RARE EARTH-BASED ACTIVE OPTICAL
FIBER DEVICE DEVELOPMENT

by
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(ABSTRACT)

This work concentrates on the study, analysis, and development of rare earth-based optical fiber active devices. The properties of the neodymium ion are analyzed and related to its potential role in the operation of various active optical devices. Existing technology in rare earth-based fiber amplifiers is reviewed. Novel techniques for the fabrication of rare earth-based glass rods and fibers are presented. Further, a discussion of results and ideas for the point sensing of temperature, and the simultaneous sensing of temperature and strain using optical time domain reflectometry techniques with such devices is also presented.
Acknowledgements

I wish to express my sincerest appreciation to my advisor, Dr. Richard O. Claus, for his guidance, encouragement, and help in this work and throughout my masters program. I also wish to thank Dr. T. C. Poon and Dr. R. J. Pieper for useful discussions and for serving on my graduate committee.

I am grateful to my research colleagues Kent A. Murphy and Ashish M. Vengsarkar for their suggestions and help on this project. I also wish to thank all my fellow researchers, and Ann Goette and Linda Jones, for making FEORC a pleasant place to work.

Finally, I wish to thank my parents for their continuous encouragement and moral support.
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1.0 INTRODUCTION

Using rare earth elements with optical fibers to construct various active devices dates back to 1964 when C. J. Koester and E. Snitzer first reported amplification in a rare earth-based fiber laser [1]. However, it was not until 1985 that interest in these devices was rekindled due to the development of reliable techniques for their fabrication, and advances in optical fiber technology, and semiconductor lasers. At present, several researchers worldwide are investigating into these active devices ranging from amplifiers and lasers to filters and sensors. This report investigates the study and development of rare earth-based fiber amplifiers; and fiber sensors, which allow point sensing of temperature, and also simultaneous sensing of local temperature and distributed strain.

Rare earth-based glass rods or optical fibers are simply systems in which ions of elements such as neodymium, erbium, ytterbium, or holmium have been incorporated in the glass matrix. They exhibit very high absorption levels in the visible
and near-infrared regions of the spectrum, without significantly compromising the low-loss windows of telecommunication-type fibers.

The concept of rare earth-based optical amplifiers and lasers is based on obtaining the required optical gain by pumping the active region. The pumping is frequently implemented by illuminating the gain medium with light at a wavelength that is absorbed strongly by the dopant ions. This absorbed energy is in part stored in the excited ions. And, the transition back to a low-energy state occurs preferentially in the presence of photons having an energy equal to that associated with the transition, a process known as stimulated emission, which in turn gives rise to the optical gain. The laser action can also be achieved by sandwiching a gain medium between two mirrors, thereby forming a Fabry-Perot cavity. The lasing occurs when the gain exceeds the natural loss of the cavity.

The technique involved in sensing of temperature is by monitoring the decay time of the fluorescent material, e.g. a Nd:glass or Nd:YAG system. The "decay-time" change with temperature as a measurement technique in these systems has the major advantage that a determination of the input light intensity is not required. Simultaneous sensing of temperature and strain can be made possible by employing optical time domain reflectometry (OTDR) techniques.

1.0 INTRODUCTION
There is seen to be a large and increasing amount of international interest in the research, development, and application of these active devices [2]. Fiber amplifiers are being developed to function as in-line amplifiers for the long and short-haul communications industry, thus replacing conventional electronic repeaters. These can be fusion spliced into the main data links thus eliminating the Fresnel-reflection feedback that limits the gain in semiconductor laser amplifiers. A vast majority of interest is also focused on erbium-doped fiber amplifiers because they can provide exceptionally high gains at 1536 nm which lies within the third telecommunications window. Fiber lasers are compact and may be spliced directly onto conventional optical fibers with minimum insertion loss. Their Q-switched performance makes them ideally suited to high-resolution OTDR for fault location in telecommunication links or distributed sensors. Rare earth-based temperature sensors can prove useful in a wide variety of applications ranging from medical treatment to monitoring industrial equipment. To obtain information of local temperature and discrete strain simultaneously and independently with the same sensing device can prove advantageous for various avionic applications. All these attractive applications justifies the exploration of this upcoming technology.

This presentation is organized into five chapters. Chapter 1 introduces the reader to this growing technology, including a justification for rare earth device

1.0 INTRODUCTION
development. Chapter 2 presents an insight into the rare earth ions. As the experimental study involved neodymium-based samples, a detailed spectroscopic analysis of the trivalent neodymium ion is also given. Chapter 3 deals with the study and development of fiber amplifiers. It also describes novel techniques and ideas for the fabrication of rare earth-based glass rods and optical fibers by employing inexpensive methods. Chapter 4 presents the possibility of using these rare earth devices as sensors. Point sensing of temperature and the simultaneous sensing of temperature and strain is discussed. Chapter 5 summarizes the experimental results, highlights the important aspects of the various systems presented, indicates some problems and limitations, and suggests possible improvements for future work.
2.0 INSIGHT INTO RARE EARTH IONS

Rare earth ions have been shown to exhibit amplification and fluorescence in liquid, crystal, glass and gaseous media. Crystal and glass host materials are of practical use thus far [3]. It is of interest to have an insight into these lasing ions so as to comprehend the underlying principles of the devices in which they are used.

Rare earths come under Group III B in the periodic table. The inner transition metal series from atomic numbers 58 to 71 is of specific interest and is referred to as the 'lanthanides'. Table 1 provides a list of these elements. The electronic configuration of neodymium with atomic number 60 is, for example, 

\[ 1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^2 4d^{10} 5p^6 6s^2 4f^{14} \]

For these inner transition elements, it is seen that as the atomic number increases, the added electrons do not fill in the outer level, but rather go into an inner incomplete level. Entry of electrons into the f-orbital of a lower principle quantum
number is the pattern of these elements. Therefore, the lanthanides have a partially or totally filled set of 4f-orbitals. These orbitals are located considerably inside of the 6s-orbital. Thus, the physical and chemical behavior of the members of this series is not significantly related to the 4f-orbital electron configuration, which leads to their having similar properties. However, the major differences in the properties observed within the series are due to a smooth decrease in the atomic or ionic radius with increasing atomic number. And this arises due to the increased nuclear charge. This effect is called the "lanthanide contraction" [4].

Further it should be noted that the predominant oxidation number of this series is $+3$, but some of the elements do exhibit variable oxidation states. Also, many rare earth compounds are colored and are paramagnetic presumably as a result of unpaired electrons in the 4f-orbital. While $\text{Nd}^{3+}$ is by far the most studied of all the rare earth ions, $\text{Er}^{3+}$ appears as an attractive element for the fabrication of fiber amplifiers and fiber lasers as it generates radiation at 1.54 microns, a wavelength which coincides with the low-loss transmission window of silica fibers [2].
<table>
<thead>
<tr>
<th>Atomic Number</th>
<th>Element</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>58</td>
<td>Cerium</td>
<td>Ce</td>
</tr>
<tr>
<td>59</td>
<td>Praseodymium</td>
<td>Pr</td>
</tr>
<tr>
<td>60</td>
<td>Neodymium</td>
<td>Nd</td>
</tr>
<tr>
<td>61</td>
<td>Promethium</td>
<td>Pm</td>
</tr>
<tr>
<td>62</td>
<td>Samarium</td>
<td>Sm</td>
</tr>
<tr>
<td>63</td>
<td>Europium</td>
<td>Eu</td>
</tr>
<tr>
<td>64</td>
<td>Gadolinium</td>
<td>Gd</td>
</tr>
<tr>
<td>65</td>
<td>Terbium</td>
<td>Tb</td>
</tr>
<tr>
<td>66</td>
<td>Dysprosium</td>
<td>Dy</td>
</tr>
<tr>
<td>67</td>
<td>Holmium</td>
<td>Ho</td>
</tr>
<tr>
<td>68</td>
<td>Erbium</td>
<td>Er</td>
</tr>
<tr>
<td>69</td>
<td>Thulium</td>
<td>Tm</td>
</tr>
<tr>
<td>70</td>
<td>Ytterbium</td>
<td>Yb</td>
</tr>
<tr>
<td>71</td>
<td>Lutetium</td>
<td>Lu</td>
</tr>
</tbody>
</table>
2.1 Neodymium as the lasing ion

2.1.1 Study of host materials

The lanthanide ions which have shown amplifying/lasing action in glass are trivalent \( \text{Nd}^{+3} \), \( \text{Yb}^{+3} \), \( \text{Ho}^{+3} \), and \( \text{Er}^{+3} \). Of these the most studied and useful is \( \text{Nd}^{+3} \) as it can be operated at room temperature with high efficiency. It has lased in almost all the basic glass systems. Some specific examples can be \( \text{K-Ba-Si, La-Ba-Th-B, Na-Ca-Si, and Li-Mg-Al-Si} \) [5]. These ions have lased in crystals as well, a good example being the \( \text{Nd:YAG} \) system.

It is of interest to discuss the various host materials for these active devices. Of all the host materials, glass is the easiest to fabricate in large or complex shapes and with good optical perfection. It can be obtained as rods a few centimeters in diameter or as several micron diameter fibers. It can also be relatively inexpensive in large volume production and can be fabricated by a number of processes such as drilling, drawing, fusion, and cladding, which are generally unsuitable for the processing of crystals. Further, by proper selection of glass base, indices of refraction can be varied from approximately 1.5 to 2.0, or which will set the peak emission wavelengths for neodymium at any one of a number of wavelengths.
between 1.047 and 1.063 microns. A greater importance lies in the ability to adjust the temperature coefficient of index of refraction and the strain-optic coefficients to produce thermally stable cavities.

Further, the amount of rare earth doping in glass can be flexibly varied according to the application. For example, in telecommunication-type host glasses relatively low concentration of rare earth ions are doped. These low dopant levels are necessary if clustering [6] effects are to be avoided. There are however some applications for which short fiber lengths are desirable, for example, fiber lasers operating with only a single longitudinal mode [7]. These require high dopant levels in the core to obtain high efficiencies and output powers. Similarly, in the case of sensing, short lengths (~3 cm) of heavily doped glass or glass fiber can be used to measure temperature by means of change in fluorescence lifetime whereas low dopant concentrations can be used to fabricate a low-loss fiber to act as a distributed temperature sensor where it may be required to extend a length of several hundred meters.

The major disadvantage of glass is its low thermal conductivity. This imposes limitations on the diameter that can be used in CW operation and in high repetition rate applications. The inherent nature of the glass host produces inhomogeneously broadened lines which are wider than would be found in
crystals. This makes it difficult to obtain threshold, because a larger inversion is required to achieve the same gain at the center of the line. However, the broadened line provides an advantage in Q-switched and amplifier applications. Compared with a narrow line, the broadened line gives less loss due to amplified spontaneous emission for the same inversion.

A comparison of glass to crystals suggests that these materials complement each other. Glasses are more suitable for high energy pulsed operation because of their large size, flexibility in their physical parameters, and the broadened fluorescent line. On the other hand, crystals have the advantage of higher thermal conductivity and narrower emission linewidths, which make them more appropriate for CW and high repetition rate applications [3].

A brief mention of liquids as host material can also be made. Their advantages are that the complicated technique of single crystal growing and shaping is avoided, and the concentration of the rare earth ions can be varied in a wide range. The disadvantage of using liquid as a host is that the spectra of the emitting rare earths are broader in liquids because of the constantly changing environment. Also, liquids are particularly prone to large changes in refractive index brought about by changes in temperature. By circulating a liquid, however, one can effectively eliminate such temperature gradients and hence any associated variations in
refractive index. It is seen that circulation entails no loss of optical quality [8] due to variations in density, since liquids are incompressible.

So far the most efficient liquid host has been found to be selenium oxychloride [5,9]. In its pure form it is a nearly colorless, highly toxic liquid with a density comparable to glass and a high dielectric constant. By itself it is capable of dissolving only limited amounts of substances such as neodymium oxide. The solubility of these substances can, however, be increased by adding such compounds such as tin tetrachloride (SnCl₄) or antimony pentachloride (SbCl₅).

It has been observed, in very high power lasers, that solids tend to crack or shatter, whereas liquids naturally do not. Finally, the cost of a solid-state laser rises rapidly with its size, which is limited in any case by the method of fabrication. No such inherent limitations exist for liquid lasers.

2.1.2 Spectroscopic study of neodymium ion in glass

To optimize the glass rod/fiber design, and hence the overall efficiency of an active device, a detailed spectroscopic study of the Nd⁺³ ion in the host material is needed. This section presents such an analysis.

2.0 INSIGHT INTO RARE EARTH IONS
Figure 1 shows the energy level diagram for trivalent neodymium in a barium crown glass host. The energy levels are labeled according to the Russell-Saunders approximation, which is simply a technique to name different energy levels which gives knowledge of the excited state of the ions [9]. Absorption at any of the excited levels above $^4F_{3/2}$ state leads to fluorescence from the $^4F_{3/2}$ state. Approximately one-third of the pumping is provided by the three levels shown in the near infrared. Another third of the pumping is done by the strong absorptions in the yellow at about 17,000 cm$^{-1}$. The near ultraviolet absorptions at 28,000 cm$^{-1}$ gives about 20% of the pumping. The other levels contribute the remainder of the pumping. The resultant fluorescent emission is in the form of three bands with their peaks at 0.88, 1.06, and 1.35 microns. These correspond to the emission from the $^4F_{3/2}$ to $^4I_{9/2}$, $^4I_{11/2}$, and $^4I_{13/2}$ levels, respectively [10]. However, the strongest emission arises from the $^4F_{3/2} \rightarrow ^4I_{11/2}$ transition, which corresponds to the radiation emission at 1.06 microns.

Analysis of the energy levels of the Nd$^{+3}$ ions in a barium crown glass host was first performed by Mann and DeShazer [11]. In the past, these measurements were hindered because the spectrum of the neodymium ion in glass is composed of broad groups of overlapping lines. However, these energy levels were easily deciphered by variation in the absorption and fluorescence spectra obtained by changing the glass temperature from 4 to 300K. The sublevels of the various
energy levels were also observed. These sublevels are usually called as "Stark components." Table 2 gives a listing of the Stark components of the ground state $^4I_{9/2}$, the $^4I_{11/2}$ state, the $^4I_{13/2}$ state, and the metastable state $^4F_{3/2}$ for the Nd:glass system. And, Figure 2 gives a visual description of the detailed energy level diagram of Nd:glass system showing the Stark splitting pattern of the $^4I_{11/2}$, and the $^4F_{3/2}$ states. From this figure it is seen that the $^4F_{3/2}$ has two sublevels separated by 142 cm$^{-1}$. And, the $^4I_{11/2}$ shows six sublevels. Thus, twelve component lines are possible for the laser transition fluorescence from the $^4F_{3/2}$ to $^4I_{11/2}$, which happens to be the main transition line. However, it has been proven experimentally [11] that the laser emission usually consists of four overlapping lines corresponding to transitions from the two sublevels of $^4F_{3/2}$ to the two lowest sublevels of $^4I_{11/2}$ centered around a peak of approximately 1.06 μm.

The phenomenon of line broadening in these devices can be mentioned here. The lanthanide ion linewidths are greatly broadened in glass, a fact that makes glass lasers most suitable for high energy pulse work [3]. It should be noted that the energy level shifts for ions in different environments lead to changes in the transition wavelength from ion to ion, which in turn produces a broadening of the single spectral line. Also, broadening caused by this heterogeneity of the environment is inhomogeneous as it arises from perturbation differences in

2.0 INSIGHT INTO RARE EARTH IONS
individual ions. The subject of line broadening is a complex one and the theoretical studies of the broadening mechanism in solids are difficult. However, from the chemical point of view, it can be seen that if a large number of non-equivalent sites exist for the emitting ion in a material, the linewidths are greatly broadened - the extreme example is probably found in glasses. Random occupation of a crystallographic site by ions of differing charges also give a broadening effect. Besides the symmetry broadening effect, vibrational effects and strains can also cause line broadening [12]. To avoid the vibrational or collision broadening, the material must be cooled or else a material must be chosen so that the vibrational effects are small at the desired temperature of operation.

Also, it can be noted that the energy level scheme for Nd:glass is much the same as for Nd:crystal system. This is because the Stark splitting levels of various energy levels involved are not strongly influenced by the crystal field [13].
Figure 1. Energy levels for trivalent neodymium ion in glass [10].

2.0 INSIGHT INTO RARE EARTH IONS
Figure 2. Stark splitting pattern for Nd:glass [13].
Table 2. Energy levels and corresponding Stark splitting levels of trivalent neodymium in a barium crown glass host.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Energy (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>^4I_9/2 (a)</td>
<td>0</td>
</tr>
<tr>
<td>(b)</td>
<td>55</td>
</tr>
<tr>
<td>(c)</td>
<td>155</td>
</tr>
<tr>
<td>(d)</td>
<td>255</td>
</tr>
<tr>
<td>(e)</td>
<td>495</td>
</tr>
<tr>
<td>^4I_11/2 (a)</td>
<td>1954</td>
</tr>
<tr>
<td>(b)</td>
<td>2035</td>
</tr>
<tr>
<td>(c)</td>
<td>2145</td>
</tr>
<tr>
<td>(d)</td>
<td>2220</td>
</tr>
<tr>
<td>(e)</td>
<td>2250</td>
</tr>
<tr>
<td>(f)</td>
<td>2301</td>
</tr>
<tr>
<td>^4I_13/2</td>
<td>4000</td>
</tr>
<tr>
<td>^4I_15/2</td>
<td>—</td>
</tr>
<tr>
<td>^4F_3/2 (a)</td>
<td>11388</td>
</tr>
<tr>
<td>(b)</td>
<td>11530</td>
</tr>
<tr>
<td>^4F_5/2, ^4H_9/2</td>
<td>12575</td>
</tr>
<tr>
<td>^4F_7/2, ^4S_3/2</td>
<td>13470</td>
</tr>
</tbody>
</table>
2.2 Co-Doping and Sensitization Effects

This section concerns the advantages of co-doping and sensitizing the rare earth ions in the host material. These effects increase the performance of the rare earth-based active devices.

Namikawa et. al. [14] have observed that the solubility of rare earth ions in silica is low and "clustering" results when certain concentrations are exceeded. Additionally, the fluorescence intensity of the $^4F_{3/2} \rightarrow ^4I_{11/2}$ transition, the main lasing line in Nd$^{3+}$, becomes low. Ainslie et. al. [7,15,16] have thoroughly studied this problem and have reported that the addition of a few mole percent of P$_2$O$_5$ or Al$_2$O$_3$ retards the cluster centers, and hence makes possible the development of highly doped glass which can be used for short length devices. Arai et. al. [17] found that a doping level less than ten times the number of Nd for the Al co-dopant and less than about fifteen times for the P co-dopant was enough to remove undesirable fluorescence properties of Nd-doped SiO$_2$ glass.

Sensitization is a process of absorption of light by one ion and its subsequent transfer to the fluorescent ion. This effect is particularly used to increase the effective pumping in a rare earth-based active device. A large variety of sensitizing ions have been identified [3]. However, it should be noted that if one ion
sensitizes in one glass matrix it will not necessarily do so in another matrix. A few sensitizers of Nd$^{3+}$ are \( \text{UO}_2^{+2} \), Mn$^{+2}$, Ce$^{+3}$, Tb$^{+3}$, Eu$^{+3}$, and Cr$^{+3}$. It has been observed that energy transfer may increase the population of excited levels of lanthanides by one or two orders of magnitude compared with direct absorption of light by the rare earth ions. In effect, the sensitization process increases the pumping and hence the gain in these devices.
3.0 RARE EARTH-BASED FIBER AMPLIFIERS

This chapter deals with rare earth-based amplifiers. The basic concepts governing the performance of these devices is presented. A literature review of this technology is reported which includes a brief summary of some of the current problems being encountered in their development. The experiments performed related to the development work on these devices are described, and novel suggestions and ideas are also included which may aid in future development work in this field.
3.1 Basic concepts

The underlying concepts of fiber amplifiers can also be applied to fiber lasers, a topic which will not be considered in detail in this section. However, it is seen that lasing action in a fiber amplifier can be brought about with the forming of a Fabry-Perot configuration. This in turn can be obtained by using external mirrors or dielectric mirrors deposited directly on the end surfaces [18].

It is seen that their operation is based on three-level and four-level systems [13,19,20]. Figure 3 gives the energy level diagrams of these two systems.

In the three-level system, shown in Figure 3(a), operation relies on a strong absorption between the ground level and the highest excited level, followed by a rapid downward transition to the upper laser level. A population inversion occurs when the population of the upper laser level exceeds the thermal equilibrium level of the ground state. Therefore, in order for inversion to be achieved easily between levels 2 and 1, it is essential for the transition from level 3 to level 2 to be rapid (i.e., for the $3 \rightarrow 2$ transition to have a very short lifetime) and the energy level 2 to be metastable. If both these conditions are met and the electromagnetic radiation with wavelength corresponding to the transition wavelength between level 2 and level 1 is used as the input signal, it will cause the emission of stimulated
photons at the same wavelength, coherent with the input signal thereby producing amplification.

The three-level pumping generally requires very high pump powers as the terminal state of the laser transition is the ground state, and more than half of the ground state atoms must be pumped to the upper laser level to achieve population inversion. On the other hand, the four-level systems are characterized by greatly reduced pumping requirements [20].

In the four-level system, shown in figure 3(b), the pump excitation lifts the atoms from the ground state to the highest excited level. This is followed by a fast decay from level 3 to level 2 which is the upper laser level. From the upper laser level, there is a relatively slow fluorescence to the lower laser level. In other words, the radiative lifetime is relatively long in the \(2 \rightarrow 1\) transition. Again, there is seen a fast decay in the \(1 \rightarrow 0\) transition, which facilitates the occurrence of population inversion between the upper and the lower laser levels. In this case, the signal to be amplified has a wavelength corresponding to the transition wavelength between levels 2 and 1. Further, it should be understood that since the ground state, i.e. level 0, is not the lower level of the population inversion, the ground state population may be large as compared to the population of the lower laser level. Thus, pumping needed to achieve inversion need not be intense.

3.0 RARE EARTH-BASED FIBER AMPLIFIERS
Figure 3. Three level and four level systems.
The lanthanide ions which have shown laser action are mostly four-level systems except for the divalent thulium system which is three-level [5]. And, because of the line broadening, only trivalent neodymium, ytterbium, holium, and erbium have shown laser action in glasses. In these solid state lasers, it is seen that the separation between the lower laser level and the ground level runs from one hundred wave numbers to several thousand. With several thousand wave numbers, one can well afford to operate the laser at room temperature. An example is trivalent neodymium which has a difference of about 2000 wavenumbers between its terminal state and the ground state [10].

As discussed earlier, Nd:glass amplifiers/lasers have several gain lines but the strongest and thus the most commonly used is at \( \lambda = 1.06 \mu \text{m} \). As shown in Figure 2, the two main pump bands occur at 0.73 and 0.8 \( \mu \text{m} \). These bands are coupled by a fast nonradiative decay to the \( ^4F_{3/2} \) level. Also, the nature of the transition from the lower laser level \( ^4I_{11/2} \) to the ground level \( ^4I_{9/2} \) is nonradiative. Further, the energy difference between the \( ^4I_{11/2} \) and \( ^4I_{9/2} \) levels is almost an order of magnitude larger than \( kT \), which makes the Nd:glass system work on the four-level scheme [13].
For a four-level material, the population in the terminal level is generally negligible. Thus, the small-signal gain $g$ of the amplifier is related to the population density of the upper laser level $N_u$ by the relation [21,22]

$$g = \sigma N_u.$$  \hspace{1cm} (3.1)

Here $\sigma$ is the peak stimulated emission cross-section. The quantity, $\sigma$, is used as a convenient way of measuring the strength of a transition used for the laser action [12]. A typical value of $'\sigma'$ for Nd:YAG is $8.8 \times 10^{-19}$ cm$^2$ [23].

Further, the population density of the upper lasing level is given by the following relation:

$$N_u = (P_p / V) [(\eta_p f_B \tau) / (h \nu_p)].$$ \hspace{1cm} (3.2)

where $P_p$ is the pump power absorbed at threshold, $V$ is the volume pumped, $\eta_p$ the pump quantum efficiency, namely, the fractional number of neodymium ions in the $^4F_{3/2}$ state per absorbed photon, $h \nu_p$ is the energy per pump photon, $\tau$ the measured fluorescence lifetime, and $f_B$ the effective spectral overlap of pump output, namely, the fractional number of Nd$^{3+}$ ions in the appropriate laser sublevel of the $^4F_{3/2}$ state.
Combining equations (3.1) and (3.2), we obtain

\[ g = \frac{(\sigma P_p / \gamma)[(\eta_p f_B / \tau)]/(\hbar \nu_p )]. \quad (3.3) \]

If there were complete overlap of the two different sublevels of the \(^4F_{3/2}\) state, then \(f_B = 1\). Normally, for a Nd:glass system, \(f_B = 1\) is a good approximation. When Nd:glass is pumped with a flashlamp or some other light source, it has been observed that the excitation predominantly occurs to levels lying higher than the \(^4F_{3/2}\) state. The \(^4F_{3/2}\) level, in turn, gets populated almost entirely by rapid nonradiative relaxation from these higher-lying levels. Thus, each absorbed pump photon leads to a Nd\(^{3+}\) ion in the \(^4F_{3/2}\) state and, therefore, to a close approximation, we can consider \(\eta_p = 1\).

Equation (3.3) thus reduces to

\[ g = \frac{(\sigma P_p / \gamma)[(\tau)]/(\hbar \nu_p )]. \quad (3.4) \]

Further, it is seen that if it is assumed that the whole input power is coupled in glass, then the pump power can be approximated to the signal used for pumping the active medium. Considering all these approximations, the expression for gain is simplified.

3.0 RARE EARTH-BASED FIBER AMPLIFIERS
3.2 Literature Review

Current literature concerning rare earth-based fiber amplifiers is documented in this section. Although the review is not comprehensive, information relevant to this study is included.

In one sense this area is not new since the basic ideas were demonstrated experimentally 20 years ago. In 1963 Young [24] demonstrated lasing in a fiber laser, and in 1964 Koester and Snitzer [1] reported amplification in a fiber laser. Following these initial demonstrations this area underwent a long period of quiescence and has just now reemerged as a result of other technological advances in the laser field. The key advance has been the development of a technique for producing doped monomode fiber with very low loss [25]. A brief review of this technique is presented in Section 3.3.1. This section will also present some problems being faced by researchers at present.

The amplification in a fiber laser reported by Koester et. al. [1] was made on neodymium-doped glass fibers which were pumped transversely by incoherent sources. Their experimental set up is shown in Figure 4. One meter long fibers were fabricated by cladding a neodymium glass core with a lower index glass. Typical diameters were 10 μm for the core and 0.75 mm to 1.5 mm for the
cladding. The whole assembly was wound hot into the form of a helix for convenient pumping with a flash tube. To prevent oscillation, the ends were polished at an angle so the reflected light was lost from the cavity. This angle was of the order of $10^{-1}$. The signal to be amplified was provided by a neodymium glass laser rod ($\lambda = 1.06 \, \mu m$), and pulsed operation was used. The gain was found to be a function of both pumping energy and the time during the pumping pulse at which the gain was measured. Gains as large as $5 \times 10^4$ were reported.

One of the disadvantages in systems with transverse pumping is that the rod diameter is determined more or less by the pump absorption length, which is of the order of 2 and 3 millimeters, which in turn forces the volume of the laser material, and therefore the power level and size of the laser, to be large. Thus, advances were made in this technology by providing end pumping of these devices. The end-pumped configuration allows straightforward miniaturization by scaling down the rod diameter.

Shaw et. al. [22] have demonstrated a fiber optic amplifier which consists of a Nd:YAG crystal placed in series with a signal-carrying optical fiber which allowed end pumping of the Nd:YAG crystal. Their experimental set up is shown in Figure 5. A multiplexing coupler is used to couple both the pump signal and the signal to be amplified onto a single fiber, which directs both the signals to the

3.0 RARE EARTH-BASED FIBER AMPLIFIERS
Figure 4. Experimental set up for fiber amplifier employing transverse pumping [1].
Figure 5. Experimental set up for fiber amplifier employing end pumping [22].
Nd:YAG rod. Using this arrangement, pumping illumination can be continuously supplied to the amplifying Nd:YAG without interfering with its signal carrying characteristics.

Thus, since the ends of the amplifying fiber are always available for direct signal coupling to the optical fibers within the optical system, careful time sequencing between the application of pumping illumination and the signal to be amplified is not necessary. A theoretical analysis of optical fiber laser amplifiers and oscillators has been reported by Digonnet et. al. [26]. This analysis is based on the general formalism of mode overlap and it introduces the concept of normalized overlap coefficient and provides a general solution for either guided or unguided laser devices. Simple and accurate closed-form expressions are derived for the gain of fiber amplifiers in terms of the fiber parameters and the pump and signal modes.

There is also a large and increasing interest in erbium-based fiber amplifiers as they can provide exceptionally high gains at 1.54 μm, within the third telecommunications window. Erbium-doped fiber amplifiers have achieved gains in excess of 30dB at modulation rates of up to 400 MHz and with extremely low noise [2]. Laming et. al. [27] have reported amplification in an erbium-based fiber
amplifier, and have shown the advantage of using pump bands where no excited state absorption (ESA) is present. ESA is a parasitic absorption that drains pump power and limits the available gain. They have identified practical pump wavelengths of 532 nm and 980 nm as optimal, the latter giving a gain as high as 2.2 dB/mW of pump. The pump power used was 11 mW. Further, it was observed that by shifting from a pump wavelength of 514.5 nm to 528 - 532 nm resulted in a gain increase from 16 dB to 32 dB for the same pump power, thus suggesting frequency-doubled mini-YAG lasers as practical pump sources. In a recent paper by Becker et. al. [28], gains of up to 20 dB at 1.56 μm have been reported for 30 mW of launched laser diode pump power of 1.48 μm.

Desurvire [29] confirmed through a transient gain analysis that erbium-based fiber amplifiers are advantageously immune to patterning and crosstalk effects at the higher bit rates used in fiber optic communications. Giles et. al. [30] have recently demonstrated the first high speed (2 Gbit/s) signal amplification in an erbium-based fiber amplifier at 1.53 μm. Also, it has been shown that the fiber amplifier gain was independent of signal polarization, which is considered to be an advantage over semiconductor amplifiers which may exhibit large gain variation between TE and TM input signal polarizations.
Although fiber amplifiers show exceptional promise, their application in transmission systems will be limited unless optimum solid-state pump sources can be found. To date, the best amplifier performance is at 514 nm or 670 nm, using either an argon-ion laser or a dye laser. Both of these sources are unsuitable for use in a device that must be compact and low cost. The excitation spectrum shows an absorption band at the diode-laser wavelength of 807 nm. Unfortunately, not only is this band relatively weak, but it also coincides with a region of ESA. Thus, pumping at 807 nm requires high pump power to overcome the pump efficiency, and a fiber with a core too small to match that of telecommunications fiber, to increase the pump before high gain can be achieved. The most promising pump-source currently available, however, seems to be the frequency-doubled mini-YAG. These lasers are both rugged and relatively compact and operate at 532 nm, where the erbium absorption bands are both strong and free from ESA [2].

Thus, the combination of two novel solid-state laser technologies could produce a practical high-performance in-line fiber amplifier in the not too distant future. Current research and development in these devices is a highly important and increasingly active area, and holds great promise for future communication systems.

3.0 RARE EARTH-BASED FIBER AMPLIFIERS
3.3 Experiments

The main area of interest in this work was to look into the existing techniques of manufacturing rare earth-based optical fiber and to develop some novel and potentially inexpensive techniques to fabricate such a fiber/glass rod. An experiment to demonstrate light amplification with the new developed glass rod was also performed. However, a significant amount of amplification could not be observed due to the unavailability of a suitable pumping source. Some suggestions are also provided within the framework of these attempted experiments which would aid in future research work in this area.

3.3.1 Existing technique to manufacture rare earth fiber/glass rod

Before discussing the ideas and the development work performed for the fabrication of rare earth-based fiber/glass rod, a brief review of their existing manufacturing technique is provided.

The technique presently used is an extended MCVD process [25]. It allows the fabrication of both singlemode and multimode optical fibers containing rare earth ions at concentrations of up to 0.25 weight percent in the core region. The process is shown in Figure 6. The starting material can be a rare earth halide, e.g.
NdCl₃H₂O (99% pure, melting point = 758 °C). It is first inserted into a dopant carrier chamber, where it is dehydrated by heating in a Cl₂ atmosphere. This step also fuses the anhydrous NdCl₃ crystals to the chamber wall, thus preventing them from passing down the tube and forming bubbles in the glass which is subsequently deposited. The inside of the glass tube is then cleaned by gas-phase etching using SF₆ to remove any dopant deposited during the drying process. After this drying stage, the cladding glass is deposited. During the core deposition, the dopant carrier chamber is heated to about 1000 °C by a stationary burner which produces small amounts of NdCl₃ vapor. This vapor is subsequently carried downstream, is oxidized to form Nd₂O₃, which in turn is incorporated in the core. This process takes place in the hot zone which is formed due to the deposition moving burner. In order to produce low-loss fibers, a second drying stage is also introduced. In this process the core, consisting of SiO₂, GeO₂ and a small amount of Nd₂O₃, is deposited unfused at a low temperature. This porous core layer on the inside of the deposition tube is subsequently dried by heating in a Cl₂ atmosphere, after which it is fused to form a clear nonporous layer. The tube is then conventionally collapsed to form a solid rod and then pulled into a fiber.

This is a very flexible technique as many other rare-earth and transition metals can be incorporated into optical fibers [25]. Fibers fabricated by this technique have

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produced losses as high as 3000 dB/Km in the visible and near infrared regions, and less than 2 dB/km in the low-loss window between 950 and 1350 nm.

### 3.3.2 Diffusion technique to fabricate rare earth fiber/glass rod

A novel technique to fabricate rare earth-based fiber/glass rod was investigated here by diffusing the rare earth ions from the outside surface of a glass rod. The glass rod selected for this experiment was a soda-lime glass rod (Fisher catalog number 11-375C). This type of glass contains a relatively large amount of easily displaceable impurity ions, and hence the process of indiffusion by the ion displacement technique can be made possible.

Several techniques were attempted which involved coating different rare earth compounds on the outside surface and then subjecting the glass rod to high temperatures for various time intervals. One of the problems faced in coating the glass rod was that the rare earth compound did not adhere to the glass surface very firmly because of its smoothness. As a result, a uniform layer of coating was not achieved. This problem was alleviated by first sandblasting the glass rod. This
Figure 6. Extended MCVD process to fabricate rare earth-based optical fibers [25].
made the surface rough, which resulted in a better adherence of the rare earth compound to the glass surface and also enabled to achieve a relatively uniform coated layer. The rare earth compound used was neodymium 2,4-pentanedionate. This has the advantage that it readily dissolves in acetone, and once this paste was coated on the glass rod, the acetone evaporated leaving behind a uniform coat of this rare earth compound. This coated glass rod was then heated in a tube furnace at a temperature of 500°C for a period of ten days (the softening point of this glass rod was 700°C). Different temperatures ranging from 550°C to 650°C were also tried. However, this resulted in the bending of glass rods when a few hours had elapsed. The initial part of the experiment was performed under a fumehood since neodymium, 2,4-pentanedionate emits carbon monoxide, carbon dioxide, and other toxic fumes before forming Nd₂O₃ [31]. Figure 7 shows the experimental set up for this process.

Auger spectroscopy analysis was performed on the undiffused glass rod and also on the diffused glass rod to determine the amount of diffusion and also to find the depth of penetration of neodymium ions. The graph obtained from the Auger analysis on the undiffused glass rod is shown in Figure 8. The Auger analysis was then performed on the diffused sample. Presence of system noise at the neodymium peak position hindered the detection of the presence of neodymium ions, and, hence, an Auger plot could not be obtained. It has been observed that

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Auger analysis does not give adequate information if the concentration of the impurity ions in a bulk material is less than one percent by weight.

The diffused sample was also observed across its diameter with a cathode luminescope, where the neodymium ions were bombarded by electrons to cause their excitation. Typically, a zoning effect would be seen which determines the presence of a particular impurity in the bulk material. A zoning effect could not be observed to a significant amount with this sample. However, a bright blue layer, on the order of a few microns, close to the circumference, was observed. Again, this is not a confirmation of indiffusion since the presence of a high concentration of \( \text{Nd}_2\text{O}_3 \) on the surface can possibly give an impression of diffusion when the sample is observed under a microscope. Further characterization of this sample would be required to determine the exact nature of the diffusion effect in the glass rod.

Although the above experiments could not furnish a definite confirmation of the diffusion of neodymium ions in the glass matrix, this should not completely rule out the possibility of the presence of these ions. The neodymium ions can be present in a fraction of a percentage by weight which is sufficient to cause optical amplification, if used in conjunction with a pumping source which can be tuned to the main absorption line of the sample. This inexpensive technique may thus show
a potential for the development of active devices. An extension of this technique to fabricate a rare earth-based fiber can be envisioned. The diffused rod can be placed in a tube of comparable diameter to form a cladding. The assembly can then be fed into a high temperature furnace and drawn into a fiber.
Figure 7. Diffusion process for fabricating rare earth-based fiber/glass rod.
Figure 8. Auger spectroscopic analysis on the undiffused soda-lime glass rod.

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Figure 8. Auger spectroscopic analysis on the undiffused soda-lime glass rod.
3.3.3 Crucible method to fabricate rare earth fiber/glass rod

Another technique to fabricate rare earth fiber/glass rod is now described. The soda-lime glass is crushed into a fine powder. Nd$_2$O$_3$ is then thoroughly mixed into this glass powder in the ratio of one percent by weight. The mixture is then contained in a crucible, which in turn is heated to a temperature of 1950°C with an oxy-acetylene flame. It is to be taken into consideration that the crucible material withstands this high temperature. In order to provide uniform heating to the crucible a multiport heating flame-tip is used. The process is shown in Figure 9. Heating of the crucible is stopped when the glass and Nd$_2$O$_3$ have melted and the mixture is thoroughly mixed. The whole mixture is then allowed to cool by itself. The mixture solidifies upon cooling, thus forming a neodymium-doped glass. This glass can now be collapsed and drawn into a fiber.

3.3.4 Experiment to amplify the optical signal

The experimental set up which was used is shown in Figure 10. A 2x2 multimode FBT coupler was used to combine the pump signal and the signal to be amplified onto a single fiber. A quarter-pitch grin lens collimated the light from the fiber into the test piece, thereby allowing end pumping of the test piece. This test piece was
Figure 9. Crucible method to fabricate rare earth fiber/glass rod.
the diffused sample described earlier. The pumping source used was the 830 nm LED and the signal to be amplified came from the 1060 nm LED. This LED which had a 30 nm FWHM was selected because the main transition line occurring from the transition, $^4F_{3/2} \rightarrow ^4I_{11/2}$, was assumed to be within this region. No prior information for the main transition line was found in the available literature. Again, no significant amount of amplification was observed. This can be attributed to the fact that most of the neodymium ions were concentrated close to the surface of the glass rod and to technical limitations due to the nonavailability of a suitable pumping source.
4.0 RARE EARTH-BASED OPTICAL SENSORS

The requirement to make precise measurements of many parameters is of great importance to all sectors of modern industry. The ability to accurately determine the temperature of a piece of equipment or its surroundings is a major concern in many industrial situations. Similarly, in some applications, knowledge of the localized strain is also important. At present, a wide variety of instrumentation is available to the modern scientist and engineer. However, it is of importance to know the acceptability of a measuring device for the task to be undertaken. A major consideration in its choice for a particular application is the susceptibility of the measuring equipment to be influenced by electromagnetic signals. Optical instrumentation offers major advantages in this area due to its passive nature. In particular, fiber optic instrumentation, which uses both communication-grade fiber and some specially fabricated fiber such as the rare earth-based fiber for various applications, have attracted considerable research interest over the last few years due to the advantages it possesses over the conventional equipment. Such
instrumentation is generally free from radio frequency interference, has good
electrical isolation properties, and can operate in hazardous environments, e.g.
high temperature, chemically active, or explosion risk situations.

The use of fluorescence monitoring of temperature has been reported in the early
work of Sholes and Small [32] and McCormack [33] using inconvenient lamp
excitation sources. Further research in this area has resulted in the development
of more sophisticated systems [34-38]. The measurement technique of correlating
temperature with the "decay time" in these systems has the advantage that it is
independent of the input light intensity.
4.1 Theory

4.1.1 Fluorescence concepts

The phenomenon of fluorescence arises when some of the energy of the photons absorbed by matter (fluorescent material) is converted into vibrational energy and the rest is emitted as photons of lower energy. An electron in the ground state may be excited by the capture of an incident photon into a higher energy band. It may very quickly lose some energy through collisional nonradiative processes to occupy the lowest vibrational energy level in the higher energy band. If the quantum efficiency is then relatively high, i.e., few excited electrons lose their energy through collisonal processes, the electron will then decay to the ground state with the simultaneous emission of a photon.

The lifetime of the excited electron is of the order of nanoseconds to milliseconds. The probability of decay is independent of the lifetime of the excited electron. Thus if a large number of excited electrons are present, the number of such electrons (and their decay rate) will decline exponentially.
Knowledge of the absorption spectrum of the fluorescent material is very important as it allows the determination of the most suitable pumping source, which should have high intensity peaks corresponding to the absorption peaks of the material.

4.1.2 Fluorescence lifetime measurements

The fluorescence lifetime is the average period of time a fluorophore remains in the excited state prior to its return to the ground state. Knowledge of lifetime is important as it can be correlated to the temperature of the substance and hence allows the sensing of temperature.

There are two widely used methods for the measurement of fluorescence lifetimes. These are the pulse method and the harmonic or phase-modulation method. In the pulse method, the sample is excited with a short pulse of light and the time-dependent exponential decay of the fluorescence intensity is measured. If the pulse period is comparable to the exponential decay time, the response obtained will be as shown in Figure 11 [34].

The intensity of the fluorescence emitted at a particular wavelength is seen to fall off with time so that the intensity \( I \), at time \( t \) is given by
\[ I(t) = I_0 e^{kt}, \quad (4.1) \]

where \( I_0 \) is the initial intensity (at \( t=0 \)) and \( k \) is the decay constant, characteristic of the medium, and the reciprocal of the fluorescence lifetime \( \tau \). If the fluorescence intensity is seen to decrease from any level \( I_a \) to a level \( I_b \) (where for convenience \( I_a = 2I_b \)), then \( \tau \) is given by

\[ \tau = (t_b - t_a)/\ln 2, \quad (4.2) \]

where \( t_a \) and \( t_b \) are the relative times corresponding to \( I_a \) and \( I_b \), respectively.

In the harmonic method the sample can be excited using sinusoidally modulated light. The phase shift and demodulation of emission, relative to the incident light, is used to calculate the lifetime. In this case, the fluorescence decay time, \( \tau \), is given by

\[ \tan (\theta) = 2\pi f\tau, \quad (4.3) \]

where \( \theta \) is the resultant phase shift between the incident and the fluorescent signal, and \( f \) is the modulation frequency. As the emission is a forced response to the excitation, therefore, the emission is modulated at the same circular
frequency as that of the excitation. However, because of the finite lifetime of the excited state, the modulated emission is delayed in phase by an angle $\theta$ relative to the excitation.

The experiment performed in our laboratory for measuring the fluorescence lifetime of the Nd:YAG sample at room temperature was done using the pulse method. The experimental set up and its description are presented later in this chapter.
Figure 11. Fluorescence response to the square pulse of incident light [34].
4.1.3 OTDR concepts

Sections 4.1.3 and 4.1.4 describe optical time domain reflectometry (OTDR) techniques. These are used in the novel approach of sensing discrete strain and localized temperature simultaneously and independently, which is presented later in this chapter.

A basic OTDR system is shown in Figure 12. It consists of a pulsed laser, a beamsplitter or fiber optic coupler, and a detector. Light pulses launched into the optical fiber partially scatter or reflect the forward propagating light back towards the detector. The return optical signals are converted into electrical signals, amplified, and either sampled or displayed in real time (depending on pulse speed) by a sampler/oscilloscope [39]. Backscattered intensity versus time traces such as those shown in Figures 13 and 14 result. Figure 13 shows the trace of a fiber which has been excited with a very wide (10ns FWHM) pulse which allows intrinsic (Rayleigh) backscattered power to be detected. Spatial resolution, however, is limited to approximately 1m by the width of the pulse. Also, it is to be noted that in the case of multimode fibers, the modal spatial transient effects play a part in determining the spatial resolution. Figure 14 is a result of launching a narrow (400 ps) pulse into the fiber, causing only large refractive index mismatch (Fresnel) reflections, such as those resulting from a glass to air interface, to be detected.
Spatial resolution of much more sophisticated systems may be on the order of 1 mm or less [40,41].

The basic principles involved in fiber strain measurements using OTDR techniques can be related to one way pulse delay measurement methods [42,53]. Figure 15 shows a typical experimental set up for the one way pulse delay method. Here, the length of the fiber, $l_t$, is given by

$$l_t = \left(\frac{c}{n}\right)t.$$  \hspace{1cm} (4.4)

where $c$ is the speed of light, $t$ is the time it takes the light pulse to travel down the fiber, and $n$ is the group index of refraction of the fiber core. Differentiating the above equation, an expression for the amount of fiber elongation, $dl_t$ can be found as

$$dl_t = \left(\frac{c}{n^2}\right)(n dt - tdn).$$  \hspace{1cm} (4.5)

where $dt$ and $dn$ are the changes in time delay and group refractive index, respectively. Fiber strain $\varepsilon_t$, is defined as

$$\varepsilon_t = \frac{dl_t}{l_t}.\hspace{1cm} (4.6)$$

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which yields

$$\varepsilon_t = \frac{dt}{t} - \frac{dn}{n}. \quad (4.7)$$

Since $n$ varies linearly with respect to $\varepsilon_t$, the above equation can be written as

$$\varepsilon_t = \frac{dt}{[t(1 + a)]}, \quad (4.8)$$

where "a" is a negative constant representing the slope of $n$ vs $\varepsilon_t$ curve [43 - 45]. This coefficient, also referred to as index-vs-strain coefficient, may be found analytically or experimentally [46]. The above equation so obtained from the one-way pulse delay measurement is also valid for OTDR strain measurements, where the light pulse travels the length of the fiber twice.

4.1.4 Discrete strain sensing

Improvements which are possible for two-way OTDR measurements include fiber segmentation for quasi-distributed parameter monitoring. In particular, methods have been investigated to measure strain on a local basis by introducing discrete reflectors along the length of the sensing fiber [46,54]. Such devices have been
in the form of partially reflective air-gap splices which caused distributed Fresnel reflection in time (see Figure 16) [46].

Analysis of such a segmented fiber is possible when considering the pulse arrival times, $t_i$ and $t_{i-1}$, and their respective shifts, $\Delta t_i$ and $\Delta t_{i-1}$, of the far and near end interface of the $i$th fiber segment. Fiber strain, $\varepsilon_{t,i}$, in this segment can be expressed as

$$\varepsilon_{t,i} = (\Delta t_i - \Delta t_{i-1})/[(t_i - t_{i-1})(1+a)].$$  \hspace{1cm} (4.9)

The number of in-line air-gap splices is, again, limited by the dynamic range of the OTDR system as well as the loss budget associated with the splice [46]. The splice loss, $L_{sp}$ is given by

$$L_{sp} = 10 \log[r(1-p)/\{r + d \tan(\sin^{-1}(NA))\}]^2,$$  \hspace{1cm} (4.10)

where $r$ is the fiber core radius, $d$ is the air gap distance, $NA$ is the fiber numerical aperture, and $p$ is the reflection coefficient between glass and air [46].

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Figure 12. Basic optical time domain reflectometer system configuration [42].
Figure 13. Typical optical time domain reflectometer Rayleigh backscatter trace [42].

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Figure 14. Optical time domain reflectometer Fresnel backscatter trace [42].

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Figure 15. One-way time delay measurement system configuration [42].

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Figure 16. Segmented optical fiber and its resulting back reflections [46].

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4.1.5 Re-entrant loop technology

The reentrant loop technology allows improvement in strain resolution [53]. In order to implement this technology to our sensor system, the configuration of the two-way OTDR system may be modified to allow one-way time delay measurements by simply omitting the beam splitter or coupler, and detecting forward-propagating pulses instead of the reflected pulses.

The performance of one-way time delay measurements in conjunction with the fiber optic reentrant loops have been extensively used in fiber optic gyroscopes and delay lines [47 - 52], and are proposed to be used to optimize the strain resolution of one-way time delay measurements [53]. The operation relies on causing an optical pulse to propagate through the sensor fiber section in a repetitive manner as to effectively increase the fiber gage length, \( l \) [53]. The most promising reentrant loop tested to date consists of a tap-off coupler which has its two large core (tap-on) fiber ends fused together to create the loop. The two smaller core (tap-off) fibers are used as input and output ends, as shown in Figure 17. Multiple (harmonic) pulse arrival times, \( t_i \), result, and are given by

\[
 t_i = (l_1 + l_2 + i \cdot l_0) (n/c),
\]  

(4.11)
where $l_1$ is the input fiber length, $l_2$ is the output fiber length, $i$ is the pulse harmonic number, and $l_1$, $n$, and $c$ are, again, the fiber gage (loop) length, group refractive index, and speed of light, respectively. By the analysis similar to the one given previously, the expression for strain, $\varepsilon_i$, as a function of the ith harmonic pulse shift, $\Delta t_i$, can be given as

$$\varepsilon_i = \frac{\Delta t_i}{\left\{ t_i - \frac{n}{c}(l_1 + l_2) \right\}(1 + a)}.$$  \hspace{1cm} (4.12)

Thus, by monitoring the pulse delay time change of the ith harmonic pulse, it is theoretically possible to improve the strain resolution by a factor of $i$. Obviously, limitations exist on how large $i$ can be chosen. One limitation on $i$ is dictated by the power budget of the system. The peak intensity, $P_i$, of the ith pulse is related to the peak intensity, $P_0$, of the original input pulse by

$$P_i = P_0 F[(1 - F)SL]^i \alpha^{i+1}.$$  \hspace{1cm} (4.13)

for $i = 0, 1, 2, 3, \ldots$ . In the above equation $F$, $\alpha$, $S$, and $L$ represent the coupler splitting ratio, the coupler excess loss, the fusion splice loss, and the fiber loop loss, respectively. It is therefore the dynamic range of the time domain system which contributes in part to the limitations in achievable improvement factors [53]. Also limiting are the pulse broadening characteristics of the loop fiber [53]. For
example, it is anticipated that graded index fiber will substantially reduce the amount of pulse width increase over step index fiber [53]. It is apparent that measurement resolution of OTDR and time delay methods is limited by the temporal stability of the measurement system [53]. However, if reentrant loop technology is implemented properly, given system resolution may be improved by a factor of > 100 [53].
Figure 17. Reentrant loop configuration [53].

4.0 RARE EARTH-BASED OPTICAL SENSORS
4.2 Experiments

This section presents the various experiments performed, conclusions derived, and suggests some new ideas for future work.

4.2.1 Argon-ion laser scanning

The output of an argon-ion laser was scanned to obtain its intensity profile, and to determine how it correlated to the absorption spectrum of the Nd:YAG sample.

The experimental set up is as shown in Figure 18. The light beam from the argon-ion laser was directed into a monochromator with a 600 lines/mm diffraction grating and through a mechanical chopper. The chopper was used to provide a reference signal to the lock-in amplifier and to allow synchronous detection. The monochromator was programmed to scan from 480nm to 520nm at a rate of 0.8 nm/sec. A LeCroy 9450 oscilloscope was used to monitor the intensity profile across this range. The time division scale on the scope was set to 5 sec/division, which resulted in each division on the scope corresponding to 4 nm (0.8 nm/sec x 5 sec/division = 4 nm/division). A silicon photodetector was placed at the output slit of the monochromator and the detected signal was sent to the lock-in amplifier for processing, to obtain a noise-suppressed output.
The intensity profile obtained is shown in Figure 19. It shows four separate peaks, with two distinct peaks at 488 nm and 514 nm. Figure 20 shows the absorption spectrum of the Nd:YAG sample (with a neodymium concentration of 1 weight percent). Comparison of these two graphs shows that the argon-ion laser would serve as a suitable pump source for the Nd:YAG sample.

4.2.2 Measurement of fluorescence lifetime of Nd:YAG

The experimental set up for measuring the fluorescence decay-time of the Nd:YAG sample is shown in Figure 21. The Nd:YAG sample was supported on a post and was excited with an externally chopped light beam from the argon-ion laser. The frequency of chopping obtained with the mechanical chopper was 670 Hz. Two silicon photodetectors $D_1$ and $D_2$ were used to monitor the incident and the fluorescent signals, respectively. The detector $D_1$ was used with a set of three high-pass filters with their cut-offs at 500, 850, and 950 nms. This helped in efficiently filtering the fluorescent signal at 1064 nm and reducing the contribution from the incident light from the argon-ion laser. The two separate detected signals were sent to two different channels of the LeCroy 9450 oscilloscope. Figure 22 shows both the detected incident and fluorescent signals. The time constant of the exponential decay curve was found to be approximately 200 μs.
Figure 18. Experimental set up for scanning argon-ion laser.
Figure 19. Intensity profile of argon-ion laser.
Figure 20. Absorption spectrum of Nd:YAG [55].
This experimental set up can be successfully used for monitoring the fluorescence decay-time of the rare earth-based materials by making use of a corresponding suitable pumping source.

4.2.3 Construction and operation of fluorescence thermometer probe

A fluorescence thermometer probe was constructed in the laboratory by synthesizing a small piece of Nd:YAG crystal on the tip of a multimode silica fiber. The optical fiber had dimensions of 100/140 μm, and the Nd:YAG sample to be fused had comparable dimensions. For a fiber optic fluorescence sensor to survive over a wide temperature range, an efficient optical and mechanical coupling must be provided between the fiber and the fluorescent material. As reported by Shifflett [38], in his work related to synthesizing fluorescent materials onto the tip of a fiber, an efficient optical and mechanical coupling is difficult to achieve due to the thermal expansion and stability of the materials involved in the coupling process. However, the use of right techniques and precision during synthesis, as explained later in this section, can result in a very good optical and mechanical connection.

An oxy-acetylene flame with a microscopic tip was used as an intense heat source for melting the end of the fiber and fusing the Nd:YAG sample onto it. Figure 23
shows the shape of the Nd:YAG sample when fused onto a fiber tip. Figure 23(a) shows the ball-shape of the Nd:YAG, which should be avoided because good coupling is not achieved in this case and most of the resultant fluorescent signal is lost. The fused fluorescent material should be relatively flat in order to have a good coupling between the fluorescent material and the fiber, as shown in Figure 23(b) [56]. There is a special technique by which such a shape can be achieved [56]. In this case, the fiber with a prepared end surface is placed in a vertical position and the small sample of Nd:YAG sample is placed on the tip. The oxy-acetylene flame is then slowly brought from the top and then onto the Nd:YAG sample just enough to fuse it on the fiber tip. In this manner, a relatively flat surface was achieved and hence a better coupling was made possible. Although a stochiometrically pure Nd:YAG is unlikely to result from such a crude synthesis, the end product is nevertheless highly fluorescent at the characteristic Nd:YAG emission wavelength of 1064 nm.

As studied by Shifflett [38], there is a definite relationship between the neodymium to yttrium ratio and the fluorescent time constant. Table 3 summarizes the time constants of samples with varying ratios of neodymium and yttrium. The 1% neodymium sample had the largest room temperature time constant and it was found to be approximately 201 μs.
Figure 21. Measurement of fluorescent decay-time of Nd:YAG sample.
Figure 22. Detected pulse shape of the incident and fluorescent signal.
Figure 23. Synthesis of Nd:YAG on fiber tip.

4.0 RARE EARTH-BASED OPTICAL SENSORS
Table 3. Time constant measurements for various ratios of neodymium and yttrium [38].

<table>
<thead>
<tr>
<th>% Y</th>
<th>% Nd</th>
<th>$\tau$ ((\mu)s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>20</td>
<td>24.7</td>
</tr>
<tr>
<td>90</td>
<td>10</td>
<td>62.0</td>
</tr>
<tr>
<td>95</td>
<td>5</td>
<td>135.7</td>
</tr>
<tr>
<td>99</td>
<td>1</td>
<td>201.0</td>
</tr>
<tr>
<td>99.5</td>
<td>0.5</td>
<td>195.0</td>
</tr>
</tbody>
</table>
Figure 24 shows the experimental set up of the operation of this fiber optic temperature probe. The temperature probe can be spliced to the output port of a 2x1 fiber coupler. One end of the input port of the coupler can be used to couple light from the pump source. A suitable pumping source can be an argon-ion laser or an 810 nm laser diode. If the laser diode is to be used, the modulation can be achieved electronically. This sensor is shown operated in the reflective mode. When excited, the Nd:YAG produces fluorescent emission at 1064 nm, which is coupled into the fiber and is detected through the second input port of the fiber coupler as shown. A 10 nm wide bandpass interference filter centered at the fluorescence wavelength is used at the detector.

Shifflett [38] has studied the output characteristics of such a device in the range of 1500 to 2500°F. It was observed that Nd:YAG can be successfully used in this temperature range. Figure 25 shows the calibration curve of the time constant versus temperature in this range. The decrease in the time constant with increasing temperature is due to decreasing quantum efficiency (increased loss of excited electrons through collision processes) and the increase of other nonradiative processes. A well defined high temperature cutoff point at 2520°F was observed where the fluorescence of Nd:YAG suddenly ceased. The effects of prolonged high temperature exposure and temperature cycling are still to be investigated for such temperature probes.

4.0 RARE EARTH-BASED OPTICAL SENSORS
Figure 24. Operation of fiber optic temperature sensing probe.

4.0 RARE EARTH-BASED OPTICAL SENSORS
Figure 25. Nd:YAG fluorescence at high temperatures [38].

4.0 RARE EARTH-BASED OPTICAL SENSORS
4.3 Simultaneous sensing of strain and temperature

A fluorescence-based fiber optic discrete strain and local temperature sensor is proposed [57]. It is capable of monitoring the strain and temperature independently and simultaneously. Fluorescent markers made of different materials are incorporated at short intervals along the length of the optical fiber, which in turn fluoresce when excited by a suitable pumping source. The fluorescent signals, which are at different wavelengths, are then monitored and correlated to get the localized temperatures at different sensing positions. The backscattered pulses from these markers are observed in the time domain using optical time domain reflectometry techniques. A displacement between adjacent peaks corresponds to the amount of strain experienced in the corresponding fiber sensor section.

4.3.1 Fabrication and operation of the sensor

The fluorescent material to be used in the fabrication of the invention must exhibit fluorescence with a measurable decay time over a useful temperature range. Also, the wavelengths of the exciting and emitted light must both be transmitted efficiently through the fiber.
Different fluorescent markers are used so the decay time characteristics do not interfere as it would if the same fluorescent material is used all along the sensor. For example, if Nd:YAG is to be used along the sensor, then the distance required between successive markers would be 40 kilometers ($r$ for neodymium at room temperature is 200 $\mu$s, and hence optical fiber length, $l = rc/n = 40$ kms). Therefore, different fluorescent markers need to be selected. However, care needs to be taken in selecting the pumping source as it should be able to excite all the fluorescent markers. For the sensor proposed, the fluorescent markers selected are Nd:YAG and BaClF:Sm (barium chlorofluoride activated by divalent samarium), and the pumping source selected is an argon-ion laser ($\lambda = 514$ nm).

The materials selected are fused between sections of the optical fiber along its length to form fluorescent markers, as shown in Figure 26. It is seen that the argon-ion laser with a modulated output launches optical pulses into the optical fiber sensor through a beam splitter. A portion of the forward travelling light energy is backscattered toward the beamsplitter and the detector. The optical pulses detected are displayed in real time using an oscilloscope. The peaks are seen to be separated in time by an amount proportional to the distance between the markers. The stress so applied induces a strain in the optical sensor causing the peaks to be displaced in time which in turn gives an indication of the resultant strain in a discrete section of the fiber.
Also, the fluorescent materials when excited provide emission at wavelengths which are characteristic of the material. Nd:YAG fluoresces at 1064 nm and BaCl₂:Sm at 687 nm. As shown in Figure 26, the different wavelengths are demultiplexed and the detected signals are then processed electronically. The phase difference of signals at 1064 nm and 687 nm is seen with respect to the signal at 514 nm and the information so obtained is correlated to the local temperature at both the sensing positions. Thus, this sensor facilitates the simultaneous measurement of strain and temperature.

Figure 27 shows a schematic diagram of the sensor system which when used in conjunction with a fiber reentrant loop would enhance the strain resolution of the measurements being made.
Figure 26. Simultaneous sensing of temperature and strain.
Figure 27. Simultaneous sensing of temperature and strain using re-entrant loop technology.

4.0 RARE EARTH-BASED OPTICAL SENSORS
4.3.2 Advantages of the sensor

(i) The sensor is intrinsically free from radio frequency interference, has good electrical isolation, and can operate in hazardous environments due to its essentially passive mode of operation. Further, due to the small size of the sensor, it can facilitate strain and temperature measurements with minimum perturbation.

(ii) The sensor can be used in a noncontact, contact, or embedded mode.

(iii) The intensity of the fluorescence produced is temperature independent over a wide range.

(iv) The sensor can cover a wide temperature range and provide good accuracy, together with low-cost system components.

(v) The use of reentrant loop techniques with the OTDR system allows the sensor to monitor strain with improved accuracy [53].
4.3.3 Limitation of the Sensor

The number of fluorescent markers which can be incorporated along the length of the fiber optic sensor can be a limiting factor in certain applications due to the fact that pumping bands of the different fluorescent markers must fall within the emission spectrum of the excitation source.
5.0 CONCLUSIONS

Study, analysis, and experimentation on the performance of rare earth-based active devices has been performed. The detailed spectroscopic analysis of the neodymium ion, and the study of different host materials presented would enhance the understanding of these active devices. The basic concepts concerning the performance of rare earth-based fiber amplifiers and the state of existing technology and problems being encountered is also presented. Novel techniques of fabricating rare earth fiber/glass rods, preliminary experiments performed, results obtained, and ideas for further improvement have also been presented. Analysis and related experiments on the rare earth-based optical sensors are also given. A point temperature sensor, and a proposed sensor to simultaneously monitor local temperature and discrete strain presented can hold great potential for its implementation in various applications.
Indepth experimentation into the rare earth-based active devices could not be performed due to the unavailability of a tunable dye laser to be used as a pumping source, and other supporting equipment. However, the various experiments performed and a systematic presentation of a thorough analysis of these devices in this report would serve as a good foundation for future research work in this field.
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Vita

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