CUDOS

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

ANNUAL REPORT

2006

Professor Benjamin J. Eggleton

Benjamin Eggleton is currently an ARC Federation Fellow and Professor of Physics at the University of Sydney. He is Research Director of the Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS), an ARC Centre of Excellence. He studied at the University of Sydney, obtaining his BSc (Hons 1) in 1992 and his PhD in Physics in 1996. After graduation, he went to the United States to join the world's leading research institute in his field, Bell Laboratories, as a Postdoctoral Fellow in the Optical Physics Department. He then transferred to the Optical Fiber Research Department as a Member of Technical Staff and was subsequently promoted to Technical Manager of the Optical Fibre Grating group. Soon after this, he became the Research Director of the Specialty Fiber Business Division of Bell Lab's parent company, Lucent Technologies where he drove Lucent's research program in optical fibre devices. He has co-authored more than 170 journal papers, presented more than 40 invited and plenary presentations at international conferences, and has filed 35 patents. He has received several significant awards. Most notably, in 2004 he received the Prime Minister's Malcolm McIntosh Science Prize for Physical Scientist of the Year, in 2003 the ICO Prize (International Commission for Optics), and in 1998 was awarded the Adolph Lomb Medal from the Optical Society of America. Other achievements include the award of the distinguished lecturer award from the IEEE/LEOS, a R&D100 award, and being made an OSA Fellow in 2003. He is an Associate Editor for IEEE Photonic Technology Letters, a member of the editorial advisory board for Optics Communications and serves as Vice-President of the Australian Optical Society. In 2007 Professor Eggleton will be presented with the Pawsey Medal from the Australian Academy of Sciences.

Key areas of research contribution in Centre

Nonlinear optics and optical solitons, optical gratings and photonic crystals, optical communications, photonic crystal fibres, optofluidics, supercontinuum generation and integrated optics; fabrication of optical gratings and microstructured optical devices, such as photonic crystals and holey fibres; nonlinear pulse propagation effects and ultrafast propagation in different optical systems.

Roles and responsibilities in Centre

As the CUDOS Research Director, Professor Eggleton is responsible for setting the vision and focus for the research program and establishing and directing the research collaborations. He oversees and manages the five current CUDOS research projects and drives strong interactions with CUDOS Partner investigators and end-users. He also heads the University of Sydney CUDOS node and leads the Sydney experimental programs, in close collaboration with Professors de Sterke and McPhedran, which will be reported here. He will act as the Science Leader for the Nonlinear Optical Signal Processing project, providing the scientific and technical guidance for this highly collaborative projects that span across four Universities, and PIs, including NICTA, DSTO and USC. He will also actively collaborate and supervise staff and students in the Optical Switching Project, Slow Light Project and new projects being launched in 2007: mid-IR Microphotonics and Tunable Microphotonics.

International links and roles

During 2006 Professor Eggleton served on several international review committees, including a review panel for the DFG (Deutsche Forschungsgemeinschaft-- German Research Foundation) Cluster of Excellence Program, and as an opponent for a Doctoral Defence Committee at COM, at the Technical University of Denmark.

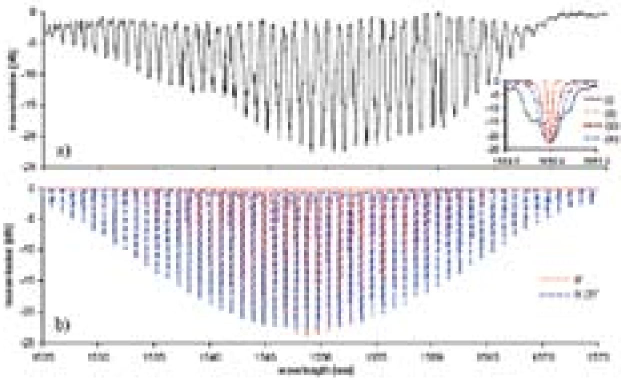
During 2006 Professor Eggleton visited and presented seminars at a series of international Laboratories including: Université de Franche-Comté, France hosted by Prof John Dudley; Princeton University hosted by Professors Jim Stirm and Claire Gmachl; Bath University in the UK, hosted by Professor Jonathan Knight; Southampton University in the UK, hosted by Professor David Richardson; California Institute of Technology hosted by Professor Oskar Painter; Sun Microsystems in San Diego hosted by Dr. Ashok Krishnamoorthy; the Technical University of Denmark, hosted by Professor Anders Bjarklev; Auckland University in New Zealand hosted by Professor John Harvey; the Network Technology Research Centre at Nanyang Technological University, hosted by Professor Ping Shum and Bangalore Institute of Science in India.

Research achievements during 2006

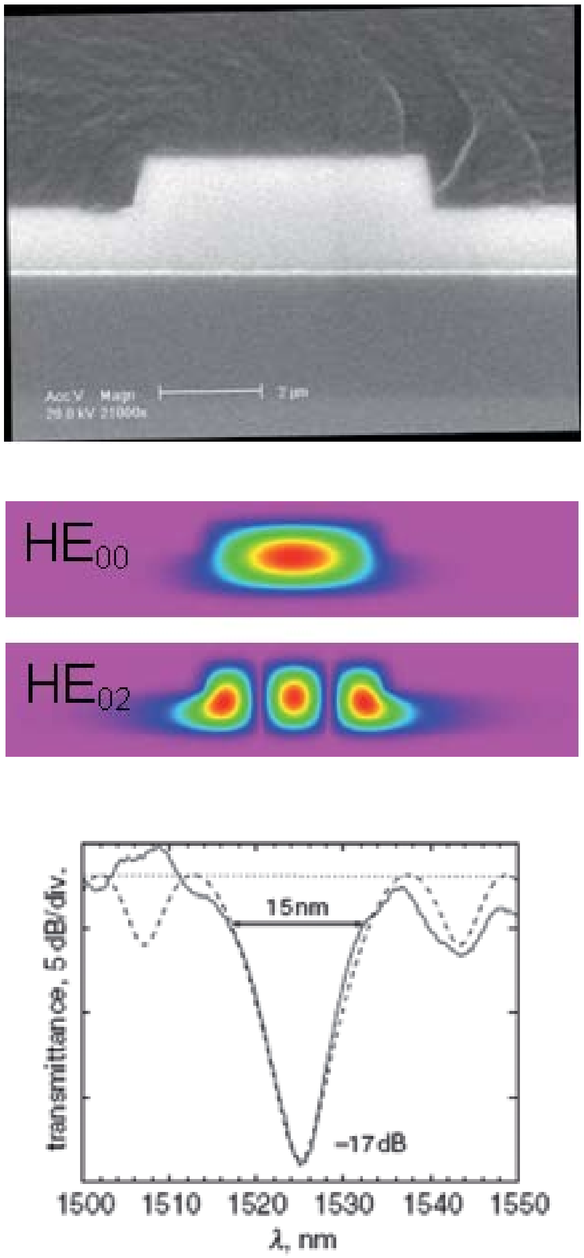
Chalcogenide optical devices

The Sydney group's ability to post-process chalcogenide fibre and waveguide devices and apply these devices to advanced signal processing functions underpins several of the CUDOS Flagship projects. The strong photosensitivity of these glasses allows us to write periodic structures (e.g. Bragg gratings and long-period gratings) in the waveguides while the viscosity of the glass allows us to taper chalcogenide fibres to create ultra-thin nanowires. Our research in signal processing focuses on applications in next generation telecommunication networks, such as optical regeneration, wavelength conversion and optical performance monitoring.

During 2006 we focused on developing complex, strong grating filters in chalcogenide waveguides [1]. These are the basis for on-chip optical filters used in optical regenerators and for the strong dispersion we exploit in slow-light applications. Neil Baker and co-workers demonstrated ultra-strong photosensitivity in chalcogenide rib waveguides [2] and developed complex grating filters, including sampled Bragg gratings that possess multiple reflection peaks distributed uniformly across the telecommunications band, shown in Figure 1. In collaboration with Duk Choi and the ANU team we developed a novel approach to sampled grating fabrication where the sampled shadow mask was integrated onto the structure, improving the grating reflection properties [3]. Klaus Fintserbusch demonstrated long-period gratings in chalcogenide waveguides [4] that couple to co-propagating higher-order modes, shown in Figure 2. These long-period gratings have strong wavelength dependent loss and are the basis for low-power optical switching devices, tunable filters and applications in mid-infrared photonics, which we will investigate further as a separate CUDOS project in 2007.

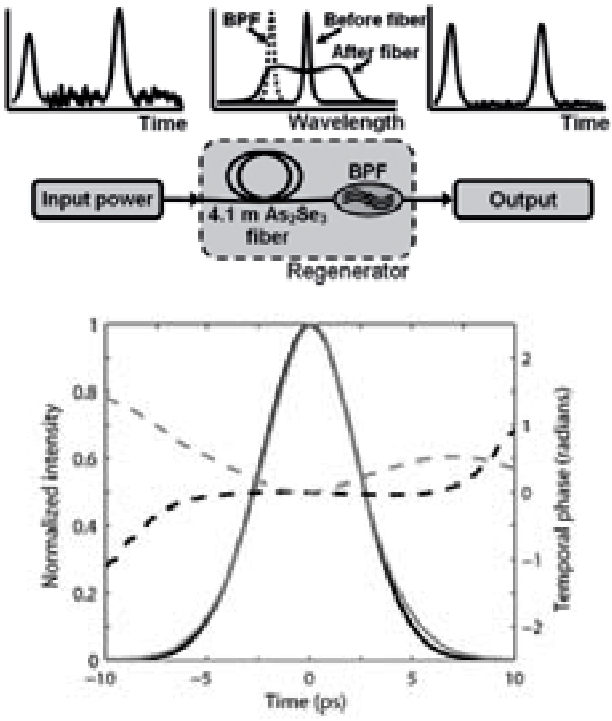


▲ **Figure 1. Measured and calculated spectra of ultra-strong high quality Sampled Bragg grating written into chalcogenide rib-waveguide.**



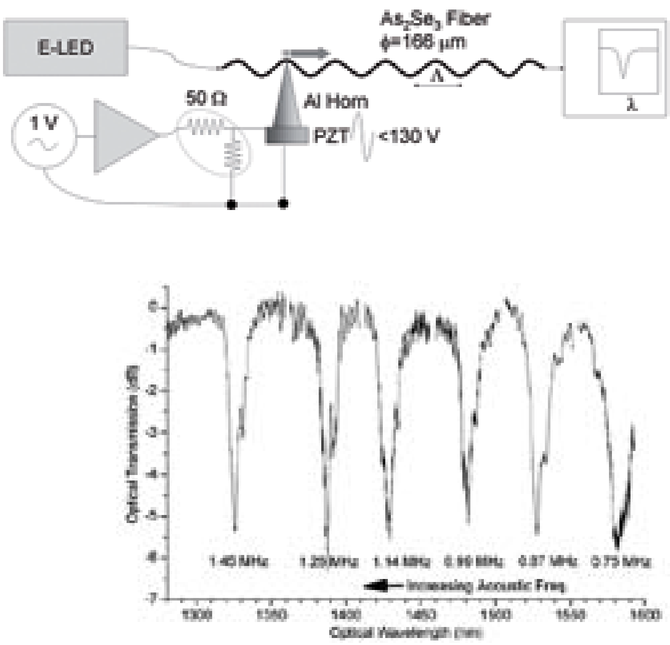
▲ **Figure 2. Coupling to higher order modes in chalcogenide rib waveguides via long-period gratings.**

Vahid Ta'eed, working with Michael Lamont, Libin Fu and Mark Pelusi demonstrated wavelength conversion in chalcogenide rib waveguides using cross-phase modulation followed by spectral filtering [5]. Results were also demonstrated in chalcogenide single mode fibres [6]. Michael Lamont and Libin Fu evaluated the performance of a chalcogenide single mode fibre-based optical regenerator using Frequency Resolved Optical Gating. They showed that the output pulse was close to transform limited and that the pulse quality was not degraded by transmission through the nonlinear fibre, as shown in Figure 3 [7].



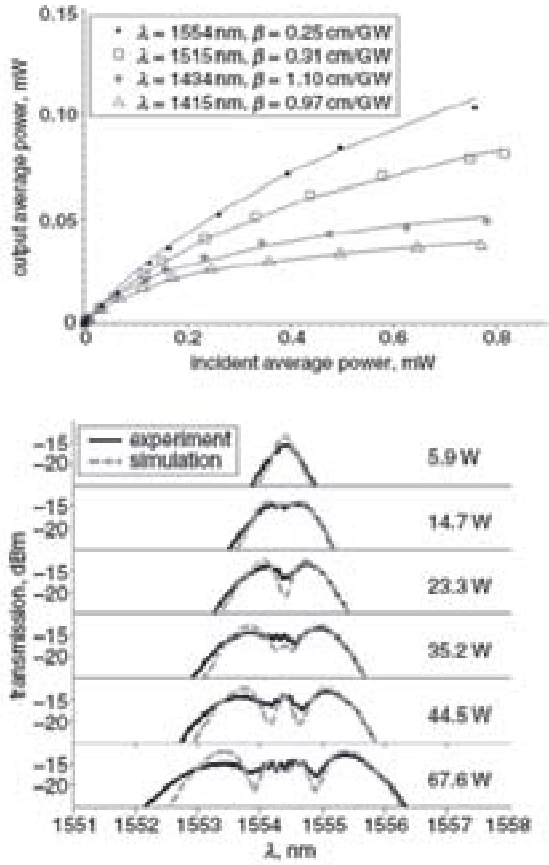
▲ **Figure 3. Investigations of pulse degradation in self phase modulation-based 2R-optical regeneration scheme in single mode chalcogenide fibre. Experimental results confirmed that the regenerated pulse is close to transform limited.**

Dominic Pudo and Ian Litter produced tunable long-period gratings in chalcogenide fibres using micro-bend gratings and acoustic gratings. This is the first demonstration of acoustic gratings in non-silica fibres, shown in Figure 4 [8,9]. These gratings are highly tunable by simply adjusting the drive frequency and voltage. This enables a range of nonlinear signal processing functions including reconfigurable filtering and pulse shaping, Figure 4.



▲ **Figure 4. Acoustic gratings are implemented in chalcogenide single mode fibre. Tunable optical resonances are induced at wavelengths determined by the drive frequency. This is the first demonstration of acoustic gratings in a non-silica optical fibre.**

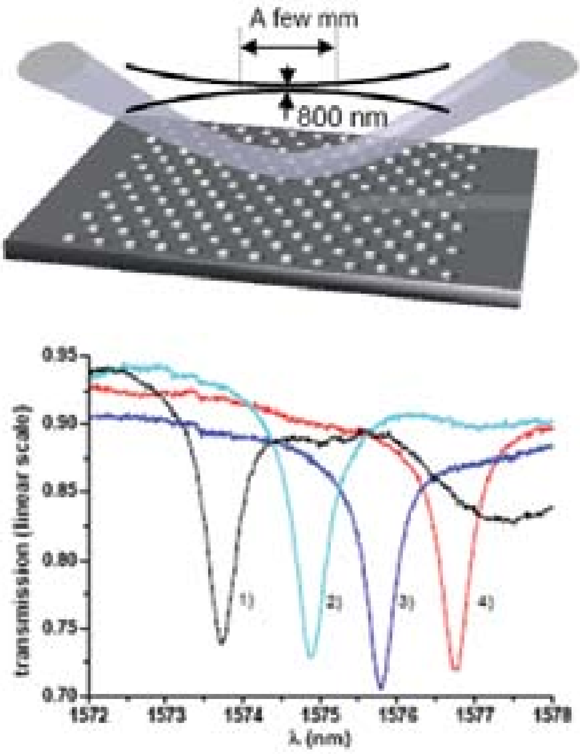
Hong Nguyen and Klaus Finsterbusch investigated the wavelength dependence of the nonlinearity and two-photon absorption in chalcogenide single mode fibre, shown in Figure 5 [10]. They found that the figure of merit for this material decreases at short wavelengths and approaches unity at the half-bandgap frequency, consistent with measurements in bulk materials. Hong also investigated optical signal processing in chalcogenide single mode fibre gratings. This approach revisits some earlier work on all-optical switching in long-period gratings in silica single-mode fibres. The Kerr nonlinearity induces an intensity dependent shift in the grating resonance leading to intensity dependent transmission. The chalcogenide geometry has the same functionality at a dramatically reduced switching threshold.



▲ **Figure 5. Measurements of SPM and TPA in single mode chalcogenide fiber and comparison with numerical simulations. Results confirm that the nonlinear FOM approaches unity at the half-gap frequency of the material.**

The switching dynamics in chalcogenide devices are somewhat complicated by the moderate two-photon absorption (TPA) of the chalcogenide glass. Tom Grujic and Martijn de Sterke developed a generalized nonlinear coupled mode equations simulation that incorporates TPA and investigated its impact on the switching dynamics of long-period grating couplers. They found that in some regimes the TPA improved switching performance. Michael Lamont investigated the impact of TPA on optical regeneration schemes based on self-phase modulation followed by optical filtering; the so-called Mamyshev system [11]. Michael showed convincingly that TPA can enhance the regenerative properties of this particular scheme over a range of values. In particular, for values of TPA similar to those seen in Arsenic Selenide glasses, the Mamyshev regenerator performance is improved by several dB. These results also demonstrated the deficiencies of silicon, which has a significant TPA.

Christian Grillet and Cameron Smith achieved efficient coupling from standard single mode fibres into chalcogenide photonic crystal cavities, including point defect cavities. These results were obtained with a specially designed bow-shaped nanowire constructed by Cameron that allows for efficient localized coupling to the point defect [12]. In a related collaboration with researchers at the NRC in Ottawa, Christian Grillet, Cameron Smith and Christelle Monat demonstrated efficient coupling to point-defects in semiconductor photonic crystals. This establishes a clear path towards optical coupling for quantum dot sources, shown in Figure 6 [13].



▲ **Figure 6. Efficient evanescent coupling via a silica loop-nanowire, to ultra-small InAs/InP quantum dot photonic crystal cavities, specifically designed for single photon source applications. This coupling technique enables the tuning of both the Q-factor and the wavelength of the cavity mode independently, which is highly relevant for single photon source applications.**

In very recent results, Michael Lee and Christian Grillet have demonstrated the ability to post-tune photonic crystal waveguides by exploiting the photosensitivity of the chalcogenide glass. These results point to a fundamentally new approach to fabrication of cavities and waveguides in photonic crystals [14].

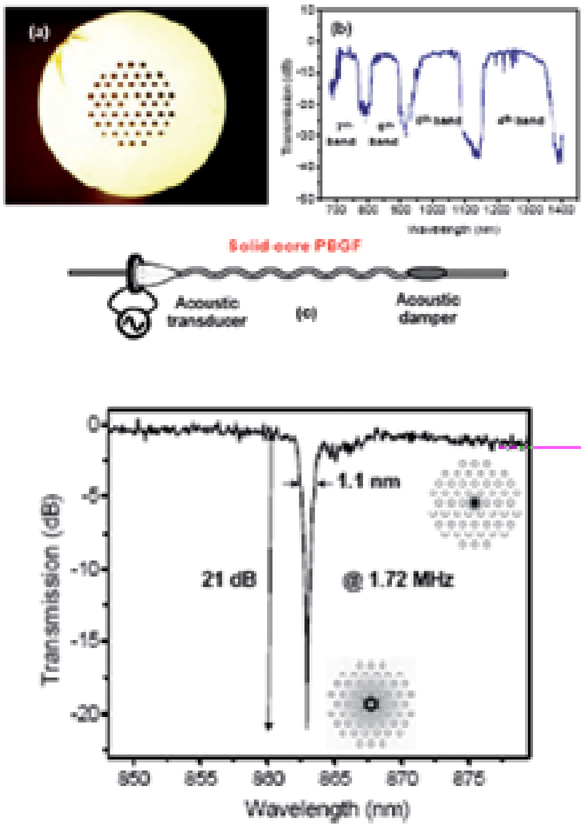
Slow-light and nonlinear propagation in periodic structures

A major highlight of the Sydney CUDOS program was the demonstration of slow-light in optical fibre gratings [15], discussed in more detail in the Flagship project summary. Our approach is based on the propagation of gap solitons in fibre gratings. This team included Martijn de Sterke, Ian Littler and Joe Mok and resulted in a publication in the prestigious journal Nature Physics and numerous articles in the press. The fundamental innovation of this work was the concept of "dispersionless" propagation, in which we overcame the intrinsic dispersive nature of all slow light schemes by launching a soliton pulse that propagates without changing shape [16]. Therese Au undertook a new experimental investigation related to the gap soliton experiments to explore optical switching effects in phase shifted Bragg gratings. These gratings can enhance the field intensity at the resonant wavelength and thus lower the switching threshold.

Ian Litter conducted a systematic study of the photothermal effect in fibre Bragg gratings [17]. These experiments revealed that this effect, which can be significant in a number of contexts, is particularly important for the nonlinear pulse propagation experiments being performed by Joe Mok. Ian proposed a simple and elegant solution that involves surrounding the fibre grating with a heat-conducting epoxy; this lowered the wavelength shift associated with the photothermal effect by over an order of magnitude.

Photonic crystal fibres

Paul Steinvurzel reported the first demonstration of optical gratings in photonic band gap fibre [18]. Working with an exchange student from the University of Colorado, Eric Moore, Paul demonstrated microbend long-period gratings in fluid-filled ARROW photonic bandgap fibres. These gratings are unique and interesting for two important reasons: (a) they reveal the underlying dispersive properties of these fibres; and (b) they are highly tunable. Paul demonstrated that these optical gratings are highly tunable and compared the experimental tuning properties with theoretical predictions [19]. Paul also demonstrated a versatile approach for introducing gratings in these fibres by fusion splicing [20]. More recently Dong-Il Yeom, a visiting Research Fellow from South Korea, has worked with Paul on a successful demonstration of acoustic gratings in solid-core ARROW fibres. These experiments demonstrated strong tuning of the grating induced resonant coupling and accurately probed the modal properties of these fibres, shown in Figure 8 [21].



▲ **Figure 8. Acousto-optic long period grating resonances in a fluid-filled solid-core photonic bandgap fiber (PBGF). The acoustic grating design enables electrically tunable notches in each of the PBGF transmission bands, where both the center frequency and depth of the resonances can be varied.**

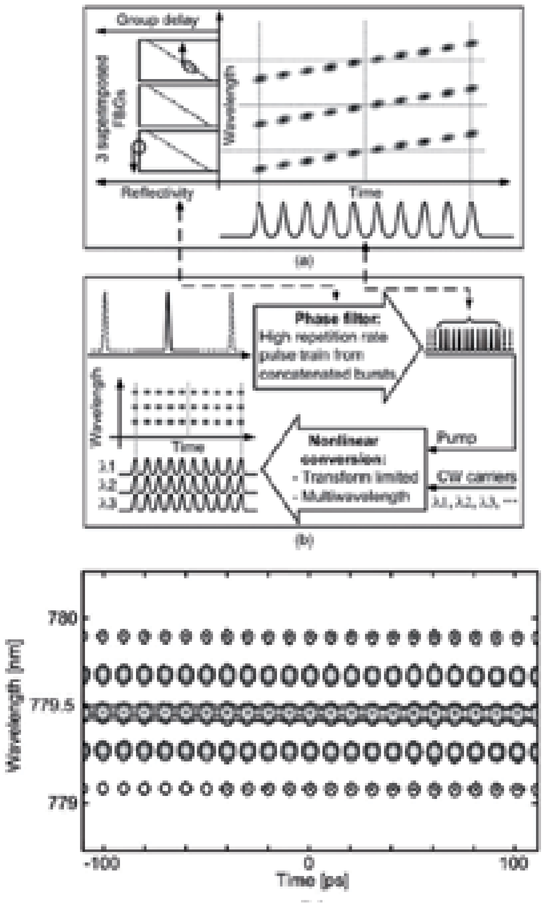
Ultrafast pulse propagation effects and optical transmission

During 2006 the CUDOS optical transmission bed facility was upgraded to operate at 160 Gb/s. Funded by a LIEF grant in 2005 (with RMIT University and NICTA) this facility utilizes optical multiplexing to multiple the bit-rate from 40 Gb/s to 160 Gb/s. Mark Pelusi implemented an optical multiplexer based on commercially available delay lines and the de-multiplexer has been implemented based on an electro-absorption modulater followed by a Nonlinear Loop Mirror.

Jeremy Bolger and Ian Littler investigated numerous schemes for pulse rate multiplication based on novel pulse shaping techniques, shown in Figure 9. Jeremy demonstrated a novel scheme based on superimposed Bragg gratings that successfully multiplied pulses from tens of gigabits to over 100 Gigabits [22]. Ian Littler demonstrated a novel scheme based on reflecting pulses of gratings with prescribed group delay ripple [23]. Related to this Ian convincingly demonstrated the detrimental impact of group delay ripple on optical regeneration schemes [24]. Jeremy was involved in a fruitful collaboration with Professor LaRochelle at the University of Laval and Professor Lawrence Chen at McGill University in Quebec that demonstrated coherent generation of multiple wavelength channels of high repetition rate pulses [25].

Martin Rochette demonstrated 3R optical regeneration with improved bit-error rate using a simple extension of the Mamyeshev optical regeneration principle that has been a central theme of the CUDOS program. The BER improvement makes the scheme attractive for receiver based optical regeneration applications [26].

Michael Roelens joins the Sydney group funded by a linkage project with Optium. Michael did his PhD studies at the ORC at Southampton University on the topic of ultrafast pulse propagation and pulse characterization techniques.



▲ **Figure 9. Generation of a 4 × 100 GHz Pulse-Train From a Single-Wavelength 10-GHz Mode-Locked Laser Using Superimposed Fiber Bragg Gratings and Nonlinear Conversion.**

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