650 Km Long Incoherent DWDM Spectrum-Sliced System Running At 10 Gb/S Utilizing a Single High-Powered LED Source and Semiconductor Optical Amplifiers (SOAS) as Pre-Amps

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ABSTRACT

The deployment of more economical and cost-effective wavelength division multiplexing (WDM) solutions for access and metro networks still remains a key research focus. This paper reports on significant performance enhancement improvements of an economical, four channel totally incoherent spectrum-sliced DWDM system using a single high-powered LED source and incorporating semiconductor optical amplifiers (SOAs) as pre-amplifiers on each channel. The total length of the link ran for an unsurpassed maximum of 650 km at 10 Gb/s, whilst still yielding reasonable Q-factors and very high signal-to-noise ratios (SNRs).

Keywords: spectrum, slicing, amplifier, link, signal-to-noise ratio

INTRODUCTION

The foundation of modern optical networks is Wavelength Division Multiplexing (WDM), which provides the immense data-carrying capacity essential for supporting global internet traffic [1]. Although systems utilizing coherent lasers deliver exceptional performance, their high cost makes them impractical for numerous access and metro-network scenarios [2]. Consequently, spectrum-sliced architectures that rely on incoherent light sources, such as Amplified Spontaneous Emission (ASE) sources or Light Emitting Diodes (LEDs), remain both an attractive and economical option for specialized uses such as Passive Optical Networks (PONs) [3], low-speed Local Area Networks (LANs) [4], and Optical Coherence Tomography (OCT) or other biomedical systems [5]. These designs employ narrowband optical filters to slice a single broadband source into multiple distinct WDM channels, thereby removing the requirement for a costly array of dedicated coherent lasers [6].

Table 1 summarizes recent practical achievements in incoherent spectrum-sliced WDM systems. It can be seen that the fastest demonstrated in a lab is ~40–50 Gb/s over short distances [7], whereas the longest achieved practical link is ~40 km at 3 Gb/s per channel [8]. For example, an ultranarrow spectrum-sliced incoherent source carried 10 Gb/s NRZ data over 20 km of SMF using a 0.01 nm slice window [9], while classic 1.3 µm LED WDM experiments achieved only a few Mb/s per channel over ~2 km [10]. Overall, modern incoherent spectrum-sliced systems realistically achieve up to ~10 Gb/s over tens of kilometers (≈ 20–40 km), whereas simpler LED-based implementations typically remain in the low Mb/s range over < a few km.

Table 1: Practical ASE / LED Spectrum-Sliced WDM Systems

Ref	Source Type	Bit Rate per Channel	Number of Channels	Link Length	Notes / Comments
[7]	ASE	40–50 Gb/s	4–8	~2–3 km	Lab demonstration, ultrafast short link
[8]	ASE	3 Gb/s	32	40 km	SS-DWDM-PON projected design
[9]	SLED / LED	10 Gb/s	4	20 km	Ultra-narrow band Bessel

					slicing, practical lab
[10]	LED	few Mb/s	4	~2 km	Classic early LED-based system
[4]	SLED	10 Gb/s	4	10–15 km	Lab test, practical for metro applications
[5]	SLED / ASE	1–2 Gb/s	8–16	5–10 km	Biomedical / OCT applications
[11]	ASE	3.84 Tb/s MUX	20	240 km	high-capacity metro and data-center interconnect optical networks

Not included in table 1 is recent work done by Forsyth [12]. Here, it was demonstrated that the performance of an incoherent spectrum-sliced WDM system could be considerably enhanced by incorporating a partially saturated semiconductor optical amplifier (SOA) on one channel. The introduction of a single SOA placed on one of the channels yielded a 4.5 improvement in the measured Q factor and an exceptional improvement of almost 52 dB in the measured signal-to-noise ratio (SNR), allowing an extra maximum of 130 km of link length travel to the 210 km already achieved - thereby extending the total reach of this single enhanced channel to a previously unsurpassed 340 km.

The fundamental challenge in all spectrum-sliced systems that employ incoherent sources is the presence of intensity noise resulting from random spontaneous emission events, which inherently restricts overall system performance [13]. This type of noise, typically marked by a poor signal-to-noise ratio (SNR), worsens as the signal travels through the fibre due to attenuation, which heavily limits the transmission distance that can be achieved [14]. The Semiconductor Optical Amplifier (SOA) has been extensively explored as a small-scale, and potentially integrable, amplification device for optical communications [15, 16]. In addition to providing straightforward gain, an SOA operating in its saturated region demonstrates non-linear transfer characteristics that reduce the dynamic range of an incoming signal. This effect can be utilized to mitigate the intensity noise from incoherent sources, thus enhancing the signal quality and, as a result, boosting the system's Q-factor and Bit Error Rate (BER) performance [17, 18]. The mechanism of this is shown in figure 1:

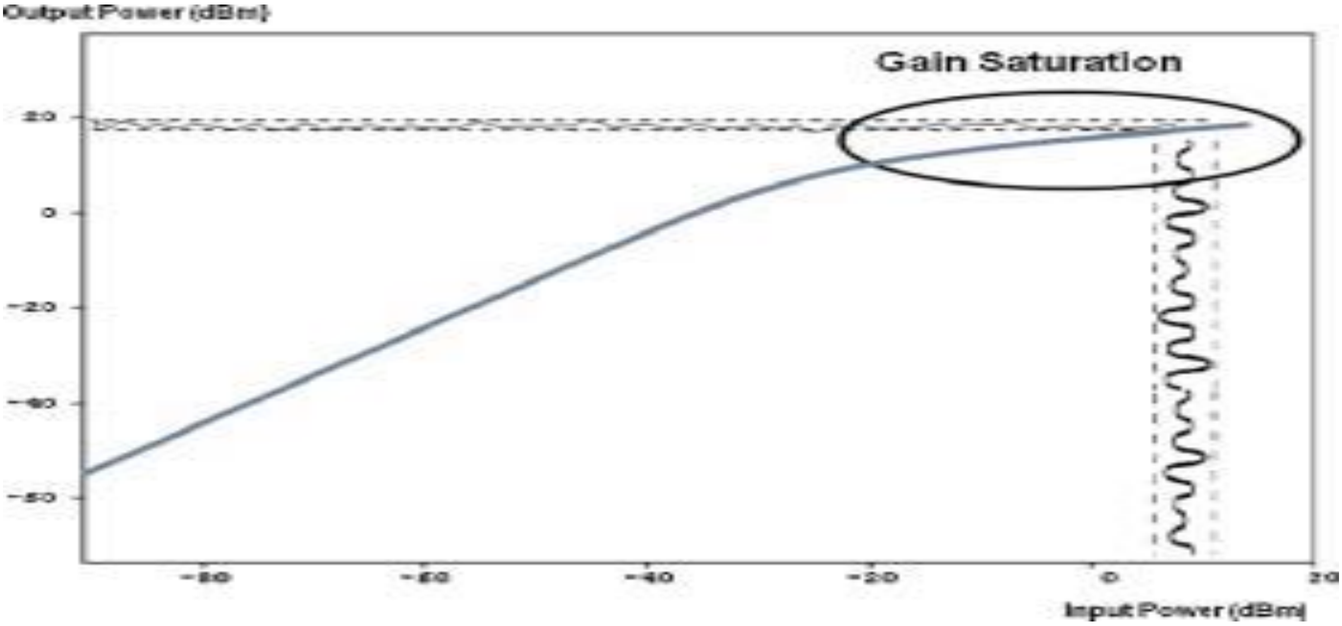


Figure 1: conceptual SOA intensity noise reduction [18]

It can be seen from figure 1 that because of the non-linear slope of the curve in the deep saturation region (mainly between 0 and 20 dBm input power), the output from the input power is effectively “squashed”, which means that the intensity noise reduces.

In this paper, we build on the work done previously in [12] to demonstrate significant performance enhancement for an even longer link length system than has previously been done in a 4-channel completely incoherent DWDM system running at 10 Gb/s by using a single high-powered LED source and integrating four SOAs as pre-amplifiers. Section 2 introduces the idea, section 3 reports on the results, and conclusions are made in section 4

Experimental set-up

Four WDM channels were spectrally sliced, using ultra-narrow band-width Bessel filters, from a single broadband, high powered incoherent LED source at frequencies of 193.1, 193.2, 193.3 and 193.4 THz, corresponding to 1552.5, 1551.7, 1550.9 and 1550.1 nm, respectively. The channel spacing was 0.8 nm in the simulated single mode fibre link running at 10 Gb/s, making it dense wavelength division multiplexing (DWDM).

Figure 2 shows the simulated set up used. There was no amplification in this link up until the four SOA pre-amps and the maximum link length achieved was 650 km - corresponding to the optical attenuation (fibre attenuation used was 0.2 dB/km) of 130 dB shown. The average Q-factor achieved from all four channels was around an acceptable value of around 7. But the SNR was measured to be a very high 25 dB on average over the four channels.

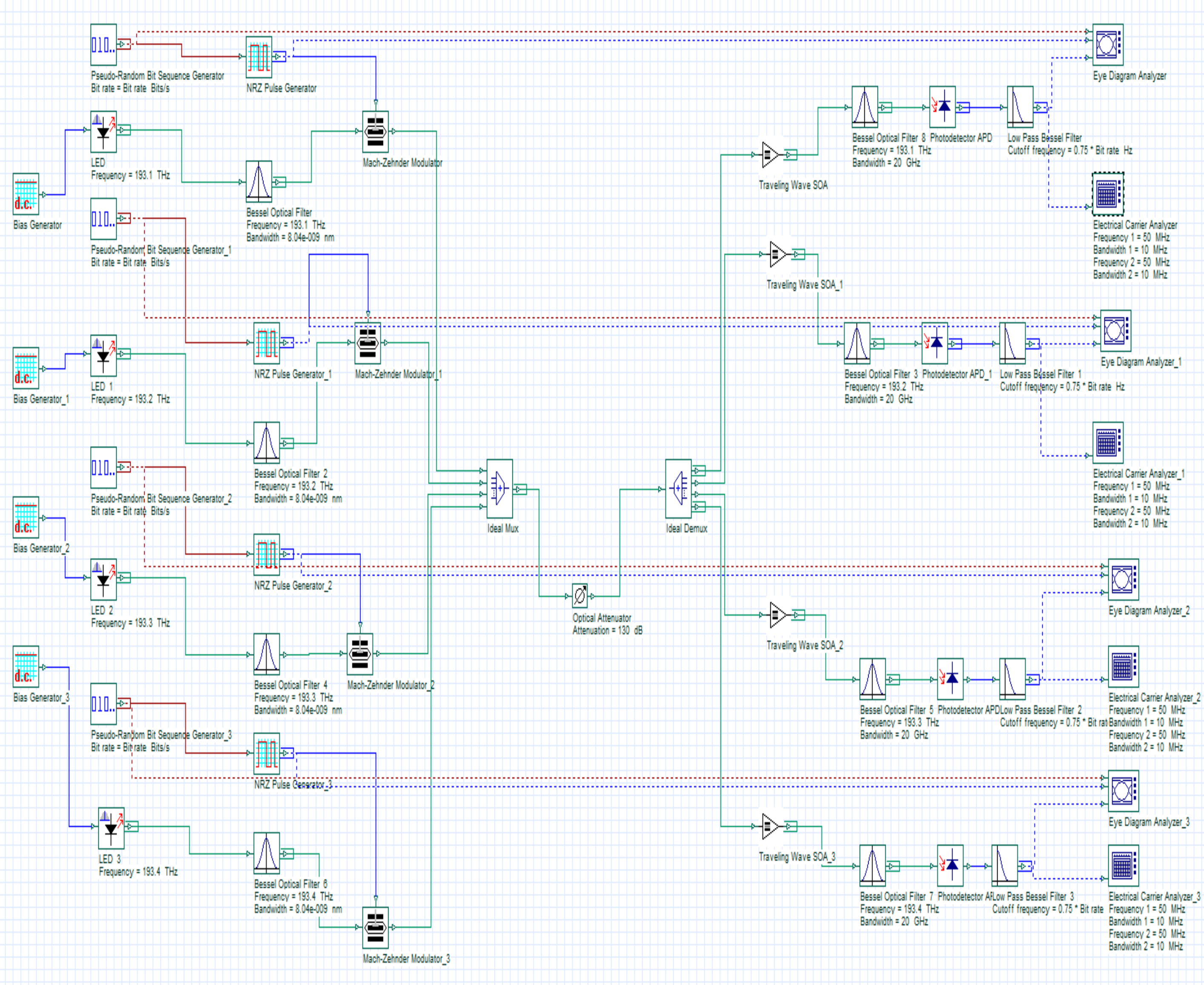


Figure 2: four channel DWDM set-up used with SOA pre-amps enhancement

An additional four Bessel filters, each set at 20 GHz bandwidth, recovered the signals to be analyzed for Q-factor and SNR using eye diagram and electrical carrier analyzers, respectively. Each SOA was biased at 250 mA for optimum effect, and its input power was measured to be around -100.7 dBm on average over the four channels. This was found to be the lowest input possible to produce the given signals at the maximum link length (650 km).

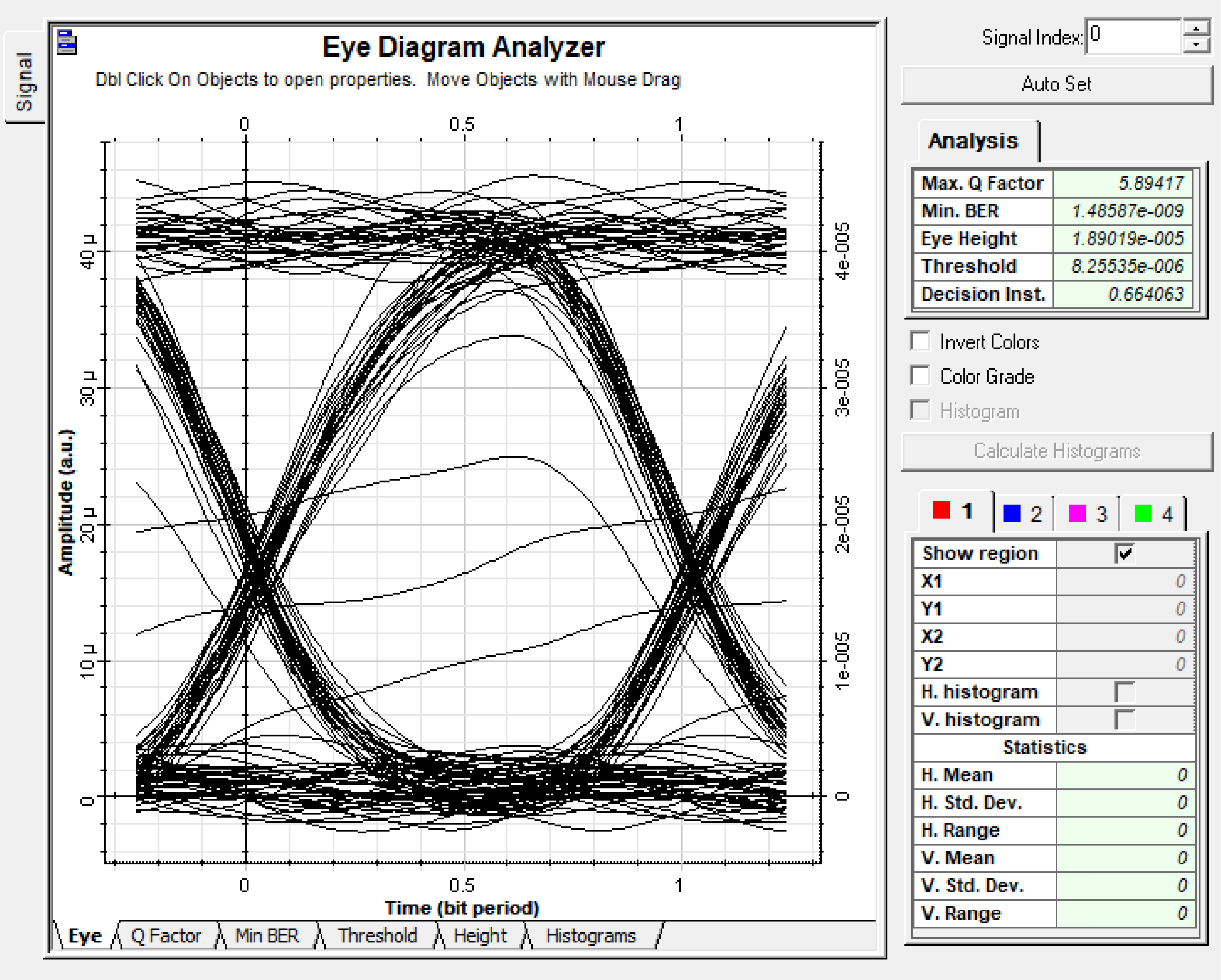
RESULTS

Table 2 shows the measured results obtained on the Q-factors and SNRs received. It can be seen that each channel achieved an acceptable Q-factor value (> 6) coupled with good SNR readings.

Table 2: Q-factors and SNRs received

Frequency (THz)	Branch of circuit	Q - factors achieved	SNRs (dB) achieved
193.1	Arm 1	5.9	23.1
193.2	Arm 2	6.4	22.7
193.3	Arm 3	6.3	25.5
193.4	Arm 4	8.3	26.1

Figure 3 shows the eye diagrams obtained from the 4 channel link in figure 2:

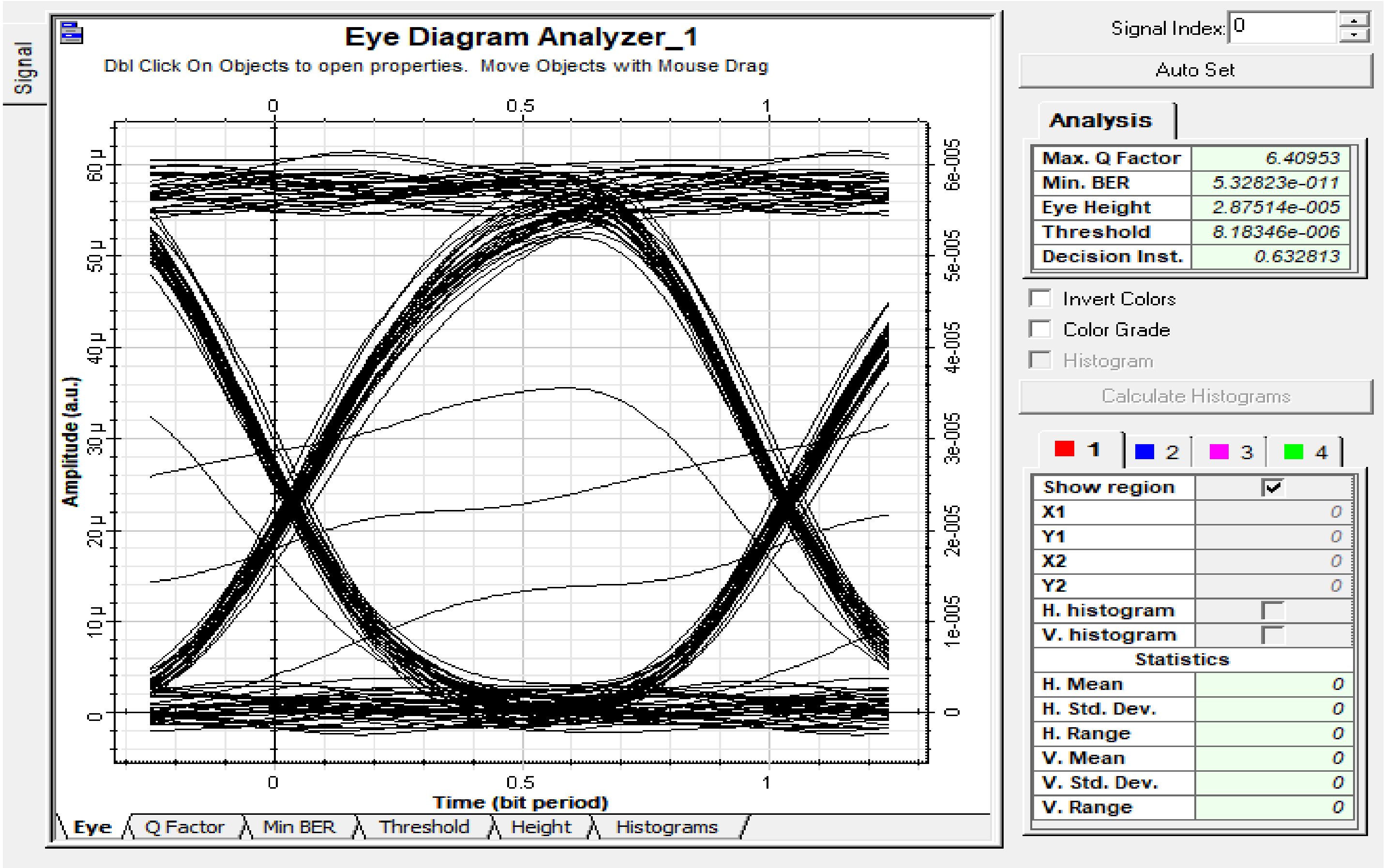


Signal Index: 0

Analysis	
Max. Q Factor	5.89417
Min. BER	1.48587e-009
Eye Height	1.89019e-005
Threshold	8.25535e-006
Decision Inst.	0.664063

☐ Invert Colors
☐ Color Grade
☐ Histogram

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0



Eye Diagram Analyzer_1

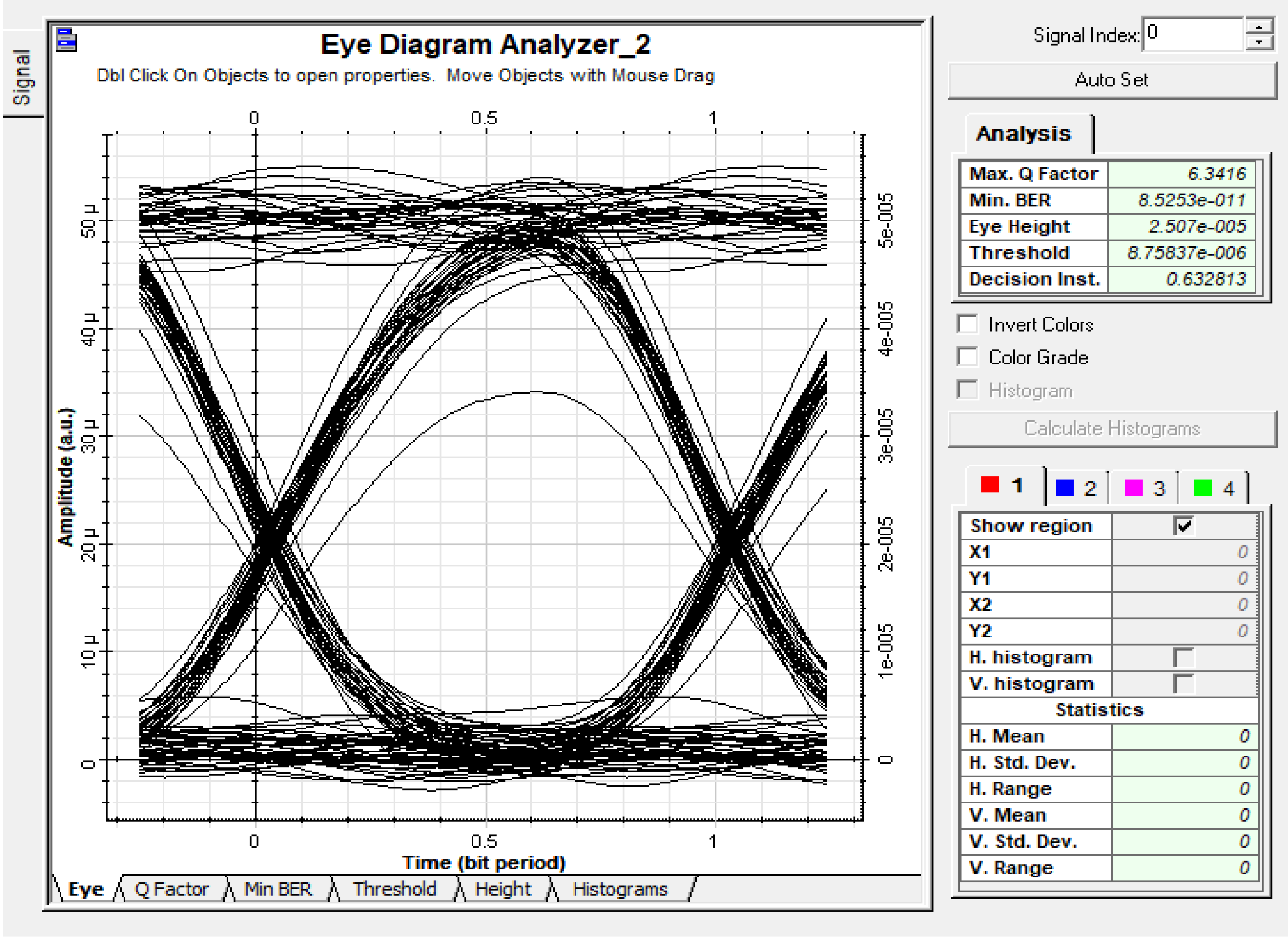
Dbl Click On Objects to open properties. Move Objects with Mouse Drag

Signal Index: 0

Analysis	
Max. Q Factor	6.40953
Min. BER	5.32823e-011
Eye Height	2.87514e-005
Threshold	8.18346e-006
Decision Inst.	0.632813

☐ Invert Colors
☐ Color Grade
☐ Histogram

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0



Eye Diagram Analyzer_2

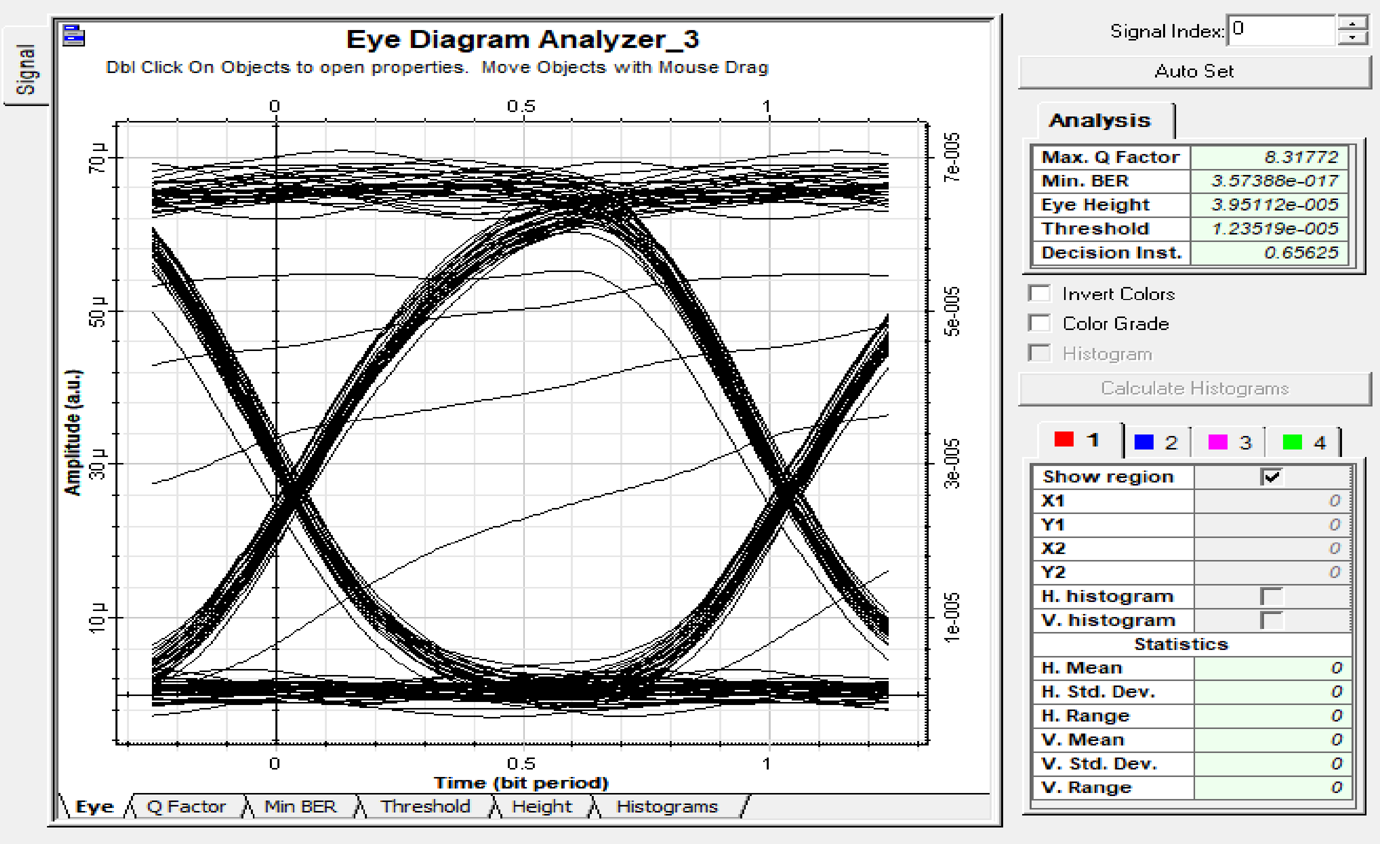
Dbl Click On Objects to open properties. Move Objects with Mouse Drag

Signal Index: 0

Analysis	
Max. Q Factor	6.3416
Min. BER	8.5253e-011
Eye Height	2.507e-005
Threshold	8.75837e-006
Decision Inst.	0.632813

☐ Invert Colors
☐ Color Grade
☐ Histogram

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0



Signal Index: 0

Max. Q Factor	8.31772
Min. BER	3.57388e-017
Eye Height	3.95112e-005
Threshold	1.23519e-005
Decision Inst.	0.65625

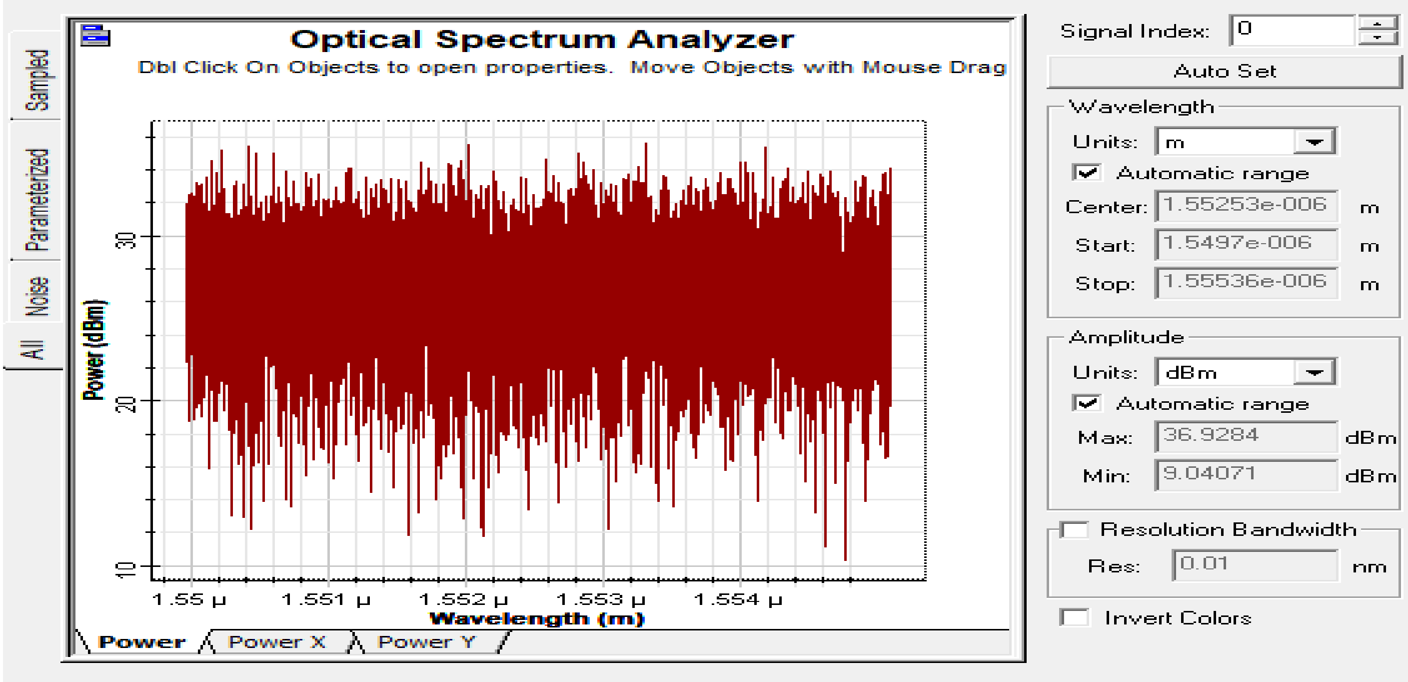
☐ Invert Colors
☐ Color Grade
☐ Histogram

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0

Figure 3: eye diagrams obtained from each channel (a) 193.1 THz, (b) 193.2 THZ, (c) 193.3 THz, (4) 193.4 THz

These values are displayed in table 2. The average Q-factor obtained was around 7, and the average SNR was around 25 dB.

Figure 4 shows the output from one of the high-powered LEDs. The total output power from LED 1 was measured at 67.2 dBm, and the other three were similar.



Signal Index: 0

Wavelength
Units: m
☑ Automatic range
Center: 1.55253e-006 m
Start: 1.5497e-006 m
Stop: 1.55536e-006 m

Amplitude
Units: dBm
☑ Automatic range
Max: 36.9284 dBm
Min: 9.04071 dBm

☐ Resolution Bandwidth
Res: 0.01 nm

☐ Invert Colors

Figure 4: output power spectrum from 193.1 THz LED

The effect of increasing the average input power from -100 dBm to the SOAs was then investigated. This was achieved using the variable optical attenuator shown in figure 2. The SNR averaged over the four channels was generally found to improve considerably with increasing input power, as shown in figure 5 and figure 6. These are both shown with 2nd order polynomial fits. This clearly demonstrates the effectiveness of SOA intensity noise saturation, particularly in the close-up SOA saturation region.

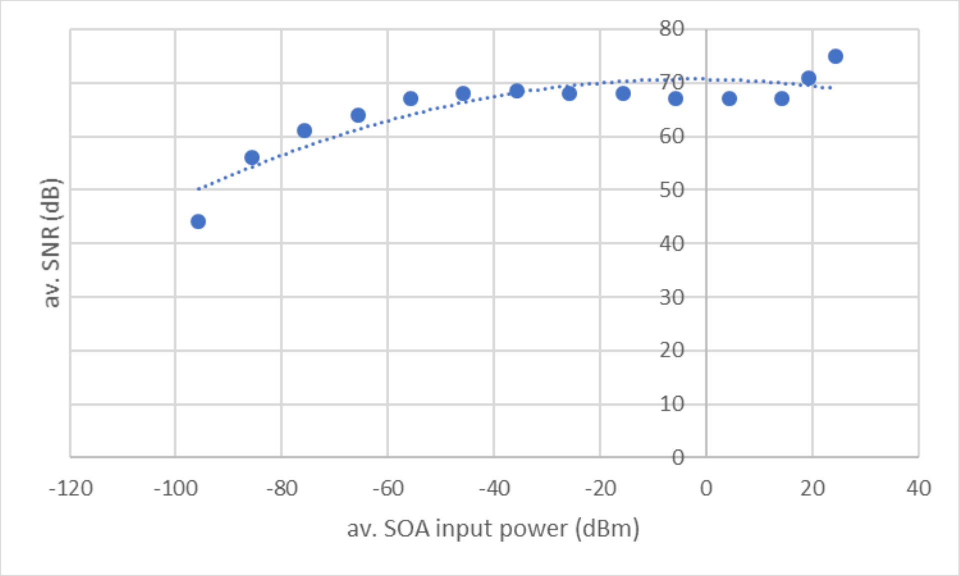


Figure 5: average SNR (dB) vs. average input power to SOA (dBm) over full range

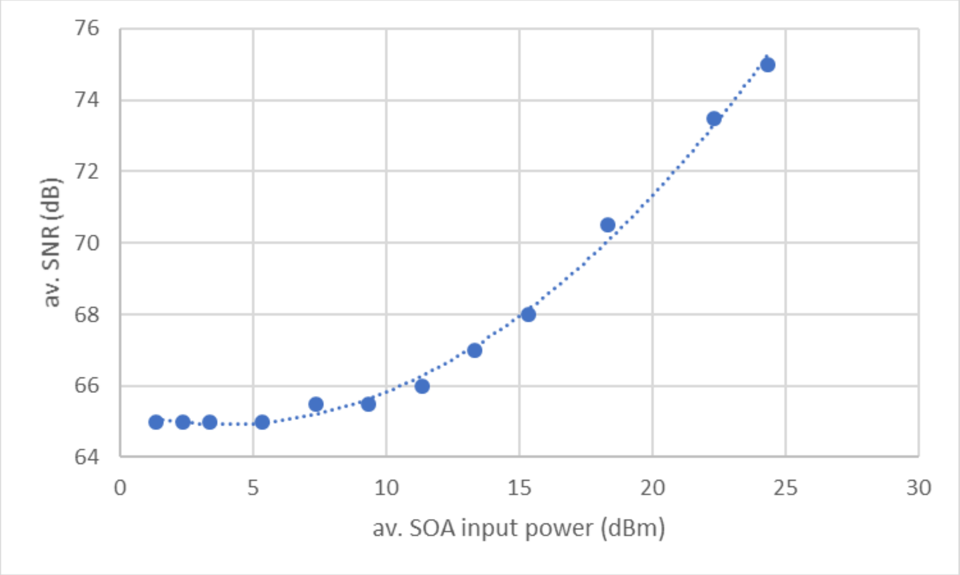


Figure 6: average SNR (dB) vs. average input power to SOA (dBm) close up within the deep SOA saturation region

CONCLUSIONS

The simulated results obtained here have shown that the performance of a highly economical incoherent 4-channel completely spectrum-sliced WDM system can be considerably enhanced by incorporating a high-powered LED source and utilizing semiconductor optical amplifiers at various levels of input power as pre-amps. The system operating at 10 Gb/s over 650 km showed acceptable Q-factors and SNRs with the addition of the pre-amps. However, without these enhancements the signals were unreadable. The modelled results confirm that a saturated SOA serves as a highly effective method for simultaneous amplification and intensity noise suppression, thereby dramatically extending the reach and improving the signal integrity in an incoherent spectrum-sliced WDM system. However, in a physical implementation, the combined effects of fibre nonlinearities, dispersion, polarization effects, and SOA dynamics would likely limit the achievable distance to slightly less than 650 km at this data rate of 10 Gb/s without significant additional compensation (dispersion management, nonlinearity mitigation, polarization tracking, and possibly coherent detection). The SOA pre-amps at the receiver help, but they cannot undo nonlinear impairments accumulated along the link. Further work could practically compare results from an experimental test bed with those achieved here. However, overall the results reported here should assist designers of such practical spectrum-sliced systems to produce more economical systems with much longer link lengths in the future, without sacrificing data rate. Optimal conditions for achieving a certain SNR at a particular link length can be inferred from the data presented here.

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