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Energy Efficient Optical Access Networks Incorporating FBGs and SOAs

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Abstract: This study uses a semiconductor optical amplifier (SOA) and fibre Bragg gratings to demonstrate an economical and energy-efficient hybrid W/TDM-PON. By providing 10 Gb/s and 1 Gb/s data rates per ONU, system load is managed and a Resource application on demand operation is made possible. The network has a capacity of 80 Gb/s upstream and 160 Gb/s downstream. By just turning on the necessary 10 Gb/s transmitters and using 1 Gb/s transmitters when greater speeds are not needed, energy usage may be decreased. Four-wave mixing in the SOA generates upstream wavelengths, and even in the event of transmitter or receiver failure, the system continues to function. The Q-factor and BER are used to compare the performance of SOA and EDFA.

Index Terms – SOA, FBG, EDFA, ONU, W/TDM-PON.

I. INTRODUCTION

The rapid proliferation of high–data-rate applications and bandwidth-intensive services has significantly increased energy consumption in optical communication networks. The information technology sector alone accounts for nearly 10% of the total energy consumption across all industries [1]. The increasing energy demand of modern optical networks is becoming difficult to sustain using limited natural energy resources. To achieve energy efficiency, two primary approaches are commonly considered: (1) deploying cloud infrastructure and data servers in remote locations, and (2) maximizing the utilization of already deployed renewable energy sources [2]. However, installing cloud servers in remote areas is not feasible for all regions, and renewable energy generation is inherently constrained by resource availability. Owing to these limitations, optimal utilization of existing renewable energy resources emerges as a more practical and effective solution. This approach also offers additional benefits, including reduced greenhouse gas emissions and a lower environmental impact [3].

Moreover, the rapid expansion of internet-based applications has led to an unprecedented demand for high data rates. Such massive bandwidth requirements can be efficiently supported by passive optical networks (PONs), particularly 10 Gb/s PON architectures. From an energy-saving perspective, PONs are among the most efficient access technologies, and intelligent resource allocation can further enhance their energy efficiency [5]. Passive optical networks offer several advantages, including high-capacity data transmission and low power consumption. A typical PON architecture comprises a central office, commonly referred to as the optical line terminal (OLT), an optical distribution network (ODN), and end-user devices known as optical network units (ONUs) [6]. Passive optical networks employ various components to perform different functions, including arrayed waveguide gratings (AWGs) and passive optical splitters. Among access technologies, fiber-to-the-home (FTTH) is widely adopted and predominantly relies on time-division multiplexed PONs (TDM-PONs) [7]. However, TDM-PONs suffer from limitations such as time skew and scalability issues, making them less efficient compared to wavelength-division multiplexing (WDM)–based systems. To exploit the advantages of both approaches, hybrid WDM–TDM PON architectures have emerged as a promising solution [8].

Several studies have reported hybrid WDM/TDM-PON systems [9], [10]. Although energy-efficient schemes have been proposed in [10] and [11], these approaches do not optimally utilize network resources. Consequently, improving energy efficiency while ensuring efficient resource utilization remains a key challenge in PON design.

This work presents a distance-extended, energy-efficient, and cost-optimized hybrid passive optical network achieved through the integration of various optical amplifiers along the transmission link. The proposed architecture supports a Resource application on demand service model. Since high–bit-rate transmission incurs substantially higher energy consumption, considerable energy savings are realized by dynamically provisioning lower data rates whenever feasible.

II. Principle Operation

As illustrated in Fig. 1, the proposed hybrid TDM/WDM-PON architecture emphasizes efficient utilization of central office resources. The outputs of 10 Gb/s transmitters are grouped into 4–4 wavelength pairs using fiber Bragg gratings (FBGs), with each wavelength carrying 10 Gb/s data and subsequently amplified by a semiconductor optical amplifier (SOA). Owing to the simultaneous propagation of multiple channels, four-wave mixing (FWM) in the SOA generates additional spectral components. Consequently, the first and fourth ports of the arrayed waveguide grating (AWG) deliver eight 10 Gb/s wavelengths along with two 1 Gb/s wavelengths, while the second and third ports are processed similarly.

Each optical distribution network (ODN) thus receives two wavelengths from each transmitter module. The operating frequencies span from 193.1 THz to 194.5 THz, with two wavelengths dedicated to 1 Gb/s transmission. As a result, each ODN supports an aggregate downstream capacity of 80 Gb/s from eight 10 Gb/s channels, in addition to 2 Gb/s from 1 Gb/s transmitters. The signals propagate over 60 km of SMF-28 fiber, and at the user end, FBGs are employed for wavelength selection. A 1×32 power splitter enables connectivity for 32 ONUs, each receiving eight wavelengths and dynamically tuning to the required data rate.

When incremental bandwidth demand arises, 1 Gb/s wavelengths are allocated instead of activating additional 10 Gb/s channels, thereby conserving energy. Transmitter ON/OFF control is managed at the optical line terminal via the medium access control layer. Furthermore, FWM in the SOA enables upstream wavelength generation without requiring additional laser sources, significantly enhancing cost efficiency. The use of compact, low-cost, and monolithically integrable FBGs and SOAs ensures minimal system complexity. The architecture is inherently flexible and resilient, as failed transmitter units can be compensated by available wavelengths from other modules, thereby improving bandwidth scalability, reliability, cost effectiveness, and energy efficiency.

III. Simulation Setup

Figure 1 illustrates the proposed energy-efficient and cost-effective hybrid TWDM-PON architecture. To realize energy conservation, two categories of transmitters—symmetrical and asymmetrical—are integrated into the system. A total of sixteen 10 Gb/s transmitters are deployed for symmetrical transmission, while four additional 1 Gb/s transmitters operate in an asymmetrical standby mode to provision incremental bandwidth on demand. Fiber Bragg gratings (FBGs) are positioned at the transmitter outputs to selectively reflect designated wavelengths, which are subsequently aggregated using power combiners. The operating frequencies associated with each combiner are specified as follows: the first combiner operates at 193.1, 193.5, 193.9, and 194.3 THz; the second at 193.2, 193.6, 194.0, and 194.4 THz; the third at 193.3, 193.7, 194.1, and 194.5 THz; and the fourth at 193.4, 193.8, 194.2, and 194.6 THz. The 1 Gb/s standby transmitters operate at 193.0 and 192.9 THz.

A semiconductor optical amplifier (SOA) is placed after each combiner to provide signal amplification and to induce four-wave mixing (FWM), thereby generating additional carrier frequencies for upstream transmission. This nonlinear wavelength generation obviates the need for dedicated upstream laser sources, leading to significant cost savings.

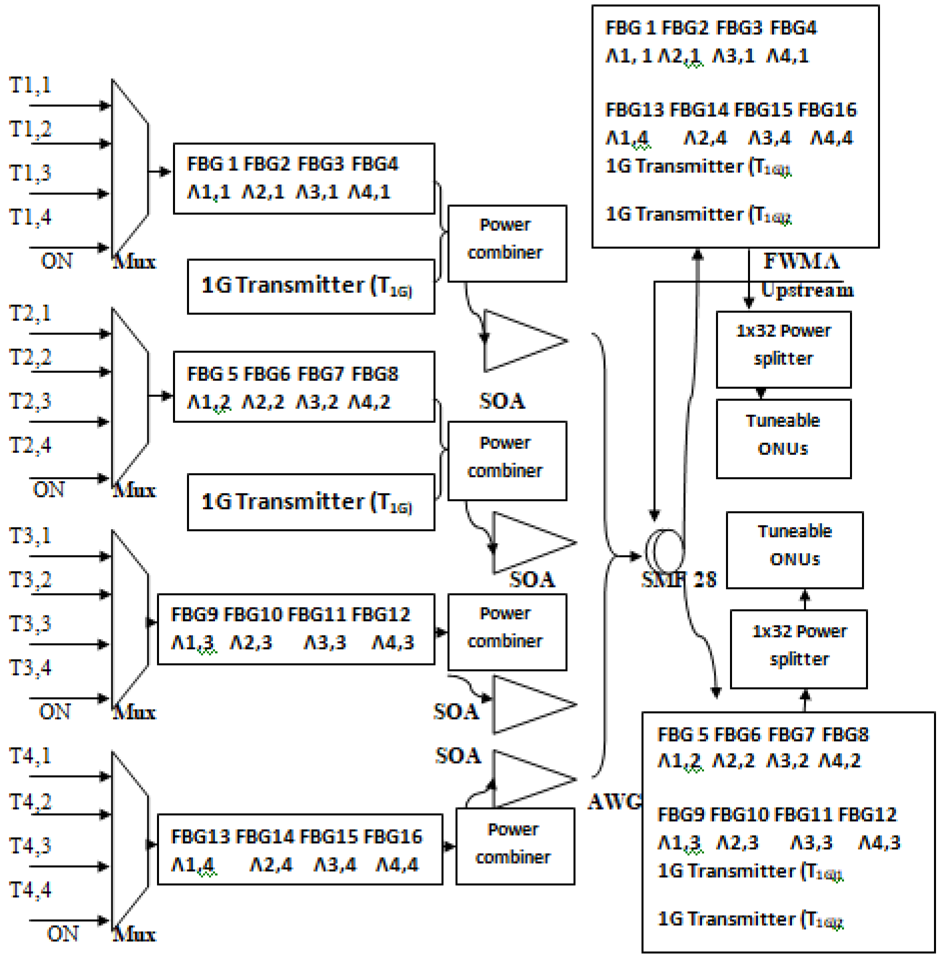


Figure 1 Proposed Energy efficient optical access network

A 4×4 AWG, driven by four SOAs, routes distinct wavelength sets to output ports 1–4. Output ports 1 and 4 carry wavelengths at 193.1, 193.3, 193.5, 193.7, 193.9, 194.1, 194.3 THz, along with the 1 Gb/s standby wavelengths at 193.0 and 192.9 THz. Output ports 2 and 3 deliver the complementary set at 193.2, 193.4, 193.6, 193.8, 194.0, 194.2, 194.4, and 194.6 THz, in addition to the 1 Gb/s channels.

The multiplexed signals are transmitted over 60 km of SMF, with both erbium-doped fiber amplifiers and SOAs deployed before the fiber for performance evaluation. At the receiver end, wavelength-selective FBGs isolate the desired channels. Upstream transmission exploits FWM-generated wavelengths, which are filtered by FBGs and conveyed over 60 km SMF to a single photodiode-based receiver.

IV. RESULTS AND DISCUSSIONS

Figure 2 illustrates the optical spectra captured using an optical spectrum analyzer (OSA) at various stages of the proposed system. The grouped 4–4 wavelength outputs corresponding to each 10 Gb/s transmitter module are depicted in Fig. 2(a)–2(d). The combined spectra measured at the output of each power combiner are presented in Fig. 2(e)–2(h). Following amplification in the SOA and the onset of nonlinear four-wave mixing (FWM), newly generated spectral components suitable for upstream transmission are observed, as shown in Fig. 2(i)–2(l).

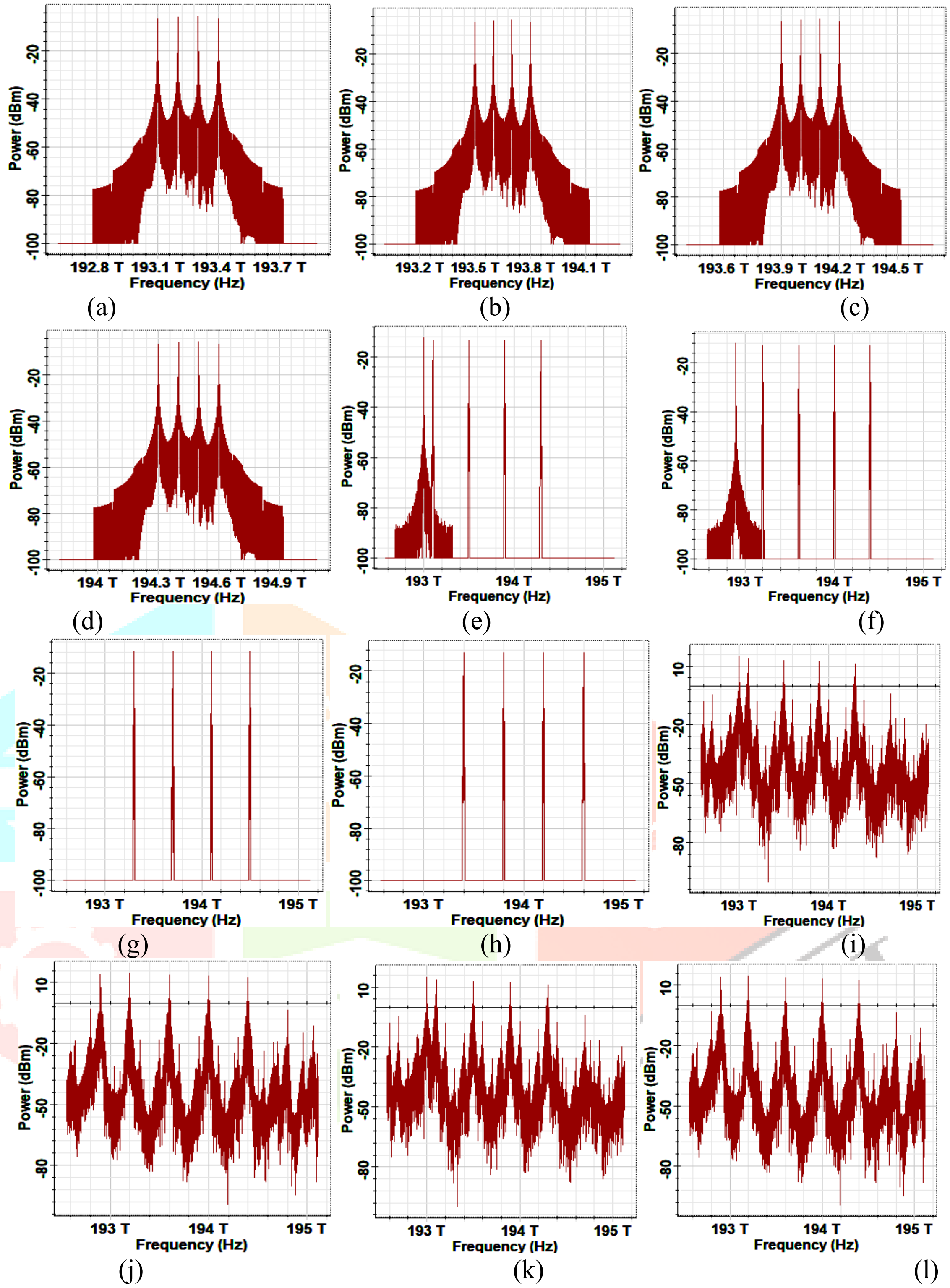
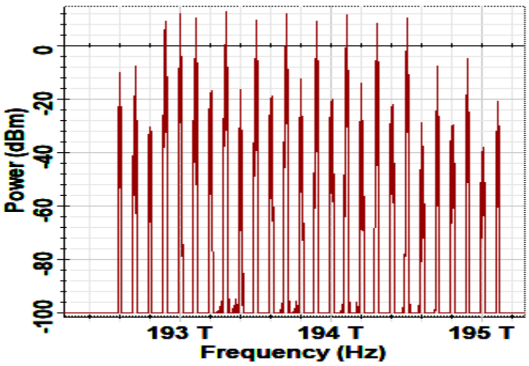
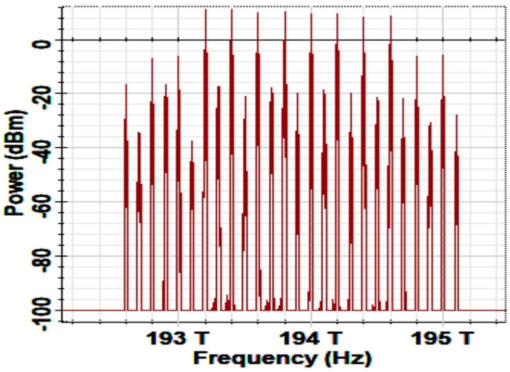


Figure 2 presents the optical spectrum analyzer (OSA) outputs at different stages of the system. Spectra corresponding to transmitter modules 1–4 are shown in Fig. 2(a)–2(d), respectively. The spectra obtained after the FBG stages for wavelength groups 1–4, 5–8, 9–12, and 13–16 are illustrated in Fig. 2(e)–2(h), respectively. Finally, the spectra observed after SOA amplification for modules 1–4 are depicted in Fig. 2(i)–2(l).

Following amplification in the semiconductor optical amplifier (SOA), the optical signals are routed to the arrayed waveguide grating (AWG) for wavelength demultiplexing. The resulting optical spectra at the AWG output ports are analyzed using a WDM analyzer. The measured spectra corresponding to the 1st and 4th output ports are presented in Fig. 3(a), while those of the 2nd and 3rd output ports are shown in Fig. 3(b), demonstrating effective wavelength separation and distribution across the AWG ports.



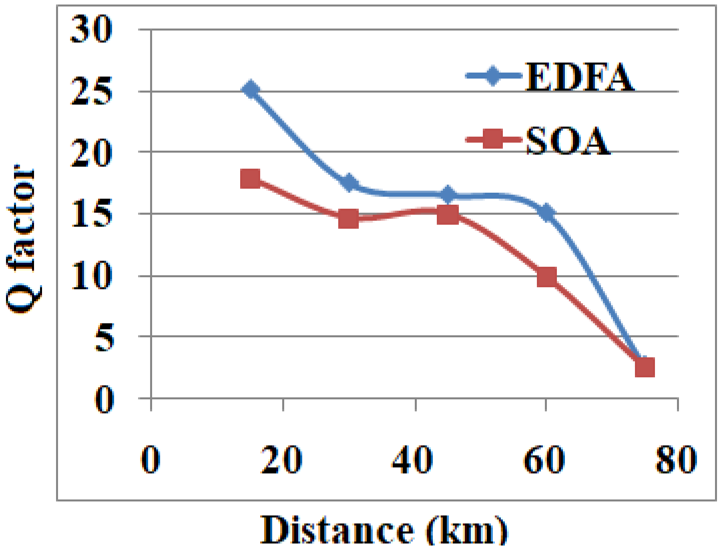
(a)



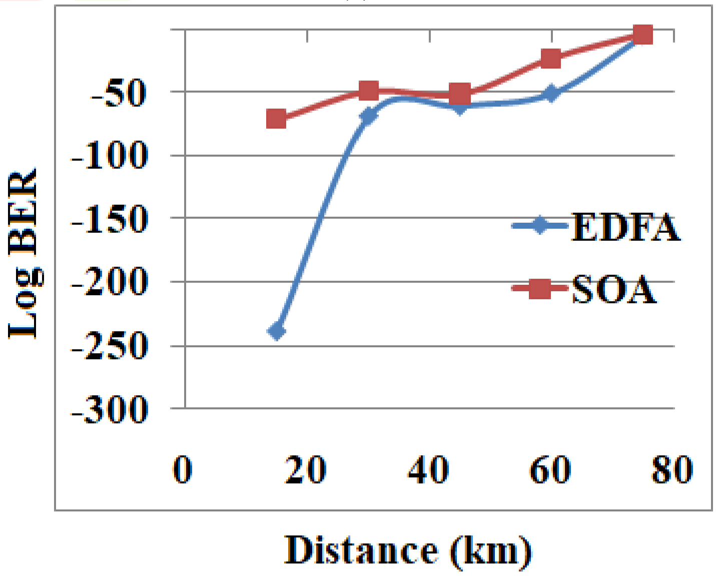
(b)

Figure 3 AWG output spectrums at (a) (b) 1st-4th port (c) (d) 2nd-3rd port

Figure 4(a) illustrates system performance at an aggregate data rate of 40 Gb/s delivered to the ONUs. As transmission distance increases, a pronounced degradation in performance is observed. The Q-factor is evaluated for link lengths ranging from 15 km to 75 km, revealing reliable operation up to 60 km within acceptable Q-factor limits when an EDFA is employed. The superior performance of the EDFA over the SOA is attributed to its favorable gain characteristics and noise performance in the C-band. Figure 4(b) presents the corresponding bit error rate (BER) analysis for 40 Gb/s transmission. As expected, BER deteriorates with increasing fiber length. Log-BER measurements across 15–75 km confirm that error-free operation is sustained up to 60 km using an EDFA, remaining within permissible BER thresholds.



(a)



(b)

Figure 4 Investigation and outcomes in terms of (a) Q factor (b) Log BER using EDFA/SOA

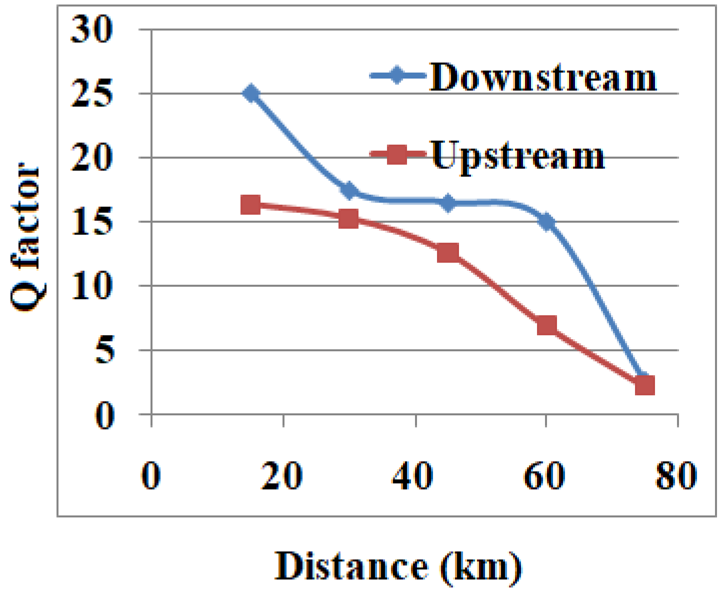


Figure 5 Performance comparisons of downstream/upstream in terms of Q factor

Figure 5 illustrates the downstream and upstream performance of the proposed hybrid WDM–TDM PON. The downstream exhibits a higher Q-factor than the upstream, primarily due to the superior signal integrity and controlled operating conditions of the OLT at the central office. Although the upstream wavelengths are generated via four-wave mixing in the SOA, they remain within acceptable Q-factor limits over a 60 km link when an EDFA is employed in the transmission line.

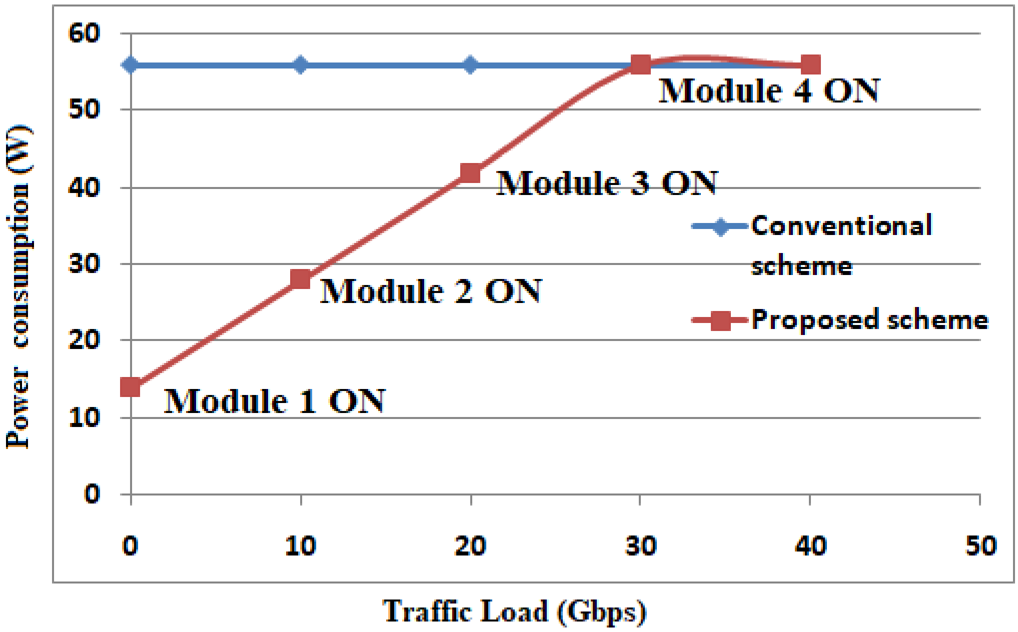


Figure 6 Energy efficiency comparisons of proposed and conventional scheme

Figure 6 shows the comparisons of proposed system where system remains active depending on the load received and therefore saves high amount of energy. On the other hand, in conventional systems, where all OLTs remain active for all the time and therefore, waste high amount of energy.

V. CONCLUSION

This work proposes a performance-enhanced and energy-efficient hybrid TWDM-PON employing EDFA and SOA amplification. Traffic demand is adaptively managed by provisioning dual data rates of 10 Gb/s and 1 Gb/s per ONU, enabling a resource allocation on demand operating paradigm. The architecture supports an aggregate capacity of 160 Gb/s in the downstream and 80 Gb/s in the upstream direction. Four 1 Gb/s standby transmitters provide supplementary bandwidth when high-rate transmission is unnecessary, thereby reducing power consumption. A key contribution of the proposed system is the selective activation of OLT transmitters, with inactive units maintained in the OFF state to enhance energy efficiency. Simulation results demonstrate superior downstream performance compared to the upstream, with reliable operation over 60 km. Furthermore, a comparative energy-efficiency analysis confirms that the proposed scheme achieves substantial power savings over conventional architectures.

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