Structures in Confined Light - from Topology to Microscopy

720. WE-Heraeus-Seminar

16 Aug - 17 Aug 2021
ONLINE

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

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Aims and scope of the 720. WE-Heraeus-Seminar:

The ability to shape light has revolutionised imaging, optical trapping and both quantum and classical communication. The simultaneous control over both spatiotemporal intensity and polarization structures requires new approaches to optical devices such as metamaterials and -surfaces while at the same time the handedness of structured light lends itself to imaging, probing and manipulating the geometry and potentially chirality of matter. In addition, the generation, propagation and interaction of structured light with matter is governed by topological invariants and conservation laws, which add a complex mathematical component to this exciting and interdisciplinary field. This is why we would like to bring together both young scientists and established, world leading experts from different areas such as mathematical optics, chemistry, microscopy, material science and biomedical physics.

Scientific Organizers:

Dr. Jörg Götte	University of Glasgow, UK E-mail: joerg.goette@glasgow.ac.uk
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Program

Program

Monday, 16 August 2021

08:50 – 09:00	Scientific organizers	**Welcome and Opening**
09:00 – 09:30	Steve Barnett	**Paraxial Skyrmionic Beams**
09:30 – 10:00	Alison Yao	**Control of spatially rotating solutions in a selffocusing Kerr cavity**
10:00 – 10:30	*COFFEE BREAK*	
10:30 – 11:00	Kobus Kuipers	**Topological structure of and for light**
11:00 – 11:30	Jörg Enderlein	**Metal-Induced Energy Transfer**
11:30 – 11:45	Alfred Meixner	**Cylindrical Vector Beams in Optical Microscopy and Laser Spectroscopy**
11:45 – 12:00	Carsten Henkel	**Light-Matter Interactions on the 10nm Scale – from Quantum Fields to Mechanical Forces**
12:00	*LUNCH BREAK*	
14:00 – 14:30	Harald Giessen	**Topological plasmonics: Watching the vector dynamics of plasmonic skyrmions on a nm length and fs time scale**
14:30 – 15:00	Henkjan Gersen	**Polarisation State Imaging in High Numerical Aperture Systems**
15:00 – 15:15	Wolfgang Löffler	**Strongly focused vortices and pinhole scanning microscopy**
15:15 – 15:30	Eileen Otte	**A single-shot responsive nano-analysis for the identification of highly confined customized light fields**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 18:00	**Poster Flash & Poster Session**	

Program

Tuesday, 17 August 2021

09:00 – 09:30	Halina Rubinsztein-Dunlop	**Sculpted light in quantum atom optics and optical trapping**
09:30 – 10:00	Simon Horsley	**Zero refractive index materials and topological photonics**
10:00 – 10:30	*COFFEE BREAK*	
10:30 – 11:00	Gerd Leuchs	**Quantum interference and directional emission**
11:00 – 11:30	Sonja Franke-Arnold	**Converting transient to spatial effects with vector vortex light**
11:30 – 11:45	Lykourgos Bougas	**Absolute chiral sensing using (nano)photonics**
12:00	*LUNCH BREAK*	
14:00 – 14:30	Cornelia Denz	**Shaping the topology of fully structured focal light fields**
14:30 – 15:00	Philipp Kukura	**Revealing the physicochemical basis of biomolecular interactions with mass photometry**
15:00 – 15:30	*COFFEE BREAK*	
15:30 – 16:00	Mark Dennis	**Skyrmionic Hopfions: 3D particle-like topologies in light beams**
16:00 – 16:30	Olivier Martin	**Structuring light with plasmonic metasurfaces**
16:30 – 16:45	Scientific organizers	**Closing remarks**

End of seminar

Posters

POSTERS: Monday, 16 August, 16:30 h CET

Eric Asché	**Customized optical spin flow topologies by translation of tailored phase flows**
Benjamin Butler	**Spin Densities in Optical Helicity Lattices**
Claire Cisowski	**On-chip generation of vector beam**
Timothy Davis	**Vector Dynamics of Surface Plasmon Polaritons and Topological Models**
Francesco Di Colandrea	**Bulk detection of time-dependent topological transitions in quenched chiral models**
Ramon Droop	**Shaping 3d topological light landscapes in the paraxial regime**
Daniel Ehrmanntraut	**Full characterization of three-dimensional electric field structures**
Jörg Eismann	**Sub-diffraction-limit multi particle reconstruction by far-field multipole analysis**
Ulrich C. Fischer	**Quantumelectrohydrodynamics of a Tunnel Gap**
Bettina Frank	**Atomically flat gold flakes for surface plasmonics**
Grant Henderson	**Mutual self structuring and novel Kerr-like fragmentation in coupled light/matter-wave interactions**

POSTERS: Monday, 16 August, 16:30 h CET

El mostafa Jalal	**Phase Diagrams of the Mixed Spin-1 and Spin-2 Blume-Emery-Griffiths Model with Attractive Biquadratic Coupling**
Brian Kantor	**Interaction of Vector Beams in Structured Epsilon-Near-Zero Materials**
Daniel Kotik	**Simulation of highly divergent Optical Beams**
Peter Lemmens	**Twisted and chiral photon states scattered on chiral molecular liquids**
Lewis Madden	**Tightly Focused Optical Modes as Quantum Pendulum Eigenstates**
Amy McWilliam	**Angular momentum redirection phase of vector beams in nonplanar geometry**
Uwe Mick	**Selective Fabrication of Nanoparticle Assemblies and Nanoparticle-enabled Devices**
Sebastião Pádua	**Single shot characterization of vector vortex beams by generalized measurements**
Eva Prinz	**Augmented control of plasmonic orbital angular momentum**
Daniel Reiche	**Quantum Rolling Friction: The Interplay between Confined Light and Moving Atoms**

POSTERS: Monday, 16 August, 16:30 h CET

Andreas W. Schell	**Freeing Light from Confinement: Extraction of Photons**
Marko Šimić	**Optofluidic Force Induction Scheme for the Characterization of Nanoparticle Ensembles**
Philipp Stammer	**High photon number entangled states and coherent state superposition from extreme-UV to far-IR**
Anda Xiong	**Universal Scaling Relation of Vortices in Wave Chaos Loop Soup**
Zhujun Ye	**Faraday Effect for Vector Vortex Beam**

Abstracts of Lectures

(in alphabetical order)

Paraxial Skyrmionic Beams

Stephen M. Barnett, Francesco Castellucci, Claire M. Cisowski, Sonja Franke-Arnold, Sijia Gao, Jörg B. Götte, Amy McWilliam, Fiona Speirits and Zhujun, Ye
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Skyrmions are topological features associated with the local direction of a spin or similar quantity. Originally they were devised for the study of mesons [1], but the idea has found wide application in quantum liquids [2], magnetic materials [3] and in the study of fractional statistics [3]. In optics they have been applied to two-dimensional photonic materials [4] and have been observed in the interference of plasmon polaritons [5].

Here we show that Skyrmions can be found in the some of the simplest of optical systems, namely freely propagating paraxial beams. They can arise when we have a superposition of orthogonally polarised fields with different spatial structures, particularly if these beams carry orbital angular momentum [6]. In such situations we find that our structured light beam can possess a topological property characterised by a Skyrmion number. This number is usually, but not always, an integer. We present some of the principles underlying such Skyrmionic beams, exploiting elements of the theory of superfluids [7].

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Absolute chiral sensing using (nano)photonics

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Chirality is a fundamental property of life with far-reaching implications among many research disciplines. Most notably, a molecule's chirality dictates its function, particularly its metabolic uptake and pharmacological effects, such as its potency and toxicity. Sensing chirality is, therefore, of fundamental importance for research in analytical chemistry, biology, and pharmacology, and is routinely applied in the agricultural, pharmaceutical and chemical industries for enantiopurity/quality control.

Traditional polarimetric techniques, such as that of optical rotatory dispersion (ORD) and circular dichroism (CD), are among the most widely used research tools for chiral sensing. However, ORD and CD measurements are particularly challenging for measurement at the nanoscale as the chiroptical signals are small and often suppressed by large backgrounds, preventing, thus, their application for the detection of trace quantities. Nanophotonic approaches have proven fruitful in accessing these weak chiroptical signals. However, in most cases, absolute chiral sensing of the total chiral refractive index has not been possible, while the strong inherent signals from the nanostructures themselves obscure the chiroptical signals.

Here we present two novel nanophotonic schemes for chiral sensing: *a)* a chiral surface plasmon resonance (CHISPR) scheme, that is directly implementable on existing surface plasmon resonance instrumentations without the need for any additional fabrication; and *b)* a dielectric metamaterial platform that enables enhanced chiroptical responses for versatile excitation modalities, and the introduction of a crucial signal reversal that suppresses undesired achiral signals originating from the metamaterial system without requiring sample removal for a null-sample measurement. Both schemes allow for the absolute detection of chirality (handedness and magnitude) of ultrathin, sub-wavelength, chiral samples over a uniform and accessible area, and are sensitive to both the real and the imaginary part of the chiral sample's refractive index, overcoming thus critical limitations in traditional polarimetric techniques and providing access to chiral sensing in the nanoscale.

References

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Skyrmionic Hopfions: 3D particle-like topologies in light beams

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Joint work with Danica Sugic, Roman Droop, Daniel Ehrmanntraut, Eileen Otte, Franco Nori, Janne Ruostekoski, Cornelia Denz

3-dimensional (3D) particle-like topological excitations, such as Skyrmions and Hopfions, were originally proposed as topological models of fundamental particles and nuclei, and have received much attention in high-energy and condensed matter systems. Rather than being based on special points and lines, the field values wrap around a 2-dimensional or 3-dimensional sphere “target space” within a plane or volume. In this sense, a full Poincaré beam, which realizes all points on the Poincaré sphere of polarizations in the transverse plane, is a 2D optical "baby skyrmion”.

The full state of light, including polarization and phase, being determined by a normalised 2-dimensional complex Jones vector, determines a point on a 3-dimensional hypersphere we call the “optical hypersphere”. Loops of varying phase and the Poincaré sphere determine the intricately tangled topological “Hopf fibration” of this 3-sphere, and intricate. We describe an optical beam configuration which realises all polarisations and phases together in a propagation volume, realising a 3D optical skyrmionic Hopfion. For sufficiently high topological degree, the 3D polarization structures are linked and knotted, yet may be understood as being built on a skeleton of C lines of circular polarisation.

Shaping the topology of fully structured focal light fields

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Within the last decades, customized focal light fields have proven their significance in various research areas, ranging from nano-scale complexity in three dimensions (3d) over optical micromanipulation to high-resolution imaging and material machining. Besides well-established amplitude and phase modulation, within recent years, polarization has been rediscovered as a degree of freedom that enriches the diversity of spatially structured light.

By tightly focusing polarization structured light, an additional dimension is added to these 3d focal light landscapes, namely, a non-negligible longitudinal vector field component. Although the huge potential of these so-called 4d fields for e.g. optical trapping of polarization-sensitive materials or the implementation of intelligent matter is obvious, until now, only simple and basic polarization modulation has been considered.

Within this contribution, we demonstrate the on-demand formation of confined 4d fields by tightly focusing fully-structured singular beams. We choose higher-order vector beams of spatially varying linear polarization as basis enabling the creation of singularity index-dependent focal intensity landscapes resembling “bright flowers” and “dark stars” [1].

Additionally, including phase vortices as a customization tool, the formation of exotic singular and topological structures as arrays of Möbius strips [2] is shown. We evince the benefit of these fields and their 3d polarization for next-generation applications of optical trapping, using elongated nano-containers. Furthermore, we present an innovative nano-tomographic approach for the identification of typically invisible non-paraxial field properties [3], paving the way to an effective implementation of 4d fields in various applications.

References

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Metal-Induced Energy Transfer

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Metal-Induced Energy Transfer (MIET) Imaging is a recently developed method [1] that allows for nanometer resolution along the optical axis. It is based on the fact that, when placing a fluorescent molecule close to a metal, its fluorescence properties change dramatically, due to electromagnetic coupling of its excited state to surface plasmons in the metal. This is very similar to Förster Resonance Energy Transfer (FRET) where the fluorescence properties of a donor are changed by the proximity of an acceptor that can resonantly absorb energy emitted by the donor. In particular, one observes a strongly modified lifetime of its excited state. This coupling between an excited emitter and a metal film is strongly dependent on the emitter's distance from the metal. We have used this effect for mapping the basal membrane of live cells with an axial accuracy of ~3 nm. The method is easy to implement and does not require any change to a conventional fluorescence lifetime microscope; it can be applied to any biological system of interest, and is compatible with most other super-resolution microscopy techniques that enhance the lateral resolution of imaging [2-4]. Moreover, it is even applicable to localizing individual molecules [5-6], thus offering the prospect of three-dimensional single-molecule localization microscopy with nanometer isotropic resolution for structural biology. I will also present latest developments of MIET where we use a single layer of graphene instead of a metal film that allows for increasing the spatial resolution down to few Ångströms [7].

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Converting transient to spatial effects with vector vortex light

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Our technical ability to design complex vectorial light fields opens new opportunities for fundamental queries of science as well as engineering applications. In this talk I will concentrate on vector vortex light, containing orthogonal polarisation states with different orbital angular momentum, and hence featuring polarisations that are modulated as a function of azimuthal angle. Applications that conventionally require the measurement of time-resolved polarisation rotations can with such light conveniently realised from single-shot image analysis. I illustrate this for the example of polarimetry [1], and vector magnetometry [2,3]. For the latter, we transfer the optical polarisation structures from vector vortex probe light onto atomic polarisation structures of a cold rubidium gas. The 3D alignment of an external magnetic field causes Larmor precession of these spatially varying atomic polarisations which can be detected in absorption images. Their Fourier analysis allows us to deduce the magnetic field alignment – realising an atomic compass.

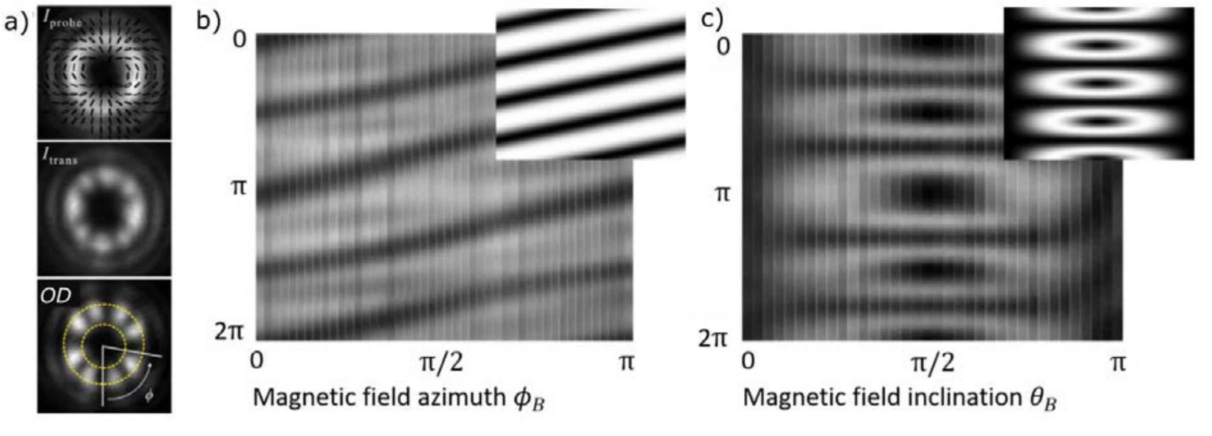

Fig: a) Intensity (and polarisation profile of optical probe, intensity after transmission and inferred absorption image. Assembled absorption images for various magnetic field alignments, with varying azimuth (b) and inclination angle (c), with insets showing the analytical predictions.

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Polarisation State Imaging in High Numerical Aperture Systems

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The potential for polarized light to highlight specific structures, such as filaments and membranes, in a living cell has long been known [1]. However, it still remains difficult to image these weakly birefringent structures due to depolarization of light at interfaces and weak signal levels when imaging through crossed polarisers. To address both these issues, we have introduced a confocal-like microscopy approach, Interferometric Cross-Polarisation Microscopy(ICPM) that has demonstrated the ability to resolve small polarisation signals against large backgrounds [2-5]. This interfometric approach allows imaging at high extension ratios with the low illumination needed for single molecule fluorescence and bio-imaging experiments.

As interferometric approaches, such as ICPM, detect fields rather than intensity one can in principle obtain all possible information on the interaction of the sample with light through controlling the polarisation states used during excitation and detection. However in realistic imaging applications this is complicated by the depolarization effects intrinsic to high numerical aperture (NA) objectives. Here I will explore this in detail by discussing our recent results on imaging individual as well as pairs of nanosized scatterering objects with controlled geometry, separation as well as orientation showing a surprisingly large impact resulting from small differences in particle shape. These results provide clear evidence for the importance of incorporating depolarization, including the spatial distribution of field-components, by high-NA objectives in polarimetry and investigations of focal field distributions.

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Topological plasmonics: Watching the vector dynamics of plasmonic skyrmions on a nm length and fs time scale

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Plasmonic skyrmions are topological defects in the electromagnetic near-field on thin metal films, recently observed using scanning near-field optical microscopy [1-2]. However, only one spatial component of the electric field was measured and one of the most intriguing features of skyrmions, namely their dynamics, was not assessed. Using time-resolved PEEM, the intensity of the plasmonic electric field could be mapped with high spatial and temporal resolution [3-5]. However, the vector information until now had been lost.

Here we introduce a new technique, namely time-resolved **vector** microscopy, that enables us to compose entire movies on a sub-femtosecond time scale and a 10 nm spatial scale of the electric field vectors of surface plasmon polaritons [6]. Specifically, we image complete time sequences of propagating surface plasmons as well as plasmonic skyrmions on atomically flat single crystalline gold films that have been patterned using gold ion beam lithography.

This allows us to unambiguously resolve all vector components of the electric field as well as their time dynamics, enabling the retrieval of the experimental time-dependent skyrmion number, and indicating the periodic transformation from skyrmion number +1 to -1 and back on a few femtosecond timescale.

References

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Light-Matter Interactions on the 10nm Scale – from Quantum Fields to Mechanical Forces

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We report on the modelling of light fields for two Potsdam experiments. The group of M. Bargheer works with aqueous solutions of gold nano-rods covered with a thin shell of the cyanine dye TDBC that forms J-aggregates [1]. Models based on Mie-Gans theory predicts a shell mode that coincides in frequency with the resonance of the J-aggregates, which is not observed in the extinction spectrum. Our explanation is that the nano-rod is a resonator with a mode volume so small that even a one-plasmon excitation saturates the narrow transition of TDBC. By including saturation into the dye susceptibility, we get excellent agreement with experiment for different sizes of nano-rods. This highlights the challenges of modelling quantum fields in nano-structures with highly polarisable emitters [2,3].

The group of S. Santer studies thin films that are irradiated with a polarisation-controlled holographic light pattern, that drives *trans-cis* isomerisations of azo-benzene in both directions. One observes a bulk birefringence grating by diffracting a probe beam and the growth of a surface relief grating by taking simultaneous AFM scans [4]. We develop a model for the molecular orientation in an elliptically polarised field. The goal is to clarify the origin of mechanical stresses (above 100 MPa) that must be at work in these glassy, hard materials [5,6].

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Zero refractive index materials and topological photonics

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Recently it has been realised that the mathematics of topology can be applied to determine the existence of confined modes of light [1]. I shall review this work, before identifying its connection with the optical Dirac equation [2,3]. I will then offer a reinterpretation of these topological results in terms of one of the most basic concepts in optics: the refractive index. The connection will be made via the general condition for achieving zero refractive index in a given direction.

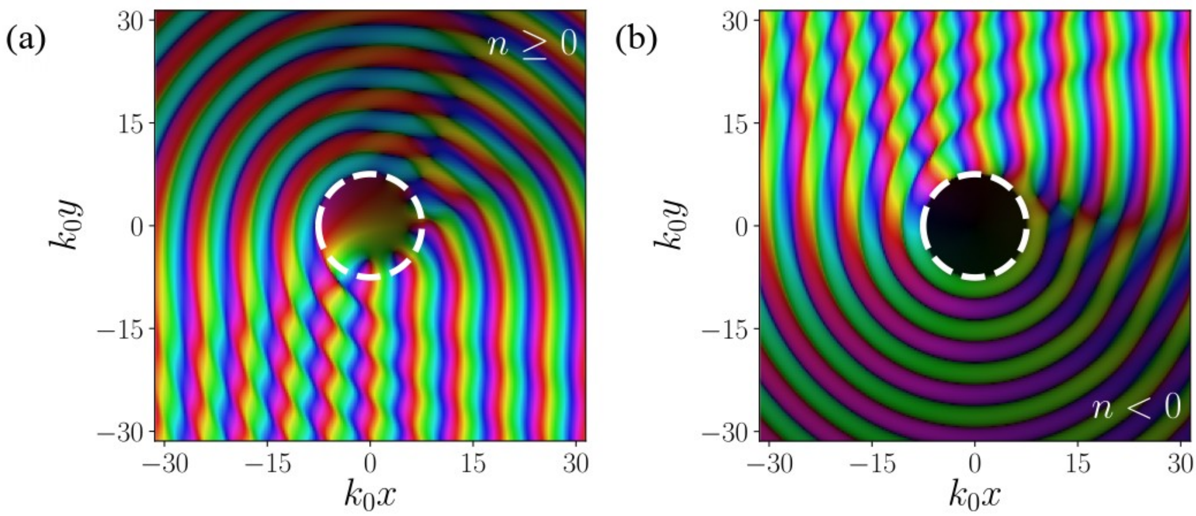

Fig 1: Scattering from a cylinder, resolved into partial waves of (a) positive, and (b) negative angular momenta.

When the zero-index direction is complex valued the material supports waves that can propagate in only one sense, e.g. in only a clockwise direction. Our condition shows that there are an infinite family of both time reversible and time irreversible materials that support one-way propagation for a particular polarization. Scattering from such media results in the complete exclusion of partial waves with one sign of the angular momentum (Fig. 1), and interfaces between such media generally support one-way interface states. As well as giving new sets of material parameters, our condition reproduces many of the findings derived using topology, such as spin-momentum locking of evanescent waves [4], and connects to some deeper results in topology, such as the Atiyah-Singer index theorem.

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Topological structures in and for light

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This lecture revolves around topological photonics. First I will address the structure of light confined to two dimensions. With experiments we study topological features in the field: phase- and polarization singularities. We count them, determine their correlations and their evolution when a parameter of the system is varied. We find different families of phase singularities, one faithful to their birth partner, the other not so; members of one family live longer. We also observe higher-order polarization singularities, which actually exhibit a topological charge imbalance. In fictitiously treating the singularities as actual particles, we use their correlation to construct a fictitious interaction potential. Some topological features are useful for manipulating light-matter interaction, e.g., for on-chip quantum optics. Secondly, I will therefore discuss experiments on edge states between topologically non-trivial photonic crystals. We investigate the relation between propagation direction and the pseudo-spin of the optical eigenstates and determine their bandstructure. With near-field microscopy we obtain subwavelength information about the wavefunctions of the states, find that the optical spin has a highly heterogeneous distribution in space, and quantify how robust robust is.

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Revealing the physicochemical basis of biomolecular interactions with mass photometry

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Interactions between biomolecules control the processes of life in health, and their malfunction in disease, making their characterization and quantification essential to our understanding of the underlying molecular mechanisms. I will introduce mass photometry, the accurate mass measurement of individual molecules in solution by light scattering, as a general approach for studying biomolecular mechanisms. The combination of label-free detection and mass measurement results in universal applicability enabling study of interaction stoichiometries, structure, energetics and kinetics. I will demonstrate the power of these measurements using recent results that reveal the molecular mechanisms, enabled by the measurement of the underlying physicochemical parameters, of fundamental processes such as filament formation and self-assembly both in solution and on bilayer membranes. In combination with future improvements in both technical capabilities and assays, mass photometry could make significant headway towards the ultimate goal of revealing biomolecular mechanisms directly at the molecular level.

Quantum interference and directional emission

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Quantum interference of different emission channels often leads to directional emission of particles. In the case of electrons generated by photoionization of an atom with high energy – and thus high linear momentum – photons, the electrons are emitted preferentially in the forward direction [1]. For lower energy photons the effect can be understood perturbatively and is a result of the interference of an electric dipole and a quadrupole interaction between the ionizing photon and the electron [2]. In the case of elastic scattering of photons similar interferences may happen, the probably most prominent example being the forward scattering of elementary Huygens waves [3]. There, the interference occurs between the light emitted by an electric and a magnetic dipole induced in superposition in the vacuum by the incident photon. For this process it is essential that the vacuum can be treated as a medium with dielectric and diamagnetic properties [4]. A related quantum interference phenomenon are quantum beats in fluorescence [5,6]. Two resonantly excited atomic states of slightly different energy – characterized by different spherical harmonics – interfere yielding a beacon sweeping around with a difference frequency [7] corresponding to the precise value for the energy difference of the two excited states. Closely related are quantum beats in photoionization [8] and field ionization [9]. In much the same way in nano optics, small metallic or dielectric scatterers can be excited to a superposition of different multipoles, which interfere to give spatially directional emission [10-12]. In this case, the emission is stationary because there is no frequency difference, respectively energy difference – closely related to the case of the Huygens waves above.

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Strongly focused vortices and pinhole scanning microscopy

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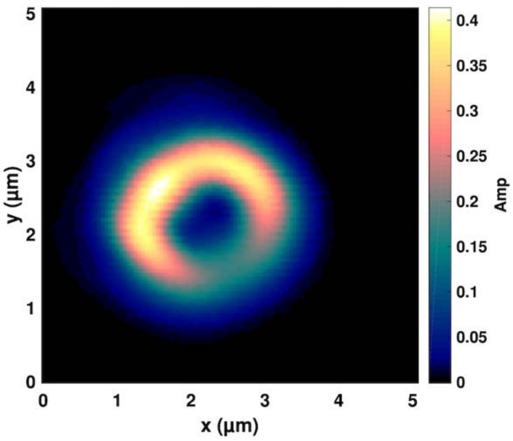
Several methods can circumvent the Abbe-Rayleigh diffraction limit, probably most importantly, stochastic super-resolution fluorescence microscopy methods. Another possibility, relying only on linear optics, is to exploit optical super-oscillations, and is far less explored to date [1]. Here we show first steps towards using *a few* optical vortices for super-resolution far-field imaging.

The nanoscale structured fields are probed using a micro-pinhole scanning microscopy method [2]. We find that our micron-sized pinhole is able to image structures much smaller than its own size and that spin-orbit interaction is strongly enhanced by the pinhole. The experimental results are compared to calculations, using a number of different analytical and numerical methods.



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Structuring light with plasmonic metasurfaces

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In this presentation, I would like to share our on-going research on both the numerical simulation of plasmonic metasurfaces and their nanofabrication. A metasurface being composed of many sub-wavelength scatterers, it is tempting to model it with a collection of dipoles. Whilst such a model can capture interesting effects, such as phase bifurcation in the metasurface optical response [1], it turns out that higher order multipoles are often required to provide a more accurate description. The different multipolar formulations will be briefly discussed, together with the appearance of somewhat less obvious toroidal moments.

Plasmonic nanostructures have a very strong electric dipolar response, which appears to always dominate the scattered light. It is however possible to engineer a collection of plasmonic nanostructures such that this electric response disappears and the scattered light becomes purely magnetic. The experimental realization of these different effects requires mastering the nanotechnology of different materials. Especially silver, which is well suited thanks to its low losses at optical frequencies. Silver nanostructures can be fabricated and stabilized to produce robust metasurfaces with strong optical responses [2,3]. Recently, we have extended the range of available plasmonic materials by introducing the low temperature alloying of Au-Ag nanostructures [4].

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Cylindrical Vector Beams in Optical Microscopy and Laser Spectroscopy

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Cylindrical vector beams, also called doughnut modes, can be used in many different branches of optical microscopy and spectroscopy such as bio‐imaging, material science, single‐molecule microscopy etc.. Their spatial polarization allows to create exclusively transversal (azimuthally polarized mode) or strongly longitudinal (radially polarized mode) fields in the diffraction limited focus of a high NA objective lens (1). They can be used to determine the 2D or 3D orientation of single molecules or nanoparticles directly from fluorescence excitation images (2,3) and enable to observe tautomerization of a single molecule (4,5). Mixing the azimuthal and radial modes the field distribution in the focus can be tailored and the ratio of the transversal and longitudinal field component (6) can be adjusted. Cylindrical laser modes allow to create large, subwavelength field gradients in an optical microcavity, which allow super localization of single emitters with an accuracy of > $\lambda/60$ (7).

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A single-shot responsive nano-analysis for the identification of highly confined customized light fields

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Recently, highly confined structured light has attracted considerable attention in areas as optical micromanipulation, high-resolution imaging, or material machining as it allows creating nano-scale light landscapes. Crucially, these non-paraxial fields do not only include transverse electric field components, but additionally reveal non-negligible longitudinal components shaped by focusing radially polarized light. Therefore, customizing paraxial polarization indirectly enables sculpting non-paraxial fields with three-dimensional (3d) polarization [1]. However, although non-paraxial fields are studied intensively and their realization is enabled by current modulation techniques, the analysis of such fields represents a major challenge due to their 3d polarization nature and nano-scale complexity. Some techniques were developed as the application of nano-particles as scanning sensors [2] facilitating a spatially highly-resolved investigation. However, known techniques are mainly based on slow scanning approaches combined with complex analysis algorithms.

Joining nano-optics and nano-chemistry, we present an experimental approach based on a responsive nano-system, namely, a fluorescent self-assembled monolayer for the single-shot identification of highly confined fields [3]. After outlining the theoretical concept of our nano-tomographic approach, we demonstrate the amplitude, phase and 3d polarization sensitive response of our nano-detector. To highlight our method's capabilities, we apply our approach to non-paraxial fields sculpted by combined spatial phase and polarization modulation, presenting the ability to visualize typically invisible focal field properties. Our technique represents an innovative tool for the fast verification of non-paraxial features, finally unlocking the full potential of tightly focused light for applied optics.

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Sculpted light in quantum atom optics and optical trapping

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Spatial light modulators (SLM) or Digital Micromirror Devices (DMD) give us a great flexibility in sculpting light. What it means is that we have perfect tools that can be used for production of configurable and flexible confining potentials and utilise them to confine atoms as well as lager scale objects and conduct novel experiments outlining light –matter interaction in these systems. We can sculpted light using time averaged methods, such as two-axis acousto-optic modulator (AOM) to create highly configurable time-averaged traps and those utilising special light modulators (SLM) and digital micormirror devices (DMDs).
Sculptured light produced using these methods gives high flexibility and an opportunity for trapping and driving systems ranging from studies of quantum thermodynamics using ultra cold atoms to trapping and manipulating nano and micron-size objects or even making measurements in-vivo inside biological cells.

Control of spatially rotating solutions in a self-focusing Kerr cavity

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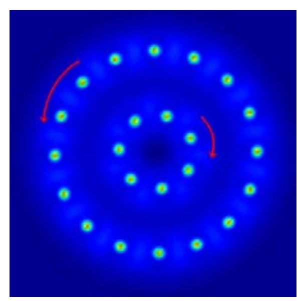
It is well-known that in a Kerr nonlinear cavity driven by a plane wave, diffraction may give rise to an instability that results in the formation of stationary spatial patterns in the transverse profile of the transmitted beam [1]. We demonstrate that when a nonlinear (Kerr) cavity is pumped by a beam carrying orbital angular momentum (OAM), the resultant Turing patterns form on concentric rings that rotate [2]. We show analytically that the speed of rotation is $\omega = 2m/R^2$, demonstrating that it can be controlled both by the magnitude of the OAM, m, and by the radius of the ring, R. We verify this prediction using Laguerre-Gaussian pumps and top-hat pumps carring OAM.

Using cylindrical vector beam [3] pumps that consist of orthogonally polarized eigenmodes with equal and opposite OAM we show that we can obtain full control over the angular velocity of the pattern in the range $-2m/R^2 \leq \omega \leq 2m/R^2$ by changing the relative weightings of the eigenmodes.



Using Poincaré beams [4] that consist of orthogonally polarized eigenmodes with different magnitudes of OAM, m_L, m_R, we show that the resultant angular velocity is $\omega = (m_L + m_R)/R^2$ if there is good overlap between the eigenmodes. However, if there is no, or very little, overlap between the modes then concentric Turing pattern rings, each with angular velocity $\omega = 2\, m_{L,R}/R^2$ will result. This can lead to, for example, concentric, counter-rotating Turing patterns creating an optical peppermill-type structure, as shown.

Full control over the speeds of multiple rings has potential applications in particle manipulation and stretching, atom trapping, and circular transport of cold atoms and BEC wavepackets.

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Abstracts of Posters

(in alphabetical order)

Customized optical spin flow topologies by translation of tailored phase flows

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Since the invention of optical tweezers, optical micromanipulation has been greatly advanced, as for example by the implementation of structured light fields. Not only due to their complex intensity structure, but also because of their transverse energy flow, these fields are of special interest for guiding, spinning and sorting trapped objects.

Among complex light structures, spatially varying phase distributions are well-established, allowing to apply e.g. orbital angular momentum and transverse energy flow (TEF) to optical trapping. Within the last years, an additional tool for shaping TEF has come to the fore: spatially structured polarization topologies providing spin flow density (SFD) patterns. Until now, the study of this tool is still in its infancy and, thus, its huge potential for optical micromanipulation and imaging, remains unexploited.

We introduce an interferometric approach, which enables the defined customization of TEF and SFD topologies [1]. By applying higher-order Laguerre- as well as Ince-Gaussian modes, we demonstrate a broad spectrum of sophisticated field configurations. We translate the corresponding transverse phase into SFD structures, leading to complex flow dynamics, which confine into fixed points, such as saddle points or centers. Depending on the chosen type of higher-order mode and their indices, we are able to control the shape of flow fields as well as position, number and order of embedded critical points. Further, we demonstrate that SFD structures may also act as sensors for identifying polarization singularities embedded in the respective vectorial beam with centers marked by C-points and saddles revealing stationary linearly polarized points. Beyond, our on-demand SFD structures pave the way for future optical trapping schemes based on the topical field of polarization modulation.

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Spin Densities in Optical Helicity Lattices

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In this work we present a study of the relative alignment of the electric and magnetic parts of the optical spin density in a helicity lattice.

In conventional optical lattices, the varying intensity gives rise to gradient forces which can be used to trap cold atoms. Helicity lattices have homogenous electric field distributions, but a varying helicity, which is a measure for the handedness of light, and it is thought they may be used to trap and separate chiral molecules.

The optical spin and the helicity are related in the same way as optical momentum and energy, that is, they obey a conservation law, and thus they are intimately connected. The spin density of an electromagnetic field is not unique, and it is possible to define both electric and magnetic spin densities. In a plane wave or even a collimated laser beam these two different densities are typically aligned, but in a helicity lattice they are not and the relative orientation changes over the lattice.

Superchiral regions, that is regions with greater enantioselectivity than circularly polarised light, are usually defined in terms of the helicity of the optical field. Such regions are found in several classes of optical lattices. Given the close relationship spin has with both helicity and circularly polarised light, it is natural to ask what happens to the behaviour of the spin in these superchiral regions and whether a definition of superchirality can alternatively be formulated in terms of the spin of the field.

On-chip generation of vector beams

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Techniques to generate vector modes are well-established in free space [1]. The transfer of these concepts to the area of integrated optics is a key requirement for future exploitation and to promote new applications in a wide range of disciplines, by offering superior scalability, size and speed. We show, using a finite-difference time domain simulation, that a silicon micro-ring cavity featuring two sidewall gratings can emit, in theory, any first order vector mode by controlling the weighting and relative phase of the TE and TM modes of the rectangular waveguide exciting the cavity. Our device operates at telecom wavelength, it is based on the orbital angular momentum (OAM) emitter ring cavity presented in [2], and as such, can also emit OAM at a selected wavelength.

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Vector Dynamics of Surface Plasmon Polaritons and Topological Models

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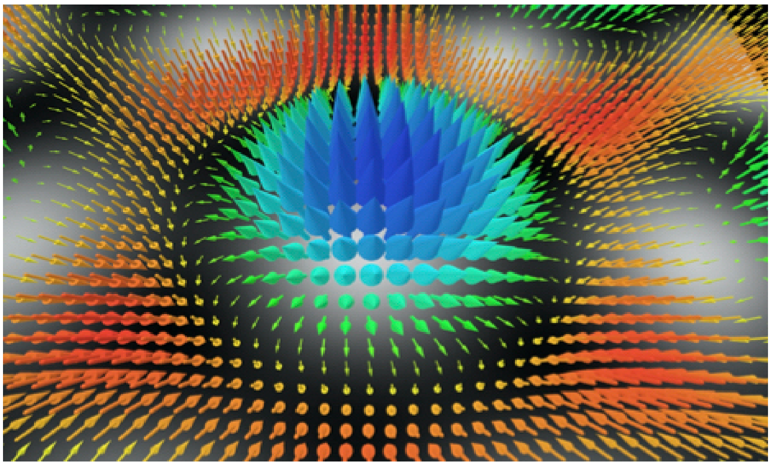
The study of two-dimensional magnetic systems has led to the discovery of novel vector topologies that influence the properties of solid state materials [1]. With growing interest in the topology of these vector fields, there has been increasing effort to create model systems for study. We recently developed a vector microscopy technique that enables us to image the electric field vectors of surface plasmon polaritons (SPPs) [2]. The technique combines a pump-probe laser field with a photo-emission electron microscope (PEEM) to image photo-electrons emitted from a metal surface. The method enables us to reconstruct the time dynamics of the SPP field vectors at sub-femtosecond time scales and nanometer spatial resolution, giving us unprecedented access to the vector properties of systems of interfering SPPs.



As an example, we have created interference patterns in the SPP electric field that mimic the properties of arrays of planar-skyrmions. From our experimental data we extract topological measures, such as the Chern number, and observe how these change with time. The figure shows a SPP-skyrmion obtained from our recently reported experiments [1]. From the time dependence of the electric fields it is straightforward to extract their spin structure as a function of position. In the last year we have created SPP spin textures that mimic merons – vector fields that have a topology not unlike a skyrmion but with half the Chern number (to be published). These fields are now being studied with our system.

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Bulk detection of time-dependent topological transitions in quenched chiral models

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The topology of one-dimensional chiral systems is captured by the winding number of the Hamiltonian eigenstates. This invariant can be read-out by measuring the Mean Chiral Displacement of a single-particle wavefunction that is connected to a fully localized one via a unitary and translation-invariant map [1-2]. Remarkably, this implies that the Mean Chiral Displacement can detect the winding number even when the underlying Hamiltonian is quenched between different topological phases. We confirm experimentally these results in a photonic quantum walk, realized in the transverse-momentum space of structured light, by means of liquid-crystal polarization gratings, known as *g-plates* [3]. We specialize this experimental validation to quenched quantum walks, realized when a localized initial state evolves according to a specific quantum walk protocol until a certain step, at which that protocol is replaced by a different one.

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Shaping 3d topological light landscapes in the paraxial regime

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Structured confined light is one of today's tool of choice for various applications [1]. Early path breaking examples are STED-microscopy, advanced optical trapping or material machining, that include 3d light landscapes. Typically, the customization of these 3d light fields is realized by tailoring different degrees of freedom of light as its amplitude, phase or polarization in the transverse 2d plane and tightly focusing the resulting paraxial field. Even though this approach enables sophisticated nano-scale non-paraxial light fields, the modulation in the propagation direction of these fields is limited to the short Rayleigh length of the tightly focused beam. Considering these difficulties, we developed a paraxial approach that does not require tight focusing, but enables at the same time the defined customization of extended 3d light fields. The spatial topology may vary within a wavelength in propagation direction. Our technique is based on the principle of counter propagating, transversely extended structured light fields. Due to the interference of the counter propagating fields, complex 3d light fields on the scale of the wavelength can be created. As an actual further development, we realize artificial digital counter propagation [2] where the beams are physically co-propagating but obtain their adequate phase structure by artificial, spatial-light modulator-based beam shaping. We employ this technique to higher-order Laguerre-Gaussian modes. We present the design respective light landscapes confined in 3d helices, whose helicity and periodicity can be tailored on-demand by incident mode indices. Beyond, including cylindrical vector beams into the counter propagating scheme, we demonstrate the fabrication of complex extended vectorial light fields with stunning polarization topologies varying in 3d space. Crucially, designed light fields can be shaped to vary between purely scalar and purely vectorial [2], demonstrating paraxial spin-orbit coupling in free space.

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Full characterization of three-dimensional electric field structures

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The topical research field of structured light has enabled not only new insights into the fundamentals of electromagnetic waves, but also a myriad of different applications [1]. Spatially shaping the different degrees of freedom has been utilized to face challenges in microscopy, data communication, quantum physics, and more. Especially topological aspects of structured light have contributed significantly to this development in recent years, as the conservation of invariants gives rise to stability. Originally, two-dimensional phase and polarization structures have been considered. Further advancements brought spatially confined phase and polarization textures to the forefront.

Until now, structures inspired by the mathematical field of topology have only been considered in phase or polarization separately. However, topological constructs embedded in both phase and polarization are an exciting new concept. The study of topological structures in the full electric field could open up new perspectives on structured light. Nevertheless, the customization and analysis of the full, vectorial electric field represents a major current challenge. We present an experimental approach to not only create such light structures but also to fully characterize them in 3d space. It is based on the superposition of structured paraxial beams of orthogonal polarization and combines sophisticated techniques of beam shaping, digital propagation, and spatially resolved 3d phase decoding and polarimetry. We realize a light field structured in polarization and phase to give rise to a three-dimensional complex topological construct, among others.

Expanding the methods and tools of structured light by embedding topological constructs in the full electric field is but one advancement on its own. The full characterization of an electric field in a finite volume, on the other hand, is an important step towards new applications of structured light. It not only paves the way for new kinds of confined light structures, but also to the measurement of related quantities.

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Sub-diffraction-limit multi particle reconstruction by far-field multipole analysis

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Breaking the resolution limit. This is an idea, probably as old as the limit itself. Since then, the selection of super resolution microscopy techniques is ever growing, with the most powerful once being either based on fluorescence dyes or completely leaving the regime of visible light to utilize material waves. Nonetheless, certain samples do not allow the usage of additives or switching to other wavelengths, wherefore utterly non-invasive techniques are of special interest. Here we introduce a far-field microscopy technique based on the multipole decomposition of the scattered light and capable of breaking the resolution limit by far. Our technique is adapted to investigate an accumulation of sub-wavelength plasmonic nanoparticles and can derive their position as well as their size with an accuracy down to several nanometers, even if multiple of them being directly adjacent. We outline the underlying principle of the presented technique and demonstrate its capabilities by a subsequent experiment.

Quantumelectrohydrodynamics of a Tunnel Gap

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We present a quantumelectrohydrodynamic interpretation of the electro-inertial Raman scattering phenomenon of a single gold atom tunnel gap as a function of a stationary electron tunnel current. Since a chemical bond between 2 identical atoms consists of a stationary single electron tunnel gap, the spectroscopy of the atomic tunnel gap can be regarded as a universal building block of the spectroscopy of single molecules which consists of an assembly of atoms, which are linked by a connected network of chemical bonds. We apply quantumelectrohydrodynamics to the quantized physical observables of spin, energy, mass and charge of the photons - and of the electrons and atoms, - respectively,to a specific model of a macroscopic experimental configuration for Tip enhanced Raman Spectroscopy (TERS) with the tunnel gap between the apex of an optically transparent dielectric tip and a macroscopic gold reservoir [1]. In this configuration, the tip serves two functions. It acts as a phase conjugating retroreflecting mirror for the incident light and the forward scattered light is detected. The influence of a stationary tunnel current $I = f_e e$ on the spectrum of the forward scattered light is determined by an analytical ab initio calculation without any adjustable parameters. The calculated spectra coincide within experimental errors with the spectra of a real TERS experiment. The dynamics of spin orbit Transformation (SPOT) [1] between photons and electrons in a tunnel gap or a chemical bond cannot be investigated in a mathematically rational manner by Quantum theory due to the uncertainty relations. It can be shown, however, that the classical quantumelectrohydrodynamic equations of motion can be based on a quantization [3] of a continuum theory of the physical space of Bernhard Riemann [4]. This approach is applied to a classically intuitive rational and analytical interpretation of a real TERS experiment of a gold tunnel gap [1], rather than a mathematically irrational approach, which might be possible by complex techniques of digital numerical computations based on Dirac's relativistic quantum theory and on quantumelectrodynamics.

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Atomically flat gold flakes for surface plasmonics

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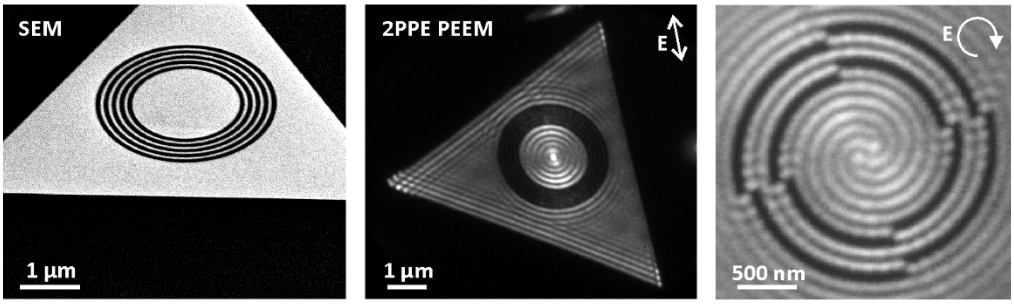
We use single crystalline gold flakes on atomically flat silicon substrates to generate ideally suitable interfaces for plasmon propagation. By electrochemical means, the thickness is tunable from a few tens to over 100 nm. Using sub-20 fs laser pulses around 800 nm, we excite surface plasmons, whose dynamics can be observed using time-resolved two-photon excitation electron emission (PEEM).

Plotting the dispersion of surface plasmons in a thin gold slab on silicon, one finds that excitation at 800 nm can lead to extreme wavelength reduction due to the dispersion slope of over five. Using focused ion beam for cutting rings with appropriate periodicity into the samples (see left image), we can excite concentric surface plasmons that create a nanofocus of only 60 nm width for 800 nm excitation



(see center image) [1].
Archimedean spirals with broken n-fold radial symmetry excite surface plasmons with angular orbital momentum on the gold flakes (see right image). This leads in case of 4-fold symmetry to cloverleaf-type nanofoci of approximately 100 nm, which rotate during four optical cycles by 360 degrees [2].

Two-pulse experiments with a subwavelength-stabilized Michelson interferometer allow for investigation of the surface pattern dynamics with (sub-) femtosecond resolution, thus giving insight into the dynamics of the nanofocus formation, plasmonic spin-orbit coupling as well as plasmonic skyrmion dynamics.

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Mutual self-structuring and novel Kerr-like fragmentation in coupled light/matter-wave interactions

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Spatial optical solitons are self-localized wave packets arising from a balance between diffraction and self-focusing (Kerr) nonlinearity as described by the (2+1)D nonlinear Schrödinger equation:

$$\partial_z F = i\nabla_\perp^2 F + i\eta(F)F,$$

where F is the optical field, $\nabla_\perp^2$ describes diffraction and $\eta(F) = \beta|F|^2/(1+\sigma_{sat}|F|^2)$ describes a saturable self-focusing medium for $\beta > 0$. The parameter σ_{sat} describes saturation in the medium, so for a pure Kerr medium $\sigma_{sat} = 0$. When uniformly polarized light has a helical phase structure, $e^{im\varphi}$, it carries orbital angular momentum (OAM) of quantum number $,m$ ($m \neq 0$), and is characterized by an on-axis optical vortex. Such light has been shown to fragment into solitons carrying angular momentum when propagating through Kerr media, with the number of solitons formed depending on the OAM, m [1, 2]. Similar results have been observed in nonlinear colloidal suspensions [3].

Here we investigate coherent vortex beams propagating through a matter-wave i.e., a Bose-Einstein Condensate (BEC) [4]. In this case, the nonlinear term for the optical field

$$\eta(F) = \left(\frac{\mp|\psi|^2}{1+\sigma_{sat}|F|^2}\right),$$

becomes spatially dependent on the BEC wavefunction ψ, which itself evolves according to

$$\partial_z \psi = i\nabla_\perp^2 \psi - i(\pm|F|^2 + \beta_{col}|\psi|^2 - iL_3|\psi|^4)\psi,$$

where β_{col} represents interatomic scattering, L_3 represents three-body loss (L_3) in the BEC and the ± refers to whether the optical field is blue (+) or red (-) detuned.

We present the results of propagating vortex beams with different values of OAM in the case of a self-focusing medium and repulsive BEC interactions. We show the novel formation of coupled optical and BEC solitons, despite repulsive BEC interactions, and demonstrate that both light and BEC solitons carry angular momentum. Despite fundamental differences between our model and the pure Kerr case, the results are in remarkable qualitative agreement, and we find that the number of solitons depends on the OAM of the vortex light beam.

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Phase Diagrams of the Mixed Spin-1 and Spin-2 Blume-Emery-Griffiths Model with Attractive Biquadratic Coupling

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The mixed spin-1 and spin-2 Blume–Emery–Griffiths (BEG) Ising system with interaction of different anisotropies (DA/zJ) for spin-1 and (DB/zJ) for spin-2, usual exchange interactions both bilinear (J) and attractive biquadratic (K), is studied within the framework of the mean field approximation. The phase diagram of the (T,D/zJ) plane with equal crystal field interaction for the two sub-lattices is obtained by studying the Blume-Capel model with mixed spins S = 1 and S = 2 [1] on the one hand and varying the exchange interaction K on the other hand. The influence of the biquadratic exchange interaction K and the crystal field of different anisotropies DA/zJ and DB/zJ are examined to obtain the phase diagrams. Very rich phase diagrams with the second- and first-order phase transition lines, tricritical and the occurrence of reentrant behavior are observed [2].

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Interaction of Vector Beams in Structured Epsilon-Near-Zero Materials

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For nearly two decades now [1], discussions of the epsilon-near-zero (ENZ) regime have led groups to discover remarkable optical properties when the permittivity tends towards zero. Whether one is exploiting the wavelength expansion in the material for waveguide tunneling [2], approaching near-zero-index (NZI) to achieve phase mismatch-free four-wave mixing [3], or utilizing the large field enhancement in an ENZ metasurface to induce strong nonlinearities [4], ENZ phenomena hosts a broad range of engaging research areas throughout modern optics. Furthermore, the rise of commercially available ENZ materials in the latter decade has made pursuing these notable traits more accessible in various topics throughout optics. In our work, we seek to observe the various roles vector beams have when interacting with structured ENZ films. By using tightly focused optical fields which feature structured polarization profiles in conjunction with structured ENZ films, numerous interactions can be considered. Such interactions vary from using thin ENZ films to facilitate optical spin-orbit-coupling, to having polarization-dependent transmission in subwavelength holes embedded in ENZ films. This interplay between the polarization profile of the incident field and the geometry of the ENZ structure may also allow the generation of nonlinear responses without the need for such traditionally high powers [5].

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Simulation of highly divergent Optical Beams

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Optical-beams-MEEP [1] provides a Cython module and several Python/Scheme scripts for spatio-temporal simulation of various optical beams in 2d and 3d dimensions.

The provided scripts are designed to serve as configurations files for the powerful Meep [2] tool, an established open-source FDTD simulation software package for electromagnetic fields. The objective of these scripts is the simulation of reflection and refraction of highly divergent polarised optical beams at plane and curved dielectric interfaces. Currently supported are Gaussian beams (2d), Laguerre-Gaussian beams (3d) and Airy beams (2d).

Utilizing Meep to simulate the propagation of a Gaussian beam in a homogeneous medium is fairly easy: specifying its real valued current distribution at waist is sufficient. However, for highly divergent beams with the waist being placed at or close to an intersection of regions of different optical properties, this requires specifying the exact complex-valued current distribution at a certain distance to the beam's waist. This is typically done by calculating the beam profile via a plane wave decomposition which involves integration of the real and imaginary parts of a highly oscillating integrand. Meep's deprecated Guile/Scheme interface could handle this with a fast numeric integration routine. With Python however, due to its expensive function call overhead, multiple integration becomes such a computationally intense task by itself that it would put Meep's Python interface almost useless for the considered simulation tasks.

In order to overcome this problem, we developed a Python extension module based on Cython, employing highly optimized C code that can be called from within Python. Since SciPy's adaptive quadrature routine allows for low-level compiled functions, we manage to completely circumvent Python's tremendous overhead when calling the integrand functions many times.

In conclusion, our module allows for using Meep's more modern, easier to use Python interface while keeping the computational overhead low.

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Twisted and chiral photon states scattered on chiral molecular liquids

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Using resonant light-matter coupling of twisted and chiral photon states [1] to chiral molecular liquids we study their inelastic response. For this instance, quasi-elastic Raman scattering (QES) is investigated in isotropic, nematic and chiral nematic phases of liquid crystals. The response is diffusive and dominated by a narrow distribution or single relaxation rate.

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Tightly Focused Optical Modes as Quantum Pendulum Eigenstates

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We propose a model for tightly focused Gaussian laser modes – represented in the paraxial regime as harmonic oscillator eigenstates – in terms of the eigenstates of the quantum 3D pendulum. Being confined to the surface of a sphere, pendulum eigenstates satisfy the Helmholtz equation in Fourier space. The pendulum's gravity parameter quantifies the degree of localisation in Fourier space, that is, the paraxiality: in the high-g limit, the Helmholtz equation reduces to the paraxial wave equation. Asymptotic approximations for large g demonstrate the way real, tightly-focused optical modes may deviate from the universal Gaussian ansatz.

Angular momentum redirection phase of vector beams in nonplanar geometry

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Phase shifts can be acquired by a propagating light beam arising due to the underlying geometry of the system; these phase shifts are referred to as geometric phases [1, 2]. Previously geometric phases have been linked to spin redirection and independently to transformation of spatial modes, resulting in the rotation of polarisation and intensity profiles, respectively [3,4]. In our system, we show experimentally that both are linked to a more general angular momentum phase.

We generate a variety of vector beams with phase and polarisation singularities and propagate these through a series of mirror reflections in an out of plane configuration. By performing a full tomography of the resulting vector beams we confirm that the angle of the polarisation rotation is identical to the spatial mode rotation and is determined by the beam geometry.

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Selective Fabrication of Nanoparticle Assemblies and Nanoparticle-enabled Devices

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The capability to select individual nanoparticles and compose them into target-designed nanoparticle assemblies opens up a new perspective for the investigation of light-matter interactions at the nanoscale. Similarly, decoration and thereby functionalization of integrated structures such as photonic or opto-electronic devices with designated and individually selected nanoparticles also enable novel fabrication pathways for prototyping optical and opto-electronic structures, which so far cannot be fabricated by conventional thin film processing and structuring strategies.
Here, we present an atomic force microscope based nanomanipulation setup that is integrated into a scanning electron microscope and permits the transfer of individual nanoparticles by pick-and-place action from a reservoir sample to a target structure or sample. It can also be used to assemble several nanoparticles on an individualized basis into geometrically targeted arrangements. Besides presenting the setup and its mode of operation, we also discuss exemplary nanophotonics applications and experiments on the chiral response of heterogeneous nanoparticle ensembles [1, 2] or the functionalization of a photonic waveguide architecture for the realization of an integrated all-optical displacement sensor [3].

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Single shot tomography of vector vortex beams by generalized measurements

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Poincaré beams are generated by superposing two light beams with orthogonal polarization in two different Hermite-Gauss or Laguerre-Gauss spatial modes. Different Hermite-Gauss and Laguerre-Gauss spatial modes are prepared by using a Digital micromirror Device (DMD). These superposed beams are non-separable in their spatial and polarization degrees of freedom and present a inhomogeneous polarization structure. Four state tomography by using POVM (positive operator value measure) was implemented for characterizing the polarization state of inhomogeneous polarized light beams. The POVMs elements are realized by an interferometer built with polarizer beam-splitters, half and quarter-waveplates with four exits. The detection of light in each exit implies the implementation of one of the four elements of the POVM. A camera collects light from all four exits in a single image. Grey scale analysis give us the polarization state in each pixel or in each small pixel area allowing the construction of the polarization map of the wave front. Our technique is able to perform full state tomography of arbitrary vector beams up to an overall phase factor.

Augmented control of plasmonic orbital angular momentum

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Surface plasmon polaritons (SPPs) are electromagnetic excitations propagating along metal-dielectric interfaces. Their ability to carry surface-confined orbital angular momentum (OAM) in the form of vortices is of great fundamental [1] and applied interest, for example in plasmonic tweezers.

Commonly, plasmonic vortices are created with segmented Archimedes spirals engraved in a metal surface. These serve as coupling structures which output plasmons with OAM when they receive circularly polarized light as input [2]. This method, however, only allows for small changes in the created OAM when switching the polarization handedness of the illumination, limiting the potential for its application in functional devices.

To improve the flexibility of plasmonic OAM generation, we present two different approaches:

1. The reflection from structural boundaries in plasmonic vortex cavities introduces a new degree of freedom in the control of plasmonic OAM as a succession of vortices is generated, with an orbital angular momentum that increases as a function of time [3].
2. When the local and global geometries of plasmonic vortex generators are tailored with metasurfaces, a change in the helicity of the incident light imposes an arbitrary change of the delivered OAM. This approach can be extended for the creation of more complex topological fields [4].

For both approaches, we track the spatio-temporal dynamics of the plasmonic fields via time-resolved photoemission electron microscopy (TR-PEEM) with subfemtosecond temporal resolution. Our results provide novel tools for plasmonic manipulation that could for example be applied in lab-on-a-chip devices.

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Quantum Rolling Friction: The Interplay between Confined Light and Moving Atoms

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Measurable forces arise from the fluctuation-induced interaction between atoms and macroscopic surfaces; even when the system is in its ground state at zero temperature. Mediated by the quantum vacuum, this so-called Casimir-Polder force is sensitive to the properties of the (quantized) electromagnetic field. For instance, surface resonances show to constitute an important contribution to the interaction.
The situation becomes considerably more involved in mechanical nonequilibrium, i.e. when the atom is in motion with respect to the surface. Due to the Doppler-shift, the motion introduces an asymmetry to the interaction that favors certain dissipative surface waves with distinct momentum vectors. As a result, we record a net transfer of angular momentum to the particle [1,2]. In simple terms, the atom starts to rotate. However, the sense of rotation is opposite to that we would expect from classical considerations.
We introduce the effect and highlight that this surprising behavior is intimately connected to the spin-momentum locking of confined light in the vicinity of the surface.

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Freeing Light from Confinement: Extraction of Photons

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Solid-state quantum emitters are a promising resource for quantum technology. Nevertheless, extracting and collecting the emitted photons in an efficient way is challenging.
Here, we present different approaches how to tackle this problem using specially engineered photonic structures such as tapered optical fibers [1,2], fiber coupled optical cavities [3,4], solid immersion lenses [5], micro-mirrors [6], and more [7].
All these different approaches have certain advantages and disadvantages that makes tailoring the extraction method the emitters and the fabrication processes mandatory.

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Optofluidic Force Induction Scheme for the Characterization of Nanoparticle Ensembles

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Momentum transfer from light to matter provides the basic principle of optical tweezers, which have been awarded the Nobel Prize in Physics 2018.[1] Most studies have hitherto employed this principle for trapping and manipulation of single nanoparticles. However, in a microfluidic channel one can also monitor the effect of optical forces exerted on ensembles of dielectric nanoparticles, to acquire knowledge about various nanoparticle parameters, such as size, shape or material distributions.

In this paper we present an optofluidic force induction scheme (OF2i) for real-time, on-line optical characterization of large ensembles of nanoparticles.[2] Our experimental setup builds on precisely controlled fluidics as well as optical elements, in combination with a focused laser beam with orbital angular momentum. By monitoring the single-particle light scattering and nanoparticle trajectories, we obtain detailed number-based information about the properties of the individually tracked particles.

We analyse the trajectories using a simulation approach based on Maxwell's equations and Mie's theory, in combination with realistic laser fields and fluidic forces.[3] We discuss the basic physical principles underlying the OF2i scheme and demonstrate its applicability using standardized Latex particles with a pre-determined size distribution. Our results prove that OF2i provides a flexible work bench for numerous pharmaceutical and technological applications, as well as medical diagnostics.

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High photon number entangled states and coherent state superposition from extreme-UV to far-IR

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We present a theoretical study on the generation of entangled coherent states and of coherent state superpositions, with photon numbers and energies, orders of magnitude higher than those provided by the current technology [1]. This is achieved by utilizing a quantum mechanical multimode description of the single- and two-color intense laser field driven process of high harmonic generation in atoms. It is found that all field modes involved in the high harmonic generation process are entangled, and upon performing a quantum operation, leads to the generation of high photon number non-classical coherent state superpositions spanning from the extreme-ultraviolet to the far infrared spectral region. These states can be considered as a new resource for fundamental tests of quantum theory and quantum information processing.

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Universal Scaling Relation of Vortices in Wave Chaos Loop Soup

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We compare the length distribution of vortex loops in spatial and spatial-temporal wave chaos loop soups and find a universal scaling relation among them. We generate wave ensemble as solution to Helmholtz, d'Alembert, Klein-Gordon, and Schrodinger equation that are spatial and spatial-temporal wave chaos ensemble, and track the vortex loops in them. We find that the length distributions of vortex loops have a universal scaling relation, and it suggests the universality of loop soup statistics among different wave ensembles.

Faraday Effect for Vector Vortex Beam

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We report on the Faraday effect for highly focussed vector vortex beams. The Faraday effect causes the plane of polarization of homogeneously polarised light beam to rotate, but in recent years vector vortex beams with an varying polarisation structure have found wide ranging applications in optical micromanipulation, sensing and communication. Interestingly, the focussing properties of vector vortex beams can give rise to very different longitudinal fields depending on the polarisation pattern of the beam before focussing. We investigate how the Faraday effect can be used to highlight this effect.