Fluoride glass fiber amplifiers for the S-band

R. Caspary*, M. M. Kozak, and W. Kowalsky
Technical University of Braunschweig, Institut für Hochfrequenztechnik
Schleinitzstr. 22, 38106 Braunschweig, Germany

ABSTRACT
Due to the growing bandwidth demands in photonic networks, new fiber amplifiers besides the C- and L-band (1530-1610 nm) will be necessary in the future. Thulium-doped fiber amplifiers (TDFA) provide gain in the S- and S⁺-band (1450-1530 nm) and are therefore important candidates for next generation photonic networks. As TDFAs usually need fluoride fibers as hosts for the thulium ions, an introduction to fabrication and special properties of fluoride fibers will be given at first in this work. It follows a detailed introduction to the operation principles and special properties of TDFAs together with a short literature review on TDFA research. After that we show a simulation model for TDFAs and its application to understand gain-shift operation, and finally some first measurements with self-made thulium-doped fluoride fibers are presented.

Keywords: fiber amplifier, TDFA, S-band, thulium, fluoride fiber, photonic networks, optical telecommunication

1. INTRODUCTION
Optical longhaul data transmission systems today usually operate in the C-band from 1530-1570 nm. The standard amplifier for these systems is the erbium-doped fiber amplifier (EDFA), which provides gain more or less in the whole C-band. For high data rate links, dense wavelength division multiplexing systems (DWDM) with increasing bitrates per channel and decreasing channel spacing are used. Of course, this process can’t be continued without limitations. One fundamental limitation is the general design of transmission systems today, which usually contain polarisation and phase insensitive photo detectors. Such a detector is detecting the intensity of an optical signal only and therefore it allows for a maximum of 1 bit/s of data rate for each Hz of optical bandwidth in a single transmission fiber. Together with EDFAs in the L-band from 1570-1610 nm, this situation limits the EDFA-technology to a maximum of 10 Tbit/s, or 256 channels with 40 Gbit/s. This value may seem to be quite large at first, but experiments with such data rates were already published, see the transmission of a 6.4 Tbit/s signal\(^1\). To avoid the mentioned capacity limit, a new generation of senders and receivers is needed, which uses e.g. polarisation multiplex techniques\(^2\) or heterodyne detection with local oscillators in the detector.

Another approach to reach very high bitrates without violating the 1 bit/s/Hz limit is the usage of transmission bands besides the C- and L-band. The usable range of the low-loss window of transmission fibers is usually considered to be 1200-1700 nm. Figure 1 indicates the spectral position of a couple of rare-earth doped fiber amplifiers in this window. Of most practical importance are amplifiers in the S and S⁺-band, on the one hand due to their spectral location close to the C-band and on the other hand because the dispersion compensation is more easy at shorter wavelengths than in the long wavelength edge of the transmission window. These S-band amplifiers use thulium for the active core instead of erbium and are therefore called thulium-doped fiber amplifiers (TDFA). Unfortunately it turns out, that EDFAs are the only rare-earth doped fiber amplifiers which operate efficiently with silica fibers. The reason is, that most other suitable amplification transitions of rare-earth ions contain at least one intermediate energy level between the upper and lower amplification level. The short distance to this intermediate level leads to a fast non-radiative (multi-phonon) depopulation of the excited state. Because the dependence of the multi-phonon relaxation rate on the number of phonons (quantized glass matrix vibrations) needed to bridge the given energy gap, is exponential, use of fibers made from glasses with low maximum phonon energy (LPEglasses) leads to substantial higher quantum efficiencies of the amplification transitions in these glasses. An example: an energy gap of 3 µm is bridged by 3 phonons in silica glass,

* r.caspary@tu-bs.de; phone +49-531-3912005; fax +49-531-3912045; http://www.tu-braunschweig.de/ihf
but 6 phonons are needed in fluoride glasses. The multiphonon rate for this transition is therefore 20 times larger in silica than in fluoride glass. In the family of LPE-glasses the fluoride glasses are the only known members with properties suitable for S-band amplifiers.

It should be noted, that besides the rare-earth doped fiber amplifiers there is considerable progress in the development of Raman fiber amplifiers. Due to their physical operation principle they are not fixed to a certain amplification wavelength and can also be used in the S-band. Although it seems, that fluoride glass is the best host for TDFAs, there are other types of glasses, which may be used. The most interesting competitor of the fluoride glasses in case of the T DFA are tellurite glasses. Due to their large refractive index of about 2, they offer a significantly broader fluorescence spectrum. However this high refractive index is a big disadvantage for practical use and fusion splices to silica fibers are not possible.

2. FLUORIDE GLASS FIBERS

The energies of the phonons mentioned in the last section are the resonance frequencies of the glass matrix. Because of the exponential dependence of the multiphonon relaxation rate on the number of phonons involved in the transition, only the phonons with the highest energies play a notable role in this process. For LPE-glasses, two points are important: First the glass components should show weak bonding forces, which usually means ionic bonding and second the glass compositions should contain heavy atoms. The result is a glass matrix with low resonance frequencies, and as a consequence the infrared absorption edge is shifted to the mid-infrared. Fluoride glasses for example are transparent from the near UV up to 5-6 µm, which allows for a wide range of applications. However, the weak bonding in the LPE-glasses leads to some drawbacks: The glasses are more or less hygroscopic, they show a high tendency to crystallize and their mechanical stability is lower than in case of the usual oxide glasses.

There are a couple of different known fluoride glass compositions. Of most practical importance are the glasses based on zirconium-fluoride with names like ZBLA or ZBLAN. Most fluoride fibers available are of this type, which is known since 1975. A newer development are the fluoride glasses based on indium-fluoride, the so-called indat glasses. Indat glasses have maximum phonon energies of about 510 cm⁻¹, compared to ZBLAN with about 580 cm⁻¹ and silica glass with 1100 cm⁻¹. At our institute ZBLAN is the standard glass and indat fibers based on a new glass composition are still under development.

The fabrication of fluoride fibers starts with a melt of extremely pure raw materials (fluorides) with melting temperatures around 800 °C. Casting of this melt in a rotating mold gives a tube of cladding glass. As an alternative, it is possible to drill a hole into a rod of cladding glass. Next a melt of core glass is prepared and filled into the cladding tube, which results in a preform ready to fabricate a multi-mode fiber. To fabricate single-mode fibers, the diameter of
the first preform has to be reduced by stretching. The resulting preform stick is then placed into a second cladding tube. Drawing and coating of fluoride fibers is not very different from oxide glasses, except of the low temperature furnace to heat the preform (about 300 °C).

The low melting temperatures of fluoride glasses, or LPE glasses in general, are a consequence of their soft glass matrix and due to these low temperatures the impurities of the raw materials do not evaporate from the melt. This fact and the high tendency of the glasses to crystallize, are the main reasons for the high attenuation of fluoride fibers compared to oxide fibers. As a general rule, fibers with an attenuation below 100 dB/km can be regarded as very high quality. It is obvious that such fibers are not useful as long distance transmission fibers, but in active applications as fiber lasers and amplifiers with typical fiber lengths from 20 cm up to 20 m, compensation of the fiber attenuation by the gain of the dopant provides no problems. Figure 2 shows the attenuation spectrum of two thulium-doped ZBLAN fibers made in our institute. Fiber amplifiers need fibers with high numerical aperture, because this results in a high power density in the fiber core, which is necessary for efficient operation. Variations of the numerical aperture are obtained by different concentrations of PbF₂ in the fiber core and/or HfF₄ in the cladding. However, as the glass formation is very sensitive to the glass composition, concentration changes usually require notable changes in the fabrication procedure to avoid crystallization.

Applications of fluoride fibers can be divided into three wavelength regions: the mid-infrared, the near-infrared and the visible range. In the mid-infrared we developed fiber lasers with wavelengths up to 3.9 µm, which is still the largest emission wavelength of a fiber laser until now. In the near-infrared, fiber amplifiers are of most interest, as thulium-doped fiber amplifiers (TDFA) in the S-band and praseodymium doped fiber amplifiers (PDFA) at 1.3 µm. Finally the large lifetime of excited states due to low multiphonon relaxation rates allows for very efficient up-conversion processes which are used for visible fiber lasers pumped with laser diodes in the near-infrared. Such fiber lasers are of interest e.g. for medical applications or color printing.

3. THULIUM-DOPED FIBER AMPLIFIERS

3.1 Principles of operation

For an understanding of the special properties of thulium doped fiber amplifiers, a discussion of the energy level system of thulium, as shown in figure 3, is necessary. To avoid unnecessary confusion, it should be noted, that two different labeling schemes for energy levels of rare-earth ions are in use, which usually result in the same name for the same state. Unfortunately, in case of thulium the order of the two names ⁴H₅ and ⁵F₄ depends on the labeling scheme which is
used. As the actual name is of no importance for practical investigations, we will use the numbers shown on the left side of the energy levels instead.

The transition used for S-band amplification is $3\rightarrow1$ with the central wavelength of the fluorescence being 1.46 µm as shown in figure 3. The lower level of the amplifier transition is not the ground state of the thulium ion, the T DFA thus is basically a four-level amplifier, and in contrast to the EDFA, an unpumped TDFA shows no signal attenuation. The first pump transition uses 790 nm and excites thulium ions from the ground state to level 3. The next step is a stimulated emission process, which ends up in level 1. At this point the system would terminate, since the lifetime of level 1 in fluoride glasses according to the measurement in figure 4 is about 11 ms, due to the low phonon energy of these glasses. Thus a second pump transition is needed to depopulate level 1. One possibility is the excited state absorption (ESA) $1\rightarrow5$ at 1055 nm. Thulium ions in level 5 will undergo a fast non-radiative decay ending in the upper amplifier level 3, so the energy loop is closed. In practice the large lifetime of level 1 leads to the fact, that the second pump is much more important than the first one, and the TDFA is even working when the 790 nm pump is omitted, although with lower power conversion efficiency.

In a pumped TDFA, level 1 due to its large lifetime plays the role of the ground state and in fact, to many respects the TDFA behaves as a quasi-three-level amplifier. When compared to the EDFA, the 1050 nm pump in the TDFA corresponds to a 980 nm pump in an EDFA, and the EDFA pumped at 1480 nm corresponds to a TDFA with its second pump at 1400 nm. In analogy to the EDFA, the TDFA pumped at 1050 nm is best for preamplifiers, as it has the lower power conversion efficiency (PCE), but a population inversion level of about 100%, resulting in a low noise figure, whereas the TDFA pumped at 1400 nm is good for power amplifiers, as it has the higher PCE, but a lower inversion level, thus a higher noise figure. A typical setup of a two stage T DFA therefore should look as shown in figure 5. The preamplifier stage is pumped co-directional at 790 and 1055 nm. Then there follows an optical isolator and a gain-flattening filter. At the end there is a power amplifier pumped contra-directional at 790 and 1420 nm. The characteristics of the gain-flattening filter are obviously different from filters used for EDFAs.

The natural operating regime of the TDFA is the S$^+$-band at 1450-1490 nm. But, as it can be seen in figure 1, the S-band shows some overlap with the OH-absorption, which is still present in existing fiber links. Therefore much effort was spent on the development of gain-shifted TDFAs operating in the S-band at 1490-1530 nm. With the pump configurations discussed above, the TDFA behaves as a quasi-three-level amplifier. Therefore the same techniques as in case of the L-band EDFA may be used to achieve low inversion levels, namely a weak pump at 1400 nm and a long fiber.

### 3.2 Spectroscopic properties

Rare-earth doping of zirconium based fluoride glasses is done by substitution of LaF$_3$ and therefore the dopand ions are regular members of the glass matrix. In contrast to silica glasses, it is therefore possible to use very high rare-earth concentrations up to about 4 mol% without the formation of dopand clusters. Nevertheless, rare-earth doped fluoride
glasses also show quenching effects when the mean distance between the individual ions is small enough to allow efficient energy transfers due to dipole-dipole coupling \(^{12}\). The corresponding transition rate follows the equation \( R \propto a + b c^2 \), with two material parameters \( a \) and \( b \) and the dopant concentration \( c \). For practical reasons it is usually preferable to use short fibers with high rare-earth concentration and therefore we carried out measurements to find the quenching limit. Figure 4 shows the lifetimes of the upper and the lower amplifier level for thulium in ZBLAN glass. The measurements show a quenching limit of about 3000 ppm for the upper and about 6000 ppm for the lower amplifier level. The fact, that both levels show different quenching limits is explained by the different overlap integrals of the electron distributions of both levels, and because the higher energy level has a larger electron distribution, the according quenching limit is smaller. As a compromise between quenching and fiber attenuation we usually use fibers with 5000 ppm of thulium.

Instead of zirconium based fluoride glasses, one may also use indium based fluoride glasses (indat). Although the energy levels of rare-earth ions are host-independent to a high degree, the quantum composition of the corresponding electronic states shows a certain dependency on the host material \(^{13}\). Therefore the line strengths of the electronic transitions are different in different hosts. A detailed investigation of the differences of the spectroscopic properties of thulium in our ZBLAN and indat glasses recently showed mainly two significant differences \(^{14}\): The excited state absorption (ESA) \(1 \rightarrow 5\) at 1050 nm is about 40% and the emission \(3 \rightarrow 2\) at 2.3 \(\mu\)m about 20% stronger in indat than in ZBLAN. All other relevant transitions are increased by about 10% in indat glass due to its slightly larger refractive index. The influence of the increased ESA transition on the TDFA characteristics depends on the pumping scheme and the operating conditions, but in general a larger pump absorption is an advantage. However, the increased emission at 2.3 \(\mu\)m is an important loss path in the TDFA and therefore may lead to a lower power conversion efficiency and higher noise figure.

3.3 Connections between fluoride and silica fibers

Besides the obvious differences to the setup of EDFAs there is a more subtle, but important one: Due to the low melting temperature of fluoride glass it is impossible to use usual fusion splices to connect the active fluoride fiber with the silica fibers of the surrounding components. Fortunately the difference of the refractive index of fluoride and silica glass is quite small, which allows butt-coupling without significant reflection losses. The standard splicing method today is therefore to prepare the ends of both fibers with angled cleaves and connect them in V grooves fixed with glue. Due to the high power density in the fiber core, care must be taken to keep the glue away from the fiber end-faces. Usually the active fluoride fiber has a high numerical aperture (HNA) and a small mode-field diameter. Since usual thermal expanded core splices (TEC) are impossible, the fluoride fiber is not directly connected to a standard single mode fiber but to a silica fiber with HNA and the same mode-field diameter as the active fiber. The connection from the HNA silica fiber to a standard single mode fiber can then be done with TEC-splices using a standard fusion splicer. This complicated technique today is the most critical point for all fiber amplifiers using a fluoride fiber. Until now no really satisfying solution was found.

To test the long-term stability of such glue splices we continuously measure the attenuation of a couple of short pieces of thulium doped fluoride fiber with silica fiber pigtails on both ends. The results from a measurement period of more than one year are compiled in figure 6. The attenuation offset for each fiber is arbitrary, as there are several sources for
the measured total attenuation which can not be separated. It should be noted, that each sample fiber contains two glue splices. Except of some variations at the beginning of the measurement period in case of fiber 1-3 due to measurement problems, most glue splices do not show large variations of the attenuation. Since fiber 2 was broken due to inadequate handling, fiber 1 was the only one which really failed until now. Except of fiber 4, which showed an increasing attenuation during the first 100 days, all fibers seem to be stable with constant attenuation.

3.4 Review of T DFA development

The development of S-band TDFAs started in 1993 with a paper from NTT, Japan. This first T DFA was pumped with a single wavelength at 1064 nm with a power conversion efficiency (PCE) of 2%. In the following years, NTT concentrated on the development of co-doping techniques (Tm/Ho-doped fibers) to reduce the lifetime of level 1 in TDFAs pumped at 800 nm. It seems, that this approach was not successful enough, because from 1996-2000 the papers from this group presented TDFAs without co-dopand, but pumped at 1047 nm with a PCE up to 12%. Starting 2000, the group used a fiber doped with 6000 ppm Tm instead of the former 2000 ppm and found that this higher concentration led to gain shifted operation even in case of a single pump at 1047 nm. A PCE of 42% in the range 1480-1510 nm was published 2001. A second active group in the field of TDFAs is located at NEC, Japan. They concentrated on gain-shifted operation with a first pump at 1560 nm. The combination with a second pump at 1047 nm was brought from a PCE of 2% to 9%. Better results were achieved with a dual second pump at 1405+1420 nm together with the first pump at 1560 nm. This pumping scheme reached up to 29% of PCE. A couple of different pumping schemes were also investigated at Alcatel, France with focus on high PCE. A PCE of 20% was achieved with a dual pump at 117+1064 nm. Significant improvements were made when 1400 nm was used as the second pump. Together with a first pump at 1238 nm a PCE of 48% was demonstrated and a first pump at 800 nm even led to more than 50% PCE. Also investigated at Alcatel were the pump configurations with a first pump at 1550 nm. It was found that, similar to the situation in gain-shifted EDFA, using a second pump at 1400 nm, directly connecting the lower and upper amplification levels, led to better results in gain-shifted operation than a second pump at 1047 or 1064 nm. Due to the telecom boom, the number of publications dealing with TDFAs grows enormously in the years 2000 and 2001. It was found that the pumping scheme 800+1050 nm is not only very efficient, but also allows amplifiers with low noise figures.

A couple of broadband transmission experiments were also reported. One of the first experiments 1999 used three amplifiers in parallel (T DFA @ S-band, EDFA @ C-band, GS-EDFA @ L-band) to transmit 54x10 Gbit/s over 3x80 km of transmission fiber. A 10.92 Tbit/s-experiment was published 2001. This experiment again used three amplifiers in parallel (GST-DFA @ S-band, EDFA @ C-band, GS-EDFA @ L-band) and a sum of 273 channels with 40 Gbit/s each were transmitted over 117 km.
For the practical usage of fiber amplifiers in WDM systems, an active control of the amplifier gain is important. In the last years a couple of papers regarding TDFAs were published in this field. Investigations on the transient response of TDFAs were reported\cite{35,36} and a gain-clamped TDFA was developed\cite{37}. Furthermore some TDFA setups with active gain-tilt control were shown\cite{38,39,40}. Obviously the controllers must be different from EDFA systems due to the different population dynamics in the energy level system of thulium. But it seems that there are no fundamental problems.

4. TDFA SIMULATION

Computer models for the simulation of TDFAs are very different from EDFA simulations as a lot of different pump wavelengths and at least five energy levels have to be regarded. The first model published was a physical model based on rate equations and was used to model the dependence of the TDFA on the pump wavelength\cite{41}. Furthermore a black box model for fast simulations was presented\cite{42} and another rate-equation model including energy transfers between the dopand ions\cite{43}. The latter one is of special interest for thulium-doped silica fibers, in which rare-earth dopands tend to form clusters.

Our simulation model is also a rate equation model which is based on a former fiber laser simulation\cite{13}. The simulation core is independent of the actual rare-earth ion used. It is just applying the full set of rate and gain equations to an unlimited number of energy levels and photon fluxes. Input data are all relevant absorption and emission cross section spectra, the radiative and non-radiative loss rates and the fiber parameters length, core diameter, numerical aperture and dopand concentration. The photon fluxes are separated into signal, pump and ASE to allow an easier interpretation of the results, but the simulation core does not make any difference. Therefore the model has no problem with a completely depopulated ground state or even gain at a pump wavelength.

The algorithm of the simulation is shown in figure 7 in a graphical representation. The fiber is divided into a number of segments for analysis.

Figure 7: Simulation procedure

Figure 8: Simulation of a thulium doped fiber pumped at 790 and 1056 nm.
Fiber data: 5000 ppm Tm\textsuperscript{3+}, NA=0.24, core=3.2 µm.
fiber segments. In each segment the incident photon flux is used to calculate the population of all energy levels using the rate equations. After that, the gain equations are used to calculate the photon flux leaving the fiber segment. This calculation is done for every segment along the fiber several times, until the results are converging. Since reflections at the fiber ends are taken into account, the model also covers fiber lasers, e.g. due to reflections at inappropriate fiber connectors. To get results with reasonable accuracy, the number of segments should be large enough that the relative differences between the fluxes entering and leaving a fiber segment are small. For fast and stable calculations 50 segments are usually enough, but several hundred fiber segments are used to get reliable results.

An example for a TDFA simulation is given in figure 8. As the upper left graph shows, the fiber is pumped with 200 mW@790 nm and 50 mW@1056 nm at the left fiber end. In the mid of the fiber, the 1056 nm pump is completely absorbed, whereas only 75% of the 790 nm pump are absorbed along the whole fiber. From the lower left graph it can be seen, that the ground state (level 0) is nearly depopulated all along the fiber and therefore the pump absorption in the upper left graph does not follow a simple exponential law. Furthermore the population distribution in the lower left graph shows remarkable differences in the first and the second half of the fiber. On the left side the 1056 nm pump transition $1 \rightarrow 3$ builds up a population inversion between the upper amplifier level 3 and the lower amplifier level 1. This part of the fiber provides the signal gain with a center wavelength of 1460 nm according to the fluorescence peak. In the right half of the fiber there is no population inversion any more, but due to the remaining 790 nm pump, more than half of the thulium ions are in the lower amplifier state 1. Therefore this part of the fiber is absorbing the signal power and due to the wavelength offset between absorption and emission, this absorption affects mainly the short wavelength side of the gain spectrum. Fortunately the absorbed signal power is not completely lost, as the absorption process is exciting the ions to the upper amplifier level 3 and therefore acts as a pump transition. The overall effect is a net gain shifted to longer wavelengths, as it can be seen in the gain spectrum shown in the right graph of figure 8. This gain-shifting process (GS) is similar to the situation in an L-band EDFA, and like the L-band EDFA, such a GS-TDFA is less efficient due to the double stage pump conversion process.

Very different to the situation in an EDFA is the case where the active fiber is too long. In case of an EDFA, the fiber attenuation is increasing with decreasing pump power and therefore the correct fiber length in an L-band EDFA must be carefully chosen. In contrast to this case, an unpumped thulium doped fiber is not absorbing the signal, because the TDFA is a four-level amplifier. The gain-shift process just stops at the point, where the 790 nm pump is completely absorbed.

The relation between the gain-shifting process and the pump power for the same fiber as in figure 8 is shown in some more detail in figure 9. For this simulation, the pump power at 790 nm was kept constant at 200 mW, and the 1056 nm pump was varied from 0-200 mW. When there is no 1056 nm pump, all thulium ions in the whole fiber stay in the first excited state. Therefore there is no gain at all, but a strong signal absorption. The opposite situation is reached when the fiber is pumped with 200 mW@1056 nm. In this case, there is population inversion along the whole fiber, which gives

![Figure 9: Gain-shift simulation for the pumping scheme 790/1056 nm.](image)

Fiber data: 5000 ppm Tm$^{3+}$, NA=0.24, core=3.2 µm, length=2 m.
maximum gain, but no gain-shift. However, when the 1056 nm pump is reduced, the part of the fiber with population inversion becomes shorter and therefore the overall gain is decreasing, but the gain-shift is increasing.

5. TDFA MEASUREMENTS

The first TDFA measurements with one of our self-made thulium-doped fluoride fibers are shown in the figures 10 and 11. At that time, only laser diodes at 1055 nm were available as pump sources. The glue splices between the fluoride and the silica fibers require fibers with similar core diameter and numerical aperture, otherwise large losses are caused by the mismatch of the mode-field diameters in both fibers. Since an appropriate silica fiber with high numerical aperture was not available, the measurements had to be carried out using fiber 1 from figure 1 with a low numerical aperture. These sub-optimal conditions should be kept in mind when the results are compared with literature values.

As it can be seen in figure 10, the TDFA shows only a very small gain-shift with decreasing pump power. This behavior is as expected for a TDFA pumped only at 1055 nm, because as long as there is remaining pump power, the lower amplifier level is always depopulated and when the pump power is absorbed, all thulium ions stay in the ground state which is not absorbing at the signal wavelength. With a pump power of 380 mW a maximum gain of about 11 dB was achieved. The large noise figures in the right graph of figure 10 are also well known for this single-wavelength pumping scheme.

Since there is no resonant ground state absorption at 1055 nm, such a TDFA is very inefficient. As it can be seen in figure 11, gain saturation is reached at an input signal level of –24 dBm. At an input power level of –5 dBm a maximum
output power of 1 dBm was achieved.

ACKNOWLEDGMENTS

This work is supported by the German ministry of education and science (BMBF) as project 01BP275 in the project cluster MultiTeraNet.

REFERENCES

22. T. Kasamatsu, Y. Yano, H. Sekata, “1.50 µm-band gain-shifted thulium-doped fiber amplifier with 1.05- and 1.56 µm dual-wavelength pumping”, Optics Letters 24(23), 1684-1686, 1999