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Introduction to Optical Amplifiers

An optical amplifier is a device that amplifies an optical signal. Optical amplifiers and lasers are both based on stimulated emission. The concept and devices of lasers and optical amplifiers were developed almost simultaneously during the 50s and 60s of the 20^{th} century by the same groups of researchers. Since then, several types of optical amplifiers have been demonstrated based on the different materials and mechanisms. They are:

- Rare Earth Doped Fiber Amplifier (EDFA) is the most used
- Raman and Brillouin fiber amplifiers
- Semiconductor Optical Amplifier (SOA)
- Parametric Optical Amplifier

Figure 1 is a simple illustration of how an optical amplifier works. An optical signal is amplified when it passes through an amplifier. In the meantime, the optical amplifier adds additional noises when it amplifies the signal. Usually, three key parameters define the performance of an optical amplifier:

Output power: P_{out}

Gain: $G = P_{out}/P_{in}$

Noise figure: $NF = SNR_{in}/SNR_{out}$

FIGURE 1

Table 1 (Page 2) summarizes the typical performances of the three types of amplifiers that have been used in many applications: EDFA, Raman amplifier, and SOA. The material used for optical signal amplification is called gain medium. The gain medium for optical amplifiers has at least two energy levels that can absorb/store pump energy and generate radiative emission in the desired wavelength band.

Several types of materials and mechanisms can be used for optical amplifiers (and lasers as well). When the gain medium is intensively pumped (electrically or optically), population inversion between two energy levels can be reached, and a small input signal can trigger stimulated emission and be amplified. To reach high pump density and effective amplification, waveguide and fiber are used to confine the lightwaves.

The distinct difference among the three commonly used amplifiers is the gain medium length. Raman fiber amplifier gain media length is typically in the scale of kilometers. EDFA has a typical length from a few meters to a few tens of meters of Er-doped fiber. SOA is electrically pumped. The gain media length can be a few hundred microns to a few millimeters.

In all three types of optical amplifiers, a semiconductor device is a basic building block, and it serves either as gain medium or as optical pump source.

EDFA is the best discrete optical amplifier in terms of performance. It uses Er-doped fiber as the gain medium. EDFA has demonstrated near theoretic low noise figure and large, small-signal gain (>40 dB). Large output power and low nonlinearity also make it ideal for many applications, especially for long-haul WDM fiber optic communication networks. The long lifetime of the Er3+ excited state prevents noise transfer from pump source to signal.

Raman optical amplifiers are mostly used in a fiber optical network where the transmission fiber can serve as a gain medium. In telecom applications, Raman amplifiers are primarily for compensating fiber loss, but not for generating net gain. The distributed nature of Raman amplifiers helps to reduce overall link noise accumulation in signal transmission. For WDM transmission, a combination of several pump wavelength sources is usually used to achieve uniform gain across operation bandwidth.

TABLE 1

Property	EDFA	RAMAN	SOA
Gain medium	Er-doped glass fiber	Optical fiber	III-VI semiconductor
Gain medium length	Meters	Kilometers	Millimeters
Wavelength range	1525 – 1610 nm	1250-1650 nm	1250-1650 nm
Net gain (small signal)	High	Low	Medium to high
Noise	low	low	Medium to high
Output power	High	Low to medium	High
Pump source	Optical (980nm, 1480 nm)	Optical (various)	Electrical
Time constant (s)	10^{-3}	10^{-15}	10^{-9}
Polarization sensitive	No	No	Yes
Cost	High	High	Low

The biggest advantage of SOA comes from its electrical pumping, small size, and low cost. It is a competitive solution for many applications. The disadvantages of SOA are its higher noise figure and stronger nonlinearity (SPM and FWM) compared to the other amplifiers. The short gain medium length of SOA may contribute to nonlinearities.

SOA Fundamentals

SOA is based on semiconductor chips that are made from compound semiconductors such as GaAs/AlGaAs, InP/AlGaAs, InP/InGaAsP and InP/InAlGaAs. Those are the same materials used for semiconductor lasers. The waveguide designs are also the same or similar for laser and SOA. The difference is that lasers have a cavity formed around the gain medium to generate and maintain oscillation, the signal experiences multiple round trips inside the cavity before output. In SOA (we limit our discussion here to a traveling-wave amplifier, which is used in most applications), light travels through the gain medium just one time. Back reflections are minimized. techniques to form three regions: P region, I region (active layer or junction), and N region. The active layer often consists of quantum wells, which improve efficiency and lower threshold current.

The physical structure of an SOA device is shown in **Figure 2**. The device is fabricated with crystal growth Through the metal contact layer, forward bias can be applied to the device to generate holes in the P region and electrons in the N region. Both are driven into the junction region. Recombination of holes and electrons happens in the junction associated with photon emission. This recombination process can be treated as a radiative transition in a simple 2-level system.
See Figure 3 (Page 3).

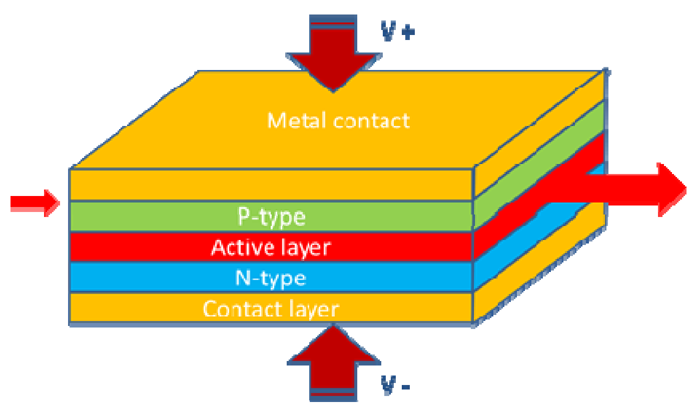

FIGURE 2

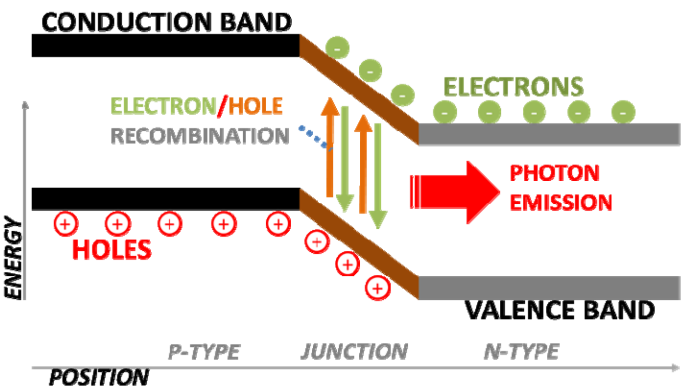

FIGURE 3

Rate equation of the transition:

$$\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_c} - \frac{\sigma_g (N - N_0)}{\sigma_m h\nu} P$$

Peak gain coefficient:

$$g(N) = (\Gamma \sigma_g / V)(N - N_0)$$

Steady-state gain in saturation:

$$g = \frac{g_0}{1 + P/P_s}$$

Where the small signal gain is:

$$g_0 = (\Gamma \sigma_g / V)(I\tau_c / q - N_0)$$

Saturation power:

$$P_s = h\nu\sigma_m / (\sigma_g \tau_c)$$

N, carrier number, σ_g, the differential gain, N_0 transparency carrier number, σ_m the cross-sectional area of the waveguide mode, Γ, optical confinement factor.

SOA Chip (Gain Chip) and Packages

Chip - The basic form of SOA is a semiconductor chip, sometimes called a gain chip. An SOA chip or gain chip is cleaved from a wafer that is made with a special fabrication process. A single wafer can produce thousands of chips.

To minimize facet reflection into a waveguide, the waveguide is designed in such a way that it is tilted to avoid perpendicular propagation at the facet.

SOA waveguide design can take different physical forms to facilitate various packaging requirements. The waveguide design shown below in **Figure 4** is a basic design with input and output on the opposite side of the chip and both facets are AR coated. This design is convenient for a stand-alone SOA packaged into a module with input and output fiber coupling.

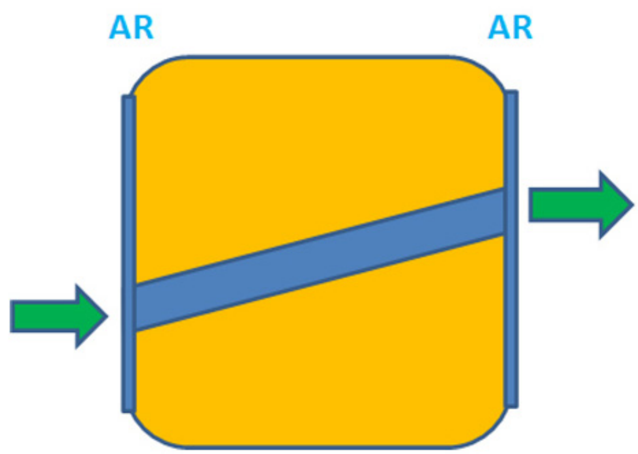

FIGURE 4

Some specialized waveguide designs can also make both input and output on the same side of the chip. Those designs can reduce overall chip size and make it easier to be integrated with other waveguides such as silicon-photonic devices.

Chip-On-Carrier - An SOA chip can be mounted to a chip carrier, that is a so-called Chip-On-Carrier (COC). The carrier serves as a platform for electrical connection and thermal dissipation.

Module - An SOA chip can also be assembled into module packages with fiber-coupled input and output. The butterfly type package is usually used. XMD and coaxial type packages with fiber coupling are also possible.

Typical SOA Performances

ASE spectrum - SOA has a very wide ASE spectrum when there is no input signal. The peak wavelength depends on composition and active layer design. **Figure 5** shows a typical ASE spectrum measured from an SOA peaked around 1530 nm.

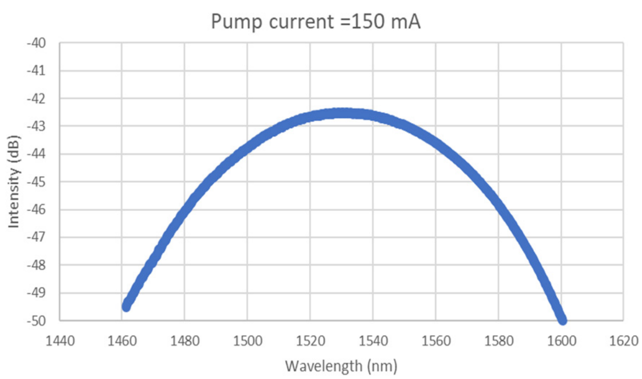

FIGURE 5

Gain and Gain Saturation - SOA can be used for achieving high gain or high output power, but not both at the same time.

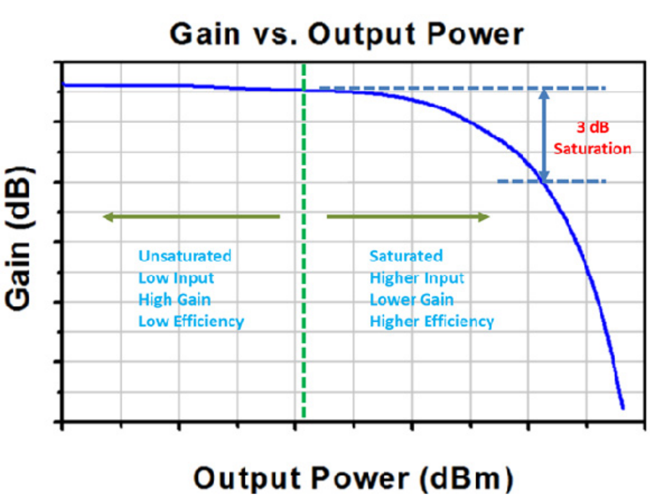

FIGURE 6

When an input signal is small, SOA is operated with approximately constant gain. Typically, 20 dB or higher gain can be achieved with an SOA. The output power and efficiency are typically low in this case.

To achieve high output power, SOA needs to be operated in deep saturation. In this case, more output power is extracted from SOA with high input signal power. Power efficiency is high.

Gain saturation is a gradual process with the increase of input signal power (and output signal power as well). **See Figure 6**.

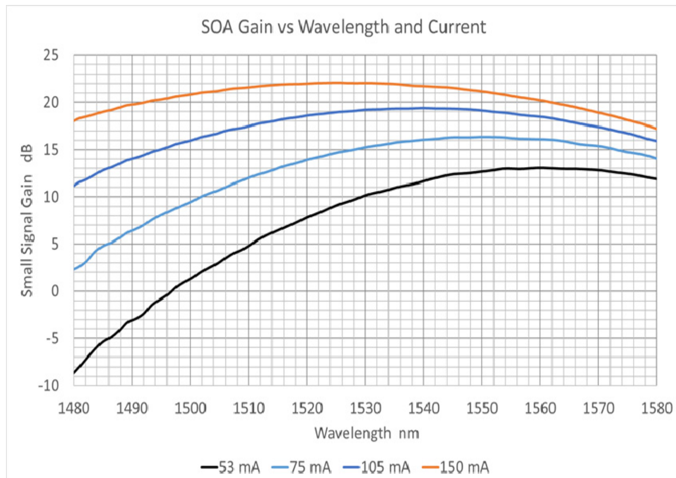

FIGURE 7

Gain vs. Wavelength - Just like the ASE spectrum, the SOA gain spectrum is also broad. The gain spectrum changes with bias current. Figure 7 shows gain spectra from an SOA at different pump currents. At normal operating conditions, 3 dB bandwidth is usually larger than 60 nm.

Output Power - Most of the SOAs available in the market are low to medium power below 18 dBm. Output power above 18 dBm can be achieved by a special waveguide and chip design, which improve pump efficiency. SOAs with output power >100 mW can potentially find new applications as high-power light sources, both CW and pulsed.

Noise Figure - Noise figure is a figure of merit used to indicate how much the signal-to-noise deteriorates as a signal passes through an amplifier. For a packaged SOA with fiber-coupled input and output, the NF measurement is the same as for EDFA. An optical spectrum analyzer can be used. The SOA chip NF can be estimated by excluding input and output coupling losses. The high noise figure of SOA is mainly caused by two factors: high coupling loss (especially from the input end), and from material intrinsic. The theoretical noise figure of SOA is:

$$F_n = 2\left[\frac{N}{N - N_0}\right]\left[\frac{g}{g - \alpha_{int}}\right]$$

When N_0~0, α_{int}~0, $F_n = 2$, that is the theoretical 3 dB noise figure limit. But N_0~0 is hard to achieve due to very short upper energy level lifetime (~ns).

SOA Functions as Optical Switch

When an SOA is not pumped, it absorbs the light that passes through it. The on/off operation can be used as an optical switch. To increase the extinction ratio, SOA can also be reversely biased.

The On/Off extinction ratio depends on waveguide length and bias current. It can be >30 dB. **Figure 8** shows the typical behavior of gain/loss vs bias current for an SOA.

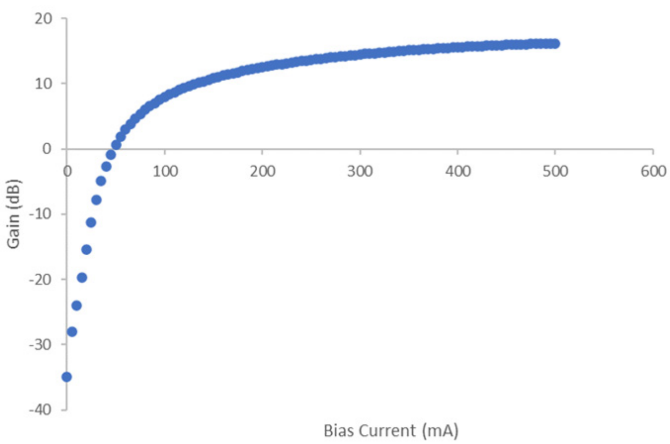

FIGURE 8

Polarization Insensitive SOA

Although SOA is an intrinsically polarization-dependent amplifier (TE mode dominant), there are a few proposed solutions for polarization insensitive SOA:

- On-chip solution: introduce tensile strain into the active region to balance TE and TM modes
- Place two SOAs in serial with the 2nd SOA rotated by 90 degrees
- Use two parallel SOAs with polarization splitter/combiner before and after the amplifiers
- Use a double pass SOA configuration with a 45-degree Faraday rotator and a mirror

Applications for SOA

With its compactness, high efficiency, and low cost, SOA provides amplification for both CW and pulsed signals. SOAs are often used in telecommunication systems operating at signal wavelengths near 1300 nm and 1550 nm. SOA gain chip can also be used for constructing external cavity laser, which has been used for high bit-rate coherent transmission and wavelength agile optical networks.

Optical sensing is another application for SOA, especially with the development activities in LiDAR for autonomous driving.

The strong nonlinearities in SOA, while presenting a problem for some optical communication applications, makes SOA attractive for other applications such as: wavelength conversion, signal and pattern regeneration, etc.

With the rapid growth of integrated optics, SOA has seen more applications as a basic building block used in conjunction with silicon photonic devices.