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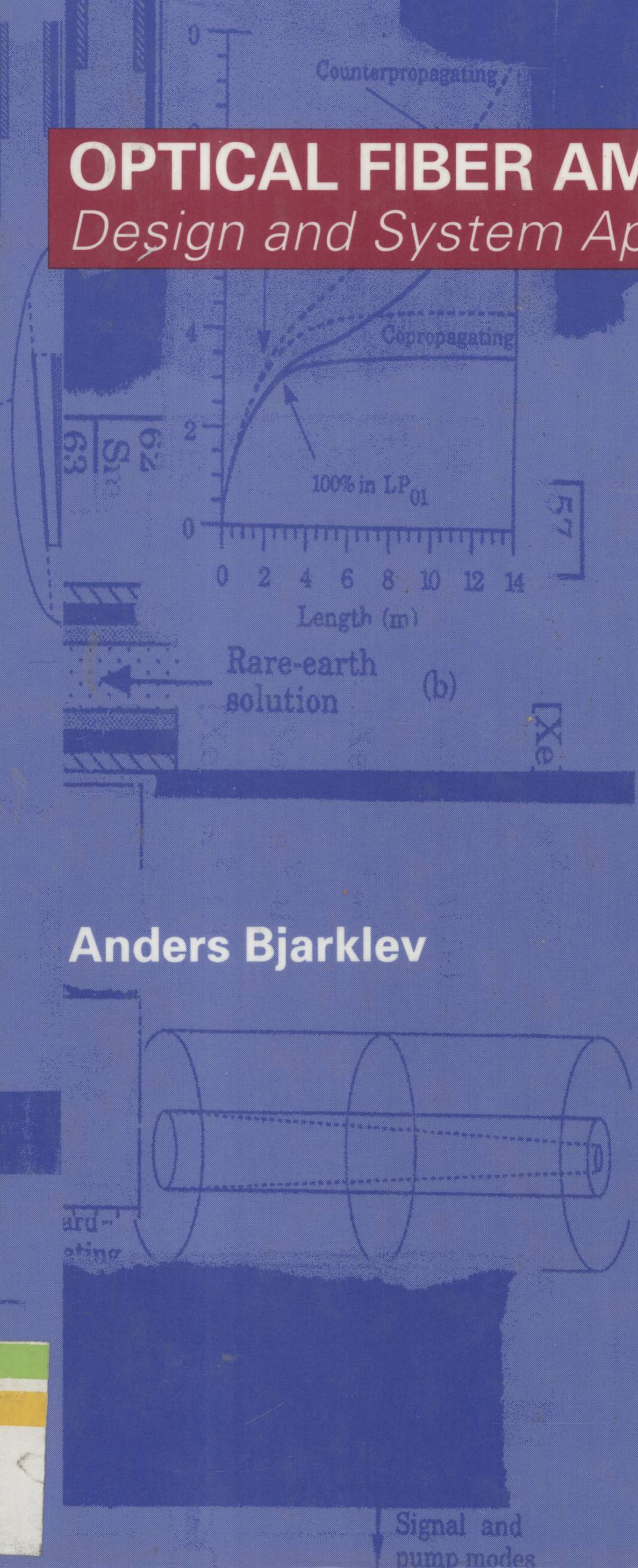
Design and System Applications



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Optical Fiber Amplifiers:
Design and System Applications

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To my wife Araceli, my son Kristian, and our family

Preface

Few components have revolutionized the area of optical communications as the fiber-optic amplifier has. The simple technology of light-pumped erbium-doped silica fibers has today provided commercially available amplifiers with high gain and low-noise properties at 1550 nm. Furthermore, recent developments in neodymium- and praseodymium-doped fluoride glass amplifiers have shown promising results for the 1300-nm wavelength band.

This book presents a review of the properties of optical fiber amplifiers, with a specific focus on the telecommunication engineering aspects. Highly accurate models for erbium-doped fiber amplifiers are shown to be very useful tools for manufacturers developing optimized 1550-nm fiber amplifiers for various system applications. The merits of optimized erbium-doped fiber amplifiers are compared both experimentally and theoretically for the relevant 800-, 980- and 1480-nm pump bands, where semiconductor laser pump diodes are obtainable. Fiber designs are evaluated and practical designs are given with emphasis on applications in digital direct detection systems. Trunk systems with lumped and distributed gain are described, and there is a short review of amplifier applications in systems employing analog modulation. Amplifiers operating around 1300 nm are also described, and the attainment of significant improvements for neodymium- and praseodymium-doped fiber amplifiers is discussed.

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Lyngby, Denmark
July 1993

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Chapter 1
Introduction

Optical communications was introduced as a concept only 20 years ago, when it became possible to reduce the attenuation in silica glass to a few decibels per kilometer. Since then, optoelectronics and silica fibers have been the subject of largescale worldwide research and product development. As a result, optical communications is today established as one of the most promising technologies within the area of short- and long-distance data transmission.

A major thrust of research activity within the area of optical communications is to increase the capacity of optical systems. The ultimate capacity limits have until very recently been determined by the spectral bandwidth of the signal source and of the fundamental fiber parameters: attenuation and dispersion. In order to characterize a given transmission line, terms such as *loss-limited* or *dispersion-limited* systems have indicated the limiting property. In reviewing the development of optical systems, it can be seen that there has been an alternation between these two extremes.

Ten years ago, when most of the systems were made using multimode fiber, the difference of propagation constants between the fiber modes caused considerable pulse broadening, and the optical communication systems were clearly dispersion-limited. As reliable semiconductor lasers with high intensity and spectral purity became commercially available, an important turning point in the development of optical communication systems was reached. Namely, multimode fiber was superseded by single-mode fiber, in which only a much weaker chromatic dispersion can result in pulse broadening. At a specific signal wavelength (i.e., 1310 nm), standard silica fibers have no chromatic dispersion. This wavelength therefore became the most dominant, and the fibers were optimized for 1300 nm operation. Using these "standard fibers," the systems were, consequently, loss-limited. However, the minimal intrinsic loss of silica fibers is not at the zero dispersion wavelength but at 1550 nm, where the chromatic dispersion, on the other hand, is nonnegligible: 15 ps/(km · nm).

Many resources in the mid 1980s were guided towards the elimination of chromatic dispersion at 1550 nm. This was done by compensating for chromatic dispersion with an opposite and equally large waveguide dispersion through a carefully controlled design and manufacturing process. However, fibers of this type, normally called *dispersion-shifted* fibers, cannot be made without the introduction of additional losses in the fibers. A large-scale spreading of the dispersion-shifted fiber into commercial systems, however, did not immediately take place, partly because no urgent needs for zero-dispersion systems were present, since the ultra-long transmission distances were still out of reach. This slightly restrained view of system improvement by dispersion-shifted fibers was supported by rapid component development, making dispersion less important as more spectrally pure signal sources were developed. Intensive international research on coherent communications, in addition, which is based specifically on signal sources of ultranarrow linewidth, indicated that installation of dispersion-shifted fibers with their somewhat poorer loss properties gave only little long-term guarantee that the best system was chosen.

There were, therefore, a number of practical problems that had to be overcome before a clear picture of future optical communication systems could be formed. Among the important subjects for clarifying this was the research on semiconductor amplifiers, which, however, suffered from problems such as cross-talk and polarization sensitivity in addition to difficult fiber-to-amplifier coupling.

At the same time, a parallel development took place, which in only three years would be shown to have a much larger impact on optical communication systems than that mentioned above. With a point of reference in work on rare-earth-doped glass lasers initiated as early as 1963 [1,2], the first fiber amplifiers (as possible useful devices for telecommunication applications [3]) were demonstrated in 1987. Progress since then has multiplied to the extent that amplifiers today offer far-reaching new opportunities in telecommunication networks [4–6]. The erbium-doped silica fiber amplifier for the 1550-nm telecommunication window has now become a well-established research laboratory tool. The fiber amplifier has been used both in system demonstrations on land and under the sea, and operational systems are commercially available from a number of manufacturers. In distribution experiments, splits of up to 39 million subpaths have been demonstrated for only two stages of amplification [7]. In short, this amplifier has revolutionized thinking on future optical fiber networks.

The main reason for the very strong impact that the optical amplifiers have and will have on data communication systems is to be found in the fact that they are unique in two respects: they are useful for amplifying input signals of different bit rates or formats, and they can be used to achieve simultaneous amplification of multiwavelength optical signals over a wide spectral region. These multiwavelength optical signals can carry different signal formats, including digital data, digital video, and analog video, allowing flexible upgrading in a broadband distribution network by adding extra *wavelength division multiplexed* (WDM) channels as needed. With optical amplifiers, therefore, the bottleneck of narrow and fixed bandwidths of electrical repeaters is avoided.

The outstanding properties offered by optical amplifiers are:

- High gain;
- High power conversion efficiency;
- Low noise;
- Low crosstalk;
- High saturation power;
- Polarization insensitivity;
- Broad spectral bandwidth;
- Very low coupling losses;
- Low cost.

This short list of fiber amplifier properties underlines the huge potential of these components, which most likely will extend to a large variety of applications in the years to come. The focus of this book will be, however, on the primary application, which is the optical amplifier for telecommunication systems, and the goal is to give a coherent description of the perspectives and limitations of fiber optical amplifiers. The organization of the book is aimed at providing the expert with a general reference source and the non-expert with a guide to the subject of rare-earth-doped fiber amplifiers.

First, it is necessary to understand in detail the physical properties of rare-earth-doped optical fiber. It is important to understand today's technological limitations, which are clarified through a description of the manufacturing process of rare-earth-doped optical fiber presented in Chapter 2. In the following chapters, the properties of rare-earth ions in glass host materials are discussed thoroughly. Chapter 3 presents the basic physical properties of rare-earth ions in silica and fluoride glass host materials, as well as the influence of different index raising co-dopants, and clarifies the most important mutual interaction between rare-earth ions. For all technical developments, it is essential to be able to characterize the components through measurements, and Chapter 4 is therefore focused on measurement techniques.

To date, the bulk of system work has centered on 1550-nm communication systems and has used erbium-doped silica-based fibers. In Chapters 5, 6, 7, and 8, the specific features and properties of *erbium-doped fiber amplifier* (EDFA) modules are discussed extensively. This naturally includes the use of other optical components, such as high-power semiconductor pump sources, fiber couplers, one or more isolators, and possibly optical filters. It is, however, not the purpose of this book to go into a thorough description of the physical properties of these additional components, since they are well characterized and described elsewhere. The focus will therefore be on erbium-doped fiber, which in Chapter 5 will be