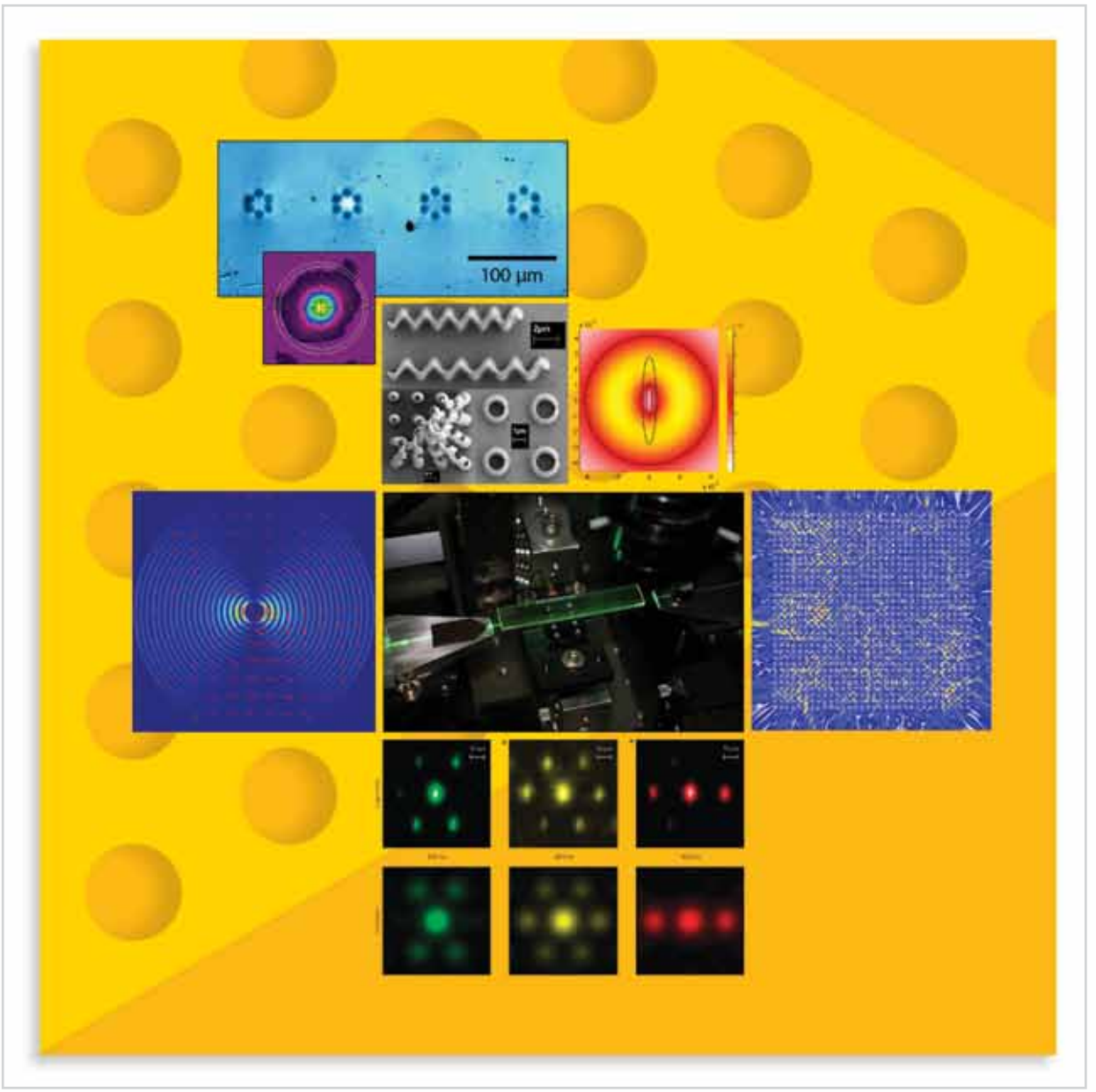
ANNUAL 2009 REPORT



CUDOS

The Centre for Ultrahigh Bandwidth Devices for Optical Systems (CUDOS)

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 waveguide devices in a wide range of optical 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' is enabling novel research in fields such as telecommunications, quantum information, defence, bio-photonics 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 DSTO, Oxford University and the Toyota Technical Institute we continue to conduct internationally leading research towards:

- the development of miniature arrays of laser sources
- the application of three-dimensional 'circuitry' to the miniaturisation of optical devices
- the study of fundamental optical physics through unique waveguide manufacturing capabilities developed at Macquarie University.

Integrated Waveguide Oscillator team

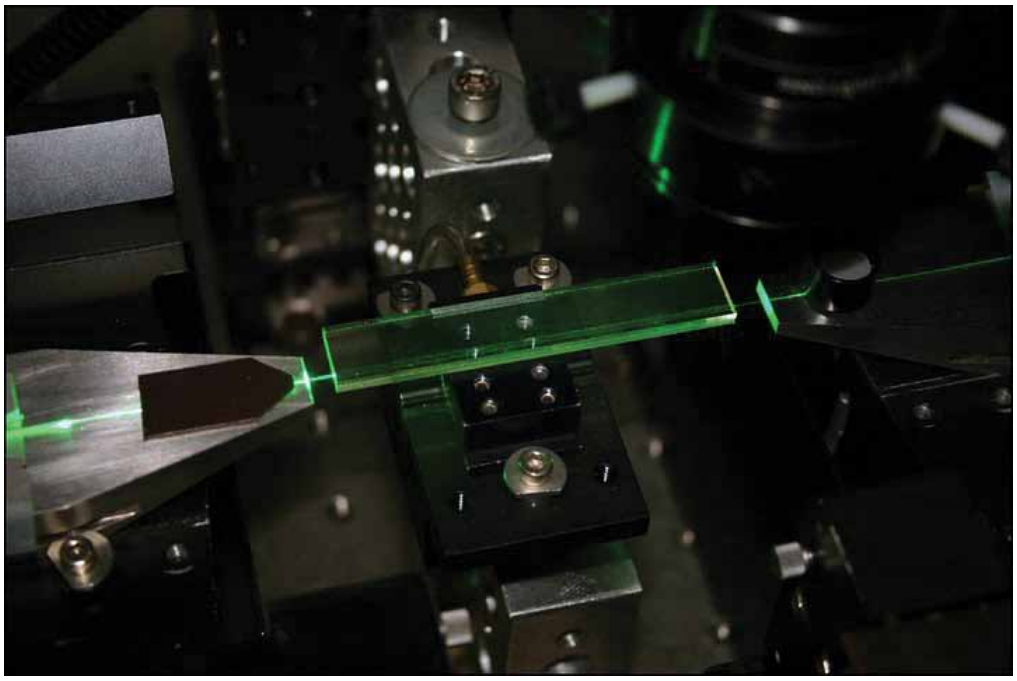

Fig 1. Photo-annealing ultrafast laser written waveguide Bragg gratings in Yb-doped phosphate glass using 532 nm light.

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

- rigorous and precise sample preparation (automated cutting, lapping & polishing)
- monitored 3D air-bearing motion control of host samples
- accurate and precise device fabrication with features sub diffraction limit
- transmission and reflection readings and spectra
- imaging of near-field and far-field mode distributions
- insertion, coupling, propagation and polarisation-dependent loss determination
- induced refractive index profiles (profilometry / phase contrast)
- device gain and laser characteristics
- NSOM and micro-Raman analysis of fabricated devices
- advanced fibre pigtailing.

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

- DSTO/University of Adelaide – user-driven perspective on requirements and applications for compact waveguide oscillators, particularly in the mid-IR.
- Oxford University, UK – In 2009 Dr Graham Marshall took part in a CUDOS funded collaborative research project with Alex Jesacher, Martin Booth and Tony Wilson at Oxford University working on the application of third harmonic generation imaging techniques for characterising ultrafast laser written waveguide devices.
- Toyota Technical Institute, Japan – supplier of tailored glass samples to host fabricated laser devices. For example, Yb-doped borosilicate glass.

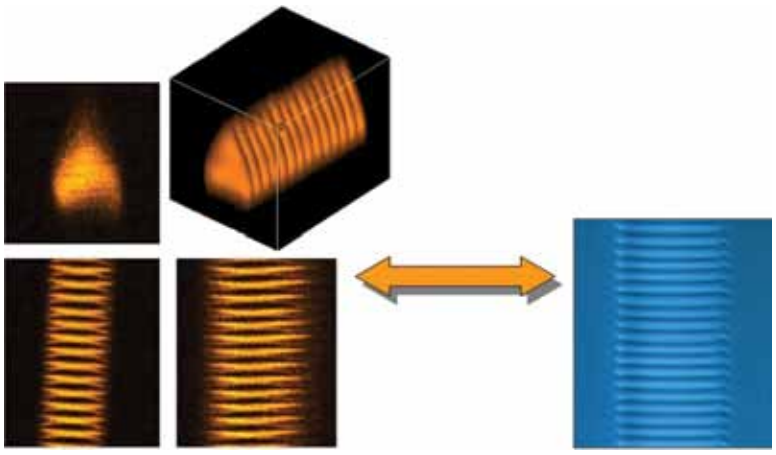

Fig 2: (left) Third harmonic generation (THG) projections of a 2 µm period waveguide Bragg grating written in Yb-doped phosphate glass and (right) a transmission differential interference contrast (TDIC) image of the same structure.

Goals for 2009

The project goals for 2009 and beyond included laying the foundation for multi-wavelength laser devices and their subsequent power scaling and reduction in lasing threshold, the demonstration of linewidth narrowed WGLs, the development of coupled waveguide Bragg grating devices, and the investigation of fundamental mechanisms of temporal beam shaping on photo-ionisation rates. In parallel with device research, the project team continued to improve the manufacturing and diagnostic facilities at Macquarie University with particular emphasis on the fabrication of short period Bragg gratings of very high quality. In light of past successes, we predominantly consolidated our studies in 2009 and focussed on understanding the underlying laser-material interactions giving rise to such gratings and their application to realising integrated waveguide oscillators.

Achievements and highlights for 2009

Power scaling of the integrated waveguide oscillator platform

The application of new, higher gain materials and a reduction of the guided mode size led to unprecedented power scaling of the laser platform. Improvements in mode-matching to optical fibres and grating fabrication techniques enabled the realisation of a 100 mW monolithic Yb waveguide laser operating at 1032 nm [8]. Multiple wavelength devices were fabricated in arrays demonstrating the flexibility and robustness of the manufacturing technique. These results triggered 3 major international invited talks in 2009 with another 2 scheduled for 2010.

Invited review article on ultrafast laser written active devices [1]

The femtosecond laser direct-write technique was reviewed as a technology capable of producing active waveguide devices inside bulk transparent materials. The application of the femtosecond laser direct-write technique to doped phosphate glass hosts was demonstrated. This paper not only raises the prospect of creating optical devices for the use in aiding all-optical access communication networks but also recognises the team at Macquarie as a genuine leader in the field of femtosecond laser written active devices. Figure 3 shows the article featured on the cover of the journal.

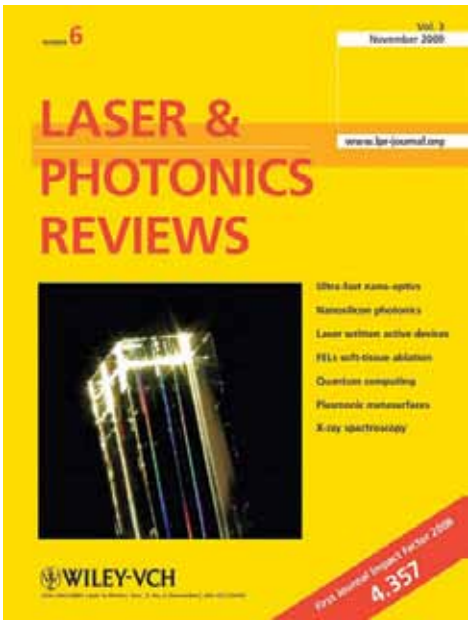

Fig 3. Journal cover showing white light diffraction from waveguide Bragg gratings fabricated in doped phosphate glass using the femtosecond laser direct-write technique at Macquarie.

Light-material consolidation studies conclude that colour centres form an important part of ultrafast laser waveguide device fabrication [7]

The formation of colour centres in waveguide devices written into Kigre 'QX' phosphate glass using infrared femtosecond laser inscription techniques was observed. Micro-Raman and refractive index profilometry studies indicate that bond breaking during the inscription process is responsible. Using waveguide Bragg gratings as a diagnostic tool, photobleaching of these induced colour centres was shown to occur from visible light generated by co-operative luminescence between neighbouring Yb ions. These results suggest that either ultrafast laser processed samples need to be 'aged' in a similar way to FBGs used in the telecommunications industry in order to obtain long lifetime stable devices or that specialty tailored samples be used.

Investigation of coupled non-linear waveguide systems [9,13]

In coordination 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.

New developments in rapid fabrication of novel waveguide oscillators

Initial studies show that 1st order waveguide Bragg gratings at 1550 nm can be rapidly realised in undoped borosilicate glass using a 5 MHz pulse train (Figure 4). Similar gratings in a doped version of this glass will reduce the fabrication time of integrated waveguide oscillators by up to three orders of magnitude. As a result, fabrication times for waveguide oscillators will be reduced to seconds in some materials. The same high power oscillator was also used to show that C-band light can be guided along a

depressed cladding arrangement fabricated in doped ZBLAN glass (Figure 5). Such a host will be used to realise mid-IR light sources in collaboration with our partners at DSTO/University of Adelaide.

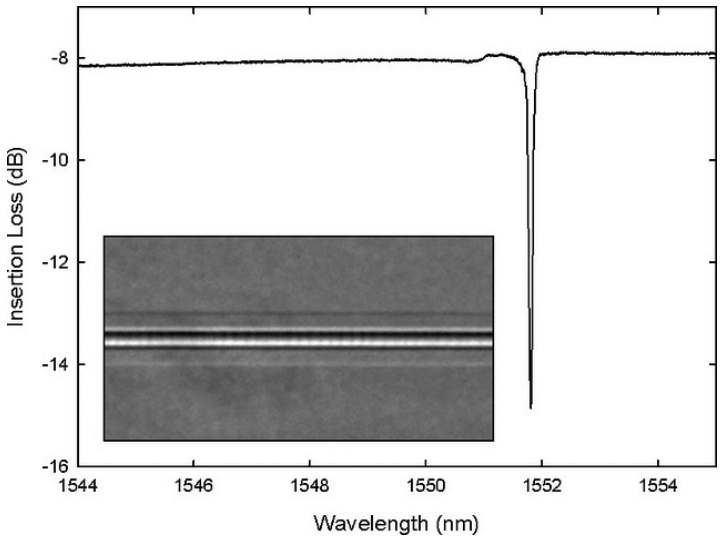

Fig 4. Transmission spectrum from a 1st order waveguide Bragg grating fabricated in undoped borosilicate glass using a high power oscillator. Inset shows an optical micrograph of the waveguide Bragg grating structure.

Targets for 2010

In 2010 we will continue to investigate and fabricate waveguide oscillators with an emphasis on targeting new wavelength regimes, increasing the functionality of current devices and decreasing the fabrication time of such devices. Our key objective will be to develop stable, linewidth narrowed, simultaneous operation, multi-wavelength laser devices. To achieve this we will pursue our efforts towards reducing the lasing threshold below 20 mW, exploiting the inherent 3D capability of the writing technique and using samples designed to realise wavelength specific waveguide devices with long lifetimes. Such samples will be sourced from our collaborators at DSTO/University of Adelaide (doped ZBLAN glasses) and the Toyota Technical Institute in Japan (doped borosilicate glasses). Together with the suite of diagnostic systems at Macquarie, in depth analysis of fabricated devices will be carried out with our collaborators at Oxford University in the UK using third harmonic generation (THG) based imaging techniques.

In parallel to these aims, we will continue our internal collaborative investigation into slow light switching in coupled waveguide Bragg grating devices with ANU. It is anticipated that such structures fabricated in nonlinear and active glasses, such as doped phosphates, will offer further opportunities for all-optical control of light. We foresee a number of journal submissions in 2010 to come from this work.

In 2010 we also plan to commission a self heterodyne detection system into Macquarie's characterisation facility in order to accurately measure waveguide laser linewidths.

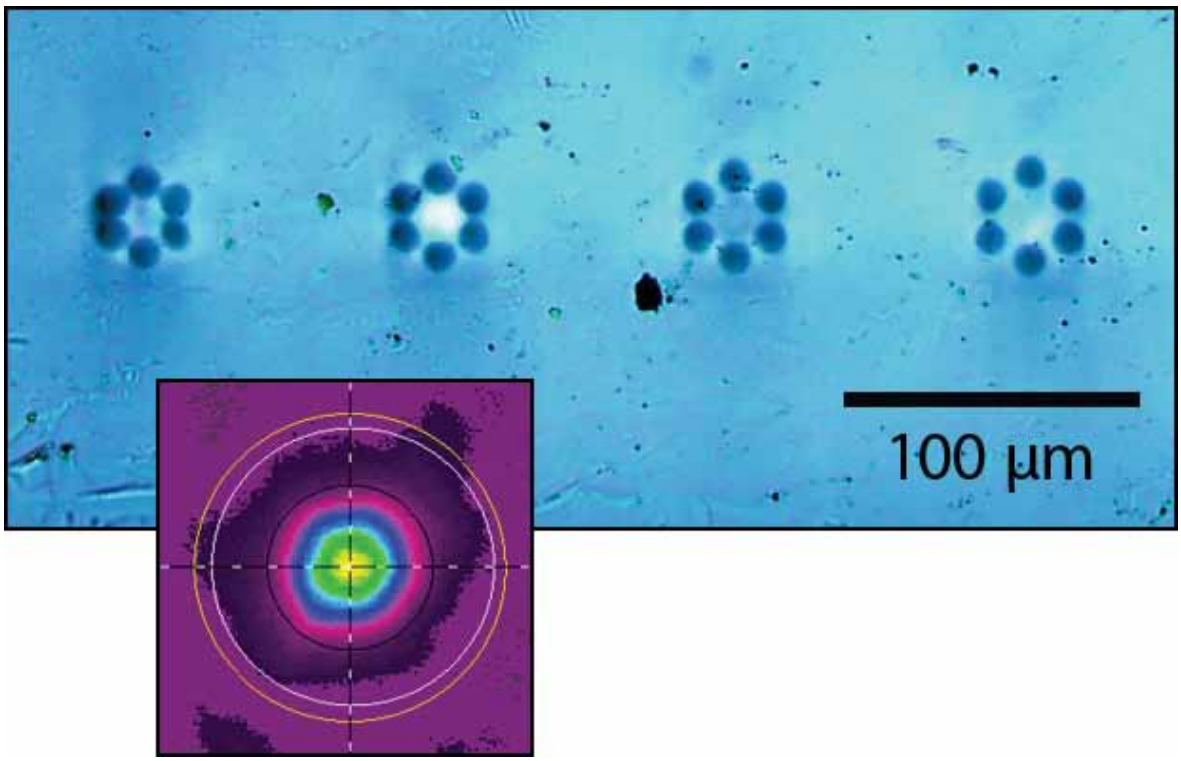

Fig 5. Optical micrograph illustrating depressed cladding arrangements of negatively induced refractive index channels going into the page. Inset shows a circular 1550 nm mode that guides down the centre of one of the depressed cladding arrangements.

Published Papers

Invited

1. M. Ams, G. D. Marshall, P. Dekker, J. A. Piper and M. J. Withford, *"Ultrafast laser written active devices"*, Laser & Photonics Reviews 3, pp. 535-544, 2009
2. 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
3. M. Ams, P. Dekker, G. D. Marshall, D. J. Little and M. J. Withford, *"Directly written DFB waveguide lasers using femtosecond laser pulses,"* Paper in the International High-Power Laser Ablation Conference (HPLA), Santa Fe, USA, 2010
4. G. D. Marshall, N. Jovanovic, M. Ams, D. J. Little, P. Dekker, A. Fuerbach and M. J. Withford, *"Recent Developments in Monolithic Fibre and Waveguide, DBR and DFB Lasers Fabricated Using Ultrafast Laser Direct-Write Methods,"* Paper LMTuC1 in the OSA Optics & Photonics Congress (Femtosecond Laser Microfabrication), San Jose, USA, 2009
5. M. Ams, G. D. Marshall, P. Dekker and M. J. Withford, *"Ultrafast laser fabrication of monolithic waveguide DFB lasers in bulk glasses,"* Paper 4.7.1 in the 18th International Laser Physics Workshop (LPHYS'09), Barcelona, Spain, 2009
6. M. Ams, *"Recent developments in bulk waveguide devices fabricated at Macquarie University using ultrafast laser direct-write techniques,"* IEEE Photonics Society (LEOS) technical meeting on "Technology and applications of ultrafast laser inscription," Heriot Watt University, Edinburgh, Scotland, 6th July 2009

Contributed

7. 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
8. M. Ams, P. Dekker, G. D. Marshall and M. J. Withford, *"Monolithic 100 mW Yb waveguide laser fabricated using the femtosecond-laser direct-write technique"*, Opt. Letters 34, pp. 247-249, 2009
9. 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
10. M. Ams, P. Dekker, G. D. Marshall and M. J. Withford, *"Ultrafast Laser Written 102 mW Monolithic Waveguide Laser in Yb-doped Phosphate Glass"*, Paper MD5 in Advanced Solid State Photonics (ASSP), Denver, USA, 2009
11. M. Ams, G. D. Marshall, P. Dekker and M. J. Withford, *"Characteristics of ultrafast laser written DFB waveguide lasers,"* Paper 230 in the Australasian Conference on Optics, Lasers and Spectroscopy and Australian Conference on Optical Fibre Technology (ACOLS/ACOFT), Adelaide, Australia, 2009
12. D. J. Little, M. Ams, P. Dekker and M. J. Withford, *"Ultrafast Laser Modification of Phosphate Glass: Influence of Polarisation on Waveguide Morphology,"* Paper 209 in the Australasian Conference on Optics, Lasers and Spectroscopy and Australian Conference on Optical Fibre Technology (ACOLS/ACOFT), Adelaide, Australia, 2009
13. S. Ha, M. Ams, G. D. Marshall, D. N. Neshev, A. A. Sukhorukov, Y. S. Kivshar and M. J. Withford, *"Direct Laser Written Bragg-Grating Couplers,"* Paper 316 in the Australasian Conference on Optics, Lasers and Spectroscopy and Australian Conference on Optical Fibre Technology (ACOLS/ACOFT), Adelaide, Australia, 2009
14. M. Ams, P. Dekker, G. D. Marshall and M. J. Withford, *"Performance Studies of Directly Written High Power Monolithic Ytterbium Waveguide Oscillators,"* Paper CJ7.2 in CLEO/Europe-EQEC, Munich, Germany, 2009
15. G. D. Marshall, P. Dekker, M. Ams and M. J. Withford, *"Annealing Properties of Waveguides and Bragg Gratings Fabricated in a Phosphate Glass Host using the Femtosecond-Laser Direct-Write technique,"* Paper CF.P.7 in CLEO/Europe-EQEC, Munich, Germany, 2009
16. C. T. Miese, A. Fuerbach and M. J. Withford, *" Dynamics of waveguide writing using a high pulse energy (600 nJ) MHz femtosecond oscillator,"* Paper in CLEO/Europe-EQEC, Munich, Germany, 2009
17. M. Ams, G. D. Marshall, P. Dekker and M. J. Withford, *"Ultrafast-Laser Inscription of Active Devices in Glass,"* Paper CFT2 in CLEO/IQEC, Baltimore, USA, 2009
18. D. J. Little, M. Ams, P. Dekker, G. D. Marshall, J. M. Dawes and M. J. Withford, *"Polarization Dependence of Photo-Ionization in Glasses and Applications to Direct-Write Photonics,"* Paper CFT4 in CLEO/IQEC, Baltimore, USA, 2009