimental and theoretical ultrafast optics
- Pulse shaping and characterization techniques
- Numerical beam propagation calculations
- Programming in MatLab and LabView

References

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

Nonlinear beam interaction in waveguide arrays

Due to the discrete nature of light propagation in optical waveguide arrays, they offer a large variety of interesting nonlinear propagation effects which are not yet fully explored. A particularly rich field is the nonlinear combination of independently excited beams in waveguide arrays. In contrast to linear fields such beams do interact with each other, allowing for phenomena such as fusion, repulsion or complete destruction of propagating beams. These could be used for all-optical signal manipulation or to study fundamental aspects of nonlinear physics.

The aim of this thesis is to investigate nonlinear beam interaction of two beams in an array of waveguides made from lithium niobate, a medium with second-order nonlinearity. To generate the input beams a polarization interferometer in Sagnac-configuration has to be aligned and characterized. The output of the waveguide array is characterized using several cameras and power detectors. Nonlinear propagation effects are studied in dependence on the relative phase and position as well as the input power of the propagating beams. Aided by numerical simulations, relevant parameter ranges for the excitation of different nonlinear phenomena should be identified and the specific signatures of these effects should be experimentally verified.

Covered subjects
- Polarization optics
- Characterization of optical beams
- Waveguide and integrated optics
- Nonlinear optics in waveguides
- Numerical beam propagation calculations
- Programming in MatLab and LabView

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Erbium doped lithium niobate photonic crystals

Photonic crystals are periodic dielectric nanostructures, in which photons behave very similar to electrons experiencing periodic perturbations from the atomic lattice in solid-state crystal. The analogy between optical and electronic waves suggests that the light dispersion in a photonic crystal consists of a photonic band structure, exactly like in solid-state crystals where the dispersion relation of electrons is described by an electronic band structure. The photonic band structure of photonic crystals is responsible for the appearance of photonic band gaps, i.e. spectral regions within which the propagation of the light is not allowed. As a consequence of these photonic band gaps, many novel properties in photonic crystals have attracted immense interest in the broader optics community, particularly if tailored defects or resonant cavities are introduced into photonic crystals to control the energy flow, enhancement, localization and dispersion of light.

We have a strong interest in photonic crystal based components in linear and nonlinear optical regimes. In particular we investigate photonic crystal structures in lithium niobate (LiNbO₃), a nonlinear material widely used in telecommunication systems. By making use of a key expertise in our Institute, i.e. the combination of high-resolution electron-beam lithography with ion beam enhanced etching, lithographically defined photonic crystals are manufactured in freestanding LiNbO₃ membranes allowing for monolithic integrated photonic devices.

A particular goal of our present studies is the integration of optical gain into a photonic crystal structure. Erbium doped lithium niobate (Er:LiNbO₃) is a ferroelectric, piezoelectric, electro-optic, acousto-optic material with high nonlinear optical coefficients, characterized by several emission and absorption bands. These unique properties make Er:LiNbO₃ a suitable host for gain devices. The goal of this project is the general investigation of the optical properties of photonic crystal membranes. In particular we are interested in the enhancement of light emission in Er:LiNbO₃ photonic crystal cavities by the Purcell effect, in slow light effects, in tunable nanolasers, and in entangled photon sources for integrated quantum optic schemes.

Covered subjects
- fundamental properties of nonlinear photonic crystals from Erbium doped lithium niobate
- spectroscopic investigation of photonic crystal waveguides and resonators by confocal microscopy and scanning Near-Field Optical Microscopy (SNOM)
- theoretical modeling and numerical simulations of photonic crystal nanostructures to investigate fundamentally new effects of nonlinear cavity dynamics and to find optimal designs

Scanning electron microscope picture of a lithium niobate photonic crystal cavity and characterization setup.

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The topic deals with cutting edge challenges on the characterization, understanding and control of ultrashort bursts of light with a maximum number of degrees of freedom. In particular we try to understand the dynamic interaction of the fundamental optical effects of dispersion, diffraction and nonlinearity on the scale of single ultrafast oscillations of the electric field.

Using theoretical modeling, sophisticated numerical analysis, and state-of-the-art high-power ultrafast laser sources we investigate various effects that have no analogies in the classic, low-dimensional environments of nonlinear optics. Instead we investigate optical effects in high dimensional systems such as microstructured fiber arrays or gaseous media. This way we are advancing the leading role that nonlinear optics has for all areas of nonlinear sciences such as ocean wave-, biological-, and solid state physics.

This research area poses a number of challenging tasks. Among them are the design, setup, and characterization of new experiments and applications; the generation and on-line control of few-cycle optical pulses; the modeling of nonlinear light propagation in complexly structured media; and the improvement of existing characterization methods for spatio-temporal field distributions.

**Covered subjects**
- development of spatiotemporal characterization techniques with femtosecond and nanometer resolution
- ultrabroadband, nonlinear nanophotonics
- evolution dynamics of discrete-continuous light bullets
- nonlinear effects in coupled waveguide arrays and photonic crystal fibers
- few-cycle pulses and carrier envelope phase effects in photonic nanomaterials
- implementation, and characterization of ultrafast pulse shaping techniques
- modeling and parallel, numerical simulation of spatiotemporal photonic effects

**Experimental tasks**
- development of spatio-temporal beam shaping techniques using spatial light modulators
- improvement of spatio-temporal pulse characterization techniques
- characterization of pulse light sources based on optical cavity pulse release
- investigation of ultrafast guided pulse dynamics in gaseous materials
- ultrafast, nonlinear holographic techniques

**Theoretical tasks**
- finding and solving approximate analytical models for the understanding of nonlinear space-time dynamics of optical pulses in complexly structured media
- development of parallel numerical simulation codes for the simulation of nonlinear dynamic systems on large scale compute clusters
- gravity-analogues in nonlinear optics

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Research project / Master Thesis on
Nonlinear quantum nano optics

Correlated photon pairs are the basis for many applications in quantum optics, i.e. for quantum cryptography and quantum logic devices. Conventionally, they can be generated in a nonlinear crystal and then transferred to a functional device, which usually consists of a number of beam splitters or an integrated optical system. Using integrated optical structures made from nonlinear materials can drastically improve the system by integrating photon pair generation and manipulation on one optical chip. It further leads to completely new degrees of freedom due to the interplay of linear light propagation and photon-pair generation.

The goal of this research project will be the theoretical description, numerical modeling and experimental characterization of the generation and propagation of two-photon quantum states in complex nonlinear photonic systems. The possible model systems include two-waveguide couplers, periodic waveguide arrays or nano-scaled optical devices like photonic crystals or plasmonic structures on a nonlinear substrate material. The results of the project will pave the way towards very flexible integrated quantum optics.

According to the preferences and abilities of the student the topic will include several of the listed subjects and activities:

**Covered subjects**
- linear and nonlinear optical properties of complex optical structures
- generation and propagation of non-classical quantum states
- experimental work with integrated optics devices and bulk optics, different laser types (semiconductor, pulsed), and peripheral devices (receivers, power meters, optical spectrum analyzers, etc.)

**Experimental tasks**
- characterization of spatial linear and nonlinear light propagation in integrated optics devices
- characterization of quantum states by means of two-photon correlation measurements
- design and realization of specific excitation techniques required to generate non-classical quantum states

**Theoretical tasks**
- calculation of linear eigenstates of complex photonic structures
- simulation of classical linear and nonlinear light propagation
- modeling of photon-pair generation, propagation and correlation probabilities


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Photonic nanomaterials represent a novel class of artificial matter consisting of periodically or randomly arranged unit cells, which have usually a size in the order of or smaller than the wavelength of light and promise to obtain complete control over all properties characterizing the light propagation. By designing these unit cells one can tailor the 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 long-term experience in the fabrication and characterization of photonic nanomaterials. The project ranges from the usage and optimization of available experimental setups for characterization, to the design and numerical optimization of novel photonic nanomaterials and exotic investigations like the characterization of optical properties at low or high temperatures.

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 (optical microscope, AFM, SEM, SNOM,...)
- resonant excitation of plasmonic eigenmodes in artificial structures with wavelength and 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

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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 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 the scanning near-field optical microscopy (SNOM) targeted to obtain ultimate topographic and optical resolution for nano-imaging. To break the diffraction limit, a tip enhanced SNOM (TE-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 TE-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 metallic nanostructures
- theoretical modeling and numerical simulation of the spatio-temporal dynamics of light on the nanoscale 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 dots for enhanced light-matter interaction

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Integrated nulling interferometry for astrophotonics

Astronomical interferometry is a powerful technique delivering high-angular-resolution information about astrophysical objects. The technique is based on the coherent combination (in a beam combiner) of light collected by distant telescopes. With multiple telescopes, images with the resolution of an equivalent telescope with diameter equal to the maximum distance between telescopes can be retrieved.

Integrated optics is currently used in infrared astronomical interferometry to improve the stability and performance of beam combiners (photonic beam combiners) [1]. Photonic beam combiners will be used also in future space interferometers (such as Darwin, see figure) because they do not require alignment and are small in size/weight.

In the proposed project, you will upgrade an existing optical test-bench and characterize an integrated beam combiner designed for nulling interferometry [2]. The so called nulling mode of an astronomical interferometer is used to suppress the light of a bright star and detect the photons emitted by a much weaker nearby object, such as an exo-planet [3].

The goal is to demonstrate for the first time the Angel-Woolf 4-telescope nulling scheme [4] with an integrated optical component. The work will require some programming with languages such as Matlab and LabView.

Covered subjects
- Astrophotonics
- Micro-optics
- Computer Data Acquisition and Processing

References
Astronomical interferometry is a powerful technique delivering high-angular-resolution information about astrophysical objects. The technique is based on the coherent combination (in a beam combiner) of light collected by multiple telescopes. Integrated optics is currently used in infrared astronomical interferometry to improve the stability and performance of beam combiners (photonic beam combiners). We recently investigated the potential of 3D photonic components to deliver scalable interferometric combination of multiple beams on a single chip [1,2]. It was found that a simple two dimensional array of coupled waveguides can be used to uniquely determine the mutual coherence properties for up to eight, suitably injected fields. The scheme (named Discrete Beam Combiner, or DBC) is based on the properties of light propagating in two-dimensional arrays of waveguides (photonic lattices). The work consists in two main phases. In the first phase, an existing sample of 4T-DBC (array of 5x5 laser-written waveguides, suitable for the combination of 4 telescopes) will be characterized and tested by means of a monochromatic light source. To this end, a setup consisting in a 4-channels Mach-Zehnder interferometer will be used to simulate the layout of a stellar interferometer. The setup will be controlled by a Lab-View program (to be developed) steering three phase modulators in the Mach-Zehnder interferometer and recording simultaneously the output signal from the DBC by means of a microscope equipped with a CCD detector. In the second phase, the experience gained in the characterization with monochromatic light of the DBC component will be used to design and manufacture a new sample of 4T-DBC suitable for the combination of polychromatic light. The new component will feature a DBC stage followed by a waveguide reformatter mapping the 2D array of waveguides in a 1D pseudo-slit which could feed a spectrograph. Manufacturing of the samples will be accomplished in house by direct laser-writing in glass (the samples will be manufactured by trained personnel, estimated time for manufacturing: 3 days). The characterization of the new samples will require the setup of a compact imaging spectrograph, whose development is part of the project. The final goal will be to characterize the component for a broad wavelength band (>10% of the carrier) and evaluate the precision of the measurement of the mutual coherence functions.

Covered subjects

- Experimental microoptics
- Astrophotonics
- Interferometry
- Programming in MATLAB, LabView, Rsoft.

References


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Research project / Master Thesis on

Photonic lanterns for stellar interferometry

Astronomical interferometry is a powerful technique delivering high-angular-resolution information about astrophysical objects. The technique is based on the coherent combination (in a beam combiner) of light collected by multiple telescopes. Integrated optics is currently used in infrared astronomical interferometry to improve the stability and performance of beam combiners (photonic beam combiners).

Because of atmospheric turbulence, the coupling of starlight into the single mode waveguides of the photonic beam combiners is not very efficient. To overcome this problem, it was recently proposed to use a photonic lantern (multimode to single mode waveguide converter [1]) to improve the coupling efficiency of the starlight into the photonic components [2]. Tough, an unanswered question is how the mode transformation in the photonic lantern will affect the measurement of phase in the interferometer.

The work consists in assessing numerically the interferometric response of a photonic lantern. Initially, a model of the photonic lantern will be established and implemented in a beam-propagation code (e.g. RSoft). The polychromatic response of the lantern will be studied, establishing how the input piston phase is mapped into the piston of the individual output waveguides of the lantern. In a second phase, an existing simulation tool of the atmospheric turbulence will be added to the model of the photonic lantern and the coupling efficiency of the lantern estimated as a function of the diameter of the telescope and the turbulence parameters. Temporal dynamics of the coupling will also be simulated. In a third phase, a 3-telescope photonic beam-combiner and the associated detector will be modeled numerically and added to the developed simulation tool in order to establish the efficiency of the lantern based approach in measuring the coherence function of an object. Suggestions for the amelioration of the design of photonic lantern interferometer are expected as output of the study. The activity will be developed in the frame of an international collaboration related to the design of a new interferometric facility for the observation of planet forming regions [3].

Covered subjects
- Numerical microoptics
- Astrophotonics
- Interferometry
- Programming in MATLAB, Rsoft.

References

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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. The students should contact the professors or lecturers directly and ask for appropriate topics. A collection of research projects which are offered at individual institutes can be taken from this list. However, the students should also ask other professors directly if they are interested in the professor's research activities.

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. A collection of research projects which are offered at individual institutes can be taken from this list. However, the students should also ask other professors directly if they are interested in the professor's research activities.