An Overview and Feasibility Study of Fabrication Technology and Characterization Techniques of Erbium-Doped Fiber amplifiers in Iran

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***Abstract*- In this paper, a brief summary of different methods of fabrication of optical preform and fiber is reviewed. Several methods of incorporation of erbium ions into optical preforms are studied. Characterization of the fabricated erbium doped fibers including measurements of refractive index profile, absorption, fluorescence and gain spectra and metastable lifetime are described. It is also expressed that many of these fabrication and characterization methods are feasible to be carried out in Iran.**

Keywords: Erbium doped fiber amplifier, MCVD technique, VAD technique, Solution Doping, Flash condensation, EDF fabrication, EDF characterization, Fiber drawing, Aerosol Technique.

I. INTRODUCTION

Erbium doped fiber amplifiers (EDFAs) have gained an important role in 1.55 μm, long-haul optical communication systems. These amplifiers with their high and flattened gain [1]-[9], wide bandwidth [3], [10]-[13], low noise [1], [3], [14], low inter-channel cross-talk, [15]-[17], low polarization dependent gain, [18]-[20], low cost, [21], low temperature sensitive gain [22]-[27], and compatibility with conventional single mode fibers have been the subject of intense research and development during the past two decades, [28]-[36].

In optical communication systems, EDFAs can be used in three basic aims: (i) power amplifiers for the last stage of amplification in transmitters, (ii) in-line amplifiers, for compensation of link losses, and (iii) low noise pre-amplifiers in receivers.

Parallel to the application of rare-earth-doped fibers as an amplifier, the nonlinear refractive index of them has been under intensive study. Betts *et al.* demonstrated theoretically and experimentally the enhancement of nonlinear refractive index of the EDF [37]. Chu and Wu successfully demonstrated all optical switching with low pump power of a few milli-Watts in erbium-doped twin core fibers [38]-[39]. When the fiber is optically pumped, the electronic distribution of the Er^{3+} ions is modified. This modification causes a strong nonlinear phase shift. Desurvire modeled this effect for EDFA, by a density matrix approach [28], [40]. Temperature sensors [41]-[43], and gyroscopes by using rare-earth doped fibers and other sensors constructed on the nonlinear and other useful effects of these doped fibers are examples of many applications of these fibers as reliable devices [44]-[45].

Fiber amplifiers and lasers were investigated as early as the invention of the conventional lasers. When for the first time application of fiber amplifiers in communication systems was suggested, the fiber loss was more than 2 dB/m [25], [27], [40], but still many people were interested in demonstration of theoretical

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and experimental feasibility study of doped glass fiber lasers and amplifiers [46]-[53]. Serious researches started from 1979, when the low loss optical fibers were fabricated [28]-[30], [54], [63].

Erbium doped fiber design is simple. The erbium ions must be confined to the center of the core of a high numerical aperture (NA) single mode fiber. Increasing NA allows reduction in core diameter (for a given cutoff wavelength), which increases power density and hence pump and signal intensities. Also, large NA fiber increases the pump power acceptance, and Er-confinement limits the doped area to the uniform higher pump intensity region, while because of the short length of EDFAs, except in distributed ones [9], dispersion is negligible. Another important factor in EDFA design is the amount and type of co-dopants like Ge, P or Al oxides. Ge oxide is mostly added to raise the core refractive index. Aluminum is a useful co-dopant to improve ability to dissolve Er^{3+} and to smooth somehow gain spectrum with wider bandwidth. Aluminum also prevents depletion of Er in modified chemical vapor deposition (MCVD) collapse process, while Ge or P burns out [6]-[8], [14]. Several methods of flattening and widening gain of EDFAs have been introduced [64]. Operation of the multi-channel DWDM systems with flattened gain EDFA is feasible [3].

Although, EDFA total gain of as high as 54 dB has been obtained [1]-[2], but practical EDFAs with low concentration Er (≈100 ppm) and medium gain are used [65]-[68]. High concentration EDFA has extra background loss [28, 30]. In high gain amplifiers, small end face reflections can cause oscillation.

Broad spectral bandwidth of EDFAs [4], [10]-[11] allows distortion-less transmission of short pulses. The bandwidth of 35 nm at 1.55 μm corresponds to a frequency bandwidth of more than 4 THz. Thus multi-channel transmission is possible as long as the amplifier gain is not saturated. EDFAs can amplify femtosecond pulses [31], [69]. EDFAs have long metastable radiating lifetime (≈ 10 ms) and hence very slow gain dynamics [12].

Fabrication of erbium-doped fiber amplifiers (EDFAs) is mostly the same as that of conventional fibers. The first report on rare-earth doped fiber amplifier was proposed by Snitzer [46]-[47]. The possibility of using erbium-doped fiber as an amplifier at the third low loss telecommunication window was demonstrated by Poole *et al*. [56], [58].

Glasses are commonly made up of two main groups: network formers, e.g. SiO_2, and network modifiers, e.g. Na, Ca, K, Li. Network formers form a covalently bonded structure and network modifiers form ionic bonds to SiO^- groups and therefore break up the covalent structure. The trivalent rare-earth ions like Er^{3+} take the place of a network modifier. In conventional laser glasses a high concentration of rare-earth and therefore a high concentration of non-bridging oxygen groups is necessary in the glass host. This is the reason for development of multi-component silicate and phosphate glasses. The standard optical fibers mainly consist of pure silica glasses. For compatibility of standard fiber and EDFAs, the host materials suitable for the third telecommunication window should be pure silica glasses. In pure silica glasses, the network modifiers are absent. Therefore, the structure is rigid. The lack of non-bridging SiO^- makes the coordination of Er^{3+} difficult. Thus the Er^{3+} is not soluble and cause clustering in the glass. Clustering increases the scattering loss of the fiber and diminishes the fluorescent lifetime of Er ions [71]. In telecommunication a long length of EDFA can be used. Therefore, Er concentrations of lower than 1000 ppm, which avoid clustering and crystallization, can be used. Co-dopants like P_2O_5 and Al_2O_3 can prevent the Er ions from clustering and make it possible to have concentration of a few weight percent [72]. Modifying the host can reduce the harmful effect of excited state absorption (ESA). For example, Poole demonstrated that co-dopant of aluminosilicate instead of germano-silicate can reduce the amount of ESA [73].

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In this paper, a brief summary of different methods of fiber fabrication, Er incorporation, and EDF characterization are introduced. Different techniques for fabrication of EDFs are related to the method used for fabrication of conventional standard single mode fibers (SMFs). The *modified chemical vapor deposition (MCVD)* and *vapor axial deposition (VAD)* fabrication methods and their relevant methods for incorporation of Er ions are described in sections II and III, respectively. Techniques for incorporation of Er ions into the low loss pure silica glasses are categorized as either vapor or liquid phase processes. In sections IV and V, the preform characterization and drawing methods are respectively demonstrated. Characterization of Erbium Doped Fiber Amplifiers are described in section VI. The facilities for preform and fiber fabrication and Er incorporation in Iran by both methods will be addressed in section VII. The paper is concluded in diction VIII

II. FABRICATION OF FIBER PREFORMS BY MCVD PROCESS

The modified chemical vapor deposition (MCVD) process is used for fabrication of preforms and fibers in the factories for mass production or in the laboratories for experimental research. A pure silica tube, which has been immersed in nitric acid for several days, is washed with de-ionized distilled water and dried with blown nitrogen gas. The tube is inserted into a glass-working lathe while O_2 is blowing into the system, as shown in Fig. 1. The tube is rotated and locally heated by a moving torch. It is cleaned with one run of etching gas (SF_6), and several runs of O_2 at 1800° C to dry the tube, to remove all the OH^- from the inner surface of the tube. Index raising dopant ions such as germanium, phosphorus, aluminums and titanium and index lowering dopant ions such as boron and fluorine as halide vapors (e.g. $GeCl_4$, $POCl_3$, BBr_3,…) with O_2 and $SiCl_4$ are blown into the tube. These gasses, at the high temperature created by the moving torch, react and produce particles of SiO_2 co-doped with GeO_2, P_2O_5, B_2O_3, etc.

For short lengths of fiber, or fibers with significant concentration of Er, in which background loss of fiber is unimportant, the glass of the tube can be used as the cladding material. Otherwise, by choosing suitable halides vapor, flow rates and torch temperatures, the cladding refractive index can be raised, matched or depressed.

In EDFA, for higher pump efficiency, a small core diameter with high NA is necessary. All the core or just one layer at the center can be doped with erbium. To incorporate the Er ions in the fiber core several methods have been tried, which are summarized in the following sections.

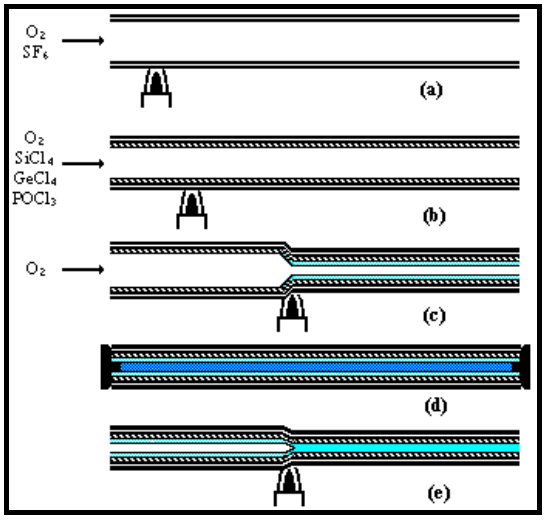


Fig. 1 Preform fabrication by MCVD method and Er incorporation by solution doping, (a) cleaning and drying the tube, (b) cladding and core depositions, (c) partial collapse, (d) solution doping, and (e) collapse process [1].

A. *Liquid Phase Process for Incorporation of Er in MCVD Technique*

This method is also called ***Solution doping technique***, which is used in most laboratories for incorporation of the rare earth ions into the fiber preforms. Townsend *et al.* used this method for incorporation of Er in a fiber preform [77]. The phosphorus and Er evaporate at high temperature of the final collapse process. This creates a dip at the center of the fiber index profile and Er concentration. Therefore, the preform should

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be collapsed at two steps. As shown in Fig. 1, after cladding layers' deposition, the preform is partially collapsed. Then the core layers (all or part of them) are deposited at lower temperatures to create a non-sintered soot layer(s). The downstream side of the preform including some soots, must be carefully soaked in water and washed out. This water should not affect other parts of the preform. A suitable amount of $ErCl_3.6H_2O$ dissolved in distilled de-ionized water or alcohol, is poured into the preform for a while. This solution doping takes time in the range of 2-24 hours, depending on the Er concentration requirement. Then, the tube is drained, dried for half an hour with temperature about 1000 °C, heated to consolidate the soot layer, and collapsed into the preform. In this method, co-dopant of Al_2O_3 can be easily added to the solution to prevent the Er ions from clustering, and also from evaporation at the time of consolidation [79].

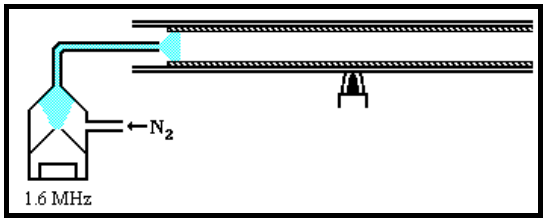


Fig. 2 Aerosol technique for incorporating rare-earth ions into fiber preform. The solution containing rare-earth compound is nebulised by a piezoelectric crystal and the N_2 gas carries the aerosol to the preform [1].

For incorporation of higher Er concentration into the fiber, a method based on the ***flash-condensation*** reaction of a suitable acid, specially H_3PO_4, can be employed [80]-[81]. An appropriate combination of $ErCl_3.6H_2O$ and other desired rare-earth and metal salts are dissolved in a melt phosphoric acid and poured into the tube. Warming the filled tube to about 140° C helps the impregnation of the core soot layers. Then, again, the solutions should be drained. The tube is inserted in the lathe and flash heated at the temperature of around 1000° C for about one hour to be dried. In this temperature, the condensation of the acid removes all the water contents of the preform and, in the presence of chlorine and oxygen, the acid is converted to HCl, which is evaporated and removed from the network. Then the tube is collapsed to a consolidated preform. Phosphorous, as a network modifier, prevents the Er ions from clustering. Some devitrification or phase separation for higher Er concentrations happens. This effect increases the background loss of EDF, but is reduced in the drawing process, when the fiber cools rapidly. Carter *et al.*, earned a background loss of 1 dB/m for a doped fiber with a 2 dB/m absorption peak at 1550 nm [80].

Many other solutions can be used for solution doping. A technique is to use solutions containing a silicon alkoxide like tetraethoxysilane (TEOS). Salts or alkoxides of rare-earths are used with an aqueous or alcoholic solution of TEOS. This solution eliminates chlorine containing precursors which prevent incorporation of elements such as the alkalis and alkaline earths. A chlorine treatment is needed at some stage to remove OH^- contamination of the preform [77].

Another liquid phase process, the ***aerosol technique,*** has been used for incorporating rare-earth ions into the fiber preforms [82]. A modified "room humidifier" nebulises the rare-earth solution by an ultrasonic generator and delivers into the tube as dimonstrated in Fig. 2. Water in the aerosol evaporates at the hot zone of the preform, and the rare-earth ions react with O_2 simultaneously with other core dopants. This technique can give appropriate results and uniformity of dopants for low rare-earth concentration preforms.

B. *Vapor Phase Process for Incorporation of Er in MCVD Technique*

The vapor pressures of all the halides used in fabrication of standard SMFs are tens of atmospheres at room temperature [71]. Therefore, delivery of a large amount of their vapor into the tube is relatively straightforward. Rare-earth compounds are less volatile than other precursor materials [76]. Therefore, temperatures up to several

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hundred degrees are needed to volatilize them into the reactant stream during deposition.

A chamber is spliced to the preform, as shown in Fig. 3. The Er halide in a dopant carrier chamber is heated [5]. The water content of $ErCl_3.6H_2O$ is evaporated and a fused, anhydrous layer on the inside of the carrier chamber is produced. The chamber can be replaced by a porous silica frit [70], [77]. This frit can be produced by depositing a soot layer inside one part of preform and then soaking into an aqueous or alcoholic solution containing $ErCl_3$ (Fig. 3b). Another alternative for the chamber is the ampoule used by MacChesney and Simpson [78]. Use of an ampoule (Fig. 3c) has the advantage that $AlCl_3$ vapor may be supplied through it to act as a co-dopant to prevent the Er ions from clustering.

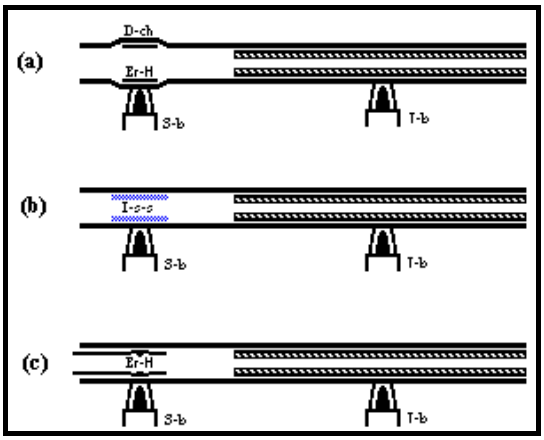


Fig. 3 Three different methods for Er incorporation by vapor phase process. (a). Er compound is melted onto chamber spliced to the preform, (b). Er compound has impregnated a porous silica frit (sponge), (c). Er compound is contained in another tube (ampoule). **D-ch:** dopant chamber, **Er-H:** erbium halide, **S-b:** stationary burner, **T- home b:** transverse burner, **I-s-s:** impregnated silica sponge [1].

During all or the center deposition of the core layers, the stationary burner warms the Er compound to evaporate [76], but not to oxidize the reactants. Therefore, the core deposition includes low level Er ions. The erbium concentration can be controlled by chamber temperature. To minimize the amount of OH^- contents, the erbium-doped core layer is deposited at a lower temperature to produce a soot layer. Then dried and fused to consolidate. The preform collapses, and is ready for characterization and drawing processes.

C. *Seed Fiber Process for Incorporation of Er in MCVD Technique*

One of the simplest methods for incorporation of very low Er^{3+} concentration (less than 1 ppm), a commercially available erbium doped glass rod is threaded into the preform just before to be collapsed and drawn into a fiber. This is called the rod-in-tube method [74]-[75].

III. PREFORM FABRICATION BY VAD PROCESS

The vapor axial deposition (VAD) technique uses an end-on deposition onto a rotating porous silica boule, as shown in Fig. 4 [83].

One torch is for cladding layers and the central one is for the core deposition. The concentric rings of these torches deliver, alternately, oxygen and dopant vapors directly onto the rotating target to create an axially grown porous preform. The dopant precursors, are carried by O_2 or Ar through the central bore of one or more torches. The porous preform is pulled upwards, dehydrated in Cl_2 gas and sintered in helium to produce a pore free preform, which is ready for elongation, if necessary, fire polishing and drawing to a fiber [78].

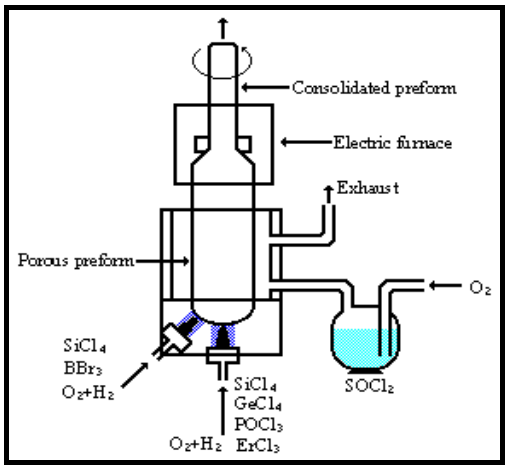
To incorporate the Er ions into the preform, again, vapor and liquid phase processes can be associated with VAD technique.

A. *Er Incorporation by Vapor Phase Process in VAD Technique*

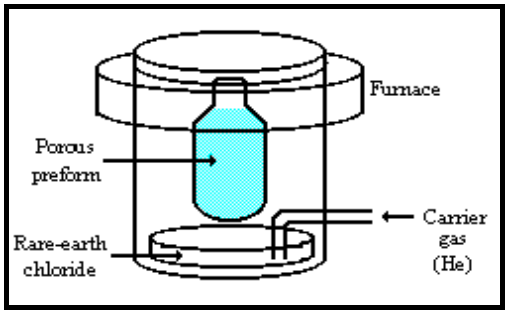
A vapor of an organic compound of rare earth is introduced via the mainstream of core dopants to the porous preform during growth Fig. 4a. Alternately, the porous core or preform may be sintered in an atmosphere containing the vapor of the Er Fig. 4b. This rod forms the core region of a preform, either

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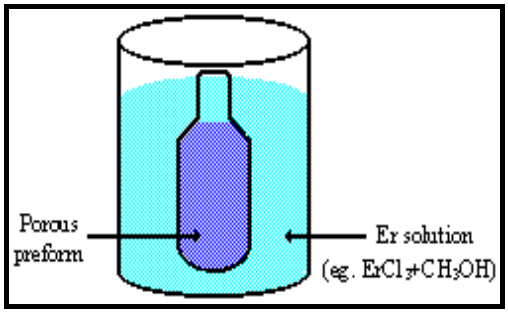
by further deposition of cladding over it, or by using the rod-in-tube technique. In this process, the fiber cannot be easily co-doped with aluminum, so the Er ions clusters and such crystals will not be melted during fiber drawing process. Therefore, this method can only be used for fabrication of low concentration Er-doped fibers [77].



(a)



(b)



(c)

Fig. 4 VAD technique for fabrication of fiber preform and Er incorporation, **(a)** vapor phase deposition**, (b)** core, cladding or Er end-on deposition, and **(c)** liquid phase deposition [1].

B. *Er Incorporation by Liquid Phase Process in VAD Technique*

The porous core, fabricated by VAD technique, is soaked in an Er-solution, analogous to solution doping technique of MCVD (Fig. 4c). After a while, the doped boule is dried, dehydrated and sintered to a solid core. This rod can form the core region of a preform in the seed fiber process of Sub-Section II.D.

IV. CHARACTERIZATION OF THE FIBER PREFORM

After fabrication of a preform, its refractive index profile should be measured. The non-destructive method used to measure the refractive index profile of the preform is the *focusing method*, which the refractive index is determined through numerical integration of the scattered light from the preform illuminated by a laser light [34], [84]-[86].

Except for the fibers with Br dopant, the refractive index of the preform does not vary during the drawing process. The preform diameter is measured and its core radius and the core-cladding refractive index difference can be estimated from the preform profile. The diameter of a standard single mode fiber is 125 μm. Due to the small core of the single mode fibers, the diameter of the fiber, after drawing becomes smaller than that of the standard one. Therefore, the preform must be *sleeved* with an extra pure silica tube and *stretched* in the glass working lathe to be sintered to a preform with longer length (elongation). This is usually the case for large NA EDFs. This is also done to increase the production throughput with a lesser time than the main production time. As it is practically done, the production time can be saved almost 50% of the total time.

V. DRAWING PROCESS

An electrical or gas furnace heats the preform to melting point of around 2200 °C. The preform is drawn through a diameter control system, coating bath, and curing furnace, and finally is wound around a drum. The diameter

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is controlled by the winding rate of the drum. To prevent the fiber from cracking while cooling and other probable surface damages in winding or handling, it is coated with a polymer. Then, the coated fiber is cured in an ultraviolet furnace with temperature around 400° C. The drawing system has to be vertical [85]-[86] to eliminate the slight effect of earth gravity on the fiber's shape (birefringence).

VI. CHARACTERIZATION OF ERBIUM DOPED FIBER AMPLIFIERS

A. *Measurement of the Fiber Refractive Index Profile*

The drawing process has little effect on the refractive index profile of a fiber. To measure the refractive index of a fiber whenever the preform index profile is not available, the interference fringe pattern in an interferometric microscope and FFT processing method can be used [85].

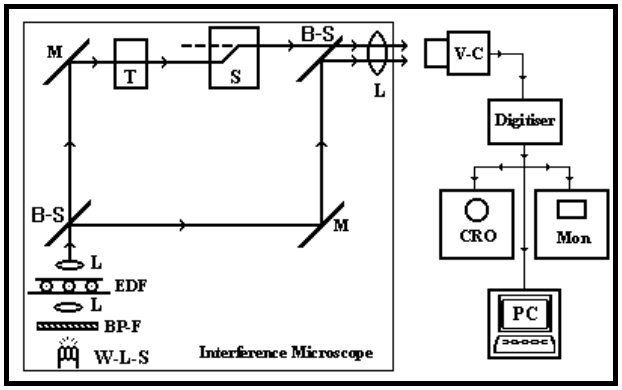
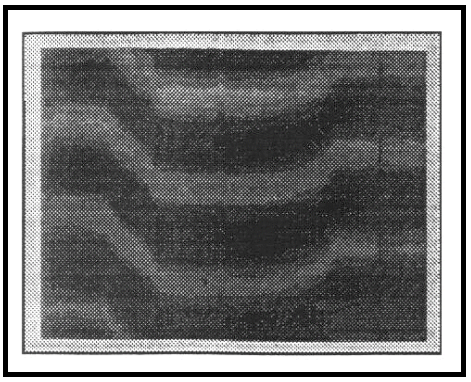


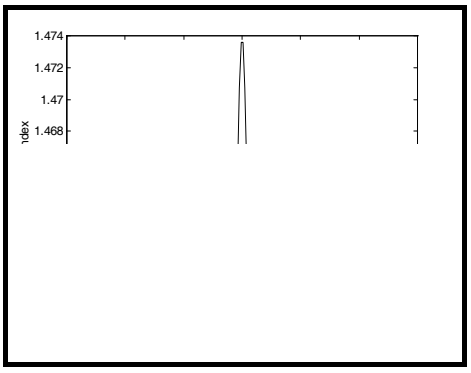
Fig. 5 Setup for fiber refractive index measurement by the interferometry method. **W-L-S:** white light source, **BP-F:** 598 nm band pass filter **L:** lens, **EDF:** erbium-doped fiber at the center, **B-S:** beam splitter, **M:** mirror, **T:** tilter, **S:** shifter, **V-C:** video camera, **CRO:** cathode ray oscilloscope, **PC:** personal computer, Mon: monitor [1].

A small piece of uncoated fiber is immersed in matching oil. A slip covers the fiber. To keep the slip horizontal, a piece of fiber must be placed on each side of the fiber under test. The slip is then inserted under an interference microscope, as demonstrated in Fig. 5. The fiber is illuminated by a monochromatic light formed by a white light source and a narrow band-pass filter. A double image is formed by a beam splitter. One of the images is slightly tilted and shifted to create a clear interference fringe pattern, as shown in Fig. 6. A video camera records the fringe pattern to be processed by a digitizer, computer and oscilloscope. The optical path length of the ray refracted by the fiber is measured by the fringes' deflection. The refractive index profile of the fiber is derived by the fast Fourier transform of this optical path length pattern.

A sample index profile of an EDF measured by this method is shown in Fig. 6. Due to the low resolution of the measurement and thin core of the fiber, the dip in the center of the core is eliminated.



(a)



(b)

Fig. 6 The Fringe pattern (a) and the refractive index profile (b) of an EDF, determined from evaluation of the optical path length from the pattern, by FFT method. The right half of the index profile is measured and the left half is determined from the symmetry [1].

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B. *Measurement of the EDF Absorption Spectrum*

The experimental setup for measurement of the absorption spectrum is shown in Fig. 7. The white light source is launched to the fiber through a lens, monochromator and a microscope objective, respectively. The signal is chopped through a mechanical chopper. The setup can be modified to swap the monochromator by an optical spectrum analyzer (OSA). The fiber output is connected to a photodetector. The detector output signal is amplified by a lock-in amplifier and connected to a computer. The monochromator or OSA sweeps over the desired wavelength bandwidth. To measure the absorption spectrum in a wide range, it should be done in two steps. For the wavelengths lower than 1 μm, a Si photodetector and for wavelengths over 1 μm a Ge or InGaAs photodetector must be used. The absorption spectrum is measured by the cut-back method.

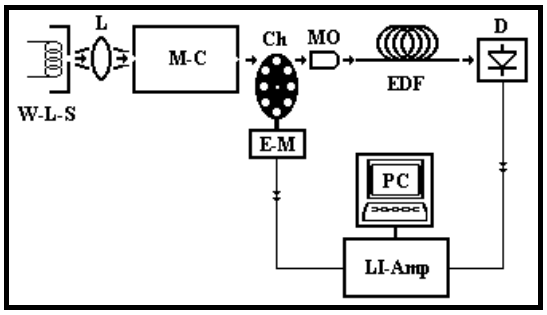


Fig. 7 Experimental setup for measurement of EDF absorption spectrum. **WL-S:** white light source, **L:** lens, **M-C:** monochromator, **Ch:** chopper, **E-M:** chopper electro-motor, **MO:** microscope objective, **EDF:** erbium-doped fiber, **LI-Amp:** lock-in amplifier, **PC:** personal computer, **D:** optical detector. The setup can be modified to swap the monochromator by an optical spectrum analyzer (OSA) [1].

After the first measurement, the fiber would be cut to shorter length and measurement repeated several times, whereas the input launching condition is kept unchanged. The absorption spectrum will be calculated as:

$$\alpha(\lambda)=\frac{10}{L_{long}-L_{short}}\log\frac{P_{o,short}(\lambda)}{P_{o,long}(\lambda)}\ \text{dB/m} \qquad (1)$$

where L_{long}, $P_{o,long}(\lambda)$ and L_{short}, $P_{o,short}(\lambda)$ are the length and the output power for different wavelengths of the main and cut fiber, respectively. Related to the value of absorption peaks, the power and length of short and long fiber can be chosen from any of those in the different steps of the experiment. For low concentration fiber and hence lower absorption, L_{long} and L_{long}-L_{short} must be long enough to have significant loss. For fibers with higher absorption, these two must be short. The absorption spectrum of a sample EDF is depicted in Fig. 8.

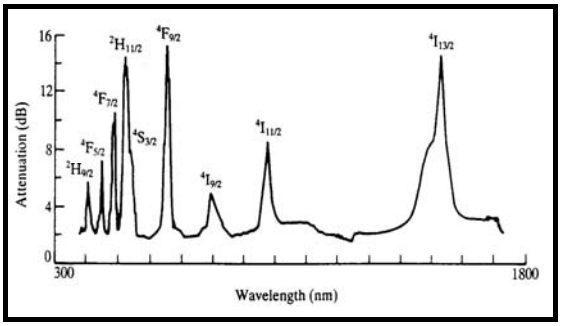


Fig. 8 Absorption spectrum of a sample EDFA [28].

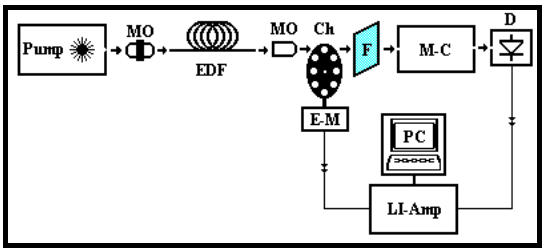


Fig. 9 Experimental setup for measurement of fluorescent spectrum. **Pump:** 514.5 nm argon laser, 980 nm, or 1480 nm laser diode, **MO:** microscope objective, **SMF:** single mode fiber, **EDF:** erbium-doped fiber, **Ch:** chopper, **E-M:** chopper electro-motor, **F:** pump rejection filter, **M-C:** monochromator, **D:** optical detector, **LI-Amp:** lock-in amplifier, **PC:** personal computer. The setup can be modified to swap the monochromator by an optical spectrum analyzer (OSA) [1].

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For measurement of the fiber background loss, $l_k(\lambda)$, the same method with much longer EDF at wavelengths far from any absorption peak, should be used.

C. *Measurement of the EDFA Fluorescent Spectrum*

The schematic diagram of the experimental setup for fluorescent measurement is shown in Fig. 9. The output of a 514.5 nm argon laser or any other laser with wavelength close to any absorption peak of Fig. 8, or the optimum cases, ie. 980 nm or 1480 nm laser diode is launched to the EDF through a microscope objective (MO). The output is chopped and launched to the monochromator via another MO. The setup can be modified to swap the monochromator by an optical spectrum analyzer (OSA). The un-absorbed pump power is reflected by a bulk filter or a fiber Bragg grating (FBG). This filter has normally negligible loss in fluorescence or signal wavelengths. The monochromator output is detected by a Ge or InGaAs detector and is connected to the lock-in amplifier and the PC. The fluorescent output is saved on the PC. It would be better to measure the fluorescence from a very short EDFA from the side- or back-scattered light. A sample fluorescent spectrum of EDFA is shown in Fig. 10.

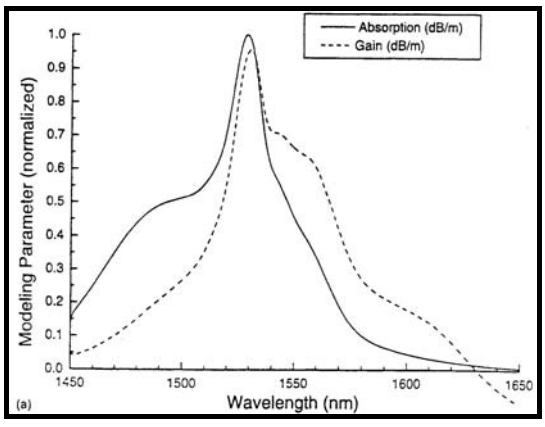


Fig. 10 The fluorescent spectrum of a sample EDFA.

D. *Measurement of the EDFA Gain Spectrum*

The schematic diagram of the experimental setup for gain measurement of EDFA is demonstrated in Fig. 11. The white light source, as signal, is focused into the monochromator (M-C) via a lens. The M-C output is chopped by a mechanical chopper and is launched to port one of the coupler by a MO. The output of a pump laser, is launched into port two of the coupler by another MO. The EDFA is spliced to port 4 of the coupler. The third port can be used for monitoring the input power. Again a bulk or a fiber Bragg grating filter reflects the un-absorbed pump power. The output signal is detected by a Ge or InGaAs photodetector. The detector output is connected to the lock-in amplifier and a personal computer. The setup can be modified to swap the monochromator by an optical spectrum analyzer (OSA).

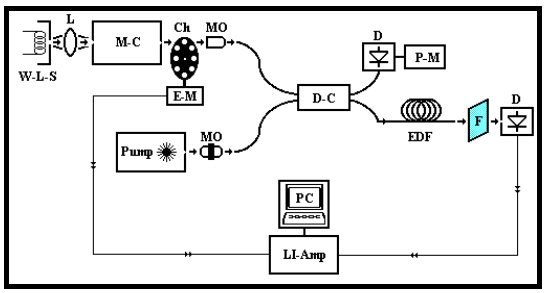


Fig. 11 Experimental setup for measurement of EDFA gain spectrum. **W-L-S:** white light source, **L:** lens, **M-C:** Monochromator, **D-C:** directional coupler, **Ch:** chopper, **E-M:** chopper electro-motor, **Pump:** 514.5 nm Argon laser or 980 nm laser diode, **MO:** microscope objective, **P-M:** power monitor, **SMF:** single mode fiber, **EDF:** erbium-doped fiber, **S:** fiber splice, **F:** pump rejection filter, **D:** optical detector, **LI-Amp:** lock-in amplifier, **PC:** personal computer. The setup can be modified to swap the monochromator by an optical spectrum analyzer (OSA) [1].

The gain spectrum can be measured through measurement of the fiber fluorescence. The monochromator sweeps between desired wavelengths, and the output fluorescent spectrum is saved. This curve will be calibrated in terms of the gain.

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The pumped and un-pumped output signal are measured and their ratio, i.e. the gain variation ($\Delta G(\lambda_s)$) is calculated. The gain spectrum obtained from the calibration of fluorescent spectrum $F(\lambda)$ will be:

$$g^*(\lambda)=\left[\frac{\Delta G(\lambda_s)}{L}-\alpha(\lambda_s)\right]\frac{F(\lambda)}{F(\lambda_s)} \quad dB/m, \quad (2)$$

where L is the amplifier length, and λ_s is the signal wavelength.

The gain spectrum can also be directly measured by conventional cut back method.

E. *Measurement of the Metastable Level Lifetime*

The metastable fluorescent lifetime can be measured by the same setup as that of fluorescent measurement **Fig. 9**, except that the chopper with low frequency must be placed at the input of the EDFA.

At each period of the pump pulse, the excited level is populated and when the pulse falls to zero, the fiber fluorescent decays exponentially with time constant (relaxation time) of metastable lifetime. The output pulse is saved in a storage oscilloscope. The metastable level lifetime is the time in which the fluorescent decays to 1/e of its maximum. Metastable lifetime depends on the length of the fiber and therefore, by measurement of the lifetime at different fiber lengths, the accurate lifetime can be derived by interpolation of the lifetime curve to zero length.

VII. FABRICATION AND CHARACTERIZATION OF EDFA IN IRAN

The first attempt for fabrication of the preform and fiber in Iran was started in Iran Telecom Research Center in 1987. A simple setup for preform fabrication by modified chemical vapor deposition was arranged and some preforms with desired refractive index profile were fabricated. The profiles were measured out of Iran, which was acceptable. This success was the basement of establishment of the "Optical Fiber Fabrication Company" in Tehran in 1989. Later on, the solar cell production line was founded and the company name changed to "Optical Fiber and Solar Cell Fabrication Company (OFFC)". The company has two hydrogen and oxygen and one nitrogen generator, two de-ionized water production machine, one tube washing machine, two MCVD systems (lathes and gas delivery systems), one sleeving machine, one preform analyzer system, two twelve meter height fiber drawing tower, one proof testing system, one fiber coloring machine and one complete set of test equipments for measuring all necessary parameters such as, loss, geometry of the fiber, attenuation spectrum, cutoff wavelength, dispersion, real length, etc. The preform fabrication was started in 1994.

The preform fabrication by MCVD technique and incorporation of the erbium ions by solution doping can easily be performed in the factory. The drawing of the sintered preform and characterization of the preform and fiber can easily be carried out in the company.

In 2002, as a project of "Optical Communication Group of Iran Telecommunication Research Center", the fabrication of fiber preform by VAD technique was started by a preliminary setup. By this simple setup, it has been shown that the fabrication of porous preform by this method is feasible in Iran. Although the feasibility of fabrication of porous preform is approved, but still the project needs more support to be optimized. Since this beneficial technology is monopoly of a foreign country, it is not possible to be imported and must be improved and established by Iranian brain-works. Therefore, the fabrication of preform by VAD technique and incorporation of Er ions by related method, given in section 2.2, is possible in Iran. Also, the characterization of the fabricated erbium doped preform and fiber by the methods given in sections IV and VI can easily be carried out in Optical Fiber and Solar Cell Fabrication Company, Optical Communication Group of Iran Telecommunication Research Center, Laser and Plasma Research Institute of Shahid Beheshti University, Tehran, Iran, Iranian

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National LASER Center (INLC), and most of physics and electrical engineering departments of the Iranian universities.

VIII. CONCLUSION

Fabrication of EDFAs is the same as that of conventional single mode fibers. Modified chemical vapor deposition (MCVD) and vapor axial deposition (VAD) methods can be employed for this task. Erbium ions can be incorporated into preforms through liquid or vapor phase processes. In liquid phase process EDFAs of low concentration erbium can be fabricated by aqueous or other solutions of erbium salts. This method can give concentration up to about 1000 ppm without Er clustering. For higher concentration the method of flash-condensation by using phosphoric acid should be employed. Due to the devitrification or phase separation of preform core dopants, the background loss of the Er-doped fibers, compared to the conventional single mode fibers is increased.

In fabrication of EDF with MCVD technique, the high temperature of collapse process causes evaporation of core dopant including Er ions. This effect causes an Er or index profile dip at the center of the fiber. The partial-collapse before Er incorporation reduces this effect.

The refractive index profile of the fabricated Er-doped preform is measured by different methods, such as scanning or focusing methods. The refractive index profile of the fiber is identical to that of the preform. If the diameter of drawn fiber becomes lower than that of the standard value, the preform must be sleeved by an extra tube and stretched for elongation. After drawing the preform to a single mode fiber, for certainty, the refractive index profile of the fiber can be measured by an interferometry microscope.

Characterization of erbium doped fiber including measurements of absorption, fluorescent, and gain spectra must be carried out before to be used as the main component of the EDF amplifier or laser.

In Iran, the machines, devices and equipments for fabrication of fiber and preform and incorporation of Er by MCVD and VAD techniques in “Optical Fiber and Solar Cell Fabrication Company” of Iran and “Optical Communication Group of Iran Telecommunication Research Center”, respectively, can be used for fabrication of preform and fiber and incorporation of Er into them. The measurement apparatuses of these two centers, as well as Laser and Plasma Research Institute of Shahid Beheshti University, Tehran, Iran, Iranian National LASER Center (INLC), and most of the physics and electrical engineering departments of the Iranian universities can be employed for characterization of the fabricated or purchased EDFAs.

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REFERENCES

[1] N. Granpayeh, *Some functional characteristics of erbium doped fiber amplifiers*, PhD dissertation, School of Electrical Engineering, University of New South Wales, Sydney, Australia, 1998.

[2] A.A.A. Bakar, M.A. Mahdi, M.H. Al-Mansoori, S. Shaari, and A.K. Zamzuri, “Single-stage gain-clamped L-band EDFA with C-band ASE saturating tone,” J. Laser Phys., vol. 19, pp. 1026-1029, 2009.

[3] R. I. Laming, M. N. Zervas, and D. N. Payne, “Erbium-doped fiber amplifier with 54 dB gain and 3.1 dB noise figure,” IEEE Photon. Technol. Lett., vol. 4, pp. 1345-1347, 1992.

[4] Y. Awaji, H. Furukawa, N. Wada, E. Kong, P. Chan, and R. Man, “Burst-mode EDFA based on a mid-position gain flattening filter with an over pumping configuration for variable traffic conditions in a WDM environment,” J.

[Downloaded from ijop.ir on 2024-03-29]

Opt. Quantum Electron., vol. 40, pp. 461-466, 2008.

[5] A.R. Mowla and N. Granpayeh, "A novel design approach for erbium doped fiber amplifiers by particle swarm optimization," Progress In Electromagnetics Research M, vol. 3, pp. 103–118, 2008.

[6] J. K. Bae, D. Koh, S. H. Kim, N. Park, and S. B. Lee, "Automatic EDFA Gain Spectrum Equalization Using LPFGs on Divided Coil Heaters," Proc. Opt. Fib. Commun. Conf. (OFC), Anaheim, California March 25, 2007.

[7] H. Shin, A. Schweinsberg, G. Gehring, K. Schwertz, H. Jeong C., R. W. Boyd, Q-H. Park, and D. J. Gauthier "Reducing pulse distortion in fast-light pulse propagation through an erbium-doped fiber amplifier," Opt. Lett., vol. 32, pp. 906-908, 2007.

[8] B. Bouzid, M.K. Abdullah, and M.A. Mahdi, "High-gain erbium-doped fiber amplifier incorporating a double-pass amplification technique as a preamplifier," J. Laser Phys., vol. 18, pp. 460-463, 2008.

[9] A.R. Mowla and N. Granpayeh, "Design of a flat-gain multipumped distributed fiber Raman amplifier by particle swarm optimization," J. Opt. Soc. Am. A, vol. 25, pp. 3059-3066, 2008.

[10] J. Yu and X. Zhou, "Ultra-high-capacity DWDM transmission system by multilevel modulations and digital coherent detection," Proc. 18th int. conf. on Wireless and Opt. Commun., Newark, New Jersey, USA, pp. 56-60, 2009.

[11] C.G. Atkins, J.F. Massicott, J.R. Armitage, R.Wyatt, B.J. Ainslie, and S.P. Craig-Ryan, "High gain, broad spectral bandwidth erbium-doped fiber amplifier pumped near 1.5 μm," Electron. Lett., vol. 25, pp. 910-911, 1989.

[12] C. Tian and S. Kinoshita, "Analysis and control of transient dynamics of EDFA pumped by 1480- and 980-nm Lasers," IEEE J. Lightwave Technol., vol. 21, pp. 1728-1734, 2003.

[13] H. Ono, M. Yamada, and M. Shimizu, "S-Band erbium doped fiber amplifiers with a multistage configuration-design, characterization, and gain tilt compensation," IEEE J. Lightwave Technol., vol. 21, pp. 2240-2253, 2003.

[14] H. Nakaji, Y. Nakai, M. Shigematsu, and M. Nishimura, "Superior high speed automatic gain controlled erbium doped fiber amplifiers," Opt. Fib. Technol., vol. 9, pp. 25-35, 2003.

[15] W. J. Miniscalco, "Erbium-doped glasses for fiber amplifiers at 1500 nm," IEEE J. Lightwave Technol., vol. 9, pp. 234-249, 1991.

[16] M.J. Pettitt, A. Hadjifotiou, and R.A. Baker, "Crosstalk in erbium doped fiber amplifiers," Electron. Lett., vol. 25, pp. 416-417, 1989.

[17] R.I. Laming, L. Reekie, P.R. Morkel, and D.N. Payne, "Multichannel cross-talk and pump noise characterization of Er^{3+}-doped amplifier pumped at 980 nm," Electron. Lett., vol. 25, pp. 455-456, 1989.

[18] C.R. Giles, E. Desurvire, and J.R. Simpson, "Transient gain and crosstalk in erbium-doped fiber amplifiers," Opt. Lett., vol. 14, pp. 880-882, 1989.

[19] M. Suyama, K. Nakamura, S. Kashiwa, and H. Kuwahara, "Polarization -independent gain of Er^{3+}-doped fiber amplifier under single mode pumping," Tech. Dig., Integrated Opt. Commun. Conf. (IOOC '89), paper 20A4-3, pp. 32-33, 1989.

[20] V.J. Mazurczyk and J.L. Zyskind, "Polarization hole burning in erbium doped fiber amplifiers," Tech. Dig. CLEO 93, Baltimore, Md, USA, Paper CPD26, 1993.

[21] V.J. Mazurczyk and J.L. Zyskind, "Polarization dependent gain in erbium doped-fiber amplifiers," IEEE Photon. Technol. Lett., vol. 6, pp. 616-618, 1994. Although the paper is discussing about polarization dependent gain and polarization hole burning, it is shown that reduction of degree of polarization of both pump and signal below 10% reduces the polarization dependent gain substantially.

[22] J.J. Pan, K. Guan, X. Qiu, M. Zhang, J. Jiang, E. Zhang, and F.Q. Zhou, "Advantages of low cost, miniature intelligent EDFAs for next-generation dynamic metro/access networks," Opt. Fib. Technol., vol. 9, pp. 80-94, 2003.

[23] N. Granpayeh, Q.T. Liang, and P.L. Chu, "A mathematical model of temperature dependence of fiber amplifier gain," Proc. 16th Australian Conf. Opt. Fib. Technol.

[Downloaded from ijop.ir on 2024-03-29]

(ACOFT - 16 '91), Adelaide, pp. 334-337, 1991.

[24] M. Bolshtyansky, P. Wysocki, and N. Conti, "Model of temperature dependence for gain shape of erbium-doped fiber amplifier," IEEE J. Lightwave Technol., vol. 18, pp. 1533-1540, 2000.

[25] F.A. Flood, "Comparison of temperature dependence in C-band and L-band EDFAs," IEEE J. Lightwave Technol., vol. 19, pp. 527--535, 2001.

[26] V.A. Alekseeva, I.F. Balashov, and S.I. Khankov, "Temperature dependence of the gain coefficient of phosphate-neodymium glass," Sov. J. Opt. Technol., vol. 49, pp 739-740, 1982.

[27] V.A. Berenberg, V.A. Buchenkov, V.L. Evstigneev, V.G. Ostroumov, V.A. Smirnov, and I.A. Shcherbakov, "Temperature dependence of the gain and of the lasing cross section of a 1.06 μm transition in gadolinium scandium gallium garnet crystals doped with chromium and neodymium," Sov. J. Quantum Electron., vol. 16, pp. 1455-1458, 1986.

[28] V.A. Buchenkov, I.B. Vitrishchak, V.G. Evdokimova, L.N. Soms, A.I. Stepanov, and V.K. Stupnikov, "Temperature dependence of giant pulse amplification in YAG:Nd^{3+}," Sov. J. Quantum Electron., vol. 11, pp. 702-705, 1981.

[29] E. Desurvire, *Erbium doped fiber amplifier: principles and applications*, John Wiley, 1994.

[30] M. J. F. Digonnett (Ed.), *Rare-earth-doped fiber laser and amplifiers*, Marcel Dekker, Inc., 2001.

[31] A. Bjarklev, *Optical fiber amplifiers: design and system applications*, Artech House, 1993.

[32] B.J. Ainslie, K.J. Blow, A.S. Gouveia-Neto, P.G. J. Wigley, A.S.B. Sombra, and J.R. Taylor, "Femtosecond soliton amplification in erbium doped silica fiber," Electron. Lett., vol. 26, pp. 186-188, 1990.

[33] S. Seoyong, K. Sungchul, and S. Sungho, "Fast gain-transient recovery of cascaded EDFAs in WDM networks using a disturbance observer with a PID controller," Photonics, Devices, and Systems IV, Proc. of the SPIE, vol. 7138, pp. 71380-71386, 2008.

[34] M. Wegmuller, P. Oberson O. Guinnard, B. Huttner, L. Guinnard, C. Vinegoni, and N. Gisin, "Distributed gain measurement in Er-doped fibers with high resolution and accuracy using an optical frequency domain reflectometer," IEEE J. Lightwave Technol., vol. 18, pp. 2127-2132, 2000.

[35] A.R. Bahrampour and M. Mahjoei, "Theoretical analysis of spectral hole burning and relaxation oscillation in all-optical gain stabilized multichannel erbium doped fiber amplifier (EDFA)," IEEE J. Lightwave Technol., vol. 19, pp. 1130-1139, 2001.

[36] H.G. Krimmel, T. Pfeiffer, B. Deppisch, and L. Jentsch, "Hybrid electro-optical feedback gain-stabilized EDFAs for long-reach wavelength-multiplexed passive optical networks," 35th Europ. Conf. on Optical Commun. (ECOC '09), pp. 1-2, 2009.

[37] G.P. Agrawal, "Amplification of Ultrashort solitons in erbium-doped fiber amplifiers," IEEE Photon. Technol. Lett., vol. 2, pp. 875-877, 1990.

[38] A.W. Naji, M.S.Z Abidin, M.H. Al-Mansoori, M.Z. Jamaludin, M.K. Abdullah, S.J. Iqbal, and M.A. Mahdi, "Dual-function remotely-pumped Erbium-doped fiber amplifier: loss and dispersion compensator," Opt. Express, vol. 14, pp. 8054-8059, 2006.

[39] P.L. Chu and B. Wu, "Optical switching in twin-core-erbium-doped fibers," Opt. Lett., vol. 17, pp. 255-257, 1992.

[40] P.L. Chu, Y.L. Xue, and B. Wu, "Optical switching in Erbium-doped fibers," SPIE vol. 1979, Lasers and Optoelectronics, pp. 434-445, 1992.

[41] E. Desurvire, "Study of the complex atomic susceptibility of erbium-doped fiber amplifiers," IEEE J. Lightwave Technol., vol. 8, pp. 1517-1527, 1990.

[42] E. Snitzer, W.W. Morey, and W.H. Glenn, "Fiber optic rare earth temperature sensors," Proc. Int. Conf. Opt. Fib. Sensors, pp. 79-81, 1983.

[43] M.C. Farries, M.E. Fermann, R.I. Laming, S.B. Poole, and D.N. Payne, "Distributed temperature sensor using Nd^{3+}-doped optical fiber," Electron. Lett., vol. 22, pp. 418-419, 1986.

[44] K.W. Quoi, R.A. Lieberman, L.G. Cohen, D.S. Shenk, and J.R. Simpson, "Rare-earth

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doped optical fibers for temperature sensing," IEEE J. Lightwave Technol., vol. 10, pp. 847-852, 1992.

[45] K.A. Fesler, M.J.F. Digonnet, B.Y. Kim, and H.J. Shaw, "Stable fiber-source gyroscopes," Opt. Lett., vol. 15, pp. 1321-1323, 1990.

[46] P.F. Wysocki, M.J.F. Digonnet, B.Y. Kim, and H.J. Shaw, "Characteristics of erbium-doped super-fluorescent fiber sources for interferometric sensor applications," IEEE J. Lightwave Technol., vol. 12, pp. 550-567, 1994.

[47] E. Snitzer, "Optical maser action of Nd^{3+} in a barium crown glass," Phys. Rev. Lett., vol. 7, pp. 444-446, 1961.

[48] E. Snitzer, "Proposed fiber cavities for optical lasers," J. Appl. Phys., vol. 32. pp. 36-39, 1961.

[49] C.J. Koester and E. Snitzer, "Amplification in fiber laser," Appl. Opt., vol. 3, pp. 1182-1186, 1964.

[50] E. Snitzer, and R. Woodcock, "Yb^{3+}-Er^{3+} glass laser," Appl. Phys. Lett., vol. 6, pp. 45-46, 1965.

[51] K.C. Kao and G.A. Hockham, "Dielectric-fiber surface waveguides for optical frequencies," IEE Proc. J. Optoelectronics, vol. 133, pp. 191-198, 1966.

[52] V.S. Letokhov and B.D. Pavlik, "Nonlinear amplification of surface light wave in active optical fiber," Sov. J. Tech. Phys., vol. 36, pp. 2181-2187, 1966.

[53] J. Stone and C.A. Burrus, "Neodymium-doped fiber lasers: room temperature cw operation with an injection laser pump," Appl. Opt., vol. 13, pp. 1256-1258, 1974.

[54] D.N. Payne and W.A. Gambling "New silica-based low-loss optical fiber," Electron. Lett., vol. 10, pp. 289-290, 1974.

[55] T. Miya, Y. Terunuma, T. Hosaka, and T. Miyashita, "Ultimate low-loss single-mode fiber at 1.55 μm," Electron. Lett., vol. 15, pp. 106-108, 1979.

[56] V.P. Gapontsev, S.M. Matitsin, A.A. Isineev, and V.B. Kravchenko, "Erbium glass lasers and their applications," Opt. Laser Technol., vol. 14, pp. 189-196, 1982.

[57] S.B. Poole, D.N. Payne, and M.E. Fermann, "Fabrication of low-loss optical fibers containing rare-earth ions," Electron. Lett., vol. 21, pp. 737-738, 1985.

[58] R.J. Mears, L. Reekie, S.B. Poole, and D.N. Payne, "Neodymium-doped silica single-mode fiber lasers," Electron. Lett., vol. 21, pp. 738-740, 1985.

[59] R.J. Mears, L. Reekie, S.B. Poole, and D.N. Payne, "Low-threshold tunable cw and Q-switched fiber laser operating at 1.55 μm," Electron. Lett., vol. 22, pp. 159-160, 1986.

[60] E. Desurvire, J.R. Simpson, and P.C. Becker, "High-gain erbium-doped travelling-wave fiber amplifier," Opt. Lett., vol. 12, pp. 888-890, 1987.

[61] C.A. Millar, I.D. Miller, B.J. Ainslie, S.P. Craig, and J.R. Armitage, "Low-threshold cw operation of an erbium-doped fiber laser pumped at 807 nm wavelength," Electron. Lett., vol. 23, pp. 865-866, 1987.

[62] R.J. Mears, L. Reekie, I.M. Jauncey, and D.N. Payne, "Low-noise erbium-doped fiber amplifier operating at 1.54 μm," Electron. Lett., vol. 23, pp. 1026-1028, 1987.

[63] E. Snitzer, H. Po, F. Hakimi, R. Tumminelli, and B.C. McCollum, "Erbium fiber laser amplifier at 1.55 μm with pump at 1.49 μm and Yb sensitized Er oscillator," Opt. Fib. Commun. Conf., Tech. Dig., paper no. PD2, 1988.

[64] R.J. Mears and S.R. Baker, "Erbium fiber amplifiers and lasers," Opt. and Quantum Electron., vol. 24, pp. 517-538, 1992.

[65] I. Riant, "UV photoinduced fiber gratings for gain equalization," Opt. Fib. Tehnol., vol. 8, pp. 171-194, 2002.

[66] Alireza Mowla and Nosrat Granpayeh, "Optimum design of a hybrid erbium-doped fiber amplifier/fiber Raman amplifier using particle swarm optimization," J. Appl. Opt., vol. 48, pp. 979-984, Feb. 2009.

[67] M. Shimizu, M. Yamada, M. Horiguchi, T. Takeshita, and M. Okayasu, "Erbium-doped fiber amplifiers with an extremely high gain coefficient of 11.0 dB/mW," Electron. Lett., vol. 26, pp. 1641-1643, 1990.

[68] M. Shimizu, M. Yamada, M. Horiguchi, and E. Sugita, "Concentration effect on optical amplification characteristics of Er-doped silica single-mode fibers," IEEE Photon. Technol. Lett., vol. 2, pp. 43-45, 1990.

[Downloaded from ijop.ir on 2024-03-29]

[69] M. Shimizu, M. Yamada, M. Horiguchi, and E. Sugita, "Gain characteristics of erbium-doped single-mode fiber amplifiers operated at liquid-nitrogen temperature," Appl. Phys. Lett., vol. 56, pp. 2273-2275, 1990.

[70] K. Kurokawa, and M. Nakazawa, "Wavelength-dependent amplification characteristics of femtosecond erbium-doped optical fiber amplifiers," Appl. Phys. Lett., vol. 58, pp. 2871-2873, 1991.

[71] B.J. Ainslie, S.P. Craig, and S.T. Davey, "The fabrication and optical properties of Nd^{3+} in silica-based optical fibers," Mat. Lett., vol. 5, pp. 143-146, 1987.

[72] J. Simpson, "Fabrication of rare earth-doped glass fibers," SPIE, vol. 1171, *Fiber Laser sources and Amplifiers*, pp. 2-7, 1989.

[73] A.W. Snyder, and J.D. Love, *Optical Waveguide Theory*, Chapman and Hall, USA, 1983.

[74] S.B. Poole, "Fabrication of Al_2O_3 co-doped optical fibers by solution-doping Technique," Proc. ECOC' 88, pp. 433-436, 1988.

[75] D.J. DiGiovanni, "Fabrication of rare earth doped optical amplifier," SPIE, vol. 1373, *Fiber Laser sources and Amplifiers II*, pp. 72-79, 1990.

[76] E. Snitzer, and R. Tumminelli, "SiO_2-clad fibers selectivity volatilised soft glass cores," Opt. Lett, vol. 14, pp. 757-759, 1989.

[77] S.B. Poole, D.N. Payne, R.J. Mears, M.E. Fermann, and R.I. Laming, "Fabrication and characterization of low-loss optical fibers containing Rare-earth ions," IEEE J. Lightwave Technol., vol. 4, pp. 870-876, 1986.

[78] J.E. Townsend, S.B. Poole, and D.N. Payne, "Solution-doping technique for fabrication of rare-earth-doped optical fibers," Electron. Lett., vol. 23, pp. 329-331, 1987.

[79] J.B. MacChesney and J.R. Simpson, "Optical waveguides with novel compositions," Proc. OFC'85, Paper WH5, p. 100, 1985.

[80] B.J. Ainslie, "A review of the fabrication and properties of erbium-doped fibers for optical amplifiers," IEEE J. Lightwave Technol., vol. 9, pp. 220-227, 1991.

[81] A.L.G. Carter, S.B. Poole, and M.G. Sceats, "Flash-condensation technique for the fabrication of high-phosphorous-content rare-earth-doped fibers," Electron. Lett., vol. 28, pp. 2009-2011, 1992.

[82] L. Cognolato, B. Sordo, E. Modone, A. Gnazo, and G. Cocito, "Aluminum/erbium active fiber manufactured by a non-aqueous solution doping method," SPIE, vol. 1171, *Fiber Laser sources and Amplifiers*, pp. 202-208, 1989.

[83] T. F. Morse, L. Reinhart, A. Kilian, W. Risen, and J. W. Cipolla, "Aerosol doping technique for MCVD and OVD," SPIE, vol. 1171, *Fiber Laser Sources and Amplifiers*, pp. 72-79, 1989.

[84] J. M. Senior, *Optical Fiber Communications: principles and practice*, Prentice-Hall International, Inc. London, 3rd Ed., 2008.

[85] P. L. Chu, "Nondestructive measurement of index profile of an optical fiber preform," Electron. Lett., vol. 13, pp. 736-738, 1977.

[86] P. L. Chu, and T. Whitbread, "Nondestructive determination of refractive index profile of an optical fiber: Fast Fourier transform method," Appl. Opt., vol. 18, pp. 1117-1122, 1979.

[87] J. Gowar, *Optical Communication Systems*, Prentice-Hall International, Inc. London, 1984.

[88] A. Ghatak and K. Thyagarajan, *Introduction to Fiber Optics*, Cambridge University Press, 1998.

[89] G. Keiser, *Optical Fiber Communications*, McGraw Hill, 3rd Ed., 2000.



Nosrat Granpayeh was born in Tehran, Iran, in 1952. He received his B.S., M.S., and Ph.D. degrees in telecommunication engineering from Telecommunication College of Iran, Radio and Television College, Tehran, Iran and School of Electrical Engineering of University of NSW, Sydney Australia, in 1975, 1980, and 1996, respectively.

In 1975, as an honor graduate of the Faculty of Electrical Engineering of K. N. Toosi University of Technology (formerly,

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Telecommunication College), Tehran, Iran, he was employed as an instructor there, where he was later promoted to lecturer and assistant professor in 1980 and 1996, respectively. Since 1980, he has been involved in simultaneous teaching and doing research in the University, as well as in Iran Telecommunication Research Center (ITRC). His research interests are in optical devices, equipments and materials, optical fibers, and optical fiber nonlinear effects. He is the author or co-author of more than 25 journal- and 50 conference- papers. He is a member of IAEEE **(**Iranian Association of Electrical and Electronics Engineers), OPSI (Optics and Photonics Society of Iran), IEEE and IEEE Photonic Society.



Memoriam: Professor Pak Lim Chu[1]
12 November 1940 – 15 March 2008

The fiber-optics community has lost a great icon with the passing of Prof. Pak Chu after a one year battle with cancer. His passing was commemorated with an extended service of thanksgiving, eulogy, tributes, and valediction at the West Sydney Chinese Christian Church that was attended by an overflowing congregation of colleagues, friends, and fellow Christians.

Prof. Chu is a great champion and a pioneer in the field of fiber optics in Australia. He set up the very first academic fiber-optics research laboratory in Australia at the University of New South Wales (UNSW) in 1970s. The laboratory was equipped with the first preform-making and fiber-drawing facilities in the country. For the last 30 years, Prof. Chu has made extensive contributions to the optical fiber technology. In early 1980s, he invented an acclaimed method to measure the refractive-index profiles of fiber preforms. The method was adopted in an advanced commercial instrument for the characterization of optical fibers. In the mid-1980s, he successfully solved the problem of soliton interaction, which laid an important foundation for soliton communications, a field in which he maintained an interest for over 20 years. In addition, Prof. Chu had worked on a large number of innovative optical devices, including nonlinear optical switches, fiber-optic acoustic sensors, polymer fiber Bragg gratings, and vertical optical polymer waveguide couplers. This work has attracted considerable attention over the years. His study on chaos communications is also very influential. In recent years, he spent much effort in promoting polymer optical fiber technology, a growing field with many potential applications in short-distance transmission and optical sensing. His contributions to the field of fiber optics are invaluable.

On the teaching side, Prof. Chu supervised over 40 doctoral and numerous honours students and developed the first undergraduate courses in optical communications technology in Australia.

Prof. Chu was a popular speaker, particularly at meetings in Southeast Asia, giving numerous contributed and invited talks as well as short courses and tutorials. He was a Fellow of several scientific societies including the Australian Technological Society and the Optical Society of America. He published almost 500 journal and conference papers, and was honoured in 2001 with the Centenary Medal of Australia for his contribution to optical communications.

In 2001, Prof. Chu retired from UNSW and moved to the City University of Hong Kong (CityU) where he became Professor and Director of the Optoelectronics Research Centre (RCO). During his Directorship of RCO, he made significant contributions to the development of the photonics research programs at CityU. His cheerful, positive, and supportive temperament enabled him to be an excellent mentor and a real friend of many people. Prof. Chu was also active in fostering collaborations with industry and organizing international conferences and training

[1] By LEOS: http://photonicssociety.org/newsletters/jun08/memoriam.html

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workshops to raise the profile of the photonics community in Hong Kong. After his retirement from CityU in 2006, he joined a local company, LINKZ International Limited (the former Networking Cable Business Unit of LTK), where he continued to make contributions in photonics for the rest of his time in Hong Kong.

Prof. Chu is survived by his wife Eva, daughter Evelyn, son Desmond and five grandchildren.



Dr Iain Skinner received his B.Sc. and Ph.D. degrees in Applied Mathematics and Optical Physics from University of Queensland and Australian National University, in 1981 and 1985, respectively.

He was employed in University of Surrey, as a research fellow in 1985-1987. He was employed in The University of New South Wales as a Research Officer in 1987-1989. After one year work as visiting scientist for Canadian Government, in 1990-1991, he was employed again in The University of New South Wales as a Lecturer in 1992, while was promoted to Senior Lecturer in 1997.

Dr Skinner has been a visiting fellow in The University of Edinburgh and The University of Surrey in 1995 and 1999, respectively.

He is the author or co-author of 9 journal and several conference papers. He is a member of Australian Mathematical Society

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