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FOREWORD

Since the realization of diode-pumped Er-doped optical fiber amplifiers in 1987–1988, interest in optical fiber amplifier as a repeater in the long-haul light-wave system has been exploding. The small size and the ease of operation make EDFAs the ideal replacement for the electronic regenerators that are complex and usually expensive. Various applications of optical amplifiers have been studied, such as booster and in-line amplifiers, as well as low noise pre-amplifier before the lightwave signal is detected at the receiver. The receiver sensitivity using optical pre-amplifiers has reached the quantum noise limits. The simplicity and practicality of such receivers have surpassed those with either avalanche photodiode or coherent detection. With the advancement of optical amplifier technologies, the transmission distance of lightwave systems is no longer limited by the loss, but rather by the dispersion and non-linearity in optical fibers. In addition, the optical amplifiers perform well at very high bit rates because the amplification is not hindered at these speeds due to the very short stimulated emission lifetime. The next-generation transoceanic systems will use EDFAs as repeaters that will yield a capacity ten times larger than what is available today.

The other salient feature of optical amplifiers is the wide bandwidth of the optical gain. In EDFAs the optical gain extends to a width of about 30 nm. This means that multiwavelength signals can be amplified simultaneously by a single optical amplifier. This capability of multi-channel amplification is the key technology breakthrough for the application of the wavelength-division-multiplexed systems. Using WDM technology we will not only increase the system capacity, but also be able to create new network architecture that enhances operational flexibility, survivability, network functionality, and network management.

The semiconductor optical amplifier was a hot research subject concurrent with the coherent lightwave system research in the early 1980s. Previous lightwave systems experiments employing semiconductor amplifiers have shown promises of high speed and multichannel applications. However, due to the short carrier lifetime and gain saturation in semiconductor optical amplifiers, pattern effect and cross gain modulation limit the applications to gigabit-per-sec data rates. Moreover, severe

limitations were found due to the high fiber-to-chip coupling loss and polarization dependent gain. Improvements to these limitations are the subjects of current research.

However, the unique advantage of semiconductor amplifiers is that it can be monolithically integrated with other optical elements such as lasers and waveguides on the same chip. Thus, it can become an element in a photonic integrated circuit that can serve as a building block for functional devices. For example, by taking advantage of its gain, semiconductor amplifiers can be used as loss-compensating elements in an integrated optical cross bar switch. The effect of gain saturation can be utilized to our advantage for wavelength conversion or for optical time-division demultiplexing at rates over 100 Gbits/sec. These functional devices will be useful for optical switching and very high speed optical signal processing.

This book issue is devoted to these kinds of applications of optical amplifiers discussed above. The first chapter by Sudo presents an overview of the recent progress in fiber-based optical amplifiers that include Er-doped fiber amplifier for a 1.5 μm wavelength band and Pr-doped fiber amplifiers for a 1.3 μm wavelength band. Discussions also cover methods of constructing fiber amplifiers for 0.8 μm , 1.4 μm and 1.65 μm wavelengths. Special attention is paid to the design and operation of broad band and high power EDFAs, and techniques used for pumping. The reliability of fluoride-fiber-based amplifier is reviewed.

For applications of EDFA in an amplifier chain, it is essential that each amplifier must have a flat gain spectrum. However, in reality the gain spectrum over the 30 nm bandwidth is not exactly flat. The second chapter, by Goldstein and Eskildsen, discusses in detail this issue and its impact on the performance of multiwavelength lightwave networks. Gain flattening methods are also proposed to overcome this limitation.

The reliability of the EDFA depends largely on the reliability of the high power pump laser. Two pump wavelengths at 0.98 μm and 1.48 μm are commonly used. For the 0.98 μm laser, InGaAs/AlGaAs strained-layer quantum wells grown on a GaAs substrate are used. This kind of diode lasers has produced very high powers over 100 mW with a pump efficiency of about 4 to 5 dB gain per mW and a noise figure of 3 to 4 dB. High power 1.48 μm InGaAsP/InP quantum well lasers have also been made with a pump efficiency of 2 to 3 dB gain per mW, and a noise figure of about 5 dB. Extensive reliability studies of both types of lasers have been made. In the third chapter, Fukuda describes a comprehensive analysis of the failure mechanisms and the proper ways to avoid them. The mean-time-to-failure of these high power pump lasers are well above 100,000 hours.

One of the unique features of semiconductor optical amplifier (SOA) is the capability of integration with waveguides, lasers, modulators, couplers, etc. on the same chip. Such integration will improve the functionality of the device. The following four chapters illustrate this point well. Kirihaara and Inoue present a review of their extensive work on the optical switch array using SOAs as either gate or as booster amplifiers in a 4×4 optical switch. They describe in detail the

design and fabrication process, and present the performance characteristics of the switch, including crosstalk, loss compensation, spontaneous emission noise, and gain saturation. From these results, they conclude that the scalability of the size of the switch matrix is limited to a maximum of 16-stage cascade. The limitation is due to the accumulation of the spontaneous emission noise of the SOAs. Such a cascade can allow a 512×512 switch matrix to be made that would have a throughput of more than 1 Tbit/sec for a strictly non-blocking matrix. For a rearrangeable switch matrix, a throughput of 100 Tbit/sec can be reached. It indicates that this technology is potentially useful in very large scale photonic switching systems.

The above chapter describes the utilization of the linear gain of the SOAs for gating in switch applications. On the other hand, SOAs exhibit a very large non-linear gain that can be utilized to our advantage for applications in ultra-fast all-optical switching, four-wave mixing, and optical wavelength conversion. Kang, Glesk, and Prucnal in their chapter describe the operation of the ultra-fast optical interferometric devices that utilize the resonant optical nonlinearity in the interferometer using SOA elements. The device is actually an optical time demultiplexer, capable of operating beyond 100 Gbit/s with the switching energy as small as 650 fJ. The chapter also examines the advantages and disadvantages of various designs of such optical time demultiplexers.

In the following chapter, Vahala *et al.*, discuss in detail the underlying physics of the ultra-fast four-wave mixing mechanism in SOA, and its application to Terahertz spectroscopy of intraband scattering. In particular, they present a review of their recent work on the wavelength conversion function by four-wave mixing. Comparisons of different wavelength conversion techniques are also discussed.

Wiesenfeld in the final chapter presents a comprehensive review of the gain dynamics and the associated non-linearity in semiconductor optical amplifiers. The gain dynamics of SOAs originated from interband and intraband carrier dynamics. The dynamical processes affects both the gain and the refractive index of the semiconductor amplifiers. While the carrier dynamics set a limitation for linear amplifier applications on one hand, it also provide unique advantages for other functional devices at very high speed on the other hand. With the potential of photonic integration technology, the use of the nonlinearity in SOA for such functional devices may be the dominant future applications of semiconductor optical amplifiers. Weisenfeld's chapter also presents a brief review of such applications that complement the work presented in the two preceeding chapters by Kang and Vahala.

In summary, this book introduces the new trend in the research of optical amplifiers. While the Er-doped fiber amplifier using laser diode pump has reached the maturity stage for long-haul repeaters, applications of the semiconductor optical amplifiers are still at the research stage. The focus is on its integration with other optical components and circuits to create new functionality. Several examples are presented in this volume. Although the functional devices shown here are still in their infancy, the potential impact of their utilization in future optical systems and

networks is indeed very large. For instance, a 100 Gbit/sec optical time-division-multiplexed system will increase the capacity of present systems by 40 times. Eventually, many local area networks will be linked together to form a wide area network of national and global scale. Wavelength-division-multiplexed optical networks will emerge. In such WDM optical networks, wavelength interchangeability and rearrangeability can be accomplished by the wavelength interchangeable cross-connect switches employing waveguide switches, amplifiers and wavelength converters. With such capabilities, the bandwidth is so large that it will be cheap for everyone to use. The optical network will become the backbone of the information highway of the 21st century.

The editor is most grateful to the authors of the chapters cited above, who have put in a great deal of effort for this book. He would also like to thank Dr. P. K. Tien, the Editor-in-Chief of the Series on Selected Topics in Electronics and Systems, for his enthusiasm, encouragement, and support of this book. Sincere thanks also go to Barbara Aman, Editor of World Scientific Publishing Co., for her patience and resourceful support throughout the preparation of this volume.

Tien Pei Lee
Editor

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Dr. Lee has frequently given lectures in China. In 1992, he was honored as Guest Professor by Peking University. In 1994, he was named an Honorary Professor of the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, a Consultative Professor of Huazhong University of Science and Technology, Wuhan, China, and an Honorary Professor of the Wuhan Research Institute of Post and Telecommunications. In 1995, he was named a Consultative Professor of Beijing University of Post and Telecommunication, Beijing, China.

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