INTEGRATED WAVEGUIDE OSCILLATOR

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Long term goal and motivation

The femtosecond laser direct-write technique is a unique tool for the creation of integrated optical waveguide systems. Using this technique it is possible to fabricate arbitrary networks of optical waveguide devices in a wide range of transparent media including passive, active and highly-nonlinear glasses. The ability to combine different waveguide functional forms such as splitters, amplifiers, gratings and lasers in 3D 'circuits' enables novel research in fields such as telecommunications, quantum information, astrophotonics, defence, bio-photonics, metrology and micro-sensing. Our work leads the international field in the development of active integrated optical systems. Examples of devices developed at Macquarie include waveguide amplifiers and monolithic waveguide oscillators.

The miniaturisation and integration of components for optical communication and sensing networks is recognised as an essential step in the development of these technologies. These goals lie at the core of the CUDOS research program. This Flagship program encompasses these goals in its aims to develop integrated optical systems for amplifier and laser applications while enabling the experimental realisation of coupled non-linear waveguide devices designed by our colleagues at ANU. In collaboration with external research partners such as Adelaide University, DSTO, Oxford University and the Toyota Technical Institute we conduct internationally leading research towards:

- the development of miniature waveguide laser arrays
- the application of three-dimensional 'circuitry' to the miniaturisation of optical devices
- the study of fundamental light-matter interactions through unique waveguide manufacturing and characterisation capabilities at Macquarie University.

CUDOS approach

Macquarie University is an international leader in the field of femtosecond laser materials processing. Our expertise has enabled the development of world-class facilities dedicated to the field of direct-write photonics. Through several ARC and internal university funding programs we have strategically invested in ultrafast laser, nanopositioning, sample processing and optical diagnostics systems to enable us to develop device fabrication and characterisation facilities that are uniquely flexible and almost without equal in our field. Our combined approach of fundamental light-materials interaction research and practical device development

Integrated Waveguide Oscillator team.

has enabled us to conduct insightful research and demonstrate world leading photonic device results. At Macquarie we have the following capabilities:

- precise automated cutting, lapping & polishing of host materials
- monitored 3D air-bearing motion control of host samples
- device fabrication with features below the diffraction limit
- collection of device transmission and reflection characteristics
- imaging near-field and far-field mode distributions
- determination of insertion, coupling, propagation and polarisation-dependent loss
- obtaining induced refractive index profiles (profilometry / phase contrast)
- measure device gain and laser characteristics
- NSOM and micro-Raman analysis of fabricated devices
- advanced fibre pigtailing
- RSoft device design and modelling.

Collaborative links

Within CUDOS

- ANU - expertise in the theoretical underpinnings and design of coupled waveguide devices. Characterisation of slow light switching devices.

External to CUDOS

- Queensland University of Technology – Dr Esa Jaatinen visited MQ for 2 weeks commencing plans to commission a self heterodyne detection system into Macquarie's characterisation facility in order to accurately measure waveguide laser linewidths.
- DSTO/University of Adelaide - User-driven perspective on requirements and applications for compact waveguide oscillators, particularly in the mid-IR. Supplier of doped ZBLAN glass substrates.
- Oxford University, UK - In 2010 Dr Graham Marshall took part in a CUDOS funded collaborative research project with Alex Jesacher, Martin Booth and Tony Wilson at Oxford University extending their initial application of third harmonic generation imaging techniques to characterising ultrafast laser written waveguide devices. This work was published in Optics Letters [5].
- Toyota Technical Institute, Japan - Supplier of tailored glass samples to host fabricated laser devices. For example, Yb-doped borosilicate glass.

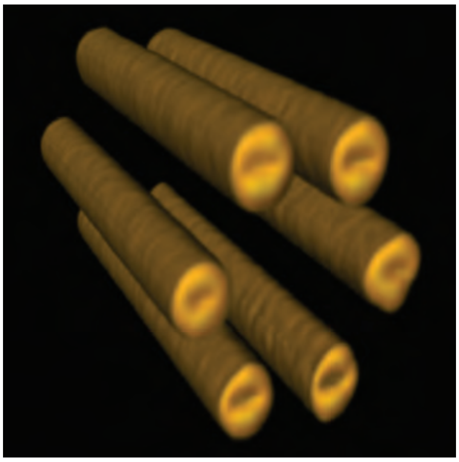

Fig 1: A 3D reconstruction of a hexagonal waveguide array using third harmonic generation imaging techniques.

Goals for 2010

The project goals for 2010 and beyond include demonstrating multi-wavelength laser devices and their subsequent power scaling, the characterisation of coupled waveguide Bragg grating devices, and the investigation into fabricating mid-IR laser sources. In parallel with device research, the project team aimed to re-engineer the manufacturing and diagnostic facilities at Macquarie University in order to improve the quality of short period Bragg gratings inscribed into a number of transparent materials using different writing regimes. Further studies into understanding the underlying laser-material interactions giving rise to such gratings and their application to realising integrated waveguide oscillators was also to be undertaken in 2010.

Achievements and highlights for 2010

Waveguides written in active glasses and that incorporate Bragg gratings form the basis of a stable, monolithic waveguide laser platform fabricated at Macquarie University. Previously we have demonstrated single wavelength structures based on ytterbium doped phosphate glasses; these allow laser operation near 1030 nm and with output powers of several hundred milliwatts. The distributed-feedback laser devices can be unidirectionally or double-end pumped and the balance of laser power emitted from the facets controlled by the position of a phase shift in the grating structure.

Sampled gratings and dual wavelength lasers [6]

The point-by-point method of fibre Bragg grating fabrication enables complete positional control of each index modification in the grating. Sampled gratings that incorporate phase-shifts are thus easily fabricated. In a $\pi/2$-phase shifted design we showed that the fundamental Bragg resonance in a fibre Bragg grating is suppressed leaving the sampled grating sidebands [6]. We then transferred this knowledge to the waveguide-Bragg grating writing technique to create phase-modulated sampled grating based multi-wavelength lasers in Yb-doped phosphate glass. When manifest in a DFB waveguide laser, a sampled $\pi/2$-phase shifted grating results in a dual wavelength laser in which the absolute wavelength and laser line spacing is controlled by the phase-shifted grating's parameters. By fabricating a range of waveguide Bragg gratings around the gain peak at 1030 nm we obtained dual wavelength laser operation with separation of 10 to 20 nm. Wavelength separation less than this exhibits strong mode competition, indicative of the broadened gain bandwidth of the material. Improvements are possible using more complicated DFB structures where individual gain regions are separated.

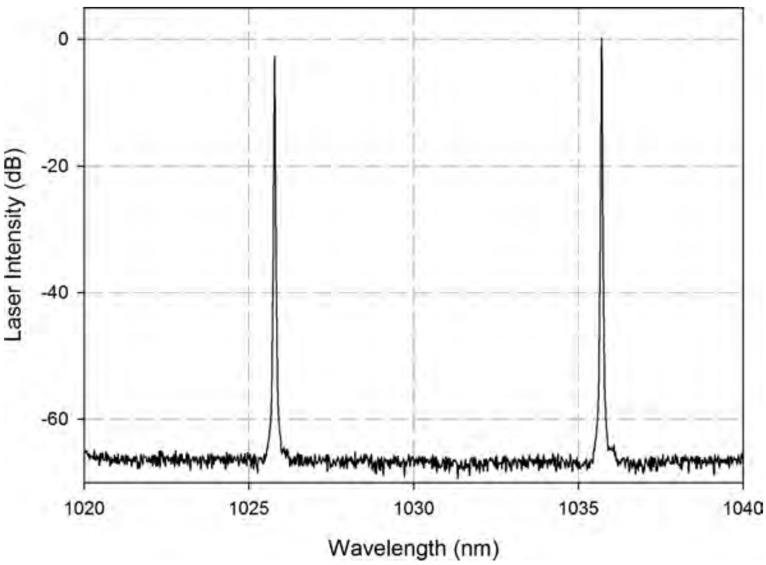

Fig 2: Dual wavelength laser fabricated in Yb-doped phosphate glass using a phase modulated sampled waveguide Bragg grating.

High inversion ratios and a large gain bandwidth

Dual wavelength lasers are interesting for such areas as Terahertz generation however multiple line operation is also relevant for applications in spectroscopy. Presently mode competition places a lower bound on the laser line separation. There are also unanswered questions regarding the usable gain bandwidth and what pump powers might be needed. To explore the range of possible wavelengths we wrote DFB structures in a 10 mm long Yb phosphate glass sample, ranging from the pump wavelength at 976 nm up to 1100 nm. Laser operation was possible at 985 nm, less than 10 nm away from the zero phonon line / pump wavelength, and up to 1075 nm (and indeed up to 1085 nm using a 20 mm long sample). The ability of the material to lase at 985 nm implies that, with the pump power available to us, we are pumping around 75% of the available Yb ions to inversion. With such high inversion ratios (hence high gain) and a gain bandwidth of 100 nm, the simultaneous operation of at least ten laser lines should be possible with appropriate grating designs. This study forms part of our ongoing work.

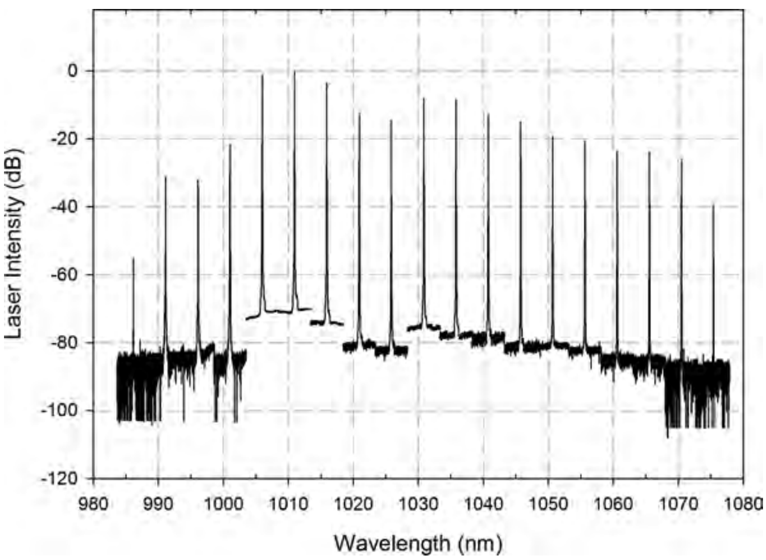

Fig 3: Single wavelength waveguide lasers operating from 985 nm up to 1075 nm.

Glass modification upon exposure to femtosecond laser pulses [7, 8]

A general picture of refractive index change mechanisms in glass modified by a femtosecond laser has proven elusive. Raman microscopy was used at MQ in conjunction with refractive near-field profilometry to analyse the structure of both borosilicate glass (Schott BK7) and Yb-doped phosphate glass (Kigre QX) modified by a femtosecond laser and determine the mechanisms of the observed refractive index change. The table below summarises our work in this area.

1 kHz Rep Rates	MHz Rep Rates
Successive, abrupt bursts of heat	Cumulative heating –gradual changes in temperature
Generation of non-bridging oxygen atoms (NBOs) and breaking of R-O bonds (R=P, B, Si etc.)	Expansion and contraction of R-O-R linkages (R=P, B, Si etc.)
Formation/removal of colour centres and increase in molar refractivity	Density changes of the glass network
Ideal for creating waveguide Bragg gratings	Better photostability and no reduction in UV cut-off wavelength

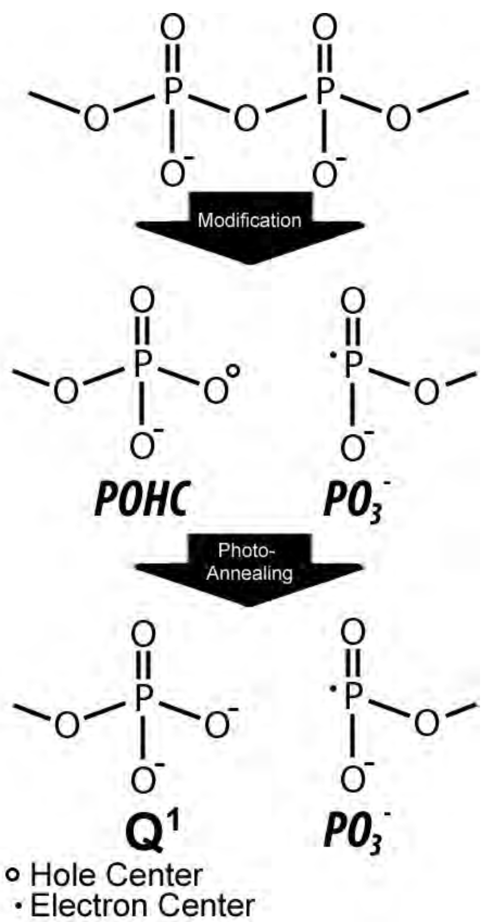

Fig 4: Colour centre formation/removal in phosphate glass under kHz rep rates. Phosphorous–oxygen hole centres (POHCs) and PO_3– ions form as a result of P–O bonds being broken during the modification process, and the subsequent removal of POHCs give rise to the increased proportion of Q^1 P-tetrahedra.

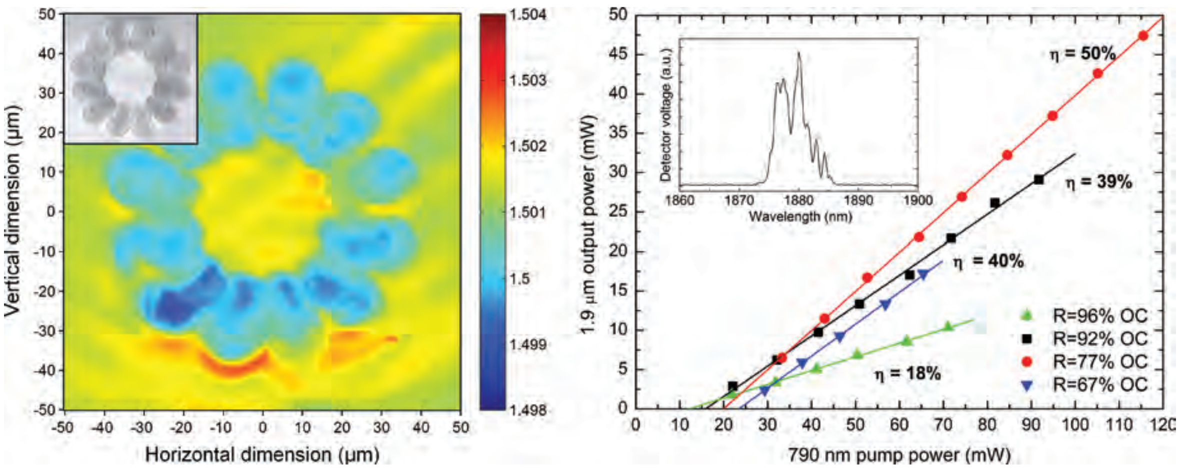

Fig 5: Caption: (Left) Absolute refractive index profile at 637 nm of a waveguide consisting of 24 partially overlapping cylinders fabricated at 1000 mm/min. Inset shows the corresponding optical microscope image. (Right) Measured slope efficiency for a Tm:ZBLAN waveguide laser as a function of absorbed 790 nm pump power and a range of output couplers. The inset is the recorded free running spectra from the waveguide laser.

Demonstration of a mid-IR light source [12, 14]

In collaboration with our partners at DSTO/University of Adelaide, a Tm^{3+} doped ZBLAN glass buried waveguide laser which produced 47 mW at 1880 nm was demonstrated. This is the first report of a mid-IR waveguide laser fabricated using the femtosecond laser direct-write technique. The waveguide cladding was defined by two overlapped rings made up of directly written modified glass tubes, resulting in a depressed-index cladding structure (Figure 5). The laser resonator was created using external dielectric mirrors resulting in 50% internal slope efficiency and a measured M^2 value of 1.7. These results are captured in our February 2011 submission to Optics Letters. Investigations into fabricating a monolithic device which incorporates internal feedback, i.e. in the form of waveguide Bragg gratings, are ongoing.

Invited chapter in a femtosecond laser machining Springer book

The diverse range of opportunities and activity in fibre sensing and fibre lasers has triggered an equally diverse range of research into new grating fabrication methods using femtosecond lasers. Research and development of femtosecond grating inscription methods, properties and devices is reviewed in this chapter. This chapter recognises the team at Macquarie as a genuine leader in the field of femtosecond laser machining. Figure 6 shows the cover of the book to be published.

Fig 6: Research and development of femtosecond grating inscription methods, properties and devices is reviewed by the Macquarie team in a chapter of an upcoming Springer book on femtosecond laser micromachining.

Investigation of coupled non-linear waveguide systems [15]

In collaboration with the ANU, waveguide Bragg grating couplers fabricated at MQ in fused silica using the direct-write technique demonstrated precise control of the phase shift between individual Bragg gratings. Two specific couplers with symmetric and antisymmetric gratings showed characteristic differences in their transmission spectra. Most importantly, for the antisymmetric configuration, the coupling was shown to be independent of wavelength within the Bragg reflection bandwidth. This demonstrated the feasibility of laser-written devices for spatio-temporal control of slow-light pulses whose group velocity can be manipulated in the vicinity of the Bragg-resonance. A collaborative journal submission was made in January 2011 outlining this work.

Published Papers

Invited

1. M. Ams, P. Dekker, G. D. Marshall, D. J. Little and M. J. Withford, "Directly written DFB waveguide lasers using femtosecond laser pulses," Paper 56 in the International High-Power Laser Ablation Conference (HPLA), Santa Fe, USA, 2010

2. A. Fuerbach, S. Gross, C. Miese, G. D. Marshall, M. Ams, P. Dekker, M. J. Withford, "Direct writing of Photonic Devices using femtosecond laser pulses," Paper in the 12th International Conference on Transparent Optical Networks, Munich, Germany, 2010

3. G. D. Marshall, A. Jesacher, M. Ams, P. Dekker, D. J. Little, C. Miese, A. Fuerbach, M. J. Booth, T. Wilson and M. J. Withford, "Femtosecond Laser Written Bragg Gratings," Paper in Bragg Gratings, Photosensitivity and Poling in Glass Waveguides (BGPP), Karlsruhe, Germany, 2010

4. G. D. Marshall, M. Ams, D. J. Little, P. Dekker, C. Miese, S. Gross, A. Fuerbach, C. Neil, A. Lehmann, N. Jovanovic, J. Lawrence and M. J. Withford, "Recent developments in active and passive glass photonics, fabricated using ultrafast laser direct-write methods," Paper in the 19th National Congress of the Australian Institute of Physics (AIP), Melbourne, Australia, 2010

Contributed

5. G. D. Marshall, A. Jesacher, A. Thayil, M. J. Withford and M. Booth, "Three-dimensional imaging of direct-written photonic structures," Accepted to Optics Letters January 2011

6. G. D. Marshall, R. J. Williams, N. Jovanovic, M. J. Steel and M. J. Withford, "Point-by-point written fiber-Bragg gratings and their application in complex grating designs," Opt. Express 18, pp. 19844, 2010

7. D. J. Little, M. Ams, S. Gross, P. Dekker, G. D. Marshall, J. M. Dawes and M. J. Withford, "Structural changes in BK7 glass upon exposure to femtosecond laser pulses", J. Raman Spec. DOI: 10.1002/jrs.2770, 2010

8. D. J. Little, M. Ams, P. Dekker, G. D. Marshall and M. J. Withford, "Mechanism of femtosecond-laser induced refractive index change in phosphate glass under a low repetition-rate regime," J. Appl. Phys. 108, pp. 033110, 2010

9. P. Dekker, M. Ams, G. D. Marshall, D. J. Little and M. J.Withford, "Annealing dynamics of waveguide Bragg gratings: evidence of femtosecond laser induced colour centres," Opt. Express 18, pp. 3274-3283, 2010

10. M. Ams, R. J. Williams and M. J. Withford, "Direct laser written waveguide coupler with an optically-tunable splitting ratio", Paper 7925-19 in SPIE Photonics West, San Francisco, USA, 2011

11. M. Ams, R. J. Williams and M. J. Withford, "Optically-tunable waveguide coupler directly written in glass using femtosecond laser pulses," Paper in the 19th National Congress of the Australian Institute of Physics (AIP), Melbourne, Australia, 2010

12. S. Gross, D. Lancaster, H. Ebendorff-Heidepriem, K. Kuan, T. M. Monro, M. J. Withford and A. Fuerbach, "Laser direct written depressed cladding waveguides in fluoride glass," Paper in the 19th National Congress of the Australian Institute of Physics (AIP), Melbourne, Australia, 2010

13. C. Miese, M. J. Withford, A. Fuerbach, "Fast direct written waveguide Bragg gratings in the cumulative heating regime," Paper in the 19th National Congress of the Australian Institute of Physics (AIP), Melbourne, Australia, 2010

14. D. G. Lancaster, S. Gross, H. Ebendorff-Heidepriem, K. Kuan, T. M. Monro, A. Fuerbach and M. J. Withford, "Towards realisation of a 2μm thulium 'chip' laser," Paper in the 19th National Congress of the Australian Institute of Physics (AIP), Melbourne, Australia, 2010

15. S. Ha, M. Ams, G. D. Marshall, D. N. Neshev, A. A. Sukhorukov, Y. S. Kivshar and M. J. Withford, "Direct laser written couplers with shifted Bragg gratings," Paper in Bragg Gratings, Photosensitivity and Poling in Glass Waveguides (BGPP), Karlsruhe, Germany, 2010

16. C. T. Miese, M. J. Withford and A. Fuerbach, "Fast direct fabrication of waveguide Bragg gratings," Paper in Bragg Gratings, Photosensitivity and Poling in Glass Waveguides (BGPP), Karlsruhe, Germany, 2010

17. S. Gross, M. J. Withford and A. Fuerbach, "Direct femtosecond laser written waveguides in bulk Ti3+:sapphire", Paper 75890U in SPIE Photonics West, San Francisco, USA, 2010

18. C. Miese, M. J. Withford and A. Fuerbach, "Ultrafast direct written waveguide Bragg gratings utilizing a high pulse energy femtosecond oscillator," Paper in the 12th International Conference on Transparent Optical Networks, Munich, Germany, 2010

19. C. Miese, M. J. Withford and A. Fuerbach, "Micro-damage induced direct written waveguide Bragg gratings in the cumulative heating regime," Paper in Integrated Photonics Research, Silicon and Nano Photonics (IPR), Monterey, USA, 2010

SLOW LIGHT

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Project Manager: Christelle Monat **Science Leader:** Martijn de Sterke

Long term goal and motivation

Slow light can lead to strongly enhanced interactions with the optical medium, lowering the intensity requirements for nonlinear effects. One long term goal is to exploit this phenomenon to develop low power nonlinear signal processing devices.

Our second long term aim is to explore, through theory and simulation, novel optical configurations in which the propagation of optical pulses can be slowed down.

CUDOS approach/competitive advantage

Through experiments and theory we study slowing of light in a nonlinear medium with a periodic structure. The efficiency per unit length of nonlinear effects is enhanced through exploiting strong slow light–matter interaction occurring in these structures.

Most linear slow-light research suffers from the effect of dispersion with a consequent broadening of the slow-light pulses. By controlling the nonlinear response of the medium we can prevent this broadening from occurring and balance dispersion. The solitons that result are themselves a special case of slow light propagation.

Collaborative links

This is a collaborative project between researchers at the University of Sydney, the Australian National University (ANU/NL and ANU/LC) and the University of Technology of Sydney. Different aspects of the theoretical work are carried out at the three universities.

The experimental work is a collaborative effort, with chalcogenide waveguides and photonic crystals fabricated at the ANU/LC, and grating writing performed at the University of Sydney.

Collaboration with Prof. Krauss's group (St Andrews University) has developed for realising silicon and chalcogenide photonic crystal slabs. The group is also working with Prof. Kuipers's group at AMOLF (The Netherlands), on the characterisation of slow-light photonic crystal devices using a heterodyne NSOM technique. A more general collaboration between CUDOS and the European consortium, SPLASH (Slow Photon Light Activated SwitcH), has been built and benefits from a DEST-International linkage grant since October 2007.

Collaboration with DTU Fotonik group at Technical University of Denmark is continuing, with the support of visiting professorial fellowship for Prof. Andrei Lavrinenko through the award of ARC Linkage international grant on "Slow-light photonics" (CI Dr. Andrey Sukhorukov). Following a visit of Dr. Jacob Scheuer (Tel-Aviv University) to ANU/NL with the support of the European Cooperation in Science and Technology (COST) Reciprocal Pilot Programme with Australia, we have completed a joint work on all-optical pulse trapping with dark resonances. As part of the continuing collaboration with Prof. Conelia Denz's group at Munster University, Mr Sebastian Kroesen (student from Munster University) visited ANU/NL to study theoretically slow-light dynamics in nonlinear periodic structures (DAAD travel grant).

Slow light team.