1. Introduction

The increase in end-user bandwidth demand, along with the decrease in WDM component cost, implies that WDM-based devices are likely to offer performance enhancements in multiple-access networks. Arrayed-waveguide gratings (AWG's), with their potential low cost, high wavelength selectivity, low insertion loss, small size and cyclic wavelength routing characteristics (Latin routing) are probably one of the best candidates for such an application. In a cascaded format, they offer high-level wavelength routing as well as flexible and efficient bandwidth allocation [1]. In addition, they can be tuned by varying the characteristics of their waveguides and perform space-wavelength switching functions [2,3].

This joint project between the Universities of Cambridge and Essex has resulted in the first experimental demonstration of a scalable access network architecture that can serve large numbers (thousands) of concurrent clients, using only a small number of wavelengths and sharing the same optical path for both downstream and upstream transmission [4]. This is achieved by cascading AWG's and exploiting their Latin routing characteristics. Simultaneous bi-directional error free transmission of 2.5Gb/s downstream and 2.5Gb/s upstream per end-user data was achieved, with negligible crosstalk between the downstream and upstream channels.

The project has also resulted in the design and simulation of several novel active AWGs. It has been shown that these devices can be configured as equalizing filters, channel dropping (suppressing) filters to yield optical add/drop multiplexing functionality; and space/wavelength switches [5]. Furthermore, simulation using Beam Propagation (BPM) has indicated the potential for dynamic dispersion compensation of up to 160 ps/nm [6]. Several system-level simulations were carried out using the VPI TransmissionMaker package from VIRTUAL PHOTONICS.

2. Key Advances

2.1 Active space wavelength switching with novel active AWGs

A holographic AWG is one in which a phase hologram is superimposed on its arrayed waveguide section through use of an active modulator array (Fig. 1). Configuring the hologram to a suitable target function allows the output response to be controlled. Holographic AWGs have a variety of potential applications in future WDM networks. Several novel holographic AWGs were designed using a simulated-annealing method to achieve the required target function in order to achieve a range of WDM functions, to calculate the holograms. These were modelled using BPM. The forms investigated included: an optical add/drop multiplexer with channel suppression up to 15dB; and an equalisation filter designed to equalise 8×100GHz spaced WDM channels of different gains within a 10dB range. Channel control using the holographic AWG was investigated: single channel routing was simulated, with inter-channel ASE suppressed up to 19dB. Multi-channel routing was also achieved but with poorer SNR up to 10dB. The simulation results obtained using BPM compared extremely favourably with other approaches, e.g. Fourier methods. Key results are discussed in more detail below.

2.1.1 Single channel routing

In order to route a wavelength channel of interest to the desired AWG output port, the required target function is a square pulse in the position of the desired output port. In a normal AWG, one wavelength channel appears at each output port. With a suitably optimised phase hologram, it is possible to choose that wavelength. Simulation results obtained for single channel routing using three-phase holograms are shown in Fig. 2. Channel 6 is shown routed to output port 1 with the SNR around 19dB. This is close to the optimised figure of 20 dB obtained using simulated annealing and Fourier analysis. A further property that has been demonstrated is the ability of a phase hologram to control the signal passband width or power.
2.1.2 Multiple channel routing

For multiple-channel routing, the target function has multiple peaks, reflecting the number of routed channels. The selected channels are routed to the same output port. BPM simulation results for multiple channel routing were obtained for double- and triple-channel routing. Some degradation of the SNR is observed compared with the single channel case, but the data compare well with Fourier simulation results. Although the figure of 11dB achieved here is below the widely accepted SNR of 25dB for WDM networks, further optimisation of the phase hologram, can remedy this. Alternatively, using a higher number of arrayed waveguides will also improve these figures. The results obtained from the BPM are seen to be significantly wider than in the Fourier model. This is explained by the fact that amplitude variations across the arrayed-waveguides are ignored in the Fourier model, but are accounted for in BPM.

2.1.3 Phase errors

The robustness of the holographic AWG design to fabrication tolerances is of great importance. Phase errors or path-length jitter may arise from shortcomings of the design or fabrication process. A phase error of only 0.17 rad results in a crosstalk floor of approximately -25dB. The sensitivity of the holographic AWG structure to such tolerances was tested using the BPM. A range of phase errors were simulated. The results are shown in Fig. 3(a) and (b); they indicate that phase errors do not affect the general wavelength characteristics of the device, but that SNR is significantly affected. The effect of the phase error $\pi/8$ is barely noticeable. For a phase error of $\pi/4$, the SNR is around 17dB. The design starts to break down for phase errors of $\pi/2$, where the SNR is less than 7dB. These results indicate that the holographic designs are robust to individual phase modulator failures and fabrication phase errors, and are consistent with typical fabrication constraints.

2.2 Active dispersion compensation with novel active AWGs

Dispersion is a principal factor limiting the transmission performance at high data rates in optical fibre networks. Dispersion causes the pulse to spread as it travels along the fibre, leading to reduction in bit rate and hence limited bandwidth. There is great interest in dispersion compensation as it provides an opportunity to increase significantly the available bandwidth on existing fibres. An AWG with parabolic phase profile applied to the arrayed waveguides section has the potential to control the dispersion of an AWG. The dispersion introduced can be varied by adjusting the amount of parabolic phase shift, either by thermo-optic or electro-optic effects, so as to modulate the local refractive index of the individual waveguides. Several active AWGs have been modelled, and the variation of dispersion with design parameters has been tested.

As the total number of waveguides $M$ is increased, the dispersion $D$ is expected to increase. Tests performed using BPM on different arrayed-waveguide systems with $M = 64$ and $M = 128$ under conditions of different chirp $F$ show this effect clearly. Similarly, the increase of dispersion inversely as the wavelength spacing between adjacent channels was demonstrated.
Using a similar approach, the relationships between dispersion, chirp factor $F$, and apodization parameter $\alpha$ have been investigated. It is apparent there is an initial increase in dispersion with $F$, until a maximum is reached. However, the dispersion characteristics are not symmetric around $F = 0$. In the configuration modelled, maximum positive dispersion was reached for $F \approx -35$, before declining. Maximum negative dispersion is reached around $F = 17.6$ but remains almost constant for any further increase in $F$. Dispersion is maximised when $\alpha = 0$. This corresponds to applying a uniform power distribution along the arrayed-waveguides. To clarify these effects, several AWG models were simulated for different values of $\alpha$ and $F$. Figure 4(a) shows a 3-D mesh plot of the variation of dispersion $D$ as it varies with chirp parameter $F$, and normalised Gaussian apodization parameter $\alpha$. From the plot it is clear that dispersion is maximised for a uniform power distribution along the arrayed waveguides, and it is reduced by increasing $\alpha$. Dispersions in the range of -80 to 165 ps/nm were obtained. These are the first system simulations reported of dispersion compensation using an active AWG.

Further work involved system simulations to explore the performance of a parabolic AWG in a WDM system and its effect on the dispersion characteristics of an optical link. Figure 4(b) shows the topology used for simulation. P-AWGs were modelled using BPM; the resulting data files representing their response were incorporated into the VPI simulation. Three paths are shown: path 1 has a non-linear dispersive fibre; path 2 has a non-linear dispersive fibre, a fixed negative dispersion compensator (-100ps/nm) and a P-AWG ($F = -40$). The latter provides a maximum positive dispersion of 160 ps/nm. Path 3 is the same as path 2, except that the P-AWG ($F = 17$) used gives a maximum negative dispersion of -80 ps/nm. Eye diagram simulations corresponding to these paths are shown in Fig. 5.

The dispersion compensation demonstrated would compensate for 5-10km of single-mode fibre (SMF) with a 16ps/nm/km dispersion characteristic. It can be concluded that the P-AWG may be used as a fine-tuning dispersion compensation (DC) element in combination with a fixed DC device such as a DC fibre. Such a combination would result in an adaptive DC unit that could be used to compensate for 90 to 105 km of SMF. This variable dispersion feature may be vital in all-optical IP routers where packet time alignment and jitter reduction are important issues. Moreover, it can be used in long-haul submarine or terrestrial systems, where automatic dispersion correction is an attractive feature.

2.3 System simulation of cascaded passive and active AWGs

Novel simulation results have been obtained using the VPI package to evaluate passive/active AWGs with enhanced performance for system applications, primarily in new two- and three-stage wavelength-routed access architectures employing cascaded arrayed-waveguide grating technology. Two technologies were used to achieve space wavelength switching in these networks, firstly, a passive AWG with SOA array, and secondly, an active AWG. Such architectures can address up to 6912 customers while employing only 24 wavelengths coarsely separated by 1.6 nm. The results obtained demonstrate that cascaded AWGs access
architectures have a great potential in future LANs. Furthermore, they indicate for the first time that active AWG architectures are more efficient in routing signals to the destination ONUs than passive AWG architectures. The power penalty for the active AWG architectures is 0.8 dB lower than that of the passive AWG architectures. Moreover, active AWG architectures are less noisy, less costly and more compact. In addition, this work has demonstrated the potential applications of holographic AWGs as broadcasting devices in future access LANs, where the same signal has been routed to two different output ports.

System architecture

A proposed 3-stage WDM access architecture consisting of active and passive AWGs is shown in Fig. 5. There are $R = 24$ wavelengths spaced by 200GHz (1.6nm), requiring a $Q = 24$ port AWG. The AWGs at the S2 and S3 stages have matched FSR (4800 GHz), passband width and number of input/output ports, so that $Q = R$. Space-wavelength switching is carried out using active AWGs so that the incoming wavelength can be switched to any of the $Q$ output ports according to an applied voltage, $V_P$. The performance of this system and that of its equivalent implemented using passive AWGs and arrays of SOAs (semiconductor optical amplifiers) were compared.

It is clear from the spectral response and the eye diagram results that the active AWG cascaded architectures out-perform the passive AWG architectures — they demonstrate better eye patterns, and do not display the asymmetric spectral response characteristic of the passive architecture (due to the SOAs). BER simulations were repeated for several cascaded architectures with bit-rates of 2.5Gb/s for a 5GHz bandwidth receiver. Linear and holographic active AWGs were found to have substantially the same performance figures. With the specific 3-stage architecture described, for the active AWG architecture, the power penalty is 0.7 dB, compared with 1.5 dB for the passive AWG architecture. In practice, the use of active AWGs is expected to confer further advantages: they are less noisy, less costly and more compact. Active AWG can compensate for fabrication phase errors. Furthermore, an active AWG can replace two components (AWG and switch/modulator) which will reduce the total loss and offer a compact design.

2.4 Advanced nanofabrication of silicon on silica waveguides.

Silicon-on-silica waveguides offer the potential for far more compact devices with greater functionality than the prevailing silica-on-silicon designs. However, the current commercial effort in this technology, spearheaded by Bookham Technology, uses large, over-moded rib-waveguides with tight constraints on waveguide curvature, so that the resulting devices are also large. The research at Cambridge was therefore directed to much more compact designs (with greater losses and therefore less immediately
commercialisable). Silicon-on-insulator (SOI) substrates were procured from SOITEC. A large part of the fabrication research was directed towards smooth etching of sub-micron, large aspect ratio features to produce viable silicon waveguides. Because of the large index contrast ($\Delta n > 2$) between silicon and air or $\text{SiO}_2$, these single-mode silicon waveguides are an order of magnitude smaller than comparable silica waveguides and strongly-guiding, so that they are less susceptible to perturbations.

In order to produce photonic band-gap structures in the smooth sub-micron waveguides, a variety of reactive ion etching techniques were investigated. Optimisation of a novel chlorine/fluorine etch (20sccm $\text{CF}_4$, 20sccm $\text{SiCl}_4$ under 20mTorr and 300W rf power for 3.5 mins) was found to produce the smoothest waveguide results (Fig. 6).

Using simulation software from Photon Design a variety of photonic band-gap devices were designed and simulated. The goal of this work was to demonstrate photon localisation in a 1-D waveguide (with associated narrow spectral passband characteristics). The results have been published more fully in [7].

The simulated spectral transmission of the photonic band-gap device is shown below. The device shows clear localization (Fig. 8).

3. Project Plan Review and Research Impact

The programme was impeded by serious difficulties arising from unforeseen changes concerning the industrial partners and their priorities. However, despite these problems, it proved possible to re-orient the project so that continuity was not lost, and novel results tending to internationally leading were nonetheless obtained in key areas.

FTEL disbanded its research division headed by Prof South in May 2000. Dr Parker's employment was taken over by Fujitsu Network Communications Inc; his weekly interaction and strong collaboration with the project continued until September 2001, when Dr Mears went on leave to the US. Dr Parker continued to be closely involved with the programme thereafter, working weekly with Dr Stuart Walker (University of Essex) - see IGR for GR/N11070/01. With the downturn in the telecommunications industry, Nortel
Networks disbanded its AWG project in late 2000 and finally sold its components division to Bookham. All interaction with Dr Clements' group ceased at this point; no devices or services were supplied.

The original intention of the hardware part of the project was to modify silica-on-silicon AWGs provided by Nortel, with the aim of demonstrating the holographic AWG by sculpting individual arrayed waveguides. Mr Subhasish Chakraborty's M.Phil. research had been directed towards high-resolution, large aspect ratio etching of silica, and was an ideal background for the project. When Nortel closed its AWG work, the research plan was re-orientated to demonstrate the feasibility of nano-scale silicon-on-silica waveguides and potential photonic band gap devices. Efforts on the project to secure a research link with Bookham (who re-employed much of the Nortel AWG team) failed owing to Bookham's sensitivity over IP. Access to nanofabrication facilities in the Microelectronics group led by Prof. Haroun Ahmed was secured in conjunction with a Ph.D. studentship funded by the Cambridge Overseas Trust for Mr Chakraborty. Mr F El-Nahal's research concerning investigation and modelling of novel AWG architectures was less seriously affected by the downturn. He received support in terms of maintenance (3 years) and fees from the programme.

Partners maintain contact with each other and with FTEL, who take an active interest in the the work. One patent application has resulted from work done at Cambridge under this programme, and is being pursued by the innovations company of the University of Cambridge.

4. Communication of Research Output

Members of the programme presented papers at each of the last three major international conferences on optical communications (OFC, ECOC), including a number of invited papers. In excess of 20 conference papers have been presented by programme members on material generated by the project. Twelve journal papers have been authored by programme members, and further journal papers are expected to appear. Key publications are documented on the project web-site: http://www-g.eng.cam.ac.uk/mentor/acorn

5. Expenditure

There were some adjustments to expected patterns of expenditure. These arose from the participation primarily of two research students:- F I El-Nahal and S Chakraborty. Chakraborty has been awarded his doctorate for this work, and El-Nahal is expected to have receive his doctorate within the next few weeks. Both received maintenance and fees from project funds, but these were augmented from other sources. In addition, students P-K Tsai and F-C Lin undertook short-term feasibility studies, and received contributions towards their maintenance. No RA was appointed. In consequence of this there was a significant underspend on project staff costs and on exceptional items (University and College fees). Owing to the changes in direction occasioned by the withdrawal of both industrial sponsors, it proved impracticable to develop support circuitry and the provision for IC fabrication was not used. Updating of computer workstations for the research student participants called for a small extra expenditure on equipment. Overall the project was completed with a net underspend.

6. References

7. Publications

Key publications listed in IGR

1. Experimental demonstration of cascaded AWG access network featuring bi-directional transmission and polarization multiplexing, I. Tsalamantis, E. Rochat, S.D. Walker, M.C. Parker, D.M. Holburn, Optics Express, 2004


Journal Papers


3. Experimental demonstration of cascaded AWG access network featuring bi-directional transmission and polarization multiplexing, I. Tsalaminis, E. Rochat, S.D. Walker, M.C. Parker, D.M. Holburn, Optics Express, 2004


Conference Papers


Papers on which RJM/DMH/FIE-N/SC are not authors


21. Investigation of combined wavelength and polarisation division multiplexing in C-band over 50µm multimode fibre links up to 3km, E. Rochat, S.D. Walker, M.C. Parker, CLEO/Europe-EQEC, Munich, June 2003

Papers more appropriate to Oakleaf


23. Capacity enhancement of access and metro networks using combined wavelength and polarization division multiplexing over C-band in 50mm multimode fibre links up to 3km E. Rochat, S.D. Walker, M.C. Parker, IEE Colloquium on Photonic Access Technologies, 17th & 18th December 2002