Introduction

Rare-earth doped fiber amplifiers are key devices in high capacity long haul optical telecommunication systems. Their best representative is the compact erbium-doped fiber amplifier (EDFA), which since 90's of the last century found many applications in terrestrial and submarine optical links [1]. They forced a rush development of the new communication era, in which the interpersonal communication changed the operation domain from electrical to optical. The limitations of electronic telecommunications such as low frequency of the transmitted signals or easiness to intercept were simply overcome by using optical fibers. Moreover, due to the enormous transmission bandwidth of the fiber (about 50 THz compared to 1 GHz in the case of advanced copper twisted pair cables) the capacity of transmission systems reaches totaly new dimensions. The change from electrical to optical telecommunication was an impulse to develop more efficient transmission techniques as wavelength- or time-division multiplexing which help to make effectively use of the transmission bandwidth.

Nowadays, the transparent optical networks operate mainly in the wavelength range 1530 to 1570 nm employing EDFAs. The WDM technique with increasing bitrates per channel and decreasing channel spacing are used to assure high data capacity of the longhaul systems. Unfortunately, due to the limitations of the detectors such an evolution of the transmission systems was slew down. The detectors used in receiver units are typically polarization and phase insensitive and detect the intensity of the signal radiation with maximum 1 bit/s of data rate for each Hz of optical bandwidth in a single transmission fiber. It limits the capacity of transmission systems based on EDFAs and gain-shifted EDFAS to 10 Tbit/s. Although this value may seem to be very large (it is equivalent to 160 million ISDN connections or 5 million video streams 2 Mbit/s each), the experiments with similar capacities were already reported [2].

To avoid the mentioned capacity limit, a new generation of polarization or phase sensitive transmitters and receivers has to be developed or new transmission bands have to be opened for signal amplification. Since the total available bandwidth is 5 times larger than actually used, the second solution seems to be easy to realize. Thulium-doped fiber amplifier (TDFA) seems to be one of the most suitable candidates to upgrade EDFA-based longhaul optical links. First experiments with TDFAs were performed already in 1993, but the complexity of the amplifier and the still sufficient capacity of today's transmission systems are the factors, which delay its commercial premiere.

Unfortunately, the development of the TDFA is much more complicated than that of EDFA. The problem starts with many energy levels involved in the amplification process. In contrast to the EDFA, amplification occurs between two excited levels. Moreover, there is one energy level between the upper and lower amplification level leading to a fast non-radiative decay. The depopulation of the upper energy level occurs due to multiphonon relaxation. Phonons are the quantized vibrations of the glass matrix and its number needed to bridge the given energy gap is different in silica and fluoride glasses. The energy gap of $1000\,\mathrm{cm}^{-1}$ is bridged by 1 phonon in silica but 2 phonons in fluoride glasses. High maximum phonon energy in silica glass limits the efficiency of the radiative transitions in the amplifier. For that reason glasses with low maximum phonon energy are the best hosts for the amplifier. On the other hand, the predominant ionic type of bindings in the fluoride glass matrix, which causes decrease of the phonon energy results also in impair of the thermal and mechanical properties of the fibers made out of the fluoride glass. This fact hinders its connection to the silica transmission fiber.

Since many energy levels are involved in the amplification process, several pumping schemes of the amplifier are possible. Moreover, the TDFA employs two-stage pumping, for which pumps at different wavelengths are used. They are combined with the signal wavelength in a single fiber using special WDM couplers, which are commercially not available. All these issues make the TDFA development not trivial, and their solutions are of basic importance for TDFA performance.

The advanced study on TDFA presented in this work consists of seven chapters, the contest of which is given below.

Chapter 1. This chapter provides an introduction into the optical transmission systems. The amplifier types present in different fiber links are described with the special attention to their particular applications. Besides semiconductor and Raman amplifiers the state-of-art for rare-earth doped fiber amplifiers in S-, C- and L-band is given and a comparison of amplifier types for the S-band is given.

Chapter 2. In this chapter the operation principle of the thulium-doped fiber amplifier is described. Also the relevant transitions in thulium-doped fluoride glass (ZBLAN) are presented and their importance for the amplifier's performance is discussed. Since fluoride fibers are chosen as host glass for the TDFA, the features of low phonon energy glasses are compared with that of silica glass. Finally, the definitions of basic amplifier parameters as gain, noise figure, and power conversion efficiency are provided.

Chapter 3. The analysis of the amplification process in TDFA provided in previous chapter shows that special attention has to be paid on spectroscopic investigations of thulium in the glass matrix. Therefore a number of ground- and excited-state absorption as well as emission lines was investigated in two fluoride glass systems (ZBLAN and IBZP). Also the life time measurements were performed for both glass types and the concentration quenching process was observed for highly thulium-doped samples.

Chapter 4. The problem of several different radiation sources needed for the amplification process and their combination in a single fiber is subject of this chapter. The development of different types of fiber couplers was supported by a simple coupler model, the description of which is provided here. Finally, examples of various 2λ- and 3λ-WDM couplers are given.

Chapter 5. In this chapter the differences of thermal and mechanical properties of fluoride and silica glasses are discussed. Because of the fact that both fiber types can not be spliced using welding arc makes the development of a new stable and reliable connection technique necessary. As shown in lifetime measurements described in this chapter, the glue-splice technique seems to be a solution of this connection problem. Its limitations influencing the operation under high power conditions indicates the direction of further investigations.

Chapter 6. The results of investigations described in the three previous chapters are used here to simulate the complete TDFA setup. The amplifier model presented in this chapter is used to simulate the performance of the TDFA, however due to many unknown parameters required for amplifier's description the simulation results are not quantitatively comparable with measurements. The spacial aspects of TDFA operation as gain-shift and amplification in TDFA operating with a cooperative fiber laser at about 1900 nm are given as simulation examples.

Chapter 7. In this chapter measurements of the thulium-doped fiber amplifier in different pump configurations are reported. Special attention is given to the single-wavelength pumping scheme employing high-power 1056 nm laser diodes as a pump sources. Strong cross-relaxation observed for highly thulium-doped fibers is an explanation for efficient operation of this type of amplifier. As next, the investigations on typical double-wavelength pumping schemes are reported. Section 7.4 collects the measurement results of the advanced pumping scheme using a fiber laser at 1849 nm to depopulate the lower amplification level and making possible to pump the amplifier with just an 805 nm pump laser.

1 Optical transmission systems

The rush development of the optical transmission systems in the last years of the 20^{th} century clearly shown, that the interest in the new applications (e.g. video on demand, interactive media) of the optical telecommunications systems will drastically increase. This means increase in bandwidth demands, which can be satisfied by using fiber transmission bandwidths besides the standard C- and L- band and/or developing of optical transmission systems, which allow to transmit many signal channels. This forced the development of two main transmission techniques: optical time division multiplexing (TDM) and wavelength division multiplexing (WDM).

In the time domain multiplexing systems many single signals can be transmitted over a single transmission path. Each lower-speed signal is time-sliced into one high-speed transmission. For example, four incoming 1000 bit/s signals can be interleaved into one 4000 bit/s signal. The receiving end divides the single stream back into its original signals [3]. The bottleneck of TDM systems is the dispersion of the fiber, which limits the transmission distances for the higher capacities. However, by using dispersion compensation techniques it is possible to transmit high-capacity signals over long distances [4].

In the WDM technique several wavelengths are used to simultaneously transfer the data over a single fiber. Each of the wavelengths is modulated by the data stream (text, video, voice), which dramatically increases the capacity of the transmission systems. Typical channel distance in the commercial WDM systems is 200, 100 or 50 GHz. Applying several wavelengths with channel spacing of 100 GHz it is possible to increase the capacity of the transmission systems to several Tbit/s. The wavelength division multiplexing is present in different variations, for example course-WDM (CWDM) or dense-WDM (DWDM).

For the short transmission distances the best solution for WDM systems seems to be CWDM, also known as “wide WDM”. In this technique several channels are transmitted simultaneously and the channel spacing is much bigger than in standard WDM. Typical spacing between the channels is up to 20 nm (2.5 THz) and transmission is realized for relatively short distances (up to 60 km). The wider spacing tolerates higher temperature fluctuation, which makes the CWDM a low-cost version of a WDM system. Its significant cost advantage is caused by the fact, that the signal lasers do not have to be thermally stabilized and can be modulated directly by changing the drive current. Such a systems operate in the wavelength range of 1270 and 1610 nm, but due to larger channel spacing this technique is not suitable to transmit high data capacities. Nevertheless, the experiments with 40 Gbit/s transmission were reported in [5, 6].

The dense wavelength division multiplexing systems are characterized by the high total transmission capacity (up to several Tbit/s). Such a high capacity is achieved by combining many single transmission channels in one optical data stream. The wavelength of the signal can be chosen from any of the transmission bands, which cover more than 450 nm optical bandwidth. This bandwidth is divided into several bands, according the ITU recommendation G.694.1 (06/02) [7] as shown in figure 1.1.

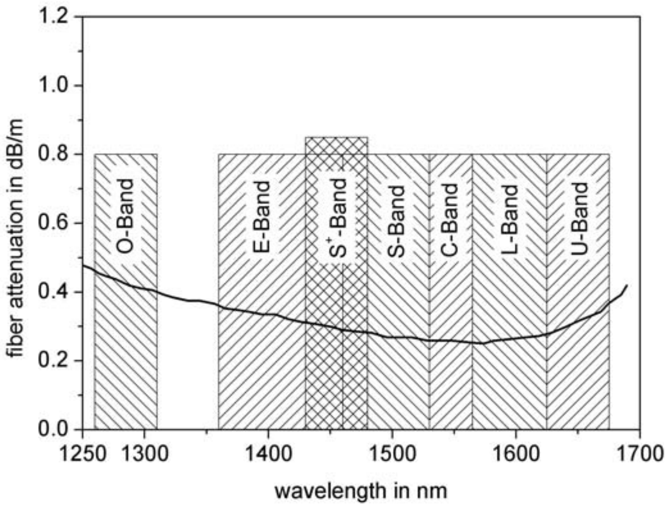

Figure 1.1: The normalized ITU bands for optical transmission systems

The broadband DWDM systems operate in more than one band. Therefore the signal bandwidth can not be covered by the single amplifier. As result one has to use a separate amplifier for each transmission band. For the most common C- and L-band erbium-doped fiber amplifiers (EDFA) are used. The signals around 1300 nm (O- or E-band) may be amplified by the praseodymium or neodymium doped fiber amplifiers, however due to the narrow flat gain bandwidth these amplifiers are not very suitable for multichannel WDM systems. The natural extension of present systems basing on EDFA are the thulium-doped fiber amplifiers (TDFA). They operates in the S- and S^+-band and reach up to 30 dB gain [8], but in contrast to EDFA they can be effectively realized in low phonon energy glasses like ZBLAN only. The transmission capacities of DWDM depends on the number of channels and their spacing and reach more than 10 Tbit. As an example 3.08 TBit/s transmission using 77 channels with the single capacity of 42.7 Gbit/s was reported in [9]. The channel spacing was 0.8 nm and to cover the whole amplification region, EDFAs and Raman amplifiers were used. The largest reported transmission capacity of almost 11 TBit/s was achieved for 230 optical channels spaced with 100 GHz (0.8 nm) located in S-, C- and L- band and described in [10].

The large enthusiasm and research activities on the telecommunication market were slowed down after the “dot-com collapse” and in the meantime the research projects concentrate on more efficient usage of the current transmission systems working in C- and partially in L-band. However, one can expect, that the problems with non-linear effects in DWDM systems and growing bandwidth demand will force the development of new rare-earth doped fiber amplifiers like the TDFA.

In the next sections, different types of amplifiers used in optical communications systems are briefly presented. They are divided in three groups according to their operation principle, manufacturing process and/or application field.

1.1 Semiconductor amplifiers in optical communication systems

The semiconductor optical amplifiers (SOA), schematically shown in figure 1.2, are constructed similar to laser diodes, but without end mirrors.

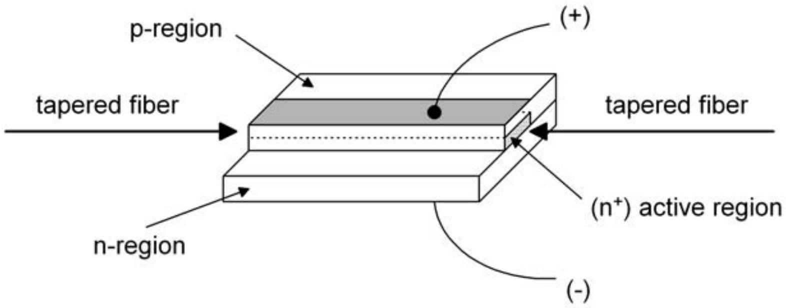

Figure 1.2: Schematic diagram of an SOA

The active region in the semiconductor amplifier generates optical gain due to stimulated emission. The operation principle bases on the pumping process, which is realized electrically by current injection. The electrons are excited from the valence to the conductive band by absorbing the energy which is higher than the energy gap in semiconductor. This results with the formation of the holes in the valence band and free electrons in the conductive bands and finally with population inversion. The signal is amplified due to the stimulated emission, but the accompanying spontaneous emission leads to noises at the signal output. The amplification bandwidth of the SOA is larger than 30 nm, which is comparable with that of EDFA.

Except of standard application of SOAs as preamplifier, in-line amplifier and postamplifier they found also many others application fields. One uses them as wavelength converters, optical gates, optical logic, multiplexers or optical pulse generators [11]. For these applications amplifiers are driven in saturation mode, where non-linear effects play an significant role.

Semiconductor amplifiers found also many applications in metropolitan area networks, which in contrast to long-haul systems are using less number of WDM channels per fiber and the transmission distances are relatively short [12]. The semiconductor amplifiers are commonly used as channel power equalizers [13]. This decreases the complexity of the power splitting-nodes and significantly reduces the costs of the networks. In the local access star passive optical networks the SOAs are used to amplify signals in less critical upstream [14]. Their low costs and broad application spectrum makes the SOAs one of the important devices for optical telecommunication systems.

1.2 Raman amplifiers in transmission systems

Another type of optical amplifier is the Raman fiber amplifier (RFA) basing on non-linear effects in transmission fiber. Its molecular vibrational level system is shown in figure 1.3 together with the Raman gain coefficient in the SiO_2 fiber.

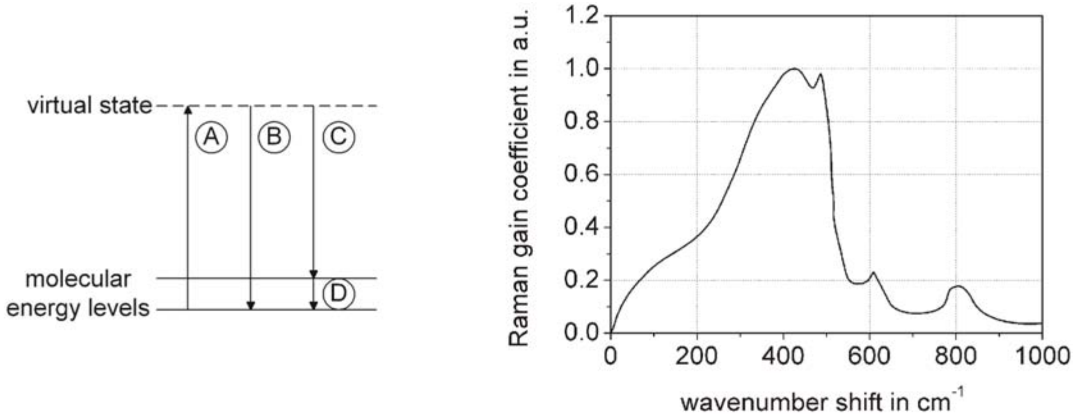

Figure 1.3: Energy diagram of RDFa and Raman gain coefficient of the SiO_2 fiber

Although the setup of Raman amplifier, which consists of high power pump diode, WDM coupler, and the transmission fiber is very simple, its operation principle is more complicated [15]. During the optical pumping process pump photon energy is absorbed into the short-lived virtual excited state (transition labelled as “A” in figure 1.3). Due to the relaxation of the molecule a photon at the same wavelength as the pumping photon is emitted (B). This dominating process is called Rayleigh scattering and acts as a source for optical losses. There is, however, a small probability, that the photon with lower energy (longer wavelength) is emitted due to spontaneous Raman scattering. The difference (D) between the pump photon and the spontaneous emission does not depend on the pump wavelength and is known as Raman shift. For SiO_2 fibers its spectrum shows a maximum at about $450\,\mathrm{cm}^{-1}$ [16] what corresponds to a difference of about 100 nm between the pump and the signal wavelength. If sufficient pump power is coupled into the fiber, the population inversion between virtual state and the final state reaches the threshold value. This causes amplification of signal due to stimulated Raman scattering (C). Since the Raman gain coefficient for typical SiO_2 fiber is very low, the length of the fiber required to achieve high gain is very long (several kilometers). The Raman gain coefficient is a material property and it can be improved by applying high germanium doped silica fibers [15]. But due to the large dimensions those amplifiers (discrete RFAs) are not very convenient for optical transmission systems.

Another group of RFAs (distributed RFAs) gained big interest in the last time. They consist of counter-directionally pumped transmission fiber and they are of great importance for high capacity optical systems. An upgrade of actual transmission systems from 10 Gbit/s to 40 Gbit/s has a large influence on their power budget, since it causes reduction of the individual data channel power of factor 4 and degradation of signal-to-noise-ratio. The decrease of the power can not be compensated by higher output power of the preceding repeater because the total input power is limited to 500 mW for safety reason. Nevertheless, this unfavorable situation can be improved assuring amplification of the optical data stream along the transmission fiber.

Since the gain spectrum can be modified by varying the pump wavelength, the RFAs are wavelength independent. This feature makes possible to construct broadband Raman amplifiers, pumped with several high-power laser diodes [17] or using second order pump wavelength [18, 19]. The highest amplification bandwidth of more than 130 nm was reported for amplifier using interleaving allocation of pump and signal wavelengths [20].

Several experiments with amplifying of 40 GBit/s optical signals using Raman amplifier were reported [18, 21, 22]. The extremely inefficient energy transfer process in RFAs can be improved by applying the pump source with the wavelength corresponding to the second order Raman shift. The signal power improvement comparing to the conventional bi-directional pumping scheme was 5 dB and the total pump power was less than 600 mW for approx. 80 km of the self-developed dispersion modified fiber.

The RFAs are commonly used to amplify signals together with the C- and/or L-band EDFAs [9, 23, 24]. As an example, an RFA was used together with the L-band EDFA to enhance the gain of the transmission system [24]. In the experiment forty 0.8 nm spaced channels located in the wavelength region from 1571 to 1604 nm were amplified using almost 1 W of the total pump power. The gain reported for -2 dBm of the total signal power was