Chapter 1

Introduction

Planar waveguide amplifiers are one of the key components of integrated optic devices. The integration of amplifiers together with other optical components such as splitters, couplers, and wavelength division multiplexers enables many optical functions to work together on a single chip without any optical loss. Erbium is used as an optically active element in waveguide amplifiers because of its intra-4f transition around 1.54μm, a standard telecommunications wavelength. Advantages of erbium-doped amplifiers includes linear gain response, temperature and polarization insensitivity, and low noise [1-2]. In order to achieve high gain values on the centimeter length scale of an optoelectronic integrated circuit, Er^{3+} concentrations in the atomic percent range are needed. At such high Er^{3+} doping levels, concentration quenching effects such as cooperative upconversion can affect the gain performance of the amplifier. By using relatively low Er^{3+} concentrations in long waveguide (up to 50 cm), optical gain has been obtained in silica-based planar devices [3-6].

Erbium doped planar optical waveguide amplifiers operating at the third telecommunication window near 1.5μm are attractive due to their small size and potential integration as loss-compensating components with other optical devices such as passive splitter or combiners [7-10]. Ideally, these waveguide amplifiers should have high gain, small size and require low pump power.

Thin film integrated optics is becoming more and more important in optical communications technology. The technology for the fabrication of passive devices such as planar optical waveguides, splitters, and multiplexers is now quite well developed, and devices based on this technology are now commercially available. One next step to further improve this technology is to develop optical amplifiers that can be integrated with these devices. [11-13]. Such amplifier can serve to compensate for the losses in e.g. splitters or other components, and can also serve as preamplifiers for active devices such as detectors.

In optical fiber technology, erbium-doped fiber amplifiers [14-15] are now used in long-distance fiber communications links. They use an optical transition in Er^{3+} at a wavelength of 1.54μm for signal amplification, and their success has set a standard of optical communication at this wavelength. Using the same concept of Erbium-doping, planar waveguide amplifiers are now being developed. For these devices, silicon is often used as a substrate, such that opto-electronic integration with other devices in or on Si (electrical devices, or Si based light sources, detectors modulators may become possible. Fig1-1 shows an example of a silicon based optical integrated circuit in which a 1 x 4 splitters is combined with an amplifying section [16].

Amplification is an integral part of any network. In a particular, optical amplifiers, with their advantages of low noise, transparency, and built-in ability for wavelength division multiplexing, has been critical in enabling establishment of all-optical telecommunication networks that have powered the information revolution [17].

Erbium-doped materials have become of great interest because of their use as optical gain media [18-19]. Er^{3+} shows an optical transition centered at 1.54μm, a standard wavelength in silica-based optical fiber communication systems. Optical fibers have been doped with Er^{3+} to fabricate lasers, and in 1987, Er-doped fiber amplifiers operating centered at 1.54μm were reported [20]. More recently a need has arisen for planar amplifiers that can be integrated with planar optical devices such as optical switches and multiplexers [21]. For example, a planar amplifier with a moderate gain of 3dB could compensate for the decreased intensity in a Y splitter. To obtain such a gain in a few-centimeters-long waveguide, as opposed to the meter lengths used for Er-doped fiber amplifiers, the Er^{3+} concentration needs to be of the order of an atomic percent. However, high Er^{3+} concentration can give rise to undesirable effects such as reduction of fluorescence lifetime and cooperative upconversion [22-24], leading to an increase in the pump power required for optical gain.

Er-doped materials are of great interest in optical communications technology, as they can serve as the gain medium in lasers and optical amplifiers operating at the standard telecommunications wavelength of 1.5μm.[25-27] Er^{3+} ions , when incorporated in a solid host, show well-defined energy levels of the 4f-shell electronic configurations (see Fig1-2) [28].

Silicon is an ideal material for the fabrication of optical waveguides that are compatible with optical telecommunication technology at 1.5 μm, because of its high transparency and high refractive index at this wavelength. The high transparency is due to the large mismatch between

1.5µm photon energy (0.8 eV) and the silicon bandgap energy (1.1eV at room temperature). At the same time, the energy mismatch also excludes the fabrication of all-silicon active waveguide devices such as detectors and emitters operating at 1.5µm. This problem may be solved by doping the silicon with small amounts of optical active erbium (Er) ions [29]. Silicon is the dominant semiconductor material, and has been called the ‘‘engine’’ behind the information revolution [30-31]. However, its poor optical activity due to its indirect band gap has led to its near exclusion from the field of optoelectronics whose exponential growth rate surpasses even the vaunted “Moore’s Law’’ of silicon integrated circuits [32]. This has motivated numerous attempts [33] at developing a silicon-based light source that would allow integrating information processing and optical communication capabilities into one single, silicon-based integrated structure. For such a structure to have a practical impact, however, more than just light emission is required. The light source should (1) emit light at a technologically important wavelength, (2) achieve its functionality under practical conditions (e.g., temperature and pump power), and (3) and offer a competitive advantage over existing technologies. Although many research groups are studying Er doped optical waveguide materials, but only a very limited number of groups has fabricated actual devices. Table I lists the most successful erbium doped waveguide amplifiers on silicon that have been fabricated to date [11].

The organization of this thesis is as follows:

In chapter 2, we introduce the basis of optical amplifiers and the theory of EDWA. The purpose of implanting Er^{3+} lies on combining WDM element and optical amplifier on the sample which we designed. The advantages of integrated Er^{3+} MMI applied in integrated optics are presented and discussed. We also present the principal and mathematical formulations of EDWA. And we show the Simulation and Analysis of Erbium Doped Waveguide Amplifier.

In chapter 3, we introduce the noise figure and simulate the WDM optical transition system of Nx1 MUX, EDWA and 1xN DEMUX. We represented the performance of simulation results of the opti-system that integrates the function of WDM elements and optical amplifier.

In chapter 4, we try to fabricate and measure these Erbium doped optical waveguide devices. Owing to the excellent guided-wave characteristics of UNIBOND, SOI substrates exhibited in waveguide devices, we focus on our attentions on the SOI waveguide devices based on UNIBOND SOI wafers. The basic semiconductor processes are discussed in Section 4-1. Section 4-2 introduces the technique and operating steps of ion implantation. The experimental processes and results of integrated optical Multimode Interference (MMI) waveguide based on UNIBOND SOI wafer which doped Erbium are also presented. Finally, we give the conclusions and discussions of our Erbium doped SOI optical devices.

In chapter 5, we give a brief conclusion of this work and research.

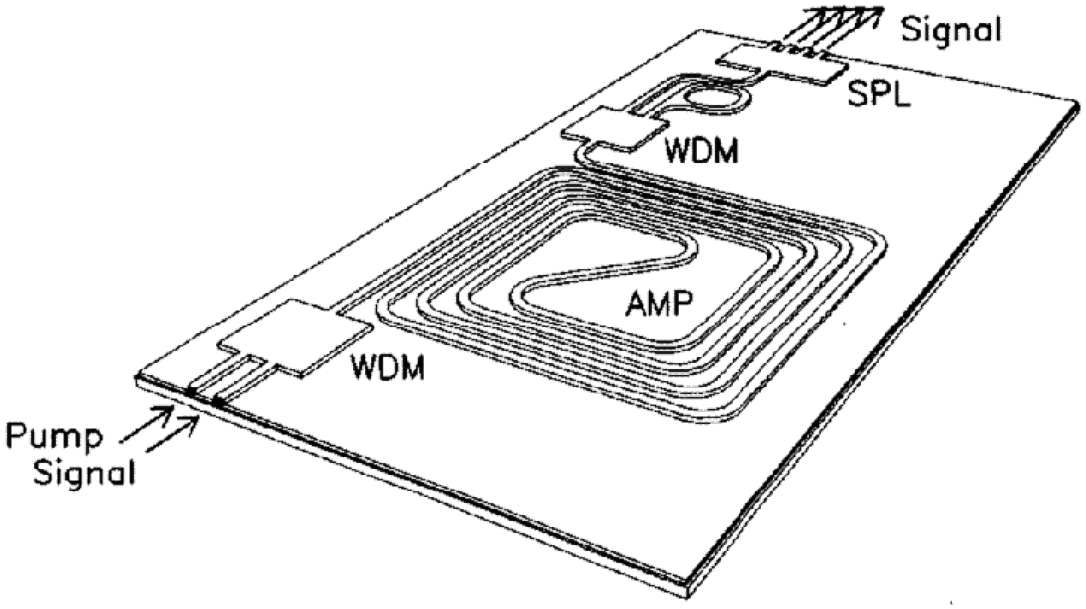

Fig. 1-1 An example of a silicon based optical integrated circuit in which a 1 X 4 splitter is combined with an amplifying section [16].

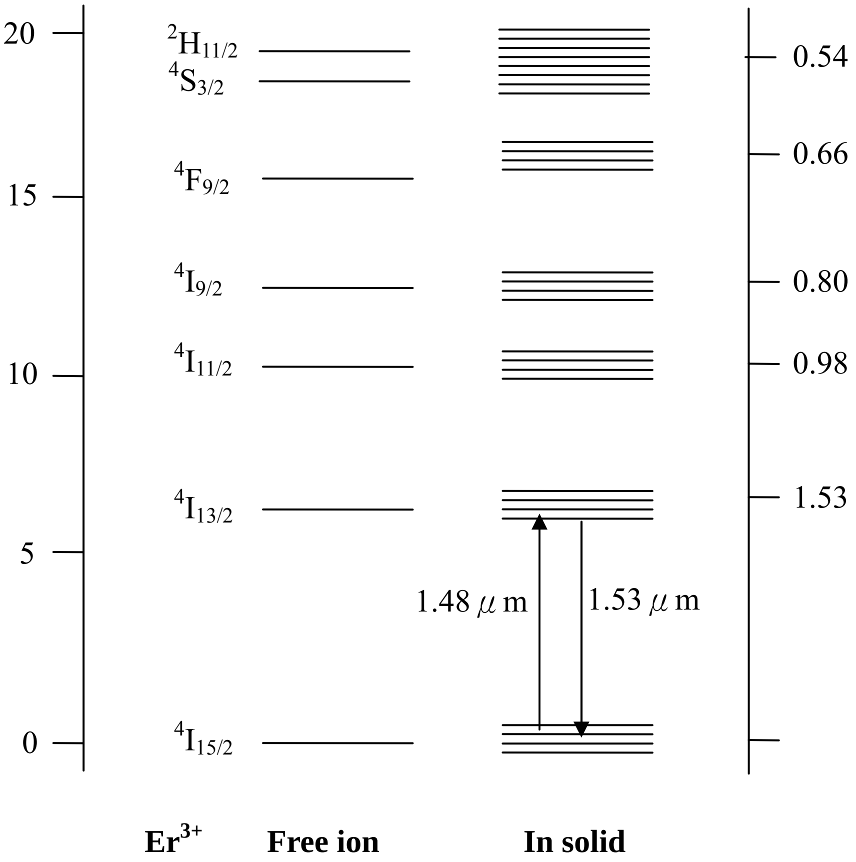

Fig. 1-2 Energy level diagram of Er^{3+} [28].

Table I. Characteristics of Er doped planar optical waveguide amplifiers operating at 1.54μm that have been fabricated on silicon to date [11].

Ref(et.al)	Hattori	Shmulovitz	Van den Hoven	Barbier	Van Weerden	Yan
date published	5-94	4-96	4-96	2-97	4-97	11-97
Waveguide Core composition	P-doped SiO_2	Soda-lime silicate glass	Al_2O_3	Yb co-doped phosphate glass	Y_2O_3	$P_2O_5/Al_2O_3/Na_2O/La_2O_3$
Internal gain	27	~6.5	2.3	>16.5	6.0	4.1
Er concentration($10^{20}cm^{-3}$)	~0.4[24]	0.7	2.7	~16[24]	1.3	5.3
Length(cm)	47.7	6	4	9	4.3	1
Gain/length(dB/cm)	0.6	1.1	0.6	>1.8	1.4	4.1
Pump power(mW) =inside waveguide	264	80	9*	200	12*	21*
Pump wavelength(nm)	980	980	1480	983	1480	980
Waveguide geometry	Ridge or channel	Ridge or channel	ridge	channel	ridge	strip
Core index of refraction	~1.46	~1.49	1.64	-	1.9	1.53
Waveguide loss(dB/cm)	0.15	0.1	0.35	~0.1	0.8	0.9