Optical Amplifiers

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Chapter 1

Introduction

In the last years optical fibres gained more and more usage and evolved from laboratory experiments to useable communication lines. Most of todays backbone networks which build what is called Internet are made of optical fibres. The interconnection of computers in the way we are used to have it today would not be possible without this technology. But that is only one aspect of the useability of fibres. They also serve as sensors, in medical applications and many others.

One main aspect of the fibres is their relative low loss at long length of lines, especially in comparison to electrical connections. But there is a loss and the signals on the fibres have to be amplified if they are to be transmitted. One way to amplify these signals is to reconvert the optical impulses to electrical signals, rebuild them and convert them again to optical informations to be put on the next fibre.

This has been done many times in the past but the main disadvantages are the need of electrical components and the need of an electrical power line for the amplifiers along the optical transmission lines. It would be much more efficient to amplify the signals in the optical domain. This is what optical amplifiers are doing and they can be supplied by optical power, without need of an additional electrical power line.

Potentially, such devices alleviate the possible bottleneck associated with the interfaces as well as providing more efficient, and hence cost effective, methods for processing the optical signals. Moreover, in some cases the use of these devices and components may represent the only realistic solution for the implementation of particular optical fibre transmission techniques and systems.

Chapter 2

Principles and Theory

2.1 Direct Amplification and Basic Configurations

The basic optical communication system consists of three elements: transmitter, fibre and receiver. Amplifiers are only necessary if the length of the fibre becomes too big for the receiver to decode the information on the fibre.

In the case of electronical amplifiers an additional receiver-transmitter pair, which is called a regenerator, is introduced to regenerate the signal. In using optical amplifiers there is no need for receivers or transmitters which are converting the signals from one domain into the other.

The optical amplifier (OA), in principle, provides a much simpler solution in that it is a single in-line component which can be used for any kind of modulation at virtually any transmission rate. Moreover, such a device can be bidirectional and if it is sufficiently linear it may allow multiplex operation of several signals at different optical wavelengths.

Optical amplifiers can be thought of as a laser with a low feedback mechanism and whose excited carriers amplify an incident signal but do not generate their own coherent signal. In doing that, optical amplifiers are not bound to one specific wavelength, bit-rate or modulation-format of the incoming signal as electronic amplifiers are, which in addition waste power and time in converting from photons to electrons and back again.

Optical amplifiers can be used to compensate for signal attenuation resulting from distribution, transmission or component-insertion losses, but they do not regenerate the signal. Therefore, fibre dispersion and nonlinear effects are allowed to accumulate unimpeded. As the optical amplifier cannot be an ideal device, additional restrictions occur: noise is added to the signal and the gain spectrum is not necessarily flat over the entire region in which signals may be transmitted.

Each amplifier requires some form of external power to prvide the energy for amplification. As this is a voltage source for electronical amplifiers, a current or optical source is needed for the optical amplifier.

The main benefits of optical amplifiers are therefore the remaining of the signals in optical form during amplification and their being potentially cheaper and more reliable than regenerators.

It should be noted[1] that for long-haul systems the signal wavelength must be near 1.55 μm for lowest attenuation and the fibre must be dispersion shifted so that the dispersion parameter has a value near to zero at the signal wavelength. In particular with single-mode fibre systems, the effects of signal dispersion can be small and the major limitation on repeater spacing becomes attenuation due to fibre losses. Such systems do not require full regeneration of the transmitted signal at each repeater and hence optical amplification proves sufficient.

Optical amplifiers can be applied at the beginning (*post-amplifier*), in the "middle" (*in-line amplifier*) and at the end (*pre-amplifier*) of an optical transmission line[2].

The first configuration boosts the signal power so the signal is still above the thermal noise level (being the limiting factor in this configuration) of the receiver. The key parameter for the power amplifier will be to maximize the saturation output power.

The second configuration can incorporate not only one but many amplifiers along the transmission path. The in-line amplifiers correct for periodic signal attenuation due to fibre absorption or distribution splitting losses. Optical filtering and isloation will have to be considered.

The third configurstion puts the amplifier directly before the receiver. The main figure of the amplifier has to be low noise and high gain, as the signal has already been significantly attenuated. The limiting factor will be the amplifier loss and not the receiver thermal noise.

2.2 Types and Characterization of Optical Amplifiers

The two main approaches to optical amplification to date have concentrated on semiconductor laser amplifiers and fibre amplifiers. Both amplifier types have the ability to provide high gain over wide spectral bandwidths.

The typical gain profiles for various optical amplifier types based around the 1.5 μm wavelength region are illustrated in [3, p.515, fig. 10.1]. The semiconductor amplifier (here called Travelling Wave Semiconductor Laser Amplifier - TWSLA), the Erbium doped fibre amplifier and the Raman fibre amplifier provide wide spectral bandwidths which makes these amplifier types suitable for wavelength division multiplexing (WDM). By contrast, the Brillouin fibre amplifier has a very narrow spectral bandwidth which can be used in WDM systems for channel selection.

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[1] According to [4, p. 403].

[2] See [4, fig. 5.3].

2.2.1 Semiconductor Optical Amplifiers

Semiconductor Optical Amplifiers (SOAs) utilize stimulated laser emission from injected carriers as they are based on the conventional semiconductor laser structure.

Depending on the reflectivity of the facets of the SOAs two major types can be distinguished:

Resonant Fabry-Perot Amplifiers (FPAs): An FPA may be defined as an amplifier having a facet reflectivity in the order to 0.30 to 0.35. For operation the amplifier is biased below the normal oscillation threshold. Light entering one facet then adds to the bias, stimulating the laser and appears amplified at the other facet together with inherent noise. A highly resonant amplifier is formed and the transmission characteristic comprises multiple very narrow passbands[3] with the mode zero corresponding to the peak gain wavelength. Due to the inherent filtering the device is very sensitive to fluctuations in bias current, temperature and signal polarization. However, because of their resonant nature, they are used in nonlinear applications as for pulse shaping or as bistable elements.

(Near) Travelling Wave Amplifiers (TWAs): If the facets are coated with antireflective material, a single pass device is formed and the Fabry-Perot resonance is suppressed. This has the effect of substantially increasing the ampflifier bandwidth and making the device less dependent upon fluctuations in bias current, temperature and input signal polarization. Hence the TWAs prove superior to FPAs particularly for linear applications and also provide advantages in signal gain saturation and noise characteristics. As the ideal state of no reflection cannot be achieved, these amplifiers are sometimes referred to as Near Travelling Wave Amplifiers.

2.2.2 Fibre Amplifiers

The fibre amplifier is a length of glass fibre that has been doped with the ions of a rare-earth metal, such as erbium. The ions act as an active medium with the potential to experience inversion of carriers and emit spontaneous and stimulated emission light near a desirable signal wavelength. The pump typically is another light source whose wavelength is preferentially absorbed by the ions. The pump and the signal must be combined by a wavelength-selective coupler, preferably at the beginning of the transmission line, so that the doped fibre can be applied along the line at some distance from the ends without need of an additonal second fibre or electrical cable. The signal and the pump may co- or counterpropagate inside the doped length of fibre. Light absorbed by the doped fibre at the pump wavelength will produce gain for a signal at a different wavelength. Because the transmission and the active medium are both fibre based, the insertion losses are minimal.

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[3] As displayed in [3, p. 516, fig. 10.3].

Erbium-Doped Fibre Amplifiers (EDFAs): The main reason to develop and use the EDFAs include the fact that Erbium ions (Er^{3+}) emit light in the 1.55 μm loss-minimum band of optical fibre and that a circular fiber-based amplifier[4] is inherently compatible with a fibre optic system. The basic operation of the fibre amplifier is similar to that of the SOA, there are some fundamental differences, though:

1. The SOA is a two-energy-level system, whereas the EDFA is a three-energy-level-system. Additionally, the EDFA is pumped by an optical source while the SOA is supplied with a current souce.
2. The length of a fibre amplifier is meters whereas the length of a SOA is ≈ 1 mm.
3. The fibre ampflifier is circular and not rectangular as is the SOA, thus eliminating significant attenuation at the connections as well as removing any polarization dependencies in the gain.
4. The carrier lifetime of erbium ions is milliseconds (SOA: nanoseconds) which reduces the two major problems[5] in multichannel systems significantly.

Praseodymium Amplifiers (PDAs): As most of todays installed optical fibre is operated at 1.3 μm it is highly desirable to have a fibre-based optical amplifier working at this wavelength. Doping a fibre with praseodymiun will enable a fibre to experience fluorescence and thus amplify with similar characteristics as EDFAs in the 1.3 μm range. However, because praseodymium is a four-level energy system the pump efficiency to achieve high gain is extremely low as hundreds of mW of pump power are required to achieve 20 dB gain, whereas <20 mW is required for EDFAs.

Stimulated Brillouin Scattering Amplifiers (SBSAs): This narrowband amplifier was preceding EDFAs by many years. It works by interacting of the incident photons with the molecules of the fibre, causing them to vibrate and forming an acoustic wave and a reradiated photon at a lower frequency[6]. The pump and the signal must be counterpropagating.

Stimulated Raman Scattering Amplifiers (SRSAs): The Raman amplifier uses the same fundamental mechanisms as the SBSA, but builds a wideband amplifier. Here the pump light photon stes the fibre in mechanical vibrations. Since these vibrations are not uniform in the fibre, the reradiated photon is not at a set lower frequency. Here, the pump and the signal may be copropagating, but the amplifier itself is much less efficient than a SBSA.

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[4] See [4, p. 456, fig. 5.35].

[5] Intermodulation distortion (four-wave mixing) and bit-rate-dependent cross-talk due to gain saturation.

[6] This photon is shifted down by ≈ 10 GHz since the acoustic wave is uniform in the fibre.

2.3 Background theory

Optical amplifiers can be classified by different parameters, depending on their fundamental mechanisms. Due to their importance only SOAs and EDFAs are covered here.

2.3.1 SOA Gain and Bandwidth

$$G_{(f)} = \frac{(1-R_1)\cdot(1-R_2)\cdot G_0}{(1-G_0\cdot\sqrt{R_1R_2})^2 + 4\cdot G_0\cdot\sqrt{R_1R_2}\cdot\sin^2\Phi} \tag{2.1}$$

with

$G_{(f)}$ ... cavity gain as a function of frequency f

G_0 ... single pass gain, maximum unsaturated spectral gain

R_1 ... input facet reflectivity

R_2 ... output facet reflectivity

Φ ... phase shift

The derivation of eq.2.1 can be found in [4, pp.406-411]. It should be noted that eq.2.1 does not include coupling losses to and from the amplifier and that the phase shift Φ may be written as

$$\Phi = \frac{(\omega-\omega_0)\cdot L}{\frac{c}{n}} \tag{2.2}$$

with

ω ... signal frequency

ω_0 ... optical frequency for maximum gain

L ... length of the active medium

$\frac{c}{n}$ ... speed of light in medium with refractive index n

The denominator in eq.2.1 is periodic, producing periodic Fabry-Perot (FP) resonances in the gain spectrum. If the reflections are suppressed and $R_1 = R_2 = 0$, then this is a wideband travelling wave (TW) amplifier, also known as a one-pass amplifier. If there are reflections and $R_1 = R_2 > 0$, then this is a narrowband FP amplifier with narrow FP ripples in the wide-gain spectrum.

The $3dB$ optical bandwidth may be expressed as a function of the FPA cavity gain G as following[7]:

$$B_{FPA} = \frac{c}{\pi n L}\cdot\sin^{-1}\left(\frac{1}{2}\cdot\frac{(1-R_1)\cdot(1-R_2)}{G\cdot\sqrt{R_1R_2}}\right) \tag{2.3}$$

2.3.2 SOA Backward Gain

$$G_b = \frac{P_b}{P_{in}} = \frac{(\sqrt{R}_1-\sqrt{R}_2\cdot G_0)^2 + 4\cdot G_0\cdot\sqrt{R_1R_2}\cdot\sin^2\Phi}{(1-\sqrt{R_1R_2}\cdot G_0)^2 + 4\cdot G_0\cdot\sqrt{R_1R_2}\cdot\sin^2\Phi} \tag{2.4}$$

with

P_b ... power of backward travelling signal

P_{in} ... power of input signal

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[7] See [3, p.518, eq.10.4].

The backward gain (10 *db*) is very significant even at low facet reflectivity (0.01%). In system with cascaded amplifiers, optical isolators may therefore be required to avoid the interaction of backward signals between the devices.

2.3.3 SOA Noise and Optical SNR

Noise is the very crucial parameter that makes all physical devices unideal. In addition it will be amplified together with the signal, making it more and more difficult to decode the information at the receiver. In trying to describe the noise, the signal-noise ratio (SNR)[8] is of importance:

$$SNR_{optical} = \frac{P_{sig} \cdot G}{n_{sp} \cdot h \cdot \nu \cdot \Delta\nu \cdot (G-1)} \tag{2.5}$$

with

P_{sig}	...	input signal power
G	...	amplifier gain
n_{sp}	...	spontaneous emission factor
$h \cdot \nu$	...	photon energy
$\Delta\nu$	...	gain bandwidth, optical bandwidth of active medium

2.3.4 SOA Electrically Equivalent SNR and Noise Figure

In sec.2.3.3 the optical SNR has been stated, but of more interest is the electrical noise generated in the optical detector and which governs the overall sensitivity of the system. The SNR is typically defined as the signal mean squared divided by the sum of the noise terms squared:

$$SNR_{electrical} = \frac{G \cdot P_{sig}^2}{\sigma_{sh}^2 + \sigma_{th}^2 + \sigma_{sig-sp}^2 + \sigma_{sp-sp}^2} \tag{2.6}$$

with

σ_{sh}^2	...	variance of shot noise
σ_{th}^2	...	variance of thermal noise
σ_{sig-sp}^2	...	variance of signal-spontaneous beat noise
σ_{sp-sp}^2	...	variance of spontaneous-spontaneous beat noise

These can be defined as follows:

$$\sigma_{sh}^2 = 2\eta q \cdot \frac{q}{h\nu} \cdot (G \cdot P_{sig} + P_{sp}) \cdot B_e$$

$$\sigma_{th}^2 = \frac{4k \cdot T \cdot B_e}{\Omega_r}$$

$$\sigma_{sig-sp}^2 = 4q \cdot \frac{q}{h\nu} \cdot P_{sig} \cdot G \cdot (G-1) \cdot n_{sp} \cdot B_e$$

$$\sigma_{sp-sp}^2 = 4q^2 \cdot (G-1)^2 \cdot n_{sp}^2 \cdot B_e \cdot B_0$$

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[8] As defined in [4, p. 419, eq. 5.31].

with

η ... detector responsitivity (typically close to 1)
q ... electric charge constant
$\frac{q}{h\nu}$ ... term to convert optical power into electrical power
B_e ... electrical bandwidth of receiver
k ... Boltzmann constant
Ω_r ... characteristic resistance of detector
T ... receiver temperature
B_0 ... bandwidth of an optical filter

The shot noise is as a quantum-mechanical phenomenon mainly due to the random generation of electrons and thus proportional to the incoming optical power.

The thermal noise is due to the thermal generation of carriers in the semiconductor detector or in any resistive element in the receiver circuitry.

The signal-spontaneous beat noise is due to the fact that the receiver is inherently a square-law device that produces a "beat" term if two different signals are incident.

The spontaneous-spontaneous beat noise is due to "beating" of noise with itself within the detector.

The Noise Figure (NF) of an optical amplifier is defined as $NF = \frac{SNR_{in}}{SNR_{out}}$ with $SNR_{in} = \frac{P_{sig}}{2q \cdot B_e}$ and $SNR_{out} = \frac{P_{sig}}{4n_{sp}q \cdot B_e}$ and can therefore be written as

$$NF = 2 \cdot n_{sp}. \tag{2.7}$$

2.3.5 EDFA Gain

In the case of fibre amplifiers the mechanisms are different, leading to different expressions for gain and noise. Mainly the gain is, in contrary to SOAs, highly nonuniform and will depend on doping, length, pump power, pump wavelength, signal wavelength and emission and absorption cross-sections for the signal and the pump.

$$G_k = e^{\int_0^L \left(g_k \cdot \frac{N_{1(z)}}{N_t} - \alpha_k \cdot \frac{N_{0(z)}}{N_t}\right) dz} \tag{2.8}$$

with

k ... number of possible wavelengths considered
L ... length of erbium-doped fibre
N_0 ... carrier density in ground state
N_1 ... carrier density in first metastable state
g_k ... wavelength dependent gain
α_k ... wavelength dependend loss

In addition, Giles and Desurvire have developed a spectrally resolved, spatially integrated model in two equations that fully describe the gain and the signal power along the erbium-doped fibre[9].

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[9] See [4, p. 442].

2.3.6 EDFA Noise Figure

As for SOAs a NF can be defined as well, only that is is wavelength-dependend:

$$NF_{(\lambda)} = \frac{SNR_{in}}{SNR_{out}} = \frac{2 \cdot P_{sp(\lambda)} + 1}{G_{(\lambda)}} = \frac{2 \cdot n_{sp(\lambda)} \cdot (G_{(\lambda)} - 1) + 1}{G_{(\lambda)}} \tag{2.9}$$

where

$$n_{sp} = \frac{P_{sp}}{h\nu \cdot \Delta\nu \cdot (G - 1)} \tag{2.10}$$

2.3.7 Comparison of Major SOA and EDFA Characteristics

Type of Amplifier	Energy Levels	Pumping Source	Lifetime	Insertion loss per facet
SOA	2	Electrical ≈100 mA	≈1 ns	≈3 dB
EDFA	3	Optical ≈20-50 mW	≈1 ms	≈0.2 dB

Type of Amplifier	Center Wavelength (BW)	Length	Fibre-to-Fibre Gain	Typical Noise Figure
SOA	1.3 or 1.55 μm (≈50-75 nm)	≈500 μm	10-15 dB	8-12 dB
EDFA	1.55 μm (≈20-30 nm)	≈10 m	10-40 dB	4-5 dB

2.4 Power Supply

As stated in sec.2.1, amplifiers need power supplies. In the case of optical amplifiers these can either be current or optical sources.For a post- or pre-amplifier both supply methods are useful, but in an in-line configuration the possibility of supplying the amplfiier with optical power gains the biggest benefit over electronical amplifiers as there is no longer a need for an extra cable along an optical transmission path.

SOAs need a current source as their power supply, so they are not that useful as in-line amplifiers as there would again be an electrical connection needed. The biggest advantage give fibre amplifiers as the needed power can be transmitted on the same optical fibre as the signal.

The different configurations[10] require an optical isolator and an optical filter to prevent reflections back into the amplifier, although they may not be needed under all circumstances.

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[10] See [4, p. 405, fig. 5.4].

Chapter 3

Applications

3.1 Present Implementations

Today most of optical fibre system are used in telecommunications to transmit data. But that is not the only field of applications that is possible with the technology of optical waveguides in form of silica fibres: the fibres can be used as sensors or measurement instruments, also.

SOAs have been successfully demonstrated as power amplifiers, in-line amplifiers and preamplifiers in long-distance communication systems. However, for their superior characteristics, EDFAs are more desirable for these applications at 1.55 μm. The real possible application for semiconductor amplifiers in long-distance communications is in 1.3 μm systems.

The main advantage of using a SOA as opposed to FAs include their small size, low cost and integratability on chips containing other optoelectronic devices. Integrated coupler, switching gates or modulators can be built that way. Another application could be an all-optical wavelength shifter.

An inherent feature of optical amplifiers due to their reflective facets (if they are not bulit as an TWA) is the possibility to use the wavelength selectivity of their cavity. In that way an optical amplifier can act as an optical filter.

A semiconuctor amplifier can also be used to tap optical energy from a signal passing thourgh it. This can be useful for measuring equipments.

EDFAs on the other hand are easily cascaded and can be used in long-distance terrestrial and transoceanic communications in an even better way than SOAs as there is no need of an electrical pump source. Isolators will be required to prevent backward propagation in most cases, though.

EDFAs have been successfully used as preamplifiers (with sensitivities of up to -46 dB at 2 $Gbps$[1]) or for power boosting at the output of a laser transmitter. As EDFAs are commercially available, implementing them possible for a reasonable low price.

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[1] See [4, p. 457].

As an early application of optical computations, recirculating loops incorporate optical amplifiers as the stored data experiences loss at each propagation around the loop.

3.2 Future Implementations

Most of the technologies associated with optical fibres find their analogies in conventional radio frequency (RF) systems. **Soliton Systems**[2] are fundamentally different. They rely on fibre properties and therefore have no analogon in RF systems. In soliton systems the basic properties dispersion and nonlinearity are used in a way that it will become possible that these two detrimental parameters cancel out each other. A pulse of light – a so called soliton – can then propagate over extremely long distances without distortion.

Because solitons rely on the exact compensation of dispersion by nonlinearities, soliton systems must sustain a fixed pulse energy throughout the link. That is possible only if fibre attenuation is compensated for by the use of optical amplifiers, which therefore are an absolute must for soliton systems. A distributed optical amplifier along the transmission line would be the best solution to achieve a constant energy level of the pulses. As EDFAs are lumped amplifiers, these requirements can only be partly met.

There are several limiting factors which describe the upper border of the performance of soliton systems, one being the Gordon-Haus effect, which leads to a jitter in pulse arrival times. Two techniques have been developed recently to overcome the Gordon-Haus limitation. Frequency-Domain Filtering and Time-Domain Filtering both improve system performances well beyond the Gordon-Haus limit and make the transmission distance virtually unlimited.

One problem with soliton systems is that it is not easy possible to implement WDM on the fibre. Solitons have to have a minimal power, but when two solitons overlap (”collide” - which happens very easily as the propagation velocity is different for different wavelength) their total power no longer satisfies the power requirements. There are certain parameters that have to be considered for designing a working WDM soliton system.

Multichannel Systems, in principle, multiplex many different communication lines onto one ”thick” line. This multiplexing can be achieved in different manners, two being Time-Division Multiplexing (TDM) or Frequency-Division Multiplexing (FDM). But only WDM systems take advantage of the enormous bandwidth available in an optical fibre.

As essential parts wavelength multiplexer and wavelength demultiplexer are needed to accomplish the tasks of transmitting many different waveguides on one fibre. In addition it is necessary to be able to produce lasers which emits different wavelengths.

Wavelength-tunable lasers (in a range from 192.0 to 193.2 THz for example) are known and can be used for that purpose. Another possiblity would be multiple different lasers in an array.

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[2] See [4, pp. 471ff., ch. 6]

Appendix A

Acronyms

EDFA Erbium-Doped Fibre Amplifier

FA Fibre Amplifier

FPA Fabry-Perot Amplifier

OA Optical Amplifier

PDA Praseodymium Doped Amplifier

RF Radio Frequency

SNR Signal-Noise Ratio

SOA Semiconductor Optical Amplifier

TWA Travelling-Wave Amplifier

WDM Wavelength Division Multiplexing

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