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Semiconductor optical amplifier: An overview

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Abstract
In this paper a study of semiconductor optical amplifier (SOA) is presented. Construction and basic device characteristics are discussed in detail. The semiconductor optical amplifier is not limited to amplification purpose their functional applications are also important. Some functional applications of semiconductor optical amplifiers are also discussed. Further SOA based WDM networks and hybrid Raman/Semiconductor optical amplifier is also presented.

Keywords: Semiconductor optical amplifier, WDM networks, amplifier gain, noise

Introduction

In optical communication systems, the transmitted power is attenuated during the transmission through the optical fiber as they propagate through it. Due to the cumulative loss, the signal becomes too weak to be detected. Therefore the signal strength has to be restored before the detection. Regenerators were doing this job before the advent of optical amplifiers. Optical amplifiers offer several advantages compared to regenerators. Regenerators are specific to the bit rate and modulation format used by the communication system. Optical amplifiers are insensitive to the bit rate or signal format [1-3]. Thus a system using optical amplifiers can be easily upgraded to a higher bit rate without replacement of optical amplifiers. Further, due to large gain bandwidth of optical amplifiers, a single amplifier can amplify several wavelength division multiplexed (WDM) signals simultaneously. Contrary to this fact one regenerator is needed for each wavelength. Optical amplifiers operate completely in the optical domain to boost the power levels of lightwave signal over the two long-wavelength transmission windows of optical fibers.

Semiconductor optical amplifier is basically a pn-junction. The depletion layer formed at the junction acts an active region. Light is amplified through stimulated emission when it propagates through the active region as shown in Figure (1). Population inversion in an SOA is achieved by forward biasing the pn-junction. With forward bias the drift of carriers increases the electrons concentration in the conduction band of the p-type region. Similarly, there is a drift of holes which increases the whole concentration in the valence band of n-type region.

In practice a thin layer of different semiconductor material is sandwiched between the p-type and n-type region (hetro-structure). This material is of slightly smaller band gap and higher refractive index than surrounding p-type and n-type regions. The smaller band gap helps to confine the carriers injected into the active regions and higher refractive index helps to confine the light during amplification. Both ends of active region are coated with antireflection (AR) coating to eliminate ripples in the amplifier gain as a function of wavelength. In case of laser, there is no AR coating.

Semiconductor optical amplifiers offer an alternative to the fiber-based counter parts at both 1300 nm and 1500 nm telecom windows. SOAs can easily be integrated on the same substrate as other optical devices and compared with Doped Fiber Amplifiers (DFAs) they consume less power and fewer components, and are more compact. They can provide 25-30 dB (fiber to fiber) gain, saturation power up to +13 dBm and noise figure of 6-7 dB over a bandwidth of ~50 nm. Despite recent considerate performance improvements, semiconductor optical amplifiers still suffer from polarization sensitivity (0.5-1 dB) and exhibit nonlinear distortions. These characteristics compare them unfavorably with Erbium-doped Fiber Amplifiers (EDFAs) and it is not clear whether they will ever compete with them and eventually be deployed in practical systems. However, characteristics of semiconductor optical amplifiers that are associated with their fast nonlinearities make them very attractive for a number of applications such as, optical signals processing, wavelength conversion and regeneration, time demultiplexing, clock-recovery, and pattern recognition. Such all-optical functions are needed in optical networks with large-traffic-handling capacities [1-3, 14-16].

Device Principles and Basic Concepts

Semiconductor optical amplifier uses the principle of stimulated emission to amplify an optical information signal as shown in Figure (2). Optical input signal carrying original data enters the semiconductor's active region through coupling optics. Coupling is required because the mode field diameter (MFD) of a single-mode fiber (SMF) beam is typically 9.3 µm, while the size of active region is less and can even be of the order of tenth of micrometers. Injection current delivers the external energy necessary to pump electrons at the conduction band. The input signal stimulates the transition of electrons down to the valence band and the emission of photons with the same energy (of same frequency). Thus optical amplification of input signal occurs. The schematic diagram of this process is given in Figure (3).

The two major types of SOAs are the resonant, Fabry-Perot Amplifier (FPA) and the non-resonant, traveling-wave amplifier (TWA). The FPA has the same configuration as a Fabry-Perot laser. In a Fabry-Perot amplifier, the two cleaved.

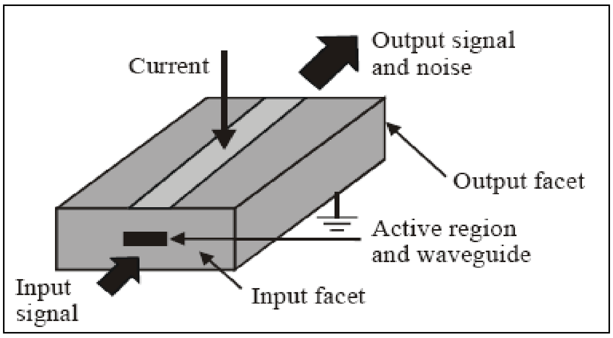

Fig 1: Schematic diagram of semiconductor optical amplifier.

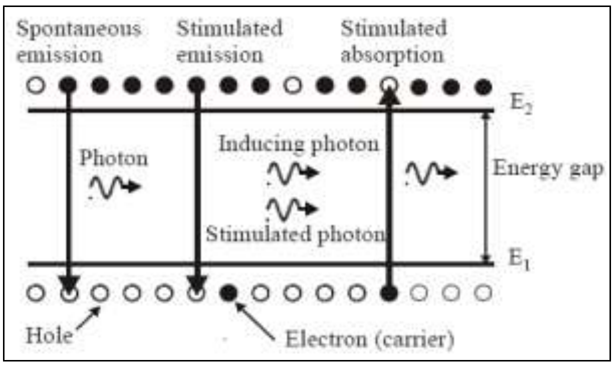

Fig 2: Spontaneous and stimulated processes in a two level system.

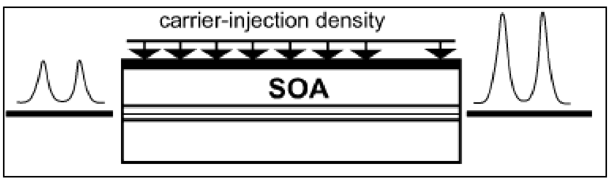

Fig 3: Schematic diagram of amplification by semiconductor optical amplifier.

facets of a semiconductor crystal act as partially reflective end mirrors that form a Fabry-Perot cavity. When an optical signal enters the Fabry-Perot amplifier, it gets amplified as it reflects back and forth between the mirrors until it is emitted at a higher intensity. Although FPAs are easy to fabricate, the optical signal gain is very sensitive to variations in amplifier temperature and input optical frequency. The structure of a traveling-wave amplifier is same as that of a Fabry-Perot amplifier except that the end facets are either antireflection-coated or cleaved at an angle, so that internal reflection does not take place. Thus, the input light gets amplified only once during a single pass through the TWA. These devices have been used more widely than FPAs because they have a large optical bandwidth, high saturation power, and low polarization sensitivity. Due to larger 3-dB bandwidth, traveling-wave amplifiers have become the semiconductor optical amplifier of choice for networking applications. In particular, traveling-wave amplifiers are used as amplifiers in the 1300 nm window and as wavelength converters in the 1550 nm region. In recent literatures, normally the term semiconductor optical amplifier is used for traveling wave semiconductor optical amplifiers.

Amplifier Gain

The primary property of interest for an amplifier is gain. When a semiconductor material with a direct band gap is pumped by injecting a current, population inversion of electrons and holes occur in the valence and conduction bands. When a light signal passes through the semiconductor, amplification takes place due to stimulated emission. Commonly, indium-gallium-arsenide-phosphide (InGaAsP) is used as gain medium. The band gap of this material corresponds to wavelength range: 900 nm to 1650 nm [2].

The active region is enclosed by cladding layers of larger band gap and smaller refractive index as shown in Figure (4). The larger band gap forms a barrier to keep the carriers in the active region and smaller refractive index of cladding increases the confinement of light signal in the active region. Altogether, this helps in obtaining efficient optical amplification.

The signal gain or amplifier gain G of an optical amplifier is defined as the ratio of output power (P_o) to input power (P_i) of the signal. The radiation intensity at a photon energy hν varies exponentially with the distance traversed in a lasing cavity. Single-pass gain in the active medium of the semiconductor optical amplifier is

$$G = \exp[\Gamma(g_m - \alpha)L] \text{ or } G = \exp[g(z)L]$$

where Γ is the optical confinement factor in the cavity, g_m is the material gain coefficient, α is the absorption coefficient of the material, L is the amplifier length, and g(z) is overall gain per unit length. Above equation shows that, the gain increases with device length. However, the internal gain is limited by gain saturation. This occurs because the carrier density in gain region of the amplifier depends on the optical input intensity. As the input signal level is increased, excited carriers (e-h pairs) are depleted from the active region. Further increase in the input signal level yields no appreciable change in the output level as shown in Figure (5), since there are not enough excited carriers to provide an appropriate level of stimulated emission. The carrier density at any point z in the amplifying cavity depends on the signal level $P_i(z)$ at that point. The gain parameter g(z) depends on the carrier density and the signal wavelength [3]. At distance z from input end, g(z) is given as

$$g(z) = \frac{g_0(z)}{1 + P(z)/P_{A,S}}$$

where g_0 is the unsaturated medium gain per unit length in absence of input signal. P(z) is signal power at point z and $P_{A,S}$ is amplifier saturation power. For an incremental length dz the light power increases by

$$dP = g_z P(z) dP$$

Using above equation we can have

$$g_0(z)dz = \left(\frac{1}{P_z} + \frac{1}{P_{A,S}}\right) dP$$

Integrating this equation we have

$$G = 1 + \frac{P_{A,S}}{P_i} \ln\left(\frac{G_0}{G}\right)$$

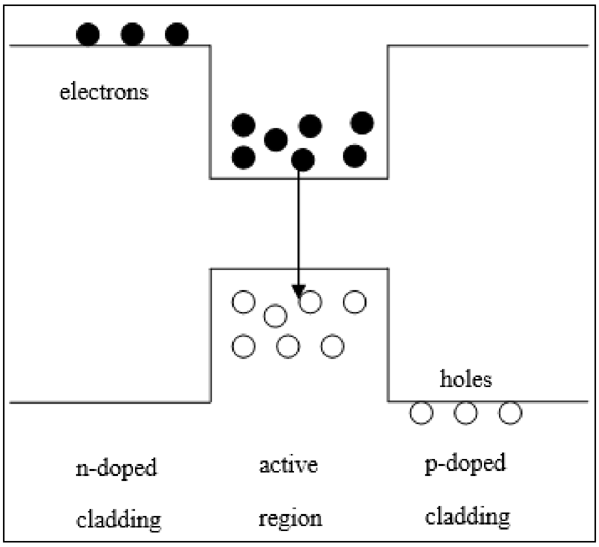

Fig 4: Carrier confinement in a semiconductor optical amplifier

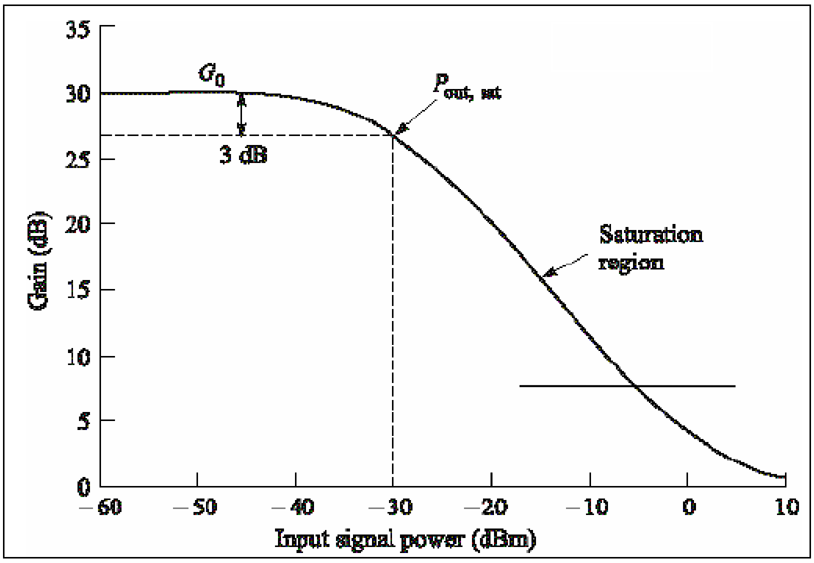

Fig 5: Typical dependence of the single-pass gain on optical input power

where $G_0 = \exp(g_0L)$ is single-pass gain is absence of light. A saturated SOA may give rise inter-symbol interference (ISI) and interchannel crosstalk in WDM systems due to the fast gain dynamics. Therefore, operation of the semiconductor optical amplifier is usually restricted to the quasi-linear regime, and consequently it is more difficult to get high output power out of a semiconductor optical amplifier.

Gain Bandwidth

The gain bandwidth is defined as the full width at the half-maximum (FWHM) height of the gain spectrum. Amplifiers with a relatively large bandwidth are preferred in optical communication systems since the gain is then nearly constant over the entire bandwidth. In general, the bandwidth depends inversely on the optical confinement and the cavity length and it will broaden as the injection current increases due to the band filling effect. Multiple quantum-well (MQW) semiconductor optical amplifiers provide wider bandwidth in comparison to bulk semiconductor optical amplifiers [1-2, 19].

Gain Ripple

The overall gain spectrum of a semiconductor optical amplifier is determined by the semiconductor bands, and has a smooth parabolic shape without the excursion seen in an EDFA gain shape. However, semiconductor optical amplifiers are extremely short devices (~1 mm, compared to many meters for an EDFA), so that reflections at the end facet can give rise to round-tip resonances that lead to a ripple with a period of a few tenths of nanometers in the wavelength domain [3-5]. With counter measures like antireflection coatings and angled facets, the magnitude of this gain ripple can be reduced to < 0.1 dB.

Polarization Dependence

The active layer of a semiconductor optical amplifier does not have dimensional symmetry. Normally it has a rectangular shape (typically 2 μm wide and 0.01 μm thick), and in addition sometimes it is not made out of bulk InGaAsP but of quantum wells, which adds further anisotropy. This leads to difference in gain and confinement factor of two orthogonally polarized modes i.e. TE and TM. This polarization dependent gain can range from a few to tens of dB, which is highly unacceptable in any application in which the input signal polarization is not controlled. If at one instant a signal enters, say, in the TE mode and at the next instant the signal enters in the TM mode then gain of the system would vary appreciably simply because of polarization [2, 6].

There are several means to reduce polarization dependence in semiconductor optical amplifiers. The most obvious one is to restore symmetry between TE and TM modes by utilizing a square active waveguide. But waveguide dimension of μm order is hard to control at industrial level. A second approach is to use the anisotropy of quantum well to compensate for the difference in confinement factor. This principle is used in semiconductor optical amplifier by controlling carefully the strain in a stack of tensile strained quantum wells to match the fiber-to-fiber gains of both polarizations [1-3, 6, 20]. Another way is to connect two semiconductor optical amplifiers in series or in parallel to compensate for the orthogonal polarization's unequal gain. These measures are capable of reducing the variation in gain to 0.5 dB in commercially available semiconductor optical amplifiers.

Noise Figure

The optical amplifier not only magnifies the signal noise along with the signal itself but also adds its own noise. This results in change of signal-to-noise ratio (SNR) of both the input and output signals. The noise is mainly attributed to the following sources: (1) amplified signal shot noise (2) spontaneous emission shot noise (3) signal-spontaneous beat noise (4) spontaneous-spontaneous beat noise and (5) signal excess noise. Items (1) and (2) are related to several detector parameters. In the high output power region the signal-spontaneous beat noise dominates, while in the low output power region the spontaneous-spontaneous beat noise prevails [2, 7-8].

The noise performance of an optical amplifier is defined through figure of merit (F_n) or noise figure (NF) as

$$NF = (SNR)_{in} / (SNR)_{out}$$

Besides the stimulated emission which provides gain, the medium also produces spontaneous emission. This spontaneous emission is undesirable and is also amplified and gives rise to the amplified spontaneous emission (ASE) spectrum of the amplifier. The spontaneously emitted photons are in same frequency range as that of information signal, but they are random in phase and direction. When such photons follow the information signal direction they get amplification. Since photons are random in phase, they do not contribute to the information signal but generate ASE-noise within the signal's bandwidth. This ASE noise limits the optical signal-to-noise ratio (SNR) [3].

The average total power of amplified spontaneous emission (P_{ASE}) is given as,

$$P_{ASE} = 2n_{sp}.h\nu.G.BW \text{ , and } n_{sp} = \frac{N_2}{N_2 - N_1}$$

Here hν is photon energy, G is the amplifier gain and BW is optical bandwidth of the amplifier. n_{sp} is the inversion parameter i.e. the degree of population inversion. N_1 and N_2 are fractional number of carriers in ground and excited states respectively. For an ideal amplifier value of n_{sp} is unity, but the actual value of n_{sp} ranges from 1.4 to 4. Clearly greater the spontaneous emission quantified by n_{sp}, greater will be amplified spontaneous emission (ASE). Typically noise figure for commercially available semiconductor optical amplifiers ranges from 6 to 9 dB.

Crosstalk

When two optical signals at different wavelengths amplified simultaneously and both wavelengths are within the BW of the semiconductor optical amplifier, the presence of one signal will deplete the minority carrier concentration by the stimulated emission process so the population inversion seen by the other signal is reduced. Thus, the other signal will not be amplified to the same extent, if the minority carrier concentrations are not very large, it may even be absorbed (if population inversion is not complete then there will be net absorption). Thus for WDM network the gain seen by the signal in one channel varies with the presence or absence of signals in the other channels. This phenomenon is called crosstalk and has detrimental effect on the system performance [2-3, 21].

The crosstalk phenomenon depends on the spontaneous emission life time from the high energy to the low energy state. If the lifetime is large enough as compared to the rate of fluctuations of power in the input signal, the electrons cannot make transitions in response to these fluctuations. Thus there is no crosstalk.

Basic Network Applications

The principal application of semiconductor optical amplifiers in optical communication systems can be classified into three categories: (i) Postamplifier or booster amplifier- to increase transmitter power (ii) In-line amplifier- to compensate for fiber and other transmission losses in the links and (iii) Preamplifier- to improve the receiver sensitivity [1-3]. The main requirements of optical amplifier for different applications are listed in Table 1 and Figure (6) illustrates the three applications.

Booster Amplifier

The function of a booster amplifier is to increase power level of input signal prior to transmission. Booster amplifiers are used to increase medium and long-haul optical transmission link distance. They can compensate splitting and tap losses in optical distribution networks. In long-haul links the use of a booster amplifier can increase the link power budget and reduce the number of in-line amplifiers or regenerators required. Booster amplifiers are useful to simultaneously amplify number of input signals at different wavelengths, as in the case of WDM based transmission systems.

In-Line Amplifier

In loss limited optical communication system, in-line optical amplifiers can be used to compensate for fiber loss thereby overcoming the need for optical regeneration. The main advantages of in-line are: transparency to data rate and modulation format, WDM based amplification capability, single mode of operation, low power consumption and compactness. The latter two advantages are important for remotely located optical components.

Preamplifier

The function of an optical preamplifier is to increase the power of an optical signal before the detection. The increase in power level can increase the receiver sensitivity and allows longer span of repeaterless transmission links.

Table 1: Main requirements of optical amplifiers

S.N.	Characteristics	BoosterAmplifier	In-lineAmplifier	Preamplifier
1.	High Gain	Yes	Yes	Yes
2.	High Saturation Output Power	Yes	Yes	Not critical
3	Low Noise figure	Not critical	Yes	Yes
4.	Low Polarization Sensitivity	Not critical	Yes	Yes
5.	Low-insertion loss	Not critical	Yes	Yes
6.	Optical Filter	Not necessary	Not critical	Yes
7.	Optical isolators	Yes	Not critical	Not critical

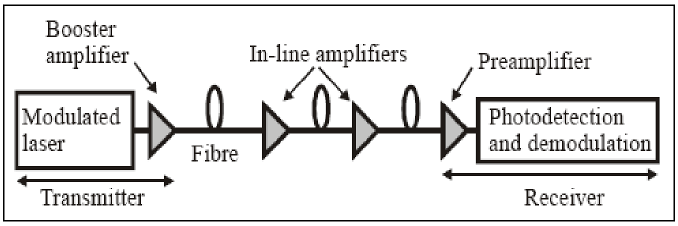

Fig 6: Application of SOAs as booster amplifier, in-line amplifier and preamplifier in an optical transmission link.

Functional Applications

The carrier dynamics of the semiconductor optical amplifier make it a very rich device that can be applied in various ways for all-optical signal processing. These all optical functions can help to overcome the electronic bottleneck, which is major limiting factor in the deployment of high-speed optical communication networks. Many functional applications like wavelength conversion and data regeneration are based on nonlinear response of semiconductor optical amplifier, while fast gain dynamics allow for applications in optical time-division multiplexing [9, 13-15].

As the speed of telecommunication systems increases and reaches the limit of electronic devices, the demand for all-optical logic operations such as switching, decision-making, regenerating, and basic or complex computing is rapidly increasing. All-optical logic gates are essential elements for optical signal processors and networks. By exploiting cross-gain modulation (CGM) and cross-phase modulation (CPM) mechanism, semiconductor optical amplifier can be used as AND, OR, NOR, and XOR gates. Even, complex digital systems like half-adder and full-adder can also be developed [16-17].

Wavelength conversion

All-optical wavelength converters will play an important role in broadband optical networks. Their most important function will be to avoid wavelength blocking in optical cross-connects is WDM networks. Wavelength converters increase the flexibility and capacity of a network using a fixed set of wavelengths. Wavelengths conversion can be used to centralize network management. In packet switching networks, tunable wavelength converters can be used to resolve packet contention and reduce optical buffering requirements. SOA nonlinearities like cross-gain modulation (CGM), cross-phase modulation (CPM) and four-wave mixing (FWM) can be exploited for wavelength conversion [9-15].

Wavelength conversion is traditionally accomplished by converting the signal to the electrical domain and retransmitting it at another wavelength. It can be accomplished by employing the interaction between wavelength channels in a semiconductor optical amplifier offered by mechanism of cross-gain modulation. Wavelength conversion based on cross-gain modulation has been demonstrated to operate at bit-rates as high as 40 Gb/s [11].

The cross-gain modulation (CGM) wavelength conversion is associated with two problems. The first problem is due to band-filling. It is more difficult to compress the gain at longer wavelengths than it is at shorter wavelengths. Therefore, there is an extinction ratio penalty in wavelength conversion at longer wavelengths. The second problem is that the gain compression caused by the modulation of the carrier density is accompanied by a phase modulation due to changing refractive index. This results in chirping of the signal, which limits the ability to transmit the signal over dispersive fibers [12].

The refractive index of semiconductor optical amplifier's active region is not constant but depends on carrier density, which is responsible for cross-phase modulation (CPM) phenomenon. When semiconductor optical amplifier is kept in an interferometric structure, it converts cross-phase modulation into an intensity modulation. A phase shit of only π is needed to obtain complete extinction in an interferometer, which can be achieved with only a few dB of gain compression in the semiconductor optical amplifier. The phase shift is virtually independent of wavelength, so conversion to longer wavelengths is no problem with CPM. The most important disadvantage of the inter formetric structure is that a phase shift of more than π will cause an overshoot, which will impair the extinction ratio. A Mach-Zehnder interferometer based SOA wavelength converter is shown in Figure (7).

Four-wave mixing (FWM) is an ultra-fast all optical effect that can be used for high bit-rate wavelength conversion [13]. Since, four-wave mixing preserves the phase of optical signals in addition to their intensity it can handle intensity and phase modulated signals as well as frequency shift keying (FSK) when used for wavelength conversion, offering enhanced transparency in all optical networks [2, 20]. By careful optimization of the input powers, the power penalties associated with the signal-to-noise ratio (SNR) degradation in FWM wavelength conversion can be minimized.

Regeneration

The nonlinearity of transfer function of interferometers used for cross-phase modulation wavelength conversion can be exploited for partial 2R-regeneration i.e., reamplification and reshaping of the signal. The sinusoidal response function of the interferometer redistributes the noise at the 0 and 1 rails, leading to limited 2R regeneration. Transmission of 10 Gb/s data over a total distance of 200,000 km comprising thousand regenerated spans has been demonstrated using this types of regeneration [2, 14].

Optical Time-Division Multiplexing

The cross-phase modulation mechanism in semiconductor optical amplifiers can also be employed for temporal demultiplexing of optical time-division multiplexed (OTDM) signals. The phase shift triggered by a properly timed control pulse train injected into the semiconductor optical amplifiers can be used to select one in every n bits. Demultiplexing a 40 Gb/s bit stream to 10 Gb/s has been shown in a single-interferometer-arm configuration that cancels out the effects of long-lived refractive index nonlinearities. In an integrated device, 80 to 10 Gb/s demultiplexing was demonstrated [15, 20]. The interferometer in this device is equipped with two input and two output ports, allowing simultaneous adding and dropping of time-division multiplexed channels from a bit-stream going through the device [15, 20].

SOA-Based WDM Systems

Design of systems based on semiconductor optical amplifiers is different from designing an erbium-based system. The SOAs are essentially constant gain devices that should not be saturated in order to avoid cross-gain modulation (CGM), while Er-doped fiber amplifiers are used in constant output power mode under heavy saturation. An example of a WDM transmission experiment is shown in Figure 8 [2, 18-20]. The transmitter consists of eight laser diodes combined by an 8x1 coupler. The wavelengths are in the range 1558-1570 nm with a channel spacing of 200 GHz. The channels are externally modulated at 20 Gb/s. Three booster semiconductor optical amplifiers are used to compensate for the coupler and modulator losses. The transmission link is comprised of four amplified 40 km single-mode fiber links including dispersion-compensating fiber (DCF). The span loss is 13 dB. The 12 to 14 dB of gain available from each amplifier is adequate to compensate for the link loss. The receiver consists of two SOA preamplifiers between which the signal is demultiplexed to 10 Gb/s by a modulator. The demultiplexed data is then detected by a photodiode.

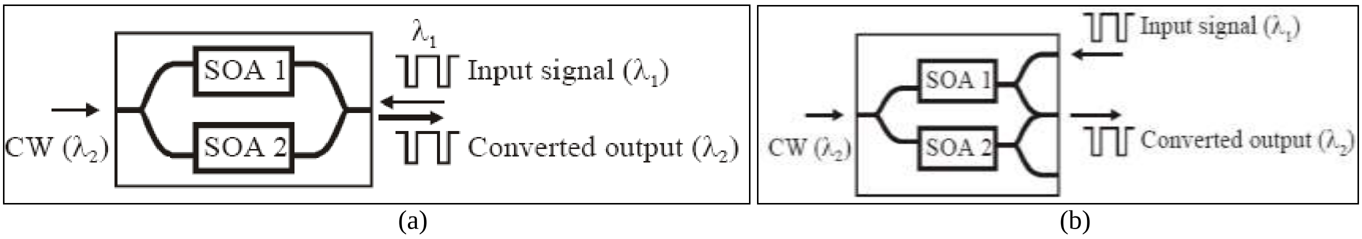

Fig 7: Mach-Zehnder interferometer based SOA wavelength converter (a) Asymmetric MZI wavelength converter and (b) Symmetric MZI wavelength converter.

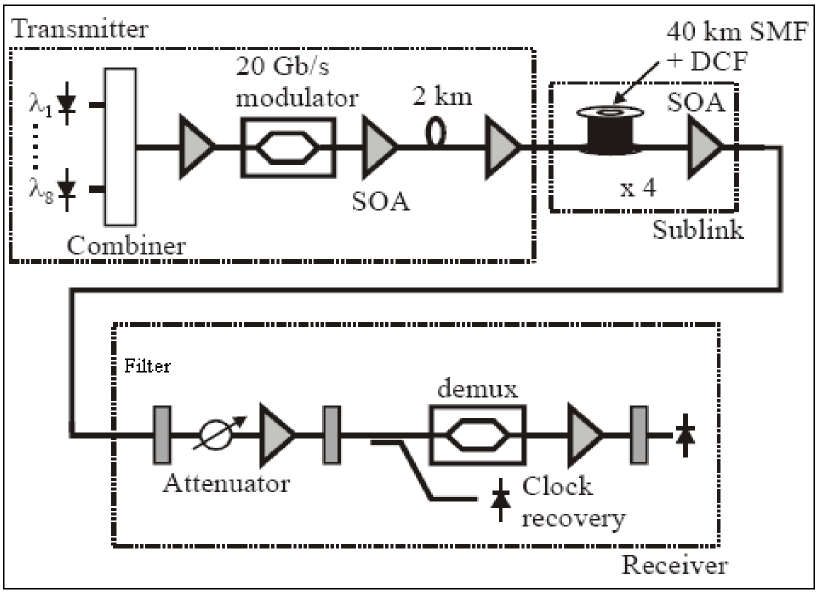

Fig 8: SOA-based 8-channel WDM transmission system

Conclusion

The semiconductor optical amplifier is a rich device with many properties that are potentially useful in optical telecommunication. The major advantage of semiconductor optical amplifier is its ability to operate at the 1300 nm and 1550 nm wavelengths, even simultaneously. Semiconductor optical amplifiers are associated with a wide bandwidth up to 100 nm. One more important quality of semiconductor optical amplifier is its suitability of integration with other semiconductor and photonic devices on a monolithic chip called an opto-electronic integrated circuit (OEIC). The many forms of all-optical processing like wavelength conversion, optical time-division multiplexing and all-optical regeneration are possible with semiconductor optical amplifiers [22-23].

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