Bidirectional WDM Access Architecture Employing Cascaded AWGs and RSOAs.

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Abstract—Here we propose a bidirectional wavelength division multiplexing (WDM) access architecture employing cascaded cyclic arrayed waveguide gratings (AWGs) and reflective semiconductor optical amplifiers (RSOAs) for system applications mainly in wavelength routed fiber-to-the-home (FTTH) networks. These architectures can address multiple N^2 customers using N wavelengths by employing multiple NxN AWGs at the central office (CO) and multiple $1 \times N$ AWGs at the distribution points (DPs). A 20 km range colorless WDM passive optical network (WDM-PON) was demonstrated for both 4 Gbit/s downstream and 2.5 Gbit/s upstream signals respectively. The BER performance of our scheme demonstrates that our scheme is a practical solution to meet the data rate and cost-efficient of the optical links simultaneously in future access networks.

Index Terms—Wavelength-division-multiplexing passive optical networks (WDM/PONs), Fiber to the home (FTTH). Arrayed waveguide gratings (AWGs), Reflective semiconductor optical amplifiers (RSOAs).

I INTRODUCTION

The rapid growth in Internet traffic and bandwidth intensive applications is continuing to fuel the penetration of fiber networks into the access network segment [1]. Wavelength-division-multiplexing passive optical networks (WDM/PONs) are an attractive option due to their high capacity, easy management, network security, protocol transparency, and easy upgradability [2]. PON systems in fiber to the home (FTTH) networks have been widely deployed to fully support "triple-play" services including data, voice, and video services. Among various PON technologies, WDM/PONs, which offer point-to-point connectivity via a dedicated wavelength to each customer, are believed to eventually provide an optimal FTTH architecture [3].

The rapid deployment of WDM into the core and metropolitan networks has cut down WDM components costs, and pushed WDM technology closer to the end-user. The AWG is a key WDM technology, offering high wavelength selectivity, low insertion loss, small size, high channel count and potentially low cost [4-6]. Several WDM/PON systems have been studied recently where a reflective semiconductor optical amplifier (RSOA) plays an important role [7–15]. The RSOA replaces the high cost WDM source at the ONU and can be used as a modulator and amplifier [16-18]. This gives additional gain enabling the possibility of avoiding the use of an Erbium Doped Fiber Amplifier (EDFA) in the system. In these systems, both the upstream and downstream channels use the same wavelength for improving the wavelength utilization efficiency.

Cascaded Arrayed-Waveguide Gratings (AWGs) access architectures are discussed here [19-24]. These architectures can route to a large number of customers using a minimal set of wavelengths by employing AWGs [25], while offering scalability and improved crosstalk. In this work a cascaded AWG-based access architecture that consists of multiple $N \times N$ AWG's at the CO and multiple $1 \times N$ AWG's at the distribution points (DP) is investigated. N wavelengths are multiplexed and transmitted from the CO, offering unique optical path for each end user for both downstream and upstream transmission. Each AWG at the DP addresses N end users where the end users transmit in the same wavelength that they receive. A commercially available simulation tool was used for the calculations reported in this work [26].

II PROPOSED ARCHITECTURE

Space wavelength switching can be attained by utilizing the periodic spectral response of the AWG, and its Latin routing capability [4]. This is achieved by setting the AWG Free spectral range (*FSR*) to match the product of the number of output ports and the channel spacing. In addition, the number of wavelengths must equal the number of output ports. Consequently, for a symmetric $N \times N$ AWG, the output port from which wavelengths appear will depend on the input port at which the wavelengths were launched. The minimum number of wavelength channels needed for N^2 connections is N. An example of the wavelength assignment is shown in Table 1, where the same wavelengths are used for different connections. For example, λ_4 is used for N connections such as #4 to #1 and #3 to #2 [4].

TABLE 1
An example of the wavelength assignment in an N×N AWG router.

	Input ports						
	1	2	3	4	5	...	N
1	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	...	λN
2	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 6$	....	$\lambda 1$
3	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 6$	$\lambda 1$	...	$\lambda 2$
4	$\lambda 4$	$\lambda 5$	$\lambda 6$	$\lambda 1$	$\lambda 2$	...	$\lambda 3$
5	$\lambda 5$	$\lambda 6$	$\lambda 1$	$\lambda 2$	$\lambda 3$	...	$\lambda 4$
.	.	.	.	.	.	...	.
.	.	.	.	.	.	...	.
N	λN	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	...	$\lambda N-1$

(Output ports label at left of table rows)

The same functionality can be achieved by employing active AWG, an AWG with an array of phase modulators on its arrayed-waveguides section, where a programmable linear phase-profile or a phase hologram is applied across the arrayed-waveguide section. Following the second free propagation region, this results in a wavelength shift at the output section of the AWG. This effect can be used to tune the device, and also allows space-wavelength switching functionality [27,28]. Thus, just one input port of the $N{\times}N$ AWG can be used for downstream transmission, whilst the remaining ports are used for upstream reception. Since active AWG's cost is relatively higher than passive AWGs, A passive $N{\times}N$ AWG, circulators, and an opto-mechanical switch are used to achieve the desired wavelength routing in this work [19].

Fig. 1 shows the proposed access architecture. Packets are modulated onto one of R wavelengths from a fast tunable laser depending on the destination Optical Network Unit (ONU) [22]. The cells reach the first stage S1, which consists of a P-way passive optical splitter. The cells are routed into the appropriate arm and progress to the second stage S2, consisting of a Q-way power splitter, where each of the arms of the splitter are connected with one of the upstream ports, respectively, of the Pth $N{\times}N$ AWG. Space-wavelength switching is achieved by using an AWG in conjunction with a power splitter and an opto-mechanical switch. For the proposed WDM access architecture shown in Fig. 1, there would be $R = 24$ wavelengths spaced by 100GHz (0.8nm), requiring a $Q = 24$ port AWG. The AWGs at the second and third stages (S2 and S3) are matched to have the same FSR (2400 GHz), passband width and number of input/output ports, so that $Q = R$. The packets are routed out of the CO and onto stage S3, located at the distribution points (DPs), consisting of AWGs with $R = 24$ ports. Each AWG acts as a fixed optical wavelength router directing the wavelength multiplexed cells to the destination ONU located in the customer premises. At the ONU, using optical splitter/coupler,

portion of the signal is fed to a receiver. For up-link, the other portion of the downstream signal from the splitter/coupler is re-modulated using 2.5 Gb/s NRZ upstream data by RSOA in the ONU. The re-modulated On-off keying (OOK) signals are sent back over the fiber to the CO where they are de-multiplexed by the AWG. The reflected optical signal is detected by a PIN-photodiode. Uplink optical sidebands produce crosstalk when uplink data was detected at the CO. Crosstalk can be reduced by using Bessel filter. The total number of ONUs served is the product PQR. For $P = 12$, $Q = R = 24$ this access network can provide service to 6192 customers, thus allowing a graceful evolution from current passive optical networks (PON) infrastructures [29]. A factor P downstream bandwidth capacity can be achieved by replacing stage 1 consisting of a P-way splitter by a bank of P tunable lasers and modulators, so that the network consists of $P = 12$ sub-networks, where each can serve 576 ONUs [22].

III SIMULATION ISSUES AND RESULTS

The laser source is externally modulated by a Mach-Zehnder modulator. The data stream, which modulates the continuous wave laser source, was generated using an NRZ shaped pulse train. The average output power of the source is 20dBm while the linewidth of the laser is 10MHz. A Gaussian approximation of the modal field in the waveguides was used in the AWG model and the insertion loss is assumed to be 4dB, which is a typical value in standard AWGs. Polarization dependent loss has been ignored. The waveguide is assumed to be symmetrical and only the fundamental mode was taken into account. These assumptions can be justified as they have minimal effect on the simulation results. A polarization independent RSOAs that can handle signals with arbitrary polarization state were used. Limitations of the RSOA model used here include neglecting the gain dispersion. Neglecting the gain dispersion is acceptable as long as the bandwidth of the optical signal is significantly smaller than the amplification bandwidth, which is typically of the order of several tenth of nms. A 20 km of standard single-mode fibre (SMF) with 0.2 dB/km loss was used for fibre transmission simulations. This module solves the nonlinear Schrödinger equation describing the propagation of linearly-polarized optical waves in fibers using the split-step Fourier method. This model allows simulating nonlinear (SPM, FWM, XPM) and Raman effects in WDM systems.

BER simulations were carried out with a Bit Rate of 4 Gb/s downstream and 2.5 Gb/s upstream for a 1.7 GHz bandwidth receiver respectively. The received eye diagrams of downstream and upstream signals were measured at ONU and CO respectively. The received eye diagrams of arbitrary downstream and upstream signals are shown in Fig. 2 and Fig. 3 respectively. The eye-diagrams are widely open and prove that the system is stable and that crosstalk is negligible.
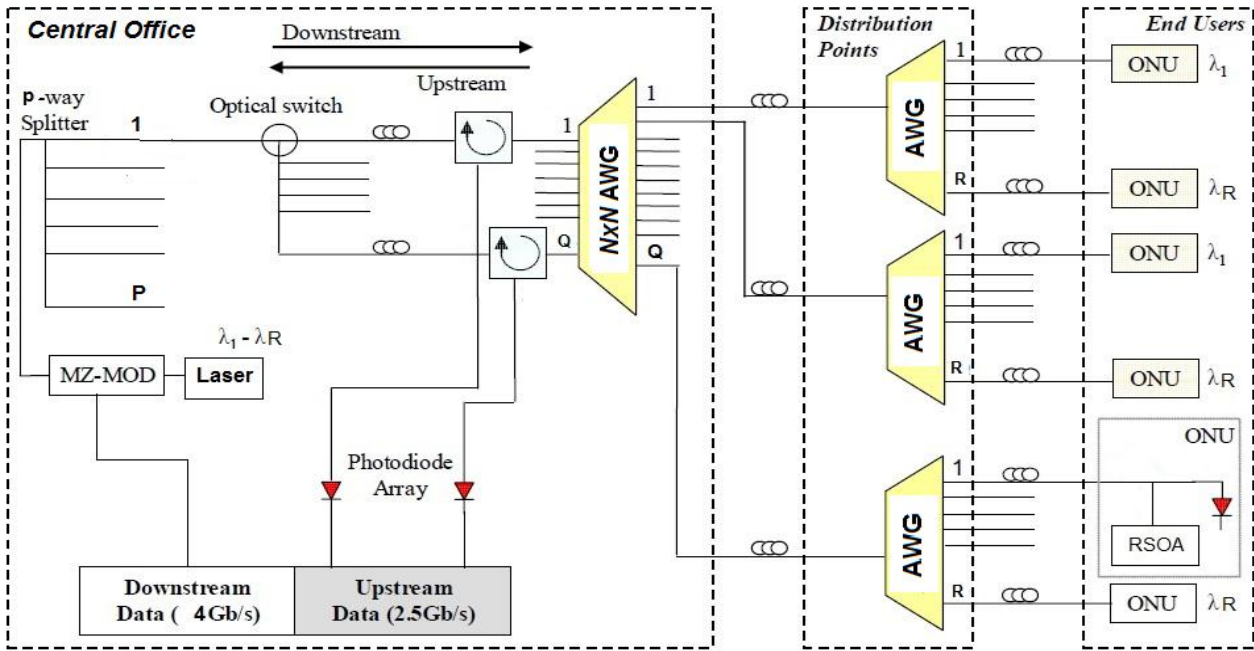
Figure 1 Cascaded AWGs based access architecture

The BER versus input optical power P_{in} curves for the downlink and uplink are shown in Fig. 4. It is clear from the results that both downlink and uplink do provide good BER performances. It is noted from the figure that the BER for the downlink and uplink goes down with increasing P_{in} from 10 dBm to 20 dBm. For the downlink, when P_{in} = 10 dBm, the BER = 1.3×10^{-9} and quality factor Q= 5.9. When P_{in} = 20 dBm, the BER = 3.2×10^{-32} and Q = 11.8. For the uplink, the BER goes down slowly with increasing P_{in} from 10 dBm to less than 15 dBm. When P_{in} = 10 dBm, the BER = 2.3×10^{-9} and Q = 5.9. For $P_{in} \geq 15$ dBm, the BER is nearly constant. When P_{in} =20 dBm, the BER = 1.4×10^{-39} and Q = 13.1. This can be explained by the fact that the RSOA is operating in the gain saturation region.

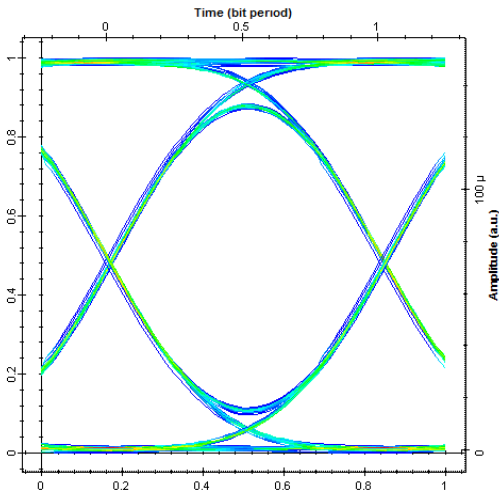The variation of the gain of RSOA with the optical input power P_{in} is shown in Fig. 5. It is clear that the maximum gain appears at P_{in} = 10 dBm, then goes down to reach the lowest gain at P_{in}= 20 dBm.
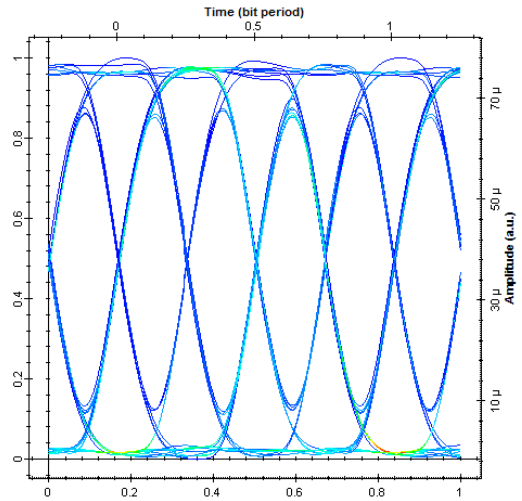

Figure 3 *Eye diagram of uplink*

V CONCLUSION

This paper has presented novel simulation results to evaluate AWGs and RSOAs for system applications mainly in new bidirectional access architectures employing cascaded arrayed-waveguide grating technology. Space wavelength

Figure 2 *Eye diagram of downlink*

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switching was achieved in these networks using a passive AWG in conjunction with an optical mechanical switch. These architectures can address up to 6912 customers employing only 24 wavelengths, separated by 0.8 nm. RSOA is used as low cost colorless transmitters for high-speed optical access exploiting WDM technology. The results obtained demonstrate that cascaded AWGs access architectures have a great potential in future FTTH networks.
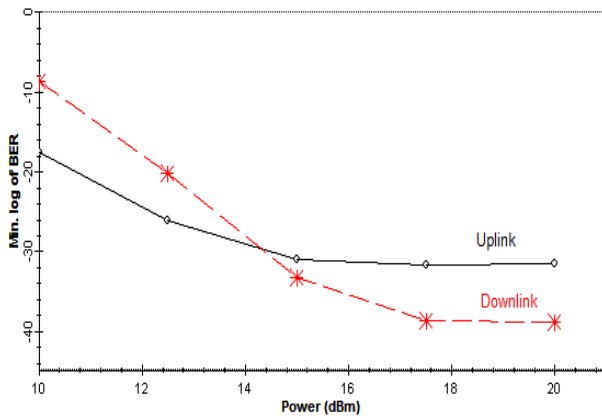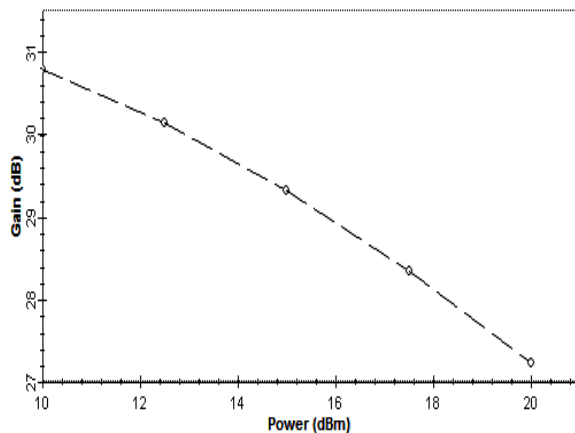
Figure 4 BER versus input power

Figure 5 The variation of RSOA gain with input power

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