

Research Summary

Much of the research within the Centre involves some aspect of materials science where there have been a number of exciting developments this year. These include the discovery of a paramagnetic carbon nano-foam produced by pulsed laser deposition; demonstration of electrochemical switching of the cubic nonlinearity in organometallic molecules; and the commercialisation of organically modified glasses (ORMOSILs) developed in the Centre with support from the Australian Photonics Cooperative Research Centre. This last development has involved the transfer of ANU-developed IP to a new start-up company Redfern Polymer Optics (RPO) which was established late in 2000 as the newest member of the Sydney-based Redfern Photonics group of companies. RPO aims to sell optical integrated circuits fabricated using ORMOSIL glasses to the telecommunications market. The company has established clean room and device fabrication facilities within the Innovations Building at the ANU and a number of RPO staff have been appointed as Visiting Fellows to the Centre. These include Dr Dax Kukulj, Dr Robbie Charters, Dr Graham Atkins and Dr Congji Zha (who transferred to RPO from a CRC funded post in September). Dr Weitang Li also joined the Centre with his time shared between the RPO project and the HARE project within the Plasma Research Laboratory.

The Centre remains an important contributor to the research of the Australian Photonics CRC and Professor Barry Luther-Davies holds positions as CRC Research Director, is a member of the CRC Executive and is a Director of Australian Photonics Pty Ltd, the Commercial and Management agent for the CRC. Other CRC supported projects include a novel scheme for spectral analysis of RF data using four dimensional holography; the application of pulsed laser deposition technology to the production of waveguide films in chalcogenide glasses; work on optical spatial solitons and non-linear optical materials; and a project fully-funded by ABB and Transgrid to develop a voltage sensor based on a polymer optical fibre. The research of the CRC in micro- and nano-technology was presented by Professor Luther-Davies at Nanotechnology Workshops in Japan and Korea attended by an Australian delegation and arranged by DISR. Follow up visits have so far involved representatives from LG Elite in Korea and AIST in Japan.

The Centre was pleased to have three of its staff promoted this year. Neil Manson was rewarded for his exceptional contributions to solid-state laser spectroscopy by promotion to Professor. Dr Ken Baldwin who heads our programs in VUV Laser Spectroscopy



Professor Barry Luther-Davies
- Head of Laser Physics Centre

The Laser Physics Centre is engaged in laser-based research on topics spanning fundamental and applied physics and engineering.



Staff associated with RPO Pty Ltd

<http://laserspark.anu.edu.au>

and is a major contributor to the Atom Manipulation project carried out in collaboration with AMPL was promoted to Senior Fellow. Dr Max Lederer, who oversees our work on the development of novel short pulse lasers, was promoted to Research Fellow.

We welcomed a number of new staff and students during the year. In addition to those involved in the RPO project, Dr Olivier Uteza joined us in June with support from an IREX Fellowship to work with Dr Andrei Rode. Dr Anna Samoc was reappointed for a further five year period. Ms Lily Luo joined us as a technical assistant working on the industry-funded Polymer Optical Fibre project replacing Therese Martin. Cindy Bradley stepped in as Departmental Administrator until September whilst Kristina Milas was on sick leave. Five students joined the Centre: Elliot Fraval, Jevon Longell, Syed Queddes, Yinlan Ruan and Eleni Notaras who was also a recipient of a Redfern Photonics Scholarship. Bronwyn Taylor worked in the Centre as a vacation scholar on laser ablation of dental tissue and has subsequently become a regular student visitor as part of a collaboration with Macquarie University on the development of Ytterbium mode-locked lasers. Ben Cornish undertook a project as part of his final year Engineering degree and also a period of work experience.

Research Accomplishments

Nonlinear Optical (NLO) Materials and Structures

Following the upgrade last year of our experimental facilities, we are now able to perform NLO measurements with high power 100 femtosecond duration laser pulses across the full range of wavelengths from 500-2000 nm. We have used this new facility to study various classes of materials including conjugated polymers, organometallic molecules, chalcogenide glasses, metal clusters and metal-glass interfaces. Our materials work involves collaboration with many groups including Professor Rob Elliman in the Department of Electronic Materials Engineering; Dr Mark Humphrey from the Department of Chemistry, The Faculties, ANU; Professor H. Hoerhold's group at the University of Jena; and Dr Wong's group from the Baptist University of Hong Kong. A highlight of this year's research has been the discovery of reversible electrochemical switching of the cubic nonlinearity in certain organometallic structures.

Our work on spatial optical solitons continues to attract much attention with a focus this year on vector solitons including stable multi-pole structures.

Third-Order Nonlinear Properties of Model Molecules and Polymers

A large number of model molecules, oligomers, dendrimers and polymers have been studied. This included a novel conjugated copolymer of polyphenylenevinylene and triphenylamine (TPA-PPV) synthesised in Professor Hoerhold's laboratory in Germany. TPA-PPV (which is also of interest because of its electroluminescent properties) offers good processability and enhanced non-linear properties.

We have found (in collaboration with Dr Humphrey's group at the ANU) that some organometallic Ruthenium complexes, of linear, octopolar and dendrimeric type possess high values of two-photon absorption cross sections (σ_2). Interestingly,



Sam Ashby and Ruth Jarvis in the device testing lab

dendrimeric structures appear to provide some advantage for obtaining high values of both the refractive and absorptive nonlinearity. Our recent development is an organometallic molecule with $\sigma_2 \approx 3000 \times 10^{-50} \text{ cm}^4/\text{s}$ which has the highest σ_2/M (M = molecular weight) ratio reported so far for an organometallic.

Soluble oligomers of poly(p-phenylenevinylene) synthesised by Dr Wong's group in Hong Kong exhibit large nonlinearities, increasing with the length of the conjugated chain. They also show strong wavelength dispersion effects manifested by a change of sign of the real part of the molecular hyperpolarisability. An unexpected and yet unexplained phenomenon is the sensitivity of the sign of the refractive nonlinearity to the solvent environment in which the NLO measurements are performed. A similar effect has already been observed for another class of oligomeric compounds: oligovanillines. (A. Samoc, M. Samoc and B. Luther-Davies; M.G. Humphrey and coworkers [Chemistry, Faculties]; M.S. Wong and coworkers [Baptist University, Hong Kong] and H.H. Hoerhold and coworkers [Jena University, Germany])

Electrochemical Switching of the Cubic Nonlinearity in Organometallics

We have discovered a new effect in organometallics containing oxidisable metal centres which causes switching and hence control of the third order non-linear optical properties of the material. Little is known about switching third-order NLO response, although any change in the structure of a molecule such as induced by light, should result in the change of the cubic hyperpolarisability.

Here we studied the effect of electrochromic switching in Ru acetylides on the third-order non-linear optical response by using in-situ femtosecond Z-scan at 800 nm. Three sample molecules: an octopolar π -conjugated complex; a linear analogue; and a relatively small complex with low nonlinearity were measured. In all three cases the transfer of an electron from the oxidisable Ru atom led to the creation of a molecule showing strong saturable absorption at 800 nm. Electrochromic switching,

therefore, led to reversal in sign of both the absorptive and the refractive parts of the cubic nonlinearity. This observation has some interesting implications and could lead to photonic devices whose non-linear properties can be switched electrically. (M. Samoc, B. Luther-Davies, M.G. Humphrey and M. Cifuentes [Chemistry, Faculties]; G. Heath and coworkers [Research School of Chemistry])

Second-Order Nonlinear Optical Materials

An efficient route for synthesis of highly-soluble unsymmetrical oligo(phenylenevinyls) (OPVs) for use as electro-optic chromophores in a PMMA host has been developed. The OPVs are end-substituted with donor alkoxy and acceptor sulfonyl groups for charge polarisation and incorporate a methacrylate unit suitable for copolymerisation with methylmethacrylate (MMA). The newly developed synthesis, which involved utilising an unsymmetrical precursor, methyl 4-(bromomethyl)benzoate proceeded via several straightforward and high-yield steps using the Wittig-Horner reaction to form all trans-configured OPV derivatives at high yields.

Replacement of the n-decyl chain utilised in work last year by a 2-ethylhexyl group results in vastly increased solubility of the oligo-PPV derivatives in MMA allowing these new monomers to be used for the preparation of homogeneous high-quality NLO chromophore-containing poly-methylmethacrylate films and fibres.

The second-order non-linear optical properties of the monomer and polymers were investigated by electric field poling of doped PMMA films. Comparing the signals due to second harmonic generation with those from a film of disperse red (DR1) side chain polymer, provided a relative value of the hyperpolarisability $(\mu\beta)_0 = 0.67$ in agreement with model calculations.

In cooperation with Redfern Polymer Optics a new dual functionalised type of azo chromophore with high non-linear optical activity has been synthesised. The silane group attached at one side of the molecule will allow the chromophore to be incorporated into an inorganic polymer glass (IPG), whereas the methacrylate unit can be polymerised during poling, which gives a highly oriented chromophore stable against de-poling. (A. Freydank, E. Notaras and M. Samoc; M. Humphrey Dept. of Chemistry, ANU)

Soliton Physics

In collaboration with our colleagues in the Nonlinear Physics Group within the Director's Unit we have continued to study both experimentally and theoretically, phenomena associated with the creation and interaction of optical spatial solitons. We have produced the first experimental demonstrations of multi-component, multi-pole (dipole, quadrupole, and hexapole) spatial solitons in self-focusing photorefractive medium. We have also observed experimentally the transverse instability of the two-component stripe soliton leading to formation of an array of dipole-mode vector solitons.

On the theory front we have developed an exact solution to the problem of bright and dark one-dimensional solitons propagating in a weakly non-local non-linear medium as well as a rigorous proof of the absence of collapse of 2D beams in a non-local Kerr-like medium. (W. Krolikowski; D. Neshev, E. Ostrovskaya and Yu S. Kivshar [DU])

Photonic Materials and Devices

Organic Waveguides for Photonics

We are involved in a project to commercialise organically-modified silicate glasses that were developed with support from the Australian Photonics CRC for the production of planar optical waveguide devices. Commercialisation is being carried out by a start-up company, Redfern Polymer Optics, with ANU and CRC staff contracted as consultants.

Organically modified silicate glasses (ORMOSILs) for integrated optical and opto-electronic devices have been synthesised by sol-gel processing of functionalised alkoxy-silanes. Process parameters were optimised to achieve highly reproducible low cost materials which possess low optical loss in the NIR range (0.3 dB/cm @ 1310 nm and 0.6 dB/cm @ 1550 nm) and show good photo-sensitivity for pattern production. Promising routes to lower optical losses and new processing methods for ORMOSIL glasses have been identified.

We have developed the expertise to create patternable metal surface electrodes on our ORMOSIL materials for control of the resulting optical devices. As part of an Honours project carried out by Engineering student Ben Cornish, we completed a study of the residual photosensitivity of fully processed ORMOSIL films to assess their use for writing Bragg gratings. An automated grating characterisation system was developed as part of the project. The material photosensitivity was characterised using facilities at the Optical Fibre Technology Centre at the University of Sydney and the Centre for Lasers and Applications at Macquarie University. (R. Friedrich, C. Zha, G. Atkins, D. Kukulj, W. Li, R. Charters, B. Luther-Davies, R. Jarvis and B. Cornish)

Polymer Fibre for Voltage Sensing

The work, funded by ABB and Transgrid, aims to develop a single-mode polymer optical fibre voltage sensor for the power industry. We have continued to work on the fabrication of polymer optical fibre (POF) preforms capable of yielding single-mode optical fibre – a task that has proven to be unexpectedly challenging. In addition we have developed new routes (reported above) for synthesising an electro-optic chromophore for incorporation into the core of the fibres.

The fibre preforms consist of plastic rods synthesised by radical polymerisation of acrylates, and contain core and cladding parts. The second-order non-linear optical chromophore was successfully attached as a side chain to the PMMA main chain by bulk co-polymerisation with methylmethacrylate, benzylmethacrylate (BMA) and ethylacrylate. Highly transparent material has been obtained using various preform manufacturing processes. A POF fibre with a relatively low optical loss in the visible spectral range, of the order of a few dB/m at 780 nm, was recently drawn although this fibre was two moded at 1550 nm indicating a reduction in core size is still required. (A. Samoc, T. Martin, X. (Lily) Luo, A. Freydank, R.M. Krolikowska, C. McLeod, J. Bottega, B. Luther-Davies and M. Samoc)

Laser/Matter Interaction Physics

Laser Deposition of Chalcogenide Glass Films

We continued to develop our patented ultra-fast laser ablation process for the creation of waveguide films with high optical nonlinearity using chalcogenide glasses. This year 3-5 μm thick As_2S_3 films were deposited by ablating bulk glass samples using the second harmonic of a mode-locked Coherent Antares Nd:YAG laser ($\lambda = 532 \text{ nm}$, $t_p = 50 \text{ ps}$). Up to 7 W of second harmonic output was available at 76 MHz (pulse energy $\sim 80 \text{ nJ}$).

The films created in this way showed improved photo-sensitivity in the as-deposited state compared with those produced last year using a Q-switched mode-locked laser. This allowed direct writing of single-mode waveguides using a computer-controlled laser writing system. The surface quality of the deposited films was exceptional with RMS roughness of the order of 0.4 nm over the $15 \times 15 \mu\text{m}^2$ area in 5 μm thick films. Waveguide losses as low as 0.2 dB/cm at 1550 nm in laser-written waveguides were measured. By coating the As_2S_3 with PMMA it was found that the intensities that could be used for laser writing could be increased approximately 100 fold relative to the uncoated films, allowing writing speeds of 16 mm/s to be achieved. This markedly reduced the production time for low-loss waveguides.

As part of our program to develop pulsed laser ablation for the production of low-loss non-linear waveguides, we have started to characterise the non-linear optical properties of a number of chalcogenide glasses. We have recently completed measurements of Gallium Lanthanum Sulphide (GLS) bulk glass that was fabricated in the Centre by Anita Smith. The nonlinearity was found to be two orders of magnitude higher than silica at 1550 nm making it a promising material for an all-optical processor. We have also obtained samples of $\text{As}_{24}\text{S}_{38}\text{Se}_{38}$ glass from the group headed by Kathleen Richardson at the University of Central Florida. This glass is expected to have an even higher optical nonlinearity although some of its physical properties are inferior to those of GLS.

In order to take advantage of the unique properties of ultra-fast pulsed laser ablation in materials research, we have begun to construct an upgraded experimental facility. We have started construction of a new vacuum chamber for laser deposition for chalcogenide films in particular and have designed a new 100-W 10-ps “slow” mode-locked laser as the ablation source. This installation will not only allow new materials and thin films to be created, but will also match industry specifications in terms of deposition rate, stoichiometry of the deposited films, surface quality and thickness homogeneity over large areas. (A.V. Rode, M. Samoc, R. Charters, B. Luther-Davies, Y. Ruan and A. Smith)

Electronic and Magnetic Properties of Carbon Nanofoam produced by Ultra-Fast Pulsed Laser Ablation

A new form of carbon material, a low-density cluster-assembled carbon nanofoam has been produced by high-repetition-rate laser ablation of a glassy carbon target in an ambient non-reactive Ar atmosphere. The carbon nanofoam is remarkable for many reasons. It displays high electrical resistivity and noticeable rigidity combined with extremely low bulk density.

Close inspection of all the data obtained (DC-conductivity, optical absorption, transmission and electron microscopy, electron

energy loss spectroscopy) has led to the following microstructural model. There appear to be segregation of sp^2 -bonding and sp^3 -bonding domains, with the latter located predominantly at the surface of the approximately 60 \AA sized foam clusters, and the former confined within the clusters. The sp^3 -bonding between the clusters accounts for the observed low conductivity of the foam. We note that this arrangement of the sp^2 - and sp^3 -bonding in the individual cluster is the reverse of that observed recently in the core of so-called carbon ‘onions’, or nested fullerenes.

Electron spin resonance (ESR) measurements have shown a number of unusual features, with the main result of a very large concentration of unpaired spins of approximately one unpaired spin per 60 atoms. The high density of spins leads to paramagnetic susceptibility of the foam, which is in a striking contrast to diamagnetic properties of all other known allotropes of C. The foam contains no paramagnetic impurities at concentrations high enough to provide this spin density. Therefore, we hypothesise that these spins are due to underbonded C atoms acting as free radicals within the clusters. The significant paramagnetic susceptibility of the carbon nanofoam arises as a consequence of its structure. (A.V. Rode and B. Luther-Davies; E.G. Gamaly, A.G. Christy and S.T. Hyde [AM]; R.G. Elliman [EME]; A.I. Veinger [Ioffe Physical-Technical Institute, Russia])

Intensity-Dependent Transient Reflectivity of Gallium during the Phase Transition induced by Femtosecond Laser

The transient reflectivity of thin gallium films induced by the femtosecond laser pulse has been studied by the pump-probe technique at different pump intensities. The time-resolved reflectivity rise rate of the femtosecond probe strongly depends on the pump beam intensity. We demonstrate that the transient electron-phonon collision rate extracted from the reflectivity data is a strong function of the temperature (laser intensity), which is drastically different from the rate observed in the equilibrium conditions. The scenario for the microscopic kinetics of the phase transition on the femtosecond time scale is proposed and discussed. New experiments for observation of time-resolved optical properties with two simultaneous identical probes are in progress. (A.V. Rode, M. Samoc, B. Luther-Davies and O. Uteza)

Sub-Picosecond Laser Ablation of Dental Enamel

Since the first use of lasers in the medical field, the contact-free application of laser light for removal of hard dental tissue has been studied as a means for replacing conventional surgical tools. To date, lasers have not succeeded in replacing the dental drill in many hard tissue applications due to slow material removal rates and unacceptable collateral damage. For conventional pulsed-laser ablation with pulses from 100 ps to microseconds, a strong thermal shock wave is accompanied by cracking of the remaining bulk material and inefficient, uncontrolled material removal. However, in recent years the development of high-average-power, high-repetition-rate sub-picosecond lasers is causing a rebirth of interest in laser surgical applications due to precise and highly effective ablation capabilities with minimal thermal and shock-wave collateral damage. We applied femtosecond laser ablation for removal of hard dental tissue with the aim of finding the laser characteristics required for replacing conventional surgical tools.

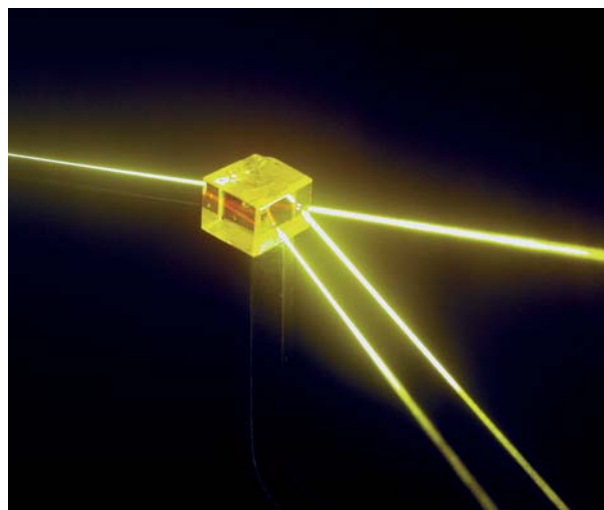
As part of a project undertaken by vacation student Bronwyn Taylor from Macquarie University, laser ablation of dental enamel has been studied over the intensity range $(0.1-1.4) \times 10^{14}$ W/cm² using 95 fs and 150 fs pulses at a pulse repetition rate of 1 kHz. The experimentally-determined ablation threshold of 2.2 ± 0.1 J/cm² was in good agreement with the theoretical predictions based on an electrostatic ablation model. The absence of collateral damage was observed using optical and scanning electron microscopy. Pulpal temperature measurements showed an increase of about 10°C during the 200 s course of ablation. However, air cooling with a rate of 5 l/min resulted in the intrapulpal temperature being maintained below the pulpal damage threshold of 5.5°C. The material removal rates for sub-picosecond precision laser ablation of dental enamel are comparable with other techniques. (A.V. Rode, E.G. Gamaly and B. Luther-Davies; B.T. Taylor and J. Dawes [Macquarie University]; A. Chan [Private dental practice]; R.M. Lowe and P. Hannaford [Swinburne University of Technology])

Electrostatic Mechanism of Ablation of Solids by Femtosecond Lasers: Ablation Thresholds for Metals and Dielectrics and Ion Acceleration

The electrostatic mechanism of ablation of solids by intense femtosecond laser pulses has been described in an explicit analytical form. It was shown that at high intensities when the ionisation of the target material is completed before the end of the pulse, the ablation mechanism is the same for both metals and dielectrics. The physics of this new ablation regime involves ion acceleration in the electrostatic field caused by charge separation created by energetic electrons escaping from the target. The formulae for ablation thresholds and ablation rates for metals and dielectrics, combining the laser and target parameters, were derived and compared to experimental data. The calculated dependence of the ablation thresholds on the pulse duration was in agreement with the experimental data in a femtosecond range, and it was linked to the dependence for nanosecond pulses. E. Gamaly [AM]; A.V. Rode and B. Luther-Davies; V.T. Tikhonchuk [University of Bordeaux, France])

Ultrafast Semiconductor Spectroscopy, Semiconductor Saturable Absorbers

We have refined our apparatus for ultra-fast pump-probe spectroscopy of semiconductors so that it can be used at all wavelengths of interest, spanning from the visible to the near infrared, and with pulses as short as 10 fs. In collaboration with EME we have continued our work on design, manufacture and characterisation of ion-implanted semiconductor saturable absorbers. Recent successes were the semiconductor saturable absorber mirrors (SESAMs) designed for solid-state laser mode-locking at 1040 nm. Using ion-implantation we have tailored the devices for use in laser crystals such as the novel Yb:YAB for which the short response times of ion-implanted SESAMs are indispensable. We are also currently working on the femtosecond differential reflectivity characterisation of ion-implanted InP. Finally, we are investigating beryllium doping of ion-implanted GaAs (collaboration with Professor U. Keller, ETH Zurich) as a promising method to increase the non-linear modulation of ultrafast ion-implanted GaAs devices. (M. Lederer, V. Kolev and B. Luther-Davies; H. Tan, C. Carmody and C. Jagadish [EME]; M. Haiml and U. Keller [ETH Zurich, Switzerland])



Rare Earth doped silicate crystal used for quantum computing

Passively Mode-Locked Ultrashort-Pulse Solid-State Lasers

In collaboration with Macquarie University and using our ion-implanted SESAMs, we have mode-locked the novel self-doubling laser crystal Yb:YAB, for the first time, producing sub 200 fs pulses at an average power of 440 mW. We have developed a number of other SESAM mode locked lasers included a high efficiency Nd:YLF system operating at 1053 nm and an ultra-low repetition rate (3.1 MHz) SESAM mode-locked high-power diode pumped Nd:YVO₄ laser for use in pulsed laser ablation experiments. The laser has the lowest repetition rate to date of any mode-locked laser.

In collaboration with the University of Karlsruhe, Germany, we have designed novel broadband ZnTe/ZnSe/CaF₂ output coupling mirrors for use with ultra-short pulse lasers and fabricated them using electron beam evaporation. These have proved to be key components in experiments that led to the first demonstration of sub 5 fs pulses with an octave-spanning spectra generated in a Kerr-lens mode-locked Ti:Sapphire laser. (M. Lederer, V. Kolev, A. Boiko and B. Luther-Davies; H. Tan and C. Jagadish [EME]; B. Taylor and J. Dawes [Macquarie University, Sydney]; R. Ell, U. Morgner and F.X. Kaertner [University of Karlsruhe, Germany])

Solid-State Laser Spectroscopy

The Solid-State Laser Spectroscopy Group's primary concern is with the understanding and the application of quantum coherence effects in solids. These range from coherence of electronic/nuclear spin levels with application for quantum computing to coherence effects in optical transitions with application to RF and microwave signal analysis.

In all cases the coherence is detected optically and relies on a range of high-resolution lasers. The prime example is an actively frequency-stabilised tunable dye laser which has a stability of better than 100 Hz. In the past year a series of actively stabilised external tunable diode laser systems have been developed with a short-term stability of 1 kHz. These lasers operate near 1.5 μm and are aimed at applications which can use components developed for telecommunications purposes such as a 40 GHz modulator.

The two groups of materials of interest are rare-earth or ion doped crystals and colour centres in diamonds. The common feature of the two materials is long spin coherence times and the ability to monitor and manipulate the spins using optical techniques. The studies of these systems have been focussed on a better understanding of the statics and dynamics of the spin levels in the ground and optical excited state.

Rare-Earth Optical Computing

There is a growing interest in rare-earth ion doped crystals for quantum information processing as a practical alternative to atomic systems. Much of this interest stems from the long coherence times of both the optical and nuclear/electronic spin transitions. The long coherence times are reflected in the narrow homogeneous line widths which we have observed to be as small as 100 Hz for the optical transitions and 5 Hz for the nuclear spin transitions.

Currently work is being carried out to determine the feasibility of a quantum computer architecture developed within the group. The architecture, based on the optical manipulation of nuclear spins, promises to be extremely robust and flexible whilst at the same time avoiding the need for complex fabrication techniques. The feasibility study is concentrating on Eu and Pr doped Y_2SiO_5 . The first step concluded this year has been to fully characterise the wave-functions involved to determine transition frequencies and probabilities for all the hyperfine transitions. This was achieved using Raman heterodyne NMR measurements as a function of magnetic field strength and orientation. This data has been fitted to obtain accurate values for the ground and excited state Hamiltonians.

Aside from providing insight into quantum computing, work on these rare earth systems is expected to lead to impressive demonstrations of electromagnetic-induced transparency, slow light and trapped light.

Mechanisms that limit the coherence times of the spin transitions and techniques for suppressing them are also being investigated. These studies have already led to almost a ten-fold increase in the spin coherence time over what is reported in the literature.

The final aspect of the feasibility study is the characterisation of the interactions between the dopant ions. (J. Longdell, E. Fraval, M.J. Sellars and N.B. Manson)

Optical Processing

The long coherence times of rare-earth impurity ions in solids can be utilised in other ways. For example, the coherence established by short light pulses applied within the coherence time of typically 1 ms interfere with one another and give rise to a frequency grating in the ground and excited state. In the case of hole-burning material, this grating can remain for many hours and when the material is excited with a single short light pulse will regenerate the original pulse sequence. Thus the pulse sequence is stored. The technique, termed time domain optical memory, has been studied in the Centre over a numbers of years. The difference from the conventional approach is that by using the highly stable laser and an interferometer the entire light waveform can be reconstructed – amplitude and phase. The interferometer has also been simplified by providing a reference beam, which passes through the sample co-linear with the data

and signal pulses. This provides a powerful and flexible phase-sensitive time domain memory scheme.

Data storage and recovery is an example of simple optical processing. However, the approach is more attractive for advanced processing which takes advantage of the large bandwidth and time-bandwidth product. A case in point is the development of a radio/microwave frequency spectrum analyser, a project funded by DSTO and the Australian Photonics CRC. The unique feature of this device will be its ability to perform real-time spectrum analysis, monitoring of all frequency channels all of the time. In this application a grating is stored in a hole-burning material and used to scatter a beam modulated by the unknown radio frequency. The time dependence of the output indicates the frequency of the radio frequency field. The operating wavelength was chosen to be 1.54 μm corresponding to an absorption line in Er-doped Y_2SiO_5 and enables us to capitalise on the communication technology available in this region. A 16 MHz bandwidth, 50 kHz resolution prototype has been demonstrated. In principle, the analyser bandwidth is limited by the inhomogeneous width of the infrared transition, which is currently ≈ 1 GHz. Efforts are underway to increase this to 100 GHz by developing modified crystal growth techniques. (D. Scott, M.J. Sellars and N.B. Manson)

Electromagnetically-Induced Transparency

The nitrogen-vacancy centre in diamond has proven invaluable for the study of strongly driven transitions and has been studied over a number of years. Transitions within the nuclear and electron spin levels are studied using a novel optical/RF three-wave mixing scheme where a resonant laser and RF field create a stimulated optical field. The stimulated beam is detected as a heterodyne beat with the magnitude proportional to the coherence of the spin system. This provides the means of studying coherence in the spin levels and the technique can be optimised by working close to an anti-crossing of the electron spin levels. There is also a fortuitous optical pumping of the population into a single spin state which enhances the signal such that they are obtained with excellent signal to noise. The nitrogen-vacancy centre has been used in this way for studies of driven two and three level systems. In the present year we have studied the case where a three-level system is driven by two strong fields and probed by a weak field. Experiment and theory have covered both the homogeneously broadened and inhomogeneously broadened situations.

The nitrogen-vacancy centre has also been used to study electromagnetically induced transparency. This is where the application of a field resonant with one transition can reduce the absorption of a field resonant with a second transition. Such studies have been made in many laboratories world wide. However, the aspect of our work that has not been covered elsewhere is the situation where the transparency is perturbed by the application of a further electromagnetic field. In our case there are six spin levels and only three are involved in regular electromagnetically-induced transparency. There are then various ways other fields can be applied and it is found that they can destroy, shift or split the sharp transparency feature. A specific case modelled through the year is where there is an apparent interaction between an electromagnetically-induced transparency and a spectral hole. There is a splitting of the electromagnetically-induced feature and this is explained satisfactorily. (E.A. Wilson and N.B. Manson)

Spectroscopy and Crystal Growing

The spectroscopy of the nitrogen-vacancy centre in diamond used in the studies of driven two-level and three-level systems and electromagnetically-induced transparency is not well understood. However, in the current year we have been able to explain the optical pumping cycle and show that with a centre perfectly aligned with an external magnetic field it was possible to have the optical cycling pump the population into a single nuclear hyperfine level. This creates a Boltzman-type distribution which would normally require cooling to mK or lower. Although this aspect is now understood there are concerns over the ionisation state of the centre under optical excitation and this is being investigated.

The studies of up-conversion and lasing in Er-doped KYLIF_5 have been concluded in the year. This was done in collaboration with Professor Brain Henderson, Cambridge University, UK and Professor Ann Silversmith, Hamilton College, NY, USA

There has been preliminary operation of the crystal growing furnace for preparation of double doped Y_2SiO_5 material. These crystals are required for enhanced performance of the time domain spectrum analyser. (A. Smith, M.J. Sellars and N.B. Manson)

Atom Manipulation

The atom manipulation project is a joint program between the Laser Physics Centre and the Atomic and Molecular Physics Laboratories (AMPL) which uses laser cooling and trapping techniques to investigate applications of atom optical elements to new devices on nanometre scales, and to study fundamental atomic collision physics (see AMPL annual report).

The Atom Manipulation Project has a “bright” ($>10^{10}$ atoms/second) beam line source of laser-cooled metastable He atoms which is used to investigate new atom optical elements that manipulate the atomic de Broglie wave. This facility is being used to study, for example, the guiding of atoms through hollow optical fibres using evanescent light fields. A similar metastable He source facility is used to generate liquid nitrogen-cooled atoms for applications such as atom lithography, where this year we have been developing an apparatus to study the relative contributions of UV light and several metastable atomic species to the lithography process.

This year has also seen the implementation of a third beam facility based on a liquid helium-cooled, metastable He source. By operating this source at liquid helium temperatures (~ 5 K), we have generated an atomic beam with velocities of several hundred m/s. Already the cryogenic source has shown promise for focusing the atomic beam using transverse molasses, due to the



LPC students with the high resolution laser system and crystal structure models

long interaction time that the slower source allows. Using this beam, we hope to avoid the need for large scale Zeeman slowing in order to load our metastable helium magneto-optical trap for experiments with ultracold atoms. (R. Dall, V. Leung, J. Swansson and K.G.H. Baldwin; S.J. Buckman [AMPL])

UV Laser Spectroscopy

In parallel with the finalisation of the near-continuum (175 nm) spectrum of the oxygen Schumann-Runge band system (see AMPL annual report), work has continued on a joint project with Macquarie University to develop new high-resolution laser spectroscopic sources. This year we have injected cw radiation at 1.5 mm from an external cavity diode laser (ECDL) developed at ANU into an optical parametric oscillator (OPO) constructed at Macquarie that is pumped by a 1.06 mm Nd:YAG laser. The next stage is to construct a similar OPO based on a periodically poled KTP crystal injected with 842 nm light from a further ECDL system, which may ultimately be applied to improve precision measurements of the helium 1S–2S transition. (K.G.H. Baldwin; M. Kono [AMPL]; Y. He, R. White and B.J. Orr [Macquarie University])

As part of a collaborative program with the Vrije (Free) University of Amsterdam, Dr Ken Baldwin undertook a series of experiments this year using the XUV laser facility at the VU. The aim was to study the $b^1\Pi_u$ state of diatomic nitrogen, whose predissociation rate is a key input for the photochemical processes in terrestrial and planetary atmospheres. The XUV laser facility employs narrowband UV (frequency doubled visible) radiation which is frequency tripled in a pulsed Xenon jet to allow 1 + 1 (XUV + UV) ionisation spectroscopy that is single (XUV) photon resonant with the $b^1\Pi_u$ state.

This work studied the ro-vibronically resolved electronic spectra up to $v = 9$ in the isotopes $^{14}\text{N}_2$, $^{14}\text{N}^{15}\text{N}$, and $^{15}\text{N}_2$. This data measured the less abundant isotopic spectra for a number of these bands for the first time, and extends previous measurements for known bands to higher J. The data yielded both the isotope shifts and the predissociation lifetime for the $b^1\Pi_u$ state of the isotopomers, providing new information to allow further development in the UV Physics Unit (AMPL) of models for the molecular potentials. (K.G.H. Baldwin; J.P. Sprengers and W. Ubachs [Vrije University of Amsterdam, Netherlands])

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