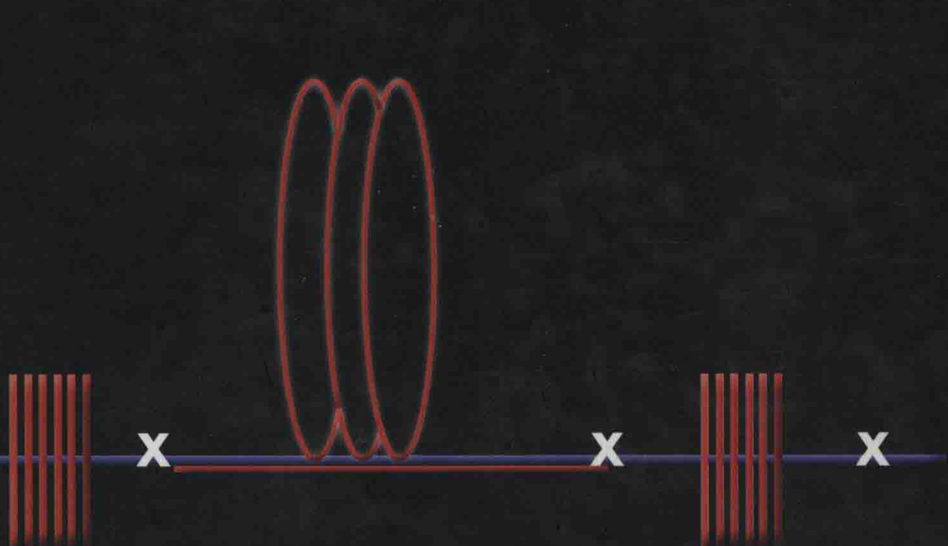
Niloy K Dutta

Fiber Amplifiers and Fiber Lasers



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Preface

The laser emission in various rare earth (Nd, Pr, Er, Ho, Tm, Yb)-doped glasses have been studied since the 1960's. However, the potential for rare earth-doped fiber amplifiers and fiber lasers were not recognized until the late 1980's and it began with a demonstration of very low threshold fiber amplifier. This pioneering demonstration conveyed an important message: that using well established low loss fiber fabrication technology and semiconductor laser fabrication technology a new class of rare doped lasers and amplifiers could be produced for new applications. This message was particularly well received immediately by optical communication technologists and they went on to develop Er-doped fiber amplifiers for various fiber communication applications.

It was also recognized that an amplifier chain could be used for long (~1000–7000 km) undersea optical communication links and that such a system could be easily upgraded to higher data rates simply by replacing the transmitters and repeaters on the shore — a much easier task than laying a new cable. The first undersea fiber optic link using an amplifier chain went into operation in the mid-1990s.

The market demand for higher capacity transmission was helped by the fact that computers continued to become more powerful and needed to be interconnected. This is one of the key reasons why the explosive growth of optical fiber technology parallels that of computer processing and other key information technologies. The need for higher capacity is continuing to encourage research in wavelength division multiplexed (WDM) based transmission, which needs high power fiber amplifier and tunable lasers. An important research area would continue to be the development of Er, Er–Yb co-doped fiber amplifiers and Raman amplifiers for this application.

Optical networking and space communications (satellite to satellite) represents the next advancement in optical communications technology. Optical fiber amplifier is a key device for all-optical networks. The advances in research and many technological innovations have led to superior designs of fiber amplifiers. Today most optical communication systems use optical fiber amplifiers for signal amplification. High power short wavelength amplifiers using Nd or Yb are important for space communication application due to low beam divergence.

Fiber-based Raman lasers and amplifiers represent an important area for lasers and amplifiers for wavelength regions where a rare earth dopant may not be efficient. Using the cascaded Raman process and multiple Stokes shifts, very efficient fiber Raman lasers and amplifiers have been demonstrated.

High power fiber lasers producing kWs of power using double clad fiber geometries is expected to become increasingly important in future industrial applications. The development of short pulse fiber laser is expected to become important in many applications such as tomography and sensors.

The book is aimed at researchers already engaged in or wishing to enter the field of rare earth-doped lasers and amplifiers. It is also useful for graduate students, scientists and engineers interested in fiber optics communication. An attempt has been made to make the book self-contained and each chapter has a set of references which can be consulted for further study.

N. K. Dutta

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Chapter 1

Introduction

1.1. Historical Developments

Laser is an acronym for Light Amplification by Stimulated Emission of Radiation. The laser operating in the microwave region (maser) was invented in 1955.[1] Extension of this to the visible wavelength range was proposed in 1958.[2] As opposed to other sources of light the laser emission is highly directional, nearly monochromatic, has high brightness, and a high degree of coherence. Laser emission requires an optical gain medium in an optical cavity; the latter provides optical feedback.[2–5] The first laser operation in doped solid state material — chromium-doped Al_2O_3 ($Cr{:}Al_2O_3$) was demonstrated by Maiman in 1960.[3] The laser material was mostly Al_2O_3-doped with ~0.1 wt.% of Cr_2O_3. The material was pumped with a high intensity pulsed flashlamp and emitted at 693.4 nm.

Since then laser emissions in various rare earth (Nd, Pr, Er, Ho, Tm, Yb)-doped glasses have been observed in the 1960's.[6–9] Although typical doping levels for obtaining gain is low (~0.1 to 0.3 wt.% or 100 to 500 ppm), higher doping levels have been used, which are feasible, for high power laser operation. The doped fiber laser was demonstrated in 1964 by Koester and Snitzer.[8] They reported a flashlamp pumped Nd-doped fiber amplifier with a high gain. The diode laser pumped Nd-doped fiber laser was reported in 1970 by Stone and Burrus.[10] However, the potential for rare earth-doped fiber amplifiers and fiber lasers was not recognized until the late 1980's and it began with a demonstration of very low threshold fiber amplifier by Payne and his co-workers in 1985.[11–13]

They reported a Nd-doped fiber laser emitting at 1088 nm pumped by a AlGaAs diode laser with an absorbed pump power for threshold of only 0.6 mW. At that time few tens of mW of pump power was widely available from semiconductor lasers made using GaAs/AlGaAs and InP/InGaAsP material systems. So, this pioneering demonstration conveyed an important message: that using well established low loss fiber fabrication technology and semiconductor laser fabrication technology, a new class of rare doped lasers and amplifiers could be produced for new applications. This message was particularly well received immediately by optical communication technologists and they went on to develop the Erbium (Er)-doped fiber amplifiers for various fiber communication applications. It was also recognized that an amplifier chain could be used for long (~1000 to 7000 km) undersea optical communication links and that such a system could be easily upgraded to higher data rates simply by replacing the transmitters and repeaters on the shore — a much easier task than laying a new cable. The first undersea fiber optic link using an amplifier chain went into operation in the mid 1990s. Er-doped optical amplifiers have been described in several books.[14–17]

Since then, rare earth-doped fiber lasers have been developed for many applications. Diode laser pumped fiber lasers have been produced that generate kWs of power, amplifiers with small signal gains of >50 dB and laser sources with fs pulse widths. Although many rare earth dopants have been studied, Er, Yb, Nd, Tm-doped glasses continue to be the work horse for many applications.

1.2. Materials

Rare earth ions doped in crystalline or glassy materials have been studied extensively for optical applications. Glasses provide a broad emission and absorption spectrum, as a result glass hosts are used in many applications. Typical glass hosts are oxide and fluoride glasses. The ground state of rare earth ions are characterized by an open 4f shell. The free ion energy level structure of rare earth ions are quite complex.[18] The spin-orbit interaction creates a fine structure and the levels are labeled not only by their J values but also the L and S values.

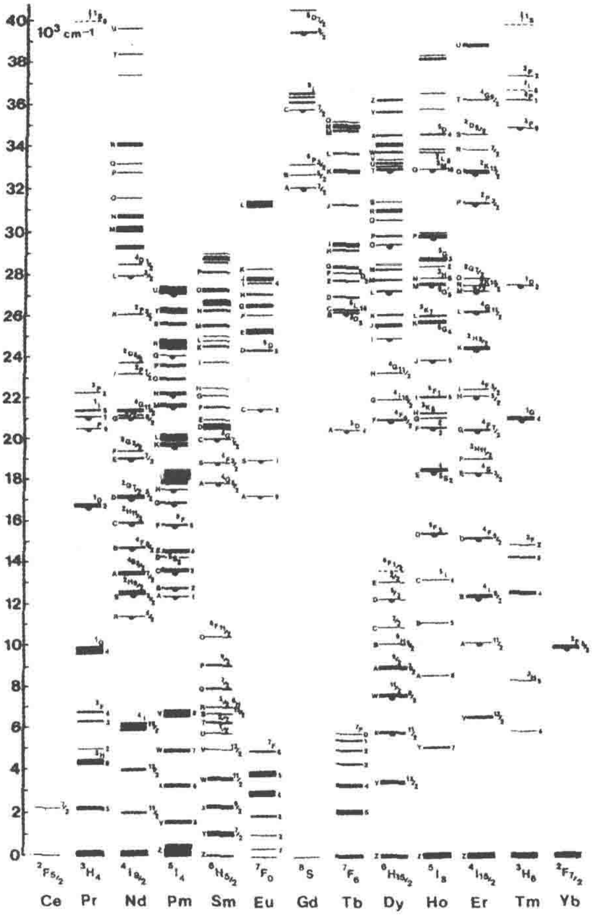

Fig. 1.1 Dieke diagram of trivalent rare earth ions.[18, 19] The width of each level represents crystal field splitting.[20]

The atomic forces split the $4f^N$ orbital to $^{2S+1}L_J$ levels, then the weaker crystal field splits each free ion level into a large number of stark levels. The crystal field splitting is ~100 to 500 cm^{-1} (see Sec. 3.2).[18]

The energy level diagram for several trivalent ions, due to Dieke, is shown in Fig. 1.1 which is often called the Dieke diagram.[18] Rare earth ions in glass comprise an important class of laser materials. The ordinary glass (SiO_2) has the advantage that it can be drawn into low loss optical fibers providing long interaction lengths. The spectroscopy of rare earth ions in glasses has been well studied. In addition to crystal field splitting, other factors such as symmetry, co-ordination, site location, determine the optical properties. They have been studied using site selection spectroscopy.[18]

1.3. Operating Principles

The schematic of a typical Er-doped fiber amplifier is shown in Fig. 1.2. It consists of a pump laser diode and typically a ~10 m long Er-doped fiber. The light from the diode laser and the input light near 1550 nm are both coupled into the fiber using a coupler. The pump light excites the rare earth ions to high energy levels which decay fast to an intermediate energy level (higher level of lasing transition) from which it decays to a lower lasing energy level with the emission of a photon. In the presence of another photon of the same

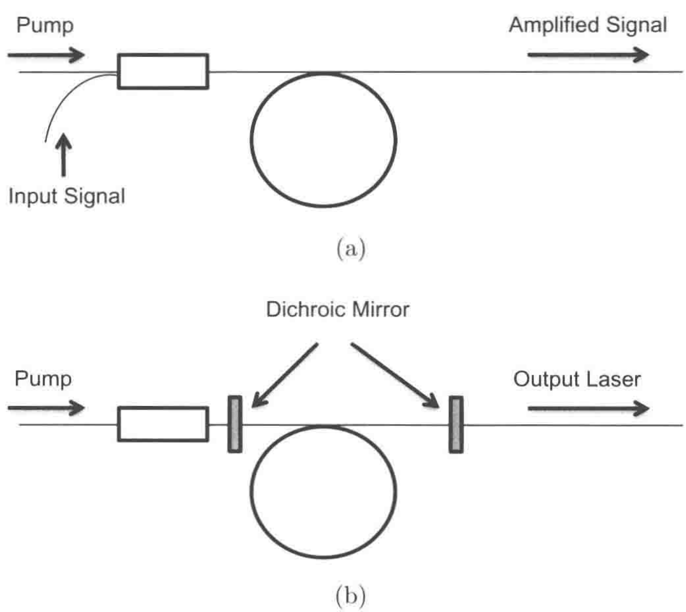

Fig. 1.2 (a) Schematic of a rare earth-doped fiber amplifier. The circle represents the rare earth-doped fiber. (b) Schematic of a fiber laser. The mirrors could be fiber Bragg gratings. The figure shows coiled fiber (circle). A wavelength division multiplexed (WDM) coupler couples both pump and input signal into the doped fiber in (a).

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