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## Progress on erbium-doped waveguide components

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**Abstract:** The recent development on erbium-doped fiber amplifiers, and fiber lasers is reviewed. Also the latest results on planar erbium-doped waveguide amplifiers and high erbium concentration characterisation methods are presented.

**Introduction:** Only few technologies have had a more profound impact on the development of optical communication systems than the erbium-doped fiber amplifier (EDFA), and since the first demonstration of a practical EDFA in 1987 [1], the EDFA has due to a huge international research and development effort become the key element in optical communication systems. Several text books have been published on the subject [2-5] in the past few years, and the basic properties of rare-earth-doped (RED) waveguide devices are thoroughly described in these, but because of a tremendous development of EDFA applications, new system related challenges continue to appear.

It is the aim of this presentation to provide an overview of the most recent progress on the development of erbium-doped waveguides (i.e., fibers and planar integrated RED waveguides). Special focus is on the system application aspects of the EDFA, and in relation to this, we have also chosen to discuss some of the latest research results within the areas of fiber lasers, integrated planar erbium-doped devices, and characterisation of high concentration erbium-doped waveguides.

**Fiber amplifiers in optical communication systems:** It has for decades been understood that optical communication systems offer a very large transmission bandwidth, and in the process of bringing this potential to practical use, the EDFAs play an increasingly important role. This is reflected in the fact that most commercial communication systems installed today include one or more EDFAs, and the amplifiers are key elements both in future digital optical networks (in contrast to the point-to-point transmission systems), and in amplitude-modulated (AM) frequency division multiplexed (FDM) systems for video transmission. Most of the recent high capacity experiments, however, employ wavelength division multiplexing (WDM) techniques, which in addition to obvious capacity improvement offer higher flexibility of future optical communication networks. Figure 1 illustrates the increase in transmission capacity for long distance optical communication systems by showing the bitrate-distance product as a function of publication year for the transmission experiment. It is obvious, how the inclusion of EDFAs has resulted in a capacity increase of more than two orders of magnitude over a period of less than 10 years.

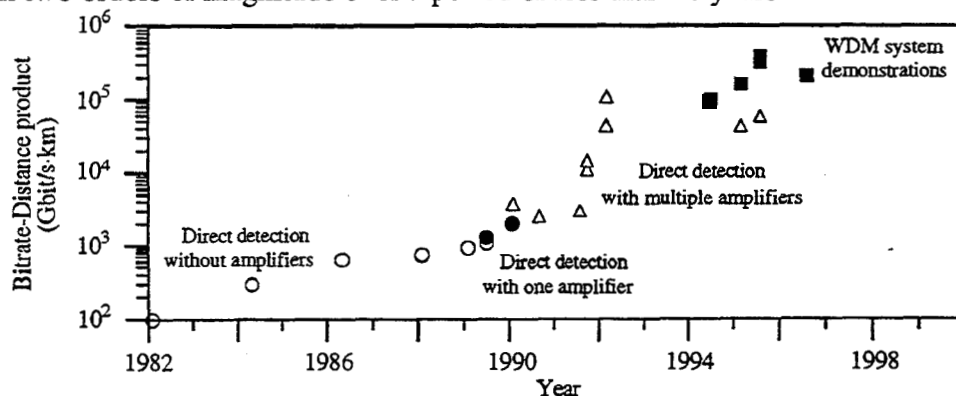


Figure 1 Bitrate-Distance product as a function of year of publication. Most of the data points origin from papers listed in [4], and details of the most recent results may be found in [6-8].

In the present and future WDM applications of EDFAs, the gain nonuniformity (or gain tilt) is one of the most important problems, and several techniques for equalizing the nonuniform EDFA gain have been proposed. Among the methods for gain flattening are the use of internal or external filtering [9], requiring accurate filter tuning and resulting in pump power loss, or the clamping of inhomogeneous gain [10] by incorporating the amplifier into a ring laser. Alternative methods for obtaining gain flatness are the application of short and highly pumped erbium-doped fibers [11], suffering from low power conversion efficiency, or changing the fiber host material such as in the case of fluoride-based EDFAs [12].

To overcome some of the problems in the reliability and the complexity of the mentioned EDFA configurations, a hybrid-amplifier approach has also been suggested [13-14], in which erbium-doped fibers

with different glass compositions are serially cascaded. The basic idea behind this hybrid-amplifier configuration is the constructive use of the opposite signs of the gain slopes of silica erbium-doped fibers (EDFs) with different codopants (in the specific case of [13-14] the Al-codoped EDF has a positive gain slope and the P-Al-codoped fiber has a negative gain slope in the 1550 nm wavelength range). It has also been suggested to combine the opposite gain slopes within one single fibre [15], resulting in improved stability towards longitudinal pump power redistribution.

As lightwave systems move towards higher bitrates, higher powers, longer span lengths, and even all-optical networks, another possibility for system upgrade exists in time division multiplexing (TDM) techniques. These are especially interesting for very highspeed systems (bitrates  $\geq 40$  Gbit/s) and may make use of soliton techniques. In such systems optical signal processing [16] becomes an interesting possibility. However, most of the present development is directed towards WDM systems, and although soliton based TDM may play an important role in future communication systems, the remaining part of this section will address WDM related issues.

The results on Figure 1 specifically represent the progress on long distance communication systems, where many (up to several hundred) EDFAs are coupled in cascade. However, also intermediate or short distance distribution systems are developing rapidly due to the EDFA. One subject of specific interest has been the realisation of communication links of a few hundred kilometers length, where the property of remote pumping of erbium-doped fibers have been applied. Hereby, inline (e.g., submarine) placement of optical pump sources may be avoided. Such solely end-pumped systems have been demonstrated to transmit 2.5 Gbit/s signals over more than 500 km [17]. In order to make this system work, a number of properties must be considered; Stimulated Brillouin Scattering (SBS) suppression, application of Stimulated Raman Scattering (SRS), high power Raman pump lasers (fiber laser pumped), dispersion compensation, forward error correction (FEC), and fiber grating pump reflectors.

The low noise amplification provided by the EDFA has already resulted in a revolution in optical communication technologies, and high power WDM optical networks seem to be a reality in very near future. For such systems, new technological and scientific challenges have to be met, and we will here finally mention some of the important considerations at this stage of the development:

- Dispersion management (Need for fibers with low and well controlled dispersion)
- Modulation formats (Forward error correction)
- Polarisation sensitivity (Need for polarisation scrambling)
- Four Wave Mixing (Need for unequal or larger channel spacing, and some dispersion)
- Self Phase Modulation (Careful consideration in systems applying high powers)
- Stimulated Brillouin Scattering (Need for carrier broadening - Signal dither)
- Cross Phase Modulation (Relevant for high power systems, and optical signal processing)
- Gain cross saturation (Need for automatic gain control, or inversion clamped amplifiers)

**Fiber lasers:** Erbium-doped fiber lasers may be viewed as EDFAs operating in the particular regime, where coherent oscillation of amplified spontaneous emission (ASE) occurs due to some means of feedback. Among the basic advantages of RED fiber lasers are: they can be pumped with compact efficient laser diodes, they are compatible with optical fibers giving negligible coupling losses, connecting by splicing alleviates any mechanical alignment of parts and provides superior environmental stability, they offer wide tunability covering the third telecommunication window (around 1.55  $\mu\text{m}$ ). Laser cavities may be categorized according to the means of feed back. In ring cavities the EDF is spliced in an endless loop, eliminating the need for laser mirrors. Furthermore, the ring cavities may be designed to operate unidirectionally by introducing an optical isolator in the loop. Output power of 4.2 mW, a tuning range of 61 nm, a threshold of absorbed pump power of 2.9 mW, and a slope efficiency of 15 % was reported in 1991 [18]. Ring configurations have proven especially promising for short pulse generation. Pulse-duration of 8 ns has been demonstrated in Q-switched EDF ring lasers [19]. Loop lengths are typically several meters making these lasers sensible to temperature drift. A second category are Fabry-Perot cavities, that relay on some sort of mirror to provide the feedback. The first reported EDF laser had a bulk mirror butt-coupled to one fiber end facet, and a bulk reflection grating as a wavelength selective mirror at the opposite end[20]. The development of the UV-induced fiber Bragg reflection grating [21] allowed for all-fiber-laser cavities. Fibers with highly wavelength selective Bragg-reflection gratings [22] were spliced to the EDF to form the laser cavity [23]. The core of the EDF itself can be made UV-sensitive by hydrogen loading, and Bragg reflection gratings may be imprinted directly in the amplifier fiber, thereby, producing a distributed-feedback (DFB) laser [24]. Hydrogen loading introduces excess losses, making this procedure less desirable. The most promising laser configuration is the DFB laser made by UV phase-mask side-writing and a UV induced permanent  $\pi/2$  phase shift [25]. Here, the fiber is made UV-sensitive by Ge-codoping. This is a true all-fiber laser. It shows robust single-mode operation over a wide temperature range. The grating in the EDF is 25 mm long and the Er-concentration is  $1.5 \cdot 10^{25} \text{ m}^{-3}$ . This yields a pump power slope

efficiency of 0.6 % due to the low absorption in the EDF. The performance is illustrated in Figure 2. Present development is focused on increasing the gain per length and pump efficiency by increasing Er-concentrations and codoping with ytterbium (Yb). Since it seems unlikely to achieve optimal gain and high UV-sensitivity in the same glass (as codoping with Ge and Yb causes phase separation in the glass), separation of Erbium-doped and UV-sensitive glass in the fiber cross section is a design possibility that could increase output power. Several DFB lasers with closely spaced lasing wavelengths may be written in the same EDF. This would produce a robust "monoblock" multiwavelength source that might be the choice for emitters in future WDM networks.

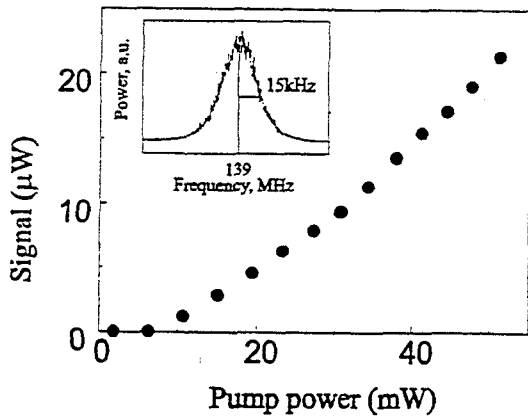


Figure 2

Output characteristic of erbium-doped fiber DFB laser. Insert shows result of delayed self-heterodyne linewidth measurement. From [25].

**Planar erbium-doped waveguides:** Planar waveguides doped with erbium show great potential for making integrated optical devices for the 1550 nm region. Er-doped planar waveguides were first presented in 1990 [26-27] opening possibilities for lasers and amplifiers. Since then Er-doped waveguides and amplifiers have been realised in a variety of host materials using different fabrication and erbium-incorporation techniques. Figure 3 gives a review of erbium-doped planar waveguide amplifiers. Among the best results are a total gain of 27 dB [33] and gain per length of 3.33 dB/cm [31]. In the references, there is no common standard for whether the gain is internal, net, or fibre-to-fibre. As can be seen, very high pump powers are often needed to achieve high gain with a few exceptions such as [29], [36], [37], and [40]. From Figure 3, two different approaches for making amplifiers appears, distinguished by the waveguide length, i.e. long waveguides (>100 mm) and short waveguides (<100 mm). To fabricate integrated devices, the ideal situation is to obtain short waveguides, since the physical size of the substrate is limited. This problem is overcome (or limited) with the long waveguides by shaping it in a spiral [28, 32-33]. As seen from Figure 3, the long waveguides are needed to achieve high gain, because the gain per length in the different materials is limited by degrading effects limiting the erbium concentration. Lossless 1x2 splitters [41] and amplifiers integrated with pump/signal WDMs have already been demonstrated [33, 36]. The lossless splitter in [41] is fabricated in an Er/Yb-codoped substrate, so the splitting region is active. Another way to combine functions is to integrate passive sections with an amplifying section on the same substrate, thereby, achieving a separation of functions. In this way simple, straight, or curved amplifiers may be used. This is done by end-to-end coupling of erbium-doped and undoped planar waveguides on the same substrate [42].

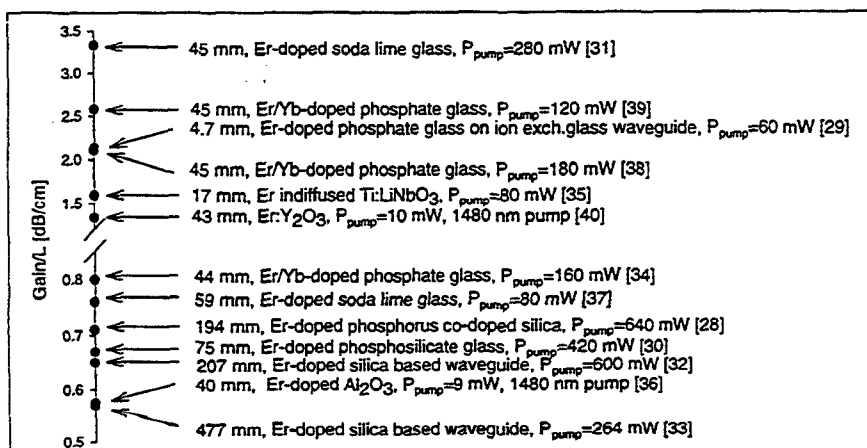


Figure 3

Review of planar erbium-doped waveguides showing the gain per length, the length of the waveguide, the host material, and the applied pump power. In [36] and [40], the pump wavelength is 1480 nm, and in the remaining references the pump wavelength is around 980 nm.

**Characterisation of high-concentration erbium-doped materials:** To obtain sufficient gain over the short device length of a planar waveguide amplifier or a fiber laser, high Er-concentrations are needed. However, at high Er-concentrations, interaction between Er-ions will lead to excitation quenching through energy transfer upconversion (ETU) between erbium ions in the upper laser level  $^4I_{13/2}$  for the 1530 nm transition [43-44]. The reduction in quantum efficiency due to quenching will be particularly strong in materials (such as e.g. silica glasses), in which Er-ions tend to form clusters [44-47].

Various methods have been used for characterizing high concentration Er-doped materials with respect to ETU. An important class of methods is time-resolved spectroscopy including studies of the non-exponential component of the 1530 nm fluorescence decay [43,45,48-50] and studies of the decay of the 980 nm or 800 nm upconversion fluorescence [43,45,50-51], usually after cutoff of a steady-state pump. These techniques are suitable for examining ETU between homogeneously distributed ions [48,52] and (provided sufficient time resolution) for evaluating quenching times for clustered erbium ions [51], but not for estimating the fraction of clustered erbium ions, since only very few clustered ions will be in the upper laser level at pump cut-off. If, on the other hand, short, strong pump pulses are used, an even excitation of clustered and unclustered erbium ions may be assumed. In [53], this principle is used for a simultaneous extraction of the fraction of clustered ions and a determination of an extremely short quenching time of 50 ns.

A more common way of determining the fraction of clustered Er-ions is through transmission measurements, where the quasi-unbleachable Er-ions within clusters result in a nonsaturable absorption of pump light [46, 54-56]. Such measurements, though easily obtainable, lack from the fact that no insight in the population of the energy levels of the Er-ions is gained. In [57], a method is presented by which information about the populations of the two first excited energy levels may be extracted. This is accomplished by observing the 1530 nm infrared fluorescence and the 550 nm green fluorescence resulting from excited state absorption of a 980 nm pump. Due to quenching, the infrared and green fluorescence show different saturation behaviours with respect to pump power. The method allows the estimation of the fraction of quasi-unbleachable Er-ions as well as an effective quenching time for these ions. Figure 4 shows the estimated fraction of quasi-unbleachable ions for various high concentration EDFs as reported in [57-58]. The fraction of quasi-unbleachable ions is seen to grow with the Er-concentration and to be reduced by lanthanum co-doping. Figure 5 shows the corresponding estimated quenching times. These are seen to increase with the erbium concentration, which may presumably be attributed to the presence of larger clusters at higher concentrations [58]. The quenching times in Figure 5 are seen to be several orders of magnitude longer than the above mentioned value of 50 ns reported in [53], which may partly be explained by different experimental conditions. In the green fluorescence setup, the Er-ions are - like in an optical amplifier - cw pumped and due to quenching only very few erbium ions per cluster will simultaneously be in the upper laser level. This will in large clusters lead to relatively slow quenching, because the excitations have to meet through intra-cluster energy migration. In the pulsed pump setup reported in [53], many Er-ions may be excited within the same cluster, which will lead to an ultra-fast quenching-component.

If other quenching mechanisms than ETU are present, the transmission measurements and the green fluorescence setup will not be able to distinguish between them. ETU may, however, be studied separately by observation of the 980 nm or 800 nm upconversion fluorescence [50,59]. In [59], this principle is combined with studies of the frequency response of the fluorescence in order to investigate separately the contributions to ETU from homogeneously distributed and clustered erbium ions.

Finally, non-spectroscopic characterisation methods include component oriented approaches, where the performance of amplifiers and lasers are used for extracting information about the degree of clustering [60-61], as well as approaches oriented towards basic physics, such as the application of transmission electron microscopy [62] for studying clusters directly. The latter method has confirmed the assumption of the existence of large clusters in high concentration Er-doped glasses [62].

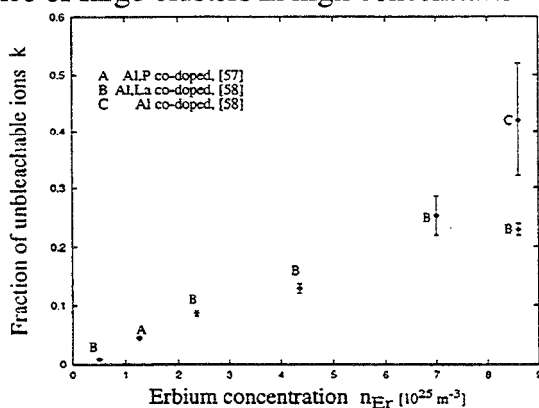


Figure 4 Fraction of unbleachable  $Er^{3+}$ -ions in different  $Er^{3+}$ -doped silica fibers.

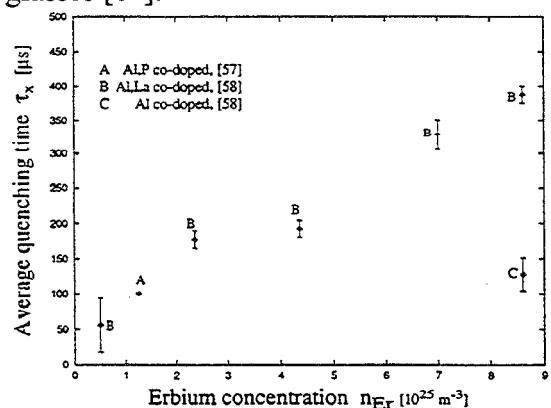


Figure 5 Average quenching time for unbleachable  $Er^{3+}$ -ions in different  $Er^{3+}$ -doped silica fibers.

**Conclusions:** The review of the development status on erbium-doped waveguide components shows that not only has the erbium-doped fiber amplifier become a key element in optical transmission systems, but erbium-doped fiber lasers do also indicate large potential for the realisation of efficient fiber lasers. Although a relatively young technology, many exciting results must be expected in the near future, including practical application of planar erbium-doped waveguides, and optimization of waveguide (and fiber) structures based on a more detailed knowledge of high erbium concentration effects in waveguides.

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