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Optics and Fluid Dynamics Department annual progress report for 2002

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Optics and Fluid Dynamics Department
Annual Progress Report for 2002

Edited by H. Bindslev, S.G. Hanson, J.P. Lynov
P.M. Petersen and B. Skaarup

Risø National Laboratory, Roskilde, Denmark
May 2003

Abstract The Optics and Fluid Dynamics Department performs basic and applied research within three scientific programmes: (1) laser systems and optical materials, (2) optical diagnostics and information processing and (3) plasma and fluid dynamics. The department has core competences in: optical sensors, optical materials, optical storage, biophotonics, numerical modelling and information processing, non-linear dynamics and fusion plasma physics. The research is supported by several EU programmes, including EURATOM, by Danish research councils and by industry. A summary of the activities in 2002 is presented.

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Contents

1. Introduction

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The Optics and Fluid Dynamics Department performs basic and applied research in laser systems, optical sensors and optical materials as well as in plasma and fluid dynamics. The research is conducted as a combination of science and technology with the following core competences:

- Optical sensors
  - Light propagation in complex systems
  - Laser-based sensors
  - Diffractive optical components
  - Phase contrast methods
- Optical materials
  - Polymers
  - Laser ablation
- Optical storage
  - Holographic techniques
  - Optical encryption
- Biooptics
  - Light/tissue interaction
  - Diode laser systems
  - Biosensors
  - Optical tweezers
  - IR spectroscopy
- Numerical modelling and information processing
  - Plasma and fluid dynamics, optics, ultrasound
  - Knowledge-based processing
  - Image processing ("data mining")
- Non-linear dynamics
  - Turbulence
  - Vortex dynamics
  - Parametric processes
  - Photorefractive materials
- Fusion plasma physics
  - Theoretical plasma physics
  - Laser and microwave diagnostics

The output from the research activities is new knowledge and technology. The users are within industry, research communities and government, and the department is responsible for the Danish participation in EURATOM's fusion energy programme.

For the solution of many of the scientific and technological problems the department employs the following key technologies:

- Microtechnology for optical systems
  - Analogue and digital laser recording of holograms
  - Injection moulding of diffractive optical elements
- Optical characterisation
  - Determination of material surfaces
  - Phase contrast measurements
- Temperature calibration and IR measurement techniques
  - Accredited temperature calibration including IR techniques
  - Fourier transform infrared (FTIR) measurements

The department is organised in three scientific programs

- Laser systems and optical materials
- Optical diagnostics and information processing
- Plasma and fluid dynamics

In the following sections, the scientific and technical achievements during 2002 for each of these programmes are described in more detail.

2. Laser systems and optical materials

2.1 Introduction

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The research programme on Laser Systems and Optical Materials (LSO) has its main competences within the areas of laser systems, active and passive polymer technology, laser-assisted deposition, optical sensors, nonlinear properties of materials, holographic storage and nanotechnology.

We have close collaboration with Danish and foreign universities, research institutes and industry. Nationally, we participate in the Danish Polymer Centre and the Centre for Biomedical Optics and New Laser Systems. The research programme plays a key role in the Danish Graduate School on Biomedical Optics and New Laser Systems that was formed in August 2002. In addition we undertake significant teaching activities at both the University of Copenhagen and the Technical University of Denmark. Internationally, the programme participates in the Virtual European Laser Institute (VELI) with financial support from the European Commission. The purpose of VELI is to enhance and promote the available laser expertise in Europe.

A major activity in LSO is within development of new laser systems. We carry out fundamental studies as well as applied research where new industrial lasers are constructed. We are currently developing new and improved laser systems for applications in materials processing, printing, rapid prototyping, biotechnology and optical sensing. An important research area is the development of new high-power, tuneable semiconductors with high spatial and temporal coherence.

The polymer optics activities in LSO are currently involved in the fabrication and replication of diffractive optics, dynamic holographic recording materials, liquid crystalline polymers as well as laser-assisted deposition of transparent coatings (indium tin oxide, ITO) on polymers. Moreover, active polymers research is undertaken with the purpose of developing new light sources.

Laser ablation is also performed in LSO with facilities that comprise a vacuum chamber for studying fundamental laser plume properties, a vacuum chamber for thin film production by pulsed laser deposition and a test chamber for production of polymer films. The facilities are based on UV light from an Nd:YAG laser with pulse energies up to 200 mJ at 355 nm.

Research in the field of non-linear optics has been a subject of intense investigations for many years. The field covering the dynamics of optical materials is concentrated on both inorganic and organic materials. Among the inorganic materials the efforts have been within photorefractives and semiconductors in which non-linear effects such as parametric oscillation and amplification, optical phase conjugation, four-wave mixing and two-step gated recording processes have been studied. The organic studies are focused on surface as well as on bulk effects. More specifically, storage effects, surface relief gratings, molecular reorientation dynamics, electrooptic properties and rotational effects are being investigated.

Finally, holographic data storage and nanotechnology in polymers are important activities that have recently led to collaboration with industry. The activities within optical storage and nanotechnology comprise development and application of polyesters and peptides.

2.2 Laser systems

2.2.1 High-brightness laser source for the graphic industries

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Broad-area semiconductor lasers are unique due to their small dimensions, low costs and high efficiency in comparison with, e.g., gas and solid-state lasers. Broad single emitters can deliver up to several watts of output power and the diodes typically have long lifetimes - between 10,000 and 30,000 hours. However, the spatial coherence of these broad-area lasers is not satisfactory. They suffer from multimode non-diffraction limited lasing along the slow axis which prohibits the laser beam from being focused properly.

In the present project, we are developing a new high-brightness diode laser source for the graphic industries in which we improve the spatial coherence of such high-power broad-area lasers substantially. In addition, we combine two laser beams into a single beam in order to double the output power of the laser source. The high-brightness source will be implemented in an image-setter machine developed by the company Esko-Graphics. By increasing the laser power it is possible to decrease the exposure time of the illuminated offset plates used in the machine, which is important for, e.g., the newspaper industry.

The basic laser system, developed at Risø, is based on external asymmetric feedback of a broad-area laser. By applying external feedback to the laser from an optical grating or a mirror, the M^2-value of the laser beam can be improved by more than one order of magnitude. Thereby, the beam can be focused down to a small spot size close to the diffraction limit. The coupled laser source is based on two similar laser systems coupled together in a polarizing beam splitter. In this way, the output power is doubled, and the M^2 value of the coupled beam is improved even further when compared with the basic laser system.[1]

Figure 1 shows a photo of a single diode laser system. The system contains several designs, developed at Risø, including the feedback unit.

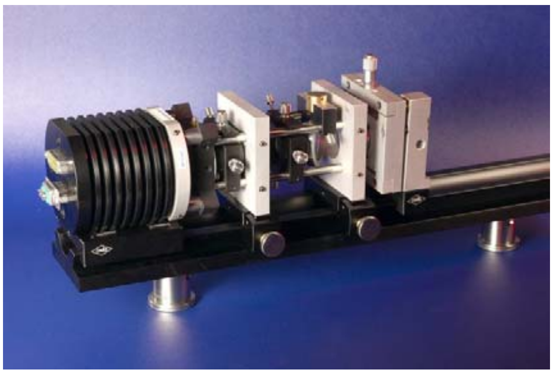

Figure 1. Photo of a single diode laser system.

The coupled setup is illustrated in Figure 2. A beam analyser is used to measure intensity profiles of the coupled beam along the optical axis.

Figure 3 shows the intensity profile along the slow axis at beam waist for the two individual laser systems and for the coupled system after focusing the laser beams with a lens. The figure demonstrates that it is possible to couple the two laser beams into a single beam with a beam width (at full-width-half-maximum) that is even smaller than that of one of the individual beams.

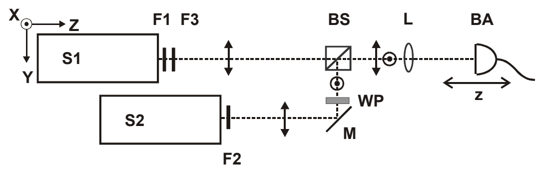

Figure 2. Schematic presentation of the polarization coupling setup seen from above. S1, S2: Laser systems, F1, F2, F3: Spatial filters, M: Mirror, BS: Polarizing beam splitter, WP: λ/2 wave plate, L: lens, BA: Beam analyzer. The polarization directions have been indicated with arrows and circles.

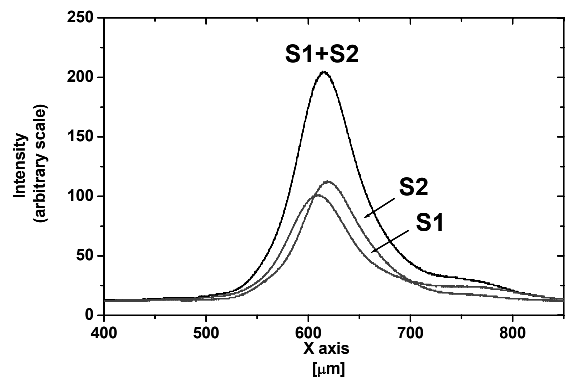

Figure 3. Intensity profiles, measured at beam waist, for the slow axis (X-axis) of S1, S2 and the coupled system, S1+S2.

1. *High brightness laser source based on polarization coupling of two diode lasers with asymmetric feedback*, B. Thestrup, M. Chi, B. Sass and P.M. Petersen, Appl. Phys. Lett. **82** (2003) 680.

2.2.2 Second harmonic generation in a two-mirror travelling wave resonator

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By passing laser light through a non-linear optical crystal it is possible to obtain light at the double frequency via the process of second harmonic generation (SHG).[1] This is a widely applied method of obtaining, e.g., blue and ultraviolet (UV) laser light. The SHG power grows quadratically with the power at fundamental wavelength and it is therefore important to make the fundamental power as high as possible for efficient conversion. For CW light this can be achieved by coupling the fundamental light into a resonator made up by dielectric mirrors to obtain power enhancement at the fundamental wavelength and by placing the crystal inside this cavity.[2] It should, preferably, be a travelling wave resonator in order to avoid retro-reflected light towards the laser source. Commonly, resonators with four[3] and three[4] mirrors have been employed. To obtain a high power build-up inside a resonator for SHG it is crucial to minimize the surface losses of the cavity mirrors and the crystal. As for the latter this can be obtained by having the crystal faces antireflection coated or Brewster-cut with respect to the phase matching direction.

We have considered the possibility of exploiting the refraction introduced by a non-linear optical crystal with anti-parallel Brewster-cut end faces to obtain a compact, travelling wave cavity configuration with only two spherical mirrors as shown in Figure 4(a). The beam round trip length may be controlled by transverse translation of the non-linear crystal as outlined in Figure 4(b). Length adjustment via translation of the non-linear crystal opens up the possibility of keeping the enhancement cavity on resonance. Hence, the non-linear crystal has three independent functions: frequency conversion, beam deflection, and resonator length control. A two-mirror resonator along these lines is presently under construction in the Optics and Fluid Dynamics Department at Risø National Laboratory. The resonator converts red laser light at 635 nm to UV light at 317.5 nm.

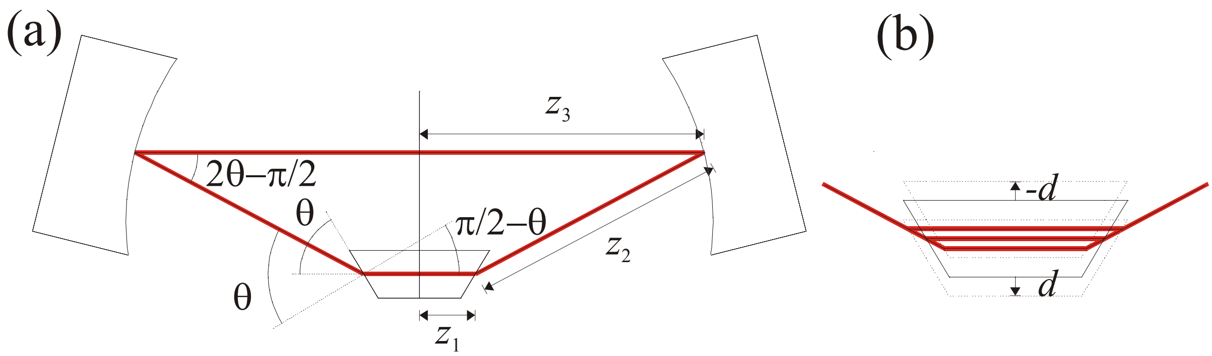

Figure 4. (a) Resonator geometry in the case of a Brewster-cut non-linear crystal; the crystal end faces have been cut so that a beam incident at Brewster's angle θ propagates along the direction of phase matching. (b) Translation of the non-linear crystal in a transverse direction in the beam plane gives rise to a change in the optical path length.

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2.2.3 Improvement of brightness and output power of high-power laser diodes in the visible spectral region

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Due to their compactness, low costs and high efficiency, laser diodes are used in a wide range of applications from medical diagnostics and therapies to printing technologies. Since the invention of semiconductor lasers in 1962,[1] their performance has improved steadily, primarily in terms of lifetime and power level. There are various types of laser diodes such as broad-area lasers, laser diode arrays and laser diode bars. In the case of broad-area lasers or diode arrays, high-power operation has been achieved by increasing the cross section of the gain region. Another approach is to use stacked arrays or the placement of several laser diodes beside each other. However, high power often results in laser diodes with poor beam characteristics such as low focus capability and directionality. Various attempts to meet the simultaneous demands for high beam quality and high power have been reported.[2] A remaining issue is the improvement of the optical power level while maintaining the improved coherence properties of the laser diode. A common way to accomplish a better performance and improve the spatial and temporal coherence of laser diodes is the use of external feedback components such as phase conjugators[3] or conventional mirrors[4] combined with spatial and spectral filtering. Recently, a laser-diode system exhibiting an M^2 value of 1.7 was demonstrated and the output coupled efficiently to a 50 µm core-diameter fibre.[5] This system was based on the coupling of a broad-area laser to an external feedback component whereby spatial mode selection and amplification was achieved. The external feedback system forced the multimode laser diode to exhibit an improved output with high coupling efficiency to optical fibres.

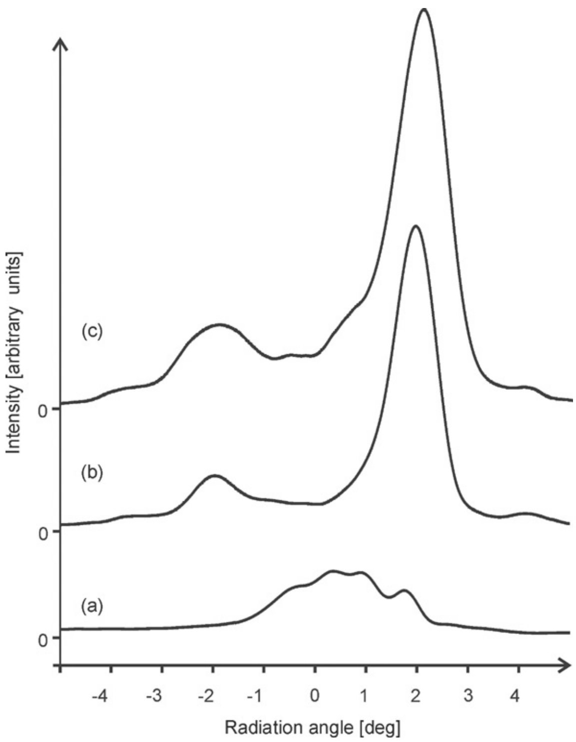

Figure 5. Far fields from one of the broad-area lasers measured in the plane of the junction. (a) The laser runs freely at I = 403 mA = $1.3 \times I_{th}$; (b) feedback is applied at I = 403 mA = $1.3 \times I_{th}$; (c) as (b), but the drive current is I = 589mA = $1.9 \times I_{th}$.

In this project[6] we have demonstrated a compact scheme that significantly improves the spatial beam quality of two laser diodes. Their improved outputs are combined using a polarization coupling technology that yields a doubling of the power, while maintaining the high beam quality. Two 260-290 mW, 635 nm, quantum well AlGaInP broad-area laser diodes are implemented in separate feedback schemes that each contains a spatial mode selection unit. The effect on the spatial properties of the laser diode due to the feedback is shown in Figure 5. The optical paths of the outputs from the two systems are combined by the rotation of the linear polarization of one laser and subsequent introduction of a polarizing beam splitter cube. The advantage of using passive optics for the beam combining procedure is that high power is obtained for the combined output while the beam quality of the individual beams is maintained, see Figure 6. Thus, the power density and the brightness are increased. Other advantages are simplicity and robustness of the technique. The beam quality parameter M^2 of the output from the system is improved from M^2 = 12 and M^2 = 16 for the two lasers to M^2 = 2.1 for the combined beam. The system is compact, stable and easy to operate.

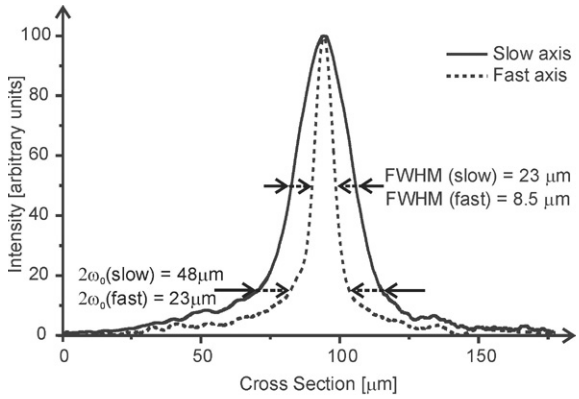

Figure 6. Cross-section of a focused spot from a combined beam in the high coherence axis (dashed) and in the low coherence axis (full). The beam is focused with an f = 40mm double-convex lens.

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2.3 Active and passive polymer technology

2.3.1 Electro-optic response of polymers

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Efficient electro-optic and photorefractive applications of polymers doped with a substantial amount of non-linear chromophores are investigated. These materials are of interest for use in high-speed photonics such as broadband modulation of light by using electro-optic polymers.[1] Poling of the chromophore by an externally applied electric field is necessary in order to change the material refractive index. Such a poling process is associated with the rotation of the dipolar chromophores in a viscous polymer matrix, and during the poling process the dipoles couple strongly to the applied electric and reorient in space relative to the zero field orientation. Thus, the electro-optic response is due to combined nonlinear optical properties and polarizability anisotropy of the rectified chromophores. We have addressed the problem of how to deal with the effect exerted from the viscoelastic polymer matrix on the chromophore reorientation dynamics. To do this we have extended the so-called oriented gas model[2] to include into the rotational diffusion equation the viscoelastic properties of a matrix polymer by incorporating a local molecular field at each chromophore site.[3] To test the theoretical predictions we have measured experimentally[4] the electro-optic response in a guest-host polymer system of PMMA:DR1 subject to DC and AC applied electric fields.

In Figure 7 we show one of the main results from including a local molecular field, namely the reduction in the order parameters of the systems as compared with those predicted using the molecular gas model.

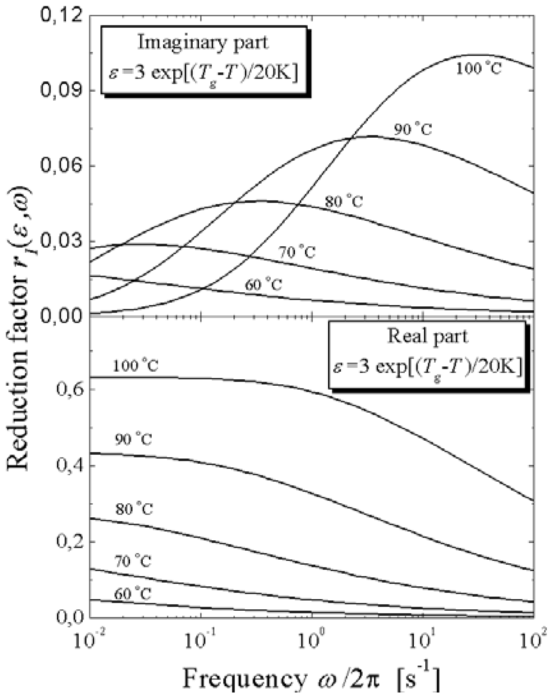

Figure 7. Predicted frequency dependence of the first reduction factor for various temperatures for a non-vanishing normalized molecular field.

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2.3.2 Injection moulded plastic gratings with diffraction efficiency close to one

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The aim of this work is to investigate the possibility of making plastic replications of deep optical surface relief gratings in order to obtain diffraction efficiencies close to 100%. As a model grating we chose a sinusoidal grating with a period of 700 nm. The master gratings are generated by exposing a photoresist plate to two interfering laser beams from an HeCd laser. The photoresist gratings are shown in Figure 8(a) Figure 8(b). Afterwards, the microstructures are transferred onto a hard nickel master using a galvano process. This nickel master is then used as an insert in an injection-moulding tool. The tool is made flexible so that it can be used as (i) an ordinary injection-moulding tool, (ii) an injection compression tool and (iii) a tool with localized heating of the nickel master. We found that with localized heating it was possible to obtain injection moulded surface relief gratings with diffraction efficiencies of up to 90%, see Figure 8(d). This is achieved when the shim temperature exceeds the glass transition temperature by more than 10-20 deg. The injection-moulded gratings are shown in Figure 8(c).

The work is sponsored by the Danish Agency for Trade and Industry through the project "Miniaturized Optical Sensors".

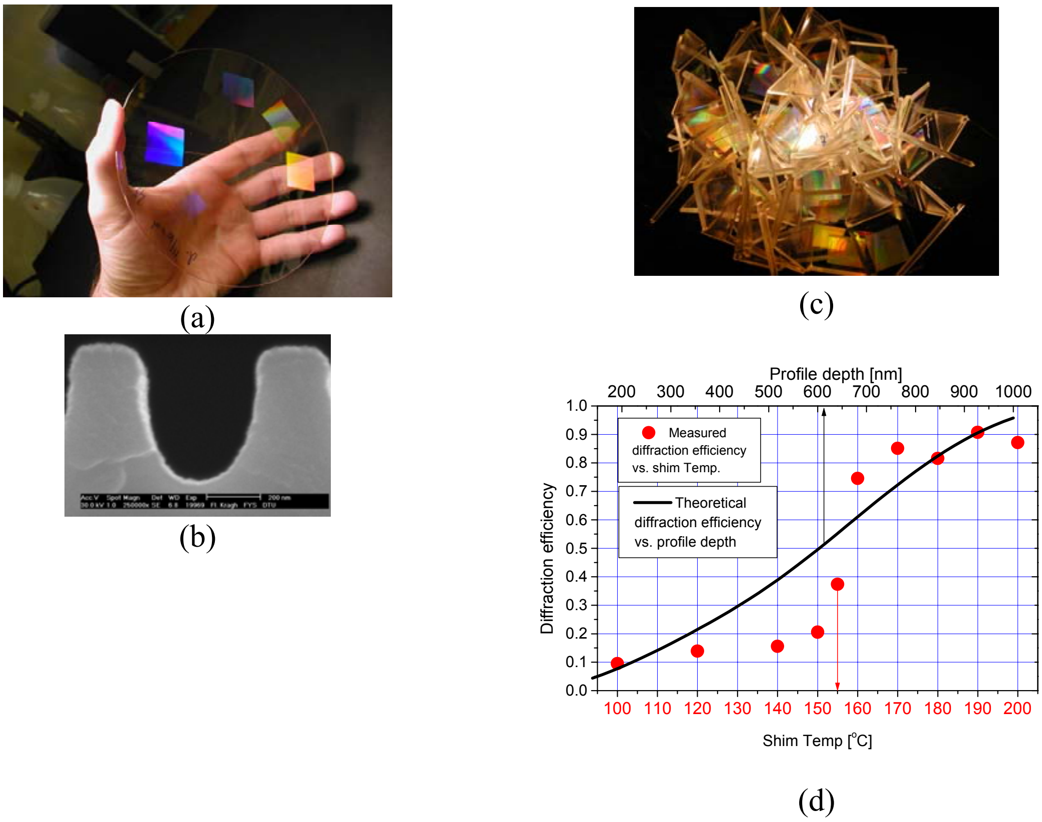

Figure 8. (a) Master gratings in photoresist. (b) Scanning electron microscope picture of grating cross-section. (c) Injection moulded plastic gratings (polycarbonate). (d) First-order diffraction efficiency of injection moulded polycarbonate gratings versus shim temperature.

2.4 Laser-assisted deposition

2.4.1 Matrix-assisted pulsed laser evaporation of organic MEH-PPV and PEG films

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The electroluminescent polymer of poly(2-metoxy-5-(2´-ethylhexyloxy)-1,4-phenylene vinylene), MEH-PPV, has for several years attracted considerable interest. Not only is it an academic challenge to explain the underlying mechanism of the electro-luminescence, but new and interesting devices such as, e.g. computer displays can be fabricated using this organic compound. At present spin coating seems to be the best way to make a large-scale production of MEH-PPV films. However, we have applied an alternative fabrication method of films using matrix-assisted pulsed laser evaporation (MAPLE) of the material.

MAPLE is a gentle laser deposition technique where the polymer is dissolved in an adequate solvent and subsequently frozen into a matrix. When this matrix is irradiated, the solvent evaporates whereas the polymer material is collected on a substrate. Figure 9 shows the deposition set-up during MEH-PPV deposition. The fabricated films were relatively rough, but luminescent.

Another polymer that we have deposited by MAPLE is polyethylene glycol (PEG).

PEG is a water-soluble polymer with many technological applications. It can for instance be used as a drug delivery coating or as a biocompatible coating. So far, the produced PEG films are somewhat non-homogeneous, but infrared spectra measured by a Fourier transform infrared (FTIR) spectrometer equipped with an attenuated total reflection cell showed that the chemical composition of the films was identical to the starting material.

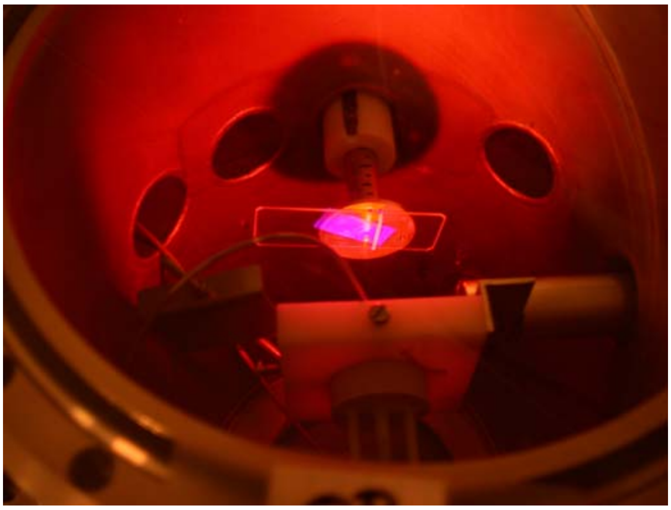

Figure 9. Shows the deposition of MEH-PPV. The chamber turns red due to the luminescence of the polymer after the laser irradiation.

2.4.2 The angular distribution of plume ions from femtosecond laser irradiation

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The dynamics of the plume from a femtosecond (*fs*) laser beam impact on a surface is important for micromachining, film production by laser deposition and microanalysis. We have studied the shape of the plasma plume for *fs* UV ablation for the simplest systems, i.e. one-component metal targets irradiated in vacuum. The *fs* results are surprisingly similar to those for *ns* UV laser beam impact.

We have used a semicircular array of 13 cylindrical (Langmuir) ion probes to measure the angular distribution of the ablated material. This setup has previously been used for measurements of the ions in the plasma plume produced by *ns* laser irradiation at 355 nm.[1] The experiments were carried out at the *fs* UV facility at IESL-FORTH at Crete, Greece. The laser ablation took place with the following parameters: wavelength: 248 nm, pulse length: 500 fs, fluence: 2.8 J/cm^2, target-ion probe distance: 80 mm (as in the *ns*-case) and beam spot area: 0.0016 cm^2 (rectangular beam spot with horizontal or vertical extension).

The angular distribution of the collected charge obtained by integration of the TOF signals for both directions of the beam spot is shown in Figure 10. The angular distribution of the collected charge for *ns* laser irradiation with approximately the same fluence is shown in Figure 10 as well. The distributions for *ns* laser impact and *fs* laser impact are surprisingly similar. The reason for this similarity is not yet known.

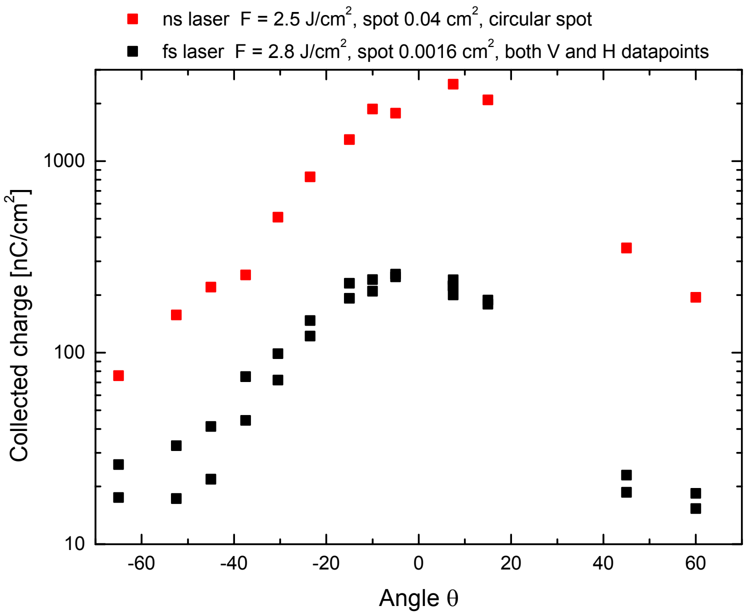

Figure 10. Time-integrated signals for *fs* and *ns* laser irradiation. Ions from a vertical (V) as well as a horizontal (H) beam spot have been included. The points for *ns* are from a circular beam spot. The wavelengths are 248 nm (500 fs) and 355 nm (6 ns).

1. Ion dynamics in laser ablation plumes from selected metals at 355 nm. B. Thestrup, B. Toftmann, J. Schou, B. Doggett and J. G. Lunney. Appl. Surf. Sci. 197-198, 175-180 (2002).

2.4.3 The expansion of a UV laser ablation plume in a background gas

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Pulsed laser deposition (PLD) has become an important technique for producing thin films of complicated composition, e.g. metal oxides or multilayers of metals. With this technique an ablation plume is produced from a target that is irradiated with a pulsed UV laser with high intensity. The ablated material in the plume is collected for the film growth on a suitable substrate. In contrast to many other film deposition methods, the composition of a PLD film is practically similar to that of the target.

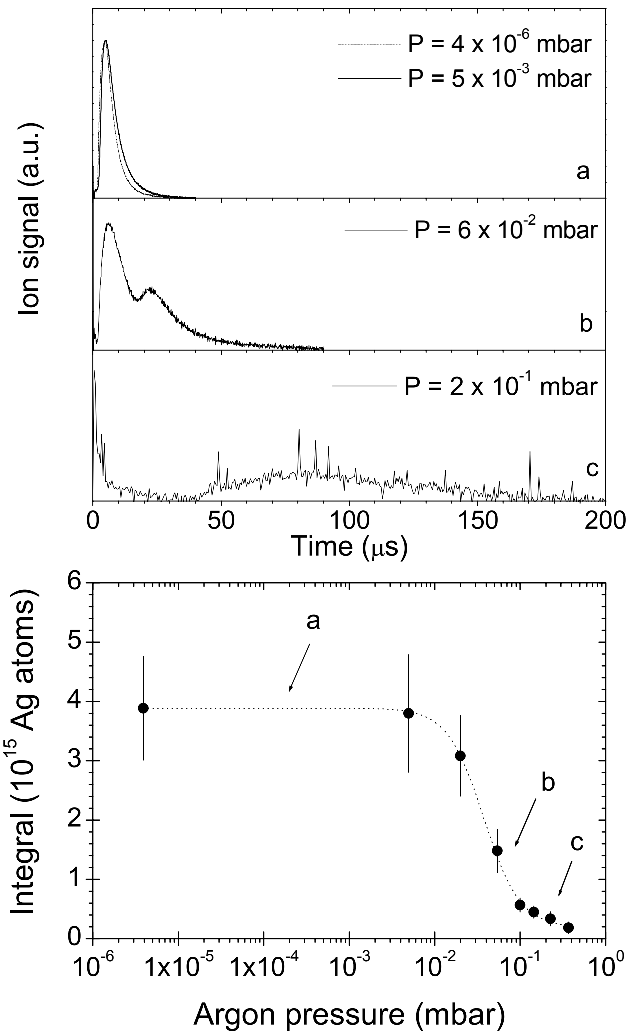

Figure 11. Data for Ag in an Ar background gas. Fluence: 2.5 J/cm^2, wavelength: 355 nm, pulse length: 6 ns. Upper figures show ion probe signals of the plume in three different regimes a), b) and c). Lower figure: these regimes are shown for the integral of the collected particles (ions and neutrals as well).

Even though the technique is used in a large number of research institutions and commercial laboratories, many of the basic processes are not yet understood. We have therefore studied the simple case of an expansion of a silver plume into an argon atmosphere,[1] and have identified three different regimes of background pressure (see Figure 11), each of which is characterized by a particular kind of behaviour of the plume: a) a vacuum-like regime at low pressure, b) a transition regime with plume splitting and shockwave formation, and c) a regime characterized by a diffusion of the ablated particles away from the plume at high pressure. The upper figures show the time-of-flight signals from a plasma probe 75 mm from the target. In regime a) the ion signal is only slightly delayed, in regime b) the ion peak splits up into two different peaks because of the gradually increasing "pressure resistance" from the background gas. In c) only a small, slow component appears at the probe. The total number of particles (ions as well as neutrals) collected at a distance of 80 mm with an array of quartz crystal microbalances is shown in the lower figure. There is a clear decrease of the collected yield in regimes b) and c).

1. S. Amoruso, B. Toftmann and J. Schou, "The thermalization of a UV laser ablation plume in a background gas: From a directed to a diffusion-like flow", to be published (2003).

2.5 Optical sensors

2.5.1 Reverse symmetry waveguide sensing in aqueous solutions

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A normal optical waveguide sensor usually consists of (*i*) a glass substrate, (*ii*) a thin dielectric film which includes a coupling grating (CG), and (*iii*) a cover medium whose refractive index (n_C) is to be measured, see Figure 12(a). By scanning the angle of incidence of a laser beam incident on the coupling grating while simultaneously monitoring the incoupled light intensity with a photodiode (PD), the optimum incoupling angle and thereby the cover refractive index may be found. When the sensor is used for biological detection, the cover medium is mostly aqueous, i.e. n_C is close to 1.33. Since this is less than the refractive index of the glass substrate ($n_S \sim 1.5$) the evanescent field, which is present in both the substrate and the cover, will have its longest tail in the sustrate and its shortest tail in the cover. As a result, the cover medium only has a limited impact on the optimum coupling angle which in turn leads to poor cover index sensitivity. We have therefore suggested a new waveguide geometry in which a fourth layer with low refractive index is applied between the substrate and the film. If the index of this layer is less than 1.33, the tail symmetry will be reversed giving rise to a significant increase in the cover index sensitivity. In our investigations we have used a layer of nanoporous silica that has a refractive index of only 1.2. In this configuration, we have demonstrated a cover index sensitivity that is 3.5 times larger than that of a commercial waveguide with normal symmetry, illustrated in Figure 13.[1]

The work is sponsored by the Danish Technical Research Council, grant #26-01-0211.

1. R. Horvath, H.C. Pedersen and N.B. Larsen, Appl. Phys. Lett., **81,** 2166 (2002).

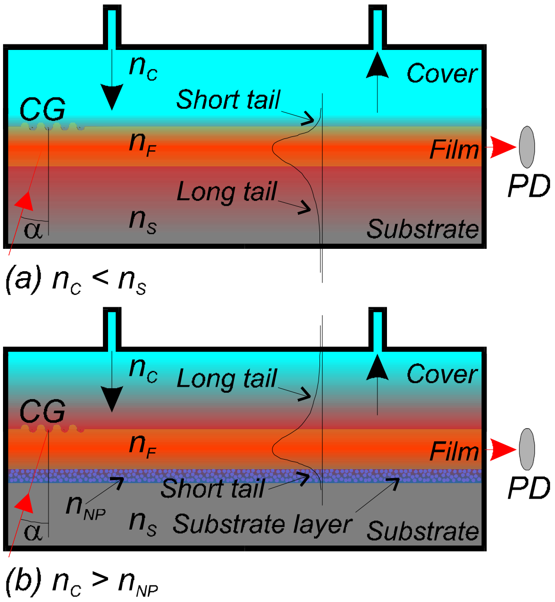

Figure 12. (a) Normal, three-layer waveguide sensor with $n_C < n_S$. (b) Reverse symmetry four-layer waveguide sensor with low-index substrate layer.

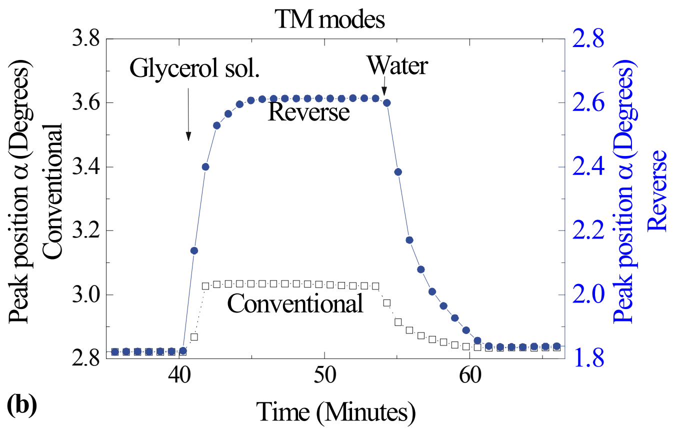

Figure 13. Optimum coupling angle versus time in the case where water (nC = 1.33), glycerol solution (nC = 1.35) and water again are used as cover media.

2.5.2 Absolute refractive index determination by micro-interferometric backscatter detection

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It is of great interest to be able to measure small changes in the refractive index in small volumes of fluid. This may be achieved by using the micro-interferometric backscatter detection (MIBD) scheme,[1] which is based on a simple optical system. MIBD is universal since the refractive index varies with a wide range of parameters. Changes in temperature, concentration and pressure may be detected inside a small volume of the liquid by this method. MIBD has previously been shown capable of measuring changes in the refractive index of liquids on the order of 10^{-7}.[2] The MIBD technique is based on interference of laser light after it has been reflected from different regions in a capillary. These reflections generate an interference pattern that moves on changing refractive indices of the liquid in the capillary. The small angle interference pattern traditionally considered has a repetition frequency in the refractive index space that limits our ability to measure refractive-index-to-refractive-index changes causing one such repetition. These refractive index changes are typically on the order of three decades. Recent modelling and experiments with the MIBD technique have shown that other intensity variations in the pattern are present for larger backscattered angles.[3]

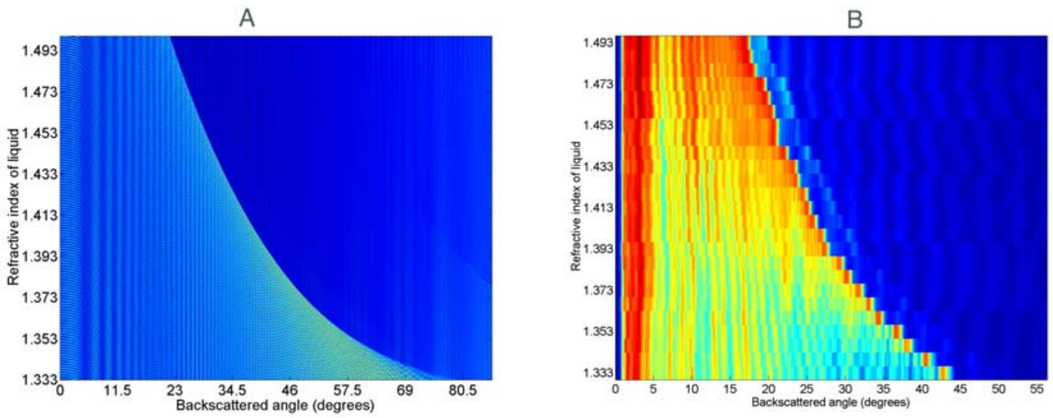

Figure 14. Simulated (A) and experimental (B) interference patterns.

By considering these variations we have shown two methods by which it is possible to extend the dynamic measurement range to make an absolute refractive index measurement. One method utilizes variations in the Fresnel coefficients while the second approach is based on the refractive index that is dependent on a set of total internal reflection angles.[3] The model[3] predicts an abrupt change in intensity that moves towards lower backscatter angles as the refractive index of the liquid approaches the one of the glass tubing, see Figure 14A. This feature of the interference pattern is also observed experimentally, see Figure 14B, and it agrees with the predicted feature in position-refractive index space within experimental error. From our experiments the precision of the absolute determination of the refractive index is found to be 2.5 10^{-4} with the refractive index in the range of 1.33 to 1.5. With our current technique and setup we are able to perform an absolute refractive index measurement with accuracy on this level on a 180 nL volume. The main limitations for accuracy such as temperature control and detector resolution are the same as for conventional MIBD. The theoretical limit to this approach is therefore similar to the limit achievable by conventional MIBD and it is possible to perform a conventional MIBD measurement simultaneously to our newly proposed method. In principle, if the dimensions and the refractive index of the capillary tube are known, then there is a one-to-one relationship between the backscatter angle and the refractive index of the liquid which enables us to determine the absolute refractive index.

1. D. J. Bornhop, Appl. Opt. **34**, 3234-3239 (1995).
2. K. Swinney, D. Markov and D. J. Bornhop, Rev. of Scien. Instruments **71**, 2684-2692 (2000).
3. H. S. Sørensen, H. Pranov, P. E. Andersen and D. J. Bornhop, UK patent appl.: 0220684.5.

2.6 Holographic storage

2.6.1 Theory of photoinduced deformation of azobenzene polymers

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Azobenzene-containing polymers exhibit strong surface-relief features when they are irradiated with polarized light. Currently proposed theories do not explain all the observed features. We have put forward a theory based on elastic interactions between the molecules created by an ordering due to irradiation with polarized radiation.[1] We show that there are two contributions to the photoelastic interaction: 1) from the dipole-dipole interaction between molecules, and 2) from the interaction which is due to the change of the van der Waals interaction energy between a molecule and all surrounding molecules in its transition to the other isomer. The former causes the film deformation under the action of linearly polarized light while the latter, together with the dipole-dipole interactions, is responsible for the surface-relief formation under the action of circularly polarized light. The deformation process is shown to require the presence of a boundary layer. Figure 15 shows a theoretical simulation of a surface relief profile induced by a single beam of polarized light in an amorphous azobenzene polymer.

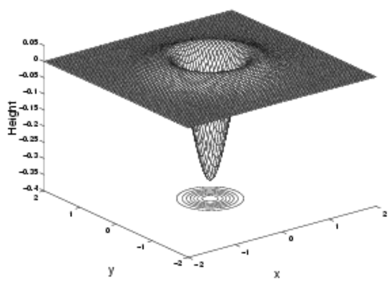

Figure 15. Surface relief induced by a Gaussian beam.

1. Y. B. Gaididei, P. L. Christiansen and P. S: Ramanujam, *Appl. Phys. B*, 74, 139-146 (2002).

2.6.2 Propagation of polarized light through azobenzene polymer films

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When elliptically polarized light of appropriate wavelength corresponding to a trans-cis-trans isomeriation process is incident on thin films of azobenzene polyesters, a helical structure is induced. We investigate the propagation of the pump light beam (self-induced) as well as a probe light beam outside the absorption band through the polyester films. Investigations are carried out in amorphous and liquid crystalline polyesters. A large rotation of a linearly polarized probe beam at 633 nm is obtained when a thin film of the azobenzene polyester is irradiated with elliptically polarized argon laser light at 488 nm. We show that an amorphous azobenzene polyester behaves like a classical helical material after irradiation with elliptically polarized light.

We have also studied the propagation of elliptically polarized light in a series of azobenzene side-chain co-polyesters in which the morphology is varied from liquid crystalline to amorphous.[1] The structure of the polymer was found to influence the configuration of optical axes and the formation of the chiral structure during illumination with elliptically polarized light. We have also determined the dependence of the photo-induced birefringence on the ellipticity of the light. The influence of the dichroism induced simultaneously with the linear birefringence has been investigated. We have shown that this can cause a significant change in the ellipticity of the light propagating through the film, as well as reduce the total angle of rotation of the azimuth of the polarization ellipse. We have developed an iterative algorithm that takes into account photodichroism during the calculation of the rotation of the polarization azimuth. Figure 16 shows the experimental data and the theoretical fit of the polarization azimuth in the presence and absence of photoinduced dichroism.

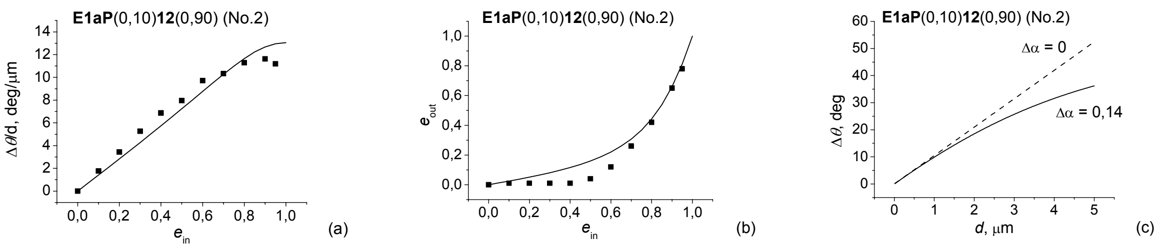

Figure 16. Experimental data and theoretical fit of the polarization azimuth rotation normalized over the film thickness $\Delta\theta/d$ (a) and of the output ellipticity e_{out} (b) on the input ellipticity of the beam e_{in} for sample **E1aP**(0,10)**12**(0,90) (No. 2). The fit is obtained for $\Delta\alpha_0 = 0{,}14$ and $\delta_0 = 0{,}23\ \mu m^{-1}$. Evolution of the azimuth rotation $\Delta\theta$ along the thickness of the film (c) in the presence and absence of photoinduced dichroism for $e_{in} = 0{,}5$.

1. L. Nedelchev, L. Nikolova, A. Matharu and P. S. Ramanujam, Appl. Phys. B, 75, 671-676 (2002).

2.7 Nanotechnology

2.7.1 Nanoplotter

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The Optics and Fluid Dynamics Department has developed an advanced laser plotter for manufacturing of two- and three-dimensional optical and mechanical structures in the nanometer and micrometer ranges. These structures can be made in a number of different materials and on substrates that are up to 100 mm × 100 mm in size.

During the past year we have especially been engaged in manufacturing structures that are too large and too complicated to be made with interferometric methods, but too complicated for classic mechanical processing such as milling and turning.

These structures are made from various polymers and are suitable for either direct use or as masters for moulds for mass production.

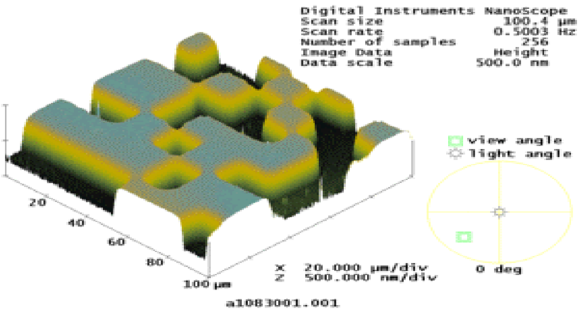

Figure 17. 3D representation of a section of a computer-generated binary holographic diffuser.

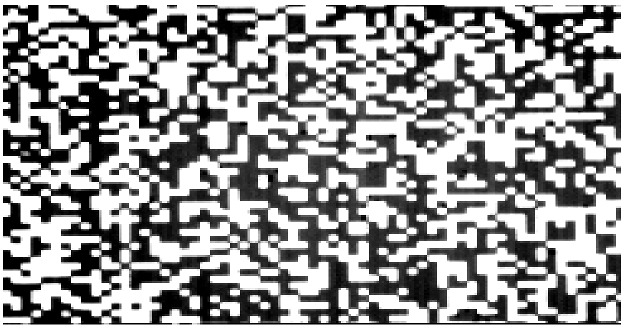

Figure 18. 2D representation of a section of a computer-generated binary holographic diffuser.

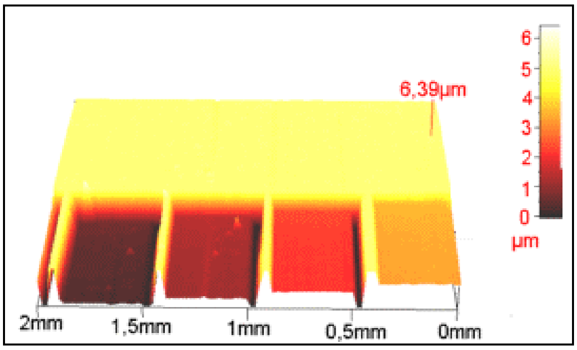

Figure 19. Part of a computer-generated multi-level system plotted directly in a photo-polymer.

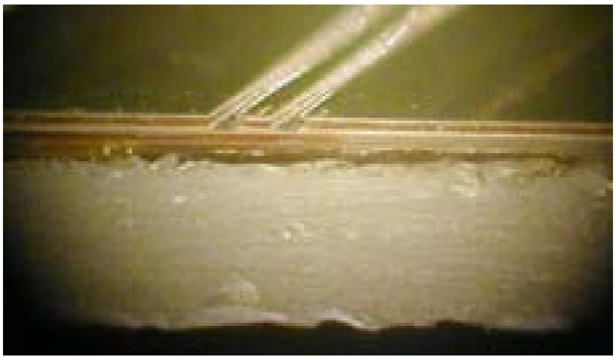

Figure 20. Section of a fixture for two optical fibres for use in a flow meter. Built in several layers of polymers on a 1 mm sheet of glass.

2.8 Collaboration with Danish and foreing universities

2.8.1 BIOP Graduate School: "Biomedical Optics and New Laser Systems"

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The BIOP Graduate School: "Biomedical Optics and New Laser Systems" has been formed under the BIOP Center, which is part of a collaborative project between the Technical University of Denmark and Risø National Laboratory. The graduate school received funding from the Danish Research Agency under grant no. 643-01-0092 for a three-year educational programme, which started in August 2002.

Professor Preben Buchhave, Department of Physics, Technical University of Denmark, heads the graduate school and he has appointed Peter E. Andersen from Risø National Laboratory school director.

The purpose of the graduate school is to strengthen the educational efforts within the area of biomedical optics in Denmark emphasizing the use of lasers and optical methods for diagnostics, manipulation and therapy. In this new interdisciplinary research area, the focus of the school will be on intensifying research activities and educational efforts and on enhancing collaboration between the fundamental physical and technical sciences and the medical, clinical and biological sciences.

Therefore, the graduate school supports PhD projects, conferences, graduate summer schools, visiting scientists and exchange students within the areas of the school.

Areas of the graduate school

The following list, although not exhaustive, shows the main research and educational areas for the graduate school:

- Laser physics, laser technology and non-linear optics for biological and medical applications
- Inference based on mathematical processing of spatial and temporal structures
- Advanced data and image processing
- Optical sensors based on optical fibres and photonic crystal fibres for biological and medical applications
- Tissue optics and light propagation in tissue
- Optical excitation of biochemical processes
- Optical tweezers systems
- Lasers and optical methods for applications in ophthalmology
- Lasers and optical methods for applications in dermatology
- Lasers and optical methods for applications in cardiology

Figure 21. Visit the homepage of the BIOP Graduate School at www.biop.dk/graduateschool and learn more about the activities.

2.8.2 VELI – Virtual European Laser Institute

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In 2001, a multidisciplinary Virtual European Laser Institute (VELI) was formed with support from the European Commission in order to enhance and promote the available laser expertise in Europe. The BIOP Center (www.biop.dk) was invited to join VELI in order to promote the use of lasers and optical methods in the field of bio-optics.

Laser laboratories and institutes all over the world perform research in many fields of expertise concerning laser and laser-based technologies. Currently, Europe holds a strong position as far as knowledge of laser and laser applications is concerned. Industry in general, but in particular small and medium sized enterprises may experience significant difficulties in reaching the enormous body of knowledge that exists at the various laser institutes across Europe. Moreover, from the point of view of industry, it is difficult to gain insight into the existing and available expertise in lasers and optical measurement technologies at the various dispersed laser centres.

A multidisciplinary Virtual European Laser Institute (VELI) was thus formed. The purposes of VELI are:

- to increase the transparency and knowledge of available laser expertise in Europe,
- to remove the current inefficiency (or lack) of exploitation of new laser knowledge and techniques,
- to create common agreements and procedures for knowledge transfer.

In the VELI network, the BIOP Center collaborates with 15 leading research institutions that have specialised in laser physics and applications of lasers, including advanced applications of lasers in bio-optics. This European effort will reach the critical mass in human and technological terms bringing together the expertise and resources needed and will therefore enhance the competitiveness of European industry. Furthermore, the wide variety of competencies of the participating scientists representing different disciplines support the creation of an outstanding state-of-the-art knowledge base on a European level.

The major output of the VELI project is:

- A fully operational core network consisting of 15 leading professional laser institutes in Europe, each possessing core competencies in the fields of laser technology.
- A database containing state-of-the-art expertise, experience and knowledge formerly dispersed at various laser institutes. Moreover, the database also contains knowledge generated from the extensive list of industrial needs at small and medium sized enterprises.
- A virtual surrounding, i.e. a site where the requests coming from the small and medium sized enterprises (industrial needs/demand) meet the available expertise and the wide array of possible applications of laser and laser technology (aser institute supply) thereby speeding up the realisation of potentially new and highly competitive applications.
- A framework or structure for knowledge and technology transfer as well as mutual assistance in fulfilling the local needs for laser and laser-based technologies on a European level prohibiting the duplication of efforts and reaching an effective and efficient provision to user demands.

Figure 22. Logo for the VELI project. Visit www.veli.net and find out more about VELI.

3. Optical diagnostics and information processing

3.1 Introduction

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The pivot point of the work in the research programme on Optical Diagnostics and Information Processing has been the dissemination of results from our basic science into the level of application. In this respect the year 2002 was a rewarding year: two new companies were launched, one of which aims at using the concept of optical coherence tomography for skin examination, while the other is directed towards low-cost miniaturized integration of optical and electronic components.

Two nationally funded projects for young scientists (so-called talent projects) have been conducted through their final phase in this period. One of these projects was centred on the use of phase optics for highly efficient structuring of light, which has shown to bring about a versatile and very promising tool for implementing dynamic tweezers. Non-invasive measurement of biological specimen based on optical coherence tomography formed the basis for the second project, the results of which have now - in combination with the development of new laser systems resulted in a large national initiative named Centre for Biomedical Optics and New Laser Systems (http://www.bio-lase.dk/). Moreover, the Danish Graduate School on Biomedical Optics and New Laser Systems (http://www.biop.dk/graduateschool/) has been granted for three years.

A new talent project has been awarded to the group. Here, the use of the LIDAR-principle (laser radar) will be investigated in combination with wind power generation, especially with respect to the applicability of newly developed laser systems.

Two major industrial projects in the field of displacement measurement have been continued, and basic science within coherent light scattering from surfaces with specific roughness characteristics has been conducted.

The work within spectroscopy has been pursued partly within the field of biooptics and partly within combustion analysis. A national centre contract, Centre of Optical (bio) Sensors (COS), has been in full activity during 2002 involving four industrial partners and three research institutions. New interesting applications of spectroscopy and especially of Fourier transform infrared spectroscopy are being examined in close collaboration with medical doctors. Combustion research was addressed in the EU programme "Minority effluent measurements of aircraft engine emissions by infrared laser spectrometry" (MENELAS).

During the period the laboratory for temperature calibration has been heavily involved in a project where the ability to perform low-temperature calibration has been crucial. Furthermore, in 2002 the laboratory was approved by the Danish Accreditation Scheme, DANAK, to issue certificates for calibration of non-contact temperature measuring equipment.

3.2 Medical optics

3.2.1 Center for Biomedical Optics and New Laser Systems - BIOP

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The Center for Biomedical Optics and New Laser Systems (BIOP), established in 2000, is a Danish initiative where engineers, physicists, chemists and physicians collaborate on the development of new biomedical applications based on the most recent progress in lasers and optical measurement techniques. The aims of the centre are to conduct research and develop advanced laser systems and optical measurement technologies, and to apply these systems within dermatology, ophthalmology and biosensing.

The main purposes of the BIOP research programme are to demonstrate and develop state-of-the-art diagnostic procedures as well as to improve therapeutic facilities at Danish hospitals. The collaboration has resulted in the development of novel biomedical applications of modern laser technology, including three-dimensional imaging in human tissue, blood flow visualization, non-invasive spectroscopy and fluorescence measurements for diagnostics and biosensors for measurements of concentrations of, e.g., glucose and protein. As an example, a mobile optical coherence tomography system has been constructed (see Figure 23 and "Optical coherence tomography in clinical examinations of skin cancer" in this report).

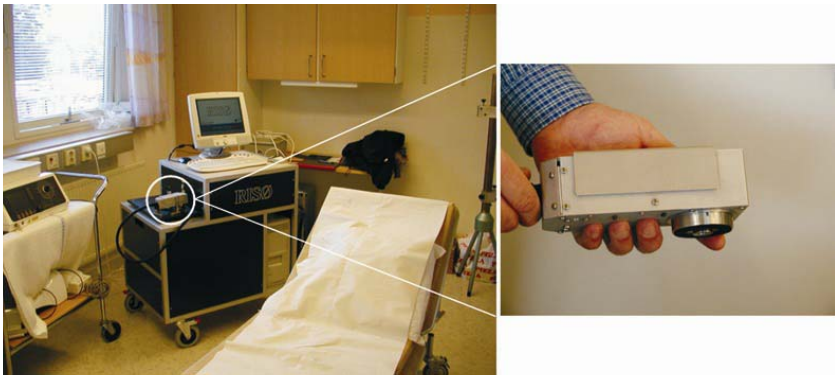

Figure 23. The mobile OCT unit at the clinic (Lund University Hospital, Lund, Sweden). The inset shows the hand-held probe that facilitates easy scanning of a variety of lesions.

In the BIOP Center five focus areas have been selected:

- Biomedical imaging systems
- New laser systems for diagnostic and therapeutic applications
- Optical tweezers systems
- Biosensing
- Biomedical image and data processing

Education in BIOP

Young scientists are offered coordinated training and education at MSc and PhD levels within the areas of laser technology, imaging, medicine and biotechnology through MSc courses and graduate schools, see also BIOP Graduate School. One of the objectives of this approach is that the education of PhD students takes place in close cooperation with the Danish business sector. The PhD projects carried out in BIOP are all structured as inter-institutional collaborative efforts. Moreover, permanently employed members of staff are given the possibilities of using facilities at other institutions and of participating in the education programme - an initiative that contributes to further strengthening of mobility.

Participants

The following partners, who hold strong positions in their own fields, participate in BIOP:

- Department of Dermatology, Aarhus Amtssygehus, University of Aarhus
- Department of Mathematical Modelling, Technical University of Denmark
- Department of Ophthalmology, Herlev Hospital, University of Copenhagen
- Department of Physics, Technical University of Denmark
- Optics and Fluid Dynamics Department, Risø National Laboratory
- Research Center COM, Technical University of Denmark

Located in the vicinity of Copenhagen, BIOP has strong collaboration with Lund Institute of Technology and Lund Medical Laser Centre, Lund (Sweden).

Another important aspect of BIOP is to establish collaboration with industrial partners through joint projects in which the technology developed is transferred to the industrial partner. Such collaborative projects may involve PhD students who participate in the research projects at the premises of the industrial partners as well as at the involved research institution.

3.2.2 Optical coherence tomography used to study heart development in chick embryos

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Birth defects of the heart and the cardiovascular system impose a significant burden on many states around the world, and account for a higher percentage of total birth defects in many states than do any other type of defect. Optical coherence tomography[1] (OCT) is a powerful non-invasive, non-destructive high-resolution imaging modality that is well suited for anatomical and functional visualization of the developing cardiovascular system. OCT is based on low-coherence interferometry, and can provide microscopic, cross-sectional, tomographic imaging by measuring backscattering properties of the scanned tissue.

We have, for the first time, demonstrated that OCT can easily (a) identify significant morphological differences between a normal and an abnormal heart and (b) detect growth and further structural differentiation between developmental stages.[2] This study was carried out using chick embryos. The chick embryo is an established model system for studying heart development in humans. The OCT system used in this study was a state-of-the-art real-time OCT system with a 22 micron axial and 27 micron lateral resolution, and an eight frames per second image acquisition rate (4000 A-scans per second).[3] 3D datasets were acquired and processed to create volumetric reconstructions and short video clips. An example of a 3D OCT reconstruction of a chick embryo heart is shown in Figure 24. After scanning, the embryos underwent routine histological cross-sectioning to compare cardiac anatomy. A strong correlation at the micron-scale level between histology and OCT was obtained.

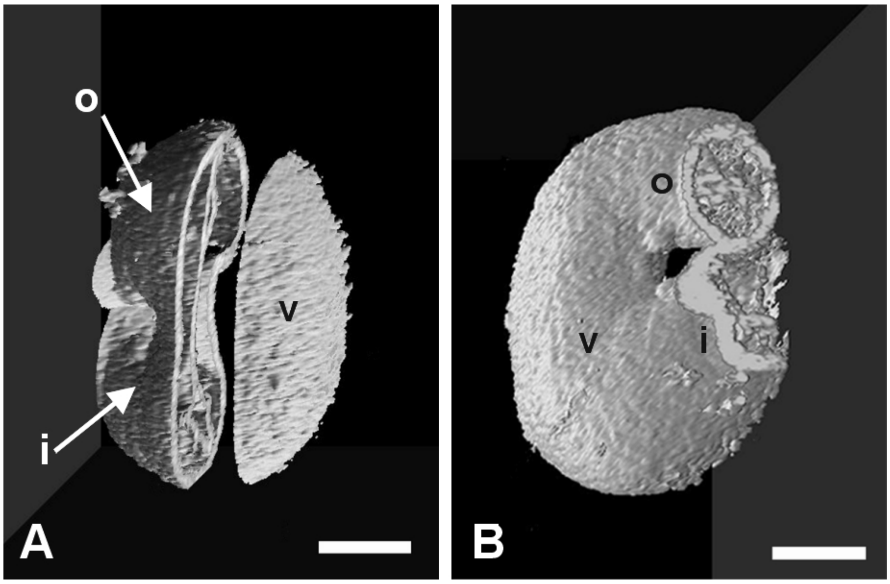

Figure 24. (A) 3D OCT reconstruction of a chick embryo heart with a cutaway through the straight outflow limb of the heart tube to reveal further internal structural detail. (B) Shows the same heart from the left lateral view. **i** indicates inflow limb; **o**, outflow limb; and **v**, presumptive ventricle. Bar = 0.250 mm.

In conclusion, OCT offers the possibility of generating and catalogueing high-resolution 3D images of embryonic development, and could allow new insight into assessing and understanding normal and abnormal heart development in established animal models such as the chick or mouse.

1. D. Huang, E.A. Swanson, C.P. Lin, J.S. Schuman, W.G. Stinson, W. Chang, M.R. Hee, T. Flotte, K. Gregory, C.A. Puliafito and J.G. Fujimoto, "Optical coherence tomography", *Science* **254**, 1178-1181 (1991).
2. T. M. Yelbuz, M. A. Choma, L. Thrane, M. L. Kirby and J. A. Izatt, "Optical coherence tomography: a new high-resolution imaging technology to study cardiac development in chick embryos," *Circulation* **106**, 2771-2774 (2002).
3. A. M. Rollins, R. Ung-arunyawee, A. Chak, R. C. K. Wong, K. Kobayashi, M. V. Sivak and J. A. Izatt, "Real-time *in vivo* imaging of human gastrointestinal ultrastructure by use of endoscopic optical coherence tomography with a novel efficient interferometer design," *Opt. Lett.* **24**, 1358-1360 (1999).

3.2.3 Monte Carlo simulation of optical coherence tomography

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Optical coherence tomography[1] (OCT) is an important imaging modality with a plethora of applications especially within medical diagnostics. Monte Carlo simulations (MCS) have proved their feasibility in terms of predicting the distribution of light in random media.[2] MCS have the advantage that there are few limitations on which geometries that may be modelled, and as a numerical experiment one has full control of all parameters, which may be cumbersome to obtain in a real experiment. With the credibility and flexibility of MCS our motivation to apply MCS to OCT is that the model may serve as a "numerical phantom". The difficulty in applying MCS to model OCT is to model the coherent mixing of fields from the sample and reference because MCS are incapable of modelling the spatial coherence properties of light.[3]

In this work,[4] an advanced novel MCS model of the detection process of an OCT system has been developed. For the first time it has been shown analytically that the applicability of the incoherent MCS approach to model the heterodyne detection process of an OCT system is firmly justified. This was obtained by calculating the heterodyne mixing of the reference and the sample beams in a plane conjugate to the discontinuity in the sample probed by the system. Using this approach, a novel expression for the OCT signal was derived that only depends upon the intensity distribution of the light from the sample and the reference beam and, thus, enables MCS. To estimate the intensity distributions adequately, a novel method of modeling a focused Gaussian beam with MCS was developed. This method was then combined with the derived expression for the OCT signal into a new Monte Carlo model of the OCT signal.

Figure 25 shows the OCT signal obtained for several beam and sample geometries using the new MCS, and comparing with results of an analytical model[5] based on the extended Huygens-Fresnel principle. With the excellent agreement obtained and the greater flexibility of MCS, this new MCS model has been demonstrated to be excellent as a numerical phantom, i.e. as a substitute for otherwise difficult experiments.

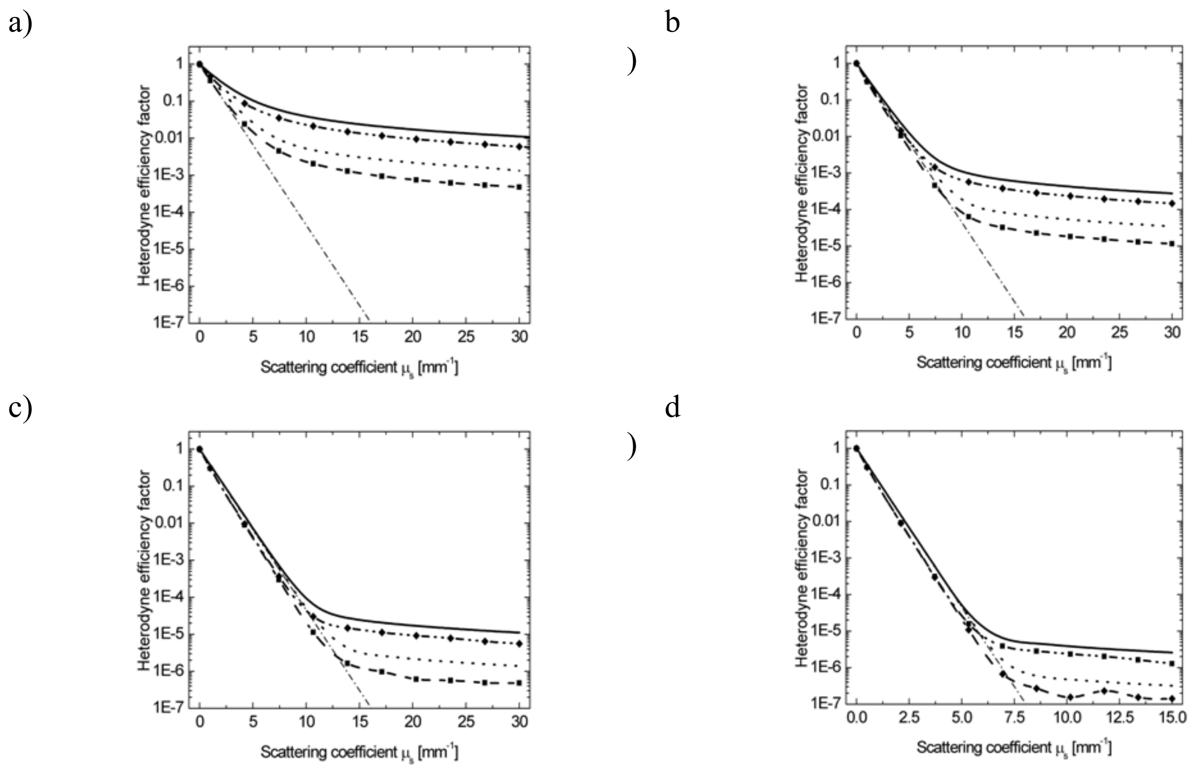

Figure 25. Monte Carlo simulation of the heterodyne efficiency factor as a function of the scattering coefficient, μ_s, for two values of the anisotropy factor *g*. The heterodyne efficiency factor is the reduction of the OCT signal due to scattering in the sample. a), b), c), and d) show the values found for sample beams with NA = 0.008 and *f* = 16 mm, NA = 0.05 and *f* = 0.05, NA = 0.25 and *f* = 0.5 mm, and NA = 0.25 and *f* = 16 mm. For all cases the wavelength is 814nm and the probed depth is *z*=0.5mm except for graph d) where *z* = 1.0 mm. Analytical results: *g* = 0.99 (solid line) and *g* = 0.92 (dotted line). MCS results: *g* = 0.99 (dash-dotted line and ♦) and *g* = 0.92 (dashed line and ■).

1. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, ”Optical Coherence Tomography”, Science **254**, 1178-1181 (1991).
2. L.-H. Wang, S. L. Jacques, and L.-Q. Zheng, "MCML - Monte Carlo modeling of photon transport in multi-layered tissues," Computer Methods and Programs in Biomedicine **47**, 131-146 (1995).
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3.2.4 Optical coherence tomography in clinical examinations of skin cancer

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peter.andersen@risoe.dk

During recent years the incidence of skin malignancies has increased. For the non-pigmented lesions there are a number of treatment modalities. Since topical application of δ-aminolevulinic acid (ALA) was introduced, photodynamic therapy (PDT) has been considered one way of treating these tumours. However, there are some limitations when PDT is applied with distant surface illumination and topical sensitisation both from the ALA diffusion point of view and from the point of view of light penetration. Therefore, it is of importance to determine the tumour thickness in the planning of the treatment. For example, for nodular basal cell carcinomas (nBCCs) it is often necessary to apply PDT more than once. Another possibility is to perform cryosurgery, curettage or some other tumour thickness reducing modality before PDT. The clinical way of determining the thickness of a non-pigmented skin malignancy is to visualise and palpate the tumour area provided a punch biopsy has not been performed.

In this study[1] a non-invasive way to visualise the tumour thickness by means of OCT[2] has been investigated in connection with ALA-PDT. This study has been focused on basal cell carcinomas (BCC) as it is the most common type of non-pigmented skin cancer and, therefore, makes it possible to obtain thorough understanding of what the OCT images represent.[3]

1. L.K. Jensen, L. Thrane, P.E. Andersen, A. Tycho, F. Pedersen, S. Andersson-Engels, N. Bendsøe, S. Svanberg and K. Svanberg, ”Optical coherence tomography in clinical examinations of skin cancer”, to be published in SPIE Proc. **5140** (2003).
2. D. Huang, E.A. Swanson, C.P. Lin, J.S. Schuman, W.G. Stinson, W. Chang, M.R. Hee, T. Flotte, K. Gregory, C.A. Pulaifito, J.G. Fujimoto, Science, **254**, 1178 (1991).
3. J. Welzel, Skin Research and Technology, **7**, 1 (2001).

Figure 26. The mobile OCT system in the clinic and the compact handheld probe.

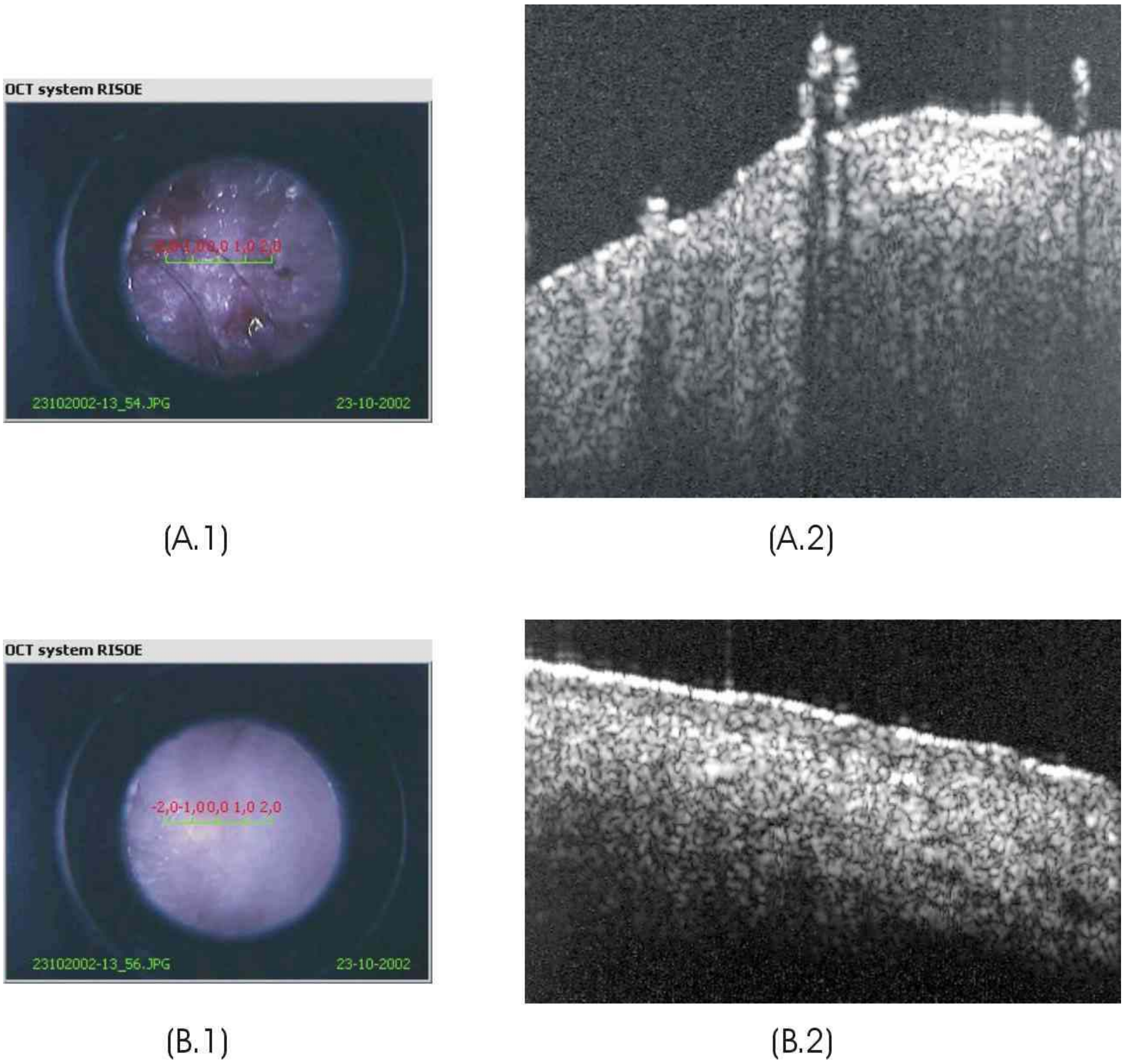

Figure 27. OCT images (A.2 and B.2) with correlated surface images (A.1 and B.1). (A) Image of BCC lesion on the leg, and (B) comparable healthy skin in the vicinity of the BCC. The lesion shows a more homogeneous backscattering than the healthy skin where separate layers can be distinguished. The line indicates the scan site.

3.2.5 Quantification of biofilm growth and structure

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Bacteria living in natural environments usually live in multispecies communities bound to surfaces under changing and uncontrollable conditions. The biofilm mode of life is the rule for bacteria while, with a few exceptions, dense populations of suspended organisms are rare.[1] These film-forming microbes excrete a glue-like substance that anchors them to materials such as metals, plastics, tissue and soil particles. Some examples of detrimental reactions caused by biofilms are microbially influenced corrosion, especially of industrial pipes, and infections caused by biofilm growing on host tissues or medical implants. During the past two decades new scientific methods have also changed the view of dental plaque so that dental scientists now see it as a biofilm. Beneficial reactions take place when bacteria within biofilms break down contaminants in soil and water; now used in wastewater treatment.

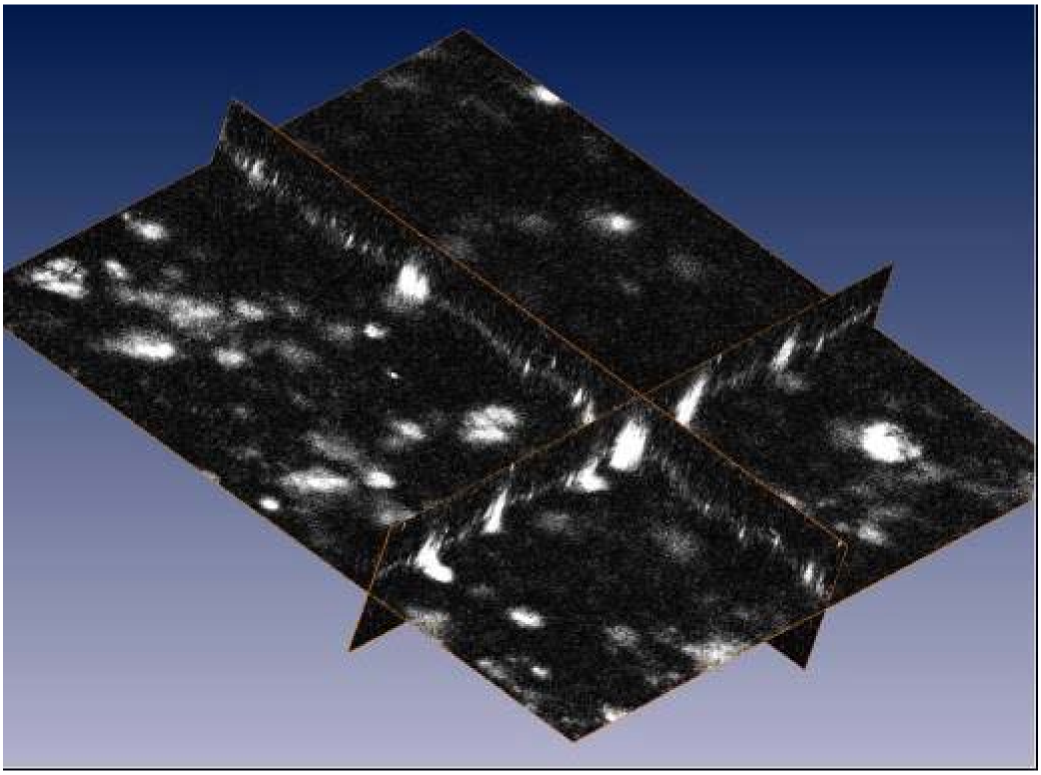

Figure 28. Three orthogonal slices through a biofilm sample from a water pipeline. The biofilm was imaged using confocal laser scanning microscopy in combination with fluorescent probes. The sample size is 0.3 x 0.3 $(\mu m)^2$ in cross-section and has a height of 1 µm.

An objective of molecular ecology is to reach an understanding of the community life of bacteria from a central dogma perspective: How does information flow in a microbial community from the external environment to the community members and between the members, and how is this information converted to coordinated activities in the community? The use of confocal laser scanning microscopy in combination with fluorescent probes has provided an informative tool for studying the growth and development of biofilm structures. The goal of the project is to extend existing software tools for quantifying the information contained in the recorded 3D images, see Figure 28. The work includes the development of automatic thresholding techniques as well as the use of mathematical morphology and distance map measures for evaluating the spatial relationships between different species over time. When characterising the biofilm structure it is important to come up with objective measures and to gain an understanding of what measures can characterise what structures. They also have to be useful for measuring the amount of agreement between experimental results and predictions obtained using different mathematical models. The work is ongoing.

1. S. Molin *et al*. (2001), Molecular ecology of biofilms, p. 89-120. In J. D. Bryers (ed.), Biofilms II: Process analysis and applications. Wiley-Liss, New York.

3.2.6 Machine learning, EUNITE challenge 2002

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Over the previous years we have developed an ensemble-based classification model founded on the so-called n-tuple classifier.[1] The model extracts information from a set of training examples and the concept belongs to the area of machine learning algorithms. In order further to validate our model we decided to participate in the EUNITE competition 2002, where the task was to predict whether a bank client is active or not based on developing a model through data-driven techniques.[2] The Bank Tatrabanka in Slovakia provided a data set with 24,000 records. Each record consisted of 36 variables, a figure that is believed to provide a characterization of a given client within the bank. In the case of the training examples (12,000 examples) a label specified whether the client was to be considered active or not. By having a predictor model the bank would be able to take specific actions in the case a client is classified as passive.

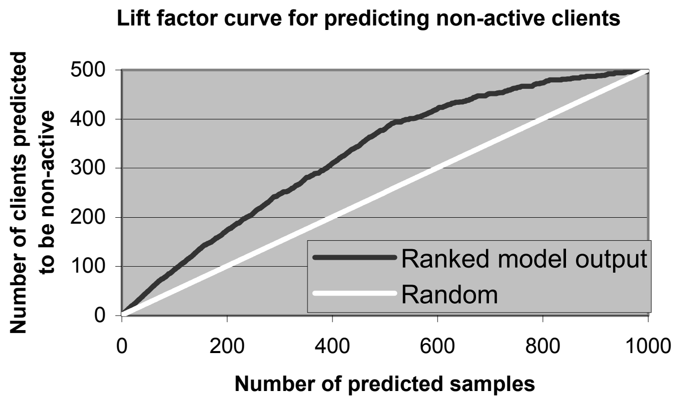

Figure 29. Lift factor curve for predicting the non-active client as a function of the processed number of ranked samples. The total sample size is 1000 for the considered validation set.

The competition criterion for evaluating the model was decided to be the raw error rate obtained in predicting the label for the 12000 test examples. Our model was ranked five (out of 15 contributed models) having a raw error rate of 26.2 % on the test set. The default error rate was 50 %. The top three ranked models had error rates of 24.5 %, 25.7 % and 26.1 %, respectively. The difference between the performance of the second ranked model and our result is within the variation obtained from retraining our model. The model obtaining rank 15 had an error rate of 40.6 %. In reality, it is likely to be relevant to have the possibility of ranking the predicted results according to a confidence in the decision. We therefore also provided lift factor curves (see Figure 29) although such curves were not used in the evaluation procedure.

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2. T. M. Jørgensen, "An N-tuple ensemble classifier model for predicting whether a bank client is active or not," in report on EUNITE World competition in domain of Intelligent Technologies, 2002. The report can be ordered from EUNITE service centre at info@eunite.org or downloaded from
http://www.eunite.org/eunite/events/eunite2002/competitionreport2002.htm
http://neuron.tuke.sk/competition2/

3.2.7 Enhancement of retinal OCT scans

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An essential noise contribution associated with the optical coherence tomography (OCT) technique is the one caused by generation of speckle on the detector surface. The speckle patterns are caused by interference between nearby scatterers it the sample volume. Normally, it is not simple to average out the speckle noise that occurs in OCT scans, since it is necessary to invoke a variation in the optical recording configuration to invoke a change in the received speckle patterns. In the case of applying OCT for obtaining retinal scans (*in vivo*) such a variation is automatically obtained due to the saccadic movements of the eye. The challenge, however, is then to align the repetitive measurements with such a precision that we are actually able to produce an average image. We have developed a robust correlation method based on maximising an estimate of the correlation between A-scans for corresponding sets of those scans. In this way we have been able to develop a method that is capable of reducing the speckle noise. By reducing this noise contribution we hope that important details in the retinal images that are not detectable in the original images can be revealed.

The method has been tested on images recorded at Herlev Hospital, Denmark, using a commercial OCT scanning system (Humphrey-Zeiss).[1] Between five and ten repetitive recording were used for producing each picture. The technique results in an immediate visual improvement (see Figure 30) but what is more important is that the medical doctors are now able to identify pathological features not observable from the individual original OCT images.

1. T.M. Jørgensen, L. Thrane, J.L. Hougaard,; B. Sander and M. Larsen, "Enhancing imaging of retinal optical coherence tomography scans" (poster). In: Book of abstracts. DOPS annual meeting, Risø (DK), 21-22 Nov 2002. (Dansk Optisk Selskab; Forskningscenter Risø, Roskilde, 2002).

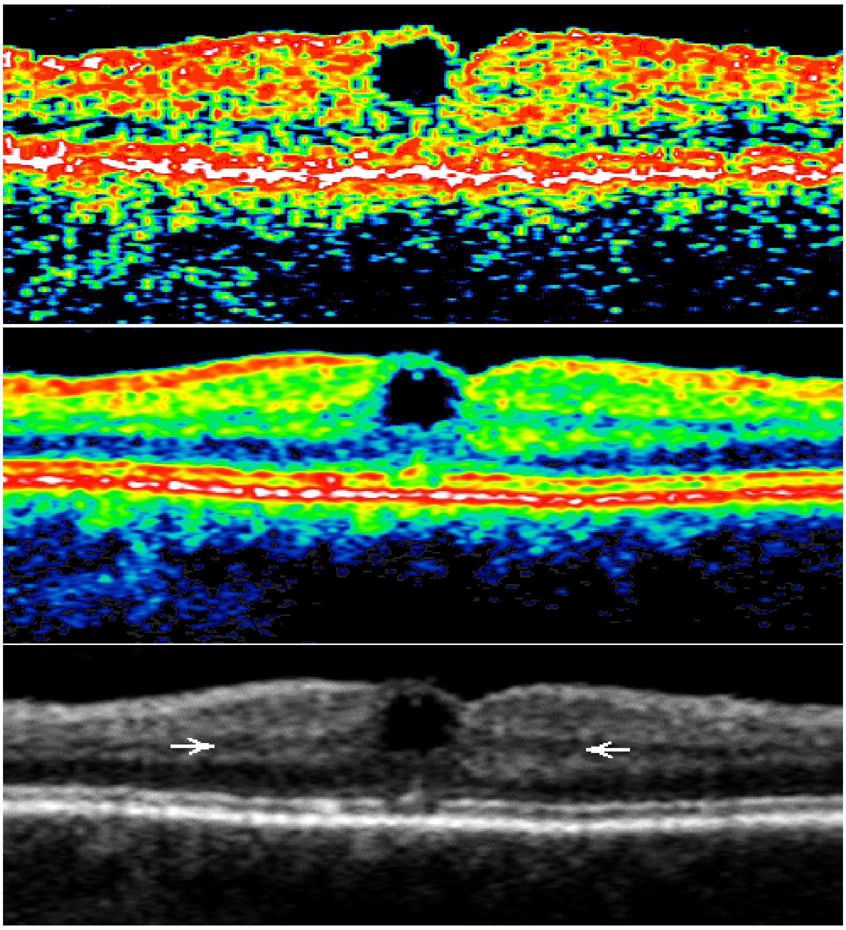

Figure 30. Top image shows an original output from the OCT scanner. The middle and bottom images show the resulting average image obtained by aligning and averaging ten OCT images (grey-level palette and false colour palette, respectively).

3.3 Phase contrast

3.3.1 Fully dynamic multiple-beam optical tweezers

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Single-beam optical tweezers are useful for a wide range of interdisciplinary research and are a practical tool for (1) the measurement of interaction forces and manipulation of cells, subcellular structures and individual DNA molecules and (2) assembly of microstructures on the micro- and nano-scales. When an array of particles has to be trapped simultaneously and manipulated independently, there is a need to generate multiple tweezer beams where the shape, size, position and intensity of each beam can be controlled individually and preferably manipulated in real time. There have been many schemes to extend conventional optical tweezers to facilitate multiple trapping using high-speed scanning mirrors or multiple light sources. However, these systems operate efficiently for a limited number of traps, but intensify in complexity or degrade in performance as the number of beams is increased to trap a large number of particles simultaneously. Hence, a desirable approach for dynamic and simultaneous manipulation of an array of particles is a multiple-beam optical tweezers system that is based on a simple, yet efficient method that enables redistribution and arbitrary shaping of a collimated incident laser beam.

We have previously shown simultaneous trapping of four particles using a fixed tweezer-beam array based on the Generalised Phase Contrast (GPC)[1,2] method and a prefabricated phase mask.[3] Our approach to generate multiple-beam optical tweezers is non-mechanical and an alternative to techniques that are either component intensive, restricted to specific trapping pattern geometries or mechanically complex.

Subsequently, we have demonstrated a fully dynamic system that makes use of the same principle and a computer-programmable phase-only spatial light modulator (SLM) to enable real-time manipulation of micro-particles.[4,5,6] In this approach, a phase-only SLM encodes the desired pattern directly in the phase component of a collimated and expanded laser beam. This phase-encoded information serves as the input for a GPC system in which a phase-contrast filter (PCF) generates a high-contrast intensity pattern that directly corresponds to the phase perturbation of the input wave front. The intensity pattern is focused using a microscope objective lens for trapping of microscopic particles. We use an optically addressed phase-only SLM that is addressed with the video signal from a computer. It is therefore possible to control the position of the tweezer beams by movement of the computer cursor or a pointing device, and this results in real-time direct manipulation of individual optical traps. The phase-only SLM is not pixelated and this fact combined with the straightforward phase-encoding procedure results in an efficient, real-time re-distribution of light from the incident laser beam into the individual tweezer beams. With our method it is possible to hold certain traps stationary, whilst other traps are moved. Furthermore, it is possible to adopt an arbitrary beam profile best suited for a given trapping task.

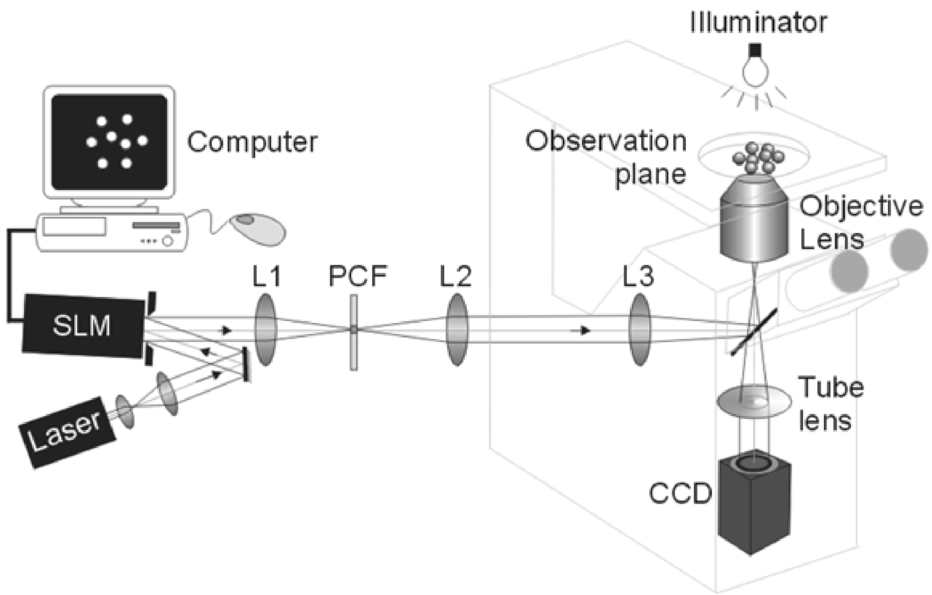

Figure 31. The schematic diagram of the experimental set-up for the dynamic multiple-beam phase contrast-based optical tweezers system using a reflection-mode phase-only spatial light modulator.

Figure 31 shows the schematic diagram for the implementation of the GPC-based fully dynamic multiple-beam optical tweezers using a phase-only SLM. A 200 mW diode laser operating at a wavelength λ = 830 nm is expanded, collimated and incident on a reflection-geometry SLM. The SLM is a parallel-aligned nematic liquid crystal type (Hamamatsu Photonics) that can modulate phase of at least 2π at 830 nm. The SLM is optically addressed by a VGA-resolution (640 x 480 pixels) liquid crystal projector element that is controlled from the video output of a computer. The phase-modulated light is directed into the GPC-based filtering system composed of two lenses (L1 and L2) and a PCF positioned at the Fourier plane. The 50 µm-diameter PCF is designed to provide a π-phase shift at 830 nm and is fabricated by depositing photo-resist on a glass optical flat. The lens L3 and the objective lens scale the intensity distribution for trapping microscopic particles in the observation plane of the microscope. Visible light from an external white light illuminator is scattered by the trapped particles and imaged to a CCD-camera using the same microscope objective and the tube lens.

Figure 32 shows an image sequence that demonstrates simultaneous trapping of eight polystyrene micro-spheres arranged in six- and two-fold traps that rotate in opposite directions and at different speed. The time lapse between each image frame is 240 ms, as shown in the upper right corner of each frame. A scale bar has been placed in the first image, indicating a distance of 10 µm. The first frame of the sequence has two dotted circles with an arrow indicating the rotation directions of the particles. The two particles rotating in the inner circle rotate anticlockwise nearly one full rotation and the outer six particles rotate clockwise 1/8 of a full rotation. The peripheral speed of the inner two particles is 3.3 µm/s and the outer six particles rotate at a peripheral speed of 1.6 µm/s. As can be seen in the sequence, two particles present to the left and right of each frame are moving freely due to Brownian motions and are clearly not under the influence of radiation pressure effects from the trapping beams. The laser power of each trap was kept at the same level as in the first experiment.

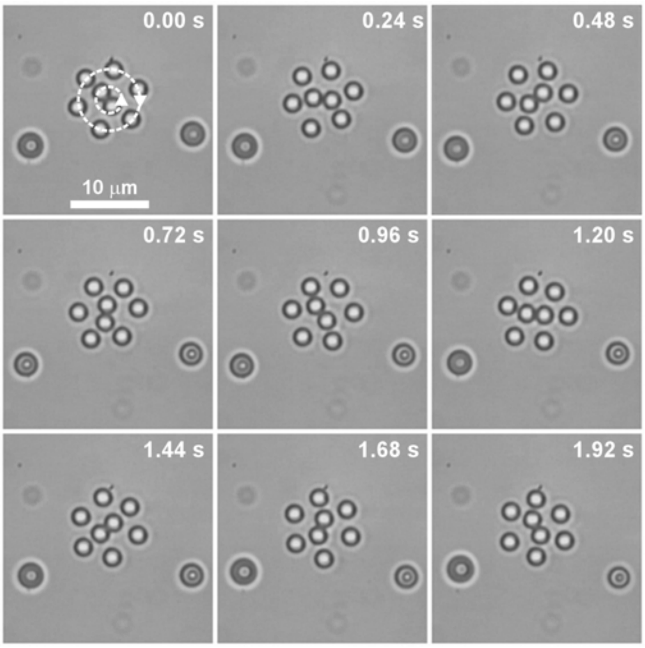

Figure 32. An image sequence showing the dynamic rotation of eight trapped polystyrene beads (2 µm in diameter) in the phase-contrast-generated optical traps. The outer six particles rotate clockwise 1/8 of a full rotation while the inner two particles rotate anticlockwise nearly one full rotation.

1. J. Glückstad, "Phase contrast imaging," US Patent No. 6011874.

2. J. Glückstad and P. C Mogensen, "Optimal phase contrast in common path interferometry," Appl. Opt. **40**, 268-282, (2001)
3. R. L. Eriksen, P.C. Mogensen and J. Glückstad, Opt.Lett. **27,** 267-269 (2002).
4. R. L. Eriksen, V. R. Daria and J. Glückstad, "Fully dynamic multiple-beam optical tweezers," Opt. Express **10** 590-602 (2002)
5. Opto & Laser Europe, "3D array holds 400 traps", September 2002.
6. Photonics Spectra, World Tech Briefs: "Phase contrast produces dynamic, multiple-beam optical tweezers", October 2002.

3.3.2 Optimising the generalised phase contrast method in a planar-optical device

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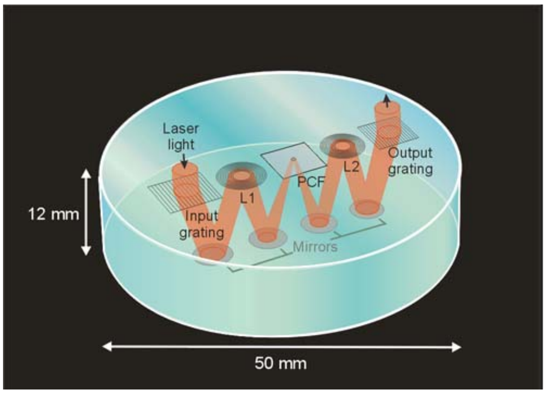
Efficient conversion of a phase pattern into a high-contrast intensity distribution is one way to project light for use in array illuminators, optical lithography, multiple-beam optical tweezers and visualisation of two-dimensional phase distribution as applied in wave front sensing and optical decryption. A more comprehensive analysis of phase-to-intensity conversion that provides an elaborate analytic model of the process has been demonstrated by the Generalised Phased Contrast (GPC) method.[1,2] The GPC method is an enhanced approach because it enables an analytic determination of the exact working parameters where any disturbance in the incident phase, being it weak or strong, yields optimised information visualised by optimised intensity distribution at the output.

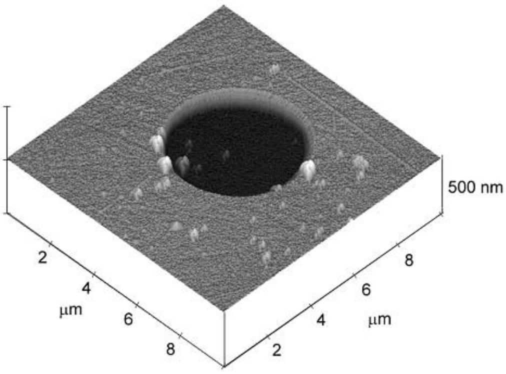
In a recent work, we have demonstrated the feasibility of implementing the GPC method in an integrated planar optical (PO) device.[3] The PO implementation extends the applicability of the GPC method to contemporary technologies in integrated electro-optical data communications, such as its application for optical phase decryption. A PO device implementation enables coupled light to undergo free-space propagation between micro-optical components not prone to tolerancing and alignment problems, which are major problems when we use discrete optical components. A major drawback, however, is the optical losses due to the low diffraction efficiency caused by the use of binary diffractive gratings for the input and output coupling. In addition, binary gratings generate higher-order diffracted beams that lead to encroachment of unwanted interference and introduce constraints for optimising the output. These problems, however, can be resolved by redesigning the PO device to make use of either four-level diffractive input/output coupling gratings or by use of refractive wedges. The proposed solutions nevertheless require fabrication of gratings with feature sizes that are either beyond what is achievable by current lithographic technology or require extraordinary processes to deposit thick refractive phase structures to achieve the necessary optical functionalities.

For specific applications that basically demand efficient visualisation of spatial phase modulation while maintaining portability, miniaturisation of the optical set-up is of similar concern to obtaining optimised light throughput. It is therefore important to evaluate the working parameters where a practical and cost-effective design of the PO implementation of the GPC method performs in the best possible way.

We have made a brief overview of the mathematical foundation of the GPC that describes the essential points that influence the choice of working parameters to maximise the visibility of the output information under constrained optical conditions.[4] Changing the diameter of the Phase Contrast Filter (PCF) can optimise the performance of the GPC-PO device, which is a practical and cost-effective approach compared with changing the coupling gratings to four-phase-level diffractive optical elements or by using refractive phase structures. This miniaturised phase visualisation system has less light efficiency but will still be a useful device for electro-optical data communications, particularly in security and product authenticity verification applications.



(a)



(b)

Figure 33. (a) Implementation of the Generalised Phased Contrast method in a 50-mm-diameter and 12-mm-thick planar optical device. (b) A topographic image of the phase contrast filter taken with an atomic force microscope. An anisotropic etching process is used to form the steep-edged 5-μm-diameter cylindrical hole with a depth designed to carry out a π-shift of the laser operating at wavelength $\lambda = 632.8$ nm.

To implement the GPC method in an integrated PO device, the two diffractive microlenses (L1 and L2) are arranged linearly on top of a glass substrate as presented in Figure 33(a), which also shows the beam path that illustrates a folded version of the 4-f lens configuration. L1 focuses the beam to the spatial Fourier plane where a reflection-coated PCF is fabricated on the substrate to perform a π–phase shift of the on-axis region of the focused light. The PCF is designed for operation at $\lambda = 0.633$ μm and is etched as a hole with diameter, $D_{PCF} = 5$ μm, on the substrate. Figure 33(b) shows a topographic image of the PCF taken with an atomic force microscope. An anisotropic etching process is used to form a steep-edged cylindrical hole.

This PO implementation will be a practical and effective miniaturised approach for visualisation of a two-dimensional phase distribution as applied in wavefront sensing or in optical decryption. A miniaturised optical decryption system as shown in figure 2 will have a significant impact in electro-optical data communications where security and authenticity verification are apparent motivations.

1. J. Glückstad, "Phase contrast imaging," US Patent No 6011874.

2. J. Glückstad and P. C Mogensen, "Optimal phase contrast in common path interferometry," Appl. Opt. **4**0, 268-282 (2001)

3. V.R. Daria, J. Glückstad, P.C. Mogensen, R.L. Eriksen and S. Sinzinger, "Implementing the generalized phase-contrast method in a planar-integrated micro-optics platform," Opt. Lett. **27,** 945-947 (2002)

4. V.R. Daria, J. Glückstad, R.L. Eriksen and S. Sinzinger, "Performance of the generalised phase contrast method implemented in planar-integrated micro-optics." In: Technical digest. Part 1. 19. Congress of the International Commission for Optics (ICO XIX): Optics for the quality of life, Firenze (IT), 25-31 Aug 2002. Consortini, A.; Righini, G.C. (eds.), (International Society for Optical Engineering, Bellingham, WA, 2002) (Proceedings of SPIE, 4829) p. 501-502.

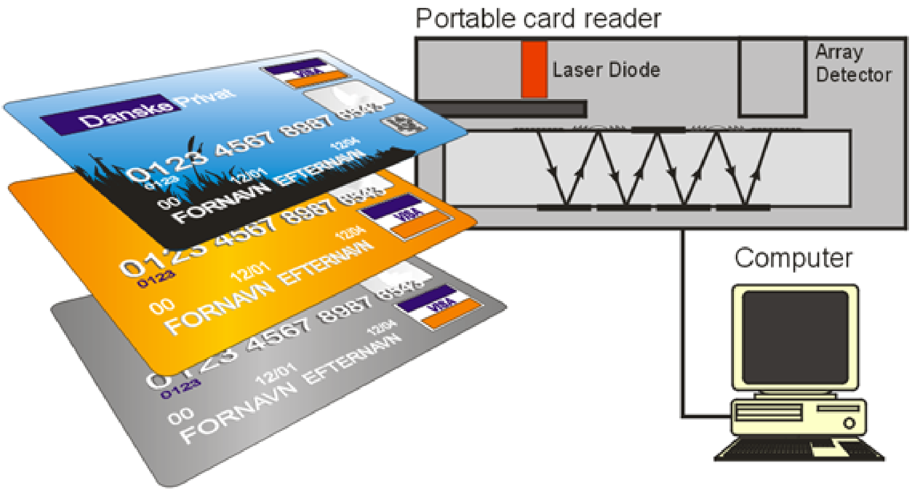


Figure 34. A miniaturised optical decryption system will have a significant impact in electro-optical data communications where security and authenticity verification are apparent motivations.

3.3.3 Formation and manipulation of microscopic colloidal structures

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Observation and manipulation of colloidal structures in the micro- and nano-scale has attracted considerable attention because it can provide answers to fundamental issues on the forces that constitute arrays of particles as well as verify theories on self-assembly of materials, particularly of that of crystalline structures. The study of these structures also enables development of practical applications that are based on large array systems for use in photonic crystals, micro-fluidic processes and bio-chemical sensing devices. This can, in time, be the future of nano-scale hybrid processing systems and a prelude to photonic computing devices and sensing chips.

Current techniques used in the study of colloidal structures, however, entail only passive observation methods such as the use of image forming instruments based on optical microscopes or scanning probe techniques. Similarly, in cases where aggregated structures are fabricated, the methods involved, either by self- or guided-assembly, are hampered by the lack of controllability that results in structural arrays that are both spatially and temporally inflexible. In order to achieve a comprehensive study of colloidal structures, it is desirable to develop techniques that enable active observation as well as dynamic formation and manipulation of arbitrary arrays of particles.

We propose the use of fully dynamic multiple beam optical tweezers for dynamic formation and manipulation of colloidal suspensions. The system is based on the use of the GPC method[1] for the generation of fully dynamic multiple trapping beams[2] achieved by a direct conversion of an input phase pattern into high-intensity beams. This direct-conversion process does not depend on complex algorithms used for computer-generated holograms, multiple beam paths that make use of diode laser arrays or intricate optical set-ups with mechanical scanning devices. The GPC method facilitates a straightforward process that generates an adjustable number of traps and enables real-time control of the position, size, shape and intensity of each trapping beam in arbitrary and asymmetric configurations by encoding the appropriate phase pattern on an SLM. Individual manipulation of the particles is performed in real time and trapped particles can be moved at a speed that is only limited by the response time of the SLM.

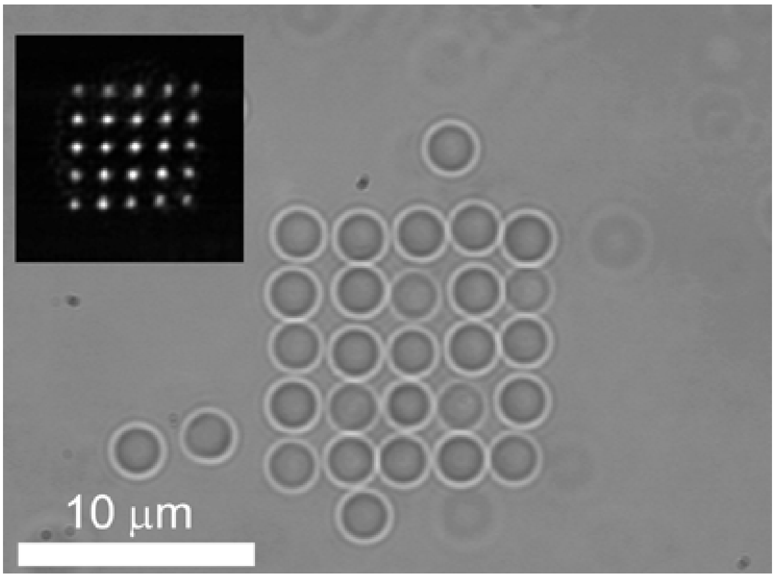

Figure 35. Optical trapping of 25 silica beads, 2.25 μm in diameter, arranged in a five-by-five array. The spacing between each bead is 3 μm. (Inset) The measured GPC-generated intensity distribution in the trapping plane.

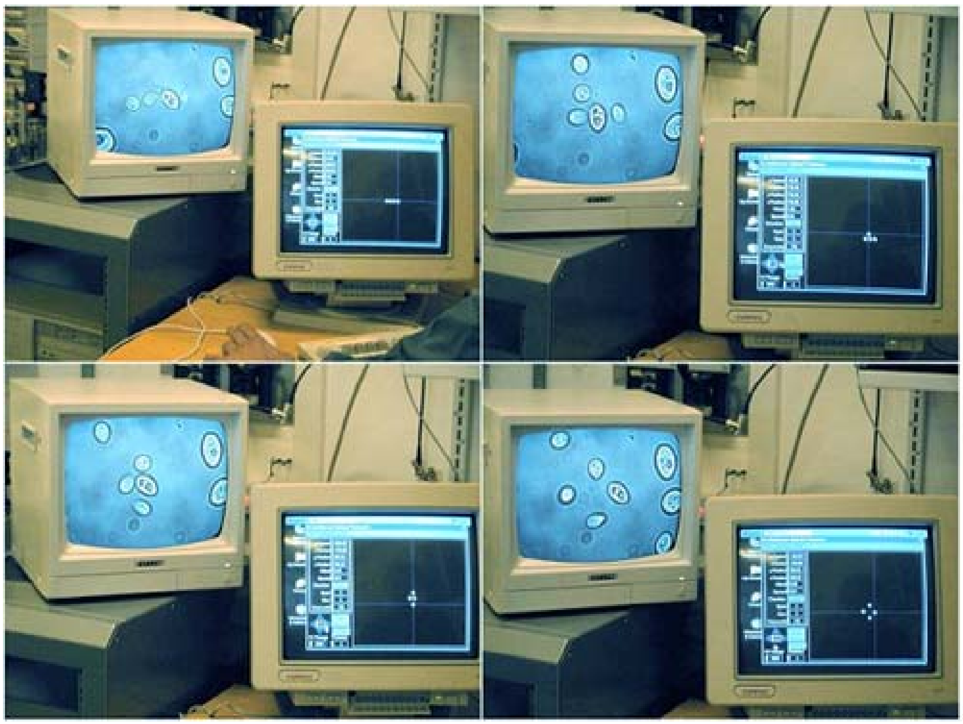

Figure 36. Interactive sorting and reorientation of yeast cells using multiple trapping beams generated by the GPC method. Trapping-beam configurations are dynamically reconfigurable by a simple graphical user interface.

Using the fully dynamic multiple-beam optical tweezers, we have demonstrated formation and manipulation of colloidal structures that consist of 2.25-µm-diameter silica beads suspended in de-ionised water with a small amount of surfactant added.[3] We have also demonstrated the system's capability to trap and re-orient yeast cells suspended in water[3]. Figure 35 shows the array formation of 25 silica microspheres that are trapped using our system. A scale bar has been placed at the bottom indicating a length of 10 µm. Figure 36 shows trapping and reorientation of four yeast cells in different formations using a graphical user interface (GUI) built on the LabView programming platform. The graphics shown in the computer is identical to the trapping configuration in the trapping-plane. The GUI enables "mouse"-controlled manipulation of arbitrary trapping geometries. Trapping of multiple cells can be applied in cell-division cycle experiments where identical daughter cells and the process, as a whole, can be monitored and analysed.

1. J. Glückstad, "Phase contrast imaging," US Patent No 6011874.
2. R.L. Eriksen, V.R. Daria and J. Glückstad, "Fully dynamic multiple-beam optical tweezers," Opt. Express **10** 590-602 (2002).
3. V.R. Daria, P.J. Rodrigo, R.L. Eriksen and J. Glückstad, "Formation and dynamic manipulation of an assembly of micro- and nano-scale particles," In: Proceedings. Biomedical applications of micro- and nanoengineering, Melbourne (AU), 16-18 Dec 2002. Nicolau, D.; Lee, A. (eds.), (International Society for Optical Engineering, Bellingham, WA, 2002) (Proceedings of SPIE, 4937) p. 41-48.
4. V.R. Daria, J. Glückstad and R.L. Eriksen, "Efficient generation of multiple tweezer-beams for parallel manipulation of particle aggregates." In: Programme and abstracts. International conference on optics within life sciences (OWLS VII), Lucerne (CH), 2-5 Sep 2002. (International Society on Optics Within Life Sciences, Lucerne, 2002) p. 25.

3.4 Infrared technology

3.4.1 Centre of Optical (bio) Sensors (COS)

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The objective of the project is to investigate and develop new methods for determination of small amounts of chemical compounds in drugs and food, compounds that influence human welfare. The COS project, which was initiated in 2002, is a multidisciplinary cooperative project between industry and research institutes. Common for all the projects in COS is that the analytical sensors developed are based on optical methods. The project is sponsored partly by the Danish Ministry of Economic and Business Affairs and the Danish Council for Research Policy. The partners in the project are the Technical University of Denmark, Biotechnological Institute, MMP A/S, Crystal Fibre A/S, NUNC A/S, Foss Electric A/S and Risø National Laboratory.

In cooperation with Foss Electric A/S and Biotechnological Institute, Risø will investigate the potential use of a dual-beam FT-NIR/IR experimental set-up for determination of small amounts of key important chemical compounds in aqueous solutions and, later on, in selected samples of practical importance. One of the important and interesting issues in this part of the project is to find out why dual-beam FT-IR spectrometry seems to be capable of predicting concentrations with much higher accuracy than common single-beam FT-IR spectrometers.

3.4.2 Measurement of trace components in aqueous solutions with Fourier transform infrared spectroscopy

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The measurement of trace component concentrations in aqueous solutions has a number of important applications in areas such as in the dairy industry and for medical diagnostics. At Risø National Laboratory we seek to apply Fourier transform near- and mid-infrared (FT-(N)IR) spectroscopy in combination with multivariate chemometric calibration methods. The advantages of using optical techniques lie in the non-invasive nature of the measurement and the potential for reagentless on-line measurements with instant answers. Our interest has been focused on the fundamental limits imposed by the absorption of light by water, which presents a background that is much larger than the absorption of the trace components of interest, and on the optimization of instrumentation under these restrictions. Issues such as the temperature variation of the absorption spectrum of water[1] and the choice of optimal path length of liquid transmissions cells have been studied.[2] In addition, a special dual-beam, optical null instrument has been demonstrated to eliminate the instrumental variations that are normally present in traditional measurements.[3] The results are that simpler calibration models may be employed and that the stability of the instrument is increased compared with the stability of a traditional FT-IR spectrometer. The results obtained form the basis of a collaborative project with a Danish company and the newly developed instrumentation is currently being applied for on-line measurements of urea concentrations in spent dialysate in collaboration with the Department of Nephrology at Rigshospitalet in Copenhagen.

1. Peter Snoer Jensen, Jimmy Bak and Stefan Andersson-Engels, "The Influence of Temperature on Water and Aqueous Glucose Absorption Spectra in the Near- and Mid-Infrared Regions at Physiologically Relevant Temperatures," *Appl. Spectrosc.*, **57**, 1, pp. 28-36 (2003).
2. Peter Snoer Jensen and Jimmy Bak, "Near- Infrared Transmission Spectroscopy of Aqueous Solutions: The Influence of Optical Pathlength on Signal-To-Noise Ratio," *Appl. Spectrosc.*, **56**, 12, pp. 1600-1606 (2002).
3. Peter Snoer Jensen and Jimmy Bak, "Measurements of Urea and Glucose in Aqueous Solutions with Dual-Beam Near-Infrared Fourier-Transform Spectroscopy," *Appl. Spectrosc.*, 56, 12, pp. 1593-1599 (2002).

3.4.3 Quantitative measurements of urea in dialysate liquids with FT-NIR/IR

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In cooperation with the Department of Nephrology at Rigshospitalet in Copenhagen, Risø has initiated a project in which infrared spectroscopic techniques will be tested for potential use in on-line measurements of urea in spent dialysate liquid during a haemodialysis treatment. Preliminary investigations have shown that urea in the relevant range of concentrations can be quantified in the dialysate liquid with FT-NIR/IR. The next step is to test the experimental set-up and the quantitative methods for on-line determination of urea during treatment of a patient.

Figure 37. On-line measurements of urea during hemodialysis.

The main objective of the project is to investigate the potential of an on-line monitor of urea. If such a monitor can be developed and implemented, it will be possible to check the quality of each separate treatment. This should be compared with the situation today where the treatment is planned a couple of months ahead based on blood samples drawn from the patient. In addition, the on-line monitor can be used as research tool for medical investigations during haemodialysis treatment.

The project is funded by Risø and private funds: Dir. Ib Henriksen's Foundation, Augustinus Foundation and The Pharmacy Foundation of 1991.

3.4.4 Minority effluent measurements of aircraft engine emissions by infrared laser spectrometry (MENELAS)

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The objective of the EU-funded project MENELAS initiated in 2002 and scheduled for 2005 is to improve the environmental friendliness with respect to low pollutant emissions from aircraft engines and combustors. In the project new laser spectroscopic techniques for quantitative gas analysis will be developed. The lasers can be tuned in the mid-infrared spectral region where pollutant gases absorb infrared light. The laser systems developed in MENELAS will be calibrated and validated for several key important gases such as CH_4, NO_2, CO and CO_2. In this project Risø provides a heated gas cell for calibration and validation of the three mid-infrared laser systems developed in the project; the gas cell is part of the hot gas cell test facility developed and used in the earlier AEROPROFILE project, see Figure 38. The other partners in the project are ONERA (F), DLR (D), Norsk Elektrooptik (N), Technical University Clausthal (D), SNECMA (F) and NLR (NL). It is planned that the research partners will bring their experiment to Risø for calibration and research.

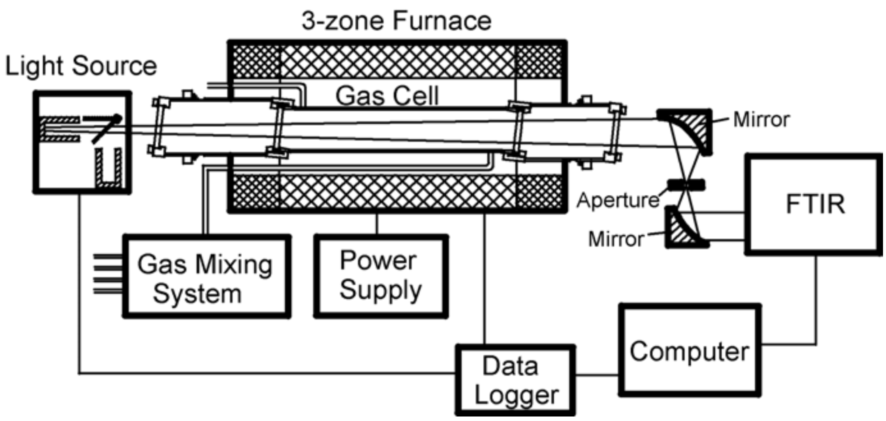

Figure 38. The hot gas test facility at Risø.

3.4.5 Infrared temperature calibration and related projects

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A reference laboratory for calibration of infrared instruments was established at Risø National Laboratory in 1996. Traceable calibration of infrared thermometers and blackbodies is offered in the temperature range -50^{0}C to 1600^{0}C. In 2001 the laboratory was approved by the Danish Accreditation Scheme, DANAK, to issue certificates for calibration of non-contact temperature-measuring equipment.

The work affects the following seven main topics to reduce uncertainties of non-contact temperature measurements:

- Calibration service of infrared thermometers for customers
- Temperature measurements for customers
- Development of new and improved methods for infrared temperature measurements
- Measurement of spectral emissivity of samples and coatings
- Consultative service and information
- International comparisons of standards and procedures
- Design and construction of special blackbody sources for customers

Risø National Laboratory was evaluated and given status as national reference laboratory for non-contact temperature measurements in 2002. The nomination was given by the Agency for Enterprise and Housing based on an evaluation led by the Danish Institute of Fundamental Metrology. As a national reference laboratory Risø shall:

- disseminate traceable non-contact temperature measurements with the lowest uncertainty in Denmark under the accreditation of DANAK
- participate actively in national and international collaboration, and carry out research and report in the literature and at conferences
- maintain a broad knowledge of the field, and communicate it to relevant institutions and users
- contribute significantly to the evolution of temperature metrology in Denmark.

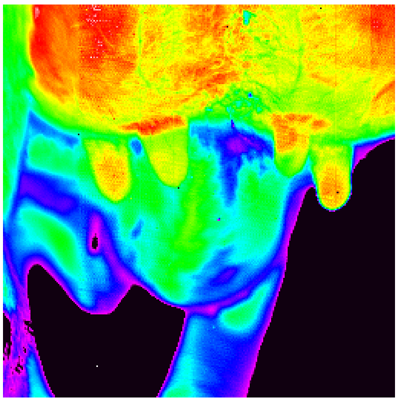

Figure 39. Infrared picture of cow udder taken between hind legs with Risø's infrared camera. Right rear quarters were milked with a soft experimental liner and left rear quarters with a standard liner, see reference list for further details. Infrared thermography was used to monitor indirectly the influence of liner type and over-milking on teat tissue recovery in co-operation with the Danish Institute of Agricultural Sciences, Research Centre Foulum.

In the short term the nomination will strengthen Risø's contact to international project partners in the field, and in the long term it will improve measurement capabilities. The nomination is an important highlight and points out the importance and quality of the work carried out by the temperature laboratory at Risø National Laboratory.

With the combination of high-accuracy traceable blackbody sources and spectral measurements of infrared radiation with FTIR spectrometer, Risø has state-of-the-art calibration capabilities in the spectral range 1 – 25 μm. A powerful method has been developed for the measurement of spectral emissivity of samples, objects and blackbodies by an FTIR spectrometer. Further details about the basic principles can be found in the Refs. 1-3. The technique has been used for full spectral radiation and emissivity measurements for a number of customers in 2002.

Risø participates in the NORDTEST project "Blackbody radiators for calibration of wide-looking IR-thermometers" with national measurement institutes in Sweden, Norway and Finland. The project continues in 2003.

Risø is involved in the EU project "EVITHERM" that will start up in 2003 with participants of laboratories from most of Europe. The overall objective of the project is to form a European virtual institute in thermal metrology.

1. Clausen, S., Measurement of spectral emissivity by a FTIR spectrometer. In: Proceedings. Vol. 1. 8. International symposium on temperature and thermal measurements in industry and science (TEMPMEKO 2001), Berlin (DE), 19-21 Jun 2001. Fellmuth, B.; Seidel, J.; Scholz, G. (eds.), (VDE Verlag, Berlin, 2002) p. 259-264.

2. Ham, E.W.M. van der; Battuello, M.; Bloembergen, P.; Bosma, R.; Clausen, S.; Enouf, O.; Filipe, E.; Fischer, J.; Gutschwager, B.; Hirvonen, T.; Holtoug, J.U.; Ivarsson, J.; Machin, G.; McEvoy, H.; Pérez, J.; Ricolfi, T.; Ridoux, P.; Sadli, M.; Schmidt, V.; Staniewicz, C.; Struss, O.; Weckström, T., Intercomparison of local temperature scales with transfer radiation thermometers between -50 deg. C and 800 deg. C. In: Proceedings. Vol. 2. 8. International symposium on temperature and thermal measurements in industry and science (TEMPMEKO 2001), Berlin (DE), 19-21 Jun 2001. Fellmuth, B.; Seidel, J.; Scholz, G. (eds.), (VDE Verlag, Berlin, 2002) p. 831-838.

3. Paulrud, C.O.; Clausen, S.; Andersen, P.E.; Bjerring, M.; Rasmussen, M.D., Infrared thermography to evaluate milking induced alterations in teat tissue fluid circulation. 2002 ADSA-ASAS-CSAS Joint annual meeting, Québec (CA), 21-25 Jul 2002. *J. Dairy Sci.* (2002) **85** (no.Supp. 1) , 84.

3.4.6 Calibration of temperature measuring equipment

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For more than 40 years the Thermometry Laboratory has calibrated temperature-measuring equipment. The Thermometry Laboratory was accredited in 1978 and has been approved by the Danish Accreditation Scheme, DANAK, to issue certificates for calibration of temperature-measuring equipment.

The instruments in the laboratory are traceable to international standards. The reference thermometers are regularly calibrated at National Physical Laboratory in London (NPL) to secure accordance with the international temperature scale, ITS-90.

The range is now the largest for any Danish accredited laboratory. The range is from -196 ^{o}C to 1600 ^{o}C. The scope of accreditation and measuring capacity can be seen in the figure below. The temperatures are achieved in a set of thermostats depending on temperature as shown in Figure 40.

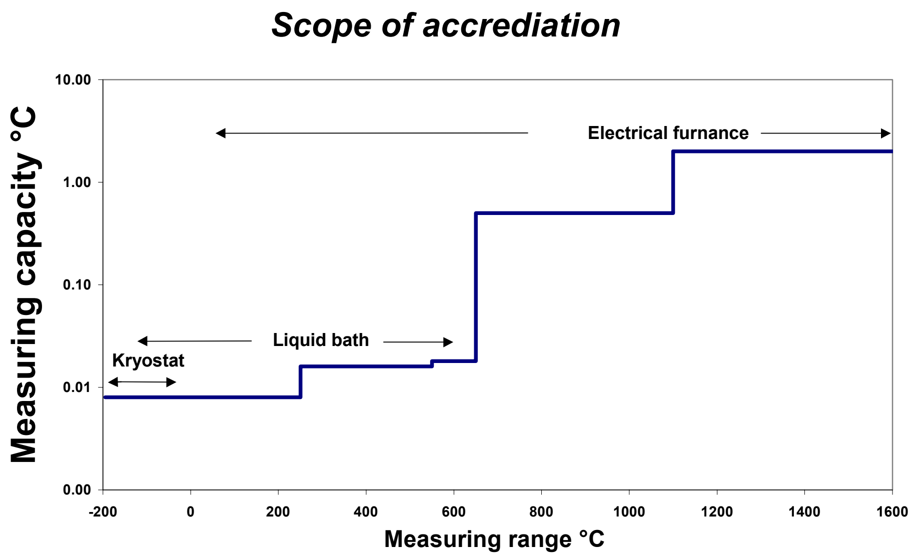

Figure 40. Scope of accreditation and measuring capacity.

3.4.7 Calibration of voltage, resistance current and pressure measuring equipment

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In connection with temperature measurements it was found necessary to perform measurements of voltage, resistance and current. For that reason these parameters have been accredited in a smaller area (Scope of accreditation and measuring capacity). In measurements at autoclaves it has also been found advantageous to measure pressure; therefore this parameter has been accredited in the range from 0 to 4 BarA.

3.4.8 Process measurement

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The Thermometry Laboratory performs accredited "in situ" measurements, especially with respect to demanding temperature measurements in all kinds of process plants such as medical sterilisation, large power plants and incinerators. This service includes process measurements and visualisation with advanced measuring techniques developed by the research activities and not generally available.

For further information and quotations, please contact Mogens Kirkegaard, Finn Eliasen or Finn Andersen. For further information on infrared temperature, please contact Sønnik Clausen.

3.5 Optical measurement techniques

3.5.1 Miniaturizing of optical sensors

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As a part of the Centre for Miniaturizing of Optical Sensors (MINOS) (http://www.sensortec.dk/stc.htm), we have been investigating the potential of using miniature and low-cost light sources for the next generation of optical sensors. The need for sensors and particularly for non-contact optical sensors is increasing rapidly these years as conditional monitoring in more traditional manufacturing processes becomes important and, further, as the end products themselves are expected by the consumers to be more intelligent and automated. Thus, low-cost, miniaturization and high reliability are necessary demands for future sensor technology. Within the MINOS project the concept of micro-optical sensor systems is studied, including miniature light sources, detectors, diffractive gratings, refractive miniature structures and their replication in plastic, as well as technologies for packing these micro-optical components.

This year the main achievements have been the development and testing of three different miniaturized optical sensor concepts for non-intrusive measurements of surface velocity and fluid flow velocity. These concepts are based on non-expensive laser sources, such as edge emitting lasers (EELs) and vertical cavity emitting lasers (VCSELs), and diffractive and refractive micro optics that can be replicated in, e.g., polymers. For the same reasons, the sensor designs must passively compensate for the influence of environmental effects such as, e.g., the temperature dependency on the emitted wavelength from a laser diode. Three corresponding patents will be filed around these sensor concepts.

One of the sensors is a multiple-beam time-of-flight system for measuring velocity of a fluid flow or a non-specular surface. The sensor is based on a VCSEL array. The near field of the emission from the VCSEL array is imaged onto the measurement volume, in order to form a linear array of either spots or parallel light sheets.[1] The set-up is illustrated in Figure 41. The characteristic features of this sensor are medium optical power velocimetry, a high degree of compactness and robustness, low-cost and temperature influence mostly due to thermal expansion of the VCSEL array (thermal expansion coefficient of the order of 10^{-6}). The sensor has been tested at characterising the degree of turbulence versus the Reynolds number in a water-pipe flow.[2] Further, characterisation of the sensor has been carried out on surface translations.

Moreover, theoretical work has been carried out and published on partially developed speckles statistics and optical speckle formation from fractal structures, described separately.

1. Hanson, S.G.; Jakobsen, M.L.; Kitchen, S.R.; Osten, S., Compact optically based systems for linear and angular displacement sensing. In: Proceedings. Part 2. 7. International symposium on laser metrology applied to science, industry, and everyday life, Novosibirsk (RU), 9-13 Sep 2002. Chugui, Y.V.; Bagayev, S.N.; Weckenmann, A.; Osanna, P.H. (eds.), (The International Society for Optical Engineering, Bellingham, WA, 2002) (SPIE Proceedings Series, 4900) p. 863-872.

2. Jakobsen, M.L.; Osten. S.; Kitchen, S.R.; Dam-Hansen, C; Hanson, S.G., "Multiple beam time of flight sensor based on a VCSEL array." *Accepted for publication in* Measurement Science and Technology, July 2002.

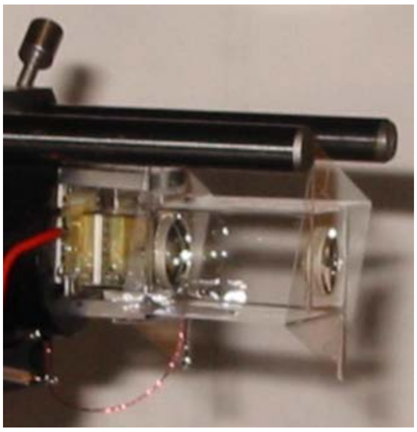

Figure 41. Miniaturised velocity sensor for flow and surface applications.

3.5.2 CO_2 laser anemometer for performance testing of wind turbines

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The objective of the project is to improve the market position of wind power by enhancing the credibility by more accurate performance assessment of wind turbines.

A laser anemometer to measure wind velocity in front of a wind turbine has been built by staff members of the Optics and Fluid Dynamics Department. Instead of using a cup anemometer mounted on a tower, a laser anemometer is found to constitute a more flexible instrument for performing measurements of the wind velocity in front of the wind turbines.[1] The laser anemometer is intended to be mounted on top of the nacelle and will focus a single laser beam in front of the wind turbine. The velocity of the wind is determined by measuring the introduced Doppler shift of the laser light, scattered backwards from the airborne aerosols in the focused laser beam. The measurement should be done so far upstream that the measured wind is unobstructed by the turbine.

The instrument is based on a CO_2 laser with an invisible optical wavelength of 10.6 μm. The laser is a sealed waveguide laser, and has been specially designed for the laser anemometer in cooperation with Ferranti Photonics, Scotland.

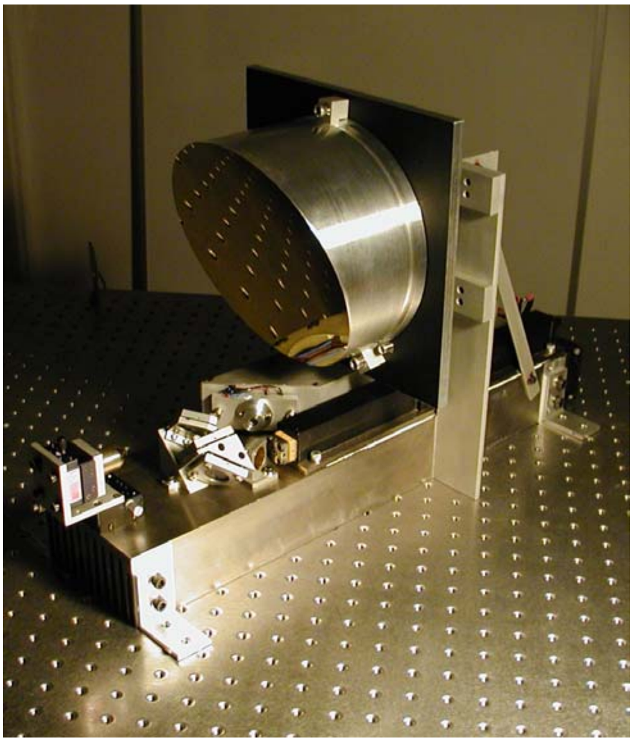

Figure 42. The optical assembly of the laser anemometer. The long black rod is the waveguide laser. The unit with the cooled detector and the low-noise amplifiers is seen mounted on the rear side of the laser heat sink underneath the large telescope mirror.

Figure 43. The final demonstration instrument mounted on a test platform on a mast in front of the large wind turbine on the Risø test site. The anemometer measures the wind velocity coming from Roskilde Fjord. The whole laser instrument is controlled from and transmits the measurements through the Internet.

Figure 44. The laser beam was focused nearby a conventional cup anemometer for comparison during measurements.

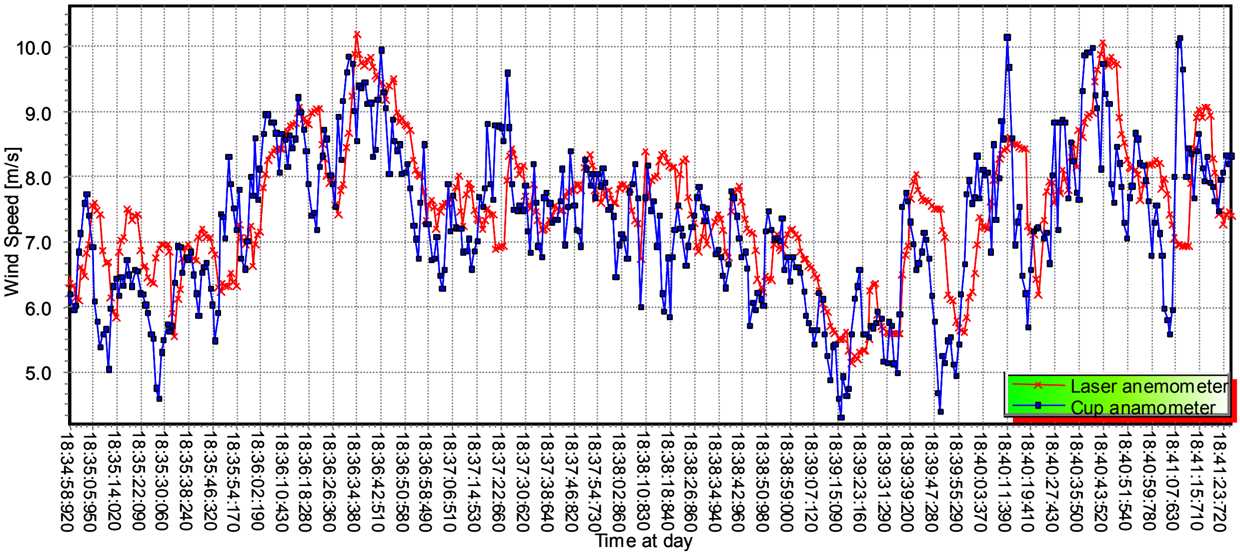

Figure 45. Comparison between the wind velocities measured by the cup anemometer (squares) and by the laser anemometer (crosses). These measurements were taken in snowy weather on 20 February 2002.

Drop-out of data has been observed in the measurement series. This drop-out is due to stabilisation problems for the CO_2 laser. Often when the laser is stabilized, the laser condition is determined by vibrating one of the cavity mirrors slightly. However, in the measurement scheme chosen for building the compact anemometer, this stabilisation scheme will cause a considerable spread of the Doppler signal spectrum thereby preventing the detection of the signal. Work on a new stabilization technique is in progress.

The research is funded in part by the European Commission in the framework of the Non-Nuclear Energy Programme JOULE III contract JOR3-CT-98-0256 and by Risø National Laboratory.[2,3,4]

1. Skov Hansen, R., and Miller, G., A laser anemometer for control and performance measurements on wind turbines, 11th Coherent Laser Radar Conference, Malvern, Worcestershire, UK, 1-6th July 2001.

2. Skov Hansen, R.; Frandsen, S.; Kristensen, L.; Miller, G.; Kjaer Hansen, J.; Sangill, O.; Lading, P., Laser Anemometry for Control and Performance Measurements on Wind Turbines, EC meeting: Wind Energy Research Projects Contractors' Meeting 2000: "*Advances in Wind Energy RTD – From FP4 towards FP5"*. 3-5 May 2000, at the National Technical University of Athens

3. Hansen, R. S.; Frandsen, S.; Kristensen, L.; Sangill, O.; Lading, P.; Miller, G., "Laser anemometry for control and performance measurements on wind turbines. Publishable final report 01.07.98 to 29.09.01, 26 pp", (2001).

4. Hansen, R. S.; Frandsen, S.; Kristensen, L.; Sangill, O.; Lading, P.; Miller, G., "Laser anemometry for control and performance measurements on wind turbines. Final report 01.07.98 to 29.09.01, 86 pp", (2001)

3.5.3 Signal processing for a CO_2 laser anemometer

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A laser anemometer to measure wind velocities in front of a wind turbine has been built by the Optics and Fluid Dynamics Department. The wind speed is determined from the Doppler shift induced on the light scattered off the airborne aerosols in the focal region of the laser beam. The scattering coefficient of the aerosols is approximately $\Gamma \approx 10^{-11}$ (corresponding to a backscattering coefficient of approximately $\beta = 1*10^{-6}\ m^{-1}sr^{-1}$) for the wavelength of the employed CO_2 laser ($\lambda = 10.59\ \mu m$). The resulting signal-to-noise ratio of the amplified detector signal lies in the range from -6 to -10 dB. The Doppler frequency thus cannot be determined directly from the detector signal and some pre-processing has to be performed. Furthermore, the back-scattered signal appears as signal burst distributed randomly in time. The objective of this ongoing project is to design a signal processor that can (1) detect the arrival of a signal burst, (2) sample the burst and (3) transfer the acquired burst signal to a computer that can subsequently determine the frequency of the burst signal.

The sensitivity of the instrument that enables remote measurements of the wind velocity is obtained by means of comprehensive digital signal processing of the detector signal. Various tests have been performed by implementing different signal processing schemes in a computer. An optimal signal processor has been found to be real-time processing of the detector signal.

The signal processing is a fast Fourier transform (FFT) followed by time averaging of the measured frequency spectrum.

3.5.4 Common-path interferometers with Fourier plane filters for measuring various types of surface deflections

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The concept of an impulse response function (IRF) for interferometers and especially for common-path interferometers has been introduced as a tool for depicting fringe appearance in electronic speckle pattern interferometry (ESPI) systems based on the shearing effect.[1,2] The IRF relates the measured phase change at an arbitrary position in the detector plane with a displacement in the object plane.[3] Thus the IRF depicts the function of a specific filter placed in the Fourier plane of the common-path interferometer. A suite of filters has been introduced to show the specific way in which the filter will control the fringe interpretation.

The use of shearing as an effective and robust way of performing interferometry, being it electronically (ESPI) or photographically recorded, is well known. Real-time measurement of out-of-plane bending of solid surfaces can consequently be obtained, and the correlation fringes can be observed on a monitor. The advantages of using shearing methods are numerous; the optical system being based on a common path scheme means that the requirement as to the coherence length of the laser is generally limited to the depth of the object. Furthermore, any whole-body movement of the object does not give rise to fringes, but will eventually cause speckle decorrelation and, as a result, loss of fringe contrast. In case the shearing element is based on a grating in the form of a holographic optical element, the calibration is moreover independent of the wavelength.

Using the shearing concept brings about one more advantage; the number of fringes for a given displacement is usually reduced compared with an ordinary interferometry system with a local reference beam. Therefore, larger deformations may usually be probed before the fringe spacing approaches the resolution of the camera, thus limiting the maximum measurable displacement. This robustness is achieved at the expense that the resolution may be reduced and that reconstruction of the out-of-plane displacement of the object calls for subsequent integration of the unwrapped phase map.

In order to bring this concept a step further and produce fringes that depict the curvature instead of the displacement itself (ESPI) and the first derivative of the displacement (shearing concept), a couple of set-ups have been proposed. An optical shearing set-up with three illuminating beams that could be switched on individually has previously been proposed. Subsequent electronic processing of the recordings facilitated the desired measurement. Other systems have used photographic recording followed by spatial filtering of the processed imagery. A recent article has shown a method with which one of the drawbacks of electronic differentiation of shearing images can be overcome. Subtraction of two fringe patterns will reveal the difference fringe pattern, well known as a Moiré pattern. Unfortunately, the two underlying high-frequency fringe patterns will persist. By using a priori knowledge about the spatial frequencies, a dedicated spatial filtering technique may eliminate the basic fringes, while preserving the difference fringes.

The present work has had a twofold objective. First, we have introduced the IRF with the purpose of being able partly to predict the effect of inserting a given filter function in the Fourier plane of a common-path interferometer, and partly with the aim of being able to design Fourier plane filters with desired performance. A set of filters has been envisaged with special emphasis on a filter for direct presentation of fringes that depict the second derivative of the out-of-plane displacement in a given direction. The previous systems all relied on a backscattering configuration, whereby only out-of-plane displacements could be probed. In case an arbitrary angle of incidence of the illuminating beams is used, or a fringe pattern is projected onto the target, arbitrary direction of object displacement can be investigated.

Figure 46 shows the generic optical system that has been considered theoretically. The effect of the filter is to divide the incident field into two contributions: An undiffracted field passing the filter without any change and a diffracted field with a desired complex amplitude change in the Fourier plane. The IRF, $\Omega\left(\mathbf{r_0},\mathbf{p_0}\right)$, is consequently found as a relative change in the detector plane given an infinitesimal change of phase of the scattered light (i.e. a physical displacement of the object) between the two recordings: $\Omega\left(\mathbf{r_0},\mathbf{p_0}\right)\equiv\lim\left\{\frac{\Delta\varphi_{out}}{A\Delta\varphi_{in}}\right\}_{for\ A\Delta\varphi_{in}\to 0}$.

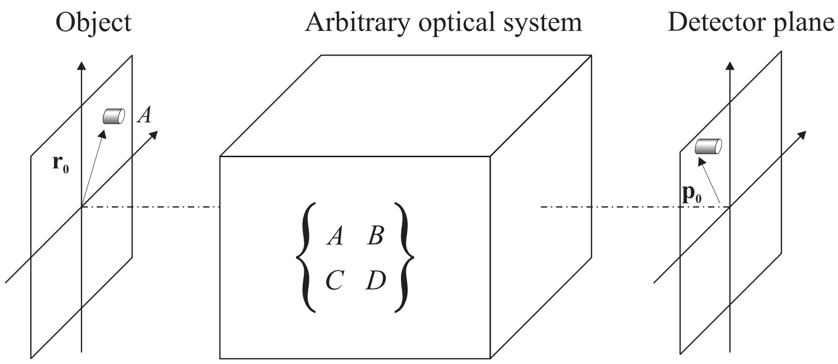

Figure 46. Illustration of the impulse response function. A piston-like deflection at $\boldsymbol{r_0}$ (phase change $\Delta\varphi_{in}$) over an area A in the object plane gives rise to phase change $\Delta\varphi_{out}$ in the detector plane at position $\boldsymbol{p_0}$.

An example of a Fourier plane filter facilitating a direct measurement of the change in curvature is shown in Figure 47. This type of filters may be expanded to measure the second derivative of an in-plane displacement provided that the scattering *k*-vector has an in-plane component.

1. Kitchen, S.R.; Hanson, S.G.; Hansen, R.S., Fourier plane filters and common path interferometry in vibrometers and electronic speckle interferometers. In: Optical engineering for sensing and nanotechnology. 2001 International conference on optical engineering for sensing and nanotechnology (ICOSN 2001), Yokohama (JP), 6-8 Jun 2001. Iwata, K. (ed.), (The International Society for Optical Engineering, Bellingham, WA, 2001) (SPIE Proceedings Series, 4416) p. 108-111.
2. Kitchen, S.R.; Hanson, S.G.; Hansen, R.S., Introduction of the impulse response function in common-path interferometers with Fourier plane filters. Opt. Rev. (2001) 8 , 378-381.
3. Hanson, S.G.; Kitchen, S.R.; Hansen, R.S., Impulse response function for common-path interferometers. In: Proceedings. 5. International conference on vibration measurements by laser techniques: Advances and applications, Ancona (IT), 18-21 Jun 2002. Tomasini, E.P. (ed.), (The International Society for Optical Engineering, Bellingham, WA, 2002) (SPIE Proceedings Series, 4827) p. 323-330.

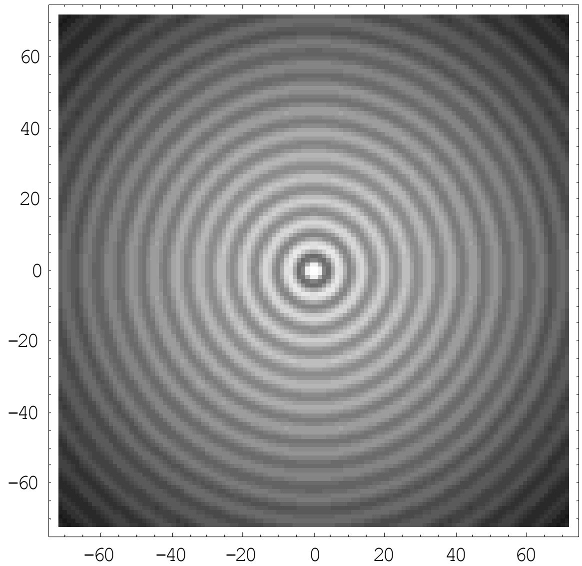

Figure 47. Functional dependence of the Fourier filter in the ***q***-plane probing the change in overall curvature of the object.

3.5.5 On the fractal description of rough surfaces

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A new feasibility has previously been considered for optical correlation diagnostics of rough surfaces with different distributions of irregularities. The influence of deviations of the height surface roughness distribution from a Gaussian probability distribution on the accuracy of optical analysis has been discussed.[1]

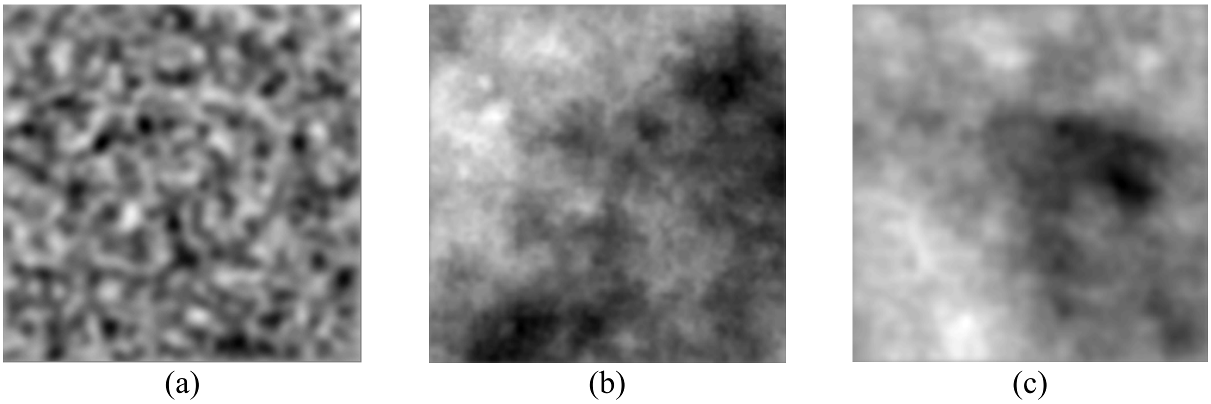


Figure 48. Simulated rough, random (a) and fractal (b), (c) surfaces smoothed following the normal law over three (a), (b) and five (c) pixels. Grey scale reflects the heights of the surface irregularities.

To provide further insight into the distinction between fractal and random surfaces, we now introduce the singular optics approach for classification of rough surfaces with large-scale inhomogeneities. The maps of amplitude zeroes of a field vs. the parameters of the rough surfaces and the position of the observation zone have been obtained and analyzed.[2,3] It is shown that the local density of amplitude zeroes in the scattered field serves as an appropriate parameter to classify the surface of interest into a surface with a height distribution that can be described as a random or a fractal process. Figure 48 shows grey scale imagery of rough and fractal surfaces produced artificially.

Valid information may be extracted from the amplitude of the field, its intensity and the accompanying phase as depicted in Figure 49.

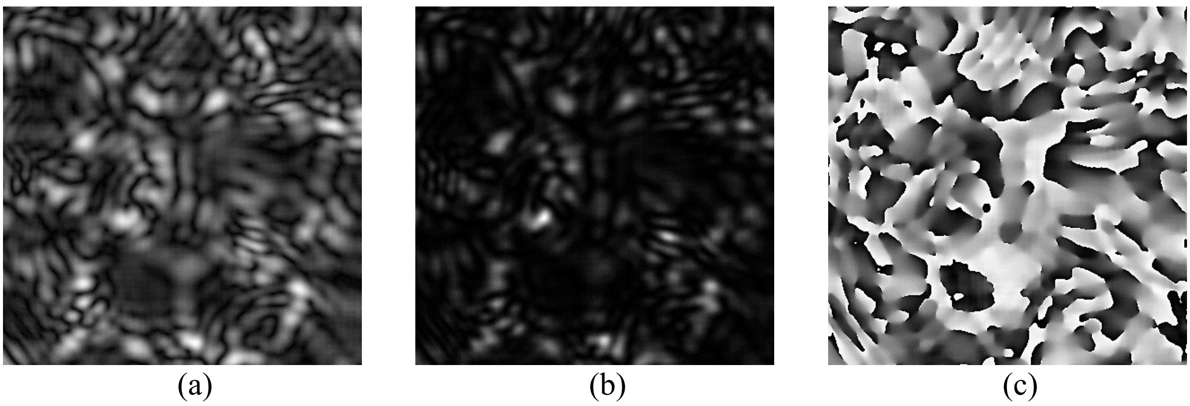
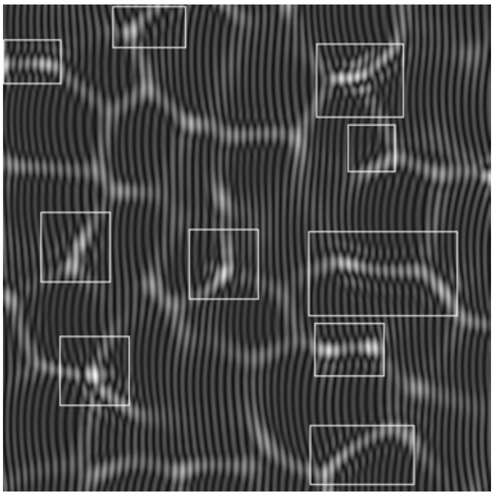


Figure 49. Distributions of the amplitude of the scattered field (a), its intensity (b) and phase (c).

If the phase is recorded by superimposing a reference wave, the behaviour of the phase about the amplitude zeroes will show bifurcations of varying topology, as shown in Figure 50.

It has been shown that the spatial distribution of amplitude zeroes of the field scattered by a rough surface, from the caustics zone to the far zone, reflects the irregularities of the surface of interest. The half-width of histograms of local density of amplitude zeroes estimated at various distances from a surface differs considerably from random and fractal surfaces. As a result, for fractal rough surfaces, amplitude zeroes are clustered in specific zones, and this fact is naturally explained by taking into account the statistical self-similarity of such structures.



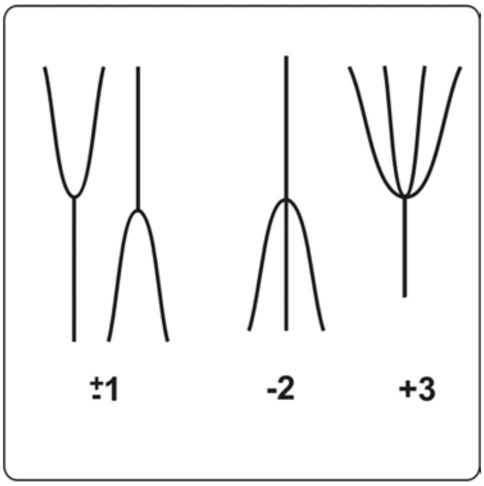


Figure 50. Interferogram of a field exhibiting phase singularities; the areas of most interest are indicated by squares to the left, while interference patterns corresponding to amplitude zeroes with various topological charges are depicted to the right.

1. Angelsky, O.V.; Maksimyak, P.P.; Ryukhtin, V.V.; Hanson, S.G., New feasibilities for characterizing rough surfaces by optical-correlation techniques. Appl. Opt. (2001) 40, 5693-5707.
2. Angelsky, O.V.; Burkovets, D.N.; Kovalchuk, A.V.; Hanson, S.G., Fractal description of rough surfaces. Appl. Opt. (2002) **41**, 4620-4629.
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3.5.6 A compact electronic speckle pattern interferometry system for displacement measurements of specular reflecting or optical rough surfaces

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A stable and compact speckle interferometer for performing out-of-plane displacement measurements on reflective as well as on diffusely scattering object surfaces has been demonstrated. The set-up is based on an almost path-length-compensated interferometer that uses diffuse illumination of the object combined with a speckled reference wave. This combination eliminates the need for special optical components, and the interferometer can be built of commonly available components. The diffuse illumination wave is obtained by scattering coherent light from a diffusely scattering surface. The speckled reference wave is established by reflecting a part of the diffuse illumination wave from a glass plate placed in front of the object. In addition to relaxing the alignment tolerances of the set-up, the diffuse illumination eliminates the need for any preparation of the surface under test, a fact that turns the system into a candidate for testing micromechanical systems. When we use the interferometer for measurements of the eye, the risk of focusing the laser beam on the retina is decreased due to the diffuse object illumination.[1]

Electronic speckle pattern interferometry, ESPI, is a very sensitive technique for measuring small mechanical displacements of a surface. The technique can be used for non-destructive testing of materials or whole units. A displacement of a small area of the object surface is measured from a corresponding phase shift of the coherent light, scattered off the corresponding area of the surface.

Figure 51 gives a schematic presentation of the optical set-up, and Figure 52 shows a measurement example. The deflection stems from a 2 μm deformation of a very thin steel membrane on a one-inch capacitor microphone, occurring when the bias voltage is applied.

1. Hansen, R.S., Simple and compact ESPI system for displacement measurements on specular reflecting or optical rough surfaces. In: Selected papers. 5. International conference on correlation optics, Chernivtsi (UA), 10-13 May 2001. Angelsky, O.V. (ed.), (The International Society for Optical Engineering, Bellingham, WA, 2002) (SPIE Proceedings Series, 4607) p. 178-183.

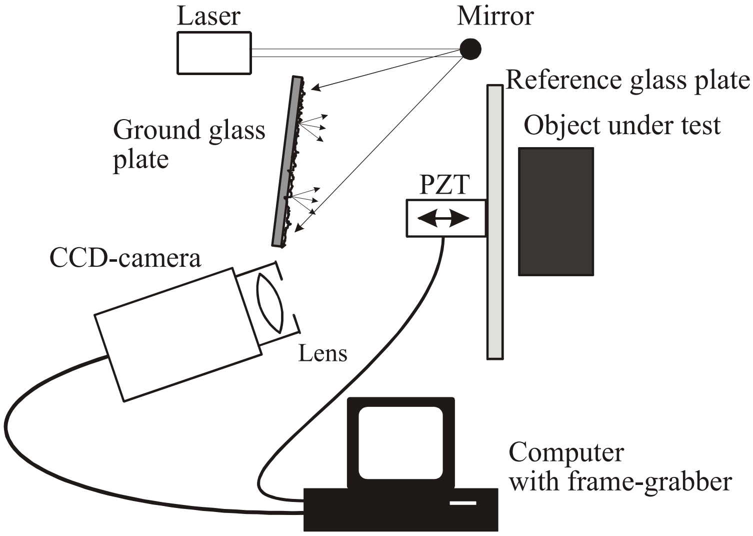

Figure 51. Schematic presentation of the optical set-up.

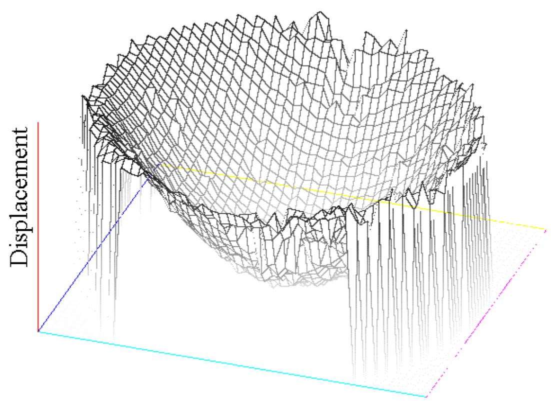

Figure 52. Measurement example.

4. Plasma and fluid dynamics

4.1 Introduction

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A unifying theme of the research performed in the Plasma and Fluid Dynamics programme is the dynamic behaviour of continuum systems. The continuum systems under investigation cover plasmas, fluids and solids. In the case of solids, the research is carried out in the fields of optics and acoustics as well as in their borderland, opto-acoutics. Both linear and non-linear problems are addressed in a combination of experimental, numerical and theoretical studies. Scientific computing in a broad sense plays a major part in these investigations and includes theoretical modelling of the physical phenomena, development of numerical algorithms, visualisation of the computed results and last, but not least, validation of the numerical results by detailed comparisons with experiments.

Due to the broad approach to the problems, the various projects are scientifically overlapping, not only inside the programme, but to a large extent also with projects in the rest of the department as well as in other departments at Risø. This overlap is considered an expression of strength since it gives rise to considerable synergy.

The goals of the scientific studies are two-fold: on the one hand the investigations aim at achieving a deeper understanding of the fundamental behaviour of complex physical and technical systems; on the other the acquired knowledge is sought utilised in the definition and design of solutions to specific technological problems. In the following three subsections, descriptions of the scientific projects carried out during 2002 have been collected under the headings: *fusion plasma physics*, *low temperature plasmas, fluid dynamics* and *optics and acoustics*.

4.2 Fusion plasma physics

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With steep gradients in plasma equilibrium parameters and with populations of energetic ions far from thermal equilibrium, fusion plasmas have considerable free energy. This energy drives turbulence, which in turn acts back on the equilibrium profiles and on the dynamics of the fast ions. The turbulence naturally gives rise to enhanced transport, but also sets up zonal flows that tear the turbulent structures apart and give rise to edge transport barriers; most likely at the root of the poorly understood, but experimentally reliably achieved high confinement mode (H-mode). This non-linear interplay between turbulence and equilibrium also supports transient events reminiscent of edge localized modes (ELMs) where energy and particles are ejected from the plasma edge in intermittent bursts.

This set of topics is the focus of our fusion plasma physics research: With first-principles based codes we seek to model the interplay between plasma turbulence, transport and equilibrium. This modelling is tested against experimental data in collaboration with other fusion plasma physics institutes. To elucidate the physics of fast ions and their interplay with turbulence, waves and transient events, we have engaged in a new activity; the diagnosis of confined fast ions by collective Thomson scattering (CTS) at the TEXTOR tokamak in Forschungszentrum Jülich, Germany, and at the ASDEX upgrade tokamak in the Max-Planck Institute for Plasma Physics in Garching, Germany.

Our aim is not only to understand the dynamics, but also to identify external actuators with which the turbulence and transport can be controlled. The first demonstrations of edge turbulence control with arrays of electrostatic probes have been made in a linear device in collaboration with other associations. Selective ejection of core fast ions by sawteeth, which in turn can be manipulated by a localized heating and current drive, was found in fast ion CTS data obtained at TEXTOR in collaboration with TEC[1] and MIT, USA.

Our fusion plasma physics research programme provides fruitful collaborative projects with other academic groups working in non-linear science. A sign of the strength of these collaborative projects is that a member of our team heads the Research School in Nonlinear Science in Denmark.

1. TEC: the Trilateral Euregio Cluster, a collaboration of FOM Institute for Plasma Physics, Holland; ERM/KMS, Belgium and Forschungszentrum Jülich, Germany.

4.2.1 Investigations on turbulence at the transition from edge to scrape-off layer

S. V. Annibaldi, F. Porcelli* (*Instituto Nazionale Fisica della Materia Torino, Italy),*
V. Naulin and J. Juul Rasmussen
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Classical plasma turbulence and transport investigations usually deal with either closed magnetic field lines (edge) or open magnetic field lines that exclusively end on material interfaces (scrape-off Layer, SOL). Here we investigate the transition from closed to open field lines in a minimal model of the development of the plasma turbulence.

From the centre of the plasma the density decays to very low values at the material walls. The traditional approach to separate the turbulence into small perturbations and a background, determined by some equilibrium, is thus not feasible. Therefore the plasma dynamics has to be described by global dynamical equations taking into account variations in the magnetic field strength and variation of parameters such as collision frequencies. Moreover, the simulations have to cover the long transport timescale and still resolve the timescale of the turbulence, which demands good computational resources. Investigations on test-particle transport in this kind of turbulence have been planned and will also address the problem of inward transport of impurities.

Preliminary results show the evolution of a self-consistent density profile as depicted in Figure 53. The drop of density and fluctuation level in the SOL is due to plasma streaming to the limiter plates. The development of a presheath-like potential structure is visible. The transport in these systems is extremely bursty and the development of localized structures in the SOL, as already observable in a reduced 2D model (see 4.2.2) will be investigated in the future.

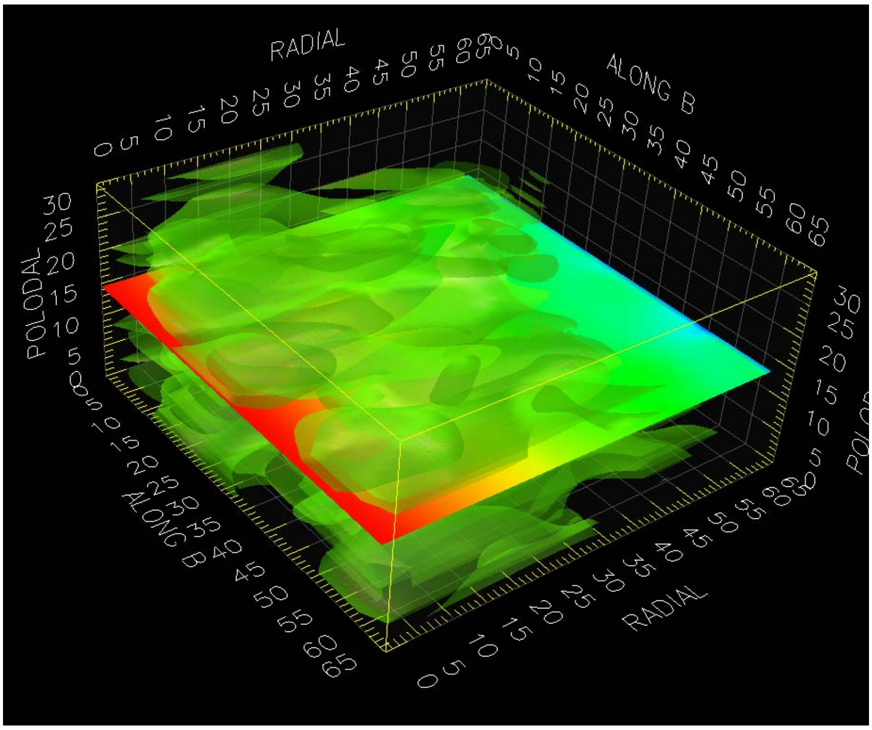

Figure 53. 3D visualisation of density fluctuations. The amplitude of the fluctuations stays relatively constant until the SOL, where they vanish. The plane shows a colour-code of the density, falling off towards the SOL. You should keep in mind that the length along the magnetic field is reduced by a factor of hundred. A high correlation of the fluctuations along the magnetic field is obvious.

4.2.2 Transport barriers and blobs in flute mode turbulence

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We have investigated the evolution and dynamics of transport barriers in the form of zonal flows in a self-consistent model of pressure-driven electrostatic turbulence of a plasma in an inhomogeneous magnetic field. This is a simplified model of the outboard side of a toroidal confinement device. It captures the effects of unfavourable curvatures in an energy-preserving manner and describes the evolution of profiles as well as fluctuations.[1]

The model is solved numerically on a two-dimensional domain bounded in the radial direction and is periodic in the poloidal direction. The poloidal periodicity length is related to the safety factor. Near the inner wall in the radial direction we have included a constant source of density and temperature. In the outer part of the domain open magnetic field lines and, thus, a scrape-off Layer (SOL) are simulated by including local damping terms that model the losses of density, heat and charge to the limiter/divertor plates.

In Figure 54 we have depicted the evolution of the temperature field and we observe the formation of a blob of strong heat perturbation moving through the SOL. During the simulation temperature, density and vorticity pile up on the left-hand side of the domain, where the sources of density and heat are located. The radial gradients of these quantities are continuously increasing. At some point in time these gradients become unstable and the flow ejects a significant part of the plasma in the form of a concentrated blob into the SOL, where the plasma is lost. These blobs can propagate through the entire extent of the SOL and hit the outer wall that makes their properties and the statistics of the transport associated with them extremely relevant to fusion devices.

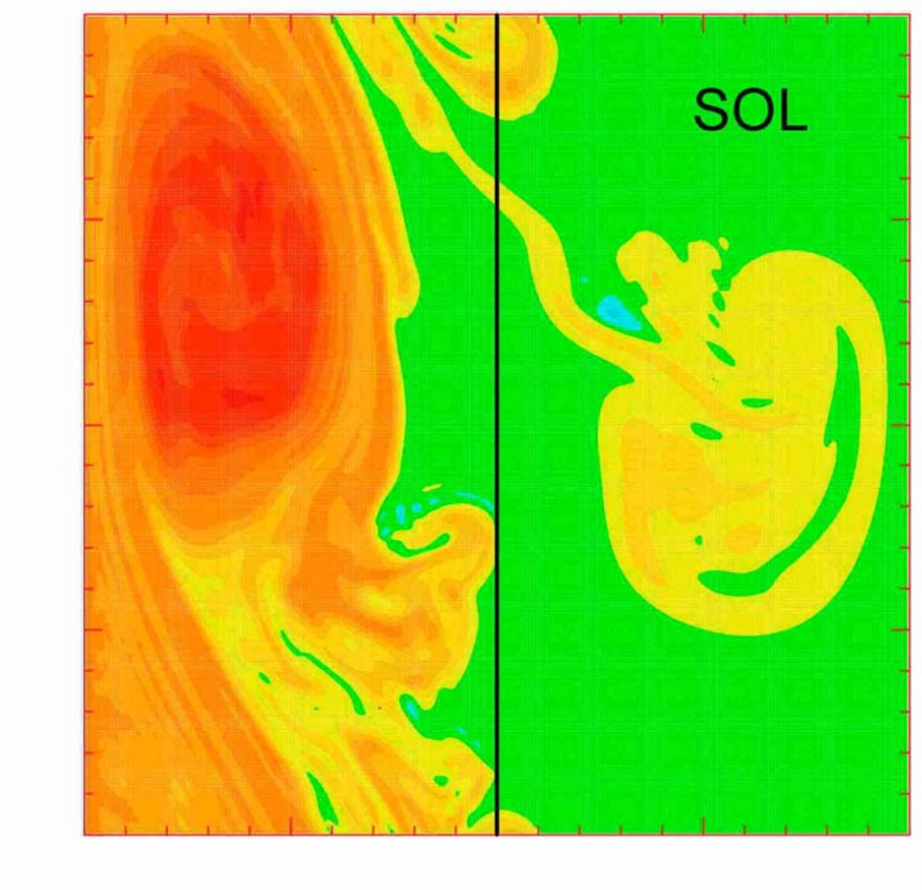

Figure 54. Temperature fluctuations during an eruption.

1. V. Naulin, J. Nycander and J. Juul Rasmussen, Phys. Rev. Lett. **81**, 4148 (1998).

4.2.3 Ballooning convection: transport modelling beyond slab geometry

O.E. Garcia (also at: Department of Physics, University of Tromsø, Norway), V. Naulin, A.H. Nielsen and J. Juul Rasmussen
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A new fluid model of low-frequency fluctuations and convective particle and heat transport in toroidally magnetized plasmas has been derived. It takes into account the full normal and geodesic curvatures of the equilibrium toroidal magnetic field. In the local limit it reduces to the classical model of two-dimensional Rayleigh-Bénard convection. The model readily predicts the experimentally observed ballooning structure of fluctuation amplitudes and radial transport - hence the proposed name. Moreover, due to geodesic curvature there is a new mechanism for generation of differential rotation that accompanies the well-known tilting instability by inhomogeneous Reynolds stresses. This leads to new dynamical modes termed geodesic oscillations.

Numerical simulations have demonstrated a rich variety of transport states. Close to the dissipative threshold we observe different modes of stationary convection. Further from the threshold different forms of geodesic oscillations are observed and, ultimately, a turbulent state ensues. In numerical simulations we have also for the first time observed a stationary state of suppressed non-linear transport corresponding to a high confinement regime. Figure 55 shows the spatial structure of the pressure, the electrostatic potential and the radial convective heat flux for the stationary high confinement regime, respectively. Note the presence of only closed streamlines that prevents strong non-linear heat transport to the confining outer boundary.

In the near future the model will be improved to conserve the true physical energy integral. This will then be implemented in cylinder coordinates to yield the first numerical solutions with this property which is essential for the prediction of transport suppression and confinement improvement by self-sustained sheared flows.

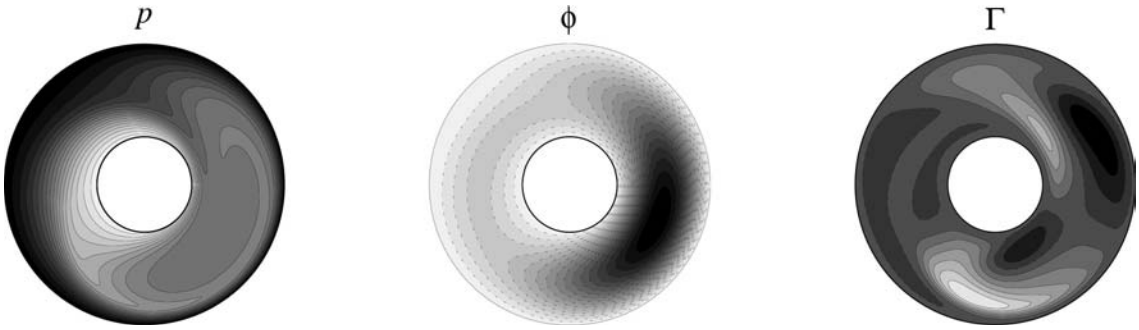

Figure 55. The distribution of pressure p, electrostatic potential φ and radial heat flux Γ in the annulus domain for the Rayleigh number R = 5.0 × 10^4. Note the presence of only closed streamlines in the potential φ.

4.2.4 Two-dimensional fluid equations for low-frequency convective modes in a plasma with full density variation

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V. Naulin, A.H. Nielsen and J. Juul Rasmussen
jens.juul.rasmussen@risoe.dk

Cross-field transport is one of the most important and difficult areas of fusion research. Recent experimental observations have revealed that the transport in the edge plasma involves large outbreaks of bursts of density and heat that has a significant effect on the profiles of density and temperature. It is thus obvious that a full description of the edge dynamics *must* include the evolution of the full profiles. A local model or a Boussinesq-like model, where the "background" profile is separated from the fluctuations, as it is standard in dynamical models, cannot describe the essential features.

We have attempted to derive a consistent set of equations describing the low-frequency 2D evolution in a slab geometry that models the outboard mid-plane of a toroidal device. The model, which is based on the fluid equations, governs the two-dimensional dynamics of the interchange convection modes. It describes the fluid drifts accurately in the presence of an inhomogeneous, curved magnetic field. In addition, it describes the adiabatic compression of a fluid parcel that is displaced into a region with a larger magnetic field. The full density (including profile) is allowed to evolve self-consistently under the influence of an external forcing, and so is the background potential profile, which corresponds to a mean flow. The model will be the basis for a numerical investigation of the dynamics of bursty transport events in the edge plasma.

4.2.5 3D Drift-Alfvén turbulence

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Turbulence in the edge of plasma fusion devices is one of the biggest challenges on the way towards building an efficient, well-controlled fusion power source. Using the TYR code we investigate the interaction between (a) shear flows created by the turbulence and (b) the transport. The TYR code includes the effects of curvature and shear in a geometry following a magnetic flux tube. In addition to the usual E×B fluctuating transport, the fluctuating magnetic field gives rise to radial transport of heat and matter as plasma flows along the perturbed magnetic field. One interesting consequence is that sheared flows can influence these transport components in quite different ways. While flow shear usually suppresses E×B flux, the shear flow is correlated with large current fluctuations. These fluctuations give rise to large magnetic perturbations and, thus, to increased levels of radial plasma transport due to magnetic field perturbations. While this contribution to the total transport is in general rather small, it can enhance the radial flux locally and as a result make the transport reduction due to shear flows less efficient. Large-scale simulations at high resolutions have been performed and they showed the detailed correlations between the fluxes (depicted in Figure 56 and Figure 57) and the correlations between flows and fluxes. The inclusion of temperature fluctuations is in progress.

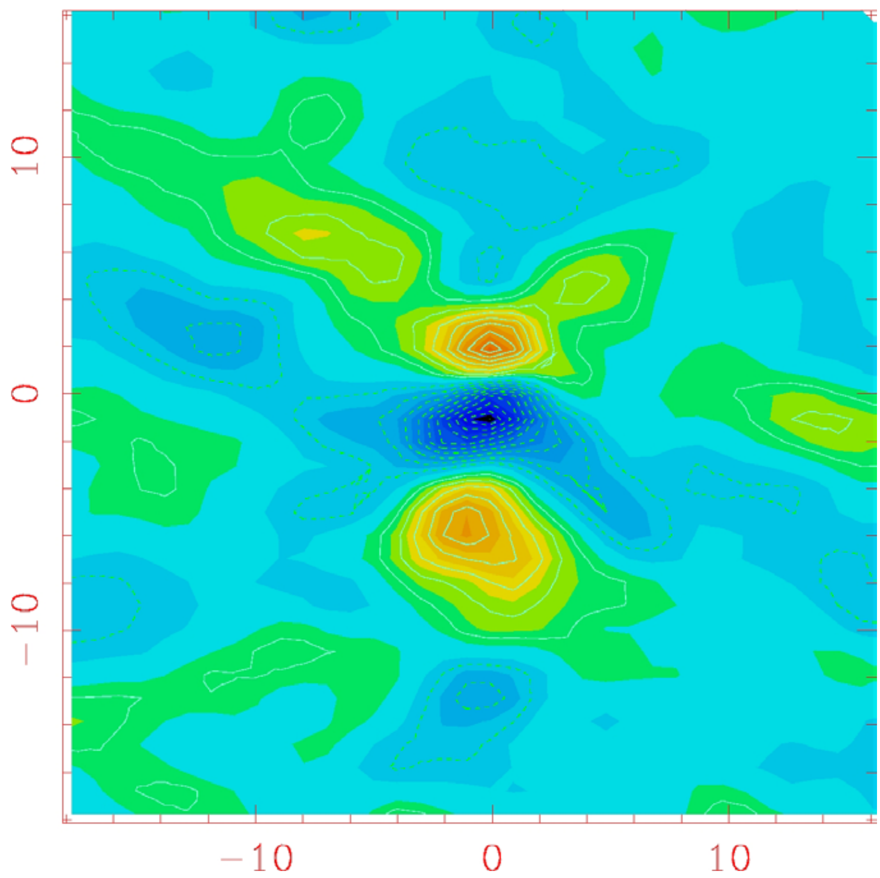

Figure 56. Spatial correlation (radially and poloidally) between ExB and electromagnetic flux, showing a well defined negative correlation for zero offset. Thus, the electromagnetic flux is large where the ExB flux is small.

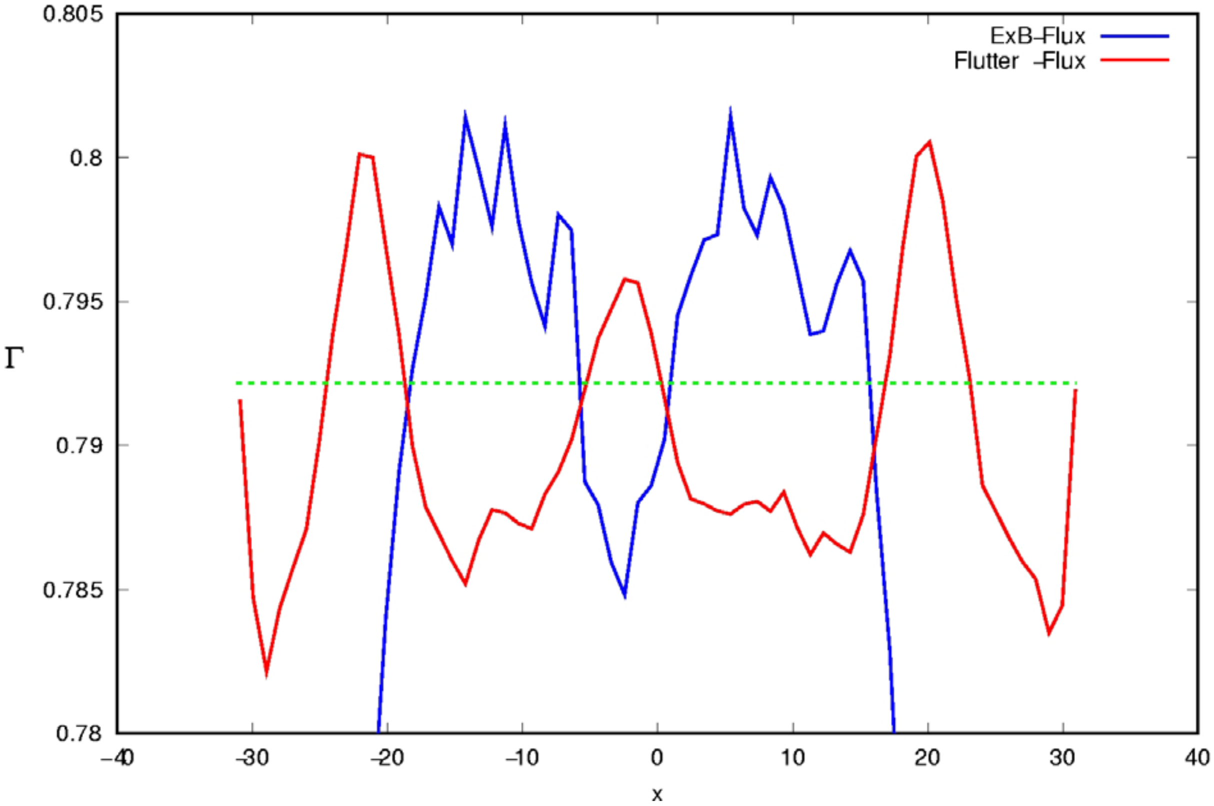

Figure 57. Radial profile of electromagnetic (flutter) flux and E×B transport, showing that both add up to a radially constant value.

4.2.6 Influence of neutrals on drift and drift Alfvén waves

O. Grulke, Th. Klinger*, Ch. Schroeder* (*IPP Greifswald, Germany) and V. Naulin*
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In the edge regions of plasmas the concentration of neutrals becomes rather large and the frequency at which the ions collide with the neutrals is no longer negligible. These collisions change the properties of the drift waves, the turbulence and, ultimately, the transport.

Experimental results on drift Alfvén waves indicate insufficient agreement with theoretical predictions that do not include these collisional effects. To be able to compare theory and experiment successfully they therefore have to be accounted for.

For this purpose an eigenmode solver was developed which can use experimental profiles and collision frequencies to calculate the eigenfrequencies and the mode profiles of drift waves. Initial results show that the collisions drastically reduce the wave frequencies. A typical plot of the mode structures for a Gaussian-like density and collision profile is shown in Figure 58.

The results of the linear analysis will be verified against experimental results and results from a full 3D model.

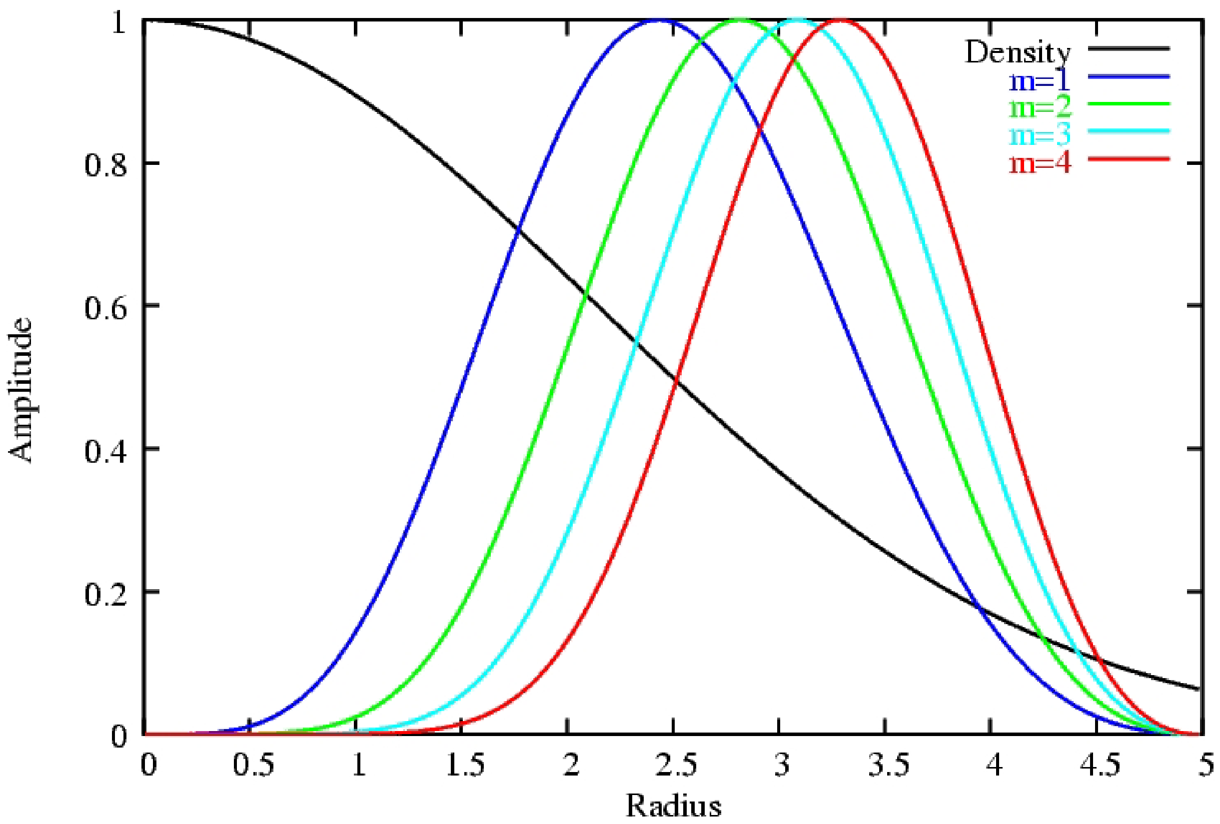

Figure 58: Radial mode structure for drift waves in a cylindrical plasma with radially varying collision frequencies.

4.2.7 Shear flow generation in 3D drift wave turbulence

S.B. Korsholm, V. Naulin, J. Juul Rasmussen and P.K. Michelsen
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Large-scale poloidal shear flows are expected to be generated spontaneously by drift wave turbulence in magnetized plasmas in toroidal devices. These flows may regulate the turbulence by suppressing the small-scale structures and set up transport barriers which can induce a transition from low (L-mode) to high (H-mode) confinement. We have investigated the generation of shear flows by drift wave turbulence using numerical solutions of the three-dimensional Hasegawa-Wakatani (HW) equations. The simulations are performed in a slab geometry periodic in y (poloidal direction) and z (toroidal direction) and bounded in the radial direction, x, by non-permeable walls. In this part of the work we have been particularly interested in investigating the cause of the shear flow generation. While it is clear that the Reynolds stress (Re) is responsible for generating the poloidal flow, it is not clear which modes contribute mostly to Re. The HW-model contains both the drift wave component with finite parallel wave number, k_z, and the flute mode (convective cell) component having $k_z = 0$. The drift modes are linearly unstable and grow until they reach a non-linear level, where they couple to the flute modes.

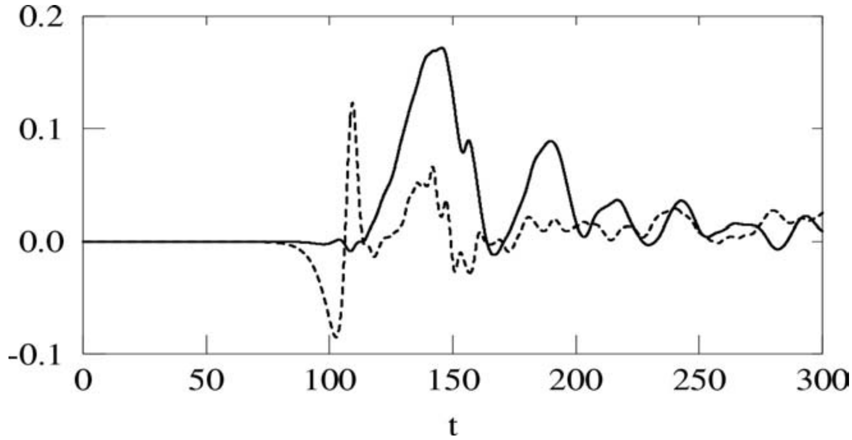

Figure 59. The temporal evolution of the contributions to the Reynolds stress from the flute mode (full line) and the drift mode (dashed line).

In Figure 59 we show the temporal evolution of the separate contributions to Re from the drift and the flute modes, respectively. We observe that initially Re is driven by the drift wave component, but when the poloidal flow (characterized by $k_y = k_z = 0$) has been established, the main contribution to Re originates from the flute modes. Ultimately, when the system has settled into a quiescent state, the two contributions become comparable and small. This implies that Re is in part driven by a non-linear instability, i.e. the flow is self-amplifying from the seed produced by the drift modes. These results emphasize the importance of considering both the direct contribution to Re by the drift modes and the contribution via the flute modes. The latter contribution is usually not accounted for in theoretical descriptions of the shear flow generation based on the simplified Hasegawa-Mima type models.

4.2.8 Modelling the formation of large-scale zonal flows in drift wave turbulence in a rotating fluid experiment

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The self-consistent generation of large-scale flows - zonal flows - by the rectification of small-scale turbulent fluctuations is of great importance both in geophysical flows and in magnetically confined plasmas. These flows can regulate the turbulence by suppressing the small-scale structures. Eventually the flows act to set up transport barriers. A relatively pedagogical description of the generation of zonal flows is provided by the idea of homogenisation of the so-called potential vorticity, which is a Lagrangian invariant of the flow, relying on the mixing properties of the turbulence.

We have modelled the generation of zonal flows by drift wave turbulence in a magnetized plasma by exploiting the analogy between Rossby wave dynamics on the β-plane and drift-wave dynamics in a magnetized plasma with a density gradient perpendicular to the magnetic field. Corresponding laboratory experiments in a rotating fluid were performed to investigate the formation of large-scale flows by mixing and homogenisation of the potential vorticity.

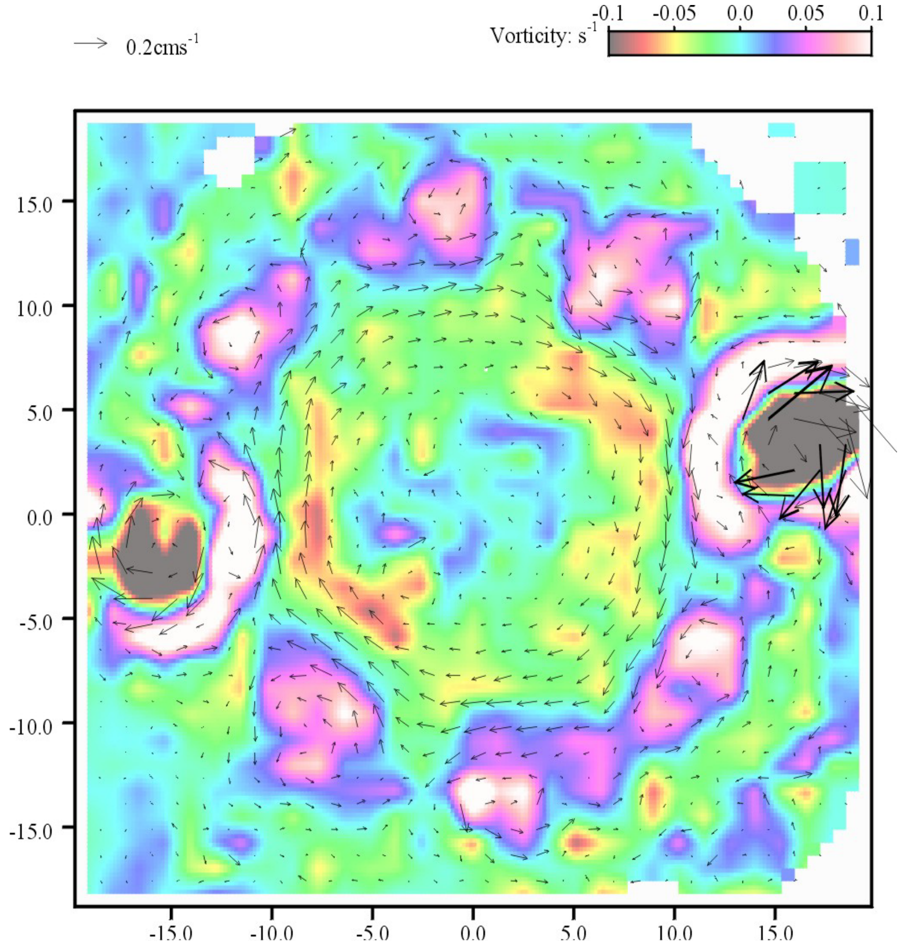

Figure 60. Velocity field shown by arrows and vorticity contours averaged over 10 forcing periods. The scales for the fields are indicated above the figure.

The experiments are conducted in a tank with radially symmetric bottom topography and a rigid lid. The bottom has a constant negative slope, β, in the radial direction. For this system the so-called potential vorticity $PV = \omega + \beta r$ is a Lagrangian conserved quantity. Here ω is the relative vorticity. Thus, it is readily seen that an effective mixing that homogenises PV will lead to replacing the high PV near the centre with low PV from the outside, and this will appear as an anticyclonic vortex over the centre. In the experiment the mixing is forced by periodical pumping near the outer boundary of the tank, and the azimuthally averaged forcing is zero. The velocity field is measured by particle tracking in the horizontal plane. After a transient time of several tens of forcing periods, we observe the formation of a zonal velocity in the anti-cyclonic direction. This is illustrated in Figure 60, where we show the velocity and the vorticity field obtained several tens of periods after the forcing was started. The fields have been averaged over 10 forcing periods. The zonal velocity peaks in the region away from the forcing regime, see Figure 61, which depicts the velocity field of Figure 60 averaged over the azimuthal direction to obtain the zonal velocity. These observations are in agreement with the discussion above. As a control case, we checked that no zonal flow appeared in the case of a flat bottom.

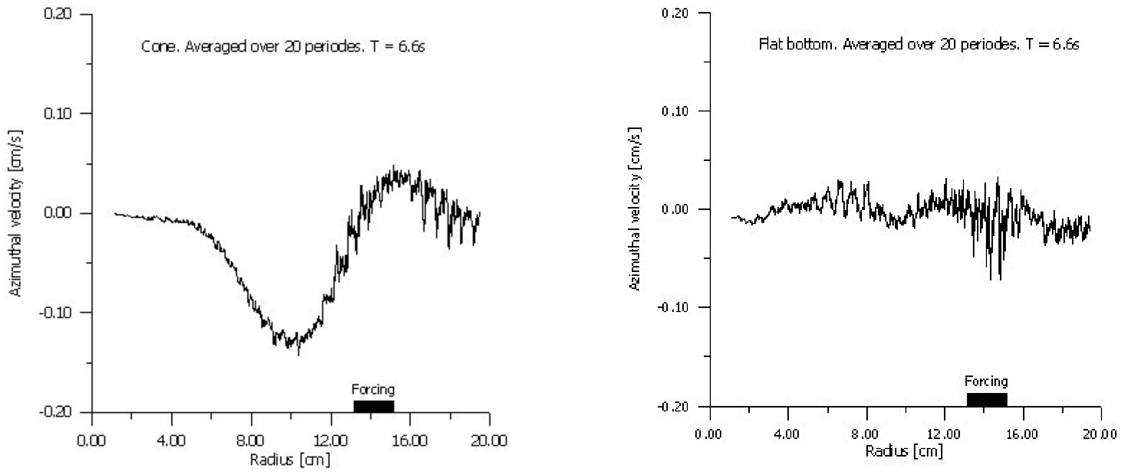

Figure 61. Averaged azimuthal velocity versus radius. The left frame shows the velocity for the case of the cone-shaped bottom, while the right frame shows the reference case with a flat bottom. The black bar shows the position of the forcing region.

The experimental results are supported by direct numerical solutions of the quasi-geostrophic vorticity equation in the β-plane approximation that models the experimental situation. This model equation is equivalent to the Hasegawa-Mima equation that describes drift wave dynamics in magnetized plasma. The mechanism of the formation of zonal flows by drift wave turbulence is just equivalent to the one in the fluid experiment. This indicates that zonal flows are the natural structures apparent in drift-wave type turbulence, while transport enhancing “streamers”, flow structures along the gradient, are of a more “artificial” nature.

4.2.9 Development of collective Thomson scattering for diagnosing fast ion dynamics

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Magnetically confined fusion plasmas contain highly non-thermal populations of fast ions resulting from fusion reactions and plasma heating. With energies in the MeV range, two to three orders of magnitude above the bulk ion and electron energies, the fast ions typically carry 1/3 of the plasma kinetic energy and even more of the free energy. It is essential that these energetic ions remain confined while they slow down and heat the thermal bulk plasma. The free energy associated with the fast ions is, however, also available for mischief. Non-linear wave particle interaction can drive waves and turbulence in the bulk plasma, significantly affecting both bulk and fast ion dynamics. In particular, it can lead to catastrophic loss of fast ion confinement. The sawtooth instability, also affected by fast ions, appears to redistribute part of the ion population. If properly tailored, this can be an effective tool for removing helium ash from the core while leaving the valuable energetic alpha particles in place.

Wave particle interaction is also the basis of ion cyclotron resonance heating (ICRH), one of the main plasma heating schemes relying on the absorption of radio waves. Wave particle interaction depends critically on the phase space distribution of the energetic ions. The effect of waves and turbulence on the ion population manifests itself in the phase space distribution.

So both to challenge and guide our understanding of dynamics involving fast ions, and to monitor our attempts at tailoring turbulence and instabilities affecting the ions, we need detailed measurements of the ion phase space distribution.

It has long been realized that collective Thomson scattering (CTS) has a unique capability for diagnosing the ion phase space distribution; that is, it can provide spatially resolved measurements of the velocity distribution. There are other techniques for diagnosing fast ions (charge exchange neutral particle spectroscopy and neutron spectroscopy), but no other diagnostic currently holds the potential for simultaneously resolving the distributions in time, space and velocity. Building on the experience gained with the fast ion CTS diagnostic at JET,[1] the technique had its breakthrough at TEXTOR Tokamak in Forshungszentrum Jülich, Germany, where a TEC-MIT team led by H. Bindslev built a proof-of-principle experiment.[2] This experiment demonstrated the feasibility of the measurements[3] and provided a wealth of new data on spatially localized ion velocity distributions at many time points in each plasma shot. These have, among others, permitted the investigation of fast ion dynamics at saw teeth.

In 2002 a team[4] of four physicists and five technicians was collected at Risø to continue developing and exploiting fast ion CTS in close collaboration with MIT,[5] The Max Planck Institute for Plasma Physics[6] and the Trilateral Eurogio Cluster (TEC).[7] This year activities in the newly formed CTS team at Risø focussed on developing a significant upgrade to the TEXTOR fast ion CTS system, and designing a new fast ion CTS system to ASDEX Upgrade Tokamak at the Max Planck Institute for Plasma Physics in Garching, Germany.[8] The work on the TEXTOR system includes the development of a new motor steerable antenna, a new transmission line and a universal polariser, significant upgrades to the receiver electronics and a new data acquisition system. For the ASDEX system activities included design and procurement. Preferential support from EURATOM was received for the procurement of the system for ASDEX.

To assist in the construction and verification of antennae and transmission lines a rig for measuring radiation patterns was built and operated. With the assistance of international colleagues (direct collaborators mentioned above and additionally colleagues from Institute für Plasmaforschung, University of Stuttgart[9]) these activities have brought a range of new competences to Risø so that the full range of competences for design, construction and testing of the CTS receivers are now in house.

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3. H. Bindslev, L. Porte, J. A. Hoekzema, D. Van Eester, A. Messiaen, G. Van Wassenhove and P. Woskov, Proceedings of the 28th EPS conference on Controlled Fusion and Plasma Physics, Madeira 18-22 June 2001. (Or.09 & P3.077) http://www.cfn.ist.utl.pt/EPS2001/fin/pdf/P3.077.pdf;
4. www.risoe.dk/euratom/cts;
5. www.psfc.mit.edu/
6. www.ipp.mpg.de/
7. www.fz-juelich.de/ipp/; www.rijnh.nl; http://fusion.rma.ac.be/

8. www.ipp.mpg.de/eng/for/projekte/asdex/for_proj_asdex.html
9. www.uni-stuttgart.de/ipf/

4.2.10 Antenna and quasi-optical transmission lines for CTS systems

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A new quasi-optical receiver antenna for the collective Thomson scattering (CTS) diagnostic system at the TEXTOR tokamak Jülich, Germany, is being constructed. The transmission line of the antenna includes ellipsoidal and hyperboloidal mirrors. The shapes of the mirrors were calculated using newly developed MATLAB codes that permit transmission lines to be specified by variable sets of constraints. The MATLAB results on mirror and beam shapes were transferred electronically to CAD software, CATIA, for further engineering design such as support and integration with actuators. From CATIA the designed components such as curved mirrors were transferred electronically to CAM software running the CNC cutting tools in the Risø workshop. Figure 1 illustrates the process *from MATLAB to metal* in the case of an ellipsoidal mirror. It should be noted that the duration of whole procedure of the mirror production (from MATLAB to metal) is about 4-5 hours. After the cut, the surfaces of the mirrors are characterized by the surface analyser at Risø's workshop.

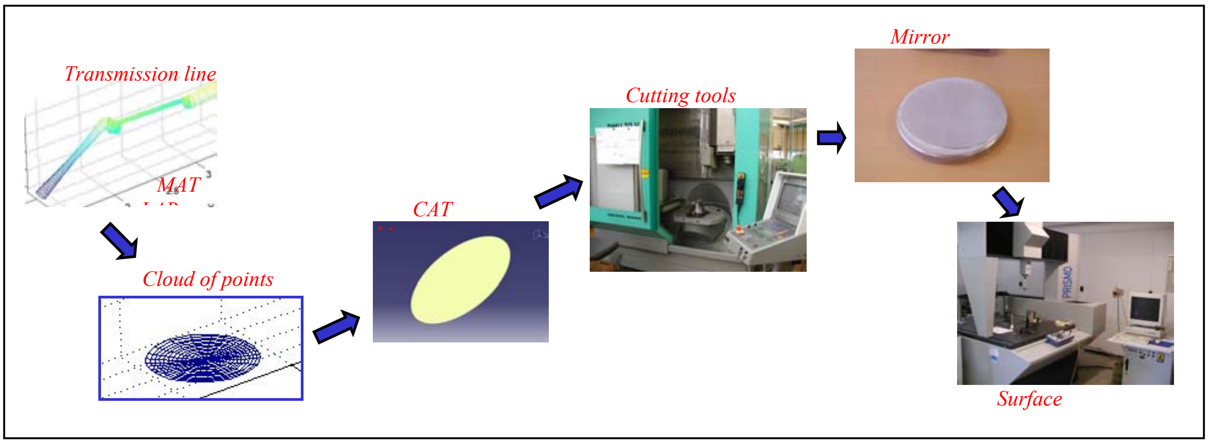

Figure 62. Illustration of the steps in the production of a quazi-optical mirror, from MATLAB to metal.

A similar quasi-optical transmission line is going to be constructed and installed at the ASDEX Upgrade tokamak in Garching, Germany.

Results of the optimisation of the CTS transmission line and the production of the mirrors were presented at the following international conference: "Fast ion millimeter wave CTS diagnostics on TEXTOR and ASDEX", S. B. Korsholm, H. Bindslev, J. Egedal, J. A. Hoekzema, F. Leuterer, P. K. Michelsen, E. Tsakadze and P. Woskov, 44th Annual Meeting of the Division of Plasma Physics, American Physical Society (DPP-APS), Orlando, Florida, USA (2002). Bulletin of American Physical Society (APS), p. 84, vol. 47, No. 9, November, 2002.

4.2.11 Electron cyclotron resonance heating and current drive

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In magnetically confined toroidal fusion plasmas the electrons gyrate in the confining magnetic field. With field strengths in the range of 2 to 5 tesla, the electron cyclotron frequency is in the range of 56 to 140 GHz. Electromagnetic waves can be absorbed by the electrons at their gyration frequency and at higher harmonics. The radial inhomogeneity of the field gives rise to radial variation in the cyclotron frequency. With electron energies in the range of 10 keV, relativistic Doppler shifts of the cyclotron frequencies are significant. The result is a finite radial extent of the resonance region for absorption of waves with a given frequency. The location of the resonance region moves inwards towards higher fields with increasing frequency, and outwards with decreasing angle between wave vector and magnetic field due to Doppler shifts. The microwaves can propagate in beams with diameters down to a few centimetres, which combined with similar radial dimensions of the resonance region permits localization of the absorption to a very small fraction of the plasma volume. Microwave powers in the range of 1 MW in pulses of 10 or more seconds are provided reliably by gyrotrons.

Electron cyclotron waves (or ECW as microwaves in the electron cyclotron frequency range are often called in the fusion community) are a powerful tool for manipulating plasmas through their capability of providing localized heating and current drive. The objectives of ECW systems include current drive for long pulse operation and current profile manipulation for reversed or low shear operation, central heating to study regimes with dominant electron heating, neo-classical tearing mode (NTM) stabilisation, and tailoring of sawtooth amplitudes and periods. Risø participates in the international effort to design an ECW system for the ITER.

4.2.12 Operations space diagram for electron cyclotron wave systems

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The objectives of electron cyclotron wave (ECW) systems are diverse. Each objective is best met with a particular optimisation of the ECW system. We take optimisation to mean not just how effectively an objective can be accomplished for one set of plasma parameters, but also over how wide a range of plasma parameters (operational range) it can be done.

Optimising the ECW system(s) requires weighting of the objectives and associated operational ranges from which a compromise can be found. This process was pursued in the design of the now disbanded ECW system for JET, and was carried out for ITER. The design optimisation includes choice of frequency or frequencies, launch locations and steering ranges of the ECW beams. Documenting the capabilities at various frequencies and launcher locations readily leads to a plethora of plots and tables that obscure the overview. In the study for the JET-ECW system a wealth of computations were presented. To gain the overview required to strike a suitable compromise between disparate objectives, it was useful to present the computed performance estimates in low-dimensional parameter spaces, focusing on those parameters that yield the largest variants of system performance. Such a space was identified. It leads to a presentation of the operational possibilities in a Clemmov-Mullaly-Allis (CMA) type diagram, the ECW-CMA diagram, see Figure 63. In this diagram, with normalized density and normalized field coordinates, the parameter range in which it is possible to achieve a given task (e.g. O-mode current drive for stabilising a neoclassical tearing mode) appears as a region. With also the Greenwald density limit shown, this diagram condenses the information on operational possibilities, facilitating the overview required at the design phase. At the operations phase it may also prove useful in setting up experimental scenarios by showing operational possibilities, avoiding the need for survey-type ray tracing at the initial planning stages. The diagram may also serve the purpose of communicating operational possibilities to non-experts. This work was presented at the 12th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating.[1]

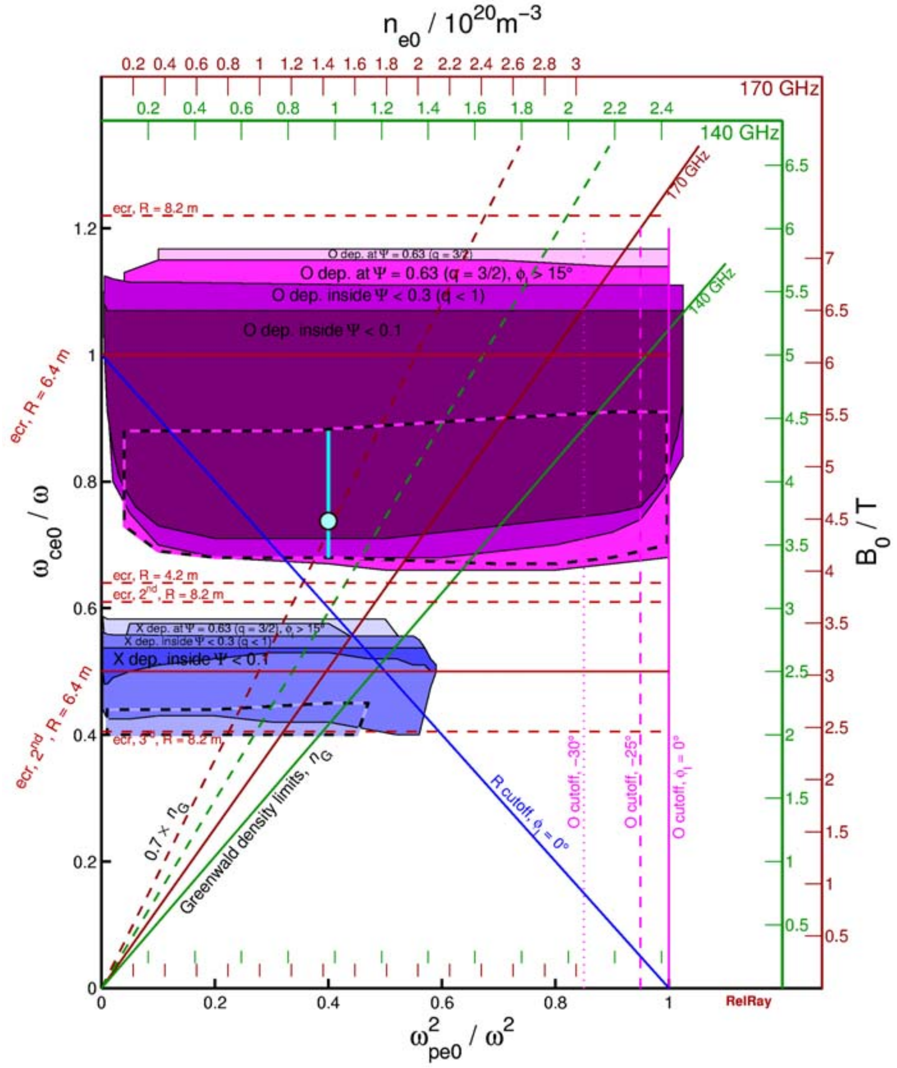

Figure 63. ECW-CMA diagram indicating operational ranges for an ITER ECW system. The axes bottom and left are normalized central density and magnetic fields. Axes top and right have physical units for a selection of EC wave frequencies. The coloured patches indicate operational ranges where deposition within a given flux surface can be achieved with O-mode and X-mode, respectively. Parameters at which EC waves are cut off at the centre are shown, as are the locations of various cyclotron resonances. The locations of the Greenwald density limits have been plotted for a selection of frequencies.

1. H Bindslev, "*Operations Space Diagram for ECRH and ECCD in JET and ITER*", 12th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Aix-en-Provence, France, May 13-16, 2002.

4.2.13 Position control of electron cyclotron resonance heating launcher mirrors by laser speckle sensor

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Electron cyclotron resonance heating, ECRH, systems are important for localised plasma heating in present and future plasma devices as, e.g., ITER. In order to have high reproducibility of the ECRH beam direction, it is necessary to know and control the exact positions of the mirrors that direct the microwave beam towards the plasma. This is not a trivial problem because of (a) thermal expansion of the vessel structures, the launcher itself and its support structure, (b) the mechanical load on the mirrors and the support structures and (c) the accessibility to the various mirrors. We suggest the use of a new technique published recently[1] which is based on a non-contact laser speckle sensor for measuring one- and two-dimensional angular displacement. The method is based on Fourier transforming the scattered field from a single laser beam that illuminates the target, here assumed to be rough and not giving rise to specular reflection. The angular distribution of the light field at the target is linearly mapped onto an image sensor array placed in the Fourier plane. Measuring the displacement of this so-called speckle pattern facilitates the determination of the mirror orientation. If a laser beam illuminates the diffuse backside of the mirror, and the speckle pattern is monitored by a detector (a CCD camera or similar), very small angular displacement can be detected.

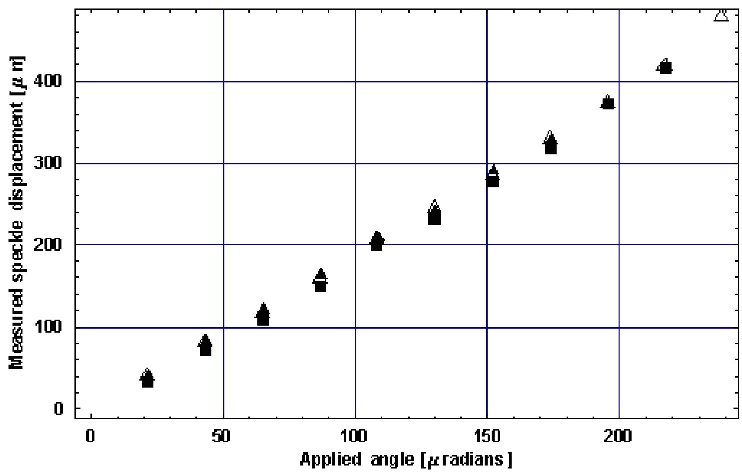

Figure 64 Correspondence between applied values of the angular displacements and the corresponding displacements of the speckle pattern. The triangles represent measurements performed at the centre of rotation and the squares represent measurements performed 70 mm from the axis of rotation.

A series of experiments were performed by probing a diffuse target that was angularly displaced by piezo-electrical tilting of a thin plane target across a knife edge. Corresponding readings of applied values for the angular displacement and measured displacement of the speckle pattern are presented in Figure 64 where the measuring distance was four meters. This demonstrates that the technique can been extended to long measuring distances. The obtained angular resolution of the order of a few μrad is in agreement with theoretical predictions. This work was presented at the 12th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating.[2]

1. B. Rose, H. Imam and S. G. Hanson, "Non-contact laser speckle sensor for measuring one- and two-dimensional angular displacement," *J. Opt.* **29**, 115-120 (1998).
2. H. Bindslev, S. G. Hanson and P. K. Michelsen**,** "Position control of ECRH launcher mirrors by laser speckle sensor and infrared spot detection", 12^{th} Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Aix-en-Provence, France, May 13-16, 2002.

4.3 Low-temperature plasmas

4.3.1 Emission reduction by means of low-temperature plasma

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Low-temperature plasma activities for the remediation of air pollution have been initiated in close collaboration with the Plant Research Department at Risø and Danish Gas Technology Centre. The activities focus on the reduction of NO_x in the exhaust gases from district heating stations.

4.3.2 Diagnostics and two-dimensional simulation of low-frequency inductively coupled plasmas with neutral gas heating and electron heat fluxes

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A 2D model has been developed to compute the global plasma parameters in low-temperature inductively coupled plasmas (ICPs) used for material processing, such as etching, deposition, implantation and surface modifications. The model takes into account the excited states of argon in the inductively generated low-pressure argon discharge. Experiments were carried out to verify the model, using low-frequency (0.46 MHz) ICPs generated in a cylindrical metal chamber by an external flat spiral coil. Langmuir probe and optical emission spectroscopy were used to investigate plasma parameters such as the electron densities and temperatures, electron energy distribution functions, and optical emission intensities of the different plasma species in low- and intermediate-pressure argon discharges. It was demonstrated that by applying this model we can achieve reasonable agreement between the computed and the experimental data. Finally, the effect of the neutral gas temperature on the plasma parameters was also investigated. It was shown that neutral gas heating at rf powers exceeding 0.55 kW is one of the key factors that control the electron number density and temperature. This work was reported in ref. 1.

1. "Diagnostics and simulation of low-frequency inductively coupled plasmas", K. N. Ostrikov, I. B. Denysenko, E. L. Tsakadze, S. Xu, and R. G. Storer, Journal of Applied Physics, 92, 9, 4935-4946, 2002.

4.4 Fluid dynamics

4.4.1 Numerical investigations of vortex crystal formation

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The numerical investigations of the interaction of turbulence and vortical structures with solid boundaries in a two-dimensional circular domain have been continued.[1] Using the Navier-Stokes equation in the limit of very small kinematic viscosity, very high Reynolds numbers, i.e. $> 10^5$, we have investigated the evolution with initial conditions in the form of a ring of concentrated vorticity. A new diagnostics for keeping track of the dominant vortices has been implemented. The study was inspired by the work of Fine et al.,[2] where vortex crystals consisting of a helical sheet or a ring of vorticity in a pure electron plasma column were observed experimentally to form spontaneously from particular initial conditions. This produces a quasi-random distribution of strong vortices. The vortex structures either collapse to one strong central vortex or "freeze" into a regular pattern – a vortex crystal.

In the plasma experiment there is virtually no viscosity, whereas in computer simulations a small amount of viscosity has to be included in order to filter out high frequency oscillations generated by the non-linearity of the equations. Hereby the vortices will slowly expand in time until they reach a size where they strongly interact and ultimately merge. The final state will in this case thus be one large vortical structure located in the centre of the domain and will be slowly decaying. Our aim is to model such a vortical structure by the two-dimensional Navier-Stokes equations using sufficiently small viscosity to observe the vortex crystal for a long period before the ultimate collaps.[3]

An example of the temporal evolution of individual vortices that arise from an initial distributed ring vorticity is shown in Figure 65. The trajectories of the dominant vortices, obtained by employing the new tracking diagnostics, are also shown in Figure 65. Note that in this case the vortices does not condense completely into a vortex crystals, but stay together in a wobbling state, where the individual vortices move in a limited domain.

1. V. Naulin, A.H. Nielsen and J. Juul Rasmussen, Risø-R-1314(EN), 67 (2002).

2. K.S. Fine, A.C. Case, W.C. Flynn and C.F. Driscoll, *Phys. Rev. Lett.* **75**, 3277 (1995).

3. J. Juul Rasmussen, A.H. Nielsen and V. Naulin, Physica Scripta **T98**, 29-33 (2002).

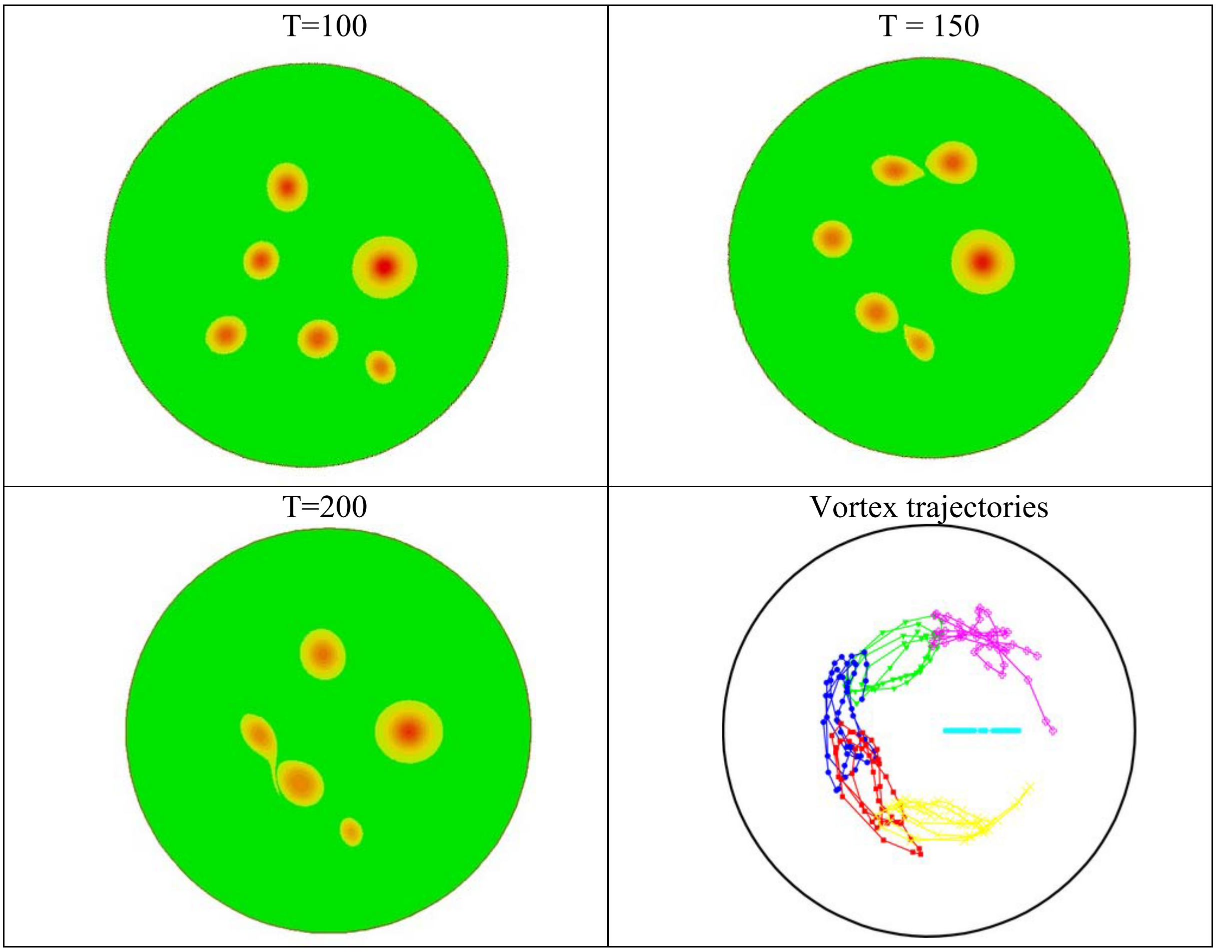

Figure 65. Evolution of isolated vortices that originate from a ring of vorticity. Reynolds number: Re = 4.0 10^5 and the spectral resolution is m = n = 1535. Time is measured in vortex turnover time. The last frame shows the vortex trajectories for the complete simulations; the strongest vortex is found to move slowly in the radial direction towards the centre (the turquoise trace).

4.4.2 Averaging method for laminar nonlinear Ekman layers

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Ekman boundary layers form in rotating systems and play important roles in many geophysical and technical flows. We have studied the non-linear properties of Ekman layers with an averaging method similar to the technique of von Karman and Pohlhausen, and have explored corrections to the well-known linear Ekman theory at large Rossby numbers. We have investigated the choice of velocity profile and have introduced a new model based on two different length scales for the oscillations and the decay of the boundary layer, respectively. We have shown that the results of the model agree well with von Karman's exact similarity solution, and we thus believe that our model will be useful and will capture important quantitative features of more general flow configurations.

4.4.3 The bathtub vortex flows with free surface evolution

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We have continued the investigations of bathtub vortex flows, i.e. swirling flows with a free surface, which may extend down to the drain-hole of the fluid container.[1] These vortex flows are abundant in nature and also of importance in many technical flow applications. The source-sink flows that produce the bathtub vortex are investigated in rotating fluids. An intense vortex is formed and the free surface is strongly perturbed and appears with a needle-like singular shape. We have particularly been concentrating on the modelling of the free surface shape that, together with the velocity profiles, has been measured for different values of the background rotation and the flow rate. The depth of the surface dip is enlarged with increasing rotation frequency, and above a critical value it extends all the way down into the drain hole. The flow field at a distance away from the vortex centre is controlled by the bottom boundary layer, and in this region the measured velocity fields agree with well-known linear theory for Ekman layers. Non-linear effects are important close to the drain-hole, and an extended theory allows us to describe the bottom boundary layer in this region. The theoretical description of the vortex flow above the drain-hole accounting for effects of surface tension is found to model the shape of the free surface dip, at least in the regime of moderate dips.

1. A. Andersen, B. Lautrup, T. Bohr, J. Juul Rasmussen and B. Stenum, Risø-R-1314(EN), 68 (2002).

4.4.4 The shape and stability of a falling liquid thread

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When a viscous fluid, like oil or sirup, streams from a small orifice and falls freely under gravity, it forms a long slender thread that can be maintained in a stable, stationary state with lengths up to several metres. We shall discuss the shape of such liquid threads and their surprising stability.

We have performed both analytical and experimental investigations of the shape and the stability of a freely falling thread. It turns out that the strong advection of the falling fluid can almost outrun the Rayleigh-Plateau instability and change the usual exponential growth of small perturbations to the stretched exponential form $\exp(c\, t^{1/4})$.

4.5 Optics and acoustics

4.5.1 Modelling optically active polymers

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The understanding of relaxation processes in non-linear optical polymers is of critical importance for the development of materials for potential opto-electronic applications. We consider the relaxation behaviour of an active polymer with a finite electric dipole moment embedded in a polymer matrix without an electric far field.

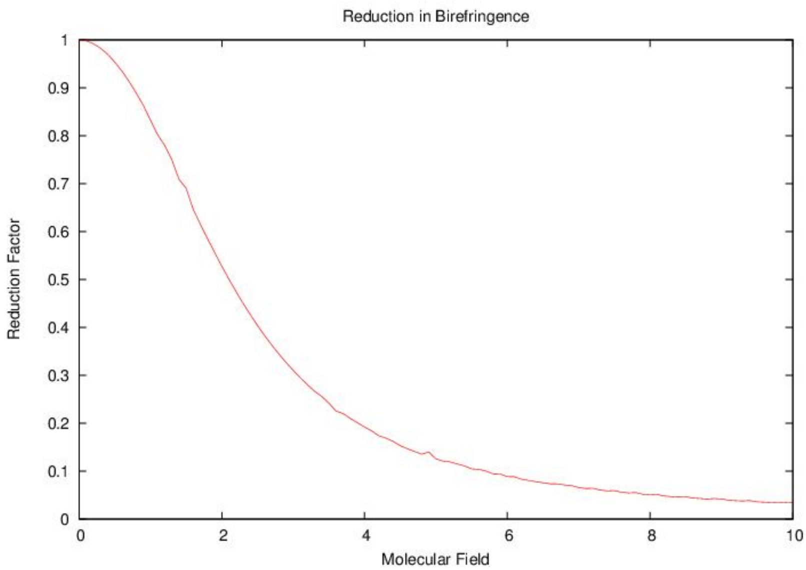

Figure 66. The reduction in the birefringence obtained from a numerical solution of the rotation diffusion equation.

The frictional backreaction of the matrix material onto the rotating polymer chains leads to a way of behaviour that is often characterized by a phenomenological diffusion time. However, this approach only accounts for the influence of the polymer matrix in lowest order, and the observed behaviour of the material is not well described by this ansatz. Better results are obtained by also considering the local molecular fields and their interaction. In a numerical model we moreover consider the backreaction of the matrix material on the rotation of the polymer chains. Initial experimental, analytical and numerical investigations show promising results, see Figure 66.

4.5.2 Generic features of the modulational instability in nonlocal non-linear Kerr media

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The phenomenon of modulational instability (MI) of plane waves has been identified and studied in various physical systems such as fluids, plasma, non-linear optics and discrete non-linear systems (e.g. molecular chains and waveguide arrays), etc. It has been shown that MI is strongly affected by various mechanisms present in non-linear systems, such as higher order dispersive terms in the case of optical pulses, saturation of the non-linearity, and coherence properties of optical beams.

We have studied the MI of plane waves that propagate in a non-linear Kerr-type medium with non-linearity (the refractive index change in nonlinear optics) that is a non-local function of the incident field. It is shown that the MI consists of a finite number of well-separated unstable bands, and it appears as a generic feature for a large class of response functions that each MI band is equipped with a unique maximum growth rate. This property holds true for the Gaussian, the exponentially decay function and the square pulse response function. For focusing non-linearity it is shown that although the nonlocality tends to suppress MI, it can never remove it completely, irrespective of the particular shape of the response function. For defocusing nonlinearity the stability properties depend sensitively on the profile of the response function. It is shown that for response functions like the Gaussian and the exponentially decay function with positive spectra, plane waves are always stable, while response functions whose spectra change sign will produce MI in the high modulation wave number regime provided the typical length scale of the response function exceeds a certain threshold. An example on the latter situation is given by the square response function.

Finally, the multiscale length situation is addressed by generalizing the single-scale length formalism to response functions that decompose to weighted means of single-scale length response functions.

4.5.3 Non-local non-linearity and soliton interaction

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We have initiated investigations of the interaction of spatial solitons in non-linear media with non-local Kerr-type nonlinearities. Experimental investigations are performed at the Australian National University in Canberra, Australia. In the employed materials the non-locality of the non-linear refractive index has its origin in the diffusive response of the refractive index to the applied optical field. The experimental observations are supported by numerical calculations based on the nonlocal non-linear Schrödinger equation. Preliminary results indicate that due to nonlocality out-of-phase solitons may attract each other, at least at short distances. This will not occur in media with local nonlinearity, where it is well-known that solitons that are in phase attract each other, while solitons that are in counterphase repel each other.

4.5.4 Optical solitons in the femtosecond regime

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When entering the femtosecond regime in the context of non-linear wave packets one has to account for both instantaneous and time-delayed Raman nonlinearities, due to the short duration of the optical pulses. In such cases one ends up with a model equation in the form of a nonlinear Schrödinger (NLS) equation extended with nonlocal terms and higher order linear as well as non-linear dispersive terms. In general, these extended NLS equations do not possess a soliton solution, except for very special combinations of coefficients. We have investigated the evolution of localized initial conditions in the presence of amplification effects and nonlocal Raman response by using perturbational analysis and direct numerical solutions of the extended NLS-equation. The analysis reveals the existence of a soliton-like structure that acts as a global attractor in certain regimes of the amplification parameters. The predictions from the perturbation analysis agree with the results obtained from the numerical solutions.

4.5.5 Supercontinuum generation in photonic crystal fibres

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The photonic crystal fibre (PCF), which is also called a microstructured or holey fibre, was first fabricated in 1996.[1] PCFs are optical fibres that employ a microstructured arrangement of low-index material in a background material of higher refractive index. The background material is often undoped silica and the low index region is typically provided by air voids running along the length of the fibre.

PCFs may be divided into two categories, high-index guiding fibres and low-index guiding fibres. Similar to conventional fibres, high-index guiding fibres are guiding light in a solid core by the modified total internal reflection principle. The total internal reflection is caused by the lower effective index in the microstructured air-filled region. Low-index guiding fibres guide light by the photonic band gap effect. The light is confined to the low index core as the photonic band gap effect makes propagation in the microstructured cladding region impossible.

The strong wavelength dependency of the effective refractive index and the inherently large design flexibility of the PCFs allows for a whole range of novel properties. Such properties include endless single-moded fibres, extremely non-linear fibres and fibres with anomalous dispersion in the visible wavelength region. PCFs are used in areas such as fibre optics, non-linear optics, quantum electrodynamics, spectroscopy, biomedical optics and metrology.

In the extremely non-linear PCF the high nonlinearity and the unusual dispersion properties permit efficient generation of a supercontinuum spectrum of light spanning more than an octave from the ultraviolet to the infrared. Supercontinuum generation has initially found applications in spectroscopy and pulse compression in ultrafast femtosecond lasers. With the recently improved efficiency they find further important applications in extremely accurate frequency metrology and multiwavelength optical sources for dense wavelength-division-multiplexing telecommunications.

In this project we study supercontinuum generation in extremely nonlinear PCFs using low-power picosecond pulses instead of high-power femtosecond pulses. We have implemented a numerical model based on the generalized coupled non-linear Schrödinger equations, and this model governs the evolution of both polarization components taking into account the full dispersion profile, self- and cross-phase modulation, four-wave mixing and stimulated Raman scattering. The model is valid for short pulses with a spectrum as broad as one third of the optical carrier frequency.

Our simulation results[2] and the experimental and numerical results in Ref. 3 show that it is the interplay between four-wave mixing and Raman scattering that is responsible for the formation of the supercontinuum. In particular, we now investigate how the efficiency of the supercontinuum generation may be improved by optimizing this interplay to enable widely separated Stokes and anti-Stokes spectral components to be generated through direct degenerate four-wave mixing, which then broaden and merge to rapidly generate an ultrabroad supercontinuum.

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4.5.6 Laser-generated ultrasound for non-contact inspection

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Laser ultrasound (LU) is a promising new technology for remote, non-contact inspection of material characteristics and defects. In this technique, a pulsed laser is used to generate an ultrasonic pulse in the material, and an optical interferometer or a piezoelectric sensor is used to detect the ultrasonic pulse after it has propagated through the material. LU has a number of unique applications: the high bandwidth of the laser-generated pulses enhances spatial resolution and provides more reliable defect detection compared with traditional ultrasonic techniques.

In this project, different types of discontinuities in steel specimens have been studied by means of laser-generated ultrasound. The defects are located by their reflections of the laser-generated ultrasound. Different types of defects have been studied in detail in order to optimize the configuration for LU inspection.

Since LU is a non-contact technique, it allows inspection of moving objects. Studies on moving specimens have shown that this arrangement can be used on industrially rough surfaces at relatively high velocities with an improved signal-to-noise ratio. At even higher velocities, the signal-to-noise ratio decreases due to speckle noise.

The project is a part of the Centre for On-Line, Non-Contact Sensing, Monitoring and Control of Industrial Processes and Systems (BIPS). The participants are FORCE Technology, Risø National Laboratory, Technical University of Denmark, Junckers Industrier A/S, Coloplast A/S, Danish National Railway Agency and SCITEQ-Hammel A/S.

5. Publications and educational activities

5.1 Laser systems and optical materials

5.1.1 International publications

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6. Personnel

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Andersen, Peter E.
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Horvath, Robert
Jensen, Peter Snoer (from 1 August)
Jensen, Sussie Juul (from 15 January)
Kasimova, Marina (from 17 June)
Kjærgaard, Niels
Korsholm, Søren (from 1 April)
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Thrane, Lars
Tsakadze, Erekle (from 1 March)
Tycho, Andreas (from 1 October)

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Andersen, Eva Samsøe
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Jensen, Peter Snoer (until 31 July)
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Jensen, Søren Blaaberg (12 August – 31 October)
Nedelchev, Lian (from 1 October)
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Sørensen, Henrik Schiøtt (1 April – 31 May)
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Abstract (max. 2000 characters)

The Optics and Fluid Dynamics Department performs basic and applied research within three scientific programmes: (1) laser systems and optical materials, (2) optical diagnostics and information processing and (3) plasma and fluid dynamics. The department has core competences in: optical sensors, optical materials, optical storage, biophotonics, numerical modelling and information processing, non-linear dynamics and fusion plasma physics. The research is supported by several EU programmes, including EURATOM, by Danish research councils and by industry. A summary of the activities in 2002 is presented.

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DYNAMICS; FLUIDS; LASERS; NONLINEAR OPTICS; NONLINEAR PROBLEMS; NUMERICAL SOLUTION; PLASMA; PROGRESS REPORT; RESEARCH PROGRAMS; RISOE NATIONAL LABORATORY; THERMONUCLEAR REACTIONS