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SIGNAL AMPLIFIERS IN OPTICAL COMMUNICATION SYSTEMS

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Abstract. *This work focuses on modelling an optical soliton-based pulse amplitude modulation (PAM) system incorporating linear semiconductor optical amplifiers (LSAs). Simulations were performed to determine the maximum output power for different bit/symbol PAM soliton configurations, with single-soliton propagation analysed over a 200 km optical fibre link. The study also evaluates the peak Q-factor for these PAM schemes at 200 km under varying injection currents supplied to the semiconductor optical amplifiers. In addition, the simulations examine the total electrical power detected at the photodetectors for soliton systems across different PAM formats and SOA injection levels, all over the same fibre length. Results show that increasing the injection current raises the electrical output power of the amplifiers, while the corresponding Q-factor in the soliton transmission tends to decrease.*

Keywords: electrooptic modulators, pulse amplitude modulation, SOA injection current, soliton pulse

WZMACNIACZE SYGNAŁU W SYSTEMACH ŁĄCZNOŚCI OPTYCZNEJ

Streszczenie. *Niniejsza praca skupia się na modelowaniu systemu modulacji amplitudy impulsu (PAM) opartego na solitonach optycznych, wykorzystującego liniowe półprzewodnikowe wzmacniacze optyczne (LSA). Przeprowadzono symulacje w celu określenia maksymalnej mocy wyjściowej dla różnych konfiguracji solitonów PAM typu bit/symbol, analizując propagację pojedynczego solitonu na odcinku światłowodu o długości 200 km. W badaniu oceniono również szczytowy współczynnik Q dla tych schematów PAM na odcinku 200 km przy różnych prądach zasilających dostarczanych do półprzewodnikowych wzmacniaczy optycznych. Ponadto w symulacjach zbadano całkowitą moc elektryczną wykrytą przez fotodetektory dla systemów solitonowych w różnych formatach PAM i przy różnych poziomach zasilania wzmacniaczy optycznych, dla tej samej długości światłowodu. Wyniki pokazują, że zwiększenie prądu zasilającego podnosi elektryczną moc wyjściową wzmacniaczy, podczas gdy odpowiadający mu współczynnik Q w transmisji solitonowej ma tendencję do spadku.*

Słowa kluczowe: modulatory elektrooptyczne, modulacja amplitudy impulsu, prąd zasilający SOA, impuls solitonowy

Introduction

The first experimental case in this study examines performance gains achieved using a dual-index fibre loop with a directly modulated reflective semiconductor optical amplifier (RSOA). This configuration improves the RSOA's modulation bandwidth and signal quality through the application of a unidirectional fibre loop. As a result, the RSOA reached modulation speeds of 4 Gb/s with a bit error rate (BER) of 1.0×10^{-9} and 11 Gb/s within the forward error correction (FEC) threshold of 3.8×10^{-3}. These findings indicate that a unidirectional loop fibre can significantly contribute to the performance of RSOA-based modulation and amplification systems [10, 25].

The paper also presents a hybrid optical amplifier (HOA) capable of operating in the O+E bands while providing broadband, uniform gain. The HOA consists of a semiconductor optical amplifier (SOA) combined with a praseodymium-doped fibre amplifier (PDFA). Numerical simulations show the HOA can deliver a stable 24 dB gain across wavelengths of 1270–1450 nm. BER analysis further demonstrates that this amplifier supports reliable data transmission at rates up to 10 Gb/s over 60 km in CWDM systems. These results highlight an effective approach for improving signal amplification in optical communication networks [14, 23].

Additionally, the discussion addresses the capabilities of SOAs operating in the 1550 nm band. Due to their high broadband gain, they can enhance both capacity and signal quality in optical links. They are also cost-effective and simple to integrate, making them suitable for use in applications such as LiDAR systems [11, 30].

This paper examines the potential of passive optical networks (PON) to expand broadband capacity and highlights the role of optical and electro-optical amplification in achieving higher speeds and longer transmission distances. The principles of optical amplification are reviewed in the context of 2R (re-amplification, re-shaping) and 3R (re-amplification, re-shaping, re-timing) regeneration, along with their influence on PON performance. The discussion also considers the advantages and limitations of optical amplifiers, as well as the main concepts behind their design and operation [12, 13].

It further evaluates the use of semiconductor optical amplifiers (SOAs) to extend the bandwidth of next-generation optical systems beyond 100 nm. The development of ultra-wideband (UWB) SOA modules is described, together with potential approaches to enhance their operational efficiency [24, 28].

The paper also reviews various amplification methods aimed at boosting the transmission capacity of optical communication systems. It discusses amplifier behaviour across different wavelength ranges, feasibility for short- and medium-term deployment, and the main factors influencing efficiency. Special attention is given to the selection and availability of laser pump sources as a key performance criterion, with proposed solutions for near-term and mid-term implementation [6, 20].

The modelling work focuses on pulse amplitude modulation (PAM) using soliton pulses in conjunction with semiconductor optical amplifiers. Simulations determine the maximum power achievable in soliton systems for different bit/symbol PAM schemes over 200 km of fibre and analyse how varying SOA injection currents affect both Q-factor and electrical power. The results indicate that higher SOA injection currents increase electrical power output but cause a reduction in Q-factor [1, 19].

1. Materials and methods

Networks today can achieve speeds of around 100 Mb/s through the use of optical carriers. Standards have been developed to support gigabit-per-second throughput, such as the Fibre Channel Standard (FCS) and the High-Performance Parallel Interface (HIPPI) [2, 3]. The HIPPI approach uses multiple parallel channels, each operating at 100 Mb/s [21, 22]. Over short distances of a few meters, these channels employ electrical cabling, while for several-kilometre links they rely on optical fibre. However, extending optical fibre use to further boost network capacity faces challenges due to electronic speed limitations. Additionally, transmitter and receiver components designed for operation above the gigabit-per-second range remain expensive [7, 15].

To achieve higher bit rates, optical multiplexing and demultiplexing techniques are implemented, with experiments underway to develop switched optical networks capable of very large bandwidths [17, 18].

A soliton is a localized wave-like entity that retains its shape over long distances, arising as a solution to specific nonlinear equations. Its stability comes from its ability to preserve form during interactions with other waves [4, 5].

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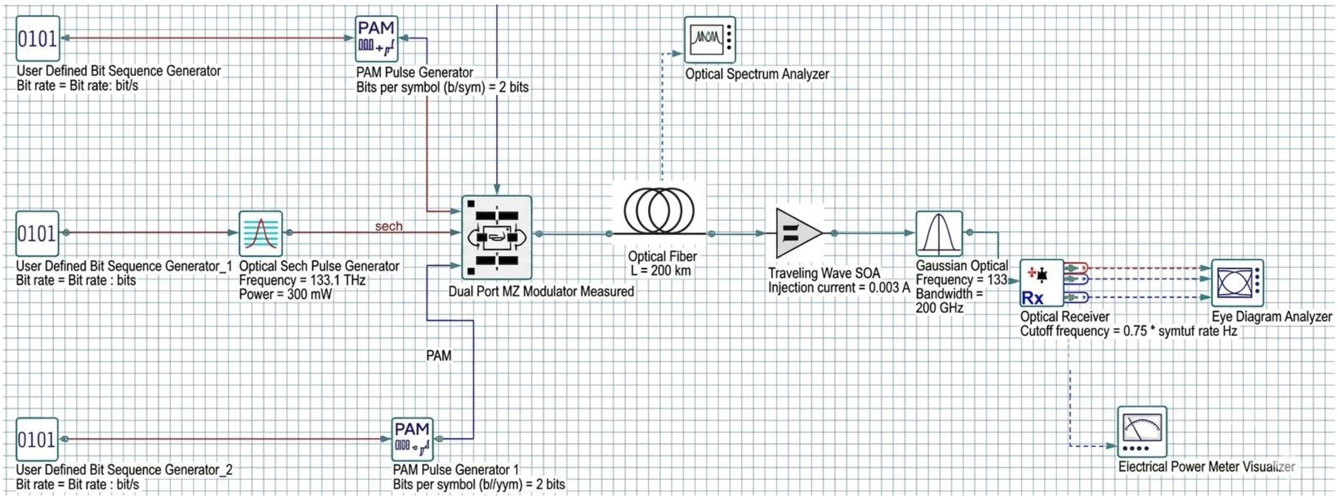


Fig. 1. Schematic description of the proposed model for this study

As shown in Fig. 1, the proposed soliton-based system integrates a semiconductor optical amplifier (SOA) with pulse amplitude modulation (PAM). User-defined sequence generators produce the data streams, which are modulated via a PAM electrical modulator. Optical Sech pulse generators then create the soliton pulses [31]. In soliton systems, dispersive effects tend to broaden the pulse, while nonlinear effects compress it. When these two phenomena are balanced, the resulting soliton pulse remains stable and can travel the maximum feasible transmission distance without distortion [26, 27].

The soliton pulse in this setup operates at a frequency of 193.1 THz with an output power of 100 mW. The LiNbO₃ electro-optic modulator functions as a three-input device, accepting two electrically modulated signals along with the soliton optical pulse. The modulated signal is launched into a 200 km optical fibre link, with optical spectrum analysers used to monitor its power [29]. Signal amplification, along with additional processing, is carried out at the SOA stage [8, 9]. A Gaussian optical filter is employed to suppress noise by removing unwanted spectral components. At the receiver end, an avalanche photodiode (APD) photodetector converts the optical signal into electrical form. Measurements of total electrical power, maximum Q-factor, and minimum BER are performed using a power meter and an eye diagram analyser.

2. Research results

The soliton system's maximum power output was determined for multiple bit-per-symbol PAM modulation formats over the 200 km fibre span. Experiments also established the maximum Q-factor for the same distance, incorporating an inline SOA with varying injection currents under the soliton PAM modulation configuration.

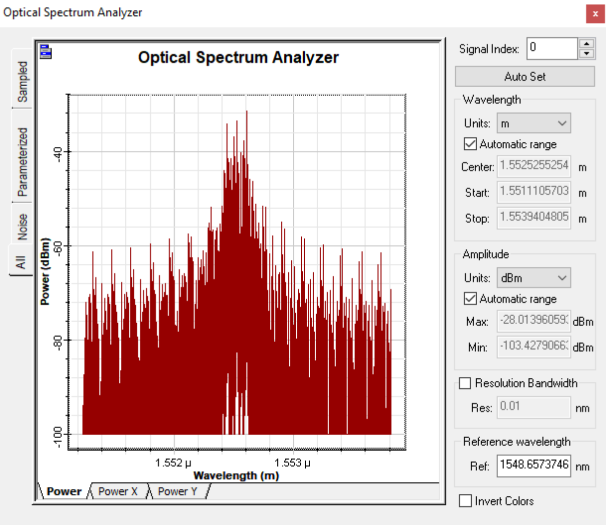
Results indicate that, for the soliton PAM scheme, total electrical power at 200 km was measured for different SOA injection levels. All measurements were based on the parameters listed in Table 1.

Table 1. Key parameters of the proposed model

Variable	Value / Unit
Pulse frequency	193.1 THz
Pulse power	100 mW
Fibre length	200 km
SOA injection current	30 mA – 100 mA
Modulator extinction ratio	20 dB
Modulator bias voltage	4 V
Modulator insertion loss	5 dB
Optical filter bandwidth	250 GHz
Optical filter frequency	193.1 THz
Optical receiver type	APD
APD gain	10
APD sensitivity	0.9 A/W

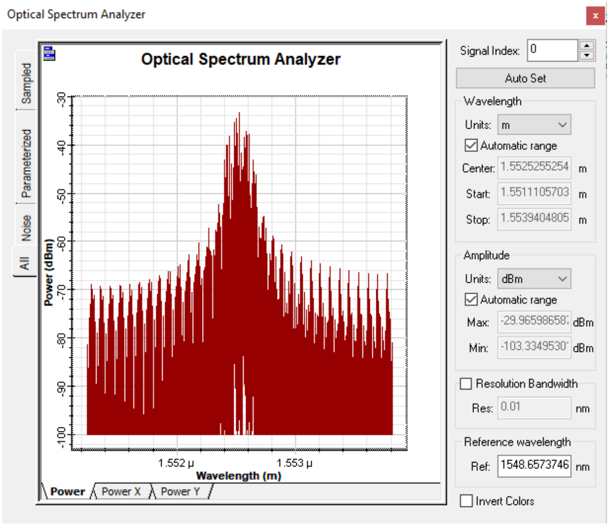
The corresponding power optimization outcomes for the various PAM formats after 200 km of fibre are illustrated in Fig. 2–6.

Fig. 2 presents results for a 2-bit/symbol PAM soliton system over 200 km, recording a peak soliton power of –28.01 dBm and a noise floor of –103.42 dBm.



Signal Index: 0
Wavelength
Units: m
☑ Automatic range
Center: 1.5525255254 m
Start: 1.5511105703 m
Stop: 1.5539404805 m
Amplitude
Units: dBm
☑ Automatic range
Max: -28.01396059: dBm
Min: -103.4279066: dBm
☐ Resolution Bandwidth
Res: 0.01 nm
Reference wavelength
Ref: 1548.6573746 nm
☐ Invert Colors

Fig. 2. Maximum power for a soliton system based on a 2-bit/symbol PAM modulation scheme after a 200 km fibre length

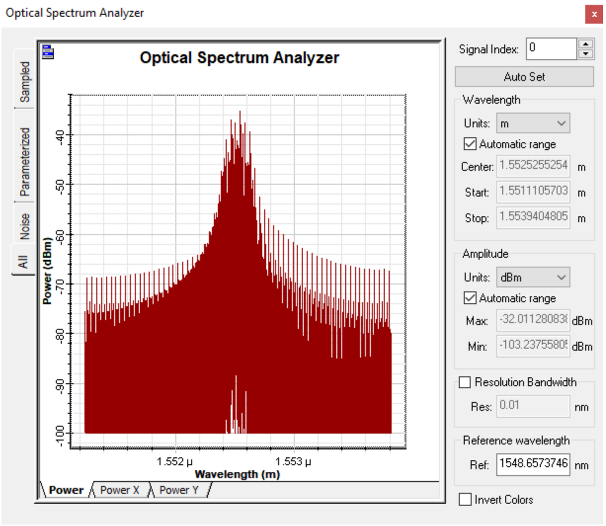


Signal Index: 0
Wavelength
Units: m
☑ Automatic range
Center: 1.5525255254 m
Start: 1.5511105703 m
Stop: 1.5539404805 m
Amplitude
Units: dBm
☑ Automatic range
Max: -29.96598658; dBm
Min: -103.3349530 dBm
☐ Resolution Bandwidth
Res: 0.01 nm
Reference wavelength
Ref: 1548.6573746 nm
☐ Invert Colors

Fig. 3. Maximum power for a soliton system based on a 4-bit/symbol PAM modulation scheme after a 200 km fibre length

For the 4-bit/symbol PAM configuration at 400 km (Fig. 3), the maximum soliton power measured is –29.96 dBm, with noise power at –103.33 dBm.

The 8-bit/symbol PAM outcome, shown in Fig. 4, yields a maximum soliton power of –32.01 dBm and noise power of –103.23 dBm.


Optical Spectrum Analyzer

Signal Index: 0

Wavelength
Units: m
☑ Automatic range
Center: 1.5525255254 m
Start: 1.5511105703 m
Stop: 1.5539404805 m

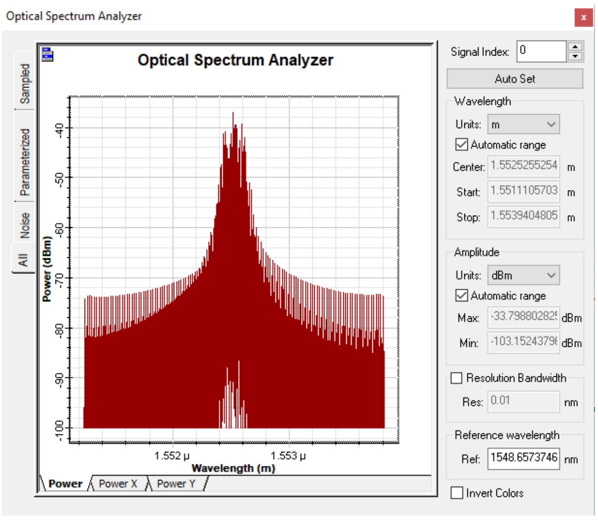
Amplitude
Units: dBm
☑ Automatic range
Max: -32.01128083(dBm
Min: -103.2375580! dBm

☐ Resolution Bandwidth
Res: 0.01 nm

Reference wavelength
Ref: 1548.6573746 nm

☐ Invert Colors

Fig. 4. Maximum power for a soliton system based on an 8-bit/symbol PAM modulation scheme after a 200 km fibre length


Optical Spectrum Analyzer

Signal Index: 0

Wavelength
Units: m
☑ Automatic range
Center: 1.5525255254 m
Start: 1.5511105703 m
Stop: 1.5539404805 m

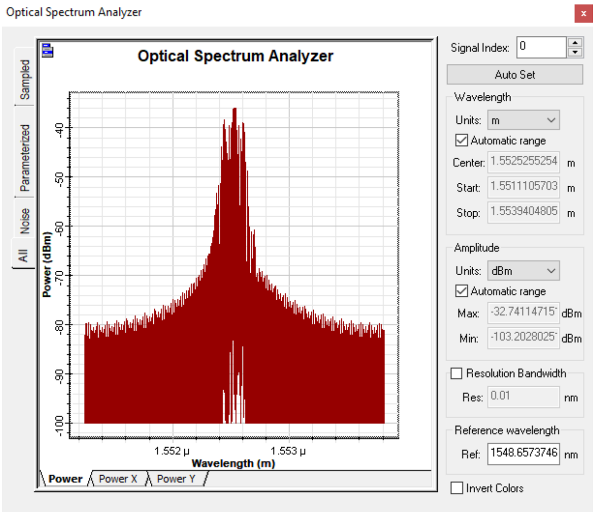
Amplitude
Units: dBm
☑ Automatic range
Max: -33.79880282! dBm
Min: -103.1524379(dBm

☐ Resolution Bandwidth
Res: 0.01 nm

Reference wavelength
Ref: 1548.6573746 nm

☐ Invert Colors

Fig. 5. Maximum power for a soliton system based on a 16-bit/symbol PAM modulation scheme after a 200 km fibre length


Optical Spectrum Analyzer

Signal Index: 0

Wavelength
Units: m
☑ Automatic range
Center: 1.5525255254 m
Start: 1.5511105703 m
Stop: 1.5539404805 m

Amplitude
Units: dBm
☑ Automatic range
Max: -32.74114715 dBm
Min: -103.2028025 dBm

☐ Resolution Bandwidth
Res: 0.01 nm

Reference wavelength
Ref: 1548.6573746 nm

☐ Invert Colors

Fig. 6. Maximum power for a soliton system based on a 32-bit/symbol PAM modulation scheme after a 200 km fibre length

In Fig. 5, the 16-bit PAM scheme over 200 km produces a soliton peak power of –33.79 dBm and noise power of –103.15 dBm.

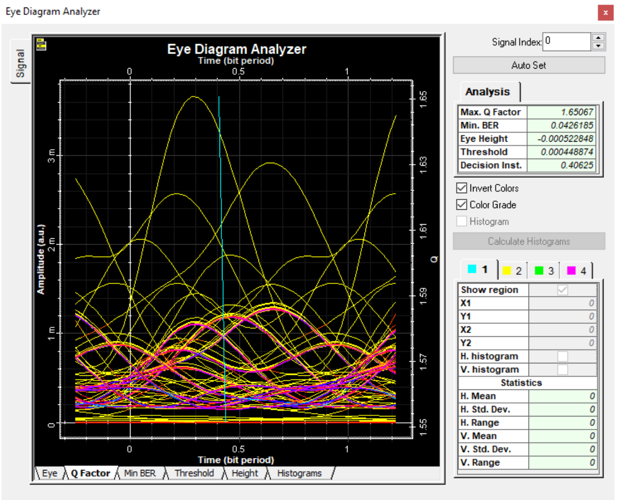
Fig. 6 summarizes measurements for the 32-bit/symbol PAM case, showing a maximum soliton power of –32.74 dBm and noise power of –103.20 dBm. Across all cases, the trend indicates that increasing bits per symbol in PAM leads to a reduction in soliton peak power.

Fig. 7–12 provide theoretical results for maximum Q-factor and total electrical power in soliton PAM systems with an inline SOA at varying injection currents over a 200 km fibre span.

Fig. 7 reports results for a soliton PAM system at 30 mA SOA injection current over a 200 km fibre span, yielding a peak Q-factor of 1.65 and a minimum BER of 0.0426185.

Under identical conditions, Fig. 8 shows total electrical power measured at 336.64×10^{-9} W (–34.72 dBm).

When the SOA injection current is increased to 65 mA (Fig. 9), the Q-factor reaches 2.261, with the corresponding BER improving to 0.0110558


Eye Diagram Analyzer

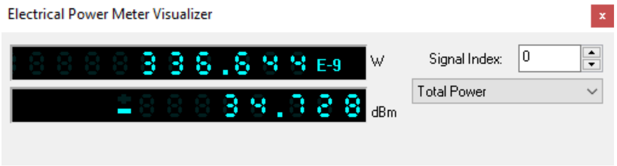
Signal Index: 0

Analysis	
Max. Q Factor	1.65067
Min. BER	0.0426185
Eye Height	-0.000522848
Threshold	0.000448874
Decision Inst.	0.40625

☑ Invert Colors
☑ Color Grade
☐ Histogram

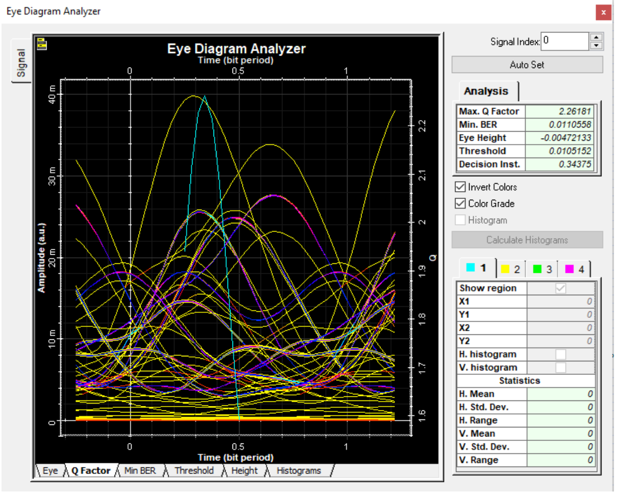
Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0

Fig. 7. Maximum Q-factor for a soliton PAM modulation scheme with a 30 mA SOA injection current over a 200 km fibre length


Electrical Power Meter Visualizer

336.644 E-9 W
-34.728 dBm
Signal Index: 0
Total Power

Fig. 8. Total electrical power for a soliton PAM modulation scheme with a 30 mA SOA injection current over a 200 km fibre length


Eye Diagram Analyzer

Signal Index: 0

Analysis	
Max. Q Factor	2.26181
Min. BER	0.0110558
Eye Height	-0.00472133
Threshold	0.0105152
Decision Inst.	0.34375

☑ 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

Fig. 9. Maximum Q-factor for a soliton PAM modulation scheme with a 65 mA SOA injection current over a 200 km fibre length

Fig. 10, for the same case, indicates a total electrical power output of 155.593×10^{-6} W (–8.08 dBm).

At 100 mA SOA injection in Fig. 11, the maximum Q-factor is 2.544, and the BER drops to 0.00523929. The associated total electrical power, shown in Fig. 12, is recorded at 1.2 mW (0.858 dBm).

Electrical Power Meter Visualizer

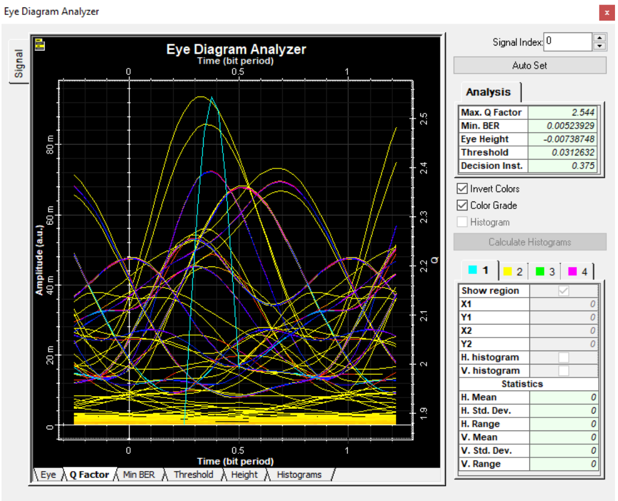
155.593 E-6 W

-8.080 dBm

Signal Index: 0

Total Power

Fig. 10. Total electrical power for a soliton PAM modulation scheme with a 65 mA SOA injection current over a 200 km fibre length



Signal Index: 0

Analysis

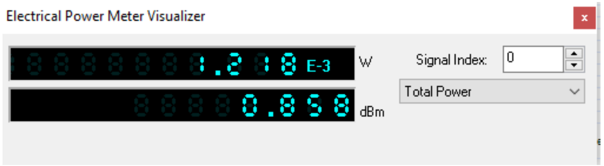
Max. Q Factor	2.544
Min. BER	0.00523929
Eye Height	-0.00738748
Threshold	0.0312632
Decision Inst.	0.375

☑ Invert Colors
☑ Color Grade
☐ Histogram

🟦 1 | 🟨 2 | 🟩 3 | 🟪 4

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

Fig. 11. Maximum Q-factor for a soliton PAM modulation scheme with a 100 mA SOA injection current over a 200 km fibre length



Electrical Power Meter Visualizer

1.218 E-3 W

0.858 dBm

Signal Index: 0

Total Power

Fig. 12. Total electrical power for a soliton PAM modulation scheme with a 100 mA SOA injection current over a 200 km fibre length

3. Conclusions

This work presents detailed modelling and evaluation of soliton-based pulse amplitude modulation (PAM) in optical communication systems employing semiconductor optical amplifiers (SOAs) under varying injection current conditions. Preliminary discussion covered key advancements in optical amplification, including hybrid optical designs, doped fibre amplifiers, and reflective SOAs, with emphasis on their role in addressing issues such as modulation bandwidth limitations, gain variation, and overall system capacity.

Simulation outcomes revealed a clear link between PAM modulation order and achievable maximum soliton power: as the number of bits per symbol increases, the maximum soliton power attainable over a 200 km span decreases. Analysis of SOA injection currents showed a performance trade-off – higher currents increase electrical output power but reduce Q-factor, while lower currents provide improved Q-factor values.

Overall, both the choice of PAM modulation order and the tuning of SOA operating parameters must be balanced to optimize transmission quality, power efficiency, and spectral efficiency in long-haul soliton-based optical networks. The insights gained here can guide the design of future high-capacity, long-distance systems, where the nonlinear pulse dynamics are influenced by both the inherent sources of nonlinearity and the nonlinear behaviour of the amplifiers that form a critical part of the link.

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