Chapter 8

Conclusion: Project achievements and future developments

This chapter serves the purpose of summarising the simulation and experimental work accomplished in the course of this research programme in developing and demonstrating an original coarse-routed access network architecture, allowing for the interoperability of various PON technologies by means of a wide-passband AWG. Following a review of the project achievements, the potential network evolution to support long-reach, wide-splitting connectivity is examined in view of a 7 nm-wide AWG which when readily-available is expected to demonstrate scalability and dynamicity comparable to standard reach infrastructures with extended ease of implementation and network coverage.

8.1 Research background

This thesis has commenced by providing a justification as to why passive optical networks have accomplished recognition from incumbents, among various wireline and wireless access network technologies, as a cost effective solution to form the basis for developing broadband access networks [1, 2] with subscriber bandwidths reaching up to 100 Mbit/s in the near future [3]. Owing to different needs and business plans of network operators and governments, Asia and North America constitute the worldwide leaders in the deployment of TDM-PON infrastructures, compared to Europe that although has developed plans for vast deployment in the coming years has only accommodated so far a few fibre deployment projects as a result of the regulatory environment uncertainties [4]. On the other extreme, South Korea has adopted primarily WDM-PON architectures to provide subscribers more than 100 Mbit/s dedicated bandwidth although the WDM-PON has not been standardised yet [2].

To allow even higher bandwidth, greater coverage and penetration than the currently deployed standards, various potential research paths for building next-generation PONs have been studied, with a common aim to support new bandwidth-hungry online services and further reduce the cost for delivering the existing ones [4]. These initiatives include the increase of standard PON [5-9] aggregate data rates to 10 Gbit/s [10, 11] complemented by extending their physical reach and split to distances of at least 100 km [12, 13] and 1024 users respectively, offering economical bandwidth and service upgrade from the end-user all the way up to the core network at significantly reduced cost for network operators. An alternate path, aspects of which have very recently been standardised [14], considers multiple wavelength operation over standard splitter PONs to allow 2-D allocation of network resources and a smooth migration for the future [15]. In addition, CWDM [16] has been investigated as a potential low-cost solution, expected to have a large impact on the economics of near-term optical access deployment [17]. As a result, combining the merits of CWDM [18, 19] as a cost effective, relaxed specification wavelength multiplexing technique with installed-base time multiplexing is believed to offer a great prospective for solving the challenges in the development of access networks [15, 20, 21] articulated by transparency, smooth upgradability, scalability and dynamicity [2, 4, 22, 23].

8.2 Original contribution

In that direction, this thesis has provided the justification, design criteria, implementation and evaluation both in the form of VPI simulations and test-bed experimentations of an innovative approach employing the coarse [16] and dense [24] WDM grids to allow coarse-routed [21] connectivity of TDM and WDM PON topologies through a single termination in the OLT, in contrast to competitive designs. This has been achieved by the application of coarse-fine grooming by which a single coarse AWG device in the OLT can access ONUs independently of whether terminated to a TDM or increased capacity WDM PON by means of its wide passbands and the use of just a single transceiver due to the AWG Latin-routing. Which PON will be served at a given time would depend on the operating channel of the transceiver in the OLT and the AWG input port connected. Depending on the total number of I/O ports of the AWG the number of network ONUs can be scaled up, by using the same device. In addition, by adding extra transceivers to the unused AWG inputs, depending again on the actual connection established, different coarse channels can be assigned to the same AWG output simultaneously in order to increase the transmission capacity of a PON with higher traffic load requirements. Although in that case multiple transceivers are employed they would all operate through the connection paths of a single device that of the AWG, allowing for a more efficient control management.

In downstream, because of the Gaussian passbands of the coarse AWG, different wavelengths will be routed to different AWG output ports using the Latin properly of the device. For example if a TDM-PON is to be served, a tunable laser, TL1 will optimally utilise only a single wavelength, placed at the centre of the AWG coarse channel 1, which will be Latin routed to output port 1 to broadcast information to all ONUs of that TDM-PON. In the case of a WDM-PON, TL1 will make use of all 16 wavelengths sequentially, centred ±3.2 nm around coarse channel 2, to address jointly all ONUs connected to the WDM-PON. That would mean that all dense wavelengths centred around coarse channel 2 will be routed to the same output port using the coarse passband of the AWG channel. The fact that a single tunable laser assigns bandwidth to multiple PONs adds to the network considerable dynamicity since the OLT can select at each cycle which PON to serve for longer time to satisfy the corresponding bandwidth requirement.

In the upstream scenario, all wavelengths already used for downstream transmission will be reused following exactly the same paths since the tunable laser, apart from burst-data downstream, has been designed to provide the ONUs with CWs to be used by the Reflective SOAs. Consequently traffic from the TDM-PON and wavelengths around the coarse channel 2 from the WDM-PON will be routed upstream to AWG output port 1 where will be all terminated sequentially to a single receiver RX1.

The property of the network to use the same wavelengths, possible only due to the presence of an RSOA in each ONU, adds to the network dynamicity since the OLT can control the transfer of data upstream and downstream to match network traffic by readjusting at each polling cycle the time-slots used for burst-data and CWs. Although reflectivity tends to be a common property of most designs, same path transmission for upstream and downstream for all ONUs terminated to a WDM-PON can be uniquely achieved with the proposed architecture due to coarse channel routing, evenly important with the requirement of just a single transceiver in the OLT.

To satisfy extended bandwidth transfer at a given time in the scenario of an application intensive WDM-PON connection, TL2 employing a different coarse channel than TL1 could be arranged by simply defining its connection point in the OLT to dynamically assign bandwidth to the same WDM-PON.

In order to validate the new access network core features, an experimental test-bed has been implemented, by means of a readily-available 8×8 AWG with coarse Gaussian passbands to demonstrate bidirectional wavelength allocation to reflective PONs distributed in particular in a WDM configuration.

As the final contribution, the application of polarisation-division-multiplexing has been also investigated, demonstrating full-duplex operation in the architecture, by means of an innovative orthogonally-multiplexed OLT, enabling simultaneous data and CW transmission downstream to increase bandwidth utilisation for each reflective ONU and potential 10 G/bit provision over Gigabit-capable and Ethernet PONs.

In defining accurate routing of all ONUs comprising a PON, the AWG Gaussian passband and its PDW shift [25] were initially simulated in VPI. PDW is known to impose a restriction in multi-wavelength operation of wide passband AWGs and therefore to limit the routing performance of the network [25]. The Gaussian passband window of the devised AWG exhibited up to 3 dB PDL incurred on transmitted wavelengths of a PON due to a worst case PDW shift of 1.8 nm and worst case device phase errors of 270° [26]. Subsequently, network simulation results to address a fully populated WDM-PON have demonstrated error-free performance in all coarse channels and the highly attenuated wavelengths within.

Subsequent experimental results employing an experimental 8×8 AWG, utilising 2.7 nm-wide Gaussian passbands, have confirmed the feasibility of the proposed network to accommodate fully-populated WDM and TDM-PONs when current 7 nm-wide coarse AWGs prototypes become commercially-available.

Finally, transmission of the multiplexed CW and data signals in a polarisation-multiplexed network design, through 7 nm-wide passband windows of the modelled AWG, has enabled the proposed scheme to potentially double the bandwidth utilisation for each subscriber, resulting in increased network upstream and downstream throughput, in contrast to half-duplex network operation.

8.3 Active versus passive routing

The role of the AWG router in the architecture could be contrasted with a potential wavelength switch. Wavelength switches have been adopted mainly for metro and long-haul networks to provide resilience, traffic management, transparency and large number of interconnections. Wavelength switches have the potential to be integrated also in access networks as efficient routing elements in the OLT to handle a large number of PONs [27]. To contrast among the two routing solutions, key factors including tunability, transmission properties, supported network size and technology implementation have been accounted for.

Network tunability is mandatory to provide dynamicity and flexibility and in that sense the active nature of the switch offers unidirectional dynamic switching of dense wavelengths from any input to a single or multiple output ports. In comparison the AWG router, providing bidirectional routing [28] of coarse channels and dense wavelengths among any pair of I/O ports, where dynamicity is achieved by means of tunable lasers. Typical switching speed of a switch is approximately 20 ms [29], limited in performance due to the micro-electro-mechanical structures (MEMs), consequently incapable of providing increased performance comparable to laser sources, utilising typical tuning times in the range of micro to nano seconds, necessary to support real-time access.

The switch can provide easy reconfigured network resilience by protective switching in case of fibre cuts and also enables multicasting features by allowing an optical signal applied to a single input port to be broadcasted to multiple outputs potentially serving multiple PONs in parallel. Although this could also be achieved by an AWG, it will require the use of optical couplers to connect an optical source to all input ports of the AWG [30], subsequently exploiting the Latin property of the device to broadcast the signal to all output ports. Alternatively, MEMs could be applied at the device I/O ports to emulate an active AWG router, providing Latin-routing using only a single port downstream [30].

Although a typical switch can accommodate up to 190×190 I/O ports [29] with relatively low insertion loss, in the range of 2-4 dB, interoperability of TDM and WDM-PONs cannot be demonstrated with switch technology since coarse-fine grooming cannot be achieved using commercially-available devices utilising only DWDM switching. In addition, different wavelengths would not be able to be assigned to the same output simultaneously. Finally, bidirectional routing using just a single transceiver in the OLT is not viable with a switch due to its inherited unidirectional operation and the lack of Latin-routing capabilities.

8.4 Project implementation and results

A complete, bidirectional multi-PON access network infrastructure has been presented in this thesis by means of integrating RSOAs in the ONUs employed initially to accommodate upstream modulation and downstream detection in the same device. The network architecture was extended subsequently to demonstrate full-duplex operation by utilising polarisation multiplexing to propagate data and CWs, allowing for increased time-slot availability for the former.

To accommodate these characteristics, the OLT design was modified from its preliminary set-up, accounting solely for accurate AWG routing, to provide CWs in addition to burst-data for upstream and downstream transmissions respectively. To achieve this, the optical and electrical characteristics of the designed RSOA were determined to allow accurate modelling by contrasting its performance characteristics to a commercially-available device [31]. In particular, it has been demonstrated that although the simulated RSOA optical gain bandwidth spanned over 30 nm, sufficient for demonstrating the network grooming capabilities, it lacked in covering the 80 nm spectral range occupied by four physical PONs. Nevertheless, the optical gain bandwidth of commercially-available devices is expected to increase as a result of the growing interest in CWDM access networks employing reflective ONUs [32]. Currently, commercially-available SOAs facilitate 80 nm spectral bandwidth [33] and by that encompass around half of the ITU-T CWDM grid [16]. Reflective SOAs, employing currently 50 nm gain bandwidth [31], are believed to follow the same trend.

To increase the speed of simulation in the presence of RSOA broadband ASE noise, a novel time-optimisation technique has been proposed and evaluated in VPI, to detach the upstream modulated data signal from the ASE noise by means of optical filtering. Results have confirmed data and CW error-free routing of an individual reflective fully populated WDM-PON through 7 nm-wide passband windows of the AWG in the presence of 0.8 nm PDW shift and 270° worst case phase errors. In addition, the worst case 1.8 nm PDW shift demonstrated 20 km transmission at 1.25 Gbit/s of more than 93% ONUs of the WDM-PON.

To resolve the unavoidably reduced bandwidth utilisation of the current design due the time-interleaving between downstream data and CWs in the OLT [34, 35], an orthogonally-multiplexed OLT was utilised to achieve full-duplex operation by means of polarisation division multiplexing (PDM). Simulation results have confirmed error-free transmission of all ONUs representing a WDM-PON in the presence of a worst case 3 dB PDL. Contrasting between half and full-duplex operations has demonstrated a moderate 1.3 dB penalty superimposed at the later that still allows for 10^{-9} BER transmission at 1.25 Gbit/s. This transmission data rate is potentially to be increased to 10 Gbit/s when RSOA devices with extended electrical bandwidth become readily-available, since it was shown that fibre dispersion and crosstalk between the transmitted data and CW do not limit the network 10 Gbit/s transmission. As a result, by assuming the use of symmetrical broadband services such as video conferencing, online gaming [2] and Web 2.0 applications, the architecture has verified its potential to double the bandwidth utilisation for each subscriber, due to the increased bidirectional network throughput.

Finally, in order to experimentally demonstrate such architecture, a commercially-available 2.7 nm-wide coarse AWG has been employed due to lack of availability currently of 7 nm-wide devices. Results have confirmed error-free routing for the most severely degraded ONUs transmitted at the edge of the experimental AWG 2.7 nm-wide Gaussian passbands, accounting for 0.35 nm PDW shift and 1.5 dB maximum PDL, representing comparable measure of network performance due to a relative amount of PDL and PDW shifting. Further analysis, based on power budgeting, and greater than 20 dB measured signal to reflections noise, suggests that Rayleigh backscattering is not limiting the bidirectional transmission, demonstrating the feasibility of the proposed network to accommodate fully-populated WDM and TDM-PONs when current 7 nm-wide coarse AWGs prototypes become readily-available.

8.5 Future work

The proposed network architecture demonstrated high scalability and dynamic routing of various PON technologies through a single coarse AWG in the OLT with coarse-fine grooming features. 7 nm-wide passband AWGs have been extensively investigated [25, 36-40] due to the considerable interest in the application of CWDM in the access network. Although the demonstrated figures of polarisation dependency with wavelength and the amount of phase errors in the fabrication process of prototype N×N coarse AWGs [25] have been demonstrated to allow efficient bidirectional performance, they are likely to be reduced, benefiting from ongoing research development. In conjunction, the number of coarse channels available for routing is expected to be increased from a typical figure of 4 [25] to up to 18 to comply with ITU-T [16], employing multiple FSRs and greater number of I/O ports.

These advances are expected to promote the role of coarse AWGs in the evolution of access networks in general and significantly benefit the scalability of the presented architecture by accommodating increased number of PONs, and by that supporting the smooth migration from standard to densely penetrated PONs. The scalability of the architecture will be further explored by investigating its ability to demonstrate a long-reach, wide-splitting ratio access network [41, 42]. Such configuration would contribute massively to business plans of network operators [41] towards increasing bandwidth to support emerging media-rich services shared by many physical PONs, both of TDM and WDM types, potentially offering significant CAPEX and OPEX savings in an incorporate access/metro infrastructure [43]. To that extend, the current architecture is easily extendable to such a topology since it already serves a number of different physical PON locations with dedicated coarse channels. This can be achieved by exploiting the decentralised coarse routing capability of the architecture to allow amplification units to be installed on route if necessary. The wide range of coarse channels in particular [44] is important in such application due to signals amplification. In that sense, commercially-available SOAs [33] have been designed for CWDM applications, covering up to 10 channels ranging from 1430 nm to 1610 nm with gain variations of up to 10 dB across this range. Clearly the remaining CWDM channels, ranging from 1270 nm to 1450 nm, if used, would have to be amplified by another SOA device operating at this range. The work will need to be extended to investigate performance due to ranging distances and the maximum bandwidth capable of delivering. This will be achieved by increasing the link spans of one of the PON connections beyond 100 km to investigate power budgeting, fibre backscattering and bandwidth-distance measurements in the presence of SOAs [33] located on route and high performance RSOAs in the ONUs. The potential of the architecture to increase network penetration, apart from the conventional form of power-splitting [12, 13], is expected to be explored by accounting for the multiple FSRs of the AWG to route several coarse channels to each output port of the AWG downstream, consequently increasing the number of PONs connected to each port. For this, the architecture will be required to provide separation between the individual PONs of the same AWG port by means of channel filtering or add/drop multiplexers [45]. In the OLT, additional laser sources connected to the AWG input ports alongside the existing tunable lasers will be required in the case of laser failure and to accommodate additional operating wavelength ranges [46]. For the latter case, this can be attained by once again utilising the multiple FSRs of the AWG to allow those additional tunable lasers to be coupled to the already-used AWG input ports.

Finally, since the OLT will still provide CWs for extended fibre distances, Rayleigh and Brillouin backscattering are expected to become a major source of impairment [47]. To mitigate such impairment, a dual feeder fibre has been employed elsewhere [47], as well as relocating the CW signal sources, used to seed the RSOA in the ONUs, from the their original location in the OLT closer to the ONUs [47]. Alternatively, the application of polarisation division multiplexing will be further investigated to reduce the effect of the backscattering crosstalk. Since the state of polarisation (SOP) of the Rayleigh backscattered signal in a low birefringence fibre is similar to that of the downstream CW signal [48], the upstream modulated signal SOP in the ONU can be altered in such a way that it is kept orthogonal to the backscattered signal towards the OLT. Consequently, the upstream signal can be isolated from the backscattered signal prior detection in the OLT, reducing significantly the Rayleigh crosstalk and allowing the use of a single feeder fibre, maintaining in parallel the CWs sources in the OLT reducing deployment costs.

8.6 References

[1] D. Gutierrez, K. S. Kim, S. Rotolo, F.-T. An, and L. G. Kazovsky, "FTTH Standards, Deployments and Research Issues (Invited)," presented at Joint International Conference on Information Sciences (JCIS), Salt Lake City, UT, USA, 2005.

[2] C.-H. Lee, S.-M. Lee, K.-M. Choi, J.-H. Moon, S.-G. Mun, K.-T. Jeong, J. H. Kim, and B. Kim, "WDM-PON experiences in Korea [Invited]," *OSA Journal of Optical Networking*, vol. 6, pp. 451-464, 2007.

[3] P.-F. Fournier, "From FTTH pilot to pre-rollout in France," presented at CAI Cheuvreux, France, 2007.

[4] P. Chanclou, S. Gosselin, J. F. Palacios, V. L. Álvarez, and E. Zouganeli, "Overview of the Optical Broadband Access Evolution: A Joint Article by Operators in the IST Network of Excellence e-Photon/ONe," *IEEE Communications Magazine*, vol. 44, pp. 29-35, 2006.

[5] N. Ghani, A. Shami, C. Assi, and M. Y. A. Raja, "Quality of service in Ethernet passive optical networks," *Advances in Wired and Wireless Communication, 2004 IEEE/Sarnoff Symposium on*, pp. 26-27, 2004.

[6] ITU-T Recommendation G.984.2, "Gigabit-capable passive optical networks (GPON): Physical media dependent (PMD) layer specification," 2003.

[7] ITU-T Recommendation G.984.3, "Gigabit-capable passive optical networks (GPON): transmission convergence layer specification," 2003.

[8] ITU-T Recommendation G.984.1, "Gigabit-capable Passive Optical Networks (GPON): General characteristics," 2003.

[9] ITU-T Recommendation G.984.3, "Gigabit-capable passive optical networks (GPON): transmission convergence layer specification," 2003.

[10] H. Nishizawa, Y. Yamada, K. Habara, and T. Ohyama, "Design of a 10-Gb/s burst-mode optical packet receiver module and its demonstration in a WDM optical switching network," *IEEE/OSA Journal of Lightwave Technology*, vol. 20, pp. 1078 - 1083, 2002.

[11] B. C. Thomsen, B. J. Puttnam, and P. Bayvel, "Optically equalized 10 Gb/s NRZ digital burstmode receiver for dynamic optical networks," vol. 15, pp. 9520-9526, 2007.

[12] "Photonic Integrated Extended Metro and Access Network (PEIMAN)." http://ist-pieman.org/techapp.htm, 2007.

[13] G. Talli and P. D. Townsend, "Hybrid DWDM-TDM long reach PON for next generation optical access," *IEEE/OSA Journal of Lightwave Technology*, vol. 24, pp. 2827-2834, 2006.

[14] ITU-T Recommendation G.984.5, "Enhancement band for Gigabit capable optical access networks," 2007.

[15] F.-T. An, D. Gutierrez, K. S. Kim, J. W. Lee, and L. G. Kazovsky, "SUCCESS-HPON: A Next-Generation Optical Access Architecture for Smooth Migration from TDM-PON to WDM-PON," *IEEE Communications Magazine*, vol. 43, pp. S40- S47, 2005.

[16] ITU-T Recommendation: G.694.2, "Spectral Grids for WDM Applications: CWDM wavelength grid," 2003.

[17] K.-D. Langer, J. Grubor, and K. Habel, "Promising Evolution Paths for Passive Optical Access Networks," presented at 6th International Conference on Transparent Optical Networks (ICTON 2004), Wroclaw, Poland, 2004.

[18] J. Aldridge, "The best of both worlds," *Lightwave Europe*, pp. 18-19, 2002.

[19] K.-D. Langer, K. Habel, F. Raub, and M. Seimetz, "CWDM access network and prospects for introduction of full-duplex wavelength channels," presented at Conference on Networks & Optical Communications (NOC 2005), UCL, 2005.

[20] R. Rastislav, "The utilization of the DWDW/CWDM combination in the metro/access networks," presented at Joint First Workshop on Mobile Future and Symposium on Trends in Communications (SympoTIC '03), Bratislava, Slovakia, 2003.

[21] Y. Shachaf, C.-H. Chang, P. Kourtessis, and J. M. Senior, "Multi-PON access network using a coarse AWG for smooth migration from TDM to WDM PON," *OSA Optics Express*, vol. 15, pp. 7840-7844, 2007.

[22] T. Koonen, "Fiber to the Home/Fiber to the Premises: What, Where, and When?" *Proceedings of the IEEE*, vol. 94, pp. 911 - 934, 2006.

[23] F. Effenberger, D. Clearly, O. Haran, G. Kramer, R. D. Li, M. Oron, and T. Pfeiffer, "An introduction to PON technologies," *IEEE Communications Magazine*, vol. 45, pp. S17-S25, 2007.

[24] ITU-T Recommendation: G.694.1, "Spectral grids for WDM applications: DWDM frequency grid," 2002.

[25] J. Jiang, C. L. Callender, C. Blanchetière, J. P. Noad, S. Chen, J. Ballato, and J. Dennis W. Smith, "Arrayed Waveguide Gratings Based on Perfluorocyclobutane Polymers for CWDM Applications," *IEEE Photonics Technology Letters*, vol. 18, pp. 370-372, 2006.

[26] A. Wang, "Private communication." Fremont, CA: ANDevices, Inc, 2006.

[27] A. M. Minguez and P. R. Horche, "Application of WDM holographic devices in access and metro networks," *Journal of Optical and Quantum Electronics*, vol. 39, pp. 131-146, 2007.

[28] Y. Shachaf, P. Kourtessis, and J. M. Senior, "An interoperable access network based on CWDM-routed PONs," presented at 33rd European Conference and Exhibition on Optical Communication (ECOC), Berlin, Germany, 2007.

[29] GlimmerGlass, "http://www.glimmerglass.com/datasheets.aspx," 2007.

[30] I. Tsalamanis, E. Rochat, and S. D. Walker, "Experimental demonstration of cascaded AWG access network featuring bi-directional transmission and polarization multiplexing," *OSA Optics Express*, vol. 12, pp. 764-769, 2004.

[31] CIP-Photonics, "http://www.ciphotonics.com/PDFs%20May08/SOA_RL_OEC_1550_J.pdf," 2008.

[32] L. G. Kazovsky, N. Cheng, W. Shaw, D. Gutierrez, S.-W. Wong, and M. Maier, "Next-Generation Optical Access Network," *IEEE/OSA Journal of Lightwave Technology (to be published)*, 2007.

[33] CIP-Photonics, "http://www.ciphotonics.com/cip_semiconductor_2.htm," 2006.

[34] C. Bock, C. Arellano, and J. Prat, "Resilient single-fiber ring access network using coupler-based OADMs and RSOA-based ONUs," presented at Optical Fiber Communication and the National Fiber Optic Engineers Conference (OFC/NFOEC 2006), Anaheim, USA, 2006.

[35] J. Prat, C. Arellano, V. Polo, and C. Bock, "Optical Network Unit Based on a Bidirectional Reflective Semiconductor Optical amplifier for Fiber-to-the-Home Networks," *IEEE Photonics Technology Letters*, vol. 17, pp. 250-253, 2005.

[36] H. C. Woei, N. A. Rahman, and S. Shaari, "Conventional Arrayed Waveguide Grating with 4 Channel Structure Design for CWDM," presented at International Conference on Semiconductor Electronics (ICSE), Kuala Lumpur, Malaysia, 2004.

[37] T. Lang, J.-J. He, and S. He, "Cross-Order Arrayed Waveguide Grating Design for Triplexers in Fiber Access Networks," *IEEE Photonics Technology lett.*, vol. 18, 2006.

[38] N. Yurt, K. Rausch, A. R. Kost, and N. Peyghambarian, "Design and fabrication of a broadband polarization and temperature insensitive arrayed waveguide grating on InP," *Optics Express 'OSA'*, vol. 13, pp. 5535-5541, 2005.

[39] S. Shaari and M. S. Kien, "Design implementation of up to 20 channel silica-based arrayed waveguide WDM," presented at International Conference on Semiconductor Electronics (ICSE), Kuala Lumpur, Malaysia, 2000.

[40] J. L. Chemmanda, V. R. Pamidighantam, and S. Krishnamachari, "Design of Polymer Arrayed Waveguide Gratings for Access Networks and CWDM Applications," presented at Electronics Packaging Technology Conference (EPTC), 2003.

[41] R. P. Davey and D. B. Payne, "The future of fibre access systems?" *BT Technology Journal*, vol. 20, pp. 104 -114, 2002.

[42] P. Townsend, G. Talli, C. W. Chow, and E. MacHale, "10 Gbps hybrid WDM-TDM long reach PONs," presented at Networks and Optical Communications (NOC 2006), Berlin, Germany, 2006.

[43] R. P. Davey and D. B. Payne, "Long Reach Access-Transforming Future Broadband Network Economics (Invited)," presented at Conference on Networks & Optical Communications (NOC 2005), UCL, London, 2005.

[44] ANDevices Inc., "Custom design of NxN coarse AWG," 2008.

[45] Iridian-Spectral-Technologies, "CWDM Channel Splitter SPF16, http://www.iridian.ca/products/details.php?intProductID=23&intSearchCategoryID=1," 2008.

[46] J. Segarra, V. Sales, and J. Prat, "OLT Design Approach for Resilient Extended PON with OBS Dynamic Bandwidth Allocation Sharing the OLT Optical Resources," presented at 10th International Conference on Transparent Optical Networks (ICTON 2008), Athens, Greece, 2008.

[47] E. K. MacHale, G. Talli, and P. D. Townsend, "10Gb/s bidirectional transmission in a 116km reach hybrid DWDM-TDM PON," presented at Optical Fiber Communication

and the National Fiber Optic Engineers Conference (OFC/NFOEC 2006), Anaheim, USA, 2006.

[48] M. O. Van Deventer, "Polarization properties of Rayleigh backscattering in single-mode fibers," *IEEE Journal of Lightwave Technology*, vol. 11, pp. 1895-1899, 1993.