Plenary and Invited Lectures

Biomedical Optical Applications of Liquid Crystal Devices

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Liquid crystals (LCs) are birefringent materials that exhibit large electro-optic effects which make them useful for a variety of applications as fast, compact, and tunable spectral filters, phase modulators, polarization controllers and optical shutters. They have been largely developed for liquid crystal displays and in the last decade for optical telecommunications, however their application in the field of optical imaging just started to emerge. These devices can be miniaturized thus have a great potential to be used with miniature optical imaging systems for biomedical applications. Using a collection of tunable phase retarders one can perform:

1. Full measurement Stokes parameters for skin and eye polarimetric imaging.
2. Tunable filtering to be used for hyperspectral imaging, fluorescence microscopy and frequency domain optical coherence tomography.
3. Adaptive optical imaging and eye aberrations correction.

Basic optics of liquid crystals devices will be reviewed and some novel designs will be presented in more details when combined to imaging systems for a number of applications in biomedical imaging and sensing.

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Dark Resonances in Quantum Optics

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We will review the processes occurring in three-level systems and in more complex atomic configurations based on the three-level structure. Coherent population trapping, bright resonances, electromagnetic-induced transparency (EIT), laser cooling based on EIT, four-wave mixing, photon squeezing will be discussed.

Dancing Light: Counterpropagating Beams in Photorefractive Crystals

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A review of work on the dynamical behavior of counterpropagating (CP) incoherent laser beams in photorefractive crystals is presented. A brief survey of experiments displaying rich dynamics of three-dimensional CP optical solitons is given. Numerical study of CP beams of different type is carried out, in both space and time. Theory capable of capturing such dynamics is introduced and linear stability analysis (LSA) performed. Numerical simulations are found in qualitative agreement with experiment and LSA. Spontaneous symmetry breaking of head-on propagating Gaussian beams is observed, as the coupling strength is increased, resulting in the split-up transition of CP components. The development of patterns in broad hyper-Gaussian CP beams is investigated, by varying the width of beams. Owing to slow quasi-steady-state changes in the system during time evolution, the transverse characteristics of beam distributions, determined by LSA, are found to persist for long in the transient evolution of CP beams. The conservation of angular momentum of mutually incoherent copropagating (CO) and counterpropagating vortex beams is discussed. It is shown that the total angular momentum of CO beams is conserved, whereas that of CP beams is not. The difference of angular momenta of CP beams is conserved, but not their sum. The transfer of angular momentum from vortex beams to optically induced photonic lattices is demonstrated. It is found that the total angular momentum in the presence of optically induced lattices is nearly conserved if the lattice beams are interacting with the CP vortices, and that it is not if the lattice beams are fixed. For the interacting beams the difference of angular momenta of the CO and CP components is always conserved. In the fixed lattices there is always a considerable loss of angular momentum. Rotational properties of CP mutually incoherent self-trapped vortex beams in optically induced fixed photonic lattices are also investigated. Discrete diffraction, beam filamentation, as well as increased stability of the central vortex ring are displayed. Evidence of transport through tunneling between lattice sites is presented. Properties of CP mutually incoherent self-trapped beams in optically induced circular photonic lattices with ring defects are addressed numerically. Using a modified Petviashvili's method, several novel solitonic structures are found. For CP beams in optically induced photonic lattices, some of the fundamental quantum mechanical phenomena are observed, such as the tunneling of light from the first to the higher-order bands of the lattice band-gap spectrum. Other phenomena characteristic of solid state physics, such as Bloch oscillations, Zener tunneling and Anderson localization are also displayed.

Optical nanomaterials for medical imaging

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Medical imaging is widely used for diagnostic in human medicine, but also plays a great role in pharmacological studies on small animal. In this talk we will review the main techniques currently used and underline the need for optical materials to develop new techniques. On the one hand imaging based on high-energy radiation (Computed Tomography (CT), Positon Emission Tomography (PET)…) are very powerful. In CT, the patient is X-ray irradiated and the non-absorbed rays are detected by scintillators placed around him. In PET, γ-rays are emitted from a radioactive molecule absorbed by the patient and detected by fast scintillators placed around the patient. The quality of the scan depends on the scintillators performance, i.e. the scintillating materials must absorb high-energy radiation and emit intense and fast luminous signals. Best candidates are $LaCl_3$:Ce, $LaBr_3$:Ce, $Lu_2Si_2O_7$:Ce, Lu_2SiO_5 :Ce crystals depending on the specific application. New compositions for the scintillators and ease of production are pursued by designing scintillating ceramics produced by sintering of nanocrystals.

On the other hand luminescent markers present obvious advantages compared to CT and PET scan. Radiation exposure is avoided and equipment is much lighter. The markers are molecules or particles that emit visible light when excited by UV or visible. Their use is however largely restricted by the wavelength therapeutic window : biological tissues greatly absorb UV and visible light, only red and infrared can go through the tissues. Besides the tissues themselves present some luminescence that hides the marker signal (autofluorescence). Among the large choice of luminescent materials, CdS or CdSe QDots are very luminous but highly toxic, organic dyes are subject to photobleaching. There is still a need for luminescent nanoobjects able to circulate in small animal bodies. The long afterglow, observed in so-called “long-lasting phosphors”, allows to improve greatly the signal to noise ratio in the absence of any parasitic signal coming from intrinsic luminescence [1]. The label fluorescence can be observed for a long period of time (more than one hour) after injection and this allows to follow *in vivo* and in real-time the biodistribution of the fluorescent nanoprobes.

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Colour Holography, Colour HOEs and Ultra-fine-grain Silver Halide Emulsions

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Coherent inelastic backscattering of light by cold atoms

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We discuss the coherent backscattering (CBS) of laser light from a sample of trapped, cold atoms, as a genuine example of interference-induced transport features in disordered media. In particular, we discuss the influence of inelastic scattering events which become dominant as the atomic transition is saturated by the injected laser radiation. We analyse the consequences thereof for the CBS intensity and spectrum, on the basis of the simplest model which yet comprises all relevant ingredients, and compare our results with the available experimental data.

Coherent population trapping in alkali atoms

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Coherent excitation of ground-state atoms results in interesting effects with significant importance for fundamental physics and applications. Among others, Coherent Population Trapping (CPT) [1] and the related effect of Electromagnetically Induced Transparency (EIT) [2] and Electromagnetically Induced Absorption (EIA) [3] are nowadays extensively studied. Their application is expanding rapidly in fields as diverse as slowing of light [4], nonlinear optics, quantum information storage, frequency standards, precise magnetometers [5]. The CPT effect manifests itself as dip in the fluorescence, or peak in the transmitted through atoms laser light which is several orders of magnitude narrower than the width of the corresponding optical transitions.

We present an analysis of recent results related to the study of CPT effect in alkali atoms (Cs, Rb, K, Na) aimed at clarification of their potential for various applications. The CPT resonance is prepared in three configurations: (i) two Zeeman sublevels of the two ground hyperfine (hf) levels are coupled to a common excited one by two coherent fields, (ii) non-degenerate Zeeman sublevels of a single ground hf level are coupled by polychromatic light, and (iii) two polarizations of a monochromatic light are used for coupling of Zeeman sublevels within a hf level. Using the first approach, the CPT effect has been studied in Cs and Rb. For the two-field preparation, diode laser frequency modulation in the GHz region is performed. Based on the second approach, the problem with the modulation frequency is relaxed reducing it to the kHz region. However, here the hf optical pumping introduces significant loss. To decrease the modulation frequency while still involving the two ground hf levels, it is promising to use K vapour. In case of the third approach, it has been shown that in absence of depolarizing collisions the EIA resonance is observed for hf transitions with the degeneracy of the excited state larger than that of the ground one. The depolarization of the excited state results in the EIA resonance transformation into the EIT one. A disadvantage of cm-size alkali cells using is the strong overlapping between hf transitions responsible for the EIT/EIA effect. For correct study of different type of hf transitions, Cs vapour confined in Extremely Thin Cell (ETC) [6] have been used where the hf transitions are well resolved. In Cs vapour confined in ETC, the EIA resonance transforms into EIT one which is attributed to the elastic interaction processes of atoms in ETC with its walls.

The richness of the results related to the CPT preparation in alkali atoms provides a number of possibilities for tailoring of various methodologies depending on the aimed applications.

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Spatial optical solitons, nonlinear waveguides and optically induced lattices in nonlinear refractive index media

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Compensating the diffraction of an optical signal is crucial to efficiently transmit, switch or route data, or performing logical operations with optical beams and light pulses. Linear optics provides various methods to keep optical waves localized as they propagate, most prominently optical fibres, or recently, photonic crystals. Common to all these devices is a prefabricated transverse variation of the refractive index. This effectively limits their application to static waveguiding, lacking the tuneability and adaptivity that is necessary for effective processing. Nonlinear effects in optical materials in contrast provide the opportunity to dynamically generate refractive index profiles in initially unstructured media, thus allow combining optical guiding with switching operations.

Photorefractive materials have been the primary nonlinearity in experiments to generate self-induced adaptive waveguides by refractive index changes since the discovery of the spatial optical soliton in these media in 1992 [1]. One of the major features of photorefractive solitons is their nonlocal potential, which results in an anisotropic modulation of the refractive index governs the interaction behaviour of photorefractive solitons. Therefore, photorefractive solitons allow to experimentally prove and realize numerous interaction scenarios of spatial solitons [2]. In our presentation we will review these interaction scenarios, show methods to stabilize soliton complexes and present their potential for applications in waveguiding [3].

An alternative approach to novel wave guiding devices is based on wave transport through periodic media, combined with total internal reflection or resonant Bragg reflection. Increased flexibility can be achieved when light itself induces its own periodic structure through the nonlinear response of the material. Photorefractive materials have played a key role in realizing optically-induced periodic structures, being up to now mostly restricted to weak nonlinearities. Although these configurations allowed to demonstrate a series of attractive applications of optically-induced photonic lattices, especially the formation of discrete solitons [4], the full potential of the photorefractive response can only be exploited using the strong and anisotropic nonlinearity [5]. In this presentation we discuss the difference between light propagation and localization in linear and nonlinear photonic structures and demonstrate the wave guiding properties of several novel types of nonlinear modes [6].

Finally, the strong nonlinearity allows for novel configurations as the counterpropagating soliton. Although it leads to dynamical instabilities [7], we show that an appropriate photonic structure in the material allows to harness the instability and to form a stable bidirectional adaptive waveguide [8].

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Luminescence of lanthanides from xerogels embedded in mesoporous matrices

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The report summarises perculiarities of synthesis and luminescence properties of porous silicon, porous anodic alumina and artificial opals with the inclusions of sol-gel derived oxides (xerogels), doped with Er, Tb and Eu. Interest in sol-gel synthesis arises from the relatively low cost and the approach allows the chemical content and concentration ratio of the elements of the sol-gel derived films to be tailored, with ready fabrication onto different substrates. More specifically, the sol, *i.e.*, the dispersion of colloidal particles is able to penetrate through the channels of mesoporous matrices, enabling fabrication of a luminescent xerogel located within the porous layer of several micrometers thickness. Particularly the method allows synthesis of luminescent species and the structures xerogel/porous silicon, xerogel/porous anodic alumina and xerogel/artificial opals were investigated in recent years with SIMS, TEM, SEM, AFM and other techniques [1]. The fabricated structures reveal strong photoluminescence (PL) of lanthanides.

Optical excitation of lanthanide ions in xerogel/porous anodic alumina structure can be realized directly, through xerogel matrix, and due to multiple scattering of exciting light by the matrix of mesoporous anodic alumina. Multiple scattering of light and recently observed redistribution of the photonic density of states by porous anodic alumina matrix with maximum of light intensity at direction parallel to the channels of the pores [2] reveal enhanced PL of Tb and other lanthanides in the xerogel films embedded in porous anodic alumina [3]. A method for the fabrication of luminescent images based on anodizing of aluminium, photolithography and sol-gel process in proposed.

Photoluminescence excitation spectra (PLE) for the emission wavelength 1.54 μm were compared for erbium-doped titania and titania-silica xerogels embedded in artificial opals and porous anodic alumina films. Opals were chosen with photonic stop-band in green spectral range [4], where excitation of 1.54 μm emission occurs most efficiently. In comparison to the structure erbium-doped titania xerogel/porous anodic alumina the photoluminescence excitation spectra for 1.54 μm emission wavelength significantly changes for the same xerogels embedded in artificial opals. For the structure opal/TiO_2:Er the appearance of the strong PLE band at 360 nm has been found. Influence of chemical factor of SiO_2/TiO_2 composite and light scattering on erbium PLE is discussed. The strong PLE band in ultra-violet range obtained for the TiO_2/SiO_2 composites makes, from our point of view, these materials attractive for the development of light transformers for the rapidly extended market of short-wavelength optoelectronic devices on the basis of the group III nitrates.

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High-resolution spectroscopy of cold atoms

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Abstract

The lecture will start by discussing special features of cold-atom samples and their consequences for spectroscopic measurements. We will then review principal spectroscopic techniques with particular emphasis on the stimulated Raman scattering in a pump-probe arrangement. The pump-probe spectra recorded with a working MOT will be discussed for two important cases: one with the MOT beams serving as pump field, second with an extra non-resonant pump. Relevant spectra consist of several different contributions caused by different pathways of stimulated Raman scattering. Particularly interesting are the Raman spectra associated with the transitions among continuum momentum states of moving atoms, the so called Recoil-Induced Raman Resonances (RIRs). We will show how the RIR resonances can be employed for multidimensional, nondestructive thermometry of cold-atom samples. Raman spectroscopy allows also studies of atoms localized in optical lattices thanks to distinct vibrational spectra. Particularly interesting is simultaneous recording of the RIR and vibrational spectra as it allows studying dynamics of dipole trap loading. Finally, the optical spectroscopy of Bose-Einstein condensate with the Raman technique, known as Bragg spectroscopy will be discussed.

Structural colours in biology

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Beetles whiter than white, insects with metallic colours and butterflies with coloured wings that seem to shine by themselves, even in low light conditions – structural colours are omnipresent in biology. As opposed to pigment colours, structural colours are caused by the interaction of light with micro- and nanoscopic structural features of the biological material: total reflection, spectral interference, scattering, and, to some extent, polychromatic diffraction, all familiar in reference to inanimate objects, are also encountered among tissues of living forms, most commonly in animals.

The physical principles of the generation of structural colours will be reviewed, various examples from the animated world will be given and possible applications of biomimetic colours in man-made devices such as humidity sensors and allergy control fabrics (keyword smart colours) will be discussed.

Attosecond physics: Tools for observing and controlling electrons on an attosecond time scale

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Macroscopic properties of matter are inextricably linked to ultrafast phenomena evolving on an atomic and molecular scale. Observation and control of the atomic motion inside molecules in real time constituted a triumph of ultrafast science [1] and was based on developments of femtosecond laser pulses.
However the motion of electrons, that takes place typically on a scale ranging from a few tens attoseconds (1 as $=10^{-18}$ s) to a few tens femtoseconds (1 fs = 10^{-15} s), has hitherto remained inaccessible.
Here we demonstrate tools that allow tracking and controlling of electron dynamics on an attosecond time scale. They comprise a combination of attosecond X-ray pulses [2] and precisely sub-cycle controlled light fields [3] offering the highest temporal resolution available to date, that is better than 100 attoseconds (1 atomic unit of time ~ 24 attoseconds).
These tools will offer potential to interrogate the electronic properties of a broad range of physical systems for the first time. These include studies of inner-shell ultrafast electron dynamics, electron transfer in chemical processes, and the potential to investigate the ultimate limits of electronics given the day-to-day reduction of their size approaching the “few atoms per logic gate” limit.

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Atomic Nanoscope

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The interaction at mean distance between a slow atom and a surface is of the van der Waals type. As soon as the atom has a non-zero internal angular momentum, such as rare-gas metastable atoms as $Ar^*(^3P_2)$, this interaction is not a purely scalar potential but rather contains an additional quadrupolar part. This quadrupolar part breaks the atomic state symmetry and is able to induce inelastic transitions [1]. When an external magnetic field **B**, the direction of which is different from that of the normal **n** to the surface, is applied, transitions between Zeeman states ($M \rightarrow M'$) are induced [2], provided that the distance of closest approach (or impact parameter ρ) is small enough (ρ < 2 or 3 nm). When such transitions, called "van der Waals - Zeeman" (vdW-Z) transitions, are exo-energetic ($M'-M = \Delta M < 0$), the atom experiences a repulsive deflection, by an angle $\gamma \approx \left| g\ \mu_B B\ \Delta M / E_0 \right|^{1/2}$, where g is the Landé factor, μ_B the Bohr magneton and E_0 the initial kinetic energy. These vdW-Z transitions act as tuneable (*via* B) beam splitters, usable in atomic interferometers.

The simplest configuration of such an interferometer is the atomic counterpart of the bi-prism Fresnel's interferometer. It consists of two opposite surfaces, e.g. the two opposite edges of a few µm wide slit. Using a nozzle beam of $Ar^*(^3P_2)$ atoms [3] slowed down to a velocity of a few tens of m/s by a standard Zeeman slower [4], one easily gets transverse coherence lengths larger than the slit width. Under such conditions, a single atomic wave packet can be inelastically scattered by both edges, generating two coherent wave packets deflected at opposite angles. Because of the very narrow range of impact parameters where the vdW-Z transitions occur (2-3 nm), these packets strongly spread out and overlap beyond a distance of few cm from the slit, leading to a Young-slit interference pattern. For instance, with a velocity of 56 m/s, a slit width of 10 µm, one gets at a distance of 30 cm, a fringe spacing of 5 µm. It is worthwhile to note that this device realises a textbook measurement of coherences in the atomic beam: longitudinal coherence *via* the number of visible fringes, transverse coherence *via* the contrast at the centre of the interference pattern. Because of the velocity spread (a few %) (longitudinal coherence length) only a limited number of fringes (about 50) is observable, but the most interesting thing here is the *envelope* of these fringes. Indeed this envelope is the Fourier transform of the transition-probability profile at the vicinity of the surface. By this way this profile is "observed" with a sub-nanometric resolution.

The group "Interferometry and Optics with Atoms" is a member of the *Institut Francilien des Atomes Froids* (IFRAF)

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Transport in quantum cascade lasers

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This paper introduces the concept of semiconductor heterostructures and describes the theory and mathematics behind `band-gap engineering' through the solution of Schrodinger's equation in quantum well potentials.

The paper goes on to discuss the relative timescales of important electron scattering processes in semiconductor heterostructures and shows how this leads to thermalised electron distributions within the quantum well subbands. Furthermore, consideration of scattering processes which couple together electron distributions in separate subbands and which lead to an exchange of energy but not particles, drive the electron temperatures of the subbands towards a similar value. From this basis the paper shows how this has led us to propose a semi-classical Boltzmann model for electron scattering transport which is centred on the self-consistent solution of the coupled rate equations for particle numbers in each subband together with an energy balance condition which yields the average electron temperature.

This theoretical approach has been applied to mid-infrared and terahertz quantum cascade lasers, quantum well infrared photodetectors and fully discrete systems such as quantum dot infrared photodetectors and QCLs in magnetic fields and the very good comparison with experiment substantiates this *incoherent* scattering approach.

We have also developed an alternative model for transport in quantum cascade lasers which is based on the density matrix formalism and therefore, in contrast to our earlier work, allows for *coherent* processes. Three levels of approximation were implemented for the electron dynamics, namely the Boltzmann, Markovian and non-Markovian. It was found that there was little difference in the current density between the coherent and incoherent descriptions, however the non-Markovian calculation of the optical gain in a terahertz quantum cascade laser was quite different and therefore offers an opportunity for experimental confirmation.

Band Structure Calculation Methods for complex and frequency dependent Photonic Crystals

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Photonic crystals are investigated in recent literature for almost twenty years, but only recently dispersion was taken into account. Kuzmiak et al. [1] presented two methods to derive band structure for metallic PCs. The first method is a modified plane wave expansion (PWE) where the frequency dependent dielectric function $\varepsilon(\omega)$ leads to a non-linear matrix equation which is solved by reformulating this equation to an eigenvalue problem. This method works in one, two and three dimensions but requires a large computation time.
The second method is a Kronig-Penney like description which allows to calculate the dispersion only for one dimensional PCs. In this model one uses the continuity conditions of the electric field as well as Bloch's theorem. The resulting equation allows to derive the wave number for any frequency. This yields for a frequency dependent (and via Kramers-Kronig complex) dielectric function of a PC a complex wave vector **k**. The imaginary part of the wave vector is a measure for the spatial damping.
In our contribution we study one dimensional systems where we use either a Drude model (metallic PC) or a Lorentzian dielectric function (polaritonic PC) and investigate all angles of incidence. For normal incidence there is a degeneracy between the two polarizations (TE and TM). In this case one observes an additional band gap next to the structural ones. This metallic or polaritonic band gap is located at frequencies where the dielectric function has a large imaginary part (huge absorption).
This metallic/polaritonic band gap is complete for all angles of incidence except for solutions which propagate parallel to the periodically orientated metallic/polaritonic sheets. These states exist only for the polarization where the magnetic component is parallel to the layers and are strongly connected to surface plasmons or surface polaritons. One will note that these states are coupled over adjacent layers [2].
It is also discussed, how the dispersion relation can be tailored to achieve infinite and negative values of the group velocity by coupling bulk and surface excitations. Furthermore we construct a dispersion relation with negligible imaginary part and significantly influenced real part, where the coupled surface excitations can propagate at least a factor of 1000 further than plasmon polaritons on a single interface. It is shown that in our system Kramers Kronig (KK) relations are invalid. Finally additional terms between the unequal energy velocity and group velocity due to absorption and dispersion are derived.

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Towards p-doped intersubband quantum cascade infrared emitters: SiGe and AlGaAs

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Intersubband transitions within the conduction band in semiconductor quantum wells have been widely explored, which eventually led to their application in quantum well infrared photodetectors and quantum cascade lasers. There have been considerably fewer studies of hole intersubband transitions, which are more complicated than their electronic counterparts. They are very interesting, however, because of optical activity for both TM and TE light polarization, offering the possibility of both edge and surface-normal emission or absorption. Earlier studies have mostly focused on bound-continuum transitions in GaAs/AlGaAs and Si/SiGe systems for infrared detection. The interest in hole intersubband transitions has been recently renewed in view of their application for mid- and far-infrared emitters, including quantum cascade lasers. Considerable progress has been made in the theoretical considerations and design [1–5] as well as in realization of p-doped Si/SiGe quantum cascades, and luminescence has been obtained in the THz [6] and mid-infrared [7] range, although laser action has yet to be demonstrated.

While the SiGe material system presents considerable growth challenges due to the lattice-mismatch induced strain, the GaAs/AlGaAs system is virtually strain-free, and has a much better developed growth technology, which makes it attractive for realization of devices using hole intersubband transitions. Recent efforts have indeed resulted in growing rather complex p-doped multilayer GaAs/AlGaAs structures, showing well-resolved line-like spectra in absorption [8] and emission [9].

In this work we review the progress and the present status of p-doped quantum cascade structures, and discuss the challenges and prospectives of achieving laser action.

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Measuring the Unmeasurable – Atomic Clocks and the Limits of Accuracy

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Atomic clocks have progressed steadily from fractional inaccuracies of $\delta f / f \approx 10^{-9}$ fifty years ago to the best microwave clocks giving inaccuracies at the $\delta f / f \leq 10^{-16}$ level, with optical clocks promising even more phenomenal performance at the 10^{-17} level and beyond. This level of performance requires an excruciating attention to detail when attempting to correct for frequency biases. For example, an uncertainty of 1 meter in the altitude of the device with respect to a fictious reference geoid (about mean sea level) causes a frequency uncertainty of more than $\delta f / f = 10^{-16}$ while un uncertainty in the temperature of the radiation field to which the atom is exposed of 1K yields frequency shifts of several times this much. In this talk we will discuss some history of these devices, the current state of the art in laser-cooled microwave clocks and some fundamental limits to their attainable accuracy (we are almost there!) Finally we examine the new optical clocks, which share many features with the current best microwave atomic clocks but with the promise of much higher accuracy.

Since the early days of atomic clocks, our most sensitive tests the nature of physical laws comes from tests involving inter-comparisons of these atomic clocks. We have recently completed two such experiments in our laboratory. The first, which compares the long -term frequency of a hydrogen maser to laser-cooled atomic clocks has reduced the limits on any local position invariance (LPI) violating terms in the frequency of these clocks by a factor of more than 20 [1]. The second test, a long-term inter-comparison of the frequency of a laser-cooled cesium fountain clock and an optical clock based on a single trapped Hg^{+} ion places stringent limits on any time variation of the fine structure constant, α [2]. Finally inter-comparisons of optical clocks with one another promise to greatly enhance our understanding of the universe around us by even more sensitive tests of the time and position invariance of fundamental physical laws.

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Nonlinear optics and light localization in periodic photonic structures

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We review the recent developments in the field of optical lattices and periodic photonic structures emphasizing their unique properties for controlling linear and nonlinear propagation of light. We draw some important links between optical lattices and photonic crystals pointing towards practical applications spatial light control [1].

In particular, we overview our recent results on spatio-spectral control, diffraction management, broadband switching, and self-trapping of polychromatic light in periodic photonic lattices in the form of rainbow gap solitons, polychromatic surface waves, and multigap color breathers. We show that an interplay of wave scattering from a periodic structure and interaction of multiple colors in media with slow nonlinear response can be used to selectively separate or combine different spectral components. We use an array of optical waveguides fabricated in a LiNbO3 crystal to actively control the output spectrum of the supercontinuum radiation and generate polychromatic gap solitons through a sharp transition from spatial separation of spectral components to the simultaneous spatio-spectral localization of supercontinuum light. We also show that by introducing specially optimized periodic bending of waveguides in the longitudinal direction, one can manage the strength and type of diffraction in an ultra-broad spectral region and, in particular, realize the multicolor Talbot effect [2].

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The Effect of Disorder in 2D Photonic Crystals

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Ideally, photonic crystals (PhC) are defined as structures with a spatially periodic refractive index. However, deviations from this periodicity will appear in manufactured PhCs. These deviations can be reduced, but they cannot be avoided altogether. Therefore studying the effect of disorder is important for the application of PhCs.

Disorder appears in different forms in PhCs. For example, in a two-dimensional array of cylindrical holes etched into a semiconductor layer, the positions of the centers may deviate randomly from their undisordered lattice positions (positional disorder). On the other hand, also the diameters of the holes can vary from their nominal value (size disorder) or the shape of their cross sections may deviate from a circular shape (shape disorder).

Here, we concentrate on the effects of positional disorder in 2D PhCs. We model the disorder by assigning each element of the PhC (index i) a random shift $\delta_{x,i}$ and $\delta_{y,i}$ from its ideal position in x- and y-position respectively. $\delta_{x,i}$ and $\delta_{y,i}$ are uniformly distributed in the interval $[-\delta,\delta]$. In this way δ determines the strength of the disorder. The PhC systems which are investigated here are square lattices of rods and triangular lattices of holes.

To investigate the effect of disorder on the propagation in disordered PhC in detail we examine the propagation of collimated Gaussian beams determined by the finite difference time domain method. Because of their peculiar properties special interest is placed on the frequency regions where negative refraction occurs for these beams.

These calculations are complemented by determining the density-of-states (DOS) and the modes of the electromagnetic waves in the PhCs by bandstructure methods as the plane wave expansion method (PWE). Since the PWE method requires are periodic system, the disordered PhC is approximated by periodically repeating a supercell comprised of $N \times N$ unit cells each containing a rod or hole which is shifted randomly and individually [1, 2].

The effect of increasing disorder on the DOS is found to be a narrowing of the photonic band gaps, more pronounced at higher frequencies, and the appearance of states with frequencies deep within the gaps of the ideal PhCs. The field patterns of these gap modes are localized in a small region of the supercell. For states in the bands the field patterns (even for high disorder $\delta = 0.1a, a$ is the lattice period) resemble those of the undisturbed PhC with their long-wavelength Bloch wave patterns.

The FDTD calculations show a persistance of the negatively refracted beam as the disorder is increased, but accompanied by an increasing diffusively propagating component.

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Entanglement in multipartite Josephson systems

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Superconducting devices have attracted significant interests both because these artificial macro-atoms allow to investigate fundamental properties of quantum theory on a mesoscopic/macroscopic scale and more recently in view of possible applications in quantum communication and information processing. So far, experimental research in this field has mostly focused on the behaviour of single isolated qubit while in the last few years, significant achievements on superconducting two-qubit systems were reported, i.e., the generation of entangled states in systems of coupled flux and phase qubits, as well as the observation of quantum coherent oscillations and conditional gate operations using two coupled superconducting charge qubits.

Generation of multi-qubit entanglement will be the next significant and very challenging steps towards quantum information processing based on this scalable solid-state systems.

Within this framework we discuss the performances of theoretical coupling schemes for the controlled generation and manipulation of entangled states and of nonclassical superposition in circuit QED systems.

Femtosecond laser frequency comb influence on the atom velocity distribution

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Femtosecond laser frequency comb became a very important tool in the present day spectroscopy. Its versatility is still an intensive subject of vibrant research activity. A few results already point out to outstanding features especially when accumulation of populations and coherences in atomic and molecular systems are within a focus of actual research.

When femtosecond laser passes the cell filled with pure rubidium 85 isotopes the frequency comb content will be modified due to absorption of comb lines within ^{85}Rb Doppler broadened lines. At slightly elevated temperatures the absorption within the cell will remove all comb lines overlapping spectral region of hyperfine spectral lines of 85 isotopes. In this way modified frequency comb passing through the second rubidium cell with natural abundances of rubidium isotopes will act only on ^{87}Rb atoms, leaving ^{85}Rb atoms unaffected. A weak cw scanning probe laser copropagating with the femtosecond pulse train in the second cell will experience peculiar absorption profile only at ^{87}Rb hyperfine lines. The $5\ ^2S_{1/2} \rightarrow 5\ ^2P_{1/2,3/2}$ fs pulse train excitation of a Doppler broadened Rb four-level atomic vapor will be essentially modified by using atomic filter at different rubidium atom densities. This effect could be applied in different subsequent experiments. Basic physics has been described in [1,2], and the development of the experimental methods and theoretical description applied to Rb and Cs atoms is presented in references [3-6].

We shall also present and discuss the latest results concerning the treatment of the velocity distribution of rubidium and cesium atoms using enhanced sensitivity, different pure isotope absorption cells and different parts of the velocity comb. A special attention will be given to zero velocity, which is connected to possible cooling mechanism by femtosecond laser frequency comb.

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Optical Spectroscopy of the Haldane Chain Compounds R_2BaNiO_5

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This talk presents recent results of the research on R_2BaNiO_5 compounds performed by the author`s group in cooperation with the Moscow, Kazan, Paris, and Geneva Universities. The nickelates R_2BaNiO_5 (here R stands for a lanthanide (Ln) or yttrium) that contain isolated nickel (S=1) chains attract a considerable attention as model systems to study quasi-one-dimensional magnetism, the crossover from one-dimensional quantum to three-dimensional classical behavior and a transformation of Haldane-gap excitation through this crossover. While the yttrium compound does not order magnetically (at least down to 1.5 K) a substitution of a magnetic Ln ion for yttrium leads to the antiferromagnetic ordering with Neél temperature T_N that depends on Ln and x for a $(Y_{1-x}Ln_x)_2BaNiO_5$ compound.

We studied high-resolution broad-band spectra of the polycrystalline $(Y_{1-x}Ln_x)_2BaNiO_5$, Ln=Er [1] or Nd [2], samples and of an oriented single crystal Gd_2BaNiO_5 at different temperatures (2.0 – 300 K) by means of Fourier spectrometers DA3.002, Bruker 125HR, and Bruker 66v. In the first part of this work, crystal-field levels of the Ln^{3+} ion and their exchange splittings in a magnetically ordered state were determined from the spectra. Crystal-field calculations were performed starting from the exchange-charge model. The results of the calculations were tested by comparison the calculated and experimental temperature dependences of the magnetic susceptibility. A simple molecular-field model was shown to be valid for the rare-earth magnetic subsystem [1-3].

In the second part of this work, exchange splittings of Nd3+ were used to determine x-dependent Neel temperatures in the $(Y_{1-x}Nd_x)_2BaNiO_5$ system, in search of the quantum critical point. The third part was devoted to the optical spectra of Gd_2BaNiO_5 single crystals. It has been shown earlier that at T_N=58 K Ni magnetic moments of Gd_2BaNiO_5 order antiferromagnetically along the a–axis (chain direction), while at TR=24 K they reorient to the perpendicular b-axis of the crystal [4]. Polarized optical transitions within the nickel subsystem in the near-infrared and visible spectral regions were studied. We discuss their temperature behavior and a possible connection of several spectral features with the Haldane-gap excitations of nickel chains. Lattice vibrations were investigated by means of far-infrared reflection spectra. Peculiarities in the spectra possibly connected with magnetic absorption and magnon-phonon interaction are discussed.

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Symmetry and transport in a rocking ratchet for cold atoms

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Brownian motors, or ratchets, are devices which “rectify” Brownian motion, i.e. they can generate a current of particles out of unbiased fluctuations.

We experimentally implemented a Brownian motor using cold atoms in an optical lattice. This is quite an unusual system for a Brownian motor as there is no a real thermal bath, and both the periodic potential for the atoms and the fluctuations are determined by laser fields.

With the help of such a system, we investigated experimentally the relationship between symmetry and transport in a rocking ratchet, both in the periodic and in the quasiperiodic case.

Medical application of multi- wavelength lasers

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Bending Back Light: The Science of Negative Index Materials

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The possibility of negative refraction has brought about a reconsideration of many fundamental optical and electromagnetic phenomena. This new degree of freedom has provided a tremendous stimulus for the physics, optics and engineering communities to investigate how these new ideas can be utilized. Many interesting and potentially important effects not possible in positive refracting materials, such as near field refocusing and sub-diffraction limited imaging, have been predicted to occur when the refractive index changes sign. In this talk, I will review our own work on negative refraction in metamaterials, and describe the possible impact of them as new types of optical elements. In particular, I will present theoretical and experimental results on engineered microstructures designed to have both ε and μ negative.

Most of the negative index materials (NIMs) sample implementations to date have utilized the topology proposed by Pendry, consisting of split ring resonators (SRRs) and continuous wires. Recently different groups [1] observed indirectly negative μ at the THz region. In most of the THz experiments only one layer of SRRs were fabricated on a substrate and the transmission, T, was measured only for propagation perpendicular to the plane of the SRRs, exploiting the coupling of the electric field to the magnetic resonance of the SRR via asymmetry. This way it is not possible to drive the magnetic permeability negative. Also, no negative n with small imaginary part has been observed yet at the THz region. One reason is that is very difficult to measure with the existing topology of SRRs and continuous wires both the transmission, T, and reflection, R, along the direction parallel to the plane of the SRRs. So there is a need for alternative, improved and simplified designs that can be easily fabricated and experimentally characterized, especially in the infrared and optical regions of the spectrum. Such designs are offered by pairs of finite in length wires (short-wire-pair) and the fishnet structure, which will be discussed below.

A short-wire-pair can behave like an SRR, exhibiting a magnetic resonance followed by a negative permeability regime. Moreover, short-wire-pairs can give simultaneously a negative ε in the same frequency range, and therefore a negative n, without the need for additional continuous wires. Recent experiments have not shown though evidence of negative n at THz frequencies in the short wires-pair cases that were studied. Very recent work [1, 2] introduced new designs of short-wire-pair based metallic structures to obtain negative index of refraction in the different regimes. In addition, the fishnet structure was used and demonstrated experimentally [2] negative n at 1.5 microns with low losses. Finally, negative n at 780 nm was obtained [3] using the fishnet arrangement.

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Spatiotemporal dissipative solitons in optics

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Far from the thermodynamical equilibrium nonlinear systems can reach stable steady state providing appropriate input of energy and matter. Such systems may self-organize into dissipative structures introduced by Prigogine [1]. Recently, the transport and processing of information using achievements of nonlinear optics, received much attention. Solitons appear as best candidates for caring information. The diffraction and dispersion of a optical pulse need to be compensated by saturating nonlinearity, in order to be completely confined in space and time forming so-called “light bullet” [2]. In a real experiment, light bullet cannot propagate without losses. In order to maintain solitonic structure, the linear and nonlinear loss must be compensated by a gain giving self-organized dissipative light bullet. We demonstrated that only cross compensation between saturating nonlinearity excess, loss, and gain maintains such dissipative structure in stable dynamic equilibrium, on the stable non thermodynamical brunch of bifurcation diagram [3]. We developed the dissipative variational method in order to find steady state solutions of complex cubic-quintic Ginzburg-Landau equation which describe well dissipative solitonic structures of one, two, and three dimensions. A stability criterion is established rendering a large domain of dissipative parameters [4]. Analytically obtained symmetric steady state solutions of Ginzburg-Landau equation are stable in this domain. If these approximate solutions are taken as input for numerical simulations of full Ginzburg-Landau equation, their evolution will always lead to stable dissipative solitons in dynamic equilibrium. It is worthwhile to stress that even very asymmetric input pulses, for the same dissipative parameters from our domain, which are far from stable spherically symmetric steady states, always self-organize into solitons. Analytically obtained stable steady states are in the domain of attraction of the exact solution. As a consequence, bullets are very robust resisting to the successive increase of amplitude during evolution. Variety of different solitons can appear for various parameters. The opportunity to treat analytically and numerically asymmetrical input pulses propagating toward necessarily stable and robust dissipative light bullets, opens possibilities for diverse practical applications including experiments.

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Discrete breathers and solitons in left-handed metamaterials

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Optical metamaterials are structures typically made of split ring resonators (SRR's) and long wires where electric permittivity and/or magnetic permeability may vary wildly and even take negative values. In several cases the index of refraction of the material becomes negative leading to, among other things, wave propagation with wavevector direction different from that of the Poynting vector. The peculiar properties of metamaterials have led to proposals for perfect lensing and object cloaking. When nonlinearity is also included, new phenomena emerge leading to multistability in wave propagation, generation of compound electric and magnetic solitons as well as formation of intrinsic localized modes (discrete breathers) with characteristic magnetic properties.

In this talk we will analyze general properties of nonlinear metamaterials focusing on dynamical modes that may appear due to nonlinearity. We study two classes of systems; the first consists of standard metamaterials made of SRR's and long wires. In these systems nonlinearity is extrinsic and it is introduced through embedding the metamaterial in a dielectric medium with Kerr nonlinerity. The second class of metamaterials is made of rf-SQUIDS; in this case nonlinearity is intrinsic and appears as a result of the presence of the Josephson junction.

For a medium of long wires and split ring resonators embedded in a nonlinear medium we find that compound electric and magnetic solitons can form that have interesting dynamical properties [1]. When coupled SRR's, on the other hand, are embedded in a nonlinear medium we find that dissipative discrete breathers may be generated in the discrete limit [2] while the localized modes may turn into NLS-type solitons in the continuous limit [3]. In the effective medium approximation a lattice of driven rf-SQUIDS has magnetic metamaterial properties manifested through a negative permeability [4]. When this intrinsically nonlinear lattice becomes inductively coupled it is seen to support various localized excitations.

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Recent progress in high-speed optical fibre communications

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During the late nineties, Erbium-doped fiber amplifiers (EDFA) had a deep impact on the performance and design of optical networks, resulting in the deployment of a large number of high-capacity long-distance optical transmission systems. The best performance of a fibre transmission system corresponds to an optimal trade-off between maximization of optical signal-to-noise ratio (OSNR) and minimization of nonlinear impairments. The output OSNR is determined by the power budget of the line, whereas some control of the nonlinear effects accumulation can be achieved through the optimization of dispersion management. Distributed Raman amplification (DRA) is an attractive technique to achieve required OSNR margins while decreasing the impact of nonlinearity. Compared to EDFA-based transmission, DRA introduces a possibility to adapt the power distribution control to the dispersion map allowing a better control of signal power (and nonlinearity) along the spans. The released margins can be used for extending the transmission distance and/or decreasing the signal power injected into the fiber span. Distributed amplification can also be combined with point EDFA amplification providing new degrees of freedom for the system design. The properties of the fibers used (Raman gain efficiency, attenuation, effective area, Rayleigh backscattering coefficient) and the design of the dispersion map have to be taken into account in the optimization of the amplification scheme. Raman amplification is not restricted to a particular spectral band, and can be implemented at any wavelength for which a suitable pump is available. This property is extremely useful for the development of broadband multi-channel communication systems, in which a large number of signal channels are wavelength-multiplexed over wide spectral intervals. Raman amplification requires powerful and stable pump sources. Recent progress in reliable high power laser pumps is another important demonstration of the Raman-assisted fibre technology.

The aim of the lectures is to overview recent developments in Raman-assisted fibre technologies. First lecture will be an introduction into the field of optical communication, key enabling transmission technologies and basic physical principles of distributed Raman amplification, Raman-based wavelength converters and pumps. Basic physics and mathematics of key Raman-based fibre devices will be discussed. The lecture will provide a general overview of key approaches and techniques. Second lecture will focus on the problems of advanced distributed amplification and optimal signal power evolution within the transmission span. The application of distributed Raman amplification in long-haul, broadband transmission using wavelength division multiplexing relies on the ability of the amplification schemes to provide a flat gain profile to enable maximum reach of all signal channels. Advanced techniques, such as, higher-order pumping schemes and multi-pumping configurations aiming gain-flattening distributed amplification will be discussed. Recent results on practical implementation of ultra-long fibre lasers with application to optical transmission will be also presented.

Some equations of electrodynamics before and after appearance of negative refraction

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The appearance of material with negative values of dielectric and magnetic permeabilities ε and μ and with negative index of refraction n forces to revise the accustomed forms of some well-known formulas of electrodynamics. This is connected with fact, that these correlations in repressing majority of sources is written in tacit suggestion that magnetic permeability of most of materials is $\mu = 1$, factor of refraction $n = \sqrt{\varepsilon}$ and is undoubtedly executed the correlation $n > 0$. Such approach could be named as “nonmagnetic”. However if $n < 0$, this nonmagnetic approach can bring very hard mistakes. As example possible to bring one of the well known Fresnel`s equation

$$r_{\perp} = \frac{n_1 \cos\varphi - n_2 \cos\phi}{n_1 \cos\varphi + n_2 \cos\phi}$$

which under negative n can give undoubtedly wrong result. Indeed this formula has the form of

$$r_{\perp} = \frac{z_2 \cos\varphi - z_1 \cos\phi}{z_2 \cos\varphi + z_1 \cos\phi}$$

where values z means so-called wave impedance of the media, which is equal $z = \sqrt{\frac{\mu}{\varepsilon}}$.

This value is positive under simultaneously negative values of ε and μ .

The detailed analysis of validity of well-known equations happens in report for event of negative refraction.

Near Infrared (≈ 1 μm) High Power and Femtosecond Lasers

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In the field of laser materials for 1 μm emission, ytterbium dopant now substitutes neodymium for many applications. Efficient pumping is possible around 980 nm and new laser designs, such as thin disc configurations, well exploit the properties of the Yb^{3+} ions: very simple energy level schemes and high doping levels. Yb doped crystalline hosts can be used, on one part for the generation of ultrashort pulses, and on the other part for high power laser applications. For instance several kilowatts, have been recently obtained with this dopant. Considered matrices for such applications are based on a very limited number of materials taking mainly into account elaboration and optical spectroscopic parameters.

In the present work are expressed chemical, structural and spectroscopic considerations to analyzed Yb^{3+} doped crystalline hosts which can be elaborated by the Czochralski process. For the research of crystalline hosts for the generation of ultrashort laser pulses, broad absorption (around 980 nm) and broad emission (around 1 μm) are required. Among all the new developed materials (mainly double tungstates and aluminates); Yb:$CaGdAlO_4$ recently appears as a good material for high power laser applications. Its broad emission with an unusual flat plateau between 987 nm and 1060 nm is indeed very favourable to ultra-short pulses generation. In Yb:$CaGdAlO_4$, 66 fs have been recently obtained with an average power of 440 mW [1, 2]. Moreover, this material presents a relatively high thermal conductivity value (of about 7 $Wm^{-1}K^{-1}$) which prevents thermal damage in comparison with other well known laser materials.

In the presentation state of the art in the Yb-lasers for high power and ultrashort pulses generation will be presented with a focus on Yb:$CaGdAlO_4$ and the understanding of the origin of the broadening of the optical properties.

References

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