PAŁAC WOJANÓW

Book of Abstracts

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Aspects of Contemporary Optics

September 5–9, 2022, Wojanów, Poland

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Faculty of Fundamental Problems of Technology,
Wrocław University of Science and Technology

Edited by Katarzyna Sztylińska

Wrocław 2022

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Conference Program

Monday, September 5, 2022

15:00–21:00 Arrival/registration

19:00–21:00 Supper

Tuesday, September 6, 2022

Hot Topics I — Wojanowska Room

8:30 – Opening
8:45 – *Ultrastrong coupling between light and matter for quantum technologies* [Invited lecture], presented by Adam Miranowicz (page 17)
9:15 – *3D photonics for applications on a chip and optical fiber* [Invited lecture], presented by Dušan Pudis (page 18)
9:45 – *Optical ion clocks: from single ion to Coulomb crystals* [Invited lecture], presented by Ondřej Číp (page 19)
10:15 – *Event Horizon Telescope and the progress in very long baseline interferometry* [Invited lecture], presented by Maciej Wielgus (page 20)

10:45–11:15 Coffee Break

XUV Optics I — Wojanowska Room

11:15 – *Nanoscale laboratory-based coherence tomography with extreme ultraviolet and soft X-ray light* [Invited lecture], presented by Silvio Fuchs (page 21)
11:45 – *Challenges in soft X-ray spectromicroscopy using Fresnel zone plates* [Invited lecture], presented by Tolek Tyliszczak (page 22)
12:15 – *Astronomical X-ray optics* [Invited lecture], presented by René Hudec (page 24)
12:45 – *Laser-driven X-ray sources for user experiments at ELI Beamlines* [Invited lecture], presented by Jaroslav Nejdl (page 25)

13:15–14:45 Lunch

Quantum Optics I — Wojanowska Room

14:45 – *Stokes and anti-Stokes photon-pair generation in Raman scattering*, presented by Kishore Thapliyal (page 26)

15:00 – *Two-beam light with simultaneous anti-correlations in photon-number fluctuations and sub-Poissonian statistics*, presented by Jan Peřina Jr. (page 27)
15:15 – *Unconventional photon blockade in a passive RT-symmetric system*, presented by Ewelina Lange (page 28)
15:30 – *Catalysis in charging quantum batteries*, presented by Borhan Ahmadi (page 29)
15:45 – *Optimal Quantum Control of Charging Quantum Batteries*, presented by Ricard Ravell Rodriguez (page 30)

XUV Optics II Karkonoska Room

14:45 – *Laser plasma sources of soft X-rays and extreme ultraviolet based on a gas puff target*, presented by Henryk Fiedorowicz (page 31)
15:00 – *Spatio-temporal measurements of laser or EUV induced plasmas, in soft X-ray and optical range*, presented by Andrzej Bartnik (page 32)
15:15 – *Nanoscale optical coherence tomography using extreme ultraviolet radiation produced with a laser plasma source based on a gas puff target*, presented by Antony Jose Arikkatt (page 33)
15:30 – *Investigations of laser produced plasmas in a low-pressure gas environment*, presented by Mateusz Majszyk (page 34)
15:45 – *Ray-tracing simulations of a UV/VUV beamline for the PolFEL free electron laser*, presented by Martyna Wardzińska (page 35)

16:00–16:30 Coffee Break

Quantum Optics II Karkonoska Room

16:30 – *Decay of one subsystem as a counterpoise to decay of another in quantum computing*, presented by Grzegorz Chimczak (page 36)
16:45 – *Nonclassical correlation of photon-phonon in cross mode of the hybrid system*, presented by Shilan Abo (page 37)
17:00 – *Entanglement generation in a system of two interacting anharmonic quantum oscillators*, presented by Joanna K. Kalaga (page 38)
17:15 – *Measuring concurrence in qubit Werner states without an aligned reference frame*, presented by Jan Soubusta (page 39)
17:30 – *Transfer of EPR quantum steering along two non-interacting qubit chains*, presented by Wiesław Leoński (page 41)

Optical Sensing Wojanowska Room

16:30 – *Laser spectroscopy of methane near 1650 nm using photoacoustic spectroscopy combined with a fiber amplifier*, presented by Magdalena Zatorska (page 42)

16:45 – *Mid-infrared laser-based gas sensing inside hollow-core fibers*, presented by Grzegorz Gomółka (page 43)
17:00 – *The optical performance of anti-reflective coatings in iodine-filled absorption cells*, presented by Jindřich Oulehla (page 44)
17:15 – *Light beam polarization scrambling by the umbilical defects in the liquid crystals cell*, presented by Paweł Marć (page 45)
17:30 – *Rapid structural transformations in metals after sub-ps pulsed laser annealing*, presented by Ryszard Sobierajski (page 47)

18:00–20:00 Poster Session (see page 11)

20:00–23:00 Grill

Wednesday, September 7, 2022

Hot Topics II — Wojanowska Room

8:30 – *Pushing the boundaries of entanglement with light, atoms and optomechanics* [Invited lecture], presented by Michał Parniak (page 49)
9:00 – *Quantum non-Gaussianity of multi-phonon states of trapped ions* [Invited lecture], presented by Lukáš Slodička (page 51)
9:30 – *Spatio-temporal optical imaging – new step in noninvasive biopsy* [Invited lecture], presented by Maciej Wojtkowski (page 52)
10:00 – *Free-form gradient index microoptics using nanostructure engineering* [Invited lecture], presented by Ryszard Buczyński (page 53)

10:30–11:00 Coffee Break

Optical Trapping — Wojanowska Room

11:00 – *Vacuum levitation of nanoparticles* [Invited lecture], presented by Vojtěch Svak (page 55)
11:30 – *Optically trappable flexible micro-structures* [Invited lecture], presented by Gregor Bánó (page 56)
12:00 – *Optical force aggregation of gold nanoparticles as a tool to fabrication a multifunctional sensor*, presented by Silvie Bernatová (page 57)
12:15 – *Compliance of numerical modelling with experiment in optical tweezers in geometric regime*, presented by Aleksandra K. Korzeniewska (page 58)

12:30 – *Optically powered train of microparticles*, presented by Pawel Karpinski (page 59)

12:45–14:30 Lunch

Fiber Optics I Wojanowska Room

14:30 – *Phosphate glass nanostructured core fiber for laser with dual wavelength emission*, presented by Marcin Franczyk (page 60)
14:45 – *Negative curvature hollow-core silica optical fibres with extended spectral transmission range*, presented by Pavel Honzatko (page 61)
15:00 – *Nanostructured large mode area fiber for laser applications*, presented by Alicja Anuszkiewicz (page 62)
15:15 – *Selective excitation of different combinations of LP_{01} and LP_{11} polarization modes in a birefringent optical fiber using a Wollaston prism*, presented by Kinga Żołnacz (page 63)
15:30 – *Spectral properties of photonic crystal fibers infiltrated with ferroelectric liquid crystals doped with nanoparticles*, presented by Daniel Budaszewski (page 64)
15:45 – *Fiber-optic distributed monitoring of temperature change in active layer of permafrost*, presented by Adam Paździor (page 65)

Eye and Vision Karkonoska Room

14:30 – *Two-photon vision – infrared light perception in the function of duty cycle and wavelength*, presented by Marcin J. Marzejon (page 67)
14:45 – *Spatio-temporal optical coherence tomography (STOC-T) for high-resolution, wide-field structural and blood flow imaging of the human retina in vivo*, presented by Dawid Borycki (page 69)
15:00 – *The mechanism of the self-adjustment of the human eye*, presented by Agnieszka Jóźwik (page 71)
15:15 – *Birefringence of the cornea*, presented by Marcelina Sobczak (page 72)
15:30 – *Age-related changes in the morphology and optical density of the crystalline lens*, presented by Ashish Gupta (page 73)
15:45 – *Probing asymmetries in corneal biomechanical properties with optical coherence tomography*, presented by Karol Karnowski (page 74)
16:00 – *Engineering of light delivery system to improve the imaging capabilities of optical coherence tomography instruments*, presented by Ireneusz Grulkowski (page 76)

16:15–16:45 Coffee Break

Optical Imaging — Wojanowska Room

16:45 – *3D printed HMM metamaterial near-field probe for sub-diffraction imaging*, presented by Patrik Miček (page 77)
17:00 – *Calibration procedure of the multimode optical fibre micro-endoscope*, presented by Petr Jákl (page 78)
17:15 – *Extended depth of focus lensless holographic microscopy imaging*, presented by Mikołaj Rogalski (page 79)
17:30 – *Optimization of signal-to-noise ratio and attempt to increase resolution in lensless in-line digital holographic microscopy*, presented by Piotr Arcab (page 80)

Fiber Optics II — Karkonoska Room

16:45 – *Nonlinearity shaping in nanostructured glass-diamond hybrid materials for optical fiber preforms*, presented by Grzegorz Stępniewski (page 81)
17:00 – *Gradually twisted highly birefringent optical fiber for vortex modes generation*, presented by Marta Bernaś (page 82)
17:15 – *Development of single crystal $CsPbBr_3$ perovskite core optical fiber*, presented by Paweł Socha (page 83)
17:30 – *Observation of soliton trapping in the microstructured optical fibers with different group birefringence*, presented by Karolina Stefańska (page 84)

Thursday, September 8, 2022

Hot Topics III — Wojanowska Room

8:30 – *Optical detection of nuclear magnetic resonance at zero magnetic field* [Invited lecture], presented by Szymon Pustelny (page 85)
9:00 – *Quantum machine learning with linear optics* [Invited lecture], presented by Karel Lemr (page 86)
9:30 – *Toward coherent beam combining* [Invited lecture], presented by Jan Jabczyński (page 87)
10:00 – *Computational techniques in lensless holographic microscopy for biomedical imaging* [Invited lecture], presented by Maciej Trusiak (page 88)

10:30–11:00 Coffee Break

Photonic Technologies — Wojanowska Room

11:00 – *Paramagnetic nitrogen-vacancy color centers in diamonds for magnetic mapping and sensing*, presented by Zuzanna Orzechowska (page 90)
11:15 – *Magnetization rotation-based polarization control of spintronic terahertz emitter*, presented by Pierre Koleják (page 91)
11:30 – *Electrical tuning of optical properties in metal-oxide-semiconductor multilayer*, presented by Alexander Korneluk (page 92)
11:45 – *Optimisation of exposure parameters for direct laser writing in optical lithography*, presented by Tomas Kohut (page 93)
12:00 – *Laser color printing on semicontinuous aluminum films*, presented by Piotr Nyga (page 94)
12:15 – *Hot-electron driven optical phenomena in metamaterial structures*, presented by Tomasz Stefaniuk (page 95)
12:30 – *Advanced functionalities in subwavelength photonic and plasmonic structures*, presented by Ivan Richter (page 96)

13:00–14:30 Lunch

15:30–18:30 Excursion

19:30–23:00 Banquet

Friday, September 9, 2022

Hot Topics IV — Wojanowska Room

9:00 – *Nanocoated optical fiber sensors and biosensors* [Invited lecture], presented by Mateusz Śmietana (page 98)
9:30 – *Optical noiseless quantum amplifiers* [Invited lecture], presented by Jaromír Fiurášek (page 99)
10:00 – *Surface plasmon resonance enhanced photonic devices* [Invited lecture], presented by Piotr Wróbel (page 100)

10:30–11:00 Coffee Break

Wave Optics — Wojanowska Room

11:00 – *Field investigations of the FOS5-04 huge fiber-optic rotational seismograph operating in a closed-loop configuration*, presented by Leszek R. Jaroszewicz (page 101)

11:15 – *Propagation of non-diffracting beams through scattering media*, presented by Spozmai Panezai (page 102)
11:30 – *A microscope-based interferometer with the variable wavelength illumination system*, presented by Dariusz Litwin (page 103)
11:45 – *DeepVID: deep-learning accelerated variational image decomposition for filtration of different types of fringe patterns*, presented by Maria Cywińska (page 104)
12:00 – *Study of impact of decentration of Light Sword Lens in a patient's eye on vision quality*, presented by Jan Bolek (page 105)

12:15 – Closing

12:30–14:00 Lunch

Poster Session
Tuesday, September 6, 18:00–20:00

1. *Experimental measurement of the Hilbert–Schmidt distance between two-qubit states as a means for reducing the complexity of machine learning*, presented by Vojtěch Trávníček (page 109)
2. *Entanglement detection and quantification from collective measurements processed by artificial intelligence*, presented by Jan Roik (page 111)
3. *Intensity modulation/direct detection optical key distribution*, presented by Konrad Banaszek (page 112)
4. *Experimental hierarchy of quantum correlations of Werner-like states*, presented by Kateřina Jiráková (page 113)
5. *Comparison of optical properties of 1×8 Y-branch and MMI splitter based on silicon nitride material platform*, presented by Stanislava Serecunova (page 114)
6. *Using a commercially available LIDAR scanner in cultural heritage research*, presented by Jindřich Švihel (page 115)
7. *Polarization controlled terahertz time domain spectroscopy using dual-color plasma*, presented by Iva Hlobílková (page 116)
8. *EPR quantum steering in a two- and three-mode PT-symmetric system*, presented by Małgorzata Kostrzewa (page 117)
9. *Custom-terminated multimode fibre probe for holographic microendoscopy*, presented by Miroslav Stibůrek (page 118)
10. *Sensor probes for monitoring temperature changes in active layer of permafrost*, presented by Adam Paździor (page 119)
11. *Comparison of optical methods for 3D model generation*, presented by Antonín Černoch (page 120)

12. *Lab-on-a-chip sensing based on 1DPhC resonant cavity*, presented by Jana Durisova (page 121)
13. *Open source workflow for multispectral imaging based on artificial neural networks*, presented by Daniela Růžičková (page 123)
14. *Design of 256-channel 25-GHz AWG for ultra-dense wavelength division multiplexing*, presented by Dana Seyringer (page 124)
15. *Mode locked and free running operation of Nd,Gd:CaF_2 crystal fiber laser*, presented by Václav Kubeček (page 125)
16. *How does ultra-resolution spectrometry help to measure femtosecond impulses?* presented by Marcin Jastrzębski (page 126)
17. *IP-Dip inverted pyramids for application in SERS*, presented by Ivana Lettrichova (page 128)
18. *Optimization of 3D laser printing process for reflective polymer surfaces*, presented by Matej Goraus (page 129)
19. *Split-step methods for numerical modeling of synchronously pumped crystalline Raman laser*, presented by Milan Frank (page 130)
20. *3D photonic structures for optoelectronics applications*, presented by Lubos Suslik (page 131)
21. *Polymer Inverted Refractive-Index-Contrast Grating prepared by laser lithography on Si substrate*, presented by Daniel Jandura (page 132)
22. *Spin-lasers with periodic gratings: toward ultrafast polarization modulation*, presented by Oliver Hejtman (page 133)
24. *Micromanipulation of macromolecules and colloidal particles in complex environment by optical and thermo-optical traps*, presented by Tomáš Kužela (page 134)
24. *Compact vacuum setup for Al^+ and Ca^+ ion trapping*, presented by Jakub Grim (page 135)
25. *Mid-infrared tunable diode pumped Cr:ZnSe laser continuously tunable from 2.1 μm up to 2.7 μm operated at room temperature*, presented by Adam Říha (page 136)
26. *Optical 1:9 splitter based on MMI, prepared by 3D lithography*, presented by Peter Gaso (page 137)
27. *Tunable decoherence of single photons*, presented by Josef Kadlec (page 138)
28. *Spectral and magnetic field dependence of the birefringence of a magnetic fluid*, presented by Norbert Tarjányi (page 139)
29. *Electro-optic shearing interferometry of femtosecond impulses in Hong–Ou –Mandel interferometer*, presented by Stanisław Kurzyna (page 140)
30. *High-precision measurement of the center frequencies of the hydrogen cyanide (HCN) hyperfine transitions in the 1.5 μm wavelength band*, presented by Martin Hošek (page 141)
31. *Analysis of the possibilities to generate and analyze different polarization states of light by twisted nematic liquid crystal*, presented by Monika Owczarek (page 142)

Abstracts

INVITED LECTURE

Ultrastrong coupling between light and matter for quantum technologies

Adam Miranowicz[a,b], Anton Kockum[b,c], Simone De Liberato[a,d], Salvatore Savasta[a,e] and Franco Nori[a,f]

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ABSTRACT

The achievement and control of strong coupling of light and matter has lead to various applications for lasers, quantum sensing, and quantum information processing since 1980s. In my talk, I will review [1] recent theoretical and experimental progress in the ultrastrong coupling (USC) of light and matter, which refers to the light-matter extreme -interaction regime, characterized by the coupling strengths comparable to their transition frequencies. In the last few years, the USC regime has been experimentally achieved in a wide range of different systems with very different spectral ranges. These systems include: superconducting quantum circuits, intersubband polaritons, Landau polaritons, organic molecules, magnetic systems, nano-plasmonics, and optomechanical systems. Emerging applications of the USC regime are focused on quantum technologies and quantum information processing. More specifically, the proposed applications include: cavity- and circuit-quantum electrodynamics (QED), quantum optics, nonlinear optics, quantum metrology, cavity optomechanics, quantum plasmonics, superconductivity, metamaterials, material science, and even quantum field theory, quantum thermodynamics, and photochemistry. Such a plethora of experimental platforms and proposed applications indicates that the USC regime has been attracting great interest among researchers belonging to several different communities of physicists, chemists, and engineers.

REFERENCES

[1] A. F. Kockum, A. Miranowicz, S. De Liberato, S. Savasta, and F. Nori: Ultrastrong coupling between light and matter, Nature Reviews Physics 1, pp. 19–40 (2019).

INVITED LECTURE

3D photonics for application on a chip and optical fiber

Dušan Pudiš*[a,b], Petra Maniaková[a], Tomáš Mizera[a], Patrik Miček[a], Daniel Jandura[a], Peter Gašo[a], Matej Goraus[a], Ivana Lettrichová[a], Jana Ďurišová[a], Ľuboš Šušlik[a], Anton Kuzma[c,d]

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ABSTRACT

Three dimensional (3D) technologies enhance recent panar micro- and nanotechnologies, mainly in the field of photonics, where polymers often effectively substitute semiconductors with very interesting 3D designs and properties. There are many of promising areas of photonics where polymers are useful substitution of semiconductor materials and glass. One of the very promising application field are photonic crystals (PhC). Another area where 3D technology could accelerate research are the passive photonic components for on-chip and on-fiber applications. Passive silicon waveguide and splitting structures have shown a reduction in footprint and attractive designs were presented also in interferometric optical devices as ring resonators and components with integrated Bragg gratings.

Many approaches have been explored for the fabrication of 3D photonic structures and devices, including layer-by-layer surface micromachining, self-assembly and lithographical methods. The laser lithography based on direct laser writing process (DLW) reached remarkable results. This technology achieves highly submicrometer resolutions and acceptable optical quality, what favors it for using in 3D photonic technologies. Here we present different fields of our research where 3D DLW laser lithography was used for different 3D components fabrication: PhC structures, photonic devices for waveguide optics, microstructures for lab on fiber and structures for lab on a chip.

Keywords: direct laser writing, photonic devices, PhC, fiber

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INVITED LECTURE

Optical ion clocks: from single ion to Coulomb crystals

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ABSTRACT

The laser-cooled ion is an excellent absorber that allows accurate laser frequency detection at the long-lived quantum transitions in the ion. By locking the frequency of a highly coherent laser for such a quantum transition, we obtain an optical clock, which currently achieves ultimate relative stability in the 18th order and better. While the most accurate optical clocks with trapped ions (optical ion clocks) are based on individual ions, it is advantageous for the laser frequency locking process to use multiple ions simultaneously. By trapping multiple ions in one electrical trap, a so-called set of ions can be obtained in the Coulomb coupled solid-state, known as the Coulomb crystal. A multi-ion approach can provide a higher signal-to-noise ratio for optical ion clocks with improved stability, but only if all the ions in the crystal are sufficiently cooled and homogeneous electric and magnetic field conditions are provided. In this work, we present an overview of methods and implementation of apparatus for trapping and laser cooling of individual ions and Coulomb crystals, which are necessary for implementing optical ion clocks. The work will also present the current state of signal transmission from optical clocks over the photonic network in Europe.

Keywords: optical ion clocks, laser cooling, Coulomb crystal, electric trap, metrology

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INVITED LECTURE

Event Horizon Telescope and the progress in very long baseline interferometry

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ABSTRACT

In recent years we witnessed an unprecedented progress in the field of high frequency very-long-baseline interferometry (VLBI), driven by the Event Horizon Telescope (EHT) project. Following the formation of a global interferometric EHT array, increase in instrumental bandwidth and sensitivity, and algorithmic developments towards robust sparse interferometric imaging, in 2019 the EHT Collaboration presented the first VLBI image ever obtained at 230 GHz. These developments unlock a new regime in VLBI observations, exploring highest available angular resolutions and emission frequencies, most notably resolving supermassive black holes in M87 and in our own Galactic Center with the resolution comparable to the black hole's Schwarzschild radius. We will discuss the developments leading to these novel capabilities as well as perspectives for the further progress.

Keywords: interferometry, radio astronomy, image analysis

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INVITED LECTURE

Nanoscale laboratory-based coherence tomography with extreme ultraviolet and soft X-ray light

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ABSTRACT

Optical coherence tomography (OCT) is an established method for the non-invasive acquisition of 3D cross-sectional images with broadband near infrared radiation. However, the axial resolution of OCT is limited to a few micrometers.

In our XUV coherence tomography (XCT), broadband XUV or SXR radiation is used instead. This drastically improves the axial resolution. With radiation within the wavelength-range of 2-4 nm an axial resolution below 3 nm could be demonstrated.

Laboratory-based setups for XCT have been built in Jena and Warsaw using XUV radiation of high harmonic generation and laser plasma sources. In these setups, the broadband reflected spectrum of the sample is recorded. It contains information about the depth structure as well as material composition of the sample. Using a novel one-dimensional phase retrieval, both, structure and composition can be reconstructed from a single measurement. The sensitivity is very high. We could even resolve the number of mono atomic layers of graphene encapsulated in silicon.

XCT paves the way for sub-surface nanometer imaging with unique material contrast. Its applications range from solid state physics, semiconductor inspection up to biological imaging. Furthermore, XCT is a very well-suited application for intrinsically broadband HHG and thermal radiation from laser plasmas.

Keywords: tomography, coherence, OCT, extreme ultraviolet, high harmonic generation, laser plasma, nanoscale imaging

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INVITED LECTURE

Challenges in soft X-ray spectromicroscopy using Fresnel zone plates

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ABSTRACT

X-ray microscopy is very useful tool in many fields from fundamental physics through medical application to cometary science. The main advantage is a possibility of chemical analysis on nano scale. There are a few ways to focus the X-rays. The most used in the X-ray microscopy are zone plates.

Soft X-ray scanning microscopes are used primarily for X-ray absorption spectroscopy at the nanoscale. Typically, the spatial resolution is being quoted using resolution of individual images. Presently, those images can be recorded with 15–25 nm resolution. Unfortunately, spatial resolution for spectroscopic analysis is much worse. The reason for this reduction of resolution is the shape of the zone plate focused X-ray beam (see the Figure). Almost all soft X-ray microscopes are using zone plates as focusing element.

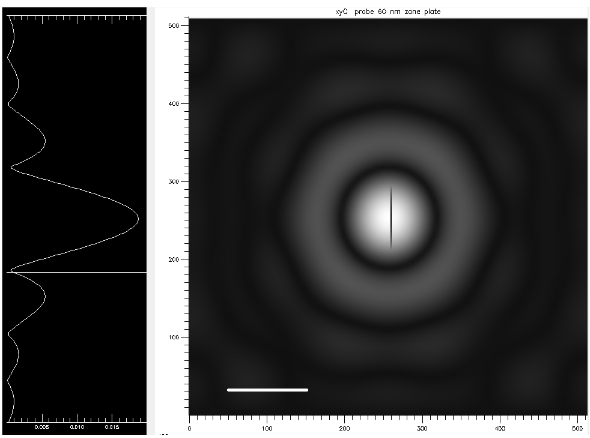

Figure: Typical focused beam profile. Up to 50% intensity can be in the beam wings.

Recent development of ptychography can overcome the limitations in spatial resolution for spectroscopy because the beam shape is used in the final reconstruction of images. While soft X-ray ptychography can be used for imaging with exceptional resolution [1] the application for the spectroscopic analysis is even more important because it can favorably compete with TEM/EELS analysis.

Keywords: X-ray microscopy, zone plate focusing, ptychography, beam profile

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INVITED LECTURE

Astronomical X-ray optics

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ABSTRACT

I will give a short overview of astronomical X-ray optics covering the past, recent and future developments with emphasis on grazing incidende optics and on developments in the Czech Republic. There is long history in the X-ray optics development in the Czech Republic – the first X-ray mirror was produced in 1969. The first Czech X-ray mirror (50 mm Wolter for solar imaging) was flown to space onboard the Vertikal 8 rocket in 1979 as part of a photographic solar X-ray telescope in collaboration with Polish institutes. The recent developments focus on new technologies based on novel light-weight materials such as slumped glass foils and Silicon wafers and also on novel designs and arrangements such as wide-field Lobster Eye X-ray optics.

INVITED LECTURE

Laser-driven X-ray sources for user experiments at ELI Beamlines

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ABSTRACT

ELI Beamlines is a high-power laser facility dedicated to development and applications of laser-driven sources of X-rays and accelerated particles. In this contribution we summarize the current status of research and implementation of three types of X-ray sources: the HHG Beamline, plasma X-ray source and the Gammatron beamline. The HHG Beamline, which is a source of coherent femtosecond XUV pulses, and the incoherent sub-picosecond hard X-ray plasma source are driven by the state-of-the-art OPCPA-based laser system with design values of pulse energy of 100 mJ, pulse duration of 15 fs, central wavelength of 830 nm, and 1 kHz repetition rate. The Gammatron beamline is an ultrafast hard X-ray source based on radiation of relativistic electrons accelerated by a PW-class 10 Hz laser system.

Keywords: laser plasma, X-rays, high-order harmonic generation, K-alpha, plasma betatron

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Stokes and anti-Stokes photon-pair generation in Raman scattering

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ABSTRACT

Nonlinear optical processes are significant in quantum technology as they are often used for the generation of single photons and entangled photon pairs. Raman scattering as a candidate for photon-pair generation is explored recently both theoretically and experimentally. Here, we systematically analyze the Stokes–anti-Stokes photon-pair generation in Raman scattering, akin signal–idler photon-pair emission in spontaneous parametric down conversion, theoretically, to obtain suitable conditions for photon-pair generation. Non-zero mean phonon number and losses in the phonon mode are observed to be relevant parameters in this context in addition to the Raman active material properties and pump power. Specifically, the Raman active materials with stronger anti-Stokes coupling compared to the Stokes coupling constant are suitable for photon-pair generation. Ideal Stokes–anti-Stokes photon-pair generation is possible even for non-zero thermal phonons provided that the phonon losses are negligible. We characterized the performance of photon-pair generation using different non-classicality witnesses and measures, such as noise-reduction parameter, the Cauchy–Schwarz inequality, Gaussian entanglement and steering, and the Bell nonlocality. We also discuss the effect of phonon losses on the observed non-classical features. The results are reported in [1].

Keywords: Raman scattering, photon-pair generation, Gaussian entanglement, Gaussian steering, Bell nonlocality

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Two-beam light with simultaneous anti-correlations in photon-number fluctuations and sub-Poissonian statistics

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ABSTRACT

Two twin beams with a shared signal beam and separated idler beams are used together with the photon-number-resolving post-selection in the signal beam to arrive at two coupled beams with anti-correlations in photon-number fluctuations. Moreover, the beams exhibit the sub-Poissonian photon-number statistics in their marginal distributions under suitable conditions. The post-selected fields with the increasing mean photon numbers are reconstructed from the experimental photocount histograms by the maximum likelihood approach. Also a suitable Gaussian fit of both original twin beams and simulation of the post-selection process are applied to arrive at the corresponding photon-number distributions. Their non-classical properties are analyzed by suitable non-classicality criteria and quantified by the corresponding non-classicality depths. Determining the appropriate quasi-distributions of integrated intensities with negative values, the performance of different non-classicality criteria is discussed. Properties of the post-selected fields reached both by the used and ideal photon-number-resolved detectors are mutually compared.

Keywords: twin beam, non-classical states of light, anti-correlations in photon numbers, sub-Poissonian statistics, post-selection, non-classicality depth

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Unconventional photon blockade in a passive RT-symmetric system

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ABSTRACT

The concept of parity-time (PT) symmetry [1], which explains why some non-Hermitian Hamiltonians have positive and real spectra, was a true breakthrough in quantum mechanics. We have introduced the concept of rotation-time (RT) symmetry in bosonic systems, which is a generalization of the PT symmetry [2]. We also established general principles for constructing non-Hermitian RT-symmetric Hamiltonians.

Degeneracies of open systems described by non-Hermitian Hamiltonians, where two or more eigenvalues merge, are known as exceptional points (EPs). EPs are extensively investigated particularly in optics, where dissipative, non-Hermitian systems commonly appear. It has been shown that also systems without gain components, that include only losses, can exhibit EPs. When only losses are included, a system is known to have passive PT or RT symmetry.

Here, we present a non-linear, passive RT-symmetric system with EPs. This system exhibits conventional and unconventional photon blockade, and thus, can be considered as a single-photon source, as the nonlinearity is crucial for obtaining such phenomena. Furthermore, we can tune photon blockade due to the presence of an exceptional point.

Keywords: PT symmetry, RT symmetry, exceptional point, photon blockade

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Catalysis in charging quantum batteries

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ABSTRACT

Recently the study of energy transfer has brought forward a diverse and rich set of phenomena, in the context of quantum batteries, to be both theoretically and experimentally investigated [1, 2]. Energy transfer limitations is a crucial issue in the context of charging quantum batteries. Techniques such as quantum correlations and initial quantum coherence in the state of the charger have been proposed by authors to eliminate this issue [3–5]. We here instead present two different approaches to boost the energy transfer from a quantum charger to a quantum battery such that the transfer of arbitrary amount of energy becomes feasible. The charger is driven by an external laser field. Both the charger and the battery are modeled by quantum harmonic oscillators. The first approach is simply based on tuning the laser field with the system of charger-battery. In the second novel approach a catalyst qubit is added to the process to enhance the amount of energy transfer to the battery while no energy being stored in the catalyst qubit. Benefits of both approaches are compared and discussed [6].

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Optimal quantum control of charging quantum batteries

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ABSTRACT

Quantum control allows to address the problem of engineering quantum dynamics for special purposes. While recently the field of quantum batteries has attracted much attention, optimization of their charging has not benefited from the quantum control methods. Here we fill this gap. The two-partite charger plus battery system is considered where the energy is pumped to a charger by an external electromagnetic field. We apply for the first time the convergent iterative method for control of the population of a quantum system [1–3] for two cases. First, we apply it for a qubit–qubit case. Next, we systematically develop the formulation of the method for two-oscillators in the Gaussian regime. In both cases the charger is an open dissipative system. Our optimization considers the experimentally viable problem of turning on and off of the external laser field. Optimizing the shape of the pulse significantly boosts both power and efficiency of the charging process in comparison to the known results [4, 5]. Interestingly, when both the charger and the battery are taken as harmonic oscillators, in the regime of small temperatures the optimization yields charging schemes that are robust against the increase of the temperature environment [6].

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Laser plasma sources of soft X-rays and extreme ultraviolet based on a gas puff target

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ABSTRACT

The paper presents soft X-ray and extreme ultraviolet (EUV) laser plasma sources developed for applications in various fields of science and technology. The sources are based on a plasma resulting from the irradiation of a gas puff target with an intense nanosecond laser pulse. The use of a gas puff target in place of a solid target allows the generation of a laser plasma without producing target debris. The targets are irradiated with laser pulses generated by commercial Nd:YAG lasers with duration from 1 ns to 10 ns, energy per pulse from 0.5 J to 10 J with a repetition rate of 10 Hz. The sources are equipped with various optical systems for the spectral range of soft X-ray and EUV, including grazing incidence axisymmetric ellipsoidal mirrors, a grazing incidence multi-foil “lobster eye” mirror, and an ellipsoidal mirror with Mo/Si multilayer coating, to collect radiation from sources and form beams of radiation. The use of these sources in various fields has been demonstrated, including material processing, nanoscale imaging, pulsed radiography and tomography, photoionization of gases and radiobiology. The recent results concerning the use of these sources in plasma studies, soft X-ray absorption spectroscopy and optical coherence tomography are presented.

Keywords: soft X-rays, extreme ultraviolet, lasers, laser plasma, laser plasma light sources

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Spatio-temporal measurements of laser or EUV induced plasmas, in soft X-ray and optical range

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ABSTRACT

In this work X-ray and UV/VIS streak cameras were used for spatio-temporal investigation of laser produced plasmas (LPP) and plasmas induced by photoionization of gases with intense pulses of extreme ultraviolet (EUV). For creation of both types of plasmas, gas puff targets formed temporary in a vacuum chamber, were employed. For the X-ray measurements the streak camera was coupled to a pinhole based imaging system or a spectral system utilizing an X-ray transmission grating. For spatio-temporal measurements in the optical range plasmas were imaged on the entrance slit of the camera using a focusing lens. Investigation on the X-ray range concerned time development of the LPP, during the time corresponding to the laser pulse duration. It was shown that the LPP created at the position of the laser focus is expanding during the laser pulse, hence, the most efficient interaction takes place during the pulse rise time and pulse maximum. From the optical measurements performed for outer regions in respect to the LPP, it can be concluded that the cold gas present outside the LPP is being ionized and excited by ion streams and soft X-rays. This way the surrounding gas is converted to a low temperature plasma.

Keywords: X-rays, streak camera, plasma, imaging system, spectral system

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Nanoscale optical coherence tomography using extreme ultraviolet radiation produced with a laser plasma source based on a gas puff target

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ABSTRACT

Optical coherence tomography (OCT) is a well-established non-destructive c imaging technique providing high resolution cross-sectional views of objects. The axial resolution of OCT is limited to single micrometers when using infrared and optical wavelengths. Recently, optical coherence tomography using broadband soft X-rays and extreme ultraviolet has been proposed to improve the axial resolution. This variant of OCT, known as X-ray coherent tomography (XCT), enables to achieve an axial resolution of a few nanometers. The paper presents OCT with the use of extreme ultraviolet in the wavelength range of 10–20 nm generated using a compact laser-produced plasma (LPP) source based on a double-stream gas puff target. The use of a gas puff target enables efficient extreme ultraviolet emission without producing target debris by laser ablation from a solid target. Two axisymmetric ellipsoidal grazing-incidence mirrors were used to focus the radiation from the source to the sample, and then to focus the radiation reflected from the sample to the spectrometer. Tomograms of nanostructures with 5 nm gold layers buried in a depth range from 40 nm to 100 nm were obtained with an axial resolution of about 20 nm. We also present measurements of Silver/Zirconium multilayer periodic structures with a periodicity of 60 nm.

Keywords: optical coherence tomography (OCT), extreme ultraviolet (EUV), laser produced plasma, laser plasma EUV source

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Investigations of laser produced plasmas in a low-pressure gas environment

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ABSTRACT

For testing this type of plasma special system has been prepared in IOE. In this system, the laser (Nd:YAG) beam is focused into a chamber filled with a mixture of gases at low pressure (1–50 mbar). The focal point is located above the specially prepared gas puff valve. That valve allows to inject a small portion of the gas, forming a dense gaseous target for the LPP creation. Gaseous mixtures were prepared in a special mixing system. The mixture was used to fill the interaction chamber and the gas puff target valve system. After creation of a laser-produced plasma (LPP), the SXR/EUV radiation is emitted and propagates in the gas filling the chamber. Measurements of the LPP and surrounding low temperature plasmas were performed mainly using spectral methods in wide spectral range (SXR – VIS). Such research was used to analyze the evolution of plasma (optical streak camera) and the processes taking place in it (spectrometer). Spectral analysis was supported by the PrismSPECT and PHOPGHER numerical codes.

Keywords: plasma physics, laser induced plasma, EUV, SXR, low density gases, low pressure

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Ray-tracing simulations of a UV/VUV beamline for the PolFEL free electron laser

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ABSTRACT

The PolFEL free electron laser will generate a beam of coherent electromagnetic radiation in the ultraviolet (UV) spectral range with a wavelength of about 150 nm to 300 nm, in the form of several hundred fs pulses, energy up to 50 μJ and repetition rate 50 kHz. Vacuum ultraviolet (VUV) radiation beam in the wavelength range from 50 nm to 100 nm will be obtained by selecting the third harmonic. The optical system of the beamline consists of two plane M1 and M2 mirrors and one focusing ellipsoidal M3 mirror. The radiation produced in the laser hits on the M1 mirror at a grazing incidence angle of 5°. After reflection from the M1 mirror, the beam falls on the M2 mirror at an angle of 17°, which directs the beam to the ellipsoidal M3 mirror, focusing the beam in the image plane at the second focal point of the ellipsoid. The M1 mirror is placed behind the 3 m-thick concrete wall in a hutch separated from the experimental hall by a 1.6 m-thick concrete wall. The optical properties of the beam were tested by ray-tracing simulations using the RAY-UI software, the results of which are presented in the paper.

Keywords: PolFEL, free electron lasers, ultraviolet (UV), vacuum ultraviolet (VUV), ray-tracing

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Decay of one subsystem as a counterpoise to decay of another in quantum computing

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ABSTRACT

It has been shown that it is possible to perform quantum operations on atom-cavity systems with a fidelity high enough to make these operations useful in quantum computations [1,2], despite the fact that each subsystem, *i.e.*, an atom and a cavity field, experiences decay. Here, we show the explanation of this phenomenon – the cavity decay can be set in such a way that it acts as a counterpoise to the atomic decay, and the whole system is in a passive PT-symmetric regime [3]. In this regime the periodicity of an evolution of the quantum state is protected from a destructive effect of the atomic decay and allows for a fine tuning of quantum operations. Moreover, we present a generalization of this idea and its usefulness in quantum computing.

Keywords: passive PT-symmetry, quantum computing, high-fidelity operations

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Nonclassical correlation of photon-phonon in cross mode of the hybrid system

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ABSTRACT

We study photon, phonon, and hybrid-mode photon-phonon nonclassical correlations in a driven nonlinear optomechanical superconducting system, which is composed of linearly coupled microwave and mechanical resonators with a superconducting qubit in one of them. By analyzing steady-state second-order correlation functions, we find parameter regimes leading to 4 different predictions of either the sub- or super-Poissonian boson-number statistics, and either boson antibunching or bunching. Moreover, we find such parameter regimes, which demonstrate 8 different predictions of either blockade or tunnelling effects for photons, phonons, and hybrid-mode excitations. In particular, we find that photon- and phonon-induced tunneling (PIT) can be accompanied by the hybrid-mode photon-phonon blockade effect.

Keywords: photon/phonon blockade, photon induced tunneling, cross correlation, sub/super Poissonian, antibunching, bunching

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Entanglement generation in a system of two interacting anharmonic quantum oscillators

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ABSTRACT

The ability to create and manipulate quantum states is relevant for developing quantum information theory and its applications. Truncated states, *i.e.*, states defined in a finite -dimensional Hilbert space, play a crucial role in that point. Such states are commonly applied in quantum communication and cryptography, and quantum computing. Physical systems in which finite-dimensional states can be generated, and thus the system's evolution is limited to a certain number (usually small) of n-photon states, are called quantum scissors. In the case of linear and nonlinear systems, we call them linear and nonlinear quantum scissors, respectively.

We consider a system consisting of two interacting anharmonic Kerr-type quantum oscillators excited by a series of ultra-short pulses. For such a system, we discuss the influence of excitation on the entangled states' generation. Additionally, we show that the effectiveness of creating maximally or almost maximally entangled states strongly depends on the time between two subsequent pulses and the applied excitation scheme. For example, we check how entanglement production depends on the frequencies of excitations and fact that both subsystems are excited simultaneously.

Keywords: Kerr-type quantum oscillator, quantum correlations, quantum entanglement

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Measuring concurrence in qubit Werner states without an aligned reference frame

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ABSTRACT

The genuine concurrence is a standard quantifier of multipartite entanglement. Even though it is represented by an individual number its experimental evaluation typically requires several tomographically complete measurements that are sufficient to reveal the exact shape of a density matrix of the evaluated state. This tomography measurements require common reference frame, which is stable in the course of measurements. We propose a method that allows to quantify entanglement using random measurements in unknown measurement bases. This idea can be of particular interest for long-distance quantum communications where establishing a common reference frame is either impossible or impractical, *e.g.* orbital satellites. We study both theoretically and experimentally the genuine concurrence for the generalized GHZ states under randomly chosen measurements on a single qubit without a shared frame.

This topic was published recently [1] and the paper was selected as an Editors' Suggestion accompanied with following paragraph and Figure: "Alice lives on Venus, Bob lives on Mars… The biggest problem in their communication is to establish

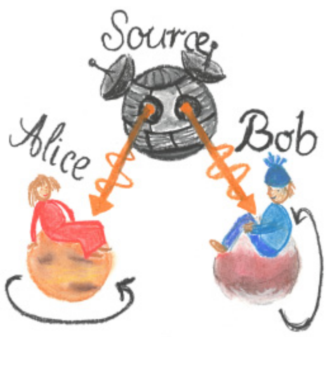

Figure: Teaser image used in Phys. Rev. Appl. as Editors' Suggestion on 23 November 2021.

a common reference frame, so that they can use quantum cryptography for their secret letters. To help them, this study proposes a method for entanglement quantification that does not rely on synchronized reference frames. Counterintuitively, measurements in random and unknown bases can be used to establish just how entangled a quantum state is. This strategy may prove useful in complex quantum communication networks, where establishing a common reference frame (measurement basis) is impractical or impossible."

Keywords: multipatrite entanglement, concurrence, random measurement, Greenberger –Horne–Zeilinger states

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Transfer of EPR quantum steering along two non-interacting qubit chains

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ABSTRACT

Quantum steering is one of the most intriguing phenomena in quantum physics, and it plays a crucial role, especially in quantum information theory. Steerable states are applied in quantum cryptography and communication protocols where they allow for certification of the entanglement between two subsystems. Studies concerning the propagation of various correlations along the chains of qubits are fundamental in the context of quantum communication and quantum computation systems design, where the perfect transfer of the steerable states plays a crucial role in quantum information transmission and quantum key distribution.

In our research, we consider a system consisting of two noninteracting chains of qubits. Each chain is modeled by N interacting anharmonic Kerr-type quantum oscillators. We analyze the time evolution of parameters describing steering between qubits belonging to the same or different chains constituting the system. We show that if the first pair of noninteracting qubits belonging to the two chains are prepared in a steerable state, then such a state can be successfully transferred from the one end of the chain pair to the second one.

Keywords: EPR steering, qubit chains

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Laser spectroscopy of methane near 1650 nm using photoacoustic spectroscopy combined with a fiber amplifier

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ABSTRACT

Quartz-enhanced photoacoustic spectroscopy (QEPAS) of methane near 1650 nm will be demonstrated. In the presented setup, a bismuth-doped fiber amplifier (BDFA) operating beyond 1.6 µm was used to enhance the amplitude of the QEPAS signal and improve the detection sensitivity. A BDFA was pumped at 1540 nm using two 1.5 W pump sources and provided up to ~300 mW at its output (with 1651 nm distributed feed-back laser diode as a seed source). A minimum detection limit of methane sensing of ~100 ppb (parts per billion) for 1 s integration time was obtained. During the conference we will present details about the sensing system, but also about the fiber amplifier, various pumping schemes, BDFA performance and limitations.

Keywords: fiber amplifier, methane sensing, QEPAS, photoacoustic spectroscopy

FUNDING

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Mid-infrared laser-based gas sensing inside hollow-core fibers

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ABSTRACT

In laser-based gas detection sensitivity may be improved through increasing the effective sensing path length, which is typically accomplished with multi-pass cells. Alternative approach is to use hollow core fibers (HCF), which may provide better opto-mechanical and thermal stability and exceptional path-length to sample volume ratio.

During the conference we will present laser-based spectroscopy in the mid-infrared spectral region inside novel, silica-based anti-resonant (AR) HCF. The fibers have been designed for the mid-infrared, where strong molecular transitions of many small molecules are located. We will demonstrate two configurations in which interband and quantum cascade lasers were used for trace gas detection of methane (near 3.3 μm) and nitrous oxide (near 4.54 μm). For both gases detection limits down to parts-per-billion levels were obtained. We will also present the result obtained during a week-long continuous monitoring of ambient air. This experiment confirms suitability of HCF-based spectroscopic sensors for applications that require continuous concentration monitoring.

Keywords: hollow core fiber; HCF; laser spectroscopy; gas sensing; mid-infrared

FUNDING

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The optical performance of anti-reflective coatings in iodine-filled absorption cells

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ABSTRACT

We investigate the optical performance of anti-reflective coatings subject to high temperatures and the presence of iodine gas to determine the most suitable technological process for iodine-filled absorption cell production. Two unwanted effects need to be avoided or mitigated. One is the settling of iodine gas in the coating structure, which reduces the transmittance of the cell windows. The other is the thermally induced spectral shift, which limits the effect of the antireflective coating. We investigate the thermal resistance of TiO_2 and Ta_2O_5 based coatings produced by electron beam evaporation (e-beam) and plasma ion-assisted deposition (PIAD). We prepared sets of quartz samples subject to a range of temperatures and the presence of iodine gas. We show that the choice of the coating technique and annealing procedure can mitigate the aforementioned effects.

Keywords: optical coatings, PIAD, e-beam evaporation, thin films, iodine cells, laser spectroscopy

FUNDING

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Light beam polarization scrambling by the umbilical defects in the liquid crystals cell

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ABSTRACT

Liquid crystals (LCs) are one of the best representatives of self-organized materials which have found a huge number of applications. However, their electro-optical properties are revealed when this material is encapsulated between two planar parallel plates whose inner surfaces are covered with appropriate conducting and ordering materials. Ordering materials allows to predefine orientation of the LC director which strongly influences the optical properties of such a liquid crystal cell (LCC). In most cases when the nematic LCs are used in planar orientation, the ordering material induces uniform orientation of the director and the LCC works as a phase shifter. However, by using specially synthetized bio-polymer alignment layers and, of course LCs, it is possible to induce a vertical orientation of the LC molecules in the LCC, as well. This homeotropic alignment is not a new technology and has been used before. This kind of alignment can be used in two ways. Nematic LC can be vertically aligned with a pre-tilted director and forms a uniform distribution of the LC and its optical properties are comparable with the phase shifter. However, a purely vertical alignment allows to induce umbilical defects in the liquid crystal, which allows to obtain a spatial distribution of a birefringence when the electric field is applied. Such kind of LCC can be called a pseudo-depolarizer or a polarization scrambler. This is because the spatially distributed birefringence in the LCC randomly changes the state of polarization of the input light beam. When this light is analyzed at the point detector, it is depolarized.

During our studies, different alignment and LCs materials were tested to manufacture such light beam polarization scramblers. We have selected materials allowing to obtain the mentioned effect when the LCs was switching not only voltage but also frequency. The thicknesses of LCs for all samples were of around 10 μm. Voltage

driven LCCs were tested within the range of 0–10 V while frequency driven LCCs were tested within the same range of the voltage and in the frequency domain up to 15 kHz for a 4.5 voltage. Optical properties of tested LCCs were characterized by using a polarimetric method. Losses, dichroism, phase shift, and depolarization were calculated with the use of the Lu Chipman theoretical model. These calculations were done in the voltage and frequency domain. Analysis has shown that all tested LCCs are free of dichroism and losses are on the expected levels. Moreover, phase shifts reflect the LCs properties. However, a random distribution of umbilical defects in LCCs allows to obtain proper spatial distributions of birefringence and the measured degree of polarization (DOP) for both types of LCCs allows their comparison. Generally, it was possible to change this parameter and its character depended on the input state of polarization of the light beam. Time stability tests of this parameter show that frequency-driven LCCs can achieve a stabile low-level DOP of around 5% after 5 s, what was impossible for voltage-driven materials.

FUNDING

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Rapid structural transformations in metals after sub-ps pulsed laser annealing

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ABSTRACT

We have studied ultrafast solid-solid and solid-liquid phase transformations in laser-excited metals. Samples (30 nm thick Fe and Pd layers) were annealed at extremely high heating rates (up to ~10^{15} K/s) by sub-picosecond laser pulses. By adjusting the irradiation fluence we have varied the maximum temperature from a ~1000 K up to approx. 3 times the complete melting threshold. The temporal evolution of samples' state was characterized using X-ray diffraction technique at the European XFEL facility. The application of the ultrashort (fs) X-ray pulses allowed to directly probe the

atomic structure of the sample with an unprecedentedly high temporal resolution of ~500 fs (relevant for the ultrafast rates of studied processes) at delay times in the range from before up to tens of ps after excitation with a pump pulse. It enabled new insight into the atomic-level mechanisms and kinetics of ultrafast phase transitions. In particular, we have measured the characteristic time scales of the martensitic transformations in Fe and melting in both, Fe and Pd samples. The proposed experimental approach is matching the timescales of experimental and computational studies of structural transformations, which for conventional annealing techniques combined with XRD characterisation differ by several orders of magnitude.

Keywords: structural transformation, melting, martensitic transformations, pulsed laser annealing, XFEL, X-ray diffraction

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INVITED LECTURE

Pushing the boundaries of entanglement with light, atoms and optomechanics

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ABSTRACT

Entanglement lies at the center of the quantum theory and is often considered an unintuitive phenomenon, characteristic of the microscopic world. To probe the boundary between classical and quantum physics, it is therefore a continuing challenge to create more elaborate entangled states.

In my talk I will present results from experiments in the group of Prof. Eugene S. Polzik at QUANTOP, as well us from labs in QOT at University of Warsaw.

In one of the scenarios we strived to entangle two distant and macroscopic objects via light. One of them is a SiN membrane which acts as a MHz-frequency harmonic oscillator of very high quality factor. The first challenge is to bring this mesoscopic harmonic oscillator to its quantum ground states. This has been achieved by Raman sideband cooling, and verified by sideband thermometry [1]. Next, we incorporated an Cs atomic ensemble into the system, by subsequently passing a beam of light through atoms and optomechanics. The collective spin of the atoms, which we can measure to within the quantum projection noise, interacts with the polarization of light and serves as an effective harmonic oscillator. Our joint measurement of the two systems allowed creation of an entangled state [2].

In the second large experiment, we concentrated on generating states particularly applicable to quantum communication, as shown in our theoretical proposal [3]. It is well known that photon-pair Bell states hold a promise to realized secure quantum key distribution, but ways to multiplex such transmission remain largely unexplored, particularly in practice. Our quantum memory based on Rb atoms was used to generate those Bell states at a very high rate in a highly multiplexed fashion [4]. We have also shown that the generated quantum state exhibits light-atom entanglement, that was for the first time captured and verified using a single camera image [5].

The presented experiments pointed to important challenges in generating macroscopic entangled states as well as their applicability in communication and metrology.

Keywords: atoms, photons, optomechanics, quantum optics, entanglement

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INVITED LECTURE

Quantum non-Gaussianity of multi-phonon states of trapped ions

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ABSTRACT

We present experimental results on deterministic generation and unambiguous estimation of the quantum non-Gaussian states of motion of trapped ions.

We realize the method for a robust experimental accumulation of nonclassicality of motion by deterministic incoherent modulation of thermal phonon number distribution. We demonstrate that repetitive application of the nonlinear anti-Jaynes-Cummings interaction monotonically accumulates the observable state nonclassicality and entanglement potential. The output states converge to a phonon number distribution with high overlap with a particular Fock state and visible quantum non-Gaussian aspects including corresponding negative Wigner function.

We demonstrate a hierarchy of quantum non-Gaussianity criteria suitable for the atomic-mechanical systems, where mechanical heating corresponds to the typical limitation for the preservation of such sensitive properties and present its implementation on up to 10-phonon states of a trapped ion oscillator. We analyze the depth of quantum non-Gaussian features under mechanical heating and predict their application in quantum sensing. These results uncover that the crucial quantum non-Gaussian features are demanded to reach quantum advantage in the applications.

Keywords: trapped ions, Paul trap, quantum mechanical motion, quantum non-Gaussianity

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INVITED LECTURE

Spatio-temporal optical imaging – new step in noninvasive biopsy

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ABSTRACT

Despite the rapid development of optical imaging methods, *in vivo* imaging with penetration into deeper tissue layers is still a major challenge. Optical axial sectioning – obtaining image information from any layer in an object – is usually possible if we have control over the shape of the beam, such as in confocal imaging, or the phase as in holographic methods. Both solutions require high coherence of light that leads to coherence noise in the images, such as speckle and crosstalk, which significantly degrades imaging quality and depth. In this article, we solve this limitation with a technique that we call Spatio-Temporal Optical Coherence Tomography (STOC-T), which uses light beams with controlled spatial coherence. To demonstrate full potential of new method we applied STOC-T to image human retina *in vivo*. STOC-T enabled axial sectioning of choroidal structures for the first time, including those of choriocapillaris, which are usually hidden behind speckles and blurred by eye movement artifacts in the images acquired by other optical *in vivo* methods.

INVITED LECTURE

Free-form gradient index microoptics using nanostructure engineering

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ABSTRACT

Free-form gradient optics is a new class of flat surface passive microoptical components where internal nanostructure determines their optical properties. The structure is composed of a few thousand of subwavelength rods made of two types of glass, ordered into hexagonal lattice according to the computed distribution pattern. According to Maxwell-Garnett's effective medium model, the binary patterns mimic continuous gradient index distribution for wavelengths much larger than the diameter of individual nanorods. Nanostructured optical elements can be developed using standard stack-and-draw fiber drawing technology. We demonstrate the capabilities of this method for the development of several types of microoptical components such as parabolic GRIN microlenses, axicons, diffractive optical elements, vortex phase masks, and artificially birefringent bulk glass. The optical properties of the components are measured and analyzed.

In this work, state-of-the-art in the development of nanostructured gradient index microoptical components is reported. In particular, we present GRIN microlenses with a parabolic refractive index distribution dedicated to operating in the mid-infra-

red range and a broadband vortex phase mask for converting Gaussian beam into an optical vortex with a dedicated charge. Limits and the ability of the method for mass manufacture are discussed.

Keywords: free-form optics, graded optics, microoptics, nanotechnology, optical vortex, beam converters

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INVITED LECTURE

Vacuum levitation of nanoparticles

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ABSTRACT

Micro- and nano-particles levitated in optical fields act as nanoscale oscillators. When operated in vacuum, they become excellent low dissipation optomechanical objects, with minimal thermal contact to the environment. Levitated optomechanics is considered the most promising platform for studying high-mass quantum physics, including macroscopic entanglement of two massive objects. Also, optically trapped nanoparticles represent the testbed for nanoscale stochastic processes. No matter what the application is, the experimenters face the problems of preparation, characterization and control of mechanical system. We present experimental realization of microscale system of two coupled oscillators, which is made up of two optically levitated and optically bound micro-particles. We reach air pressure for which the normal-mode splitting start to occur and show, that an active control of the system needs to be employed in order to prevent particle collision while decreasing the pressure even more. We introduce a Bayesian inference based framework, which uses the measured stochastic trajectories of the micro-particles to estimate the optical forces acting on them. Although this framework was inspired by the need for characterization of optical binding forces, it is usable for estimation of optical forces from stochastic trajectories in general situations.

Keywords: levitated optomechanics, optical binding, coupled nanomechanical oscillators, dual-beam optical trap, spatial light modulator, Bayesian inference

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INVITED LECTURE

Optically trappable flexible micro-structures

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ABSTRACT

The development boom of biomedical lab-on-chip (LOC) applications during the last two decades brought the need for the miniaturization of conventional mechanical actuators, sensors, and manipulators. Light-driven mechanical microstructures, trapped and moved by optical tweezers, can be easily integrated into the microfluidic LOC environment. The majority of light-driven microstructures is prepared by two-photon polymerization. In this work we overview our efforts to exploit the possibilities of working with flexible (deformable) micro-structures, which were not used in biomedical applications, yet. Two well-defined LOC application areas were targeted: micro-rheology and single-cell manipulation. Micro-viscometers utilizing the effect of the surrounding fluid medium on the deformation (deflection) of flexible micro-cantilevers were developed. The novel viscometer devices were anchored to the bottom glass surface of microfluidic systems. Light-driven elastic micro-robots were designed and tested for capture, transport, and release of single cells. To facilitate the flexible microstructure development and optimization, the material properties of the used photo-polymers were determined. It was shown that the flexible microstructures possess viscoelastic characteristics.

Keywords: two-photon polymerization, optical tweezers, micro-structure, viscosity, cell manipulation

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Optical force aggregation of gold nanoparticles as a tool to fabrication a multifunctional sensor

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ABSTRACT

Optical nano-printing provides a versatile platform to print various nanometer size particles into arbitrary configurations. Optical printing, the use of light to direct the formation of a desired structure, has been of significant interest in the last two decades. For particles much smaller than the laser wavelength, optical forces can be well described in the dipole approximation. For a focused laser beam, two main optical force components are identified: the gradient force, which attracts particles toward the high-intensity focal spot, and the scattering force, which tends to push particles along the beam propagation direction. When the light is nearly resonant with the particle localized surface plasmons resonance, optical forces are dominated by radiation pressure and can be used to efficiently push nanoparticles along the beam optical axis onto a substrate. In this context, optical forces can be applied to optically print nanoparticles into patterns aggregated elements on surfaces such as glass. Here, we summarize a recent progress in our experiments that use optical nanoprinting of plasmonic nanoparticles to create an active aggregate in a solution containing biomolecules or nanoplastics. The active aggregate, produced on the base of optical forces, serves as a sensitive sensor which is used to detect biomolecules in concentration below the limit of detection for Raman spectroscopy and/or to detection of nanometer size plastic particles.

Keywords: optical printing, optical pushing, surface enhanced Raman spectroscopy, nanoplastics, sensor, biomolecule

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Compliance of numerical modelling with experiment in optical tweezers in geometric regime

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ABSTRACT

The problem of numerical simulations of the optical trap is widely discussed in literature for three regimes: geometrical optics for objects larger than wavelength of trapping laser, Lorenz-Mie regime for object's size close to the wavelength and dipole approximation for trapped bead smaller than the wavelength. Despite the many articles in this field, the issue of comparison of numerical results with the experiment is ignored.

Here we show the compliance of numerical simulations with the experiment. By utilizing geometrical optics methods it is possible to numerically recreate behaviour of beads for specific experimental setup. The parameters available in the simulation have their direct counterpart in the experimental system, which allows for comparison and verification of numerical simulations against the experiment. The data obtained from simulation and experiment is compared using statistical analysis of trajectory.

Compliance of numerical simulations with experimental data proves useful for verification of methods of recording the object's trajectory in a trap.

Keywords: optical trapping, optical tweezers, numerical modelling, experiments, compliance of simulation with experiment, geometric optics regime

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Optically powered train of microparticles

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ABSTRACT

The optical train of microparticles waveguide the light and stabilized itself due to strong optical forces. This phenomenon is similar to the soliton creation in microparticles solution. The difference is that in this case particles develop one after another from the reservoir in direction of light propagation similarly to a chain developing from a spool or a train. We experimentally and numerically study the effect and evaluate the forces acting on micorparticles in the train depending on the microparticels size and find different regimes of behavior. Structures made of particles smaller than the laser wavelength can support only a single mode, therefore are most stable and can form chains composed of hundreds of particles long. Structures made of larger particles can support number of modes, which interfere and cause oscillations of light intensity. This makes stable only structures of a few parcels and limit the net longitudinal force acting on them. In some special cases it is possible that the net longitudinal force acting on the structure is equal to zero and the structure is a stable but does not move.

Keywords: optical tweezers, solitons, optical forces

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Phosphate glass nanostructured core fiber for laser with dual wavelength emission

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ABSTRACT

In recent years the novel active glass materials for optical fibers with broadband emission are of great interest due to potential application in spectroscopy, environmental monitoring or medicine. Development of that kind materials is based on elaborating the glass matrix co-doped with different rare earth ions, *e.g.* Er, Yb, Ho, Tm. Glasses doped with multiple rare earths characterize with a high number of spectroscopic parameters, due to the presence of energy transfer phenomena between those different rare earth ions. Nonlinear nature of that phenomena varying with the dopants concentration levels, makes the design and development of optical fibers made of glass doped with several active ions not trivial.

In this work, we present the nanostructured material composed of several separated glass areas with subwavelength size with individually designed parameters. As a proof-of-concept, we propose the active phosphate fiber with the core consisted of two types of glasses doped with Yb^{3+} and Er^{3+} ions, which exhibit independent performance. The presented phosphate fiber laser operates simultaneously at dual wavelengths at 1.04 μm and 1.535 μm with very good beam quality of $M^2 = 1.14$ and slope efficiency of 23.0% and 9.8%, respectively. To our knowledge, this kind of fiber has not been demonstrated previously.

Keywords: fiber laser, phosphate glass, ytterbium, erbium, nanostructuring

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Negative curvature hollow-core silica optical fibres with extended spectral transmission range

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ABSTRACT

We develop a technology of negative curvature hollow-core fibre drawing. The fibre glass material has extremely small overlap with guided modes. This allows extension of spectral transmission range well into ultraviolet and infrared regions. Together with tight light confinement, fibres allow for efficient interaction of guided modes with gases filling the core. We will report on design, drawing and characterization of silica fibres covering spectral range from 220 nm to 4200 nm. Experimentally measured characteristics will be compared to numerical simulations. First results on gas-light interactions will be given.

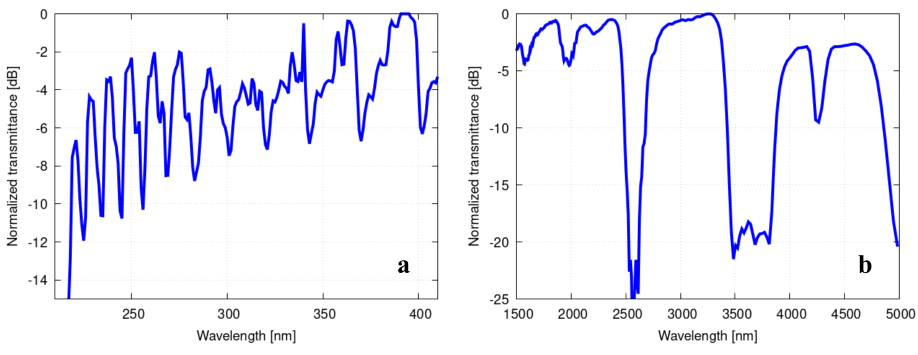

Figure: Normalized transmittance of (**a**) UV, and (**b**) mid-infrared hollow-core silica optical fibre. Spectra are not corrected for gas absorption lines.

Keywords: negative curvature hollow core fibres, gas cells

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Nanostructured large mode area fiber for laser applications

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ABSTRACT

We study a possibility of development of a passive silica based large mode area fiber with the nanostructured core (nLMA fiber) devoted to fiber Bragg grating (FBG) inscription for application in an all-fiber laser cavity. The core diameter of nLMA fiber is 30 µm. The fiber is perfectly matched to the commercial active fiber with NA = 0.06 and core/cladding diameters 30/250 µm. Measured modal characteristics and bending loss of the fiber confirm single-mode operation for bending diameter of 8 cm with bending losses as low as 0.15 dB/m. Although the nanostructured fiber core is low germanium doped, UV inscription of high reflectivity (98.5%) fiber Bragg grating was possible. The performance of fabricated FBG was verified in fiber laser setup. The laser cavity formed with highly reflective FBG inscribed in the nLMA fiber and Fresnel reflection on the free end of active fiber resulted in lasing efficiency of 65.5%. The flexibility of the nanostructuring approach gives prospects for the development of free-form large mode area fibers for passive fiber components and matched with any type of active fibers.

Keywords: fiber Bragg gratings, optical fiber lasers, optical fiber materials, nanostructured materials

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Selective excitation of different combinations of LP_{01} and LP_{11} polarization modes in a birefringent optical fiber using a Wollaston prism

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ABSTRACT

Controllable excitation of spatial and polarization modes is of high importance in numerous applications, such as nonlinear optics, mode division multiplexing, interferometric measurements or sensing. We propose an effective method for selective excitation of different combinations of modes from LP_{01} and LP_{11} groups in a birefringent fiber. In the proposed method, the mode selection is realized with only a Wollaston prism, a rotatable polarizer and a half-wave plate, which ensures the possibility of high-power operation, low wavelength dependence, and tunability. Our approach makes it possible to excite almost all possible combinations of the LP_{01} and LP_{11} polarization modes in a broadband spectrum and to continuously tune the relative coupling efficiencies between them by transverse shifting of the Wollaston prism. We demonstrate experimentally that the suppression rate of the unwanted modes with respect to the targeted mode exceeds 20 dB. As example applications we show generation of different nonlinear phenomena, including supercontinuum generated in the LP_{11} mode and intermodal four-wave mixing.

Keywords: selective modes excitation, birefringent optical fiber, higher-order modes, nonlinear fiber optics, Wollaston prism

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Spectral properties of photonic crystal fibers infiltrated with ferroelectric liquid crystals doped with nanoparticles

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ABSTRACT

Photonic liquid crystal fibers (PLCFs) have attracted significant attention since the beginning of the XXI century due to their unique electro-optical properties. The PLCFs can find numerous practical applications, including tunable long-period fiber gratings, attenuators, and polarization controllers. The innovative in-fiber optical devices require liquid crystals (LCs) with improved electro-optical properties. Chiral smectic C (SmC*) LCs, also called ferroelectric liquid crystals (FLCs), are especially attractive for this purpose due to their fast electro-optical response at low electric fields. It has been observed that the application of aligning materials to FLCs and doping of nanoparticles (NPs) in the LC matrix can further enhance their electro-optical parameters as faster switching times, lower operating voltages, and luminescent properties.

In the present study, we have focused on investigations of spectral properties of isotropic PCFs infiltrated with FLC mixtures doped with titanium dioxide (TiO_2) NPs in different concentrations. As a host material, we have used an

LMA-10 isotropic PCF with inner sides covered with photo-aligning material SD1 (DIC, Japan) to improve the orientation of the NP-FLC nanocomposite molecules along the PCF's air holes. An FLC mixture W212 (MUT, Poland) was considered in our studies, in which TiO_2 NPs were dispersed. We have analyzed electro-optical response times of the investigated PLCFs under the influence of the external electric field. Based on our observations, doping FLCs with TiO_2 NPs resulted in a significant improvement of their electro-optical response times.

Keywords: photonic liquid crystal fibers, ferroelectric liquid crystals, nanoparticles, electro-optical properties

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Fiber-optic distributed monitoring of temperature change in active layer of permafrost

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ABSTRACT

In order to adapt to climate changes and produce enough food to feed the world population humankind has to understand the processes governing the crisis and be able to model them. That requires sufficiently detailed data on the past climate changes.

The history of climate change is preserved in the permafrost. Thus, it is crucial to measure its temperature profile. But there is an even more important reason to monitor the temperature changes in an active layer of permafrost – the one that seasonally thaws – as its melting may result in releasing greenhouse gases from organic carbon contained in this layer and amplification of the positive feedback loop of the climate change.

Currently established methods of monitoring the permafrost are not ideal for this task, as the electrical resistivity tomography cannot penetrate into the frozen layers, while the thermistor strings have quite low spatial resolution.

We present a proof-of-concept for realization of a fiber-optic system for distributed monitoring of temperature profile in soils. Our system, comprised of LUNA OBR4600 optical backscatter reflectometer as an interrogator and single-mode fiber-optic cable with vertical sensor probes at the end, has been installed and tested on the island of Spitsbergen in the Svalbard archipelago.

Keywords: optical frequency-domain reflectometry, distributed temperature sensing, fiber-optic sensor, environmental monitoring

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Two-photon vision – infrared light perception in the function of duty cycle and wavelength

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ABSTRACT

Two-photon vision is a newly discovered phenomena of perception of pulsed infrared (800–1300 nm) laser beam as a color corresponding to approximately half of the laser wavelength. It occurs due to two-photon absorption in visual pigments [1]. This work aims to characterize this phenomenon regarding laser duty cycle parameters and wavelength. Similar to the normal, one-photon version, the visual threshold is a function of wavelength [2] and reflects the contribution of visual pigments of the retina to the visual process. Unlike one-photon vision, the visual threshold changes in laser pulse train parameters – its duration, repetition rate, and shape [3]. A full understanding of the phenomenon will be beneficial for the development of two-photon microperimetry [4] – a new visual field testing technique that shows a promising perspective for ophthalmic applications [5].

Keywords: infrared vision, two-photon vision, pulse duration, pulse repetition rate

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Spatio-temporal optical coherence tomography (STOC-T) for high-resolution, wide-field structural and blood flow imaging of the human retina *in vivo*

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ABSTRACT

Conventional scanning optical coherence tomography (OCT) combines time- with confocal gating enabling high-speed, high-resolution cross-sectional imaging of the human retina. Classic OCT, however, does not provide high-resolution en face images of the outer retinal layers due to eye aberrations and the fundamental tradeoff between imaging depth and transverse resolution. To solve these problems, we developed the eye imaging modality, Spatio-Temporal Optical Coherence Tomography (STOC-T, Fig. 1).

Here, we show that our retinal data sets can be also used to extract deep blood flow in the human retina. Figure 2 shows representative *in vivo* images of the healthy retina. We varied the Doppler frequency ranges to reveal either slow (< 6 kHz) or fast movement (> 6 kHz). The last band, 0–30 kHz, includes all possible frequency ranges and thus shows the flow of all moving structures at all possible speeds. We also compared our data to OCTA and ICGA angiographies. We conclude that STOC-T is a promising approach for providing high-resolution, high-speed functional eye imaging modality.

Keywords: optical coherence tomography, eye imaging, optical coherence, statistical optics, speckles, blood flow

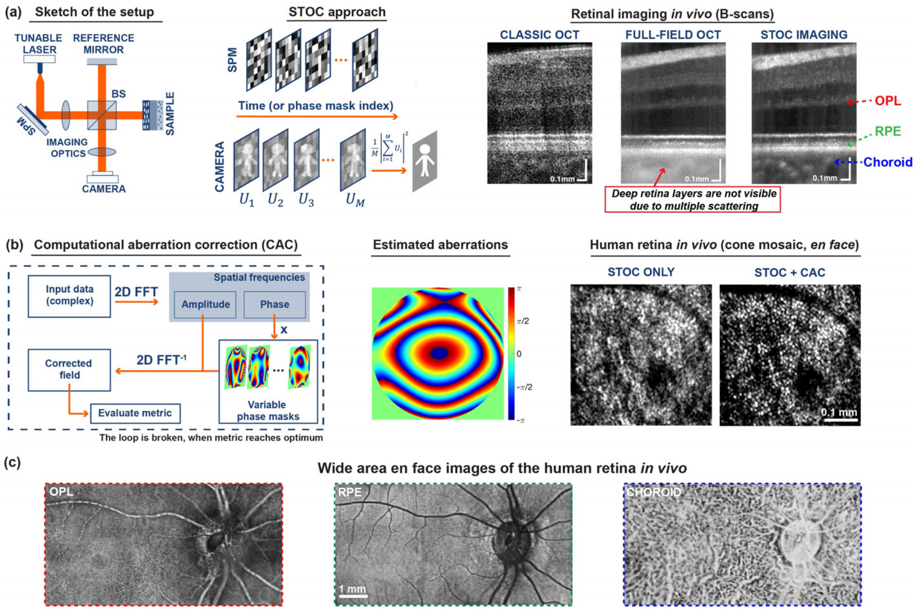

Fig. 1. High-resolution imaging of the retina by spatial phase modulation and computational aberration correction.

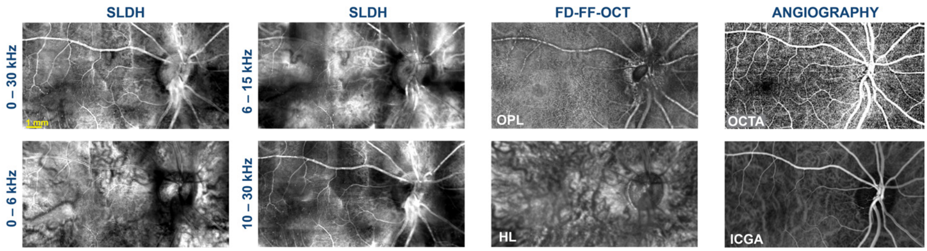

Fig. 2. Blood flow (SLDH) and structural images (FD-FF-OCT) derived from STOC-T are co OCTA and ICGA.

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The mechanism of the self-adjustment of the human eye

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ABSTRACT

The eyeball is continually subjected to forces that cause alterations to its shape and dimensions as well as to its optical components. Forces that induce accommodation result in an intentional change in focus; others, such as the effect of intraocular pressure fluctuations, are more subtle. Whilst mechanical properties of the eyeball and its components permit mediation of such subtle forces, the concomitant optical changes are not detected by the visual system. The eyeball is subjected to small daily variations in IOP and, these processes will exert forces on the outer coat of the eyeball and on the cornea, causing changes in axial length and corneal shape. These changes act in synchrony in order to preserve image quality on the retina. This requires a balance between the rheological properties of the cornea and sclera as well as a stabilizing feature that can maintain the corneal shape and to help to adjust it in response to IOP changes. Optical modelling can indicate where changes in ocular biometry are likely to occur. Optical self-adjustment is postulated as the mechanism that maintains image quality. The purpose of this study is to investigate how self-adjustment may occur using an optical model of the eyeball and to test the requisite optical and biometric conditions.

Keywords: optical self-adjustment. intraocular pressure, eye biometry, optical eye model

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Birefringence of the cornea

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ABSTRACT

Cornea is a frontal part of the eye and its existence is crucial for process of vision. It consists of hundreds of layers called lamellae which structural properties and arrangement cause optical anisotropy. There are several optical methods that allow to measure the corneal birefringence based the calculation on Mueller matrix but no of them use the same path to deliver polarized light and receive the light with information about the measured medium. Proposed optical set up makes use of the Liquid Crystal Variable Retarders and linear polarizer as the polarizer and analyzer at the same time which forces that light pass twice through the measured medium. This kind of optical set up may be used to corneal measurements assuming that the iris acts as a reflective mirror. The results obtained with the proposed optical system are comparable to those obtained with other methods.

Keywords: birefringence, anisotropy, cornea

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Age-related changes in the morphology and optical density of the crystalline lens

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ABSTRACT

The crystalline lens plays a vital role in the optical system of the human eyes to create images. As human grows older, the crystalline lens also grows in size and becomes less transparent. An increase in opacifications within the lens leads to the development of cataracts. The crystalline lens is a natural GRIN lens, due to which backscattering from the partially transmitted light is recorded as discontinuities (bright and dark zones) in the optical signal. The cross-sectional images acquired with imaging techniques like OCT, slit-lamp photography, *etc*., have been used to detect the lenticular changes. These images were also used to identify optical signal discontinuities defined using Oxford nomenclature to categorize cataract-type in the eye. We used a custom-built low-coherence interferometer to acquire high-resolution three-dimensional images of healthy crystalline lenses from 49 volunteers. We studied the optical signal discontinuities and found that a bright zone is more highly responsible than other zones for age-related morphological changes like thickness and optical scattering. With age, dark zones become thinner and contribute less to the overall thickening and transparency of the crystalline lens. We present age-related morphological changes in the crystalline lens and its degrading optical quality measured with an adaptive optics visual simulator (VAO) and double-pass system.

Keywords: cataract, crystalline lens, OCT, scattering

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Probing asymmetries in corneal biomechanical properties with optical coherence tomography

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ABSTRACT

Improving the accuracy of the assessment of corneal deformation asymmetries requires simultaneous measurements at multiple spatial points. In this paper, we present a simplified solution towards 3D measurements of the rapid, air-induced corneal deformation-recovery process. The developed prototype utilizes an adapted spatial-depth-encoded multiplexing scheme. Based on the outcomes of FEM simulations, the system was designed to acquire simultaneous measurements at nine, spatially distributed points. The central imaging channel offers the crosshair preview mode necessary for patient alignment. The remaining 8 points were circumferentially distributed along a central ring with a radius of 1.1 mm. Combination of minimal sensitivity roll-off 1300 nm swept laser with high sampling rate digitizer enabled the effective operation of multiplexing scheme. The power levels at the sample were kept well under

the safety standards for OCT corneal imaging at 1300 nm wavelength. We also developed image segmentation routines for the automatic delineation of temporal deformation profiles for each of the 9 measurement spots. Finally, the prototype system was tested on healthy volunteer eyes, as well as *ex-vivo* porcine eyes, under various IOP conditions and mechanical behavior altered by the collagen cross-linking procedure.

Keywords: corneal biomechanics, optical coherence tomography, corneal asymmetries, interferometry, air-puff, tonometery

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Engineering of light delivery system to improve the imaging capabilities of optical coherence tomography instruments

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ABSTRACT

Optical coherence tomography (OCT) is a non-invasive imaging modality enabling generation of micrometer resolution, two-dimensional (2-D) cross-sectional images and three-dimensional (3-D) volumetric data presenting internal structure of optically scattering and reflective tissues. Over 30 years after its demonstration, OCT has become a standard clinical imaging modality in ophthalmic diagnostics for the detection and treatment monitoring of ocular diseases. As any optical imaging modality, OCT requires light to penetrate the tissue in order to generate the image. Therefore, design of efficient light delivery scenario is critical to extract information on the internal structure of the object. In this talk, we will present different approaches to increase the performance of OCT systems in terms of their ability to visualize weakly scattering structures of the eye. In particular, dynamic control of the optical beam focus allows for OCT image enhancement, leading to the visualization of the vitreous details at both the vitreo-lenticular and vitreo-retinal attachment sites in an unprecedented manner. Manipulation of the light beam properties enables also sequential visualization of the anterior and posterior segment of the eye, and such whole eye imaging can be also used to perform quantitative ocular biometry

Keywords: tunable optics, optical coherence tomography, optical imaging

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3D printed HMM metamaterial near-field probe for sub-diffraction imaging

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ABSTRACT

Near-field optical probes offer genuine way to characterize, visualize and manufacture sub-wavelength features by nanolithography. Conventional state-of-the-art probes are realized by means of tapered silicon cones offering substantial resolution, however demanding complicated fabrication techniques. Herein we present a novel metal-coated near-field probe fabricated using 3D two-photon absorption lithography in combination with layered metal-based metamaterial achieving sub-wavelength resolution using hyperbolic isofrequency surface. The metamaterial is formed by periodically grown thin films of silver and PMMA with thicknesses on the order of nanometers to avoid diffraction and photonic bandgap formation. Optical response of the structures was simulated using commercial FDTD software from Lumerical. Begin the abstract two lines below author names and addresses.

Keywords: near-field probe, metamaterial, HMM, SNOM

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Calibration procedure of the multimode optical fibre micro-endoscope

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ABSTRACT

Using multimode optical fibre in micro-endoscopy has both advantages and drawbacks. Especially small footprint of the fibre probe in the order of tens of micrometers in diameter, and possibility to modify the facet to obtain special optical and/or mechanical properties are important to minimize the penetration damage when imaging a tissue of living organisms. On the other hand, the imaging procedure requires complex optical apparatus for shaping of the light entering the fiber probe to eliminate the mode scrambling originated in different group velocities of particular modes, and an intricate preparation step – calibration process mapping input holographic patterns to output foci in the sample space. Both the calibration technique and the efficiency of the focusing the light at the distal end of the optical fiber will be discussed.

Keywords: micro-endoscopy, multimode optical fibre, holography, spatial light modulator, tramission matrix, bio-imaging

FUNDING

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Extended depth of focus lensless holographic microscopy imaging

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ABSTRACT

Digital lensless holographic microscopy (DLHM) is a rapidly developing technique, that enables for extremely large field-of-view (even over 100 mm^2) imaging with a micrometer resolution. It bases on recording an in-line hologram of a thin sample, and then numerically backpropagating it to the object plane to reconstruct sample amplitude and phase distributions. When imaging a group of objects, classical DLHM solutions require that all objects are placed in the same plane, otherwise, reconstruction in a given plane would be disturbed with a Gabor fringes coming from the out-of-focus objects. Here we present a fully numerical method that can overcome this limitation and allow for sharp imaging of objects placed at a wide range of distances (even over 100 μm) along optical axis. Proposed method uses binarization routines to mask imaged objects in a plane transverse to the optical axis, and autofocusing algorithms for determining the propagation distances for each individual object. The final extended depth of focus reconstruction is obtained by propagating found objects over calculated distances and summing the propagation results. We evaluate the proposed method, on a group of simulated microbeads and on the experimental data containing a group of spermatozoids moving in a 100 μm depth chamber.

Keywords: digital lensless holographic microscopy, extended depth of focus, lensless imaging, Gabor in-line holography

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Optimization of signal-to-noise ratio and attempt to increase resolution in lensless in-line digital holographic microscopy

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ABSTRACT

Lensless digital holographic microscopy (LDHM) setups are especially attractive due to their compact setups and ability to omit limitations connected with employment of microscope objective. Main advantages of LDHM are large field of view (easily above hundred of square milimeters), micrometer resolution and quantitative phase contrast imaging. Our research aims at LDHM hardware optimization. Obtaining high resolution images requires small pixels, which can capture dense Gabor fringes, thus camera plays crucial role. LDHM systems use coherent light sources and their type determines the achievable resolution and noise presence. We show that shorter wavelength and narrower spectrum enables greater resolution, while wider spectrum enables noise reduction with a serious risk of detrimental resolution drop. In this contribution we employ rotating diffuser to alter spatial coherence of illumination and cancel out coherent artifacts (high/medium/low frequency speckles, parasitic interferences etc.). Introduced modification allows to get lower noise without any noticeable drop in resolution for both phase and amplitude imaging regimes.

Increase of resolution in LDHM is achieved by super-pixel-resolution, which usually requires precise lateral camera shifting (with, *e.g.*, piezoceramic). We attempt to augment resolution with relaxed requirements on displacement precision.

Keywords: lensless digital holographic microscopy, rotating diffusor, super pixel resolution, quantitative phase imaging

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Nonlinearity shaping in nanostructured glass-diamond hybrid materials for optical fiber preforms

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ABSTRACT

The difference of nonlinear response of the nanodiamond (ND) and the crystalline bulk diamond is a surprising, yet largely unexplored feature of these optical materials. For the bulk diamond the nonlinear index of refraction n_2 has been well investigated and its value is positive and varies in the range $n_2 = 4 \div 17 \times 10^{-20}$ m^2/W. Whereas the study of nonlinearities in water suspension of detonation nanodiamonds (DND) with particle size of 5÷10 nm shows the negative $n_2 = -6 \times 10^{-19}$ m^2/W. Negative value of n_2 opens intriguing avenues for shaping of the nonlinear dynamics of new, hybrid optical materials containing NDs incorporated into a host matrix. We investigated the feasibility of exerting an influence on the nonlinear refractive index of fiber-drawable Schott F2 glass through ND incorporation in the volume of the material. Uniform integration of NDs was achieved by nanostructurization of the optical fiber preform in which the core consisted of 790 soft glass (Schott F2) canes functionalized with NDs. Investigated samples of the preform were prepared as flat-parallel polished, 2 mm-thick cylinders and core diameter of 1.6 mm. The Z-scan measurements of the ND-functionalized core revealed about 4% lower nonlinear index of refraction compared to the pure F2 reference glass.

Keywords: nanodiamonds, nonlinear index of refraction, Z-scan method, fiber optics

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Gradually twisted highly birefringent optical fiber for vortex modes generation

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ABSTRACT

We experimentally demonstrate that by using a 3 cm long gradually twisted highly birefringent fiber with stress applying elements it is possible to adiabatically transform four LP_{11} modes of non-twisted fiber into vortex modes of highly twisted fiber in a wide spectral range. The proposed approach exploits recent theoretical findings showing that in spun fibers of this type, the first-order LP_{11} modes evolve with increasing twist rate toward left- and right-handed circularly polarized vortex modes HE_{21}^{+}/HE_{21}^{-} with an orbital angular momentum equal to ±1 (total angular momentum equal to ±2) and toward quasi-TE_{01}/TM_{01} modes with the total angular momentum equal to 0. The transformation path for respective LP_{11} mode depends on the value of its initial effective index. The proposed conversion method has a purely topological origin; therefore, it is broadband in nature, in contrast to the methods based on resonant effects. Moreover, the proposed mode converter is easy to manufacture and is based on standard, commercially available birefringent fibers. We also show that this mode converter can be used in fiber-based, optical vortex beams source operating in broadband or tunable mode. In the system we propose, the twisted PANDA fiber is powered by broadband supercontinuum or tunable Raman solitons generated in the LP_{11} polarization modes of a birefringent microstructured fiber with a specially designed dispersion. The high modal and polarization purities of the beams after successive transformations were experimentally confirmed.

Keywords: optical vortex, LP_{11} modes, mode conversion, birefringent optical fiber, nonlinear optics, optical vortex source

FUNDING

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Development of single crystal $CsPbBr_3$ perovskite core optical fiber

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ABSTRACT

In this report, we present the fabrication and properties of the first to our knowledge fiber with single crystal $CsPbBr_3$ core. Halide perovskites (ABX3; *e.g.* A = Cs^+, $CH_3NH_3^+$; B = Pb^{2+}, Sn^{2+}; X = Cl^-, Br^-, I^-) focused the attention as a new class of the functional materials due to their outstanding properties. Perovskites exhibit *e.g.* luminescence, tunable bandgaps, large absorption coefficient, high carrier mobility, and low production costs. Therefore, they are used in many optoelectronic devices like solar cells, light-emitting diodes, lasers, photodetectors, *etc*. Besides all advantages of the halide perovskites, several challenges still have to be faced. Halide perovskites are very sensitive to humidity, and their composition is not environmentally friendly. Fabrication of glass fibers with the crystalline core can solve both problems by isolation of the crystals from the external conditions. Moreover, exploiting the properties of the fibers and perovskites may lead to the creation of a new class of functional fibers. For the preparation of the crystal core – glass clad fiber molten -core-method was performed. Obtained fibers were characterized by transmission measurements, single crystal X-ray diffraction, and photoluminescence excitation and emission spectroscopy. Experiments revealed, that obtained core is crystalline $CsPbBr_3$ perovskite cubic phase exhibiting green luminescences at 340 nm.

Keywords: halide perovskites, optical fiber, molten-core-method

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Observation of soliton trapping in the microstructured optical fibers with different group birefringence

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ABSTRACT

Soliton trapping is a known phenomenon observed in conventional birefringent fibers. It results from the cross-phase modulation mechanism, where intense soliton pulse forces the common group velocity and leads to the trapping of another copropagating pulse. Interestingly, trapped pulse can be generated and amplified by the orthogonal Raman gain of the soliton, causing generation of new polarization components and therefore making this topic important for applications demanding high polarization purity of tunable sources which use Raman-shifted solitons. Our studies focus on soliton trapping in microstructured birefringent optical fibers, which has not been explored so far. The results differ qualitatively from the case of soliton trapping in conventional fibers. Soliton polarized along the slow fiber axis conserves the polarization state. Soliton polarized along the fast fiber axis partially transfers energy to the orthogonal polarization. The energy distribution between the polarization modes depends on the pump polarization azimuth angle, but the slow axis is privileged. Furthermore, the central wavelengths of the pulses have matched group velocities. In this talk, we compare the results obtained for two fibers with different magnitudes of group birefringence (10^{-4} and 10^{-3}). The measurements were performed as a function of the propagation distance and pump power and polarization.

Keywords: nonlinear optics, soliton trapping, linearly polarized solitons, soliton self-frequency shift, microstructured optical fiber, birefringent optical fiber, orthogonal Raman scattering

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INVITED LECTURE

Optical detection of nuclear magnetic resonance at zero magnetic field

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ABSTRACT

Nuclear magnetic resonance (NMR) is one of the most powerful contemporary methods of chemical analysis and medical imaging. Yet, due to ever-increasing demand on the strength of applied magnetic field, application of the conventional NMR is limited to nonmetallic materials or pace-maker-free and metallic-orthoprostheses-free patients. Moreover, generation of extremely strong, ultra-homogeneous fields constitutes the great technical challenges, making the technique immobile, expensive, and complex.

Motivated by these limitations, several years ago we started to investigate the ability to detect NMR signals at zero- and ultralow magnetic field (ZULF). These are very different NMR conditions, operation under which requires implementation of ZULF NMR required addressing several problems of both fundamental and technical nature.

During the presentation, I will present our approach toward optical detection of NMR signals at ZULFs. I will particularly focus on application of optically pumped magnetometers for detection of slowly oscillating (up to 1 kHz) magnetic fields emitted from spin-polarized samples. I will show how detection of such signals provide unique analytical information and offers good inside into intra- and intermolecular interactions. These capabilities will be briefly explored in the context of chemical-substance recognition and searches for physics beyond the Standard Model.

Keywords: nuclear magnetic resonance, optical magnetometry, spectroscopy, chemical analysis, hyperpolarization, fundamental physics searches

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INVITED LECTURE

Quantum machine learning with linear optics

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ABSTRACT

This talk summarizes several recent experiments on quantum machine learning with linear optics that have been carried out in our laboratory. These experiments prove the benefits of symbiosis between machine learning and quantum information processing on the platform of linear optics. It will be shown how reinforcement learning can be used to find parameters of a quantum gate [1], how preparation and measurement on a quantum state performs core calculation in kernel-based machine learning approach [2] and how direct measurement of Hilbert–Schmidt distance contributes to fast implementation of k-means machine learning [3]. Finally, the talk will discuss the processing of quantum measurement results by artificial neural networks to efficiently detect entangled states and measure their negativity [4].

Keywords: quantum machine learning, linear optics, discrete photons

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INVITED LECTURE

Toward coherent beam combining

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ABSTRACT

A review of concepts, architectures, technologies and last achievements in coherent beam combining (CBC) is given. The semi-analytical model of the caustics of partially coherently combined beams enabling the analysis of random effects and atmospheric turbulences was presented. Sensitivity analysis to phase, amplitude, depolarization, defocusing, tilts and wavefront aberration disturbances for a wide class of CBC systems of 2D tiled architecture with more than 100 emitters was carried out. The phase/piston disturbances impact satisfies Marechal criterion. The impact of amplitude mismatch and depolarization losses is of second order. The tilts impact is determined mainly by diffraction angle of emitter, whereas the size of lattice and number of emitters does not influence on result. The most important conclusion is that the requirements on tilt and phase compensation do not increase with the complexity of CBC systems, paving the way for designing effective CBC systems with several hundreds of emitters. In the last part, a novel concept of coherent beam combining with segmented vortex wavefront (V-CBC) was proposed to generate an open dark optical trap. Properties of the V-CBC were compared with those of classical vortex beams. The impact of random phase disturbances on the V-CBC was preliminary analyzed.

Keywords: laser beams, beam combining, aberrations, partial coherence, vortex beams, random effects

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INVITED LECTURE

Computational techniques in lensless holographic microscopy for biomedical imaging

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ABSTRACT

Optical microscopy is essential in biomedical and clinical research facilitating "seeing is believing" paradigm, capacitating diagnostically crucial examination of cells/tissues. It is under constant development with a goal of enhanced resolution, contrast, depth, speed, and information content, with computational techniques emerging recently as capable solutions (*e.g.*, deep learning). Fluorescence microscopy is the most impactful microscopic technique. It relies on labeling the structure of interest with fluorophores – nanoscopic light-bulbs attached to the specimen rendering its high-contrast images. Despite their gigantic success, all fluorescence methods have inherent limitations: (1) time-consuming fluorescence labeling is prone to phototoxicity and (2) it alters normal physiological processes invasively affecting natural cell-behavior jeopardizing the reliability of the study. Thus, a strong demand on capable label-free methods arises with a goal of studying the dynamics of live cells and their natural physiological activities. The sample is not chemically stained and therefore can be imaged basing on its endogenous contrast agents, *i.e.*, internal absorption, scattering or refractive index (phase delay). Zernike/Nomarski phase contrast microscopy are well-known marker-free methods, but they suffer from halo and low contrast and do not provide quantitative phase information, thus are not suitable for standardized analysis. Quantitative Phase Microscopy (QPM) stands out among modern label-free imaging techniques as extremely capable high-contrast approach based on the interference measurement of sample refractive index distribution. Although application oriented research provides exciting advancements, QPM benchtop devices tend to be bulky and costly, both in financial terms and in effort required to master them. They are based on a modified brightfield microscope, thus possess limitations in terms of finite microscope objective numerical aperture and small depth of focus. These disadvantages are bypassed by the lensless holographic microscopy (LHM), which in easy-to-assemble manner (light source+specimen+camera) captures a "holographic shadow" of the illuminated object. This "shadow" is a Gabor in-line hologram generated upon interference of non-scattered (reference) and object scattered wave-fronts. Numerical reconstruction opens up possibilities to study extremely large volumes (up

to thousands of cubic millimeters) without microscope-objective-driven depth of focus limitations, which is a fantastic advantage of LHM. Classical schemes employed to recover, upon backpropagation, the in-focus objects are very sensitive to low-quality of holograms (strong noise and incoherent background, low contrast, high sample density and scattering *etc*.) and apply time-consuming algorithmic/experimental solutions which impede deterministic high-throughput marker-free investigation of dynamic processes in a large holographically rendered volume. I will discuss several new computational techniques enabling fast high signal-to-noise-ratio reconstructions in LHM under challenging experimental conditions. Applications in biomedical imaging will be investigated, including mouse brain tissue slices imaging and live neural cells migration schemes examination.

Paramagnetic nitrogen-vacancy color centers in diamonds for magnetic mapping and sensing

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ABSTRACT

The negatively charged (NV-) color centers in diamond are arguably one of the most promising and studied systems due to their long coherence time and sensitivity to magnetic and electric fields, temperature, and mechanical stress. The diamond-based sensors have application in many fields such as quantum computing, bio-imaging, ultra -high spatially resolved temperature and magnetic field sensing and as a basis of single-photon sources. Based on the optically detected magnetic resonance (ODMR) in an in-house-built wide-field microscope we investigate use of color centers in diamond as magnetic field and temperature sensors. One of our interests is to magnetic mapping with bulk diamond crystal and nanometric resolution in ambient conditions. We also combine paramagnetic nitrogen-vacancy color centers with known optical components such as fibers and optical fiber bundles for imaging and gradientometric temperature measurement and magnetometry. Recently we studied in detail the influence of magnetic fields and light polarization on ODMR spectra of 140 nm diamond powders.

Keywords: nitrogen-vacancy color centers, magnetometry, wide-field microscopy, magnetic mapping

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Magnetization rotation-based polarization control of spintronic terahertz emitter

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ABSTRACT

Recently, the terahertz family of sources increased by newly-developed terahertz spintronic emitter (STE), which competes with the traditional in many ways. This 30THz-broadband gapless source is versatile due to its low-cost, easy implementation, frequency-independent excitation, and perpendicularly-given polarization to the STE's magnetization. Nowadays, the polarization control of STEs was demonstrated by rotating and multipolar magnets, a twisted magnetic field, or cascades of STEs. The methods suffer from mechanical stability, realization difficulties, and limited polarization control. We introduce here our new approach to control the emitted polarization following Stoner–Wohlfarth magnetization rotation within our FeCo/$TbCo_2$/FeCo-based STE exploiting magnetic anisotropy. The varying magnetic field along the hard magnetic axis induces the magnetization rotation, performing the polarization control. We present full-360-degree linear polarization control, not needing mechanically rotating components. This technique guarantees higher stability for polarimetry applications. We prove the whole terahertz spectrum follows the polarization control, preserving even the phase of sub-picosecond terahertz emission. It offers easy polarization calibration of the emitter for terahertz experimental setups. Moreover, we provide models to explain magnetic hysteresis defining the polarization behaviour. We predict that the polarization-controlled STEs will find many applications covering terahertz time-domain polarimetry and ellipsometry, medical imaging and security detection.

Keywords: terahertz spintronic emitter, polarization control, THz time-domain spectroscopy, terahertz photonics, polarimetry, ellipsometry, magnetic anisotropy, rare -earth materials

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Electrical tuning of optical properties in metal-oxide-semiconductor multilayer

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ABSTRACT

This work presents experimental results on the fabrication and characterization of an electro-optical modulator in the form of a metal-oxide-semiconductor multilayer. The structure exhibits refractive index change under applied external voltage, verified by spectroscopic ellipsometry measurements in UV/VIS/NIR range. This variation in optical properties is enabled by the changes in the carrier density present in the vicinity of the interface between indium-tin-oxide and fused silica. In our investigations, we identify the critical electrical and morphological parameters of the e-beam deposited semiconductor film that govern the process of accumulation/depletion layer formation. In particular, we present optimum process conditions for the low-temperature deposition of indium-tin-oxide using oxygen plasma ions. Next, via numerical calculations, we show the prospects of further development of the device by implementing a multi-interface geometry. Finally, we prove that our design is leading-edge compared to other solutions based on transparent conducting oxides.

Keywords: nanophotonics, electro-optical devices, indium-tin-oxide, MOS multilayer, ellipsometry

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Optimisation of exposure parameters for direct laser writing in optical lithography

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ABSTRACT

Various types of nano- and micro-structures, such as security holograms and diffractive optical elements, can be prepared directly into a photoresist using a direct-write optical lithography. Precise knowledge of photoresist properties, parameters of exposure, and photoresist development time are essential. We characterize and optimise exposure of the positive binary and grayscale photoresist ma-P 1200 series. Optical functions including absorption of the photoresists were obtained using Mueller matrix spectroscopic ellipsometry. The main writing parameters of the PicoMaster100 lithograph are the spot size, the power dose, the step between writing lines, and the vertical offset of the laser. Effects of the laser offset and the step size were studied on the developed 1D nanograting using the atomic force microscopy (AFM). Effects of grayscale exposition were studied on blazed gratings with AFM and confocal microscopy. The modelling and optimisation of the propagation and absorption of the exposure lithography laser was performed by an analytical solution of the Gaussian beam in an absorbing photoresist. The model allows us to study how the laser beam is absorbed in the photoresist as a function of the exposure parameters. Understanding the sensitivity of the photoresist to the exposed dose together with a model of beam propagation in the photoresist allow us to optimise procedure to obtain desired lithographic structures.

Keywords: positive photoresist, UV direct writing laser lithography, spectroscopic ellipsometry, diffractive grating, blazed grating

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Laser color printing on semicontinuous aluminum films

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ABSTRACT

Plasmonic nanostructures may exhibit vibrant colors. These colors originate from the excitation of plasmon resonances – collective oscillations of free electrons in metallic nanoparticles. Semicontinuous metal films (SMF) are a special type of disordered plasmonic structures. They can be mass-produced in a physical vapor deposition process. SMFs are comprised of random in their nature nano-island structures of various sizes and shapes resonating at different wavelengths in a broad spectral range. When irradiated with high-intensity laser radiation, the nanostructures can be locally restructured, fragmented or sintered. Spatially local restructuring originates from presence of hotspots, regions of a high local electric field, at the vicinity of nanoparticles. Thus, the spectral response of the SMFs can be altered in a controllable manner. In this work, we demonstrate the generation of structural plasmonic colors through a femtosecond laser-induced modification of thin semicontinuous aluminum films deposited on an aluminum mirror coated with an isolator layer. The structures show vivid colors in reflection. Local changes induced to nanostructures of SMF are controlled by the femtosecond laser and scanning parameters. Self-passivation effect of aluminum results in the long-term stability of generated colors. Presented results could be used in color printing and marking for esthetic, security, and anti-counterfeiting applications.

Keywords: plasmonic color, structural color, semicontinuous metal film, aluminum film, laser modification, plasmon resonance

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Hot-electron driven optical phenomena in metamaterial structures

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ABSTRACT

The concept of metamaterials opened an avenue for designing and fabricating of functional optical devices exhibiting performance unachievable in the realm of conventional optics. During the presentation, we will focus on the ultrafast response of free electrons in metallic metamaterials and associated refractive index changes on femtosecond time scales. First, we will show that the nonlinearity in such structures is not limited by the constituent materials' nonlinear properties and can be tailored by modifying the geometrical parameters. Next, we will discuss the relaxation mechanisms and show how to tailor the rates by engineering a non-uniform electron temperature distribution through nanostructuring. We will also discuss the role of nonlocal effects, and finally, we will demonstrate the performance of metamaterial structure as a pulse shaping device.

Keywords: nanophotonics, ultrafast optics, metamaterials, nonlinear effects

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Advanced functionalities in subwavelength photonic and plasmonic structures

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ABSTRACT

Recently, within our theoretical research projects, we have investigated various novel effects and functionalities, connected with subwavelength (SW) photonic and plasmonic (nano)structures. Based on the development and application of numerical methods for the analysis of the interaction of the electromagnetic field with such structures (mainly Fourier modal methods), we have recently studied several interesting and potentially perspective problems: subwavelength grating (SWG) waveguide-based structures, such as SWG Bragg and transmission narrow-band filters, novel magnetooptic (MO) plasmonic guiding structures with non-reciprocal properties, parity-time (PT) gain / loss symmetric guiding and resonant structures, resonant plasmonic nanostructures and metasurfaces for surface plasmon resonance sensing, plasmonic nanostructures with extraordinary optical transmission and nonlocal and quantum response resonances. Also, recently, we have concentrated on the studies of the bound states in the continuum (BIC), in such structures as waveguides and other resonant structures. Additionally, we have studied pyramid layered and snowman-like plasmonic structures for the applications in sensing. In this contribution in particular, we present and discuss more in detail several results selected from these problems. Concerning activities on nonreciprocal structures, based on magnetooptic Fourier modal method (MOaRCWA) simulations, both in 2D in 3D, we have studied the one -way (nonreciprocal) propagation of magnetoplasmons in plasmonic nanostructures, such as highly-dispersive polaritonic InSb material, within the THz spectral region, under an external magnetic field (mainly in the Voigt configuration). Secondly, as the characteristic dimensions of subwavelength structures are scaling down, it has turned out that the local-response approximation is no longer applicable and more complex models based on the nonlocal response (or even quantum interaction), are required for explaining novel effects, *e.g.* blue spectral shifts of the resonances, etc. Among these approaches, the longitudinal nonlocal response description based on the linear hydrodynamic model represents the starting point. In this contribution, as an alternative (and more general) approach to (quasi)analytical techniques, based on our previous long-term experience with Fourier modal methods, we have considered and developed the extension of the rigorous coupled wave analysis (RCWA) technique capable

of treating nonlocal response numerically, for more general structures. First, we have concentrated on the periodic nonlocal RCWA (in 1D and 2D case – NonLocRCWA) where we demonstrated the effects of nonlocal phenomena on plasmonic resonances. Some examples of the application will be shown and discussed.

FUNDING

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INVITED LECTURE

Nanocoated optical fiber sensors and biosensors

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ABSTRACT

Optical fibres are small, flexible, low-cost and immune to external electromagnetic fields, which are often present during medical examinations *e.g.*, in hospitals. After certain modification the fibres can be used as sensors, where light guided in the fibre interacts with external medium and thus can be used for monitoring optical properties in vicinity of the sensor surface. The interaction with external medium can be greatly modified by deposition of thin (typically less than 300 nm in thickness) overlays and nanostructures.

This paper discusses vapour-based nanocoating deposition methods and materials that can be used to modify properties of various optical fiber sensors. A special attention is paid to nanocoated sensors and label-free biosensors based on long-period fibre gratings, various interferometers, and lossy-mode resonance devices. A subjective review of the most promising optical-fibre-based biosensing devices will be shown when they are targeted towards biomolecules of different size, *i.e.*, DNA, proteins, viruses, and bacteria.

Keywords: optical fiber sensors, nanotechnology, thin film deposition, label-free biosensing

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INVITED LECTURE

Optical noiseless quantum amplifiers

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ABSTRACT

Noiseless quantum amplifiers are probabilistic quantum devices that approximately noiselessly amplify coherent states by suitably modulating the amplitudes of Fock states. These devices can find applications for instance in optical quantum communication, loss suppression, quantum error correction and entanglement distillation. In this talk we will present some recent developments in the field of optical noiseless quantum amplifiers. First, we will discuss a teleportation-based noiseless quantum amplifier, where the amplification operation is encoded into a suitable non-Gaussian two-mode entangled state that serves as a quantum channel in probabilistic continuous-variable quantum teleportation. We will then focus on optical noiseless quantum amplifiers based on generalized quantum scissors scheme and we will discuss optimization of their success probability. Finally, we will consider general linear optical noiseless quantum amplifiers driven by auxiliary single-photon states and we will analyze their sensitivity to experimental imperfections such as non-unit detection efficiency or imperfect preparation of the auxiliary single-photon states.

Keywords: noiseless quantum amplifiers, quantum teleportation, quantum scissors

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INVITED LECTURE

Surface plasmon resonance enhanced photonic devices

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ABSTRACT

Metallic nanostructures allow to excite and sustain collective charge oscillation at their surface which leads to the formation of electromagnetic surface modes called surface plasmon polaritons. Those modes exhibit high field enhancement, strong confinement, and high sensitivity to surface events. Those properties allow for manipulation and light trapping in the nanoscale and open a route to novel technologies including fast and efficient light and energy sources or ultrasensitive detectors and sensors. In this presentation, a short historical overview on the development and applications of plasmonic nanostructures will be presented. The state-of-the-art photonic approaches to light-harvesting efficiency enhancement as well as ultrasensitive biodection employing plasmonic phenomena will be discussed. Recent experimental results which confirm plasmon-enhanced efficiency of heterojunction solar cells and extraordinarily uniform and large-area surface-enhanced Raman scattering platform will be presented.

Keywords: surface plasmon resonance, plasmonic nanostructures, photonic devices

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Field investigations of the FOS5-04 huge fiber-optic rotational seismograph operating in a closed-loop configuration

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ABSTRACT

Ours nearly twenty years' experience in construction and application of the fiber-optic rotational seismograph is a subject of this presentation. The described system is dedicated to seismic (geological) area of rotational seismology where investigation of rotational effects needs the system with sensitivity about 10 nrad/s and detection bandpass from 0.01 to 1 Hz. The system named FOS5-04 fully fulfills these requirements, especially thanks to application of FOG closed-loop construction with a huge sensor loop (about 14400 m single-mode optical fiber wound in loop of 0.61 m diameter). Continuous monitoring of the seismic events in Książ castle, Poland, with the use of the FOS5-04 seismograph showed existence of the rotational motion induced by natural factors as well as mining activities.

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Propagation of non-diffracting beams through scattering media

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ABSTRACT

Non-diffracting beams are a class of light beams that preserves their shape and beam width during propagation over a considerable distance that is larger than the Rayleigh distance defined for the Gaussian beam. Light propagation through scattering media results in loss of intensity and information, whereas the non-diffracting beams preserve their shape and exhibit self-healing properties during propagation through scattering media. A vortex beam is a type of non-diffracting beam of annular shape which possesses a helical phase of $\exp(jl\varphi)$, where l is the topological charge (TC). The vortex beam radius strongly depends on the TC number, as the TC number increases, its annular radius increases. The TC-dependent radius is a key issue in some applications such as particle trapping and manipulation and also in coupling multiple OAM beams into a fiber for communications. Therefore much research has been conducted on the generation of a perfect vortex beam. A perfect vortex (PV) beam is one whose radius is independent of the TC number. The main objective of the proposed study is to generate the perfect vortex beam and to test its propagation properties through scattering media.

Keywords: non-diffracting beams, vortex beam, scattering media, hologram, spatial light modulator

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A microscope-based interferometer with the variable wavelength illumination system

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ABSTRACT

The paper demonstrates initial results of measuring the retardance of wave plates using a variable wavelength microinterferometer. The instrument utilizes a continuously variable interference bandpass filter placed in the specially designed intermediate image plane. The fringe field, created by the Wollaston prism, is processed and analysed only once, which speeds up the measuring procedure. In this application a reflected-light mode configuration is presented, however the solution is suitable also for transmitted-light systems. The interferometer provides the user the spectral characteristic of retardance of the wave plate across the visible spectrum. The instrument is based on the classical microscope with the Köhler illumination system.

Keywords: interferometry, retardance, variable wavelength interferometry, Wollaston prism, interference filter

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DeepVID: deep-learning accelerated variational image decomposition for filtration of different types of fringe patterns

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ABSTRACT

The algorithms defined as variational image decomposition (VID) constitute the state-of-the-art in solving image prefiltration problem. Historically first fringe pattern dedicated VID model uses the Chambolle projection algorithm to separate the fringes and background. The prefiltration result strongly depends on the values of the algorithm's internal parameters, to be set manually. Advancement in the form of unsupervised variational image decomposition (uVID) algorithm automatically sets the parameters and stopping criterion for Chambolle's iterative projection algorithm. Automation was done at the expense of increasing the calculation time. The idea of using convolutional neural network to map the relationship between the fringe pattern characteristic and the required number of Chambolle projection iterations has emerged. It was shown that the calculation time is reduced on average by 3–4 times by employing the deep learning-based acceleration (DeepVID) without jeopardizing the overall accuracy of the prefiltration. For the sake of metrological figure of merit, especially important in fringe pattern analysis where the characteristic and origin of fringes is generally wide and diverse, the deep learning based solution was employed to accelerate well-established VID approach, not to bypass it completely. In this contribution DeepVID was tested on different types of fringe patterns (interferograms, holograms, moiregrams, besselograms, *etc*.)

Keywords: interferometry, fringe analysis, fringe pattern filtering, machine learning, deep learning, convolutional neural network, variational image decomposition, total variation

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Study of impact of decentration of Light Sword Lens in a patient's eye on vision quality

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ABSTRACT

Light Sword Lens (LSL) is a promising type of optical element with potential application in the correction of presbyopia due to extending the depth of light focusing. However, in a possible real-world situation, as an implant in the patient's eye or used as a contact lens, there exists a possibility of movement of the element with respect to the optical axis of the eye. Since the LSL is highly asymmetric, this can affect the performance of vision correction. In this study, we investigate the influence of this movement on the optical performance and vision acuity. For instance, certain ranges of movement may improve vision quality of the elements in a specific range of defocus values, leading even to enhance the overall usefulness of the LSL. The performance of the optical elements will be compared in terms of the Strehl ratio, PSF shape, and acuity of vision. The presented results will allow for better understanding of the LSL optical element performance and its application in human vision correction.

Keywords: LSL, LSOE, presbyopia, visual acuity, visual optics

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Poster Session

Experimental measurement of the Hilbert–Schmidt distance between two-qubit states as a means for reducing the complexity of machine learning

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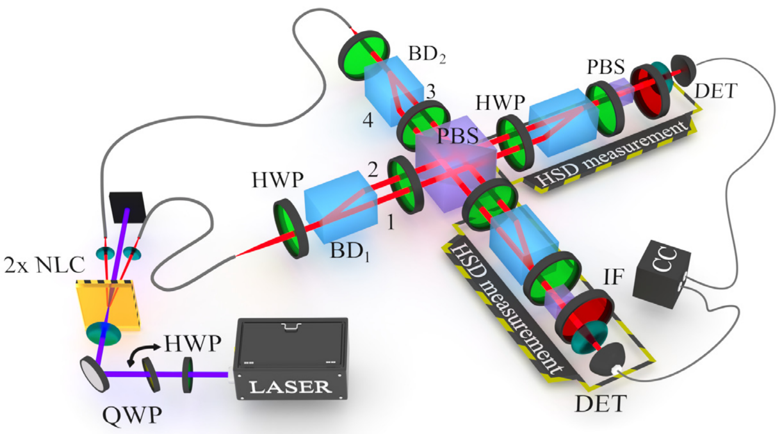
ABSTRACT

We report on the experimental measurement of the Hilbert–Schmidt distance between two two-qubit states by many-particle interference. We demonstrate that our three-step method for measuring distances in the Hilbert space is far less complex than reconstructing density matrices and that it can be applied in quantum-enhanced machine learning to reduce the complexity of calculating Euclidean distances between multidimensional points, which can be especially interesting for near term quantum technologies and quantum artificial intelligence research. Our results are also a novel example of applying mixed states in quantum information processing. Usually working with mixed states is undesired, but here it gives the possibility of encoding extra information as the degree of coherence between the given two dimensions of the density matrix.



Quantum information protocols such as teleportation and cryptography established in the field of quantum information processing have a significant impact on modern communications. In fact, early quantum communications networks based on quantum teleportation have already been reported and experimentally realized [1,2]. Their physically guaranteed security and potential for scalability makes them a preferable choice for future communications networks. In quantum communications the quality of a transmission channel is crucial. It is due to security reasons, where imperfections of the communication channel lead to signal degradation known as noise. This noise can be subsequently exploited by potential eavesdroppers. Therefore, tools for the diagnostics of the transmission channels are in demand. In quantum communications theory one can quantify the accuracy of a signal transmission by measuring the distance in the Hilbert space between the transmitted and received states. The most prominent distance measures include the Uhlmann-Jozsa fidelity (Bures metrics), trace distance, and the Hilbert–Schmidt distance (HSD) [3–5].

These distance measures are also essential for a field of quantum machine learning. Where a common method for classification algorithms (*e.g.*, k-means) is to perform a distance measurement among M sample vectors of dimension N. This procedure is a core subroutine for other machine learning algorithms, *e.g.*, supervised and unsupervised nearest-neighbor algorithms. Quantum machine learning emerges as a new field of research in quantum information processing with linear optics, where the benefits of applying this platform are unaffected by unavoidably nondeterministic implementation of a universal set of gates [6].

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Entanglement detection and quantification from collective measurements processed by artificial intelligence

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ABSTRACT

We still lack an efficient way of detecting and classifying general quantum states. One can execute a full state tomography, but this method is time demanding, especially for complex systems. Other approaches include wast variety of entanglement witnesses. These methods tend to be less demanding but lack reliability. Luckily, with the evolution of machine learning, we now possess tools capable of bringing a balance between both approaches. Here we introduce an artificial-intelligence-based approach towards entanglement detection and quantification for general two-qubit states. Our method uses ANN (artificial neural network) fed by the results obtained from the collective measurements as a resource to solve this complex task. When provided with the same measurement results, thoroughly trained ANN provides better detection accuracy than conventional witnesses [1]. Furthermore, we also investigate possibilities of efficient quantification of entangled states using ANN. Our goal is to minimize the cost of entanglement quantification while retaining high prediction accuracy. We compare prediction based on full quantum state tomography with quantification carried by our ANN. We found out that the ANN is significantly precise in entanglement quantification even when provided with less measurement configuration in comparison to a full state tomography [2].

Keywords: entanglement detection, entanglement quantification, collective measurement, machine learning

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Intensity modulation/direct detection optical key distribution

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ABSTRACT

While the ambition of QKD technology is to make the key distribution secure even against the most sophisticated physical attacks permitted by quantum mechanics, a relevant alternative is to consider a restricted class of eavesdropping attacks that can be viewed as imminent with current or near-term technology. When the actual threat takes the form of passive eavesdropping, it is possible to generate a cryptographic key using shot noise properties of the electromagnetic radiation. Here we analyze theoretically the performance of the recently proposed intensity modulation/direct detection protocol for optical key distribution assuming both Gaussian and binary signal modulation.

Keywords: optical communication, cryptography, physical-layer security, shot noise

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Experimental hierarchy of quantum correlations of Werner-like states

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ABSTRACT

We demonstrate hierarchy of various classes of quantum correlations on experimentally prepared two-qubit Werner-like states with controllable white noise. Werner states, which are white-noise-affected Bell states, are prototypal examples for studying such a hierarchy as a function of the amount of white noise. We experimentally generate Werner states and their generalizations, *i.e.*, partially entangled pure states affected by white noise. These states enable us to study the hierarchy of the following classes of correlations: separability, entanglement, steering in three- and two-measurement scenarios, and Bell nonlocality. We show that generalized Werner states (GWSs) reveal fundamentally different aspects of the hierarchy compared to the Werner states. Particularly, we find five different parameter regimes of GWSs, including those steerable in a two-measurement scenario but not violating Bell inequalities. This regime cannot be observed for the usual Werner states. Moreover, we find threshold curves separating different regimes of the quantum correlations and find the optimal states which allow for the largest amount of white noise which does not destroy their specific quantum correlations (*e.g.*, unsteerable entanglement). Thus, we could identify optimal Bell-nondiagonal GWSs which are, for this specific meaning, more robust against the white noise compared to the Bell-diagonal GWSs (*i.e.*, Werner states).

Keywords: Werner states, entanglement measures, steering, Bell's nonlocality, robustness

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Comparison of optical properties of 1×8 Y-branch and MMI splitter based on silicon nitride material platform

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ABSTRACT

This paper describes two different designs of 1×8 passive optical splitters. The first splitter consists of cascade arranged directional waveguide branches (Y-branch splitter) with (0.8×0.16) μm^2 waveguide cross-section. The second splitter is based on multimode interference occurring in a large MMI coupler, which uses a self-imaging effect for beam propagation, exhibiting the same waveguide core size as a Y-branch splitter. The waveguide channel profile, used in both approaches, is based on a silicon nitride material platform, with a refractive index of core being $n_c = 1.925$ and a refractive index of cladding $n_{cl} = 1.4575$. The splitters are designed as a planar structure for a medical operating wavelength 850 nm. Design, simulation, and optimization of passive optical components are performed by a commercial photonic software tool: BeamPROP simulation engine by RSoft Photonics Suite tool, employing beam propagation method (BPM). This work aims to find the minimum physical dimensions of the designed splitters with the satisfactory optical performance. According to the minimum insertion loss and minimum non-uniformity, the optimum length of the splitters is determined. Finally, the optical properties of splitters for both approaches are discussed and compared with each other.

Keywords: Y-branch splitter, multimode interference (MMI) splitter, optical properties, light propagation, silicon nitride

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Using a commercially available LIDAR scanner in cultural heritage research

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ABSTRACT

IR reflectography is being applied in art conservation and art history research especially for non-invasive uncovering of sublayers and underdrawings in the works of art. Often, however, outside large research teams, the technology required for investigations using IR radiation beyond the silicon detection range (above 1100 nm) is not always available. This poster shows how to access these techniques with a commercially available LIDAR for 3D scanning often used for exploration of cultural heritage, especially in architecture. Presented workflow promotes a non-traditional usage of the LIDAR. In this case, the IR reflectogram is obtained at the wavelength of 1550 nm. The working principle of this method is demonstrated in a case study of Bečov nad Teplou (Czech Republic) chapel walls.

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Polarization controlled terahertz time domain spectroscopy using dual-color plasma

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ABSTRACT

Terahertz waves have found many applications, including imaging, security, high-capacity telecommunications, and quality inspections. Moreover, sample characterization using the terahertz time-domain (THz-TDS) gives us information about both amplitude and phase, which is a significant advantage over other conventional spectroscopic methods. Several sources and detectors, such as photoconductive antennas, nonlinear crystals, or photo-Dember sources, can be used for these mentioned applications. However, they are often low-energy, limited by threshold or narrow spectrum. In our experimental setup, we generate the THz field using dual-color plasma. The generation process resides in the mixing of the first and second harmonics providing substantial conversion efficiency, excellent signal-to-noise ratio, and a broad spectrum ranging from 0.1 THz to 4 THz. Furthermore, we enhance our measurement technique by implementing ZnTe polarization-sensitive detection. Here we experimentally demonstrate plasma polarization response. Finally, we prove our method by measuring typical THz samples. Our multipurpose configuration is employed in various experimental arrangements such as transmission, reflection, or attenuated total reflection (ATR). It offers a complete sample analysis of thickness, dielectric functions, birefringence, and optical activity.

Keywords: terahertz, dual-color plasma, laser filamentation, polarization control, time domain spectroscopy, ZnTe detection

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EPR quantum steering in a two- and three-mode PT-symmetric system

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ABSTRACT

Quantum-mechanical PT-symmetric systems are open systems described by Hamiltonians that have complex eigenvalues. These values become real in some situations. In the Hamiltonians discussed here, the imaginary terms describe the interaction with the external environment and the energy transfer from the environment and its loss. When PT-symmetry occurs, loss and gain must balance each other.

For such systems, we can observe the phase transition point. If the system is in the PT-symmetric phase, all the eigenvalues of the Hamiltonian are real. On the other hand, when the system is in a phase where this symmetry is broken, its spectrum of eigenvalues becomes complex. Such a transition point between those phases is called the exceptional point.

Our research concentrates on the generation of quantum steering in PT-symmetric systems. We discuss models involving two or three single-mode optical cavities. We show how the production of steerable states is influenced by the strength of interaction between the neighboring cavities and the rate of energy gain/loss. In particular, we show how the generation of quantum steering works near the exceptional point.

Keywords: PT-symmetry, quantum correlations, EPR steering

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Custom-terminated multimode fibre probe for holographic microendoscopy

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ABSTRACT

Using multiphoton microscopy, we can image the tissue with sub-cellular resolution at depths down to 1.5 mm. Beyond this reach, the light must be delivered to the target region by optical relay elements inserted into the tissue – the endoscopes. Focusing light through a step-index multimode optical fibre (MMF) using wave-front control enables minimally-invasive endoscopy. With fibre micro-endoscopes, we can reach any depth with negligible tissue disruption and keep the resolution below 1 micrometre, sufficient for *in vivo* microscopy. We designed a novel custom-terminated multimode fibre probe. The presented poster will focus on optical fibre probe manufacturing methods (etching, polishing and coating) and their impact on imaging quality.

Keywords: optical fibre, micro-endoscope, holographic endoscopy, etching, polishing, thin layer deposition, imaging

FUNDING

The work was supported from European Regional Development Fund-Project "Holographic endoscopy for *in vivo* applications" (No. CZ.02.1.01/0.0/0.0/15_003/0000476) and grant "A step towards the deepest structures inside the brain – fabrication of optical fibre probes" realised within the project Quality Internal Grants of BUT (KInG BUT, No. CZ.02.2.69/0.0/0.0/19_073/0016948), which is financed from the OP RDE.

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Sensor probes for monitoring temperature changes in active layer of permafrost

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ABSTRACT

Rayleigh-scattering-based methods of fiber-optic distributed temperature measurement used with standard telecommunication single-mode optical fiber as a sensor are capable of measuring only a change in temperature, not its absolute value, and they suffer from cross-sensitivity to both temperature and strain.

We present results of temperature change monitoring obtained with use of sensors based on a variety of optical fibers: a telecom single-mode optical fiber, specialty highly doped optical fibers and an optical fiber inscribed with fiber Bragg grating, all interrogated with an optical frequency-domain reflectometer LUNA OBR4600. We compare their operation and discuss the influence of strain on the readouts.

Keywords: optical frequency-domain reflectometry, distributed temperature sensing, fiber-optic sensor, fiber Bragg grating, environmental monitoring

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Comparison of optical methods for 3D model generation

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ABSTRACT

The capability to capture three-dimensional objects in a form of 3D models is indispensable in many areas of modern society. 3D models are widely used for example in automotive industry or in digitization of historical artifacts. 3D imaging complements 3D printing giving us the ability to reproduce the original objects.

Plenty of optical methods for 3D recording exist, majority of them is commercially available in form of some scanning devices. In this work five methods are presented in detail – coherence scanning interferometry (aka white-light interferometry), laser trigonometry, structured light, photogrammetry and LIDAR. These methods are applied for capturing 3D models of the same objects after which results are compared with respect to surface detail accuracy and typical object size.

Keywords: coherence scanning interferometry, LIDAR, photogrammetry, laser trigonometry, structured light scanner

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Lab-on-a-chip sensing based on 1DPhC resonant cavity

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ABSTRACT

Photonic crystals (PhCs) are low-loss dielectric systems characterized by a periodic modulation of the refractive index along one or more spatial directions. They can be designed and constructed to generate photonic band gaps (PBGs) by changing either the geometry or materials of the periodic structure, what prevents from the propagation of electromagnetic waves of specific wavelengths inside the PhCs along specific directions. Moreover, the PhCs with the PBGs enable to sustain surface electromagnetic waves at certain frequencies within the PBG. This paper describes an idea of creating a liquid analyte sensor based on a one-dimensional (1D) photonic crystal - dielectric mirror - integrated on the optical fiber end face and creating a resonant cavity with the reversed structure. This geometry produces the evident resonances within the PBG spectral region which are sensitive to refractive index changes inside the resonant cavity. The main idea is to use this arrangement as a sensor in lab-on-a-chip (LOC) arrangement with two single mode optical fibers (SMFs); one with 1DPhC at

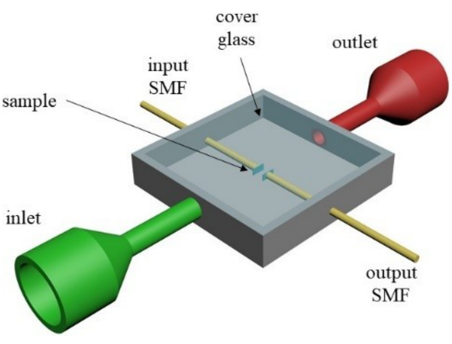

Figure: Design of LOC with integrated SMF with 1DPhC.

the end face, and second with mirror. An inlet and outlet is proposed for different liquid analyte delivery and in-situ monitoring of the refractive index change of the analyte (see the Figure).

Keywords: photonic crystal, analyte sensor, lab-on-a-chip

FUNDING

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Open source workflow for multispectral imaging based on artificial neural networks

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ABSTRACT

We present a workflow based on open source software for multispectral imaging specifically designed for analysis of works of art. Our workflow allows to capture radiometrically and colorimetrically accurate images, requiring only common photography equipment and a set of two optical filters. The input data is machine-processed using artificial neural networks to obtain interpretation-ready multispectral images. We provide the entire software package under the general public license.

Keywords: machine learning, multispectral imaging, works of art, image processing, open source

Design of 256-channel 25-GHz AWG for ultra-dense wavelength division multiplexing

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ABSTRACT

Dense wavelength division multiplexing (DWDM) is the preferable candidate for increasing the capacity throughput of optical networks. Optical multiplexers/demultiplexers based on arrayed waveguide gratings (AWGs) are the key components in such DWDM systems because of their low insertion loss, high stability, and low cost. To meet the growing capacity demands, it is necessary to increase the AWG channel count as much as possible. However, while the standard channel count (up to 40) and standard channel spacing (100 GHz or 50 GHz) AWGs feature very good performance and are relatively easy to design, increasing the channel counts and narrowing the channel spacings leads to a rapid increase in the AWG size and this, in turn; causes the deterioration in optical performance. Therefore high-channel WGs present for the designers a serious challenge.

In this paper we will show that applying our stand-alone software tool, called AWG-Parameters, we were able to design 256-channel 25-GHz AWG featuring very good optical performance in a very short time. The AWG structure was simulated with PHASAR from the commercial photonics tool Optiwave and evaluated using AWG-Analyzer tool. The achieved results confirm very good agreement between designed and simulated AWG transmission parameters.

Keywords: arrayed waveguide gratings, AWG design, ultra-DWDM, telecommunications

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Mode locked and free running operation of $Nd,Gd:CaF_2$ crystal fiber laser

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ABSTRACT

Fluoride-type crystals (CaF_2, SrF_2) doped with neodymium Nd^{3+} and codoped with non-active ions as Y^{3+}, La^{3+}, or Gd^{3+} for breaking clusters of active ions, have become interesting active media for the diode-pumped mode-locked lasers They posses broad emission spectra and longer fluorescence lifetime in comparison with widely used crystals such as Nd:YAG or $Nd:YVO_4$. The crystal fibers grown by several groups in recent years might be attractive for high power operation and possibility of beam guiding. We investigated $Nd,Gd:CaF_2$ cylinders 10 mm long with diameter of 1.9 mm end pumped by 790 nm LD. In free running regime the wavelength tunability of 41 nm (1040–1081 nm) was achieved. In continuously passively mode-locked regime using SESAM the pulses 1.3 ps long at 1065 nm with 2 nm spectral with were generated. The average output power was 200 mW for pump power of 1.6 W. Comparison with operation of standard bulk $Nd,Gd:CaF_2$ active media will be also presented.

Keywords: crystal fiber, CaF_2, SrF_2,Nd:doped, tunability, passive mode-locking

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How does ultra resolution spectrometry help to measure femtosecond impulses?

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ABSTRACT

We are currently working on electrooptical shearing interferometry method of characterizing femtosecond impulses from near IR. The setup is based on Hong–Ou–Mandel interferometer. The whole idea revolves around shifting impulses both in time and frequency domain and then calculating it's second order correlation. Then we make a 2D map of the this function with respect to time and frequency shifts. We use two custom ultra resolution spectrometers in this experiment. First one is needed to characterize the frequency shifts the electrooptical phase modulator generates. The setup works on a small range of wavelengths but it's very precise. It is based on a diffraction grating, focusing lense and the linear photodiode detector. High resolution was achieved by using the fourth order diffraction. The second spectrometer is a 4f setup with two focusing lenses and two diffraction gratings which we use to narrow the spectrum of the laser. It consists of two diffraction gratings and a precise slit. Our system is suitable for single photon measure.

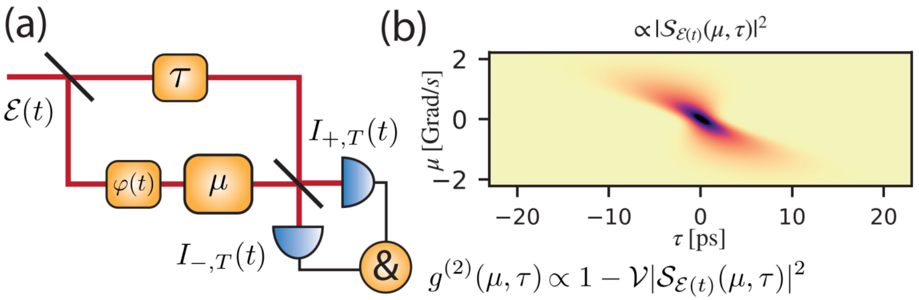

Figure: (a) Ideational scheme – in the upper arm time shifting, in the bottom frequency shifting and phase modulation. (b) Expected shape of the second order correlation function with respect to time and frequency shifts.

We are planning to modify our experiment and put a special rubidium cell to the optical system or use photons from Sagnac interferometer and then obtain the phase matching function of the used PPKTP crystal.

Keywords: ultrafast, IR, spectrometry, resolution, correlation

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IP-Dip inverted pyramids for application in SERS

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ABSTRACT

In this paper, we present concept of inverted pyramids patterned in the surface of IP-Dip polymer that can be used as a SERS substrate. Inverted pyramids are prepared using direct laser writing lithography and they are finally metal-coated. Prepared SERS structure consists of field of 10×10 pyramids with base of 5 μm and three different depths – 2.5 μm, 4 μm and 6 μm. Afterwards, an Au layer with 4 different thicknesses (10 nm, 20 nm, 30 nm and 40 nm) is evaporated. Transmission, as well as reflection spectra were simulated and measured for characterization of prepared structures.

In the next step, the sample is investigated by micro-Raman measurements using R6G as the probe molecule. The R6G in aqueous solution at concentration of 10^{-2} M is used. The micro-Raman measurements is performed in air at room temperature, in backscattering geometry. Recently published inverted pyramids in polymethylmetacrylate (S. Z. Oo, 2016) show very good qualitative SERS signal enhancement with respect to the commercial silicon-based Klarite SERS substrate.

Keywords: IP-Dip, inverted pyramids, surface-enhanced Raman spectroscopy

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Optimization of 3D laser printing process for reflective polymer surfaces

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ABSTRACT

In this paper, we will focus on the quality of polymer mirror interfaces prepared by high-precise 3D laser printing. Using this technique, it is possible to create various optical elements, such as interferometers, resonators, and sensors. For these elements to function properly, it is necessary to achieve the best possible surface roughness parameters of the mirror interfaces. The polymer mirror surfaces can be post-treated with a focused ion beam, but our goal will be to achieve acceptable polymer surfaces in a one-step lithography process. By changing parameters such as laser power, scanning speed, hatching, and slicing, we can achieve different surface roughness. We will focus on optimizing the laser printing process, for elements working in the infrared region, near to telecommunication wavelength of 1550 nm. For measurements we will use the optical spectrum analyzer and laser source, where reflection and transmission on IP-Dip and IP- PDMS polymer will be investigated.

Keywords: optical polymer, reflectance, 3D laser lithography

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Split-step methods for numerical modeling of synchronously pumped crystalline Raman laser

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ABSTRACT

Synchronously pumped crystalline Raman lasers present interesting possibility to obtain effective generation by stimulated Raman scattering in picosecond or femtosecond time-scale. Their dynamic process can be described by a system of equations for optical and phonons fields. In the case of picosecond or femtosecond regime, the describing system is a set of partial differential equations that has to be solved numerically. Due to specific character of pumping and very similar coupling equations, this issue can be solved by modified split-step methods for synchronously pumped optical parametric oscillator. In this paper we present using of split-step methods for numerical modelling of synchronously pumped crystalline Raman lasers. In good agreement with experimental results, the solution fully explained the pulse compression mechanism for detuning of ideal synchronous pumping.

Keywords: Raman laser, stimulated Raman scattering, synchronous pumping, numerical model, split-step method, pulse compression

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3D photonic structures for optoelectronics applications

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ABSTRACT

Photonics has become recently intensively evolving area, where the possibilities of photonic structures or crystals (PhC) for integrated optoelectronics were found. The used of three dimensional (3D) laser technology with combination of stable polymer resin enable printing of micro-optical and nano-optical components or other type diffractive structures for optoelectronics applications. In this work we demonstrate possibilities of 3D laser technology based on two photon polymerization for application in optoelectronics. We prepared three-dimensional polymeric structure with 2D photonic structure (see the Figure) which was successfully applied on light emitting diode (LED) chip.

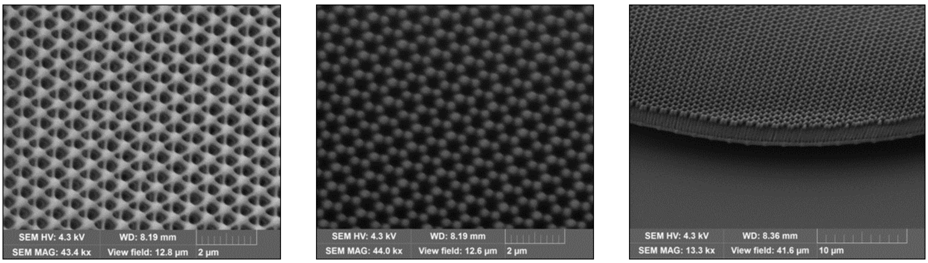

Figure: SEM images of prepared 2D photonic structures (in left Kagome lattice, in the middle Honeycomb lattice and in the right is show overall view of prepared structure).

In this work, we would like to investigate the effect of higher-order vertical diffraction of PhC structure directly applied on the LED surface for evidently modify of their far-field pattern.

Keywords: direct laser writing, photonic structure, LED

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Polymer Inverted Refractive-Index-Contrast Grating prepared by laser lithography on Si substrate

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ABSTRACT

Nanophotonic devices use a light-matter interaction leading to an enormous improvement of optical properties. This is typically achieved with optical cavities, which trap photons for many optical cycles before the photons escape. This allows, for instance, a photon to interact with an active optical material for a longer time, which is advantageous for many applications. A new class of planar optics has emerged, that is a subwavelength grating surrounded by significantly lower refractive index region, herein referred to as high-contrast gratings (HCGs). We focused on a specific concept of the grating with inverted arrangement of refractive index contrast with respect to HCG, known as Inverted Refractive-Index-Contrast Grating (ICG). We present the simulation and preparation in IP-Dip material of a polymer grating, which is used as a highly reflective and spectrally selective mirror based on ICG geometry. We simulated the power reflectance as a function of the grating parameters and prepared the grating structure in IP-Dip material using three-dimensional (3D) laser lithography according the proposed theoretical design. The morphology of the prepared structures was analyzed using a scanning electron microscope.

Keywords: grating, polymer photonics, 3D laser lithography, IP-Dip polymer

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Spin-lasers with periodic gratings: toward ultrafast polarization modulation

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ABSTRACT

The main goal of this study is to explore possibilities of using cavities with dielectric grating as a main building block of spin-injected vertical-cavity surface-emitting lasers (spin-VCSELs) for ultrafast data transfer up to hundreds of Gb/s. Spin-VCSELs allow direct control of emitted polarization by means of electron spin injection. Compared to intensity-modulated VCSELs, the information is encoded into polarization state of light. Shorter response time is offered as a result of introducing anisotropy, in this case via periodic grating, which couples circularly-polarized photons, emitted in spin-polarized quantum wells. Precise modeling of the lasing regime is essential and based upon theory developed in our previous work. Eigenmodes of cavity with periodic structures are extracted using Rigorous Coupled-Wave Analysis implemented in the scattering matrix formalism. Mathematical tools allow us to calculate optimal parameters of birefringent dielectric grating and consequently to design the cavities with required functionality. Particular focus is put on calculation of photon lifetimes, generalized confinement factors and frequencies of eigenmodes, which are necessary for studying dynamical performance of grating-based spin-VCSELs. According to the numerical model, desired gratings and grating-based cavities can be fabricated using PVD deposition of dielectric material further sophisticated by lithographic techniques along with sample etching.

Keywords: spin-VCSELs, ultrafast data transfer, anisotropy, dielectric gratings, resonant cavity

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Micromanipulation of macromolecules and colloidal particles in complex environment by optical and thermo-optical traps

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ABSTRACT

The work is aimed at the study of the motion of different colloidal objects in the combined force field composed of the optical-trapping force originating in the light-intensity gradient and the thermophoretic force caused by the temperature gradient in complex aqueous mixed solvents. Polystyrene microscopic beads of sub-micrometer diameters are used as a simple model, both unmodified and surface-modified by different molecular residues, including polymers. Their thermophoretic motion in different environments is assayed, and the dependence of the Soret coefficient on the surface-environment interaction is analyzed. The dual optical trap is used as a tool for the measurement of the thermophoretic force acting on the observed particles. Also, the generated optical trap's force constant is calculated by various methods, including Fast Fourier Transform, and the influence of differences in applied environment and light intensity is compared. The thermophoretic motion of free fluorescent macromolecules is studied, too. Results of these experiments should contribute to the theory of the thermophoretic effect, so far not understood in detail and should open a way for developing novel methods of the investigation of intermolecular interactions in complex environments.

Keywords: tweezers, trapping, laser, thermophoresis, manipulation, macromolecule, polymer

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Compact vacuum setup for Al^+ and Ca^+ ion trapping

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ABSTRACT

We present a design of a new compact vacuum chamber with an electrical trap trapping and laser cooling of Ca^+ and Al^+ ions. The custom chamber was designed to a minimum dimension to achieve ultra-high vacuum environment and good optical access to trapped ions. Combining the shape of the electrical trap with good geometrical symmetry and the size of the viewports will allow maximum efficiency of fluorescence collection from ions. The setup is ready for ablation and loading of Ca^+ and Al^+ ions to deal with quantum logic experiments for optical clock operation.

In combination with saddle coils, Helmholtz coil and external magnetic shielding made of MU-metal achieve a homogeneous magnetic field in the ion trapping area. The main part of a chamber equipped with viewports is made of titanium to maintain this homogeneous magnetic field and suppress residual fields. The presented setup allows quantum experiments with single ion and Coulomb crystals in a very stable and homogeneous magnetic field, which is necessary for many-ions optical clock systems.

Keywords: ion trap, vacuum chamber, ablation loading, coils, homogeneous magnetic field

Mid-infrared tunable diode pumped Cr:ZnSe laser continuously tunable from 2.1 µm up to 2.7 µm operated at room temperature

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ABSTRACT

The laser characteristics of Cr:ZnSe single crystals optically polished in three different lengths of 2 mm, 3 mm, and 5 mm were investigated under laser diode pumping at the wavelength of ~1.7 µm. Every characterized Cr:ZnSe laser system was operated in a pulse mode with a repetition rate of 10 Hz and pump pulse duration of 20 ms. Comparison of uncoated samples with AR coated ones was performed. Using a MgF_2 Lyot birefringent filter the laser oscillations were continuously tunable from 2.1 µm up to 2.7 µm with the spectral linewidth of ~5–10 nm and a gaussian beam profile. Maximum mean output power of ~0.35 W was obtained for 3 mm thick AR coated sample which was for about 40% higher output power in comparison with uncoated sample with the same thickness. The absorption and fluorescence spectra as well as fluorescence lifetime were also measured.

Keywords: Cr:ZnSe laser, mid-infrared laser, wavelength tuning, AR-coating, diode -pumping, pulsed laser

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Optical 1:9 splitter based on MMI, prepared by 3D litography

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ABSTRACT

In this paper, we propose and simulate a new type of three-dimensional (3D) optical splitter. There are two main approaches used to split single input optical signal into N output signals. The most obvious way is to use a cascade of one-by two waveguide branches (also called Y-branches). In contrast to the Y-branching approach, in multi-mode interference (MMI) splitters the splitting of the optical signal is based on a self -imaging effect (superposition of modes with different propagation velocities) appearing inside of the multimode section. While MMI splitters are designed for a precisely specified wavelength, the Y branches operate with broad spectrum. We propose and simulate a new type of three-dimensional (3D) optical splitter based on multimode interference (MMI) for the wavelength of 1550 nm, where the input signal is divided into 9 outputs. The splitter was proposed on the square basis with the width of $26 \times 26\ \mu m^2$ using the IP-Dip polymer as a standard material for 3D laser lithography. We present the optical field distribution in the proposed MMI splitter and its integration possibility on optical fiber. The design is aimed to the possible fabrication process using the 3D laser lithography for forthcoming experiments.

Keywords: 3D MMI splitters, polymers, DLW, MMI splitter

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Tunable decoherence of single photons

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ABSTRACT

Tailoring decoherence of single-photon states is an essential tool for benchmarking the robustness of various quantum communications and quantum machine learning protocols. A linear optical device is developed to introduce fully tunable decoherence of qubits encoded in single-photon polarization states. Most notably the setup is able of causing depolarization (white noise), dephasing, or bit-flip errors. Additionally, amplitude damping can be implemented. Parameters of these sources of decoherence are under the full control of the experimentalist in their whole ranges. The performance of the setup and the state independence of the imposed transformation was tested and the results will be presented.

Keywords: single photons, decoherence, degree of polarization, dephasing

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Spectral and magnetic field dependence of the birefringence of a magnetic fluid

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ABSTRACT

Optical birefringence induced in a magnetic fluid by a static external magnetic field has great potential in the design of future tunable polarizing optical elements and sensors. Since birefringence of a medium generally depends on the wavelength of light, we investigate the dependence of the induced optical birefringence of magnetic fluid on the magnitude of the magnetic field as well as on the wavelength. The identified dependencies are important not only for understanding the mechanism of field-induced birefringence in a magnetic fluid, but also to identify the extent of applicability of the magnetic fluid in the design of polarization-dependent optical elements and sensors.

Keywords: magnetic fluid, magnetic field, birefringence, optical sensor

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Electro-optic shearing interferometry of femtosecond impulses in Hong–Ou–Mandel interferometer

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ABSTRACT

Hong–Ou–Mandel effect is one of the most notable quantum interference phenomena. We examined this effect for coherent states of femtosecond impulses of near IR laser. We measured second order correlation function of impulses shifted in time and frequency domains. We performed frequency shifts with electro-optic phase modulator (EOM) synchronized with photodiode which was triggered by impulses from laser. Using this method we are able to calculate temporal and spectral width of impulses without using precise spectrometer. The system is suitable to measure correlation function of weak coherent states on the single-photon level. We are planning to develop this experiment to measure phase matching function of PPKTP crystal used to generate single photon state.

Keywords: Hong–Ou–Mandel, femtosecond, correlation function

High-precision measurement of the center frequencies of the hydrogen cyanide (HCN) hyperfine transitions in the 1.5 μm wavelength band

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ABSTRACT

In the field of dimensional metrology, laser spectroscopy is an essential tool for the realization of the SI-meter. While the well-proven He-Ne lasers lasing at 633 nm stabilized by vapors of molecular iodine remain the cornerstone in this area, the optical frequency standards covering an infrared range of wavelengths rely on the other spectroscopic references. A particular band of metrological interest is the C-band around 1550 nm, widespread in telecommunication, which offers a large selection of cost-effective, readily available components with features hardly achievable with the shorter wavelengths. The dominant spectroscopic media at 1550 nm has been the acetylene isotopes ($^{12}C_2H_2$ and $^{13}C_2H_2$ isotopes) that cover a limited range of wavelengths.

Our research aims to investigate the hydrogen cyanide ($H^{13}CN$) as an alternative with a broader absorption spectrum, which would simplify introducing the traceability for a wider range of wavelengths. The primary objective is the precise assessment of the center frequencies of the transitions. The outcomes should lead to the introduction of hydrogen cyanide into Mise en Pratique, making it an internationally recognized source of precise frequency for the realization of traceable laser etalons.

Keywords: hydrogen cyanide, laser spectroscopy, metrology, frequency reference

FUNDING

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Analysis of the possibilities to generate and analyze different polarization states of light by twisted nematic liquid crystal

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ABSTRACT

Twisted nematic liquid crystals (TNLCs) are an interesting alternative to the linear liquid crystal variable retarders commonly used in polarimetric systems. The first and last molecules are anchored on the bounding surface of the liquid crystal cell at 90° angles to each other. As a result of the application of an electric field, there is a change in the polarization parameters of the eigenvectors of the TNLC and the phase difference introduced by them. Theoretical analysis indicates that the use of TNLC can generate and analyze an infinite number of polarization states. Nevertheless, their practical applicability is limited and depends on the physical parameters of the liquid crystal cell. Therefore, this work presents the polarimetric characteristics (azimuth angle, ellipticity angle and phase difference) measured as a function of applied voltage of two TNLCs fabricated by Thorlabs. The study aims to test whether it is possible to achieve a phase difference greater than 4π by using TNLC, which is desirable for optimization reasons. The polarization states that can be produced and analyzed with the examined TNLCs are represented on the Poincaré sphere. This provides a base for selecting the optimal practically possible polariscope configurations in the future.

Keywords: liquid crystals modulators, twisted nematics, phase difference, polarization state of light

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Applications of machine learning to long-range quantum routing

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ABSTRACT

We consider a scalability problem of multi-user quantum communication networks [1], where the communicated signal is to reach a programmable superposition of users. This is a process with no exact classical counterpart, but it is closely related to routing. Routing of the signal from sender to receiver is a basic operation in complex quantum communication networks, where repeaters unavoidably introduce extra noise due to the non-cloning theorem, which is irrelevant to classical communication. Thus, the optimal routing problem is more complex in quantum networks and specialized quantum routing protocols are required [1–3].

To study the routing problem, we apply machine learning to the search for the optimal protocols recently developed for long-range quantum communication [4]. The use of machine learning potentially allows us finding solutions beyond the known protocols, solutions that are too complex to analyze manually. Moreover, the machine learning approach is expected to avoid problems faced by standard classical approaches which ignore the quantum nature of communication (*i.e.*, standard routing algorithms are not designed to preserve quantum superposition).

To design the optimal quantum routers automatically, we apply reinforcement learning [4, 5]. This method provides dynamically modified complex circuits that are designed to act as faithfully as possible with respect to the target operation. This reinforcement learning method quickly modifies the optimal circuit to mitigate random malfunctions of its components. Based on the selected set of basic building blocks (gates) this approach can be also applied to find a suboptimal solution, corresponding to finding the closest possible operation to the target one. This is different from using standard quantum circuit decomposition techniques. It can be run using a finite set of on non-universal gates, which is not possible in the methods based on the Sovolay –Kitaev theorem.

In our research we focused on designing a quantum routing scheme based solely on linear-optical quantum gates [1–3], but it is also possible to use gates based on nonlinear optical phenomena, which creates what gives space for development in further research.

Keywords: quantum routing, reinforcement learning, non-cloning theorem, long-range quantum communication, quantum circuit, quantum protocols, quantum algorithms

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Quantum process tomography of exceptional points in Liouvillian spectrum

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ABSTRACT

There is constantly increasing interest in theoretical and experimental studies on non-Hermitian physical systems as the sources of novel physical effects. The special group of non-Hermitian Hamiltonians with parity-time (PT) symmetry can have real spectra in the same way as usually considered Hermitian Hamiltonians [1-3]. Depending on the relation between amplification and dissipation, the system can be in a PT-symmetric broken, or unbroken phase. A phase transition occurs at an exceptional point (EP) – a special kind of singularity in the non-Hermitian Hamiltonians spectrum. Interesting physical effects have been reported near and at EPs: increased nonlinearity, enhancement of spontaneous emission, asymmetric light propagation, enhancement of weak signal sensing, and many others.

It has also been shown that when considering a fully quantum description of a dissipative system, exceptional points can also be found in a Liouvillian spectrum in which quantum jumps are also included [4-5].

We examine exceptional points in the Liouvillian spectrum of a bosonic system with amplification and dissipation processes included. We focus on the possibility of revealing LEPs experimentally with the use of the method of quantum process tomography.

Keywords: non-Hermitian Hamiltonians, exceptional points, liouvillian, quantum process tomography

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Cavity cooling of a levitated nanoparticle by coherent scattering

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ABSTRACT

The method of cavity cooling of levitated nanoparticles by coherent scattering is presented. It can be used for reaching the mechanical quantum ground state of a particle trapped in optical tweezers. This opens vast possibilities for quantum experiments. Such as quantum entanglement of nanoparticles (diameter ~100nm) or observing quantum synchronization via optical binding.

Keywords: cavity cooling, coherent scattering, optical trapping

Low-noise detection of an optically levitating nanoparticle

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ABSTRACT

We present two methods – optical homodyne and heterodyne position detection of an optically levitating nanoparticle which can be understood as an underdamped harmonic oscillator. Both methods improve signal two noise ratio in extracting information about particle's motion, which is encoded in phase, frequency and amplitude of the light scattered by the levitating nanoparticle. Homodyne detection provides a relatively easy way to measure particle's position in an optical trap with a resolution sufficient cool their transitional degrees of freedom to the ground state of harmonic oscillator. Heterodyne detection, on the other hand, can be used for measuring particle's effective temperature near its quantum ground state using a method known as Raman thermometry.

Keywords: homodyne detection, heterodyne detection, optical trapping

Methods for determining the contrast sensitivity function for two-photon vision

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ABSTRACT

Two-photon vision relies on the perception of pulsed near-infrared lasers as having colors like their half-wavelength counterparts. It is due to two-photon absorption occurring in visual pigments. The phenomenon receives increasing interest; however, many aspects of the process remain not described. In this study, we focused on contrast sensitivity function (CSF) for two-photon vision, *i.e.*, contrast sensitivity dependence on the spatial frequency of the presented stimulus. CSF was measured for eight spatial frequencies using a rotating letter E of eight angular sizes for three subjects. A contrast threshold was determined by finding the minimum stimulus brightness for which the subject was able to state the correct letter orientation. The letter E shape was projected by fast scanning the retina with pulsed infrared 1040 nm laser beam and with 520 nm beam, both perceived as green. The values of threshold contrast, defined by Weber contrast, differ significantly for visible and infrared light. The obtained results indicate that the two-photon CSF has a broader dynamic range than its one-photon counterpart. Squaring the threshold powers measured for the two -photon stimulus reduced the two-photon CSF range, although it was still slightly greater than the one-photon CSF range for all subjects.

Keywords: contrast sensitivity function, contrast, two-photon vision

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Study of polarization properties of 1D self-organizing optofluidic photonic structures

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ABSTRACT

A self-creating one dimensional photonic crystal based on gold nanoparticles suspended in a nematic liquid crystal may allow a design as well as fabrication of spectrally adjustable optofluidic photonic devices with a broad tuning range. This self-assembly process is completely reversible and can be controlled by modifying diameter of the confining space. The entire system is characterized by high refractive index contrast as the refractive index is being changed between nematic and isotropic phases. When filling the capillary, the nematic liquid crystal director usually aligns along the axis of the capillary with a result that in the nematic phase, contrast depends on the ordinary refractive index. In order to increase the contrast of the refractive indices between nematic phase and isotropic phase, orientation of the molecules in the nematic phase should be changed. The main goal of this work is to investigate the possibility of selective orientation with the electric field of composites of liquid crystals and gold nanoparticles in one-dimensional structures. Photopolymerization will be used to stabilize the molecular orientation initially controlled by temperature or external electric field. A pattern in the liquid crystal can be created by sequential polymerization of areas with different spatial orientations of liquid crystal molecules.

Keywords: gold nanoparticles, liquid crystals, photonic crystal

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Measuring sensitivity of optical frequency transfers to acoustic vibrations in photonic networks

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ABSTRACT

In metrology, optical fibre links have been used for disseminating precise optical frequencies for the past two decades. Mainly for the purpose of remote optical atomic clock comparisons. The precise optical frequency is subject to shifting due to Doppler effect induced by mechanical vibrations and thermal expansion of the fibre. These shifts can be compensated using various developed servo-loop techniques. As a side effect of these efforts, the use of optical fibres in seismological sensing has been reported by several teams. With the knowledge of these phenomena, the existing optical fibre infrastructure in buildings can be misused for eavesdropping and thus pose a new security risk. In our contribution we are investigating the transfer of mechanical vibrations to the fibre in the audible frequency band. An experimental installation of optical fibre imitating typical conditions in buildings was placed into an anechoic chamber and exposed to acoustic vibrations of defined levels and frequencies. Using a heterodyne interferometric system, the phase changes of C-band laser radiation transmitted through the fibre were detected and converted to an audio signal. The transfer characteristics of the fibre for the audible frequencies was measured. Using a special normalized test signal the Speech Transmission Index was estimated.

Keywords: optical fibre, vibrations, speech, eavesdropping, transfer characteristics, speech transmission index, interferometer

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Molecular chirality from the viewpoint of Mueller polarimetry

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ABSTRACT

Chirality – the non-superimposability of an object on its mirror image – shows its twists at all scales, from giant stellar galaxies to the electronic structure of materials. It enters into nearly every aspect of everyone's daily routine without acknowledging it. Yet, it governs the stereochemistry of all molecular processes in nature, making them life-forming or life-incompatible. It makes the knowledge of molecular spatial configuration essential in pharmacy, medicine, and biochemistry. Here, by combining spectroscopic Mueller matrix ellipsometry and exact theory, we experimentally demonstrate and theoretically verify the advantage of the proposed method to determine dispersion characteristics of molecular chirality. We first show how the Mueller matrix relates to standard physical quantities used in common techniques for studying chirality (Raman optical activity, vibrational circular dichroism, *etc*.), making it more accessible and intuitive for subsequent interpretation. Next, we determine quantitative observables such as circular birefringence and dichroism (with sensitivity <0.001 rad) of saccharide solutions, organometallic complexes, and thin-film biopolymers, and apply a physical model. We place these results into the context of the absolute configuration of the molecules. We believe that our findings can provide a new route for data interpretation into polarimetry and stereochemistry, opening the way to application in biomedical routines.

Keywords: absolute configuration of molecules, circular birefringence, circular dichroism, chirality, Mueller matrix ellipsometry, optical activity

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National infrastructure for dissemination of precise time and interconnection of quantum sources of ultra-stable optical frequency–CITAF

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ABSTRACT

In the contribution, we introduce the Czech Infrastructure for Time and Frequency activity which is a non-commercial, open activity focused on the transfer of accurate time and very stable quantum sources of optical frequency using optical networks. The national optical infrastructure for time and frequency transfer is operated on top of the CESNET network infrastructure, to have operational costs under control. We briefly summarize prerequisites in order to allow long haul transmission of ultra-precise time and ultra-stable coherent optical frequency with stability going down to 2 ps in terms of TDEV and 10^{-18} in terms of ADEV for 10^3 s averaging over optical fibers shared with telecommunication data transmission. Affordable precise time and radio frequency transmission with MTIE below 200 ps for multi hundred km distances is addressed too. Addressed is creation of bidirectional dark channels on different wavebands within shared fibers together with bidirectional compensation of fiber losses. Single path bidirectional compensation deploying lumped optical amplifiers is sensitive to feedback from fiber line (back scattering and reflections) and in case of increased feedback can produce unwanted oscillations, which potentially interfere with parallel data transmissions. Affordable detection of these unwanted oscillations without bulky and expensive optical spectrum analyzer is presented. We also address running and planned upgrades and future development plans regarding wavelength bands and considered geographic extensions.

Keywords: precise time, coherent optical frequency, quantum sources of optical frequency, time metrology, infrastructure, optical amplification, optical fiber

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Gaussian-vortex nonlinear interaction in nematic liquid crystals

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ABSTRACT

Due to their unique properties, making them reliable in many academic and industrial applications, optical vortices have gained wide attention among researchers, including those interested in nonlinear optics. Most research conducted in nonlinear regime is concerned with multi-wave mixing, harmonic generation, and solitons in Bose–Einstein condensates. However, propagation of vortices in liquid crystals in a nonlinear regime is covered in a much lower extent, restrained primarily to numerical simulations. In this paper, we would like to extend this topic, presenting experimental results of interaction between high-intensity optical vortex creating vector soliton and low-intensity gaussian beam in nematic liquid crystal. In such a setup, the first beam generates a waveguide in which the second one can propagate. The results show the significant intensity and phase change of low-intensity gaussian independent of both beams' wavelengths. We conduct experiments with TE and TM polarization, taking into account the reorientational and thermal nonlinearity, respectively. The presented results can be the first step towards the new type of broad spectral range light manipulator designed for optical vortices generation.

Keywords: optical vortex, spatial soliton, nematic liquid crystal

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Free-space optical link phase noise measurement

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ABSTRACT

Dissemination of precise time and frequency and its corresponding infrastructure has become a key tool for many scientific and industrial applications (optical clocks comparisons, global positioning systems, security). Although most of these transfers use optical fibre networks, free-space links represent an essential supplement in cases where the fibres cannot be utilised. This work presents experimental results of free-space optical (FSO) link phase noise measurement, an initial requirement for further intended phase-coherent transfer of precise time and frequency. The measurement setup consists of 40 m long unidirectional FSO (DUT) supplied by ultra-narrow 1540 nm fibre laser (locked to the ultra-stable optical cavity), and it is supplemented with parallel phase noise stabilised optical fibre delivering the reference beam to the beat-note with the signal obtained from the FSO receiver. The phase noise measurement results define the requirements for the phase-coherent link and show the limits for the intended bidirectional transfer.

Keywords: free space optical link, phase noise, phase-coherent transfer, time and frequency

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Optical cavity for ultra-narrow linewidth laser system

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ABSTRACT

The precise optical resonators represent a crucial tool for ultra-narrow linewidth lasers frequency stabilisation. They can serve as frequency references for lasers of optical clock systems, optical frequency combs locking, dissemination of precise time and frequencies over optical links, or laser interferometry. The critical properties of these resonators are determined by their design, used materials and environmental conditions where they are operated. This contribution describes the design of the sub-Hz linewidth optical cavity, and it analyses its performance in the optical setup with a frequency-stabilised 1540 nm fibre laser. The cylindrical-shaped Fabry–Perot resonator with optical mirrors and a spacer part made of ceramics with ultra-low thermal expansion coefficient is placed inside the multi-shielded vacuum and thermostated chamber. The optical setup employs the Pound–Drewer–Hall locking technique for the laser locking, and the system's performance is measured by the H-maser referenced optical comb.

Keywords: optical resonator, optical cavity, narrow-linewidth laser, laser locking

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Generation, propagation and interaction of vortex solitons in nonlocal nonlinear media

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ABSTRACT

In the presented work, we report on the generation and propagation of optical vortices in nematic liquid crystals (NLCs). Propagation of such non-trivial optical fields and stable confinement is observed due to a nonlocal nonlinear response originating from molecular reorientation and thermal nonlinearity. Experimental results show that self-confined solitary vortex beams preserve their transverse profile and can guide additional and co-polarized optical beams at a propagation distance of a few millimetres. A high degree of the nonlocal character of the nonlinear response of NLCs enables interaction between two solitary vortex beams. The experimental verification of the influence on the nonlinear propagation of the vortex beam induced by an additional optical beam will also be presented.

Keywords: optical vortices, nematic liquid crystals, self-focusing, spatial solitons

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Measurement of micro-aberrations in ophthalmic lenses using a fiber Hartmann–Shack sensor

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ABSTRACT

The problem of precise aberration measurements of ophthalmic lenses is nowadays more important since new progressive, degressive, and myopia controlling lenses are being introduced to the market. We propose a novel setup for measuring optical aberrations in such lenses on the micrometer scale. The setup is based on a high-resolution fiber Hartmann–Shack sensor. The performance of the prototype is tested using two lenses.

Keywords: ophthalmic lenses, Hartmann–Shack sensor, aberrations, measurement

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A new approach to the analysis of the corneal shape dynamics

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ABSTRACT

The aim of this study is to present a new approach to the description of dynamic changes in the corneal shape from OCT image sequences based on the analysis of spatial frequencies, cross-correlation plots and motion of MIM points, which are defined as a collective name for the minima, inflection points and maxima of the second derivative plot of the anterior corneal surface.

The spatial spectrograms of the corneal surface were used to determine the spatial frequency range for which the rapid changes in spectral power density appear. The estimated upper and lower limits of this range are between 0.820–0.839 1/mm and 0.169–0.241 1/mm, respectively, and seem to be subject-specific.

The cross-correlations analysis showed that the temporal variability of the second derivative of the first corneal surface in subsequent tomograms has the characteristics of a standing wave. The period of this wave calculated for the tested eyes was within the range of 1.50–1.75 mm.

Based on the analysis of MIM points displacements, the relationship between the peak-to-peak amplitude and the distance of the point from the corneal apex was calculated. It was found, that this dependence is quasi-sinusoidal.

Keywords: corneal shape, spatial frequencies, cross-correlation, OCT image analysis

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Spectrally-resolved microscopy study of the effect of microplastics on water moss *Fontinalis antipyretica*

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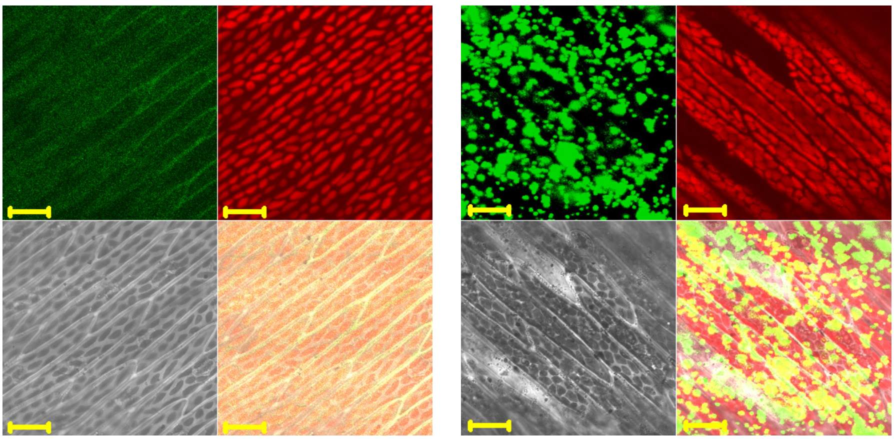
ABSTRACT

In this contribution, we investigated the effect of microplastics particles on aquatic bryophytes using spectrally resolved fluorescence microscopy. We employed water moss *Fontinalis antipyretica* as model system. Our aim was to verify the possibility of capturing microplastics from the aquatic environment using bryophytes. We have detected various fluorescently labeled microplastics on the bryophyte surface at different time-scales (days to weeks' exposure). We monitored changes in the microplastics presence (green fluorescence), together with the endogenous fluorescence of chlorophylls (red fluorescence) using spectrally-resolved fluorescence microscopy. We observed



Graph: Spectrally-resolved confocal fluorescence image of *Fontinalis antipyretica* in control conditions (left) and in the presence of fluorescently-labelled polystyrene latex beads of 0.5 μm size (right, Sigma-Aldrich). Top: green image, 500–550 nm and red image, 650–710 nm. Bottom: transmission image and composite image; scale 20 μm.

the capacity of the bryophytes to capture microplastics at a very short time scale. We also noted relatively small effect of the microplastics on the chlorophyll fluorescence. Gathered data are the first step towards monitoring pollution of aquatic environment by various microplastcs and searching for new ways of their remediation.

Keywords: *Fontinalis antipyretica*, chlorophyll, microplast

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Determination of dopant concentration in single-mode step-index optical fiber based on measured numerical aperture and mode field diameter

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ABSTRACT

Numerical modeling of many optical-fiber-based devices operation requires an exact knowledge of fiber's parameters like core diameter and dopant, usually GeO_2, concentration. While diameters are typically specified in the fiber's data sheet, material composition, including dopant in the core, is rarely available. We present a procedure utilizing an inverse engineering approach to find GeO_2 concentration in single-mode step-index optical fiber. Our method consist of several stages. First, we measured the numerical aperture NA for several commercially available fibers employing a one-dimensional far-field scan. The far-filed mode intensity was acquired by an InGaAs detector placed on a rotation stage with a stepper motor for fiber end-face positioned on the motor's axis of rotation. We calculated NA for the angular detector position when the light intensity reached 5 and 1% of its maximum value. Then, taking the corresponding values of core and cladding diameters and using the Sellmeier formula for pure (cladding) and GeO_2 doped (core) silica glass, we found the concentration of GeO_2 numerically matching calculated NA to the experimental data. We found that dopant concentration is equal to 8.16, 17.08 and 30.62 [mol %] for the fibers, respectively, 980-HP, UHNA1 and UHNA3 produced by Coherent. To verify of the correctness of the method used we compare the simulation results for several fibers with a known level of GeO_2 concentration in the core, fabricated by Laboratory of Optical Fiber Technology, Maria Curie-Sklodowska University.

Keywords: optical fiber, numerical aperture, dopant concentration

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Atmospheric turbulence simulator for satellite optical link

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ABSTRACT

The feasibility of a free space optical communication link depends on overall optical power loss due to atmospheric turbulence [1, 2]. In this project, we work towards design a laboratory setup which will be used for testing satellite optical communication modem performance by simulating the typical effects such as temporal fading, Doppler shift, Doppler rates and scintillation [3, 4]. The implementation is based on the optical fiber optics with electro-optical intensity modulator controlled by arbitrary waveform generator. The project is a part of European Space Agency contract "ARTES 4.0 SPL Optical Communication – CCSDS standardized ranging for optical communication terminals" led by Nicolaus Copernicus University in Torun in collaboration with Syderal Polska and Work Microwave GmbH.

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A bifunctional system for measuring geometrical parameters and stress distribution in fiber optic preforms

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ABSTRACT

A bifunctional system for characterization of fiber optic preform is presented. It allows for measurements of geometrical parameters of the preform core and cladding in transverse illumination, including diameter versus angular orientation, ellipticity and azimuth of the longer ellipse axes. The measurement can be done at different cross-section thus allowing for investigating an axial uniformity of the preform. The measuring principle is based on imaging of the preform (with automatic focusing) combined with spatial filtration of the most deflected rays, which leads to visualization of the core edges. Special numerical procedures allow for an exact identification of the edges position, even in the case of multi-step index profiles. After inserting the polarizer into the imaging beam, the system is capable of measuring the preform birefringence induced by thermal stress. Maps of the retardation distributions in the preform image are obtained simultaneously at two wavelengths with the use of the rotating polarizer method. This allows to determine the exact value of the stress-related retardation without order unambiguity and finally to calculate the axial stress distribution using the inverse Abel transformation. Examples of measurements for preforms of different types will be presented.

Keywords: fiber optic preforms, geometrical measurements, stress measurements

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Vortex constellation as a positioning tool

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ABSTRACT

We propose the use of optical vortices as markers in the positioning of a laser beam. Beam positioning at large distances is disturbed by atmospheric turbulence. We show numerically and experimentally that optical vortices exhibit smaller transversal displacement caused by the atmospheric disturbance compared to the centroid-based assessment of the pure Gaussian beam. We propose also a further improvement of beam localization by using a high-order vortex beam. *m*-th order vortex beam splits into the constellation of *m* single charged vortices which can be easily traced. In a turbulent atmosphere, vortex constellation geometry is changing. Beam localization can be determined by centroid position of vortex constellation. We showed that vortex constellation offers better accuracy in beam positioning than Gaussian and single charged vortex beam.

Keywords: optical vortex, positioning

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