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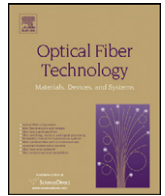
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## Multistage WDM access architecture employing cascaded AWGs

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### ABSTRACT

Here we propose passive/active arrayed waveguide gratings (AWGs) with enhanced performance for system applications mainly in novel access architectures employing cascaded AWG technology. Two technologies were considered to achieve space wavelength switching in these networks. Firstly, a passive AWG with semiconductor optical amplifiers array, and secondly, an active AWG. Active AWG is 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. This results in a wavelength shift at the output section of the AWG. These architectures can address up to 6912 customers employing only 24 wavelengths, coarsely separated by 1.6 nm. Simulation results obtained here demonstrate that cascaded AWGs access architectures have a great potential in future local area networks. Furthermore, they indicate for the first time that active AWGs architectures are more efficient in routing signals to the destination optical network units than passive AWG architectures.

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### 1. Introduction

While WDM technology is maturing in transport networks, there is a new drive to bring WDM downstream, closer to the end user. Currently time-division multiple access passive optical networks (TDMA-PONs) such as ATM PON (APON), broadband PON (BPON), generalized PON (GPON) and ethernet PON (EPON) are deployed. TDMA-PONs offer limited node complement and cannot cope with the requirements of future network evolution with respect to aggregated bandwidth. Future access networks need to offer cost-effective, high transmission capacity support for the increasing number of new broadband end-customer services. Wavelength-division-multiplexed PONs (WDM-PONs) networks offer the prospect of high security, optical transparency and increased capacity to the end user [1–6]. However, there still are some drawbacks of WDM PON networks. WDM components such as multiplexers/demultiplexers, wavelength routers, multi-wavelength sources are more expensive compared with TDM PON components [5]. Though, 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 [7–9].

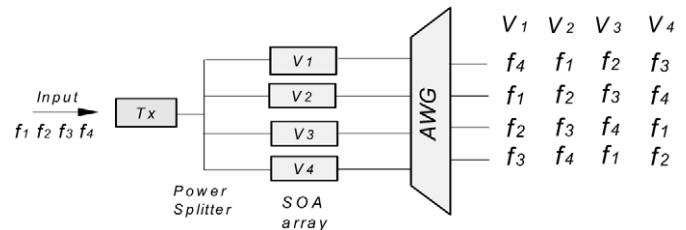


Fig. 1. Latin routing functionality of AWG with 4 wavelengths/frequencies and output ports.

Cascaded arrayed-waveguide gratings (AWGs) access architectures are discussed here [10–14]. These architectures can route to a large number of customers using a minimal set of wavelengths by employing active coarse AWGs [15], while offering scalability and improved crosstalk. A commercially available simulation tool [16] was used for the evaluations reported in the present paper.

### 2. Space-wavelength switching

Space-wavelength routing functionality can be attained by employing a passive passband-flattened AWG in conjunction with a passive power splitter and an array of semiconductor optical amplifiers (SOAs), as shown in Fig. 1. The SOA modulator attached to each arm selectively blocks, or allows through the light as required, while amplifying the signal to compensate for the splitting losses [17]. Variable optical attenuators (VOAs) may be used to achieve the same pass/block functionality but without amplification. Moreover, SOAs allow fast packet switching routing scheme.

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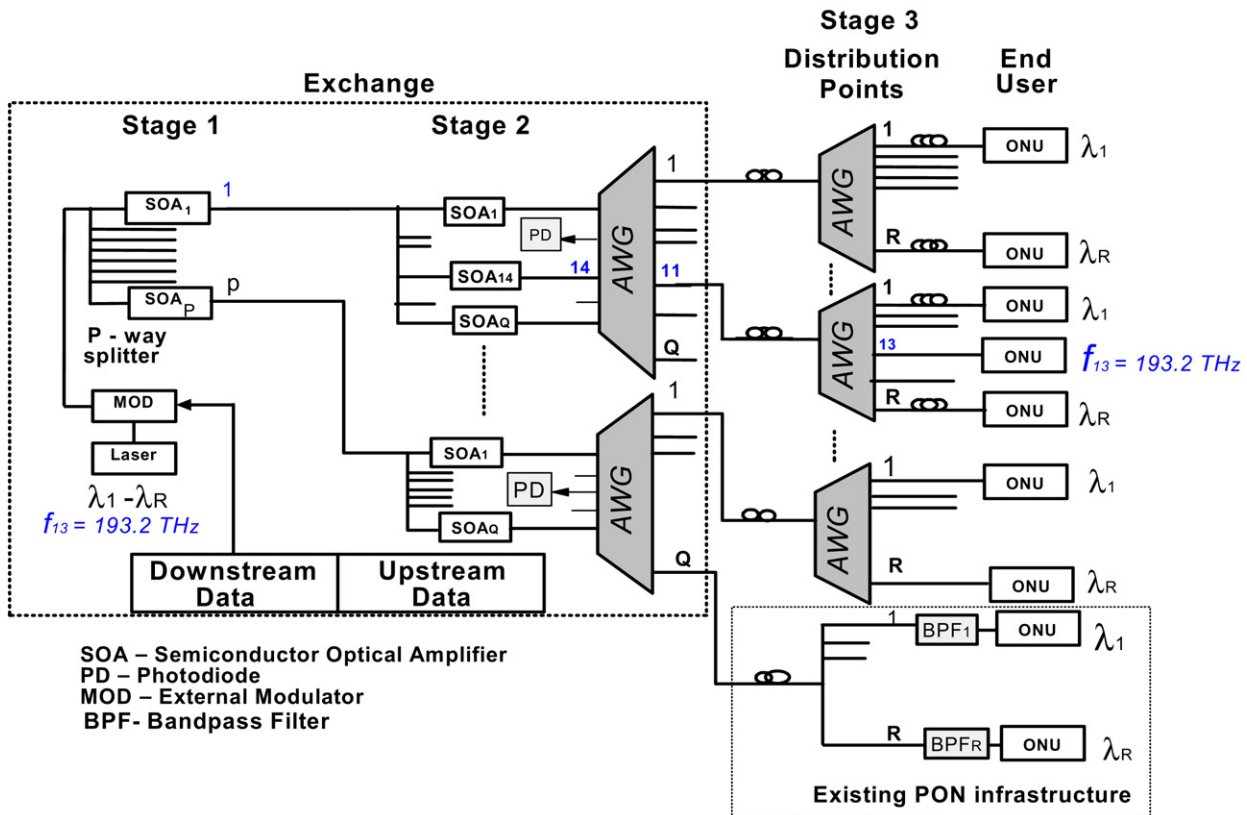


Fig. 2. Three-stage access architecture employing passive cascaded AWGs with SOAs.

The wavelength is then routed according to the Cyclical and Latin routing properties [18] of the AWG to one or more of the output ports. Thus a wavelength can be selectively routed to any of the input ports of the device, and hence to any of the outputs. 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 [19,20].

### 3. Access networks employing passive AWGs with SOA array

Fig. 2 shows a three-stage access architecture employing passive cascade AWGs with SOAs. Packets are modulated onto one of  $R$  wavelengths from a fast tunable laser depending on the destination optical network unit (ONU) [14]. The cells reach the first stage S1, which consists of a  $P$ -way passive optical splitter with semiconductor optical amplifiers (SOAs) attached to each output acting as absorbers to attenuate the signal in unwanted arms, whilst boosting it in the desired arm. 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  $P$ th passive AWG. Space-wavelength switching is achieved by using a passive AWG in conjunction with a power splitter and SOA array. For the proposed WDM access architecture shown in Fig. 2, there would be  $R = 24$  wavelengths spaced by 200 GHz (1.6 nm), requiring a  $Q = 24$  port AWG. The AWGs at the second and third stages (S2 and S3) are matched to have the same free spectral range (FSR) which equals 4800 GHz, passband width and number of input/output ports, so that  $Q = R$ . The packets are routed

out of the exchange and onto stage S3, located at the distribution points (DPs), consisting of passive AWGs with  $R = 24$  ports. Each passive AWG acts as a fixed optical wavelength router directing the wavelength multiplexed cells to the destination ONU located in the customer premises. 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 the architecture to map onto 99% of the current UK network topology [21]. 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 [14].

### 4. Access networks employing active AWGs

By replacing the combination of passive AWG, SOA array and splitter at stage 2 in Fig. 2 by an active AWG [19,20], we get a three stage access network consisting of active and passive AWGs as shown in Fig. 3. Stage 1 consists of a  $P$ -way passive optical splitter with SOAs attached to each output. Stage 2 consists of  $P$  active linear AWGs each with  $Q$  output ports. 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,  $V_p$ . Wavelengths packets are routed out of the exchange and onto stage 3 located at the distribution points (DPs) near the end-users.

### 5. Simulation issues

#### 5.1. Devices characteristics

An externally modulated laser transmitter was considered in all simulations. The laser source that provides a narrow linewidth and

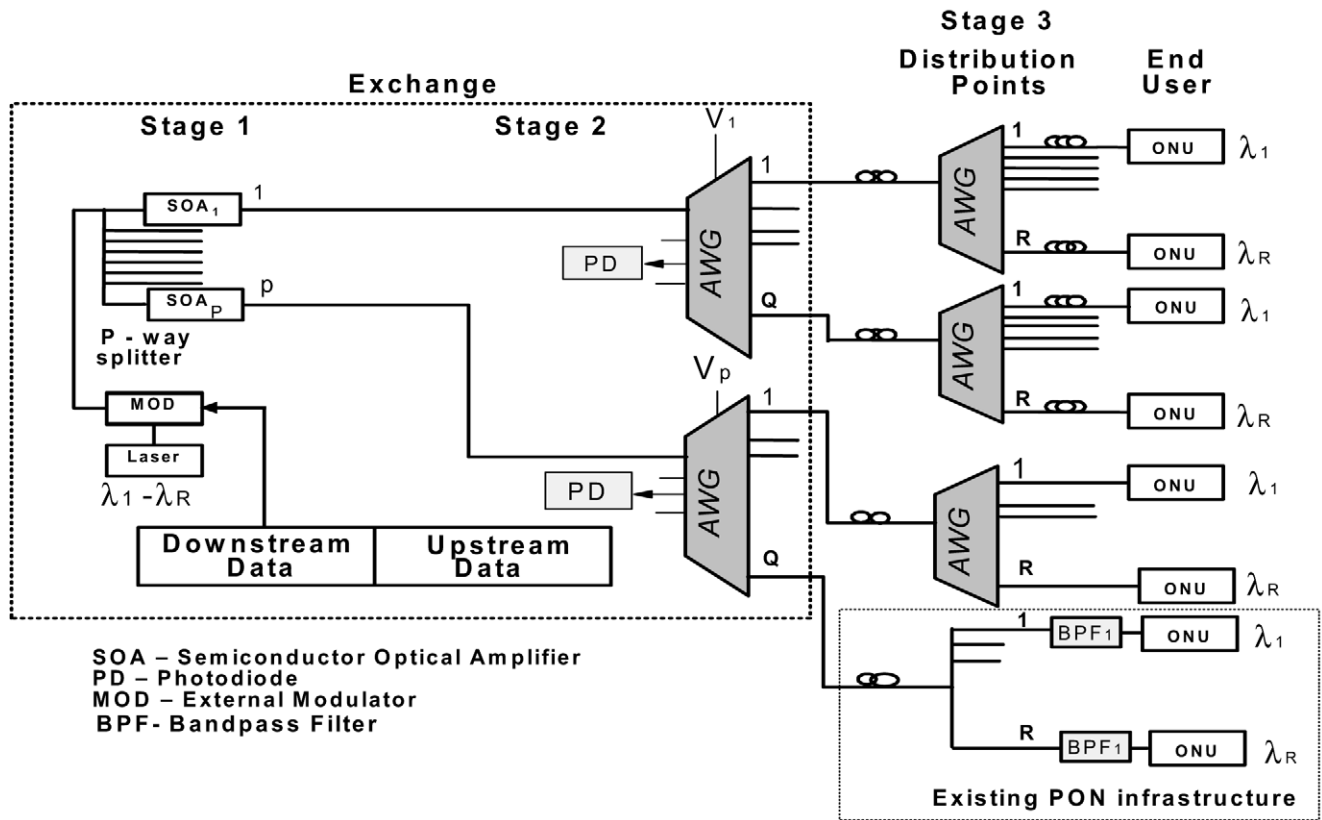


Fig. 3. Three stage access architecture with cascaded active and passive AWGs.

stable optical source is 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 1 mW while the linewidth of the laser is 10 MHz.

A Gaussian approximation of the modal field in the waveguides was used in the AWG model and the insertion loss is assumed to be 4 dB, 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.

The active AWG was simulated using the beam propagation method (BPM) and the resulting data files representing the response of the holographic AWG were incorporated into the simulation using the filter measured (optical) modules. Filter measured optical module implements an optical filter using frequency response data read from a text file. Space wavelength switching is carried out by the active AWG where the incoming wavelength can be routed to any of the output ports according to an applied phase hologram  $V_h$ .

Polarization-independent SOAs that can handle signals with arbitrary polarization state were considered. It is clear from the spectral response of an SOA shown in Fig. 4 that it is noisy and asymmetric. Limitations of the SOA 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 10 km of nonlinear dispersive fibre was considered 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.

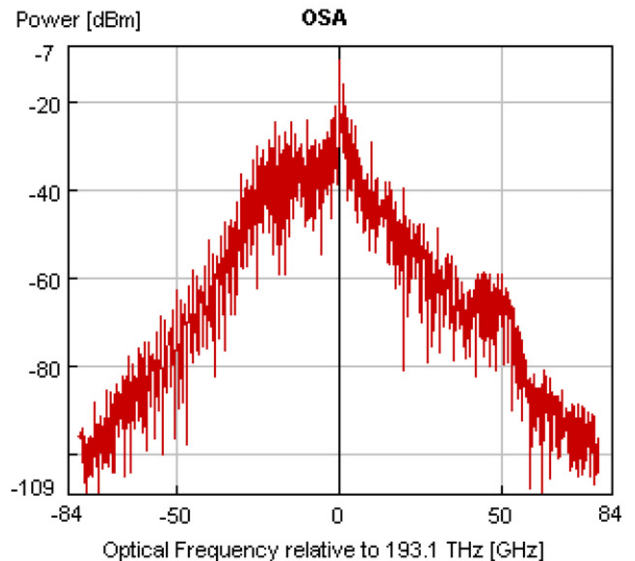


Fig. 4. The spectral characteristic of a semiconductor optical amplifier.

5.2. Simulation results

This section presents the simulation results for the cascaded AWG architectures which were modeled using a commercially available package [16]. As an example of the operation of the 3-stage passive architecture shown in Fig. 2, a channel  $f_{13}$  (193.2 THz) routed to input 14 of the 1st AWG at stage 2 will emerge from output port 11, where it will then be routed out of the exchange to the 11th passive AWG at stage 3. Finally, where it will be routed to output 13. The spectral characteristic of output 13 is shown in Fig. 5.

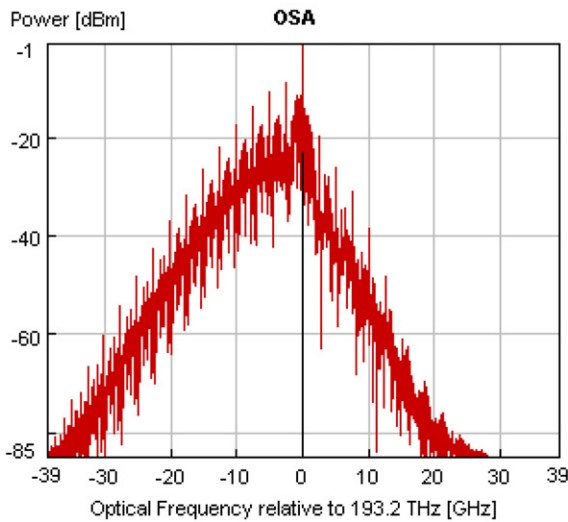


Fig. 5. The spectral characteristics of output 13 of the 11th passive AWG of the 3-stage passive AWG architecture.

As an example of the operation of the three-stage active access network shown in Fig. 3, a channel  $f_{13}$  (193.2 THz) routed to active AWG<sub>1</sub> will emerge from output port 11 and then will be routed to output 13 of the 11th passive AWG at stage 3. The spectral characteristic of output 13 is shown in Fig. 6. It is clear from the spectral response results shown above that the active AWG cascaded architectures outperform the passive AWG architectures. The passive AWG architectures spectral responses are dominated by the asymmetric response of the SOAs. A detailed comparison between the two architectures is given in Section 6.

## 6. Comparison between active AWG and passive AWG architectures

For the three stage architectures, when comparing the two approaches, it is clear from the simulation results of the passive architecture shown in Fig. 5 that the spectral response is asymmetric and the suppression ratio is lower ( $-50$  dBm at 20 GHz) compared with the active AWG result shown in Fig. 6. This can be explained by the fact that SOA has an asymmetric spectral response as shown in Fig. 4.

BER simulations were carried out for both cascaded architectures with a bit rate of 2.5 Gb/s for a 5 GHz bandwidth receiver for all the cascaded architectures. The results are plotted in Fig. 7. It is possible to isolate the degree of sensitivity degradation occurring as a result of signal propagating through the network. The general method is to carry out a separate measurement of the receiver sensitivity by connecting the transmitter and the receiver directly. The receiver sensitivity is defined as the minimum average received power required by the receiver to operate at a BER of  $10^{-9}$  [22,23]. It can be shown in Fig. 7 that when connecting the transmitter and the receiver directly, a BER of  $10^{-9}$  is realized for  $-23.7$  dBm of received power.

It is clear that both of the architectures do provide good BER performances, however the BER results for the active AWG architecture are better than those of the passive AWG architecture. For example: for the active AWG architecture, the power penalty is just 0.7 dB while it is 1.5 dB for the passive AWG architecture. In addition, active AWG architectures are less noisy, less costly and more compact. The advantage of active AWG, in comparison with commercially available passive AWGs, is that spatial-wavelength routing can be easily achieved by tuning the applied phase hologram  $V_h$ . Thus, just one input port of the central office AWG can

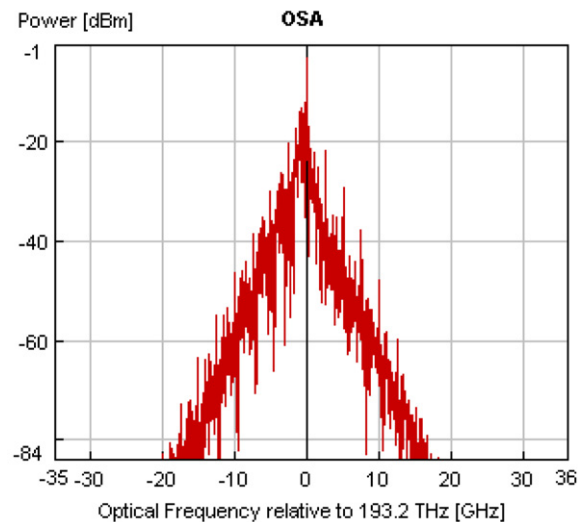


Fig. 6. The spectral characteristics of output 13 of the 11th passive AWG of the 3-stage active AWG architecture.

be used for downstream transmission, whilst the remaining ports are used for upstream detection. Moreover, active AWG can compensate for fabrication phase errors. Active AWGs are only recently commercially available so that their cost is relatively higher than passive AWGs [24]. However this will change as industry matures. Furthermore, the active AWG can replace two components (AWG and SOA switch/modulator) which will reduce the total loss and offer a compact design.

## 7. Distribution point splitter

The distribution points at the 3rd stage of the three-stage active AWG architecture may consist of an  $R$ -way optical splitter in combination with coarse optical filters at the ONUs as shown in Fig. 3 [25]. This allows an upgrade path from existing splitter passive optical networks (PONs). The spectral response at one of the output ports of the passive splitter is shown in Fig. 8, while the BER result is shown in Fig. 7. It is clear from the results that there is more power loss compared with passive AWGs at the DPs, because here the power is divided between the ONUs. However the BER results are similar as shown in Fig. 7.

## 8. Conclusion

This paper has presented novel simulation results obtained using a commercially available package [16] to evaluate passive/active AWGs with enhanced performance for system applications mainly in new access architectures employing cascaded arrayed-waveguide grating technology. Two technologies were considered to achieve space wavelength switching in these networks. Firstly, a passive AWG with SOA array, and secondly, an active AWG. These architectures can address up to 6912 customers 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.



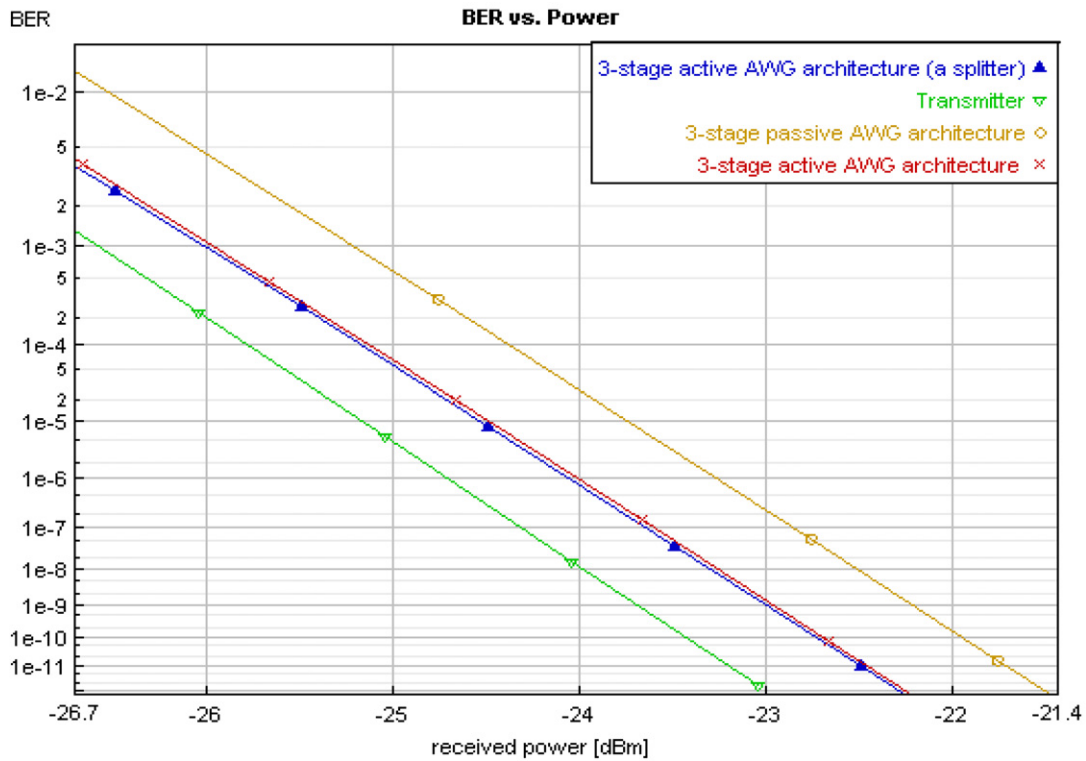


Fig. 7. A comparison between 3-stage architectures.

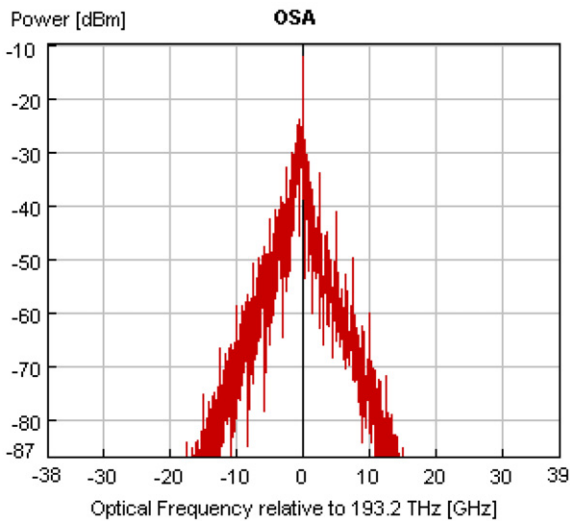


Fig. 8. The spectral characteristics of output 13 of the 11th passive AWG of the 3-stage active architecture with the passive splitter.

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