CI short biography

Barry Luther-Davies is a Professor of Laser Physics at the Australian National University with 39 years research experience in the diverse areas such as lasers, laser-matter interaction physics, photonics, optical materials and nonlinear optics. He completed a BSc in Electronics and PhD in Laser Physics from the University of Southampton, UK. Barry oversees the Centre's work at ANU fabricating planar optical waveguide devices and photonic crystals in chalcogenide glasses and is also science leader of the CUDOS flagship project *Chalcogenide Photonic Crystal All-Optical Switch* which combines the skills of researchers at ANU, The University of Sydney and the University of Technology Sydney. His broad experience contributes to all aspects of the CUDOS projects spans materials science; film deposition and patterning; optical characterization; and device design. Barry is an elected Fellow of the Optical Society of America and the Australian Academy for Technological Sciences and Engineering. He was awarded the Pawsey Medal of the Australian Academy of Science in 1986 for his contribution to laser-plasma interaction physics. He is currently a topical editor for the Journal of the Optical Society of America-B and an Advisory Editor for Optics Communications.

Key areas of research contribution within the Centre

Roles and responsibilities within centre

Group Leader: Laser Physics Centre, Research School of Physics and Engineering, ANU; Science Leader: *Chalcogenide Photonic Crystal All-Optical Switch.*

Key areas of research activity

The team concentrates on the fabrication of devices for two flagship projects: *Nonlinear Optical Signal Processing and Chalcogenide Photonic Crystal All-Optical Switch.* In addition we are involved in studying the science of chalcogenide glasses to improve materials performance in photonic chips. Our standard dispersion engineered arsenic trisulphide chips are used widely in the centre for experiments on signal processing and most recently on correlated pair generation.

Staff and Students

Professor Barry Luther-Davies

Dr Steve Madden

Dr Duk-Yong Choi

Dr Rongping Wang

Dr Douglas Bulla (until September)

Dr Tom White (Joint with NLPC)

Mr Xin Gai

Mr Ting Han

Mr Zhe Jin

Mr Khu Vu

Ms Ting Wang

Mr Kunlun Yan

Ms Maryla Krolikowska

Mr Sukanta Debbarma

Research achievements

Waveguide Fabrication

Direct Molding Chalcogenide Glass Waveguides Using Thermal Nanoimprint Lithography With A Soft Pdms Stamp (Ting Han, Steve Madden, Douglas Bulla, Sukanta Debbarma, And Barry Luther-Davies)

In 2010 we have demonstrated the production of low loss waveguides via hot embossing in As_2S_3 using a soft stamp. Last year we reported $As_{24}Se_{36}S_{36}$ based waveguides with 0.26dB/cm loss embossed with a PDMS stamp [1]. However the low glass transition temperature (~120˚C) and large photosensitivity of this material means that it is not a good for nonlinear devices. The same technique is here extended to make low loss waveguides in a proven, robust glass (As_2S_3) which has a glass transition temperature of ~170˚C.

To emboss As_2S_3 we found that temperatures around 300˚C were required and at these temperatures crystallization and surface evaporation were observed as had been reported previously [2]. However , we found that surface degradation could be eliminated by applying a thin coating to stabilize the surface prior to embossing [3]. We first demonstrated this using a 40nm SU-8 spin coated layer on top of the As_2S_3 wafer producing waveguides with losses of ~0.5dB/cm loss measured by cut back at 1550nm. However this SU-8 protective layer is not elastic enough to deformation to the shape of the stamp and hence the waveguide edges were distorted as shown in Fig. 1(a). We therefore used another approach, applying a 50nm thick film of a stable Chalcogenide ($Ge_{11.5}As_{24}Se_{64.5}$) as the protective layer. $Ge_{11.5}As_{24}Se_{64.5}$ has a higher glass transition temperature than As_2S_3 and does not suffer surface degradation at high temperature. The embossing experiment was carried out at 280˚C with 2bar uniform pressure applied over the entire surface for 5 minutes. The cross section in Fig. 1(b) indicates the waveguide edge is a much sharper than that with SU-8 coating.

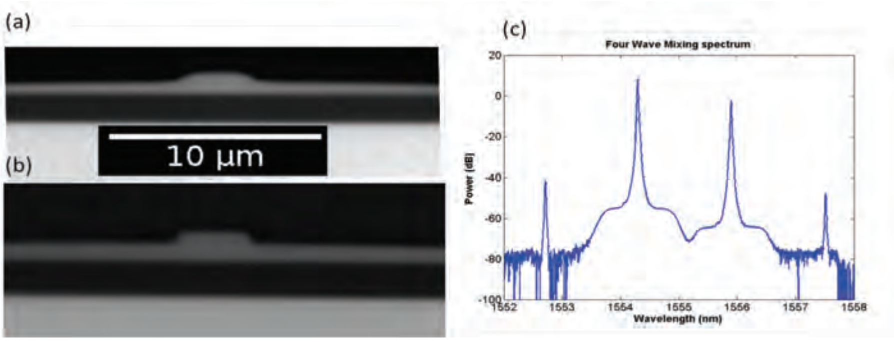

Fig 1: (a) Optical microscopic view of the embossed As_2S_3 waveguide with 40nm SU-8 coating, (b) embossed As_2S_3 waveguide with 50nm $Ge_{11.5}As_{24}Se_{64.5}$ coating (c) a typical four wave mixing spectrum produced from the embossed As_2S_3waveguide.

The insertion loss for a 3.4μm×1μm and 8.3cm long waveguide was 8.2dB for both TE and TM polarization with 5.5dB dues to coupling giving a propagation loss of ≈ 0.3dB/cm. The nonlinearity of this waveguide was characterized using CW four wave mixing. A typical spectrum is shown in Figure (1). The conversion efficiency followed the expected square law relation & the measured nonlinearity for this waveguide was $8100W^{-1}km^{-1}$. These results show that hot embossing is a viable technique for producing rib waveguides in As_2S_3.

References

1. T. Han, S. Madden, D. Bulla, and B. Luther-Davies, "Low loss Chalcogenide glass waveguides by thermal nano-imprint lithography," Opt. Express 18, 19286-19291 (2010).
2. M. Solmaz, H. Park, C. K. Madsen, and X. Cheng, "Patterning chalcogenide glass by direct resist-free thermal nanoimprint," J. Vac. Sci. Technol. B 26, 606-610 (2008).
3. G. Xin, T. Han, A. Prasad, S. Madden, D. Choi, R. Wang, D. Bulla and B. Luther-Davies, "Progress in optical waveguides fabricated from chalcogenide glasses ," Opt. Express 18, 26636 (2010).

Improved Fabrication of As_2S_3 Waveguides

The sensitivity of chalcogenide glasses to light is one of their most striking properties, but not one that suggests that are ideally suited for use in all-optical processors exposed at large light intensity. This issue is complicated by the fact that thermally evaporated thin films generally contain chemical bonds different from bulk glasses and this often means that their photosensitivity is enhanced. As part of the fabrication process films have to be annealed to relax their chemical bonds towards the state of the bulk glass however as we showed last year there are distinct limits to the processing temperatures that can be used which precludes complete relaxation.

As a consequence we have studied the use of optical annealing to drive the thin films towards the bond structure of bulk glass. This involved irradiation with filtered light from an array of halogen lamps. Previous work had shown that illumination with broadband green light at fluences around $200J/cm^2$ would cause the film index to match that of the bulk attaining a value of 2.425 compared with ≈2.305 for as-deposited films. Further illumination up to $>1kJ/cm^2$ had no effect on the film. Illumination with white of blue light had a similar effect although final values tended to be slightly less than achieved with green illumination. However overexposure caused a marked deterioration of the film whereas illumination with green light showed no noticeable deterioration. Evolution of the bonds monitored by Raman scattering spectra confirmed the green illumination resulted in a structure closest to the bulk (Fig. 3). Unlike thermal annealing optical annealing with green light in appropriate conditions, therefore, appear to result in bond relaxation to the bulk with no cracking or deterioration of the film surface.

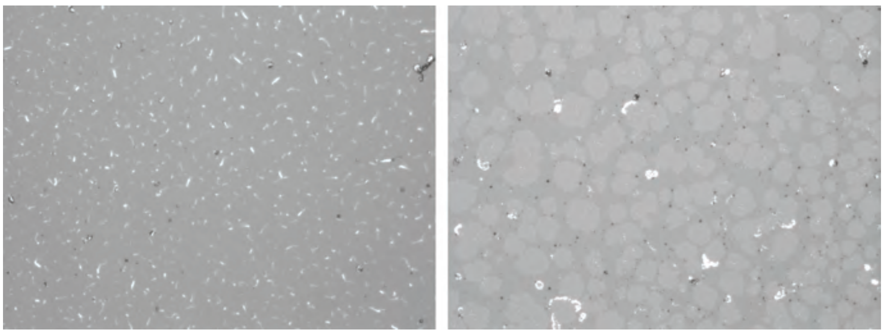

Fig 2: LHS bright field image of film break-up after exposure to about $1.5kJ/cm^2$ of blue light; RHS bright field patterns after $14kJ/cm^2$ exposure with white light.

The question that remained was whether optical annealing would affect the losses in fabricated waveguides. We had reported some years ago that narrowband green illumination with a laser at much high intensity than used here appeared to increase films losses. The assess the effect of broadband green illumination we therefore fabricated a series of rib waveguide 4μm wide and 0.85μm high and measure their losses by the cut-back method. The difference in losses could not be detected at the level of 0.03dB/cm, indicating that material losses had not risen above this level. As a result green illumination is now routinely used n waveguide production. Other techniques adopted widely in the current generations of waveguides include the use of Al_2O_3 coatings deposited by atomic layer deposition to passivate waveguide surfaces and enhance IPG adhesion and the use of SU8 protective coatings during photolithography. This has allowed the optical losses in the current generation of devices to be reduced by almost a factor of two.

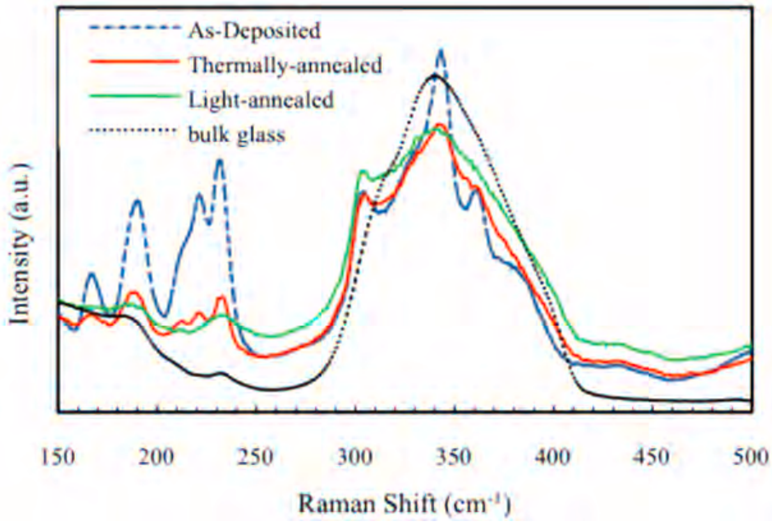

Fig 3: Comparison of Raman spectra for As2S3 for bulk glass, as-deposited film; thermally annealed thin film and light annealed film.

Glass Science

We prepared five samples of $Ge_xAs_ySe_{1-x-y}$ glasses with the same MCN of 2.5. The chemical compositions of these five samples were $Ge_{7.5}As_{35}Se_{57.5}$, $Ge_{10}As_{30}Se_{60}$, $Ge_{12.5}As_{25}Se_{62.5}$, $Ge_{15}As_{20}Se_{65}$, and $Ge_{20}As_{10}Se_{70}$ which cover the range from being as much as 10% Se-poor, through stoichiometric to 10% Se-rich. We measured their density, glass transition temperature T_g, elastic moduli, Raman and x-ray photo-electron spectra (XPS) to determine whether the physical properties are predominantly controlled by MCN or by the chemical compositions.

The density measurements exhibit a maximum for the chemically stoichiometric $Ge_{12.5}As_{25}Se_{62.5}$ sample, suggesting a rearrangement of the atoms occurs when one element is replaced by another. T_g measurements show that the glasses have almost same glass transition temperature, indicating that the glass network connectivity changes very little with chemical composition. Although the Raman (Fig. 4) and XPS spectra (Fig. 5) indicate that the percentage of the different structural units does change with the changing chemical compositions, there is no evidence of the existence of separated structural units that can cut the glass network connectivity. Therefore the glasses with same MCN but different compositions have similar glass network connectivity, the chemical compositions only slightly modify the physical properties of the glasses.

Inverse Taper Couplers for Nanowire Coupling and 3-D Hybrid Circuits

We are investigating vertical inverse tapers for coupling which are produced in a relatively straightforward manner with evaporated thin films by placing a mask spaced slightly in front of the wafer during deposition. Such vertical taper couplers can be used both to improve the coupling efficiency from fibers to nanowires as is routinely achieved using horizontal down tapers in silicon and to allow the light to transition adiabatically between vertically stacked layers in a photonic circuit in order to access the functionality of different layers distributed through a circuit.

This year we made extensive studies of the optimization of these couplers and developed the techniques to produce layers with appropriate vertical tapering. A simulation example if shown in Fig. 6. This shows the evolution of the optical mode in a tellurite glass waveguide in and out of a chalcogenide nonlinear layer. Around 85% of the power moves from the tellurite into the chalcogenide with the insertion loss being only a few %. Similar simulation show that an optimized taper coupler should achieved less than 0.5dB coupling loss to a rib waveguide fro a standard high NA fiber. Implementation of the coupler has started using an SU8 based overcladding.

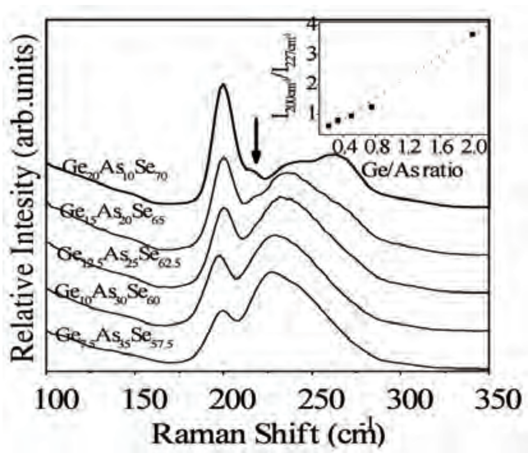

Fig 4: Raman spectra of the glasses. The insert is the ratio of the scattering intensity at 200cm^{-1} to that at 227cm^{-1} as a function of the ratio Ge/As.

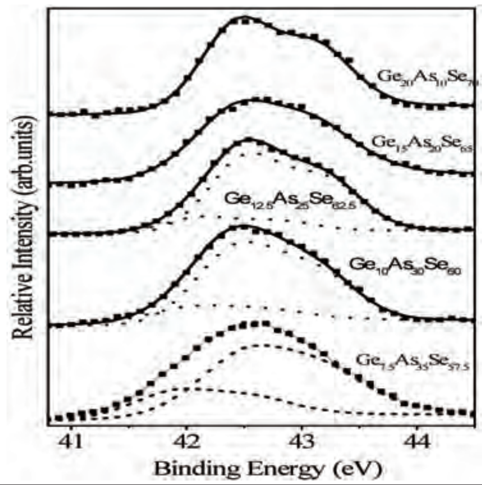

Fig 5: Typical As 3d XPS spectra of the glasses. The square dots are experimental data and the dotted lines are simulation results.

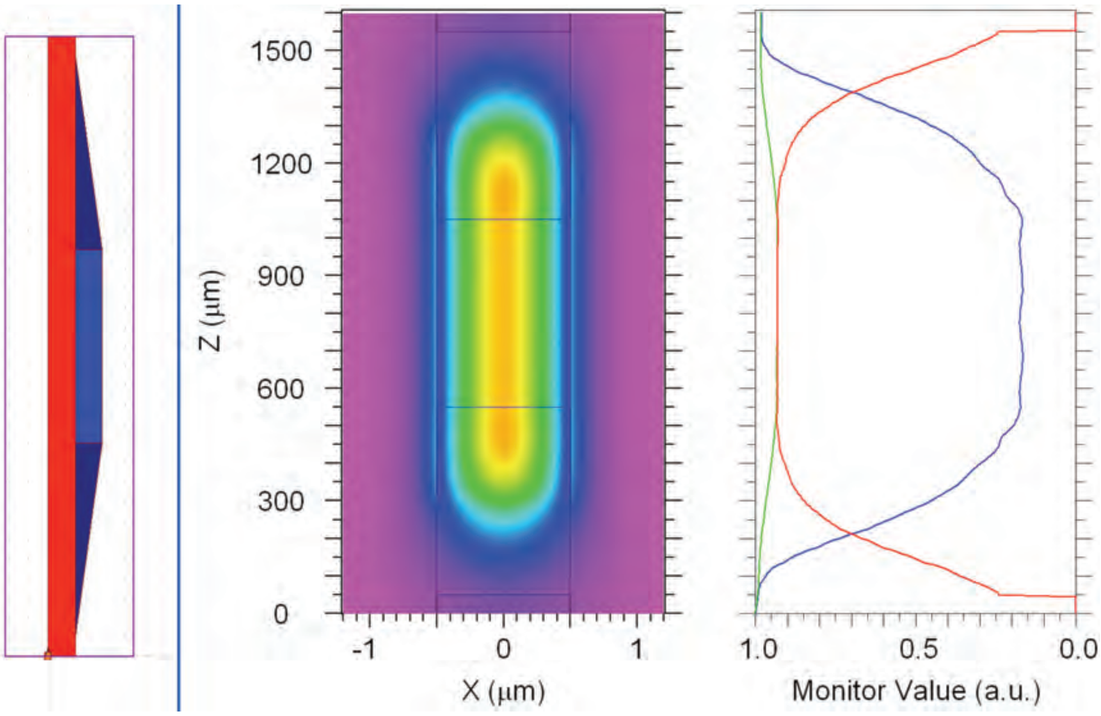

Fig 6: Simulation of the evolution of the optical mode in a tellurite glass waveguide in and out of a chalcogenide nonlinear layer.

Group Publications

Journal Articles

1. D. Y. Choi, S. Madden, D. Bulla, R. Wang, A. Rode, and B. Luther-Davies, "Thermal annealing of arsenic tri-sulphide thin film and its influence on device performance," Journal of Applied Physics **107**(5).

2. D. Y. Choi, S. Madden, D. A. Bulla, R. Wang, A. Rode, and B. Luther-Davies, "Submicrometer-thick low-loss AS2S3 planar waveguides for nonlinear optical devices," IEEE Photonics Technology Letters **22**(7), 495-497.

3. X. Gai, T. Han, A. Prasad, S. Madden, D. Y. Choi, R. Wang, D. Bulla, and B. Luther-Davies, "Progress in optical waveguides fabricated from chalcogenide glasses," Optics Express **18**(25), 26635-26646.

4. X. Gai, S. Madden, D. Y. Choi, D. Bulla, and B. Luther-Davies, "Dispersion engineered Ge11.5As24Se64.5 nanowires with a nonlinear parameter of 136W-1m-1 at 1550nm," Optics Express **18**(18), 18866-18874.

5. T. Han, S. Madden, D. Bulla, and B. Luther-Davies, "Low loss chalcogenide glass waveguides by thermal nano-imprint lithography," Optics Express **18**(18), 19286-19291.

6. M. W. Lee, C. Grillet, C. Monat, E. Mägi, S. Tomljenovic-Hanic, X. Gai, S. Madden, D. Y. Choi, D. Bulla, B. Luther-Davies, and B. J. Eggleton, "Photosensitive and thermal nonlinear effects in chalcogenide photonic crystal cavities," Optics Express **18**(25), 26695-26703.

7. M. D. Pelusi, F. Luan, D. Y. Choi, S. J. Madden, D. A. P. Bulla, B. Luther-Davies, and B. J. Eggleton, "Optical phase conjugation by an As2S3 glass planar waveguide for dispersion-free transmission of WDM-DPSK signals over fiber," Optics Express **18**(25), 26686-26694.

8. M. D. Pelusi, F. Luan, S. Madden, D. Y. Choi, D. A. Bulla, B. Luther-Davies, and B. J. Eggleton, "Wavelength conversion of high-speed phase and intensity modulated signals using a highly nonlinear chalcogenide glass chip," IEEE Photonics Technology Letters **22**(1), 3-5.

9. J. Van Erps, F. Luan, M. D. Pelusi, T. Iredale, S. Madden, D. Y. Choi, D. A. Bulla, B. Luther-Davies, H. Thienpont, and B. J. Eggleton, "High-resolution optical sampling of 640-Gb/s data using four-wave mixing in dispersion-engineered highly nonlinear As2S3 planar waveguides," Journal of Lightwave Technology **28**(2), 209-215.

10. JJ. Van Erps, J. Schröder, T. D. Vo, M. D. Pelusi, S. Madden, D. Y. Choi, D. A. Bulla, B. Luther-Davies, and B. J. Eggleton, "Automatic dispersion compensation for 1.28Tb/s OTDM signal transmission using photonic-chip-based dispersion monitoring," Optics Express **18**(24), 25415-25421.

11. T. D. Vo, H. Hu, M. Galili, E. Palushani, J. Xu, L. K. Oxenløwe, S. J. Madden, D. Y. Choi, D. A. P. Bulla, M. D. Pelusi, J. Schröder, B. Luther-Davies, and B. J. Eggleton, "Photonic chip based transmitter optimization and receiver demultiplexing of a 1.28 Tbit/s OTDM signal," Optics Express **18**(16), 17252-17261.

12. T. D. Vo, M. D. Pelusi, J. Schröder, F. Luan, S. J. Madden, D. Y. Choi, D. A. P. Bulla, B. Luther-Davies, and B. J. Eggleton, "Simultaneous multi-impairment monitoring of 640 Gb/s signals using photonic chip based RF spectrum analyzer," Optics Express **18**(4), 3938-3945.

13. T. D. Vo, M. D. Pelusi, J. Schroder, S. J. Madden, D. Y. Choi, D. A. P. Bulla, B. Luther-Davies, and B. J. Eggleton, "Simultaneous dispersion and noise monitoring for phase-modulated signals using photonic chip based RF spectrum analyzer," presented at the European Conference on Optical Communication, ECOC.

14. T. D. Vo, J. Schröder, M. D. Pelusi, S. J. Madden, D. Y. Choi, D. A. P. Bulla, B. Luther-Davies, and B. J. Eggleton, "Photonic chip-based simultaneous multi-impairment monitoring for phase-modulated optical signals," Journal of Lightwave Technology 28(21), 3176-3183.

15. R. Pant, C. Xiong, S. Madden, B. L. Davies, and B. J. Eggleton, "Investigation of all-optical analog-to-digital quantization using a chalcogenide waveguide: A step towards on-chip analog-to-digital conversion," Optics Communications **283**, 2258-2262.

Conference Papers

16. X. Gai, S. Madden, D. Y. Choi, D. Bulla, and B. Luther-Davies, "Chalcogenide nanowire waveguides with a nonlinear parameter 150,000 W -1km-1," presented at the Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference: 2010 Laser Science to Photonic Applications, CLEO/QELS 2010.

17. C. Grillet, M. W. Lee, X. Gai, S. Tomljenovic-Hanic, C. Monat, E. Mägi, D. J. Moss, B. J. Eggleton, S. Madden, D. Y. Choi, D. Bulla, and B. Luther-Davies, "Chalcogenide glass photonic crystals: Progress and prospects," presented at the Proceedings of SPIE - The International Society for Optical Engineering.

18. R. Pant, C. Xiong, S. Madden, B. Luther Davies, and B. J. Eggleton, "Investigation of on-chip all-optical quantization and novel encoding method: Paving the way for optical analog-to-digital conversion chip," presented at the Proceedings of SPIE - The International Society for Optical Engineering.

19. M. D. Pelusi, F. Luan, S. J. Madden, D. Y. Choi, D. A. P. Bulla, B. Luther-Davies, and B. J. Eggleton, "Optical phase conjugation in chalcogenide planar waveguides for compensating signal transmission effects," presented at the 2010 Conference on Optical Fiber Communication, Collocated National Fiber Optic Engineers Conference, OFC/NFOEC 2010.

20. . Van Erps, F. Luan, M. D. Pelusi, E. Mägi, T. Iredale, S. Madden, D. Y. Choi, D. A. Bulla, B. Luther-Davies, H. Thienpont, and B. J. Eggleton, "Optical sampling of ultrahigh bitrate signals using highly nonlinear chalcogenide planar waveguides or tapered fibers," presented at the Proceedings of SPIE - The International Society for Optical Engineering.

21. T. D. Vo, H. Hu, M. Galili, E. Palushani, J. Xu, L. K. Oxenløwe, S. J. Madden, D. Y. Choi, D. A. P. Bulla, M. D. Pelusi, J. Schröder, B. Luther-Davies, and B. J. Eggleton, "Photonic chip based 1.28 Tbaud transmitter optimization and receiver OTDM demultiplexing," presented at the 2010 Conference on Optical Fiber Communication, Collocated National Fiber Optic Engineers Conference, OFC/NFOEC 2010.

22. T. D. Vo, M. D. Pelusi, J. Schröder, F. Luan, S. J. Madden, D. Y. Choi, D. A. P. Bulla, B. Luther-Davies, and B. J. Eggleton, "All-optical multi-impairment performance monitoring of 640 Gb/s optical signals using a chalcogenide photonic chip," presented at the 2010 Conference on Optical Fiber Communication, Collocated National Fiber Optic Engineers Conference, OFC/NFOEC 2010.