A Low Cost, Multi-Wavelength Optical Source Enabling Independent WDM Channels Using a Single SOA and ASE Inputs

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ABSTRACT

A multi-channel wavelength division multiplexed (WDM) transmission system using non-degenerate four-wave mixing (FWM) in a semiconductor optical amplifier (SOA) with spectrum-sliced ASE inputs from a single LED high powered incoherent source is presented. Three incoherent ASE inputs generate twelve SOA output channels, nine of which are FWM generated, and all are modulated at 10 Gb/s after the FWM process to avoid phase-noise limitations. SOA input power saturation characteristics were investigated and eye diagram analysis confirms high-quality transmission for each FWM channel, with an average achievable link length of 63.9 km, proving the validity of the scheme. By decoupling carrier generation from data encoding, this post-FWM architecture enables clean performance despite incoherent seeds, offering a low-cost, scalable solution for WDM in access and metro networks and wavelength conversion if required.

Keywords: Semiconductor Optical Amplifier (SOA), Four-Wave Mixing (FWM), ASE, Spectrum Slicing, WDM, OptiSystem, Optical Communications

INTRODUCTION

The demand for high-capacity, cost-effective optical networks continues to drive innovations in wavelength division multiplexing (WDM) technologies [1]. Conventional multi-wavelength sources rely on arrays of distributed feedback lasers or optical frequency combs, which increase system cost and complexity, especially in access and metro networks [2].

Semiconductor optical amplifiers (SOAs) are attractive for their nonlinear properties, enabling wavelength conversion and signal regeneration - particularly through four-wave mixing (FWM) [3], [4]. They also possess highly desirable intensity noise reduction capabilities due to their saturation effects [5], a key feature in this work. Traditionally, arrays of expensive coherent laser inputs are required for efficient mixing, but here incoherent sources, like inexpensive broadband amplified spontaneous emission (ASE) from a high-powered LED are considered, whilst mitigating the phase noise and low coherence inherent in these systems [5].

Spectrum slicing of ASE sources partially mitigates these limitations by generating narrowband quasi-coherent carriers suitable for WDM [5]. Recent work has demonstrated significant reach extension in spectrum-sliced WDM systems using SOA enhancements, achieving transmission distances of up to 340 km for a single channel [6]. Previous novel experimental work has also shown that FWM in SOAs is feasible using total spectrum-sliced ASE inputs [7], establishing the practical viability of this approach. More recently, simulation-based studies have shown that such systems can be accurately modeled using commercial software tools such as OptiSystem [8], confirming that the nonlinear interactions required for efficient FWM can be reproduced numerically with appropriate parameter selection.

This present work is a direct variation of [7] and [8], extending these prior studies by introducing a critical architectural change: modulation is applied *after* the FWM process rather than *before*. In these prior studies, modulation was applied to the ASE slices before FWM generation, which resulted in some phase-noise transfer and degradation in signal quality. By contrast, this work extracts the FWM-generated carriers first, then modulates them independently at 10 Gb/s. This post-FWM modulation approach decouples carrier generation from data encoding, enabling clean eye diagrams and high-fidelity transmission. Additionally, the effect of SOA input power on FWM quality and therefore achievable link lengths is investigated, providing practical design guidelines for real-world deployment. Section 2 presents the theoretical background, section 3 describes the system design, section 4 presents the results, section 5 provides discussion and finally section 6 concludes the paper.

THEORETICAL BACKGROUND

When multiple optical fields at frequencies f_1, f_2, f_3 propagate through a non-linear medium such as an SOA, nonlinear interactions produce new FWM products, expressed as:

- Degenerate FWM: $2f_i - f_j$
- Non-degenerate FWM: $f_i + f_j - f_k$

The number of generated frequency components (M) increases rapidly with the number of input channels [9], the formula being

$$N = \frac{M^2(M-1)}{2}$$

where N = the number of inputs

This effect for the case of three inputs is analogous with an AND gate, as shown in figure 1:

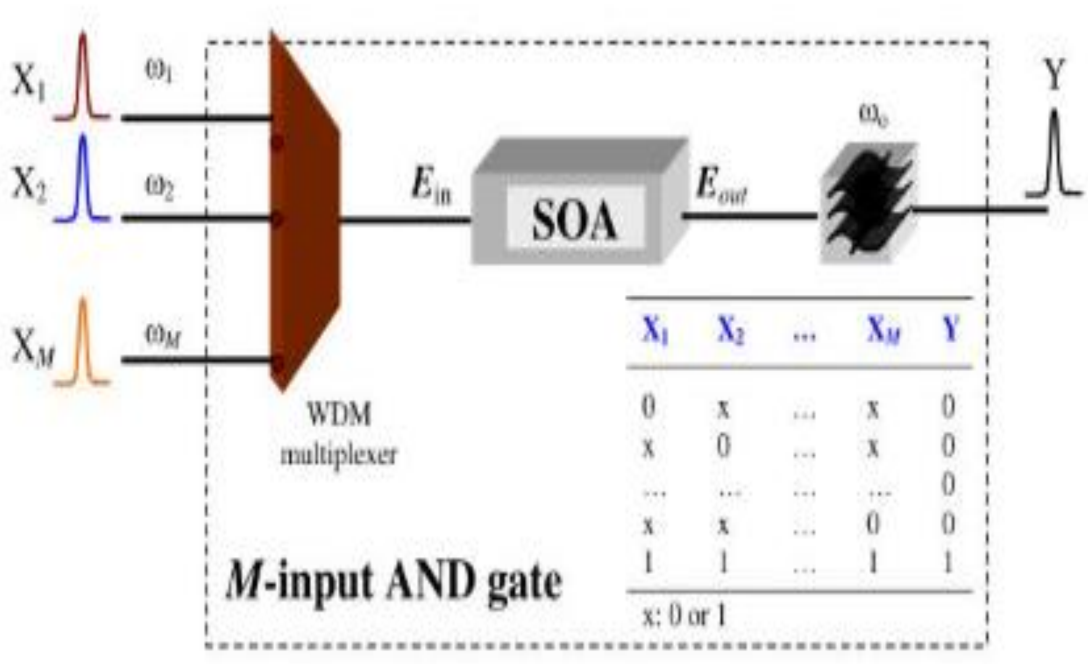

Figure 1: schematic of SOA FWM with 3 inputs

In this study, the nine newly FWM-generated channels were extracted and individually modulated from a three-input source coupled into a single SOA, making the total number of channels transmitted as twelve. In practice, limitations such as gain saturation, ASE noise and spectral overlap constrain usable channels [6]. The actual frequency values of all the channels transmitted are shown in Table 1 - the values in red being the three input signals

Table 1: channel frequencies transmitted

channel nos.	**Output Frequency (THz)**
1	192.4
2	192.7
3	192.8
4	193.0
5	193.1
6	193.4
7	193.5
8	193.7
9	193.8
10	194.1
11	194.2
12	194.5

Modulating following the FWM process ensures the generated carriers are independent, avoiding degradation due to incoherence of the ASE inputs [7], [8]. This method also allows the system to scale efficiently to multiple channels.

System Design

The proposed system is modeled using OptiSystem, with its WDM architecture shown in figures 2 and figure 3.

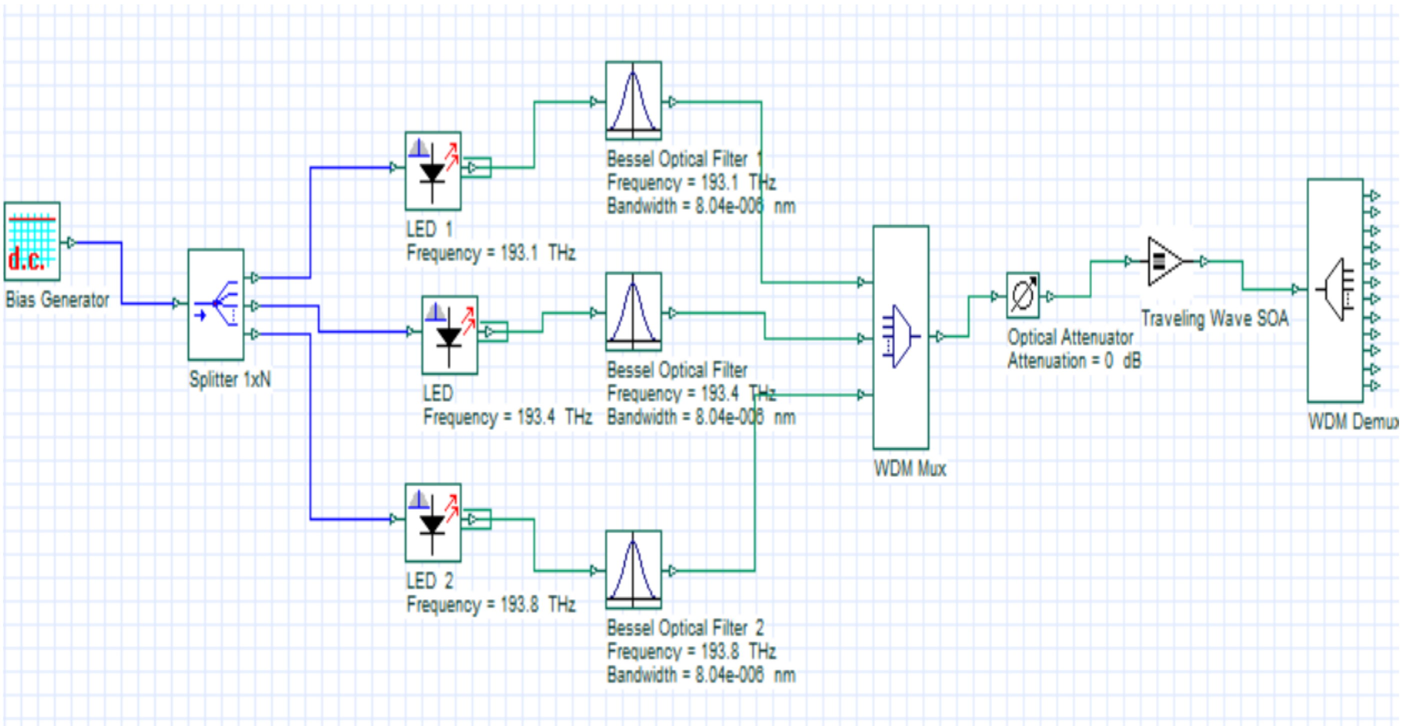

Figure 2: schematic SOA FWM with 3 inputs and 12 outputs

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The overall design is structured around a centralized Semiconductor Optical Amplifier (SOA) that acts as a nonlinear medium for four-wave mixing (FWM), followed by a post-FWM modulation stage that constitutes the principal novelty of this work.

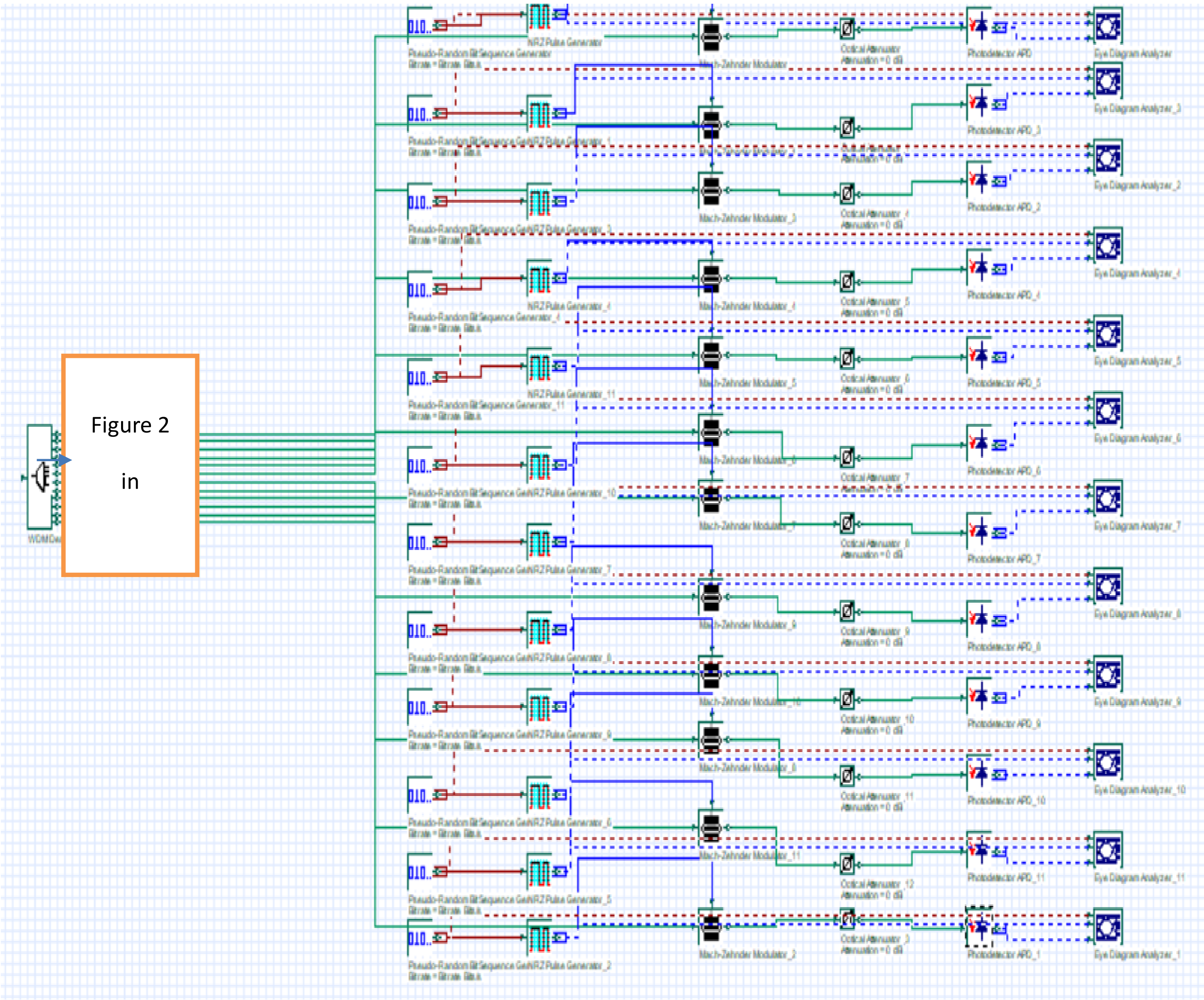

Figure 3: Block diagram of the proposed system showing demultiplexing and post-FWM modulation (inset: from figure 2)

In the transmitter section shown in figure 2, which is the input to figure 3, an incoherent high-powered LED Amplified Spontaneous Emission (ASE) source is spectrally sliced using three ultra-narrowband Bessel optical bandpass filters. The channel spacing of these filters is optimized for FWM efficiency, and the resulting filtered ASE signals serve as the inputs to the SOA. The SOA, which acts as the nonlinear medium, is operated in a regime that balances nonlinear interaction, gain saturation and noise performance to generate FWM products from the three input channels multiplexed into the SOA. The post figure 2 set-up is shown in figure 3, with the transmitter section as an inset. In the receiver and modulation section, a 1 x 12 optical demultiplexer first extracts the 12 channels. Each of these clean optical carriers is then modulated with data using external intensity modulators at 10 Gb/s, sent across simulated link lengths, detected with photodetectors and low-pass filters, and then finally evaluated via eye diagrams and electrical analyzers to assess Q-factor and SNR, respectively. This architecture improves the credibility of the simulation results and more closely aligns with a practical implementation where a shared SOA acts as a centralized multi-wavelength comb generator.

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Also, to investigate the system performance, an optical attenuator is placed before the SOA to vary the total input power into it. This allowed us to investigate the intensity noised reduction capabilities of the SOA in our ASE based system [5, 7]. Additionally, a further attenuator is placed on each arm to test the newly generated FWM signals link capabilities. With the average single mode fibre loss being 0.2 dB/km, we could easily establish the maximum link length in km. The power sweep into the SOA, covering the range from the low-gain linear regime to saturation, enables a comprehensive assessment of FWM conversion efficiency, optical signal-to-noise ratio (OSNR), eye diagram quality and channel uniformity. This analysis provides insight into optimal operating conditions and maximum achievable link lengths, complementing recent work on SOA-enhanced spectrum-sliced systems [6, 10] that demonstrated significant link length extension through SOA deployment.

RESULTS

The system's performance was evaluated through spectrum analysis, eye diagram assessment and a systematic investigation of SOA input power. Figure 4 shows the three spectrum-sliced ASE inputs to the SOA centered at 193.1 THz, 193.4 THz, and 193.8 THz:

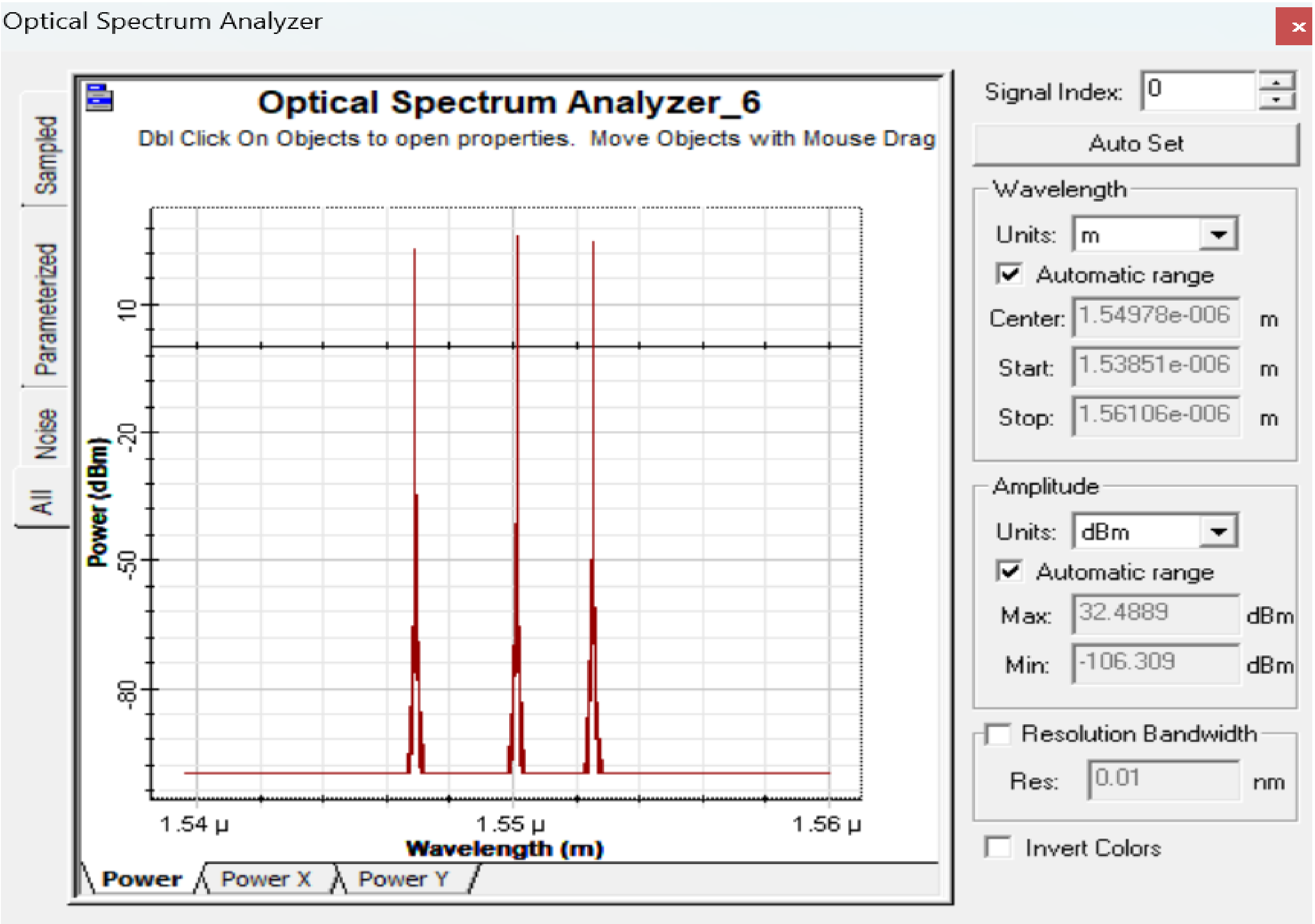


Figure 4: three spectrally sliced ASE inputs to the SOA

The total input power to the SOA was varied using the attenuator placed before it. In figure 4 the total input power was measured to be 29.6 dBm (highly saturated) for 0 dB attenuation, each frequency being almost equal in power. When the SOA bias was maximized to 1A the resulting SOA output spectrum, shown in Figure 5, displays multiple frequencies generated from the three inputs with acceptable conversion efficiency. Based on sufficient OSNR, output power, and spectral separation, a total of 12 channels spanning from approximately 192.4 THz to 194.5 THz were extracted for modulation (see Table 1).

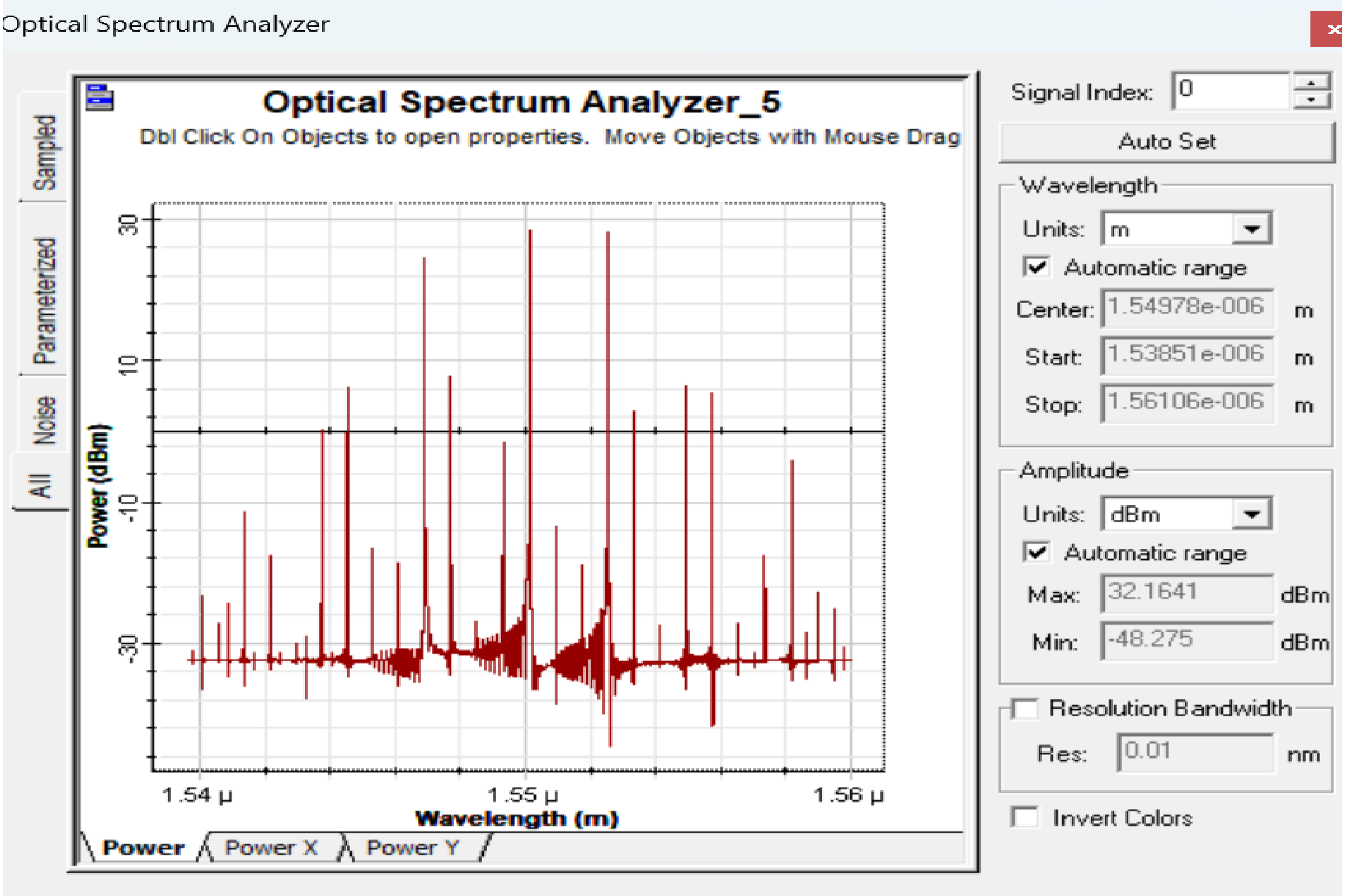
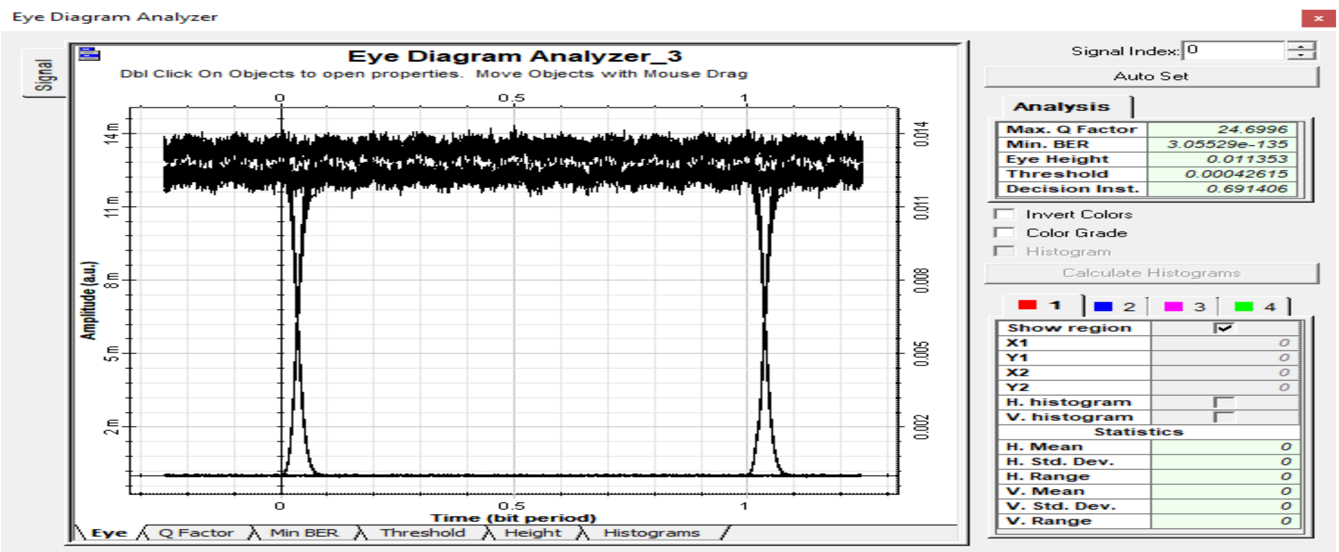


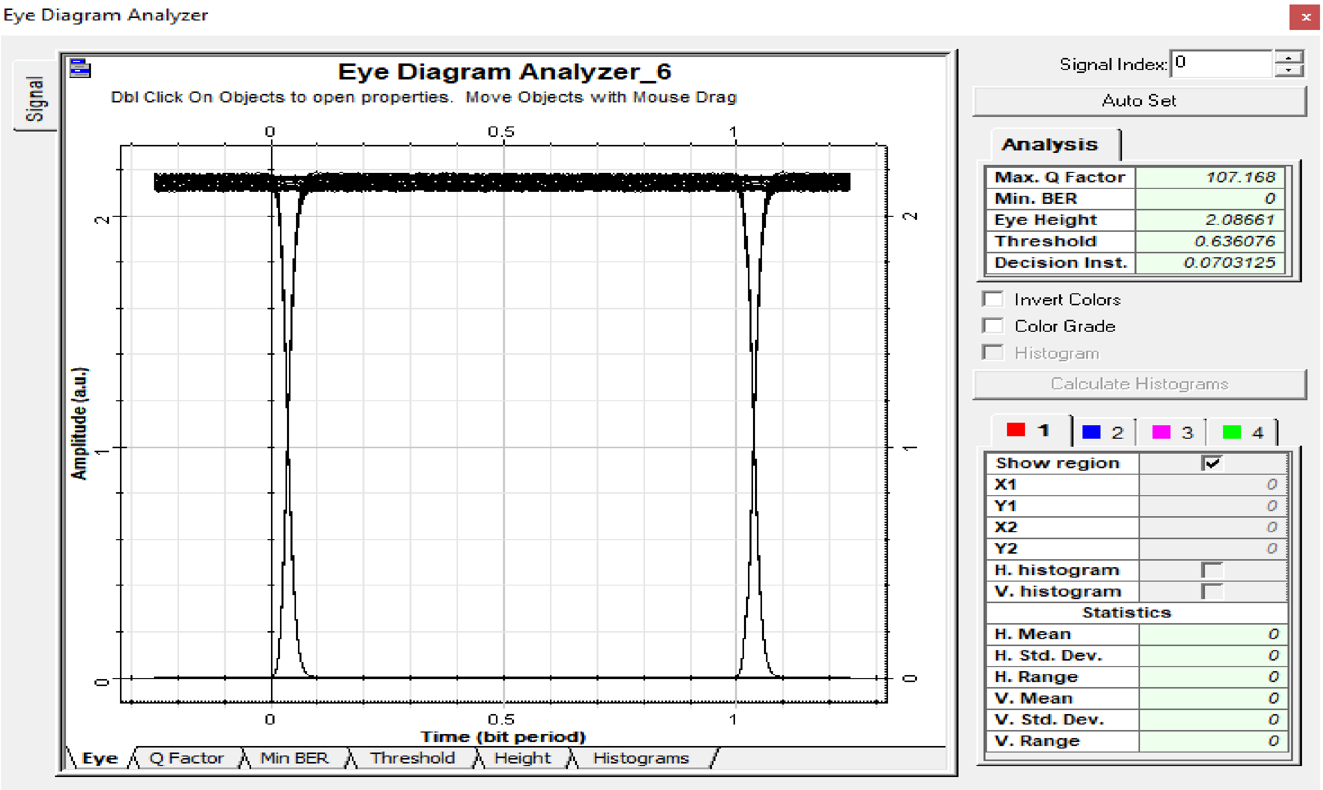
Figure 5: 12-channel output spectrum from the SOA

Following extraction, all nine FWM-generated channels were independently modulated at 10 Gb/s, as well as the original 3 input channels. To concisely represent system performance, three representative channels were selected for display: one near the lower edge of the FWM spectrum (channel 2 at 192.7 THz), one close to the center (channel 6 at 193.4 THz), and one near to the upper edge (channel 11 at 194.2 THz). Channel 6 is an original input, so was not FWM, therefore the eye yielded much higher quality. The eye diagrams for these three channels without attenuation are presented in figures 6 (a), (b) and (c), respectively. All three eyes were clear and showed very acceptable Q-factors.

(a)



(b)



(c)

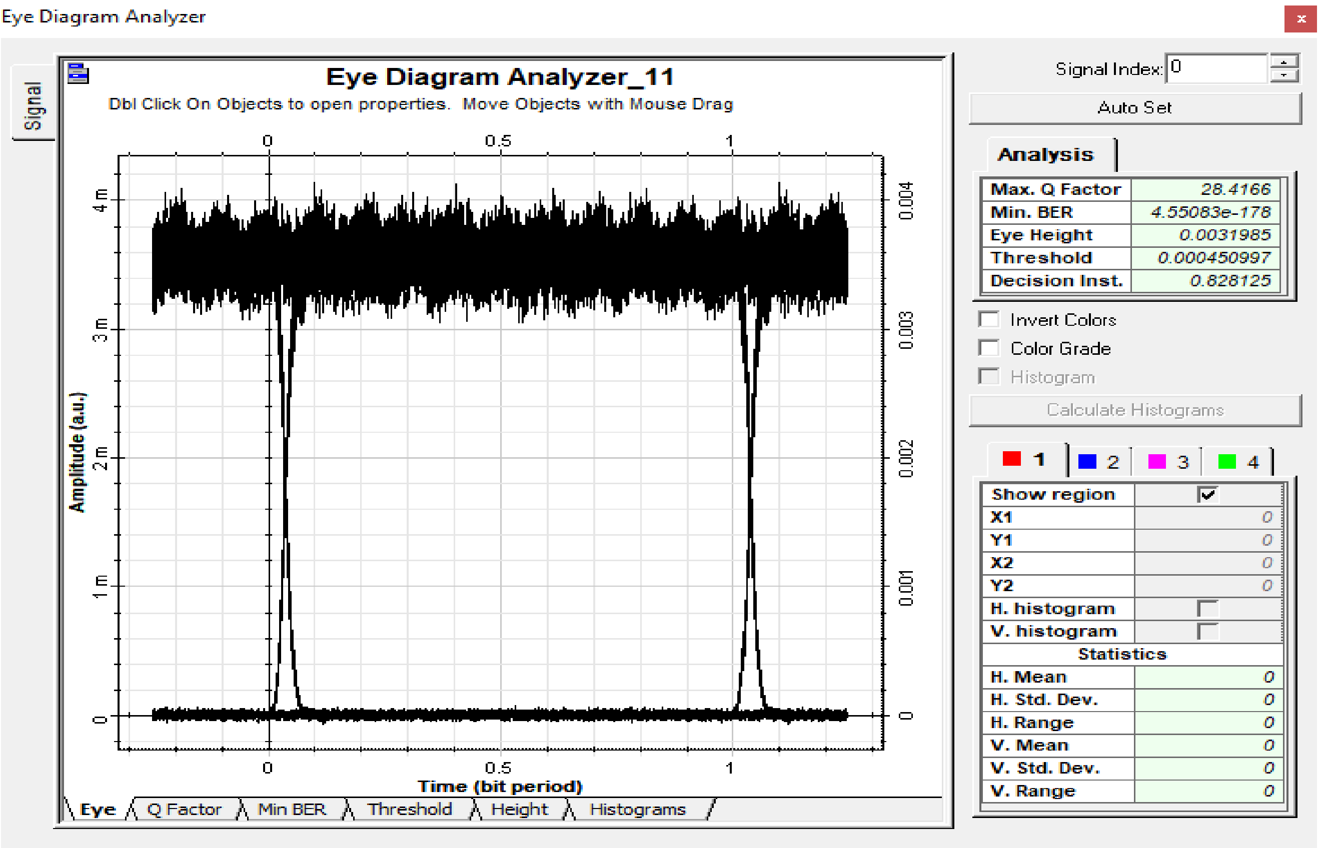


Figure 6: eye diagrams of three representative channels selected for display (a) channel 2 at 192.7 THz (b) channel 6 at 193.4 THz and (c) channel 11 at 194.2 THz

The remaining seven FWM channels showed comparative eye quality, with the average Q-factor measured to be about 24 over all nine FWM channels. This confirms that the post-FWM modulation approach effectively avoids the phase-noise transfer associated with incoherent ASE sources, enabling high-quality transmission across all generated channels. The SOA input power was then varied systematically using the attenuator placed before it (shown in figure 2) to characterize its impact on FWM conversion efficiency and signal quality. A power meter placed after the attenuator and before the SOA recorded the power into the SOA. Figures 7 and 8 plot the eye diagram Q-factor and OSNR of the two FWM channels 2 and 11 as a function of total SOA input power. Eye diagram and electrical carrier analyzers were used for this, respectively.

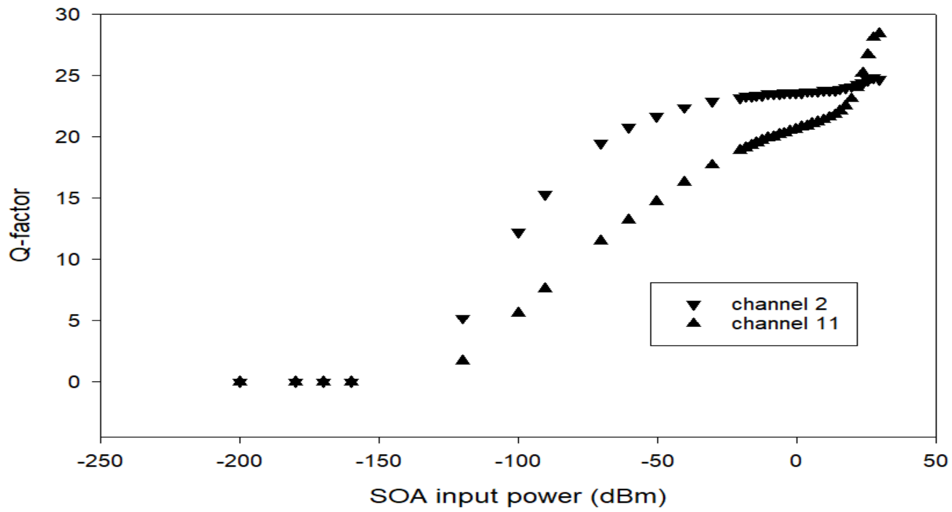


Figure 7: Q-factors received vs. SOA input power for FWM channels 2 and 11

From figure 7 it can be seen that the Q-factor of the selected channels generally increases with SOA input power, reaching a maximum value of around 28 for channel 11 and around 25 for channel 2 at the peak SOA input power (29.6 dBm). The SOA is deeply saturated at this point, giving rise to intensity noise reduction and therefore significant improvement in the Q-factor.

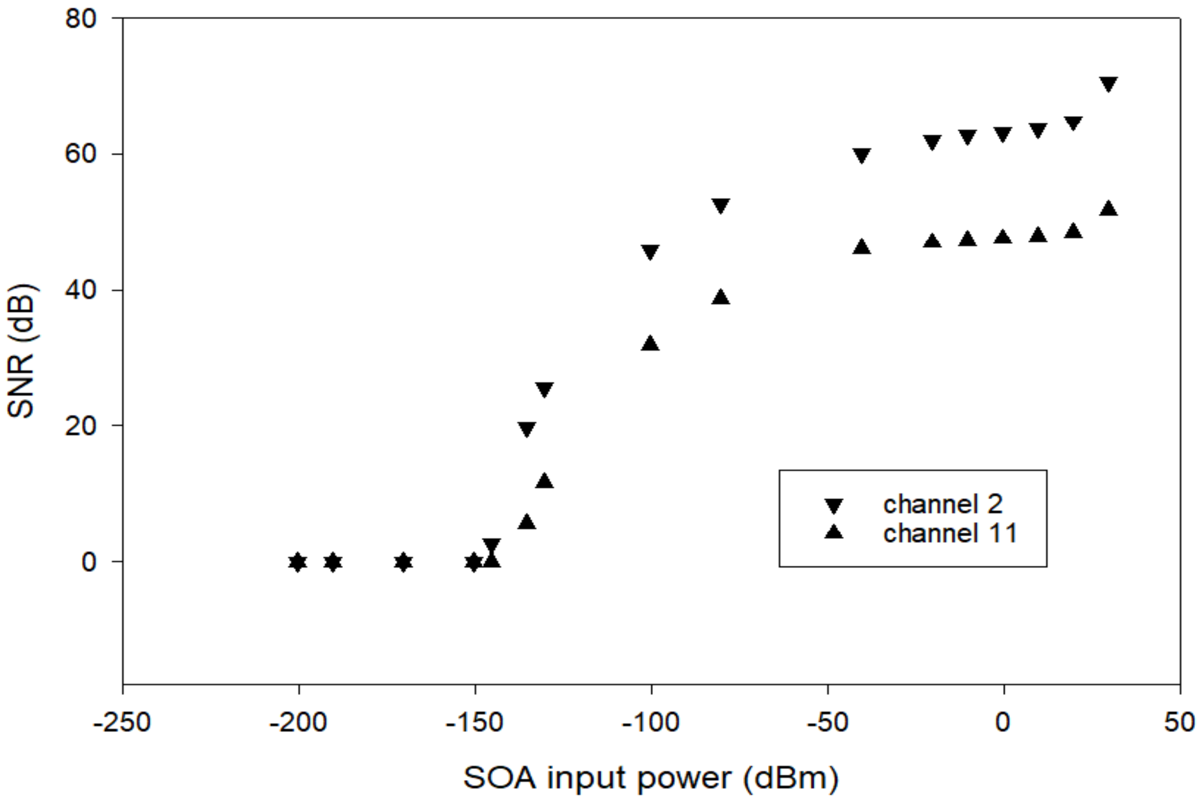


Figure 8: SNRs received vs. SOA input power for FWM channels 2 and 11

From figure 8 it can be seen that the measured SNR of the selected channels generally increases with SOA input power, reaching a maximum value of around 50 dB for channel 11 and around 70 dB for channel 2 at the peak SOA input power (29.6 dBm). The SOA is very highly saturated at this point, giving rise to intensity noise reduction and therefore significant improvement in the SNR.

To enable direct comparison across channels with differing inter-channel crosstalk performance, Table 2 presents normalized link lengths relative to the average of the nine FWM-generated channels (63.9 km). The maximum link lengths represented the longest travel possible for each channel until the Q-factor degraded and went below a value of 6. The SOA input here was optimized to the maximum of 29.6 dBm, as this was the best input value inferred from the Q and SNR data in figures 7 and 8. The link lengths were effectively created using an optical attenuator on each channel (figure 3) to degrade the input eyes along the simulated route. We assumed normal fibre loss for single mode fibre to be around 0.2 dB/km for our estimations. It can be seen that channels 5, 6, and 9 - the three non-FWM original ASE inputs - show substantially longer reach (normalized values of 3.05, 2.97, and 2.72) due to their higher input power and lower nonlinear distortion. Among the FWM channels, performance varies from 0.16 (channel 12) to 1.49 (channel 8), reflecting the wavelength-dependent efficiency of the four-wave mixing process. This normalization quantifies the channel disparity and identifies channel 12 as the weakest link, providing a clear benchmark for future gain-equalization efforts.

Table 2: Maximum channel link lengths and normalized performance

Channel No.	Frequency (THz)	Max. link length (km)	Normalized length (relative to FWM average)	Channel type
1	192.4	45	0.70	FWM
2	192.7	80	1.25	FWM
3	192.8	85	1.33	FWM
4	193.0	70	1.10	FWM
5	193.1	195	3.05	Non-FWM (input)
6	193.4	190	2.97	Non-FWM (input)
7	193.5	60	0.94	FWM
8	193.7	95	1.49	FWM
9	193.8	174	2.72	Non-FWM (input)
10	194.1	85	1.33	FWM
11	194.2	55	0.86	FWM
12	194.5	10	0.16	FWM
average (FWM only)		**63.9**	**1.00**	

(note: normalized lengths are calculated relative to the average maximum link length of the nine FWM-generated channels (63.9 km). Non-FWM channels (5, 6, 9) are the original ASE input signals and are shown for reference)

To further validate system performance using a standard telecommunications metric, using a BER analyzer we measured the bit error rate (BER) as a function of received optical power for two representative FWM channels: channel 2 (192.7 THz, lower edge) and channel 11 (194.2 THz, upper edge). Figure 9 shows the BER curves for both channels. From the power sweep measurements, the received power required to achieve BER = 10^{-9} was interpolated to be -13.8 dBm for channel 2 and -13.3 dBm for channel 11. These results are consistent with the Q-factor measurements reported in Figure 7 and confirm that both FWM channels can achieve error-free operation with adequate received power.

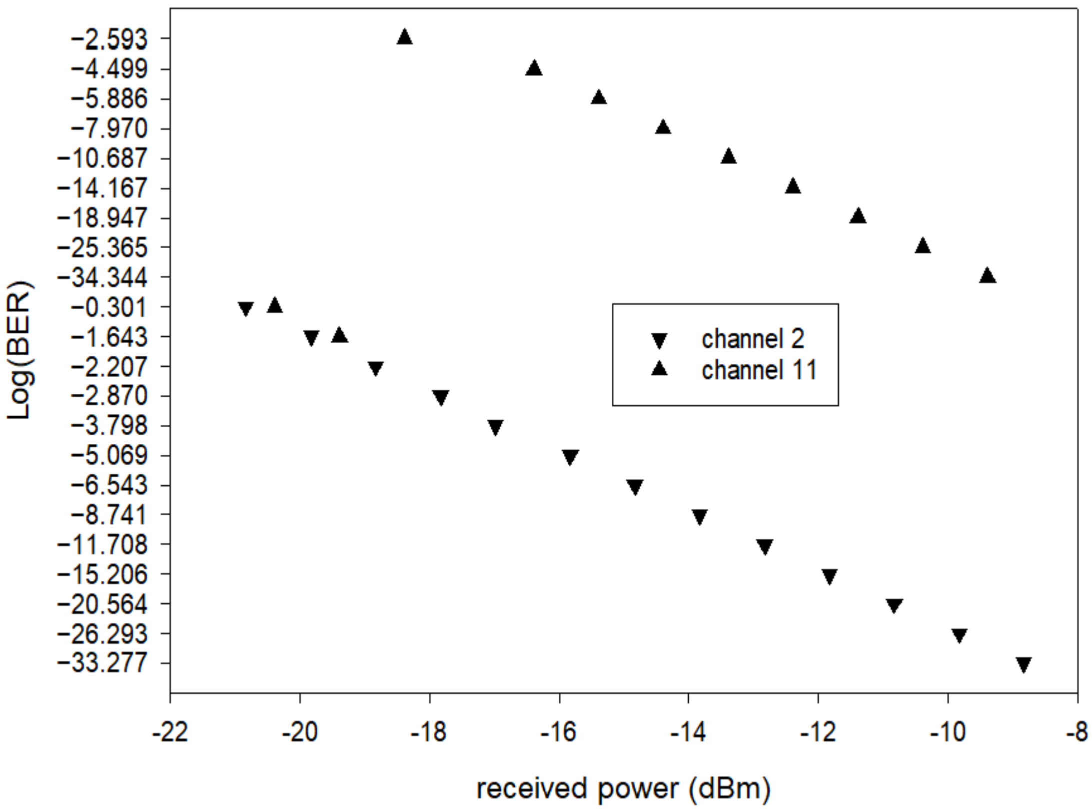


Figure 9: Log (BER) vs. received power curves for channels 2 and 11

DISCUSSION

The proposed architecture offers several system advantages. It acts as a low-cost multi-wavelength source, where a single SOA replaces multiple DFB lasers or frequency combs [3-5]. The design is scalable, as additional ASE slices can generate proportionally more FWM channels. The post-generation modulation avoids phase-noise issues associated with incoherent sources, representing the principal variation from [8]. Furthermore, the system maintains a compact footprint suitable for access and metro network deployments. The simulation methodology also accounts for tool limitations, improving result credibility and complementing experimental SOA-enhanced system work [4, 7].

However, several limitations were identified. FWM efficiency varies across the spectrum, resulting in unequal channel power that may require gain flattening or selective channel use. Also, inter-channel crosstalk from too closely spaced channels introduced additional FWM interactions, which made the eyes imperfectly clear in channels which were too close together. This crosstalk can be mitigated by increasing the frequency spacing between the three input ASE slices, which proportionally increases the separation of all generated FWM products. However, wider spacing reduces the total number of usable channels within a fixed optical bandwidth such as the C-band, presenting a fundamental trade-off between channel count and signal purity.

Finally, system performance remains dependent on precise SOA operating conditions, including bias current and input power. Another limitation observed here was the significant variation in output power across the 12 channels, with channel 12 achieving only 10 km of transmission. This disparity arises from the wavelength-dependent efficiency of FWM.

While the current version of OptiSystem does not include a native optical gain equalizer (OGE) component for direct simulation, in a practical system, an OGE or gain-flattening filter placed immediately after the SOA could substantially reduce this variation. For example, a custom-designed long-period fiber grating or thin-film filter could flatten the spectrum to within ±1 dB, potentially increasing the link length of weaker channels such as channel 12 to match the average of 63.9 km. Such an equalizer is commercially available and would add minimal cost relative to the overall system. Future physical deployments of this architecture are therefore encouraged to incorporate an OGE post-SOA to improve channel uniformity and extend the reach of the weakest FWM channels.

CONCLUSIONS

A 12-channel WDM system operating at 10 Gb/s per channel has been demonstrated using nine FWM-generated carriers generated from an SOA along with 3 spectrum-sliced ASE inputs. Post-FWM modulation yields a majority of clean eye diagrams, therefore confirming signal integrity. Investigation of SOA input power effects provides practical guidance on optimal operating points and maximum pre-SOA link loss, informing achievable transmission distances of up to 95 km under optimal conditions.

This work represents a variation of the prior simulation study in [8], with the key distinction being the application of modulation after the FWM process rather than before. In [8], modulation was applied to the ASE slices prior to FWM, which can result in phase-noise transfer and degraded signal quality. By contrast, this work extracts the FWM-generated carriers first, then modulates them independently at 10 Gb/s. This post-FWM modulation architecture decouples carrier generation from data encoding, enabling mainly clean eye diagrams despite the use of incoherent seed sources.

A 12-channel DFB laser array typically costs $3,000–6,000 (at the time of writing) and consumes 6–12 W, whereas our proposed source uses a single high-power LED (< $200) and one butterfly-packaged SOA (~$900–1,500), with total system power below 2 W. Even at this conservative SOA estimate, the total hardware cost remains under $2,200—representing a 1.5–2.5× cost reduction compared to a DFB array. In higher-volume production or chip-level integration, SOA costs can approach $300, which would widen the advantage to 5–10×. Additionally, the spectrum-slicing approach allows flexible channel allocation by changing filters, whereas DFB arrays are fixed-wavelength. These combined benefits justify the low-cost rationale of our scheme for access and metro network deployments.

Furthermore, the systematic analysis of SOA input power provides practical link budget guidance, addressing a gap in existing simulation-based studies where FWM efficiency is often idealized. Critically, this work confirms that FWM in SOAs using spectrum-sliced ASE inputs - first practically demonstrated experimentally in [7] - can be accurately simulated in OptiSystem, and that the architecture can be extended to a multi-channel WDM system with post-generation modulation to achieve high-quality transmission. These results align with recent findings [6, 10] that demonstrate significant reach extension in spectrum-sliced systems using saturated SOAs to reduce intensity noise, suggesting that the post-FWM modulation approach could further enhance such long-haul transmission.

Looking ahead, the integration of this post-FWM architecture with integrated photonic platforms could enable compact, low-cost multi-wavelength sources for next-generation passive optical networks and 5G fronthaul. Furthermore, the use of gain-equalized SOA combs and advanced modulation formats beyond 10 Gb/s per channel offers a clear pathway to Tb/s-class access networks using purely incoherent seeding.

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