WWJMRD 2022; 8(09): 24-29
www.wwjmrd.com
International Journal
Peer Reviewed Journal
Refereed Journal
Indexed Journal
Impact Factor SJIF 2017: 5.182 2018: 5.51, (ISI) 2020-2021: 1.361
E-ISSN: 2454-6615

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Theoretical Review of Semiconductor Optical Fibre Amplifiers

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Abstract
In this paper, a theoretical review of semiconductor optical fibre amplifiers is reported. Semiconductors are formed from compounds in group III and IV of the periodic table. They have indirect band gap and possess the ability to emit light rather than heat. Here, a detailed theoretical review of semiconductor optical fibre history, principle of operation, types of semiconductor optical fibre amplifiers and their applications are presented.

Keywords: Semiconductor, Optical fibre, Theoretical review, amplifier.

1. Introduction

Semiconductor optical amplifiers are fabricated from compounds in group III and V of the periodic table called semiconductors. These compounds are indirect band gap materials which have the potency to give out light rather than heat. Indirect band gap materials are made by a combination of group III and V compounds. These compounds range from binary, ternary and quaternary combinations of elements such as GaAs/AlGaAs, InP/InGaAs, InP/InGaAsP, and InP/InAlGaAs. The utilization of semiconductor optical amplifiers (SOAs) in communication systems has received astonishing breakthroughs in the communication industry. This was spurred by the advent of the semiconductor injection laser. This is a p-n junction with a thin layer of a distinct semiconductor material sandwiched between the p-type and n-type regions [1]. The semiconductor material forms the active region. Materials used for active regions have higher refractive indices which help confine the light during amplification. Amplification is deemed to take place when light propagates through the active region. Semiconductor optical amplifiers like the laser diodes gives out a positive gain through external current injection. Signal regenerators are often needed to surmount problems inherent in optical communication networks such as inherent transmission losses, distribution losses, fibre absorption and scattering, connector and component losses. Typical regenerator works on the underlying concept of optoelectronic conversion in which the optical signal is periodically converted to an electronic signal, re-modulated onto a new optical signal, and retransmitted onto the next fibre link. A repeater is added when the optical power in a link gets to the minimum detectable level. The repeater performs photon-to-electron conversion, electrical amplification, pulse shaping, and finally electron-to-photon conversion. This process is more complicated and expensive for high-speed multi-wavelength systems. This bottleneck motivated a great deal of effort in all-optical amplifiers, which operate completely in the optical domain as wide area all-optical networks cannot exist without optical amplifiers. An effective approach is the use of optical amplification-based repeaters. Optical repeaters amplify the input signal directly without photon-electron conversion. This approach provides better advantages such as longer repeater spacing, simultaneous multichannel application, and a bandwidth proportionate to the transmission window of the optical fibre. The application of optical amplifiers in operational networks has reduced maintenance costs and established a path for improving the existing fibre plants as both amplifiers and fibres are both transparent to signal bandwidth [2-3].

Two classes of optical amplifiers are applied in fibre-based systems: active fibre amplifiers and semiconductor amplifiers (SOAs). Fibre based amplifiers have progressed more rapidly in the deployment phase because of their high output saturation power, high gain, polarization insensitivity, and long excited state life time that reduces crosstalk effects. Fibre amplifiers have been efficiently used in the 1.55µm fibre optics transmission window but not ideally compatible for the 1.31µm fibre optics transmission window.

Recent applications in SOAs have actually led to remarkable improvements in gain, saturation power, polarization sensitivity, and crosstalk rejection. Semiconductor optical amplifiers possess unique properties that make their application in optical networks so appealing: their flat gain bandwidth ranges over a relatively wide wavelength that allows them to concurrently amplify signals of different wavelengths, these devices are not complex and can be integrated with semiconductor devices, switching of gain at high speed to provide modulation function is achievable, and monitored current to provide simultaneous amplification and detection. Progressively, interest in semiconductor amplifier studies has been projected by their efficacy to operate in the 1.3µm fibre optics transmission window. Hence, semiconductor optical amplifiers remain a significant research area and offer a complementary optical amplification to fibre-based amplifiers [1].

1.1. History of Semiconductor Optical Amplifiers

The first fundamental studies of SOAs were put into effect at about the time the invention of the semiconductor laser was accomplished in the 1960s. Typical studies were made using GaAs homo-junctions operating at low temperatures. The attainment of double hetero-structure devices motivated further investigation into the application of SOAs in fibre optics communication systems. During the 1970s pioneering work on SOAs was carried out by Zeidler and Personick [1-2]. The development of SOAs recorded significant advances in devices and modelling of the noise characteristics of optical amplifiers [1-2]. One of these advances was the first realization of a broad-band travelling wave amplifier at a 1.5µm wavelength [3] was a remarkable step which has contributed to the enormous increased interest in semiconductor laser optical amplifiers. Early studies focussed on AlGaAs SOAs operating in the 830nm range [2]. In the late 1980s studies on InP/InGaP SOAs were designed to operate in 1.3µm and 1.5µm region. It was the developments in anti-reflection coating technology that enhanced the fabrication of true travelling-wave semiconductor optical amplifiers. Before 1989, SOAs structures were based on anti-reflection coated semiconductor laser diodes but these devices had an asymmetrical waveguide structure leading to a strong polarization sensitive gain. In 1989 SOAs were designed as devices in their own right, with the use of more symmetrical waveguide providing much better polarization sensitivities [4-8]. With regards to that, SOA design and development has recorded fascinating advancement in conjunction with stride in semiconductor materials, device fabrication, antireflection coating technology, packaging and photonic integrated circuits, to an extent where efficient cost competitive devices are now available for application in optical communication systems. The ongoing development in SOA technology attracts interest in functional applications such as photonic switching and wavelength conversion. The use of SOAs in photonic integrated circuits (PICs) is also a captivating research area. Semiconductor optical amplifier is of small size and electrically pumped. It is relatively less expensive than EDFA (Erbium Doped Fibre Amplifier) and can be integrated with semiconductor lasers, modulators, and the performance is still not comparable with EDFA. Semiconductor optical amplifier has higher noise, lower gain, moderate polarization dependence and high nonlinearities with fast response time [4]. This originates from short pulses in the range of nanoseconds to picoseconds with less upper state lifetime, which makes the gain to react rapidly to changes of pump or signal power and the changes enhances phase changes which distort signals. However, SOA technology is advancing rapidly. The nonlinearity presents the most severe problem for optical communication applications but provides the possibility for gain in different wavelength regions from EDFA using the gain clamping techniques. High optical nonlinearity makes semiconductor amplifiers an exciting field of study for all-optical signal processing like all-optical switching, wavelength conversion, clock recovery, signal de-multiplexing, and pattern recognition. SOAs are compatible with monolithic integration (low-cost potential) and offer a wide range of variations, including optical signal processing that cannot be performed by fibre amplifiers [4-10]. It has been envisaged that the development of SOAs in evolving optical communication networks will increase.

It was predicted that the consumption of SOAs will expand rapidly from $48 million in 2000 to $903 in 2010 [1-17]. The basic use of SOAs will be as amplifiers in wavelength division multiplexed (WDM) and other digital optical communication links, and as switching elements in all-optical switches and cross-connects. The future of SOAs is promising, and even more applications of the device emerge as the technology evolves towards full development and manufacturing costs decreases.

2. Principle of Semiconductor Optical Amplifiers

A semiconductor optical amplifier is based on the principle of stimulated emission of the injection laser diode which has a shorter lifetime than the spontaneous emission on which light emitting diodes are based. This is due to colliding of input photons and excited state electrons. In thermal equilibrium the charge density of electrons in the upper level of interest is typically negligible. It is generally acknowledged that an input photon would be absorbed rather than stimulate an emission. The semiconductor can be analysed as a two-energy level system, lower energy level ground state (valence band) and higher energy level excited state (conduction band). In thermal equilibrium conditions which is given by Boltzmann distribution, the system with a lower energy level have more electrons than the upper energy level as this is a normal condition for semiconductor materials at room temperature. In order to obtain optical amplification, it is indispensable to create a non-equilibrium distribution of atoms thus the population inversion of the upper energy level greater than that of the lower energy level ($N_2 > N_1$). However, to achieve population inversion it is germane to excite atoms into the upper energy level creating a non-equilibrium distribution. This is achieved via the use of external energy source which is referred to as 'pumping'. A well-known approach used for pumping involves an application of intense radiation from an optical tube or high

radio frequency field. The pump injects current into the semiconductor to provide excess of electrons in the conduction band (population inversion).
When an incident photon is fired externally into the amplifier it creates recombination of electron in the conduction band with a hole in the valence band, which results to emission of a second photon identical to the incident photon (stimulated emission) if the gain medium is long enough. This means that the input photon is an exact replica of the output signal as both has identical properties (frequency, phase, direction and polarization). When these photons propagate in the semiconductor, the spontaneous emission process effectively occurs over and over again creating avalanche multiplication which leads to amplification of the input signal (incident photon) which is an optical input. Optical gain can be assigned to an SOA because it can amplify input photons. The optical material gain is exclusively a function of the operating conditions and basic device composition. However, the amplifier gain defines the relationship between the output and input optical power. Besides the amplification of the input photons, there is need to put into consideration how noise is generated within the amplifier when an electron in the higher energy state spontaneously recombines with a hole in the lower energy state without the aid of an incident photon and is called spontaneous emission. Spontaneous emission results in an emitted photon having energy that is equal to the difference between the electron and a hole. Photons generated from spontaneous emission will experience gain through simultaneous emission after been propagated in the amplifier. This amplification of spontaneous emitted photons is called amplified spontaneous emission (ASE), ASE is a noise mechanism which is related to the incident photon and is a random process. It also takes away amplifier gain that should be available to the signal.

2.1. Types of Semiconductor Optical Amplifiers

The operation of SOAs is based on the laser structure of a conventional semiconductor having its output facet reflectivity between 30 and 35% [4-5]. These amplifiers can be utilized for linear and nonlinear operations. We can classify SOAs as sub-threshold or gain clamped. Amplifiers operated below threshold are known as sub-threshold amplifiers while the gain clamped amplifiers are those operated above threshold. The sub-threshold SOAs can be further classified in accordance to the presence of feedback in its design. SOAs that amplify the optical signal in a single pass are the travelling wave amplifier (TWA) and the near travelling wave amplifier (NTW). These amplifiers have the potential to provide high internal gain (15 to 35dB) with low power consumption and due to their single mode waveguide structure, they are efficiently used in single mode fibre. The resonant amplifier is the second type of sub-threshold amplifier which possesses a gain medium and some form of optical feedback. For a resonant amplifier the gain is enhanced resonantly at the expense of the gain bandwidth been limited to a value less than that of the TWA for an equivalent material. Semiconductor optical amplifiers can nonetheless be classified into two major groups which are the travelling wave amplifiers and Fabry-Perot amplifiers (FPAs). We can define an FPA as a resonant amplifier with facet reflectivity between 0.01 and 0.3 [1]. These amplifiers were previously referred to as semiconductor laser amplifiers (SLAs) or semiconductor laser optical amplifiers (SLOAs). The SOA terminology was used initially for TWAs but has more recently been employed to describe Fabry-Perot and injection current distributed feedback laser amplifiers. The Fabry-Perot amplifier is a resonant cavity as it has mirrors at the input and output of its ends. An optical comb filter is created by the resonant cavity that filters the gain profile of the amplifier into uniformly spaced longitudinal modes. A travelling wave SOAs can be formed by the application of antireflection coatings to the facets of the mirrors to minimize or eliminate the end reflectivity. This is obtainable by adding deposits of silicon oxide, silicon nitride or titanium oxide on the end facets in order to reduce the reflectivity to 1×10^4 or less. The device becomes a TWA operating in the single pass amplification mode in which the Fabry-Perot is suppressed by the facet reflectivity reduction. Due to this effect, there is substantial increase in the amplifier spectral bandwidth which makes the transmission characteristics less dependent on the fluctuations in the bias current, temperature and signal input polarization. However, the FPA proves inferior to the TWA (specifically for linear applications) and more advantageous in signal gain saturation and noise characteristics [3].
The material gain limits the TWA configuration bandwidth which is relatively flat and is desirable for optical communications system application. Typically, 3dB bandwidths are of the range of 60-100nm. The Fabry-Perot amplifier experiences very large gain at wavelengths corresponding to the longitudinal modes but it rapidly decreases when there is an offset of the peak wavelengths by the input wavelength. This is responsible for the gain been strongly dependent on the input wavelength and sensitive to changes that may take place in an optical communications system.
Gain-clamped semiconductor optical amplifiers is based on the principle of the gain been kept constant through a primary lasing mode and the strength of the signals can be increased if their wavelength is kept far away from the main lasing mode. The distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers which laze into a single longitudinal mode are laser structures suitable for this application. It is obvious that only a single mode oscillates, thus the remainder of the gain profile becomes useful for amplification. The gain clamped amplifier is advantageous in crosstalk reduction and in multichannel amplifications [3].

3. Applications Of Semiconductor Optical Amplifiers

The applications of semiconductor based optical amplifiers can be divided into two namely: system applications and functional applications. In this report we are going to explore these applications explicitly starting with the system applications of semiconductor optical amplifiers.

3.1. System Applications

There are three main system applications for the semiconductor based optical amplifiers. Their classification is based on three classical ways of providing optical gain. These applications are: optical power amplifier (or booster amplifier), optical preamplifier and the optical in-line amplifier. The optical power amplifier is placed immediately after transmitter to effectively increase transmitted power and related variant is an amplifier placed immediately before a power splitter in a passive optical distributed network (PON). Secondly, we have the optical preamplifier which is placed before the receiver to increase receiver power and boost receiver performance and thus aid detection of transmitted signal at the receiver. This effectively improves receiver sensitivity to the amplified spontaneous emission (ASE) noise which is inherent in WDM (wavelength division multiplexed) networks. Finally, optical in-line amplifier is placed periodically along the transmission line to compensate for fibre loss along propagation path. This can often be arranged in either preamplifier or booster amplifier configurations [1-4]. Power amplifiers are utilised for boosting the output power of a transmitted signal. In its application as a pre-amplifier, the optical signal is increased immediately it arrives at the photo-detector thus improving the sensitivity of the receiver. The optical in-line amplifier operates as a single repeater in application and provides gain to increase the detectable loss between the transmitter and receiver. For optimum design of amplifier there is need to know the applications required for the design as application depends on the design. The most significant parameter required for the design of a power amplifier is the output saturation power. It was recently proven that amplifiers made up of multi-quantum-well (MQW) active regions possess large saturation output powers of about 50mW [5]. Multi-quantum-well (MQW) amplifier has a very strong polarization dependence gain which may not be considered in power amplifier application because in this case, the amplifier may be connected to the transmitter having a polarization preserving fibre pigtail. It was recently observed that the introduction of stress in the active region of a MQW amplifier will result to the modification of TE and TM gain characteristics which give polarization independent gain over some wavelength range [6]. The most significant amplifier parameters deployed for pre-amplifier applications are the noise figure and the input coupling efficiency. The receiver sensitivity of the system is directly proportional to both the noise figure and input coupling efficiency.

A semiconductor optical power amplifier chip with a saturation power of $20.2\ dB$ was demonstrated to operate over the entire C-band. This is a booster amplifier used in 10Gbps propagation experiment to cover $80\ km$ of a single mode fibre. It is apparent that the need for optical amplification increases as the complexity and functionality of WDM systems increases. Erbium doped fibre amplifiers (EDFAs) has been enhancing the improvement of amplification gain in complex WDM networks. Hence, optical amplification has been utilized in booster and in-line applications such as loss compensators for chromatic and dispersion compensators. They have also been put into use as pre-amplifiers for detection of high gain sensitivity at the receiving end of the WDM network. Advanced application comprises of reconfigurable add-drop multiplexers and dynamic gain equalization. Due to recent developments, there has been great pressure associated with reducing the cost of optical components as lower cost optical amplifiers have been introduced to the market. These components are mainly erbium doped waveguide amplifiers (EDWAs) and semiconductor optical amplifiers (SOAs). SOAs are utilized in booster applications for increasing the power of a specific frequency and tuneable semiconductor laser i.e., tuneable vertical cavity surface emitting laser (VCSELS) and as in-line amplifiers. High saturation power and noise figure is required to preserve the signal quality of the incident beam over the entire C-band for the above applications. Recently, high saturation power SOAs have been discussed [1-2]. It was observed that an ultra-high saturation power ($p_{sat} = 20$) semiconductor booster amplifier operating over the entire C-band will have a chip noise figure of $5.3\ dB$ constant over the C-band. When working with an operating current of $0.5\ \mu A$ the small signal gain obtained was as $17\ dB$. A flat gain is obtained to better than $1\ dB$ over the entire C-band. Due to the operation of the optical booster amplifier, it was observed that the amplifier behaves linearly. Penalty of less than $0.3\ dB$ was achieved in the bit error rate (BER) when transmitting a pseudorandom bit sequence of length $2^{31} - 1$ at $10\ Gbps$ through the booster amplifier which is in disparity with recent comments that gain clamping is unique in SOAs for achieving linear properties [3]. It was observed that in $80\ km$ single mode transmission experiment a signal boosted by a semiconductor optical amplifier exhibits a sensitivity of $2.7\ dB$ improvement over a similar measurement carried out with an erbium doped fibre amplifier (EDFA). Amplifiers are applied in three differs configurations. A power amplifier is applied after a transmitter to increase the output power. An in-line optical amplifier is typically applied in the middle of the link to compensate for link losses. Amplifier design is dependent on network configuration. An optical pre-amplifier is designed to provide high gain and the highest possible sensitivity which is a function of the BER as determined by the degradation of the amplified spontaneous emission (ASE) noise across the networks. An in-line optical amplifier is designed to provide a combination of the characteristics of the power amplifier and pre-amplifier. However, optical amplifier is never a perfect device which explains why there are major impairments that system designs should worry about when designing amplifiers for unique applications. For high power inputs the EDFAs tends to saturate which leads to gain compression and this can result to the presence of undesired transients in networks. Although, EDFAs are uniquely splendid choice for WDM systems their gain is not flat over the entire bandwidth. This is responsible for non- uniform gain distribution across the links and becomes worse when amplifiers are in cascades [10-17].

4. Optical Power Amplifier

Optical power amplifiers are positioned immediately after transmitter in order to effectively increase the transmitting power to overcome attenuation of the propagating signal. Optical amplifiers placed after the transmitter is a very significant component in WDM optical networks [1]. Semiconductor optical amplifiers are well suited for this application as they can be potentially integrated into single photonic integrated circuits which comprises of transmitter, amplifier and maybe other components.

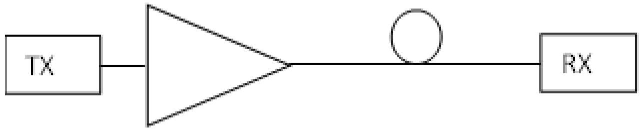

Fig. 1: Optical power amplifier configuration.

It is important that the saturation power for the power amplifier is as large as possible but it is also likely that the amplifier will perform to some level under the conditions of compressed gain. System sensitivity will be deteriorated by inter-symbol interference (ISI) at the receiver if the gain recovery time is comparable to the bit period and this is

caused by pattern –dependent gain in the amplifier [2-3]. For conventional non- quantum well semiconductor optical amplifiers, the gain recovery time has a typical value that ranges from $100 - 400\ ps$ [4], this is comparable to bit rates of $2 - 10\ GHz$ which are bit rates applicable for high-speed optical communications system. Inter-symbol interference (ISI) is usually a problem in communication system as it leads to signal distortion. To surmount inter-symbol interference, it is required that the power amplifier have a large saturation power and a rapid gain recovery time.
The above can be avoided by utilizing multiple-quantum-well (MQW) optical amplifiers which possess both features: large saturation power [5-6] and a rapid gain recovery time [7]. The optical amplifier was attributed to replenishment of carriers in the active region of the quantum well through diffusion of carriers stored in the barrier and cladding regions [7-8]. The rapid gain recovery process was exploited in an InGaAs/ InGaAsP MQW optical amplifier and was demonstrated that ISI was observed in a system operated at 8Gbps under saturated output conditions with 35Mw output power in marked contrast to the system performance of a conventional optical amplifier. The scalable approach of efficient fibre-based amplification of single frequency radiation to output powers in excess 100W was demonstrated. The master oscillator fibre power amplifier preserves excellent beam quality, efficient polarization, low noise and narrow line-width of the seed laser source [1-10].

4.1. Optical In-line Amplifier

An optical in line amplifier is placed periodically along the transmission line to compensate for fibre loss along propagation path. Its operation in application is like that of a single repeater which provides gain to increase the allowable loss between the transmitter and receiver.

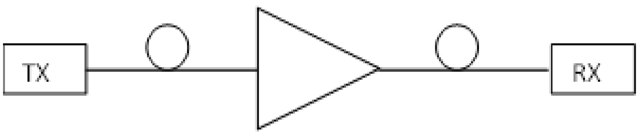

Fig. 2: Optical in-line amplifier configuration.

An experiment was carried out using an optical in-line amplifier made from a resonant amplifier with its facet reflectivity of the order $of\ 5 \times 10^{-3}$. A $400\ Mbps$ coherent system was used approximately $65\ km$ apart. Four amplifiers cascade with a total gain of $87\ dB$ was used but due to the presence of coupling losses the net gain was reduced to $47\ dB$. Despite the level of coupling losses, the amplifiers were able to enhance gain improvement to compensate for the loss in $200\ km$ of fibre which help in extending the total transmission distance to $372\ km$. Between the amplifier cascade signal power drops exponentially with distance (linear in dBs) which is due to the optical variation along the signal path. The power at each amplifier site was boosted by an equal amount to the net gain of the amplifier. Instead of using coherent detection, direct detection could be used. For instance, the same amplifiers cascade was successfully utilized in a $313\ km$ $1\ Gbit/s$ direct detection system. A disadvantage of this operation is that both distortion of signal and noise are continuously amplified as the optical signal passes down the link of cascaded amplifiers. An advantage is that optical in-line amplifiers are transparent to any form of signal modulation (i.e., analogue or digital) and to any modulation bandwidth. It is important to note that optical amplifiers act as gain blocks on a fibre optic link and do not change the transmitted optical digital signal. In travelling wave SOAs, noise present in the system may determine the number of components that can be cascaded as linear repeaters. This is because the mean noise power generated from spontaneous emission in optical amplifiers combines in proportion to the number of repeaters. Gain saturation takes place when the signal power equals the total noise power [3]. The system should be able to account for the upper limit on the number of amplifiers that can be cascaded before noise builds in the chain causes unacceptable penalties. The system noise can be analysed and the penalty is defined as the increase in the received optical power to maintain a 10^{-9} BER as a result of accumulated amplifier noise. The maximum tolerable penalty is about 2dB. An unacceptable bit-error floor develops for much larger penalties. Due to the fact that systems with amplifiers have signal dependent noise, all amplifiers are prone to bit error rate floors, but when the 10^{-9} BER penalty is less than 1dB the floor will be at an immeasurable level (less than 10^{-23}). An amplifier cascade of up to 300 amplifiers can be designed with an input power of -20dB. If an assumption of a net gain of 15dB is made for each amplifier and a fibre loss of $0.25\ dB/km$ then 300 amplifiers would allow transmission over $18000\ km$. With exception of the application of dispersion compensation techniques or dispersion shifted fibre, a system would be dispersion limited long before the above transmission distance is reached.

4.2. Optical Preamplifier

Optical preamplifiers play an influential role in the pre-amplification of optical signal in light wave receivers. Optical preamplifiers are specifically applied at high data rates. This is because the thermal noise in the receiver increases faster than the bit rate, in avalanche photo-detectors (APD) high dynamics is required. Increased avalanche gain generates excess noise which results to poor receiver performance at very high data rates.

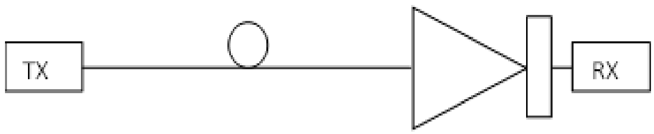

Fig. 3: optical preamplifier configuration.

A typical set up for an optical preamplifier is configuration is shown in Figure 3. A similar set-up was used in $4\ Gbps$ system operating at $1.5\ \mu m$ wavelength. The set-up used discrete lenses to couple incident light from the input fibre into the optical amplifier. A filter with optical gating is inserted between the amplifier and the receiver in order to reduce the quantity of amplified spontaneous emission (ASE) noise incident on the receiver. The set-up comprises of a very short output fibre which acts particularly as a spatial discriminator for the grating filter. The power received in the system is a measure of the input optical power in the fibre. The input coupling loss of the set-up is $5.5\ dB$ with a filter bandwidth of $10^{10}\ H_z$ and the fibre-to-fibre gain of the amplifier is $14.2\ dB$. An amplifier input power of $-34.3\ dB$ was needed to achieve a BER of 10^{-9} when the input to preamplifier receiver was a 4Gbps pseudo random data stream from a directly modulated DFB laser. The sensitivity of the receiver was $-25\ dB$ without an optical preamplifier. At aforementioned data rate the preamplifier receiver is about a factor of 2 (two) more sensitive than the best APD. The optical filter helps to reduce the bandwidth of the amplified spontaneous emission (ASE) noise at the receiver. In the absence of the optical filter the bandwidth of the optical amplifier becomes larger than the required bandwidth which leads to excess noise that will reduce the amplifier sensitivity at the receiver [1-15].

5. Conclusion

Theoretical review of semiconductor optical fibre amplifiers was carried out and reported. This was due to its significance to modern communication systems that uses optical fibre networks for telecommunications, imaging, sensing, lasers and amplifiers. For efficient and effective planning and design of an optical network, it's important to have in-depth knowledge of optical fibre operations and applications. Hence, we provide a theoretical review of its history, principles of operation, types of semiconductor optical fibre amplifiers and system applications.

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