A Review of the Fabrication and Properties of Erbium-Doped Fibers for Optical Amplifiers

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(*Invited Paper*)

Abstract—**During the last two years, erbium-doped fiber has risen to prominence to become the central component of all optical amplifiers. Applications reported include repeaters, power amplifiers, preamplifiers, and distributed amplifiers. To date, nearly all the fiber used in these devices has been silica based and fabricated by variations on the major telecoms fiber technology. Disadvantages of the silica-based host glass, such as low solubility of the rare-earth ions and narrow-band fluorescence, have been carefully addressed and solutions have been found to overcome these potential drawbacks.**

Details of the current status of fabrication methods, matching particular fibers for specific applications, together with optimizing the fiber for high efficiency is presented.

I. Introduction

THE first reports of rare-earth doped fiber amplifiers date back to the 1960's [1]–[3] when Snitzer fabricated fiber amplifiers and lasers from Nd^{3+} laser glasses. These structures demonstrated the advantages to be gained in terms of increased power densities by confining the pump power in a waveguiding structure. The significance of this work was not capitalized upon until single-mode optical fibers were used as the standard telecommunications transmission medium at 1.3 and 1.5 μm some two decades later. The possibility of using Er^{3+} doped fiber as an amplifier in the third-telecomms window was reported by Payne *et al.* [4] in 1987, using fiber which was essentially silica based and was fabricated by a variation to the inside tube deposition method, which was first attempted some two years earlier [5], [6]. The key points which had been demonstrated were 1) the possibility of trading off low dopant concentration and hence low absorption with increasing fiber length, thus introducing silica as a practical laser host glass and 2) observing an efficient room temperature emission which coincided with a telecoms wavelength. In contrast, the Nd^{3+} system for 1.3-μm emission proved not to be a practical proposition, in that excited state absorption of signal photons severely restricted efficiency at this wavelength [7]. Other advantages using silica are that it is directly compatable with telecoms fibers and hence fusion splicing is possible yielding ultra-low reflection joints, coupler technology based on silica [8] can be employed and silica has the advantage of being an exceptionally durable glass.

From this time, progress has been extremely rapid. All the major silica-based fiber making technologies have reported Er^{3+} doped fiber. This has entailed dealing with starting materials which are much less volatile than the standard halide sources. Studies have been undertaken to show that virtually unity quantum efficiency can be obtained in optimized fibers. Sophistocated structures have been reported to make best use of available pump powers and importantly, the availability of semiconductor laser diodes with high output powers [9], [10] have made Er^{3+} doped fiber amplifiers a very practical device.

This paper starts by briefly looking at rare-earth ions in glasses and moves into reviewing the fabrication methods. The later section covers the important materials related results which have enabled high-quality fiber to be made.

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II. Rare-Earth Ions in Glasses

Glasses are commonly made up of network formers, e.g., SiO_2, which form a covalently bonded structure and network modifiers, e.g., Na^+ which form ionic bonds to SiO^- groups, which break up the covalent structure thus allowing more modest processing temperatures. The rare-earth ions, of which Er^{3+} is one, are usually trivalent and take the place of a network modifier. In conventional laser glasses, a high concentration of nonbridging oxygen groups is important to allow for the incorporation of a few weight percents of rare-earth ions [11]. The relatively short-path lengths, over which the pump radiation is absorbed, make a relatively high rare-earth ion concentration necessary. This is one of the reasons for the development of multicomponent silicate and phosphate laser glasses. In glasses where network modifiers are absent, such as pure silica, a very rigid structure exists and there is a lack of nonbridging Si-O^- groups. This makes the coordination of Er^{3+} difficult and contributes to a lack of solubility, which leads to clustering in the glass [12], [13]. Clustering is extremely harmful, reducing radiative transitions and hence various techniques have been used to keep rare-earth ion concentrations low. Alternative approaches have been to study other host-glass compositions, which may alleviate the clustering problem, but still be within the confines of providing high-silica-based fiber. Of significant success have been the addition of P_2O_5 and Al_2O_3 to silica [14]–[16], which has enabled the incorporation of several weight percents of rare-earth ions without clustering effects. It should be pointed out however, that provided clustering effects can be overcome, silica is very efficient at concentrating the output in the 1.5-μm region and minimizing emissions at other wavelengths. Fig. 1 shows the fluorescence spectrum from a GeO_2–SiO_2 preform, after pumping at 514 nm with an argon ion laser. The optical output from other possible levels is at least three, orders of magnitude lower than the main $^4I_{13/2} \rightarrow {}^4I_{15/2}$ emission and is associated with the position of the multiphonon edge. This contrasts with some other glass systems, such as fluorozirconate [17].

Another important feature of the host-glass environment is the effect on the rare-earth ion absorption and fluorescence spectra. The widths of the various rare-earth ion energy bands and to a lesser extent the positions can be controlled to some degree by a suitable choice of host glass. Here again the rela-

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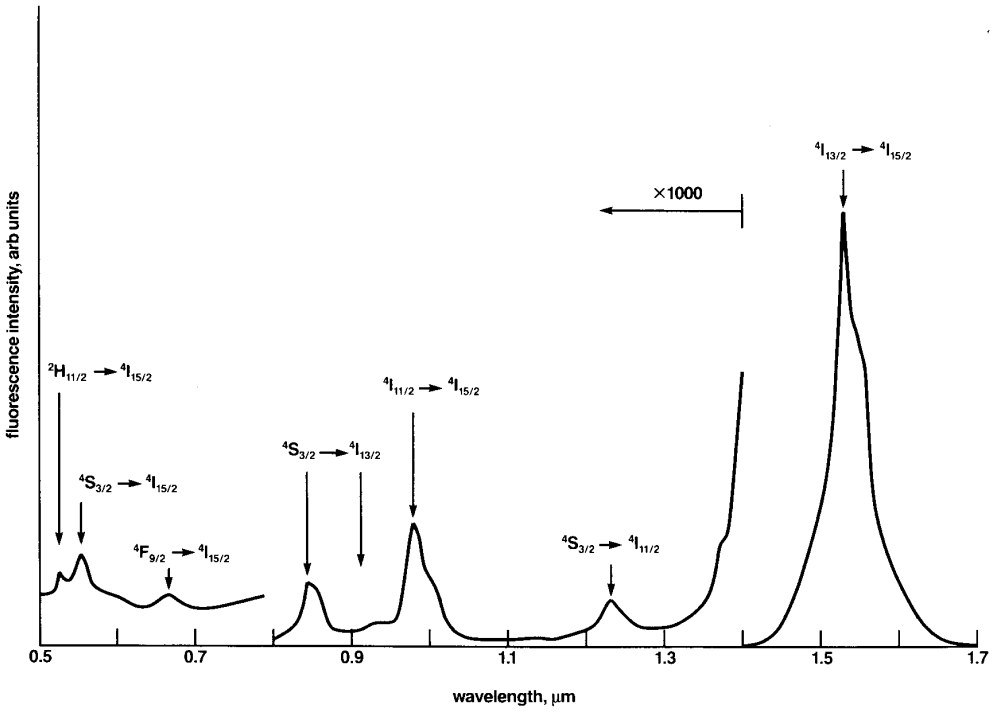


Fig. 1. The fluorescence spectrum of Er^{3+} in a GeO2–SiO2 host glass measured on a preform sample after excitation at 514.5 nm, showing the radiative output concentrated in the $^4I_{13/2} -> {}^4I_{15/2}$ transition.

tively narrow fluroescence of Er^{3+} in pure silica (and with it the narrow amplifier bandwidth) has been considerably broadened by the addition of Al_2O_3 to the network [14].

III. Fabrication Methods

The basic rod in tube technique, which formed the basis of all the pioneering work with multicomponent glasses has received very little attention for Er^{3+} amplifiers, although some work with phosphate laser glasses has been pursued [18]. This method will not be considered further here. Instead we consider first the vapor-phase techniques which have recently been developed and applied to the various mainstream fiber-making technologies.

A. Vapor-Phase Techniques

The vapor pressures of all the halide starting materials used in telecoms fiber are several tens of torr at room temperature and hence delivery of large quantities of vapor for reacting into high-quality glass to form a boule or preform is relatively straightforward. The rare earth halides have a much lower vapor pressure, and several hundred degrees Celsius are required to approach a working vapor concentration. This is illustrated for the case of neodymium in Fig. 2, a rare earth for which reliable data are available. Solutions to the low-vapor pressure problem as applied to the inside tube deposition technique are shown schematically in Fig. 3(a). A standard silica substrate tube has been modified just upstream from the start of the deposition by adding a dopant chamber inside which a rare-earth salt has been fused to the wall [5], [6]. Cladding deposition is carried out in the normal way, but during core deposition, as the $SiCl_4$, $GeCl_4$, and O_2 are fed down the tube, a stationary burner warms the dopant chamber to drive off the rare earth. Some control of the rare-earth concentration is possible by adjusting the temperature of the dopant chamber. This basic method has been modified [14], as shown in Fig. 3(b), by replacing the dopant chamber with a silica sponge impregnated with the rare-earth salt which yielded very good reproducibility of rare-earth incorporation. This method has been used to incorporate very low concentrations of Er^{3+} in very long lengths of fiber for use in distributed amplifier systems [19]. A concentration of 1 ppm Er^{3+} could be uniformly doped in a 6-km length of fiber to $\pm 12\%$ with negligible background loss. Assuming a Rayleigh scattering background-loss model, the attenuation at 1.55 μm was estimated from shorter wavelength behavior to be 0.26 dB/km as shown in Fig. 4. This exciting result means that "lossless" links can be fabricated by compensating for the loss of the fiber by gain from the pumped Er^{3+}. Very recently a 10-km length of lightly Er^{3+} doped fiber was rendered lossless by pumping with only 15 mW of power at 1.48 μm [20].

A further addition [21], as shown in Fig. 3(c), which incorporates the very important codeposition of Al_2O_3, by transporting Al_2Cl_6 in heated lines to the reaction zone, has also been reported. Codoped Er^{3+}-Al_2O_3 fiber prepared in this way has also been studied [22] as a distributed amplifier. In this case a multimode "seed fiber" was drawn and inserted into the center of a preform before the final collapse pass. Although the end product distributed-fiber core also contained the original seed fiber support tube material, the background loss of the fiber was reduced to negligible levels.

The possibility of using rare-earth organometallic sources to provide a reasonable vapor-pressure source was investigated [23] originally for the fabrication of cerium-doped fiber by the outside vapor deposition (OVD) process. A cerium betadi-

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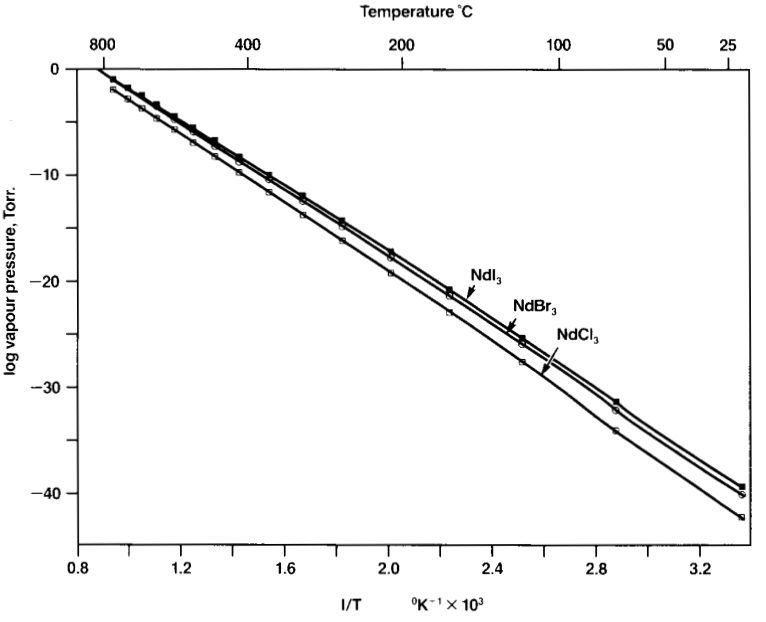


Fig. 2. The vapor pressures of the Nd^{3+} halides as a function of temperature.

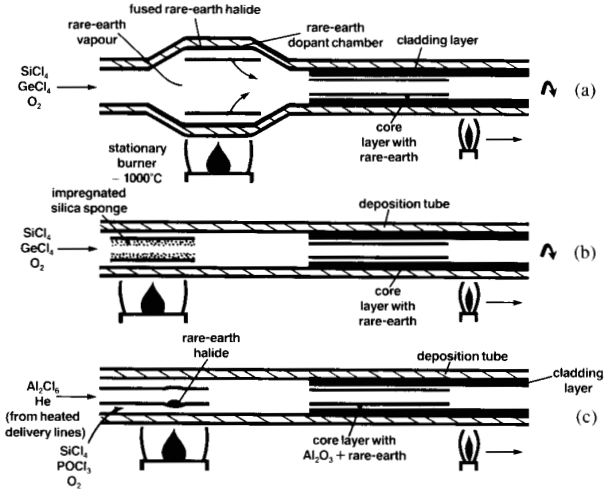


Fig. 3. Vapor-phase methods of rare-earth incorporation applied to the inside tube deposition (ID) method. a) Using the ''dopant chamber'', b) with the dopant chamber replaced by an impregnated silica sponge, and c) incorporating Al_2O_3 deposition from Al_2Cl_6.

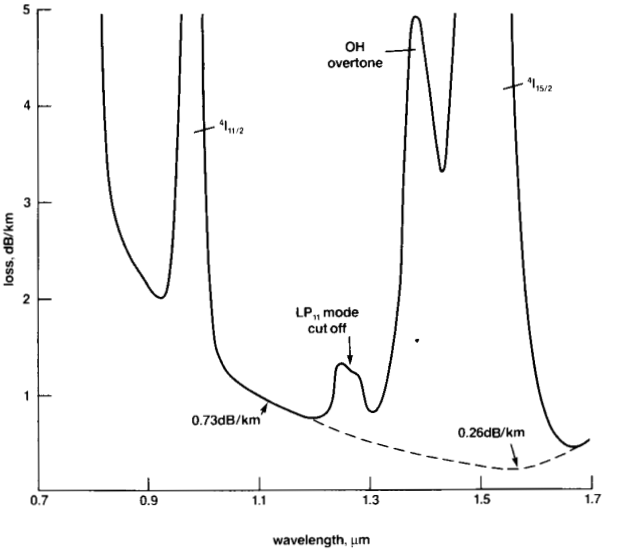


Fig. 4. The total loss spectrum of a 6-km length of fiber doped with 1 ppm Er^{3+} showing virtual ellimination of background loss.

ketonate ($Ce(fod)_4$) was developed which possessed a vapor pressure of about a torr between 150–200°C. This has been extended to Er^{3+} incorporation and by heating delivery lines into an OVD burner, as shown in Fig. 5, high-quality doped boules [24] have been reported.

Vapor-phase methods with the vapor axial deposition (VAD) method should in principle be very similar to the OVD technique, hence organo metallic precursors would be possible here also although none have so far been reported. Consolidating porous boules is usually carried out at very high temperatures (1400–1500°C) to fully sinter the silica-based material. Per-

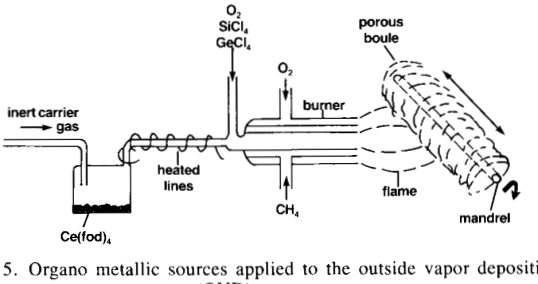


Fig. 5. Organo metallic sources applied to the outside vapor deposition (OVD) process.

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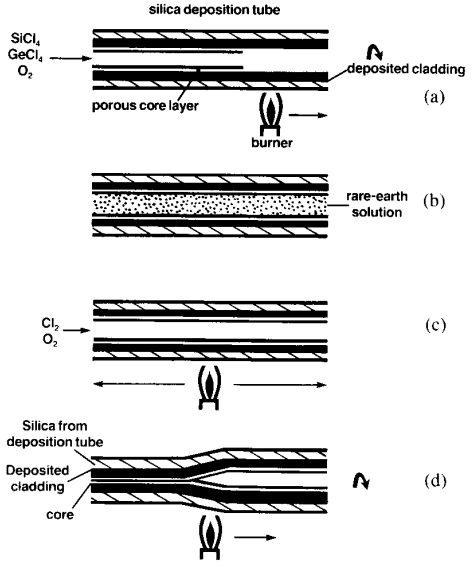


Fig. 6. Solution doping applied to the ID method. a) Deposition of a porous core layer, b) soaking the porous layer in a solution of rare-earth salt, c) drying the impregnated porous layer, and d) fusing the porous layer and collapsing the tube into a solid-rod preform.

forming this consolidation in an atmosphere of a rare earth has been attempted with some success with Nd^{3+} [24]. Care in the choice of the consolidating atmosphere was found to be important, as oxidizing conditions gave a buildup of Nd_2O_3 on the outer surface of the boule. A uniform distribution resulted when using helium as a sintering gas. This technique could also be extended to Er^{3+} incorporation.

B. Liquid-Phase Techniques

The first reported liquid-phase method for incorporating rare-earth ions into a silica-based fiber waveguide was reported by Stone and Burrus in 1973 [26]. The method is also known as the "solution doping technique" and in principle is quite straightforward, as illustrated in Fig. 6. A cladding layer is deposited inside a substrate tube in the normal way, but the following core deposition is carried out at lower temperature so that the layer is not fully sintered. The porous layer is then soaked in an aqueous or alcoholic solution of the rare-earth salt and allowed to impregnate the pores. This impregnated layer is dried and fused into a clear glassy layer (careful Cl_2 drying may be necessary for this step [27]) and subsequently the tube is collapsed into a preform in the usual way. This technique has been used by several workers [15], [28] and can be very conveniently used to codope with Al_2O_3 as well as the rare earth.

The refractive index and elemental profile of preforms made by this technique are shown in Fig. 7(a) and (b). Interestingly the Er^{3+} profile mirrors the Ge and Al elemental scans and hence in the case of the GeO_2 doped fiber it would seem difficult to maintain a high concentration of Er^{3+} in the center of the core, due to "burn off". This highlights an advantage of Al_2O_3 doping in that the absence of the familiar central-index depression [29] does allow a high concentration in this region. This is an important observation as it has been shown that confining the Er^{3+} to the central region of the core makes more efficient use of the pump power [30] and hence more efficient amplifiers.

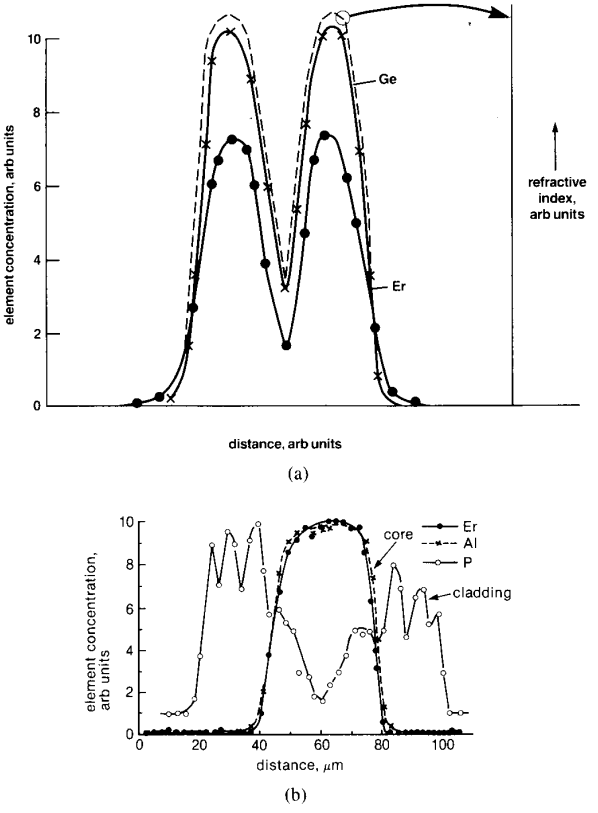


Fig. 7. Refractive index and elemental profiles of Er^{3+} doped preforms in a) GeO_2–SiO_2 host glass and b) Al_2O_3–SiO_2 host glass.

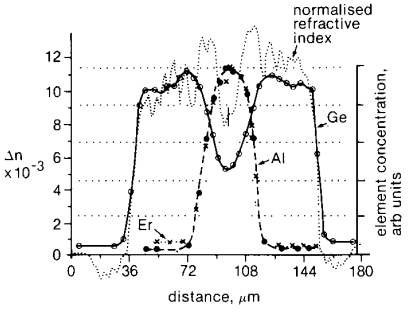


Fig. 8. Refractive index and elemental profiles of a partially drawn "confined" preform, showing the Er^{3+} occupying the central region only.

Composite core structures have been reported [31] an example of which is shown in Fig. 8. In this work a fiber has been fabricated with an outer core of GeO_2–SiO_2 and an inner core of Al_2O_3–SiO_2. The Er^{3+} was doped in the Al_2O_3–SiO_2 material only and hence was "confined" to the central 25% of the core. The principle of liquid-phase doping can be used for any porous silica-based material and hence the VAD technique has similarly been adapted [32]; this method is sometimes termed molecular stuffing, or the extended VAD technique. In this case, the porous core boule is soaked in an appropriate rare-earth ion solution (see Fig. 9), allowed to dry and is sintered in the usual way. The cladding glass is applied on top of the sintered core

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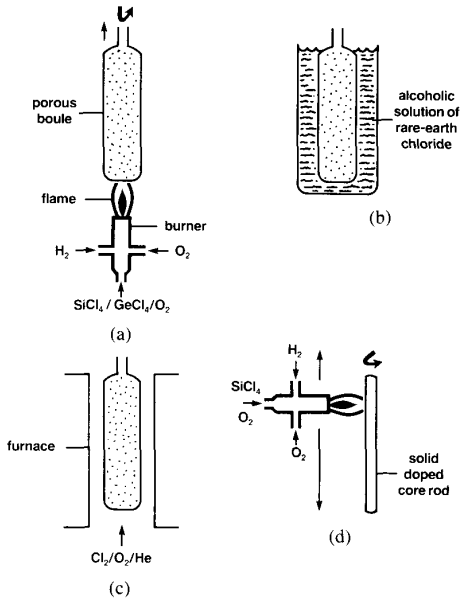


Fig. 9. Solution doping applied to the VAD technique. a) Deposition of a porous boule, b) soaking the boule in a solution of rare-earth salt, c) drying and fusing the boule in a consolidating furnace, and d) using the consolidated boule as the core glass of the rare-earth doped boule.

boule and this in turn is sintered, and the whole composite assembly drawn into fiber.

C. Other Methods

Nebulisers [33] and aerosols [34] have been used for the incorporation of involatile species into silica-based fibers. These will not be discussed here as Er^{3+} incorporation has not been reported by these methods. For more detail on these techniques the reader is referred to a recent review [35].

IV. Optical Assessment

The effect of the concentration of Er^{3+} in both Al_2O_3–SiO_2 and GeO_2–SiO_2 host glasses has been studied [36] and the results are shown in Table I. The essential features are that up to 1 cationic wt% and 7 cationic wt% Er^{3+} (here after simply wt%) can be incorporated into GeO_2–SiO_2 and Al_2O_3–SiO_2, respectively, without clustering effects. The quantum efficiency measurements, which were made by pumping the fibers with relatively low powers at 514 nm and comparing the absorbed power with the integrated fluorescence power in the 1.5-μm region, indicated that high efficiencies were obtained in all the unclustered fibers. Fluorescence lifetime measurements indicated that efficiencies could be considerably reduced even with much lower concentrations of Er^{3+} in either host glass. Fig. 10 shows the fluorescence delay, ln(decay) and d/dt(ln(decay)) as a function of time, after exciting a 0.07 wt% Er^{3+} Al_2O_3–SiO_2 fiber with low powers at 807 nm and measuring the emission transversely to the fiber as close to the excitation as possible. A single exponential decay, with a $1/e$ lifetime of 10.3 ms was observed and increasing the pump power to 50 mW, revealed very similar traces. The GeO_2–SiO_2 fiber doped with

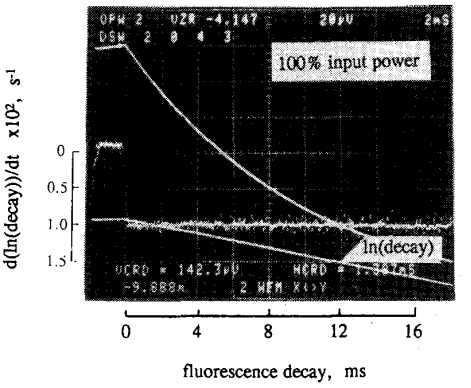


Fig. 10. The fluorescence decay, log decay, and derivative curves for low concentration (0.07 wt%) Er^{3+} doped fiber in Al_2O_3–SiO_2 host glass.

TABLE I
The Fluorescence Lifetimes and Quantum Efficiencies of a Range of Er3+ Doped Fibers
(For detailed explanation see text)

$[Er^{3+}]$ (wt%)	Host Glass	$1/e$ Cluster	Lifetime, ms Fast Comp	Slow Comp	Quantum Effic., a.u.
0.02	Ge	none	none	10.8	—
0.07	Al	none	none	10.3	—
0.15	Ge	none	11.0	11.9	206
0.15	Al	none	8.7	9.8	202
0.6	Ge	none	4.1	11.5	—
0.2	Al	none	8.7	10.3	—
1.1	Ge	none	8.0	11.3	197
1.5	Al	none	4.5	9.5	267
2.3	Al	none	2.5	9.5	216
2.4	Ge	<10 μs		10.9	89
7.5	Al	none	1.0	8.5	—
14	Al	<10 μs	4.0	8.4	—
18	Al	<10 μs	4.0	8.8	—

a very low concentration of Er^{3+} also exhibited a single exponential decay even with 50-mW pumping.

Increasing the Er^{3+} concentration significantly to 2.3 wt% in the unclustered Al_2O_3–SiO_2 fiber revealed very different fluorescent lifetime behavior. Fig. 11 shows an increase in the decay rate, particularly in the early stages of decay, which is proportional to the pump intensity. At high pump powers, the $1/e$ fluorescence lifetime is 2.5 ms early on in the decay process (this is termed fast component in the table) and reduces to a steady-state value (termed slow component), which is similar to the low-doped-fiber results. The table shows the lifetime results for a wide range of fibers and it is clear that for a single exponential decay under typical amplifier pumping powers, either host glass is suitable, but that very low Er^{3+} concentrations are important. This behavior of the lifetime has been attributed to a cooperative unconversion mechanism [37], whereby a transfer of energy takes place between two ions in the excited state, thus promoting the acceptor ion to a higher energy level and quenching the donor ion back down to the ground state nonradiatively. The two requirements for this mechanism to be operative are for the ions to be sufficiently close and for a high proportion of the ions to be at the metastable level, i.e., when there is a high concentration of Er^{3+} and for high-pump intensities.

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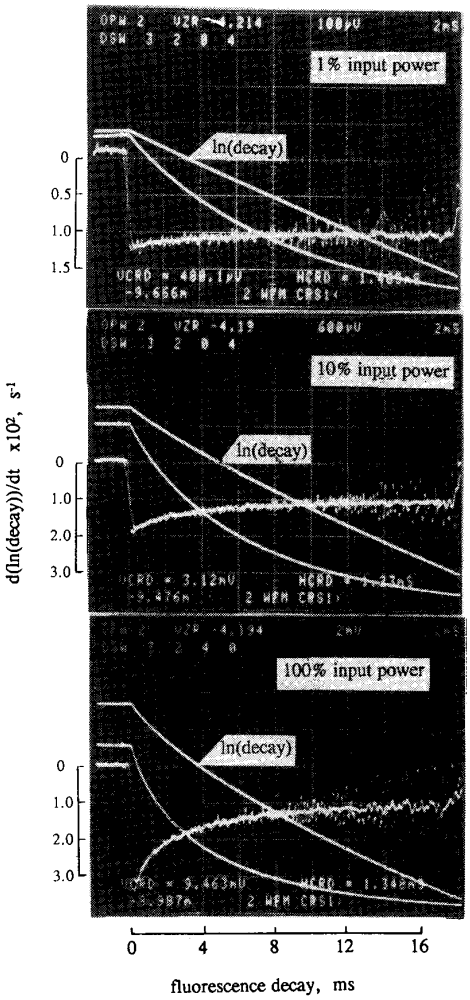


Fig. 11. The fluorescence decay, log decay, and derivative curves for 2.3 wt% Er^{3+} doped fiber in Al_2O_3-SiO_2 host glass as a function of pump power (100% = 80 mW).

Very impressive gain results have now been reported for a number of low Er^{3+} concentration fibers.[1] A commonly employed figure of merit, which is particularly applicable in the small signal regime, is gain per unit absorbed pump power. The current highest reported value [38], of 10.2 dB/mW was achieved by pumping at 980 nm and using a small-core high NA fiber to maximize pump-power density in the core. The fiber was fabricated by the VAD method with an Er^{3+} concentration of 70 ppm. Gains in excess of 30 dB with only 5 mW pump power were reported.

Measuring the efficiency of transfer of pump power to signal power complements the fluorescence lifetime work and is particularly important for power amplifier applications. As above, a range of fibers has been studied [39], [40], but concentrating on low Er^{3+} doping levels. Pump powers at 1.48 μm and a signal of about 1 mW at 1.55 μm were launched into a series of fibers. The absorbed pump power and the corresponding measured signal output power are shown in Fig. 12, where the Er^{3+} absorption has been kept constant at 6 dB/m at the peak 1.53-μm absorption wavelength and the core host glass spans from GeO_2–SiO_2, GeO_2–Al_2O_3–SiO_2, through to Al_2O_3–SiO_2. The slope of the line gives a good indication of the efficiency of transfer of pump power to signal power and in the best case (GeO_2–Al_2O_3–SiO_2), almost unity quantum efficiency was obtained. In the case of GeO_2–SiO_2, equally high efficiencies were reported, but for much lower Er^{3+} concentrations (1.5-μm peak absorptions of 1 dB/m).

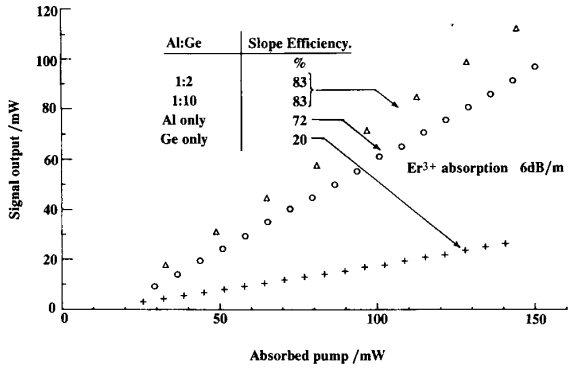


Fig. 12. Signal output power for various host glasses as a function of absorbed pump power for pumping at 1480 nm.

The fluorescence spectra of Er^{3+} in a variety of silica-based host glasses has been studied by numerous workers [4], [14], [41]. Fig. 13 shows the results [39] of a series of glasses which span the narrow-band to broad-band emission. Clearly shown is the dependence of the full-width half-maximum (fwhm) bandwidth on the host glass. Also shown is the ratio of Al:Ge in the core glass and it is apparent that only a very low concentration of Al_2O_3 is necessary to significantly broaden the spectrum. This important result means that there is much scope for optimizing amplifier bandwidth, fiber numerical aperture and telecoms compatability.

Finally in this section, it should be pointed out that the bandwidth of an amplifier is dependent not only on the host glass, but also on the relative populations of the ground state and metastable level [42] of the Er^{3+}. This added degree of freedom allows some choice over bandwidth, center wavelength, relative gain, and amplifier noise. This will not be explored further here, but is likely to form the basis of additional future work.

V. Conclusion

Er^{3+} doped fibers have very recently become the key element in practical fiber amplifiers, despite the principle of rare-earth doped fiber being being conceived and demonstrated some three decades ago. The great progress made in fiber development has centered on modifications to standard telecoms high silica technologies. Potential problems concerning poor rare-earth ion solubility and limited amplifier bandwidth have been successfully addressed and sophisticated structures with carefully controlled concentrations of Er^{3+} have led to the reporting of high gains and high optical efficiencies, with practical semiconductor pumping and fiber-based multiplexing technology.

[1]See for example; 1) Proceedings of Topical Meeting on Optical Amplifiers and their Applications (OSA), Monterey, CA, USA, session MB, 1990. 2) Proceedings of 7th International conf. on Integrated Optics and Optical Fiber Communication (IOOC), post deadline session, Kobe Japan, 1989. 3) Proceedings of Optical Fiber for Communications (OFC), San Francisco, CA, post deadline session, 1990.

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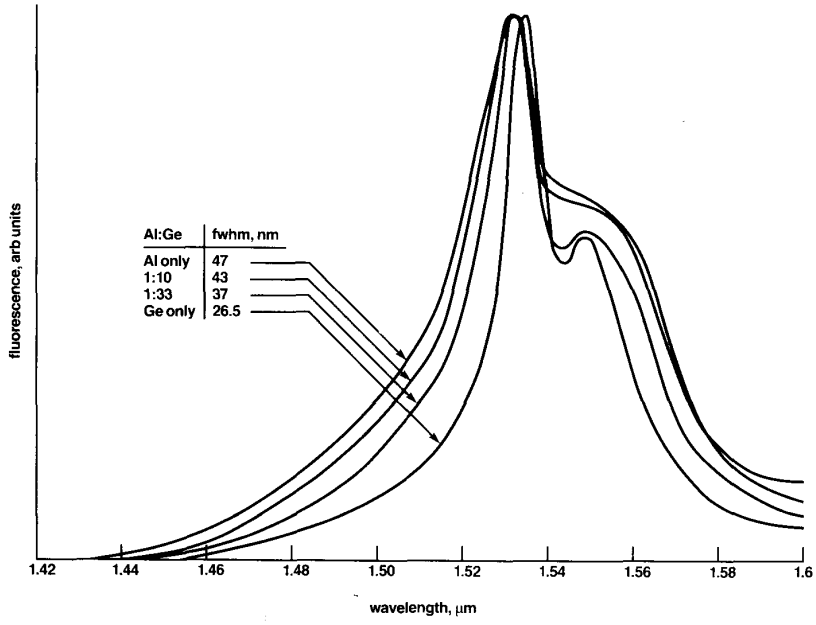


Fig. 13. Fluorescence curves for different host glasses.

Exciting possibilities with distributed amplifiers, made from very low-doped fiber, providing "lossless links" have just begun to emerge, which complements the work done with the more conventional lumped amplifier. It is certain that more important work will be reported in the near future in this rapidly developing field.

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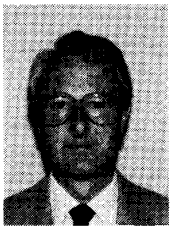
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