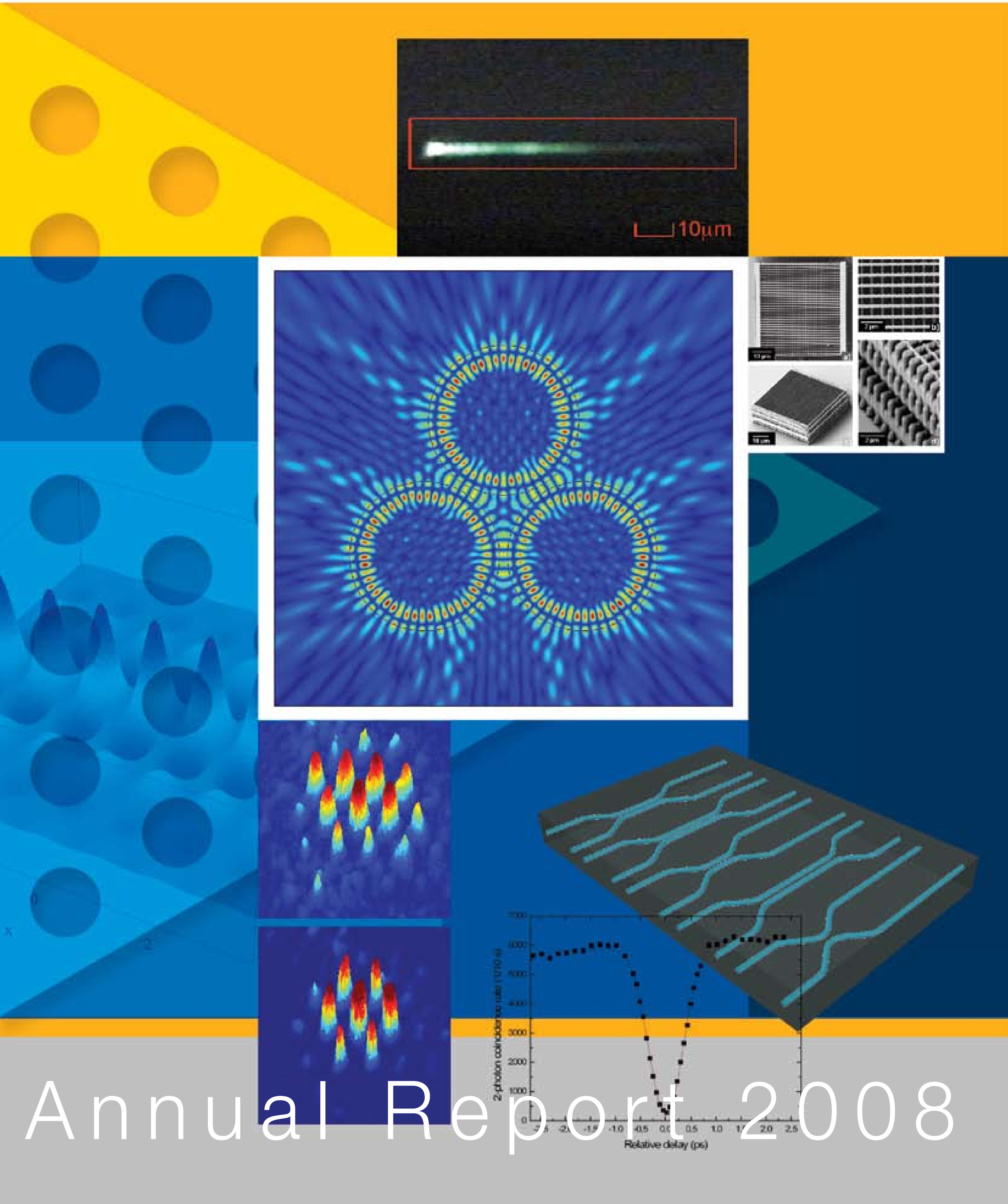
CUDOS

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



Annual Report 2008

Fig 1. Macquarie University group photo. Withford is middle row, third from the left.

CI short biography

A/Prof. Withford was awarded a PhD from Macquarie University in 1995 for his investigations of the effects of gas additives on copper vapour laser performance. His continuing work in this field led to the development of a new sub-class of metal vapour, termed *kinetically enhanced copper laser*, in 1998. His current research interests include laser micromachining and fabrication of a range of photonic devices such as fibre Bragg gratings, periodically poled ferroelectric materials, guided wave devices and self assembled photonic crystals. Dr. Withford leads both the Macquarie University node of Australian Research Council (ARC) Centre of Excellence: Ultrahigh-bandwidth Devices for Optical Systems (CUDOS) and NCRIS Node OptiFab incorporating the Bandwidth Foundry, the University of Sydney's *Fibre fabrication, tapering and measurement facility* and Macquarie University's *Laser Micromachining Solutions.*

Awards, honours, major international visits

Withford had an extended visit with Prof. John Dudley's group at the Universite Franche Comte, Besancon, France from July 2008 to early January 2009. During this period he worked with Prof. Dudley's team researching processing of dielectric materials using ultrafast laser pulses and Bessel beam configurations. During his visit he also lectured in a Summer School run by the European Framework Program NEMO, delivered Department seminars and lectured post-graduate students. He also visited and presented at the research groups of Dr Razvan Stoian at the Hubert Curien Laboratoire, Universite St. Etienne, France; Prof. Stefan Nolte at the Freidrich Schiller University, Jena, Germany; and Prof. Anton Zeilinger at Quantum Optics and Quantum Information, University of Vienna, Austria.

Key areas of research contribution within the Centre

Withford is Science Leader for the Flagship project: Waveguide Amplifiers and Oscillators. In this role he is responsible for determining the broad research directions, building links with end-users such as DSTO and identifying commercial opportunities. Withford also leads a project developing quasi-phased devices for non-linear optical processing. He collaborates with CI Assoc/ Prof. Judith Dawes on self assembly of 3-D photonic platforms for studies into radiation dynamics [1], and laser fabrication of 1-D photonic crystals in polymer rib waveguides [2,3]. He also collaborates with Dr Alex Fuerbach both investigating ultrafast laser interactions with photonic materials and developing novel fibre lasers with Dr Stuart Jackson of the OFTC. Withford and Dawes also collaborates in a research project with partner investigators at the Astrophotonics group at the Anglo-Australian Observatory investigating optic fibre instrumentation for astronomy.

Researchers and students

A/Prof Judith Dawes
A/Prof Mike Steel
Dr Graham Marshall
Dr Alex Fuerbach
Dr Peter Dekker
Dr Alex Khanikaev
Martin Ams
Ben Johnston
Doug Little
Luke Stewart
Nem Jovanovic
Jacek Gosciniak
Chris Miese
Dionne Haynes
Sara Ek
Robert Williams
Nick Cvetojevic

Research Achievements 2008

Flagship Project: Waveguide Amplifiers and Oscillators.

The program continued to build on our landmark success of 2007, where we demonstrated a world's first monolithic waveguide laser fabricated using ultrafast laser direct-write techniques. In particular, we exceeded our 2008 milestone of realising a stable monolithic waveguide laser producing 1 mW [4,5] by a hundredfold, showing real power scaling was possible with this technology in the form a 100 mW distributed feedback Yb doped waveguide laser, measuring only 9 mm in length, that ran stably for a period exceeding 50 hours. This result was presented as a postdeadline paper at the European Optical Society meeting in Paris in 2008 [6]. The journal paper capturing this result was accepted by Optics Letters for publication early 2009.

Fig 2. Fibre pigtailed monolithic Yb doped DFB waveguide laser operating at 1 µm, fabricated using direct write techniques. Note the power reading in the background. Inset: Difference interference contrast micrograph of a waveguide Bragg grating inscribed inside Er-Yb doped phosphate glass. The period is ~ 500 nm, suitable for feedback at 1.5 µm.

Our ability to manufacture these devices reliably has also improved dramatically [7,8]. Indeed, 20-50 waveguide amplifiers and waveguide lasers are routinely fabricated in small samples of glass measuring 10mm x 10mm x 4mm, highlighting the scope for complex integration. This program has also resulted in some interesting insights into the fundamental mechanisms by which ultrafast laser pulses interact with and modify optical materials. Of note in this context was our demonstration that the degree of index change can be mapped to photo induced ionisation rates within fused silica samples. This research thrust has enabled us to explain, for the first time, why different laser polarisation trigger different responses in optical glasses [9]. Our preliminary studies indicate similar mechanisms are at play when phosphate glasses, the material of choice for the waveguide laser program, are exposed to ultrafast laser radiation. Studies comparing low repetition rate (kHz) with high repetition rate (MHz) laser processing, in collaboration with Prof. Ian Bennion's group at Aston University, UK, also revealed key insights into the conditions leading to laser induced positive and negative index change in phosphate glasses [10]. These insights underpin advances in the waveguide laser project that have resulted in stable and high power performance. Team member Martin Ams also completed his PhD in 2008.

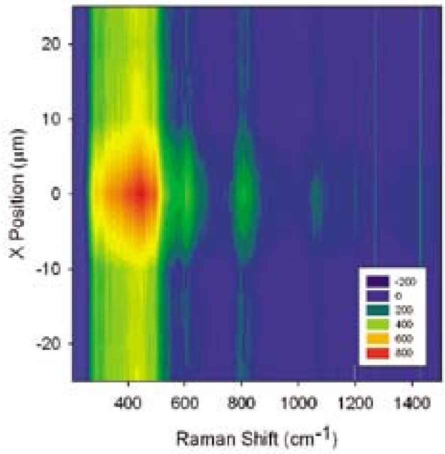


Fig 3. Raman microprobe analysis of a cross section of fused silica that includes a central ultrafast laser inscribed waveguide. The dashed lines indicate the edges of the waveguide. Features of note are the increased concentration of 3-ring (450 cm^{-1}) and 4-ring (605 cm^{-1}) Si-O groups, resulting in a change in refractive index, associated with the waveguide. The total photo-induced index is shown to be related to the rate of photo-ionisation triggered inside the glass.

Quasi phase matched devices

In this project we continue to develop novel quasi-phase matched lithium niobate devices fabricated using our laser based rapid prototyping facility. In previous studies we developed themes exploring instantaneous energy exchange between the two fundamental waves, via the shared harmonic wave, in high quality lithium niobate devices designed for simultaneous phase matching of Type 0 (eee) and Type I (ooe) interactions. In 2008 we pursued variations on this scheme to produce phase reversed lithium niobate devices to facilitate multiple phase matched processes in a single crystal. Team member Ben Johnston completed his PhD in 2008 and continued to advance the poling capabilities within the group through interaction with staff at the lithium niobate plant at the Bandwidth Foundry, Redfern. Highlights in this context include demonstration of 1st order poled lithium niobate chips designed for green and blue generation.

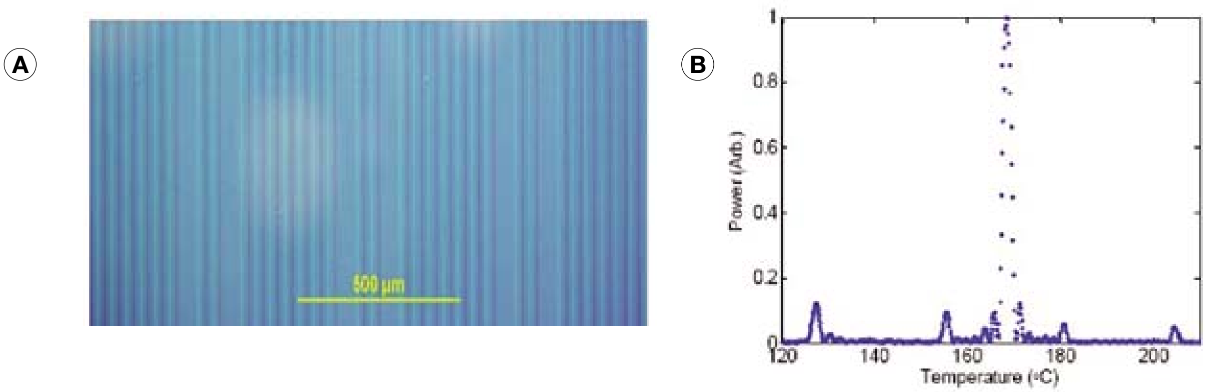


Fig 4. Micrograph of a phase reversed lithium niobate sample and the temperature detuning response.

Fibre Lasers

This project leverages the direct-write techniques developed by the Flagship Project and applies them to producing novel fibre laser sources, in collaboration with Dr Stuart Jackson, Prof. John Canning and Dr Mattias Aslund of the former Optical Fibre Technology Center (OFTC). In 2008 we undertook a study seeking to understand the short wavelength losses associated with ultrafast laser inscribed point-by-point fibre Bragg gratings [11]. Modelling and optical characterisation highlighted the role that Mie scattering plays in this style of fibre Bragg grating. This result has important implications that must factor into the design of high power fibre lasers employing intra core optical resonators based on these gratings. Additional work in this field includes demonstration of simple diode laser pumping configurations [12] and the start of a new initiative exploiting the polarisation dependent features of point-by-point gratings. The latter resulting in a joint publication [13] with Dr David Lancaster of the Defence Science and Technology Organisation (DSTO) reporting a narrow linewidth fibre laser with switchable linear polarisation, based on birefringent fibre. Ongoing studies have shown that highly polarised fibre lasers can also be realised in non-birefringent fibres by exploiting the polarisation dependent loss associated with point-by-point gratings.

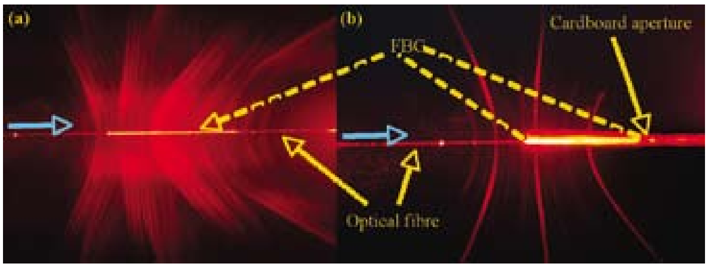


Fig 5. Photos of diffraction orders of 632 nm light emanating from a point-by-point fibre Bragg grating, written in Yb doped fibre, due to Mie scattering. Incoming light is propagating in the direction of the blue arrow in each image. (a) Complete diffraction pattern, (b) spatially apertured diffraction pattern. Note that wavelengths below 400 nm scatter back into the numerical aperture of the fibre in contrast to the radiative losses observed for 632 nm light in the image above.

Fibre based instrumentation for astronomy

In 2008 our investigations into light loss mechanisms in optical fibres used for astronomical instrumentation has continued to deliver new insights. Focal Ratio Degradation (FRD) is a major potential source of light loss in fibre based astronomical instruments and it is therefore a significant design consideration. In order to avoid light loss instrument designers must quantify the FRD in the fibres prior to designing the instrument optical components, such as the spectrograph collimator. We have quantified the effect surface roughness has on the far field light distribution of the fibre, and in doing so have developed and alternative FRD model which includes the contributions from scattering, diffraction and modal diffusion. Because our model is based on physical processes happening within the fibre it can be used to deconvolve the various components of FRD and quantify their contribution to the light loss [14]. On the basis of interest tabled from European researchers in fibre based astronomical instrumentation this model has recently been used to analyse FRD contributing factors in their fibre samples.

We also undertook a new project, in collaboration with the Anglo Australian Observatory, investigating an opportunity to use fibre Bragg gratings to resolve features of interest in the temporal domain. This is one area of astronomy that has yet to be properly exploited. In particular, the project seeks to assess this technology as a tool for monitoring the spectral shifts associated with rotating binary stars and other rapidly varying temporal astrophysical phenomena. Honours student Nick Cvetojevic demonstrated that the steep band edge associated with fibre Bragg gratings, when tuned to the vicinity of a variable spectral line, can offer superior resolving power over conventional spectrographs, a result that has important implications for the next generation of Extremely Large Telescopes and their associated diagnostics.

Integrated Quantum Photonics

2008 saw the start of another new initiative within the group, using ultrafast laser direct write methods to fabricate integrated quantum photonic devices. This work, undertaken in collaboration with Prof. Jeremy O'Brien of Bristol University UK, taps into a pursuit that is considered to serve as an enabler for the next generation of quantum information experimentation and breakthrough science. For example, current quantum experiments are reliant on bulk optic configurations which suffer from misalignment, beam pointing instability and difficulties maintaining phase between entangled photons. These experiments must be reduced in size from their current format, typically covering an optical table, to miniature chip-scale experiments in order to perform more complicated quantum experiments and advance the field. The 1st attempt to do so, based on a silica on silicon lithographically fabricated device was recently reported by Prof. O'Brien's team in a Science article (Politi *et al*. Science **320**, 646-649, 2008). In what we believe is only the second demonstration of miniaturisation in this arena we showed that ultrafast laser direct writing could produce quantum interference devices with superior visibility, measured by Hong-Ou-Mandel techniques, than the silica-on-silicon device reported previously. Furthermore, the first demonstration of 3 photon interference was undertaken on the Macquarie device. Of key note here is that the direct write method can open the way to 3-D integrated quantum photonic devices which are critical for many quantum operations [15,16,17].

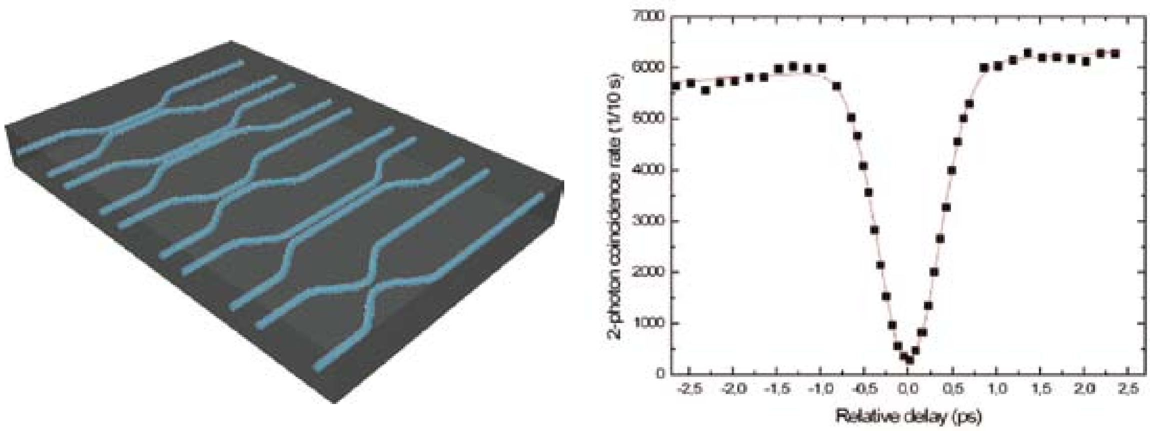


Fig 6. Left: Schematic representing the device under test consisting of a series of evanescent couplers with different splitting ratios. Right: Quantum interference measured in a laser direct-write 50: 50 directional coupler. The number of coincident detections are shown as a function of the arrival delay between the two interfering photons. The fringe visibility is 95.2%

References

1. J. R. Rabeau, Y.-H. Zhai, L. Stewart, M. J. Steel, J. M. Dawes, M. J. Withford, *"Nanodiamond single colour centres in an opal photonic crystal"*, International Conference on Quantum Optics, Lithuania, 2008 [**Invited Paper**].

2. A. J. Lee, A. Rahmani, J. M. Dawes, G. D. Marshall and M. J. Withford, *"Point by point inscription of narrow band gratings in polymer ridge waveguides"*, Appl. Phys. A (ISSN 0947-8396), Vol. 90(2), pp. 273-276, 2008.

3. A. J. Lee, J. M Dawes and M. J. Withford, *"Investigation of femtosecond laser induced thermal ablation of polyethylene"*, J. Laser Appl. (ISSN 1042-346X), Vol. 20, pp. 154-159, 2008.

4. G. D. Marshall, M. Ams, N. Jovanovic, P. Dekker, A. Fuerbach, J. A Piper and M. J. Withford, *"Ultrafast laser direct writing of resonant photonic devices"*, in SPIE Photonics West Technical Abstract Summaries, Laser Applications in Microelectronic and Optoelectronic Manufacturing XII, 6879A-19, 2008 [**Invited Paper**].

5. G. D. Marshall, P. Dekker, M. Ams, J. A. Piper, M. J. Withford, *"A Directly-Written Monolithic Waveguide-Laser Incorporating a DFB Waveguide-Bragg Grating"*, Opt. Lett., Vol. 33(9), pp. 956-958, 2008.

6. M. Ams, G. D. Marshall, P. Dekker, M. J. Withford, *"A compact, monolithic, 36mW Yb-doped DFB waveguide laser fabricated using femtosecond laser direct-write techniques"*, in Digest of European Optical Society Annual Meeting'08, Paris, France, 2008 [**Post-deadline Paper**].

7. G. D. Marshall, M. Ams, R. J. Williams, P. Dekker, M. J. Withford, *"A new approach to fabricating glass photonics"*, Congress of the International Commission for Optics, Sydney, Australia, 2008 [**Invited Paper**].

8. M. Ams, D. Little, R. Williams, P. Dekker, G. Marshall, J. Dawes, M. Withford, *"Overview of laser microfabrication techniques for photonic devices"*, Optoelectronics and Communications Conference and ACOFT, Sydney, Australia, 2008 [**Invited Paper**].

9. D. J. Little, M. Ams, P. Dekker, G. D. Marshall, J. M. Dawes and M. J. Withford, *"Femtosecond laser modification of fused silica: the effect of writing polarization on Si-O ring structure"*, Opt. Exp. (ISSN 1094-4087), Vol. 16 (24), pp. 20029-20037, 2008.

10. M. Ams, G. D. Marshall, P. Dekker, M. Dubov, V. K. Mezentsev, I. Bennion and M. J. Withford, *"Investigation of ultrafast laser-photonic material interactions: challenges for directly written glass photonics"*, **Invited Paper** IEEE J. Select. Topics Quantum Electron. (ISSN 1077-260X), Vol. 14 (5), pp. 1370-1381, 2008.

11. M. L. Åslund, N. Jovanovic, N. Groothoff, J. Canning, G. D. Marshall, S. D. Jackson, A. Fuerbach and M. J. Withford, *"Optical loss mechanisms in femtosecond laser-written point-by-point fibre Bragg gratings"*, Opt. Exp. (ISSN 1094-4087), Vol. 16 (18), pp. 14248-14254, 2008.

12. M. L Aslund, S. D Jackson, N. Jovanovic and M. J Withford, *"Efficient double-clad Yb3+-doped silica fibre laser pumped by an unfocused diode laser"*, Opt. Commun., Vol. 281(15), pp. 4092-4094, 2008.

13. N. Jovanovic, G. D. Marshall, A. Fuerbach, G. E. Town, S. Bennetts, D. G. Lancaster and M. J. Withford, *"Highly-narrow linewidth, cw, all-fibre oscillator with a switchable linear polarisation"*, Photon. Technol. Lett., Vol. 20, pp. 809-811, 2008.

14. D. Haynes, J. M. Dawes, M. J. Withford, R. Haynes, J. Bland-Hawthorn, *"Focal ratio degradation: A new perspective"* SPIE Conference on Astronomical Instrumentation, Marseilles, France, 2008.

15. A. Politi, J. C. F. Matthews, A. Laing, A. S. Clark, J. Fulconis, G. D. Marshall, P. Dekker, M. Ams, M. J. Withford, W. J. Wadsworth, T. Rudolph, M. J. Cryan, J. G. Rarity, A. Stefanov, S. Yu, and J. L. O'Brien, *"Quantum information science with photons on a chip,"* Australian Institute of Physics, 18th National Congress, Adelaide, Australia, 2008 [Invited Paper].

16. J. C. F. Matthews, A. Politi, G. D. Marshall, M. Ams, M. Withford, A. Laing, M. J. Cryan, J. G. Rarity, S. Yu, and J. L. O'Brien, *"Quantum Photonics on a Chip,"* Proceedings Optical Engineering and Applications, SPIE, Paper 7092-46, San Diego, USA, 2008.

17. J. C. F. Matthews, A. Politi, A. Laing, A. Stefanov, M. J. Cryan, J. G. Rarity, S. Yu, G. D. Marshall, M. Ams, M. Withford, and J. L. O'Brien, *"Multi-Photon Quantum Optics on a Chip,"* Quantum Communication, Measurement and Computing, Calgary, Canada, 2008.