All optical 2R regenerators for long haul optical transmission systems

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Abstract: Current optical networks are operating at 10 Gb/s channel rate; however, future network traffic demand will require a new technology to meet the additional performance requirement. The issue of achieving long-distance dense wavelength division multiplex (DWDM) transmission at bit-rates of 40 Gb/s and above per channel is vital for reducing size, power requirements and cost in future optical communication networks. We propose here an integrated fast recovery ion-implanted multiple quantum well saturable absorber with semiconductor laser amplifiers to realise all optical 2R regenerators for such systems.

1 Introduction

Modern telecommunications networks are enabled by optoelectronics. Central for their operation is the Internet/telephone network that will eventually converge. Long-distance telecommunication services began using optical fiber in the late 1970s and the modern Internet is nearly 100 percent optical, beyond the building.

The recent explosive growth of data traffic has stimulated the demand for high-capacity information networks. In order to increase the capacity in optical transmission, the number of Wavelength Division Multiplex (WDM) channels or the base channel rate can be increased. Current commercial DWDM systems operate with >100 channels at 10 Gb/s channel rate using a channel spacing of 50 GHz in both the C- and L-band (1,530 nm and 1,600 nm respectively) of the optical fibers [1]. However, to fill these two transmission windows in a single silica optical fiber requires 175 transmitters and receivers, with their considerable cost, power and space requirements, while to achieve 10 Tb/s per fiber would require 1000 transmitters and receivers. Thus, an increase in the channel rates beyond 40 Gb/s is an attractive approach which can offer high spectral efficiency to further reduce the cost/bit/km, and also the power and space consumption of terminals.

In long-haul transmission system, the maximum achievable transmission distance without Forward Error Correction Code (FECC) is limited to less than 5000 km with increasing channel bit-rate [2], as a consequence of ever-growing propagation impairments such as optical signal-to-noise ratio (OSNR) degradation, jitter accumulation, and polarization mode dispersion (PMD) [3, 4] caused by interactions between fiber non-linearities and chromatic dispersion. Therefore, a method to increase throughput and channel rate is to use non-linear supported systems that offer the advantage of increased resistance to PMD effects [5], rather than state of the art linear transmission systems. However in high bit-rate non-linear systems, there are performance limitations due to problems such as Gordon-Haus jitter, soliton-soliton interactions, amplified spontaneous emission (ASE) noise, higher order dispersion, and the Raman effect.

These degradations have lead to the major interest in the investigation of 3R regeneration (Re-amplification, Re-shaping, and Re-timing), which uses all-optical system in network nodes to extend the transmission distance. All-optical techniques are required in order to overcome the electronic circuit bottleneck [6]. A number of researches have been carried out on various 3R regeneration techniques for transmission over long distances, but all these techniques require clock extraction and re-modulation, which increases the systems complexity and costs, and would lead to a significant challenge when bit rates approaches 80 Gb/s and above [7-9].

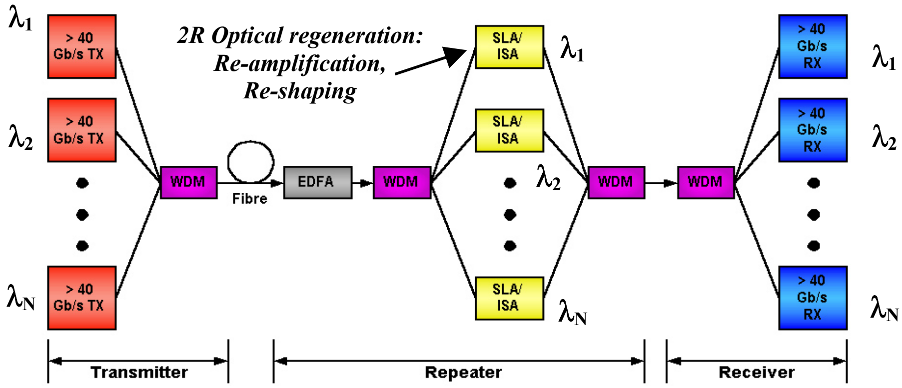


Figure 1: Long-haul ultra-fast optical transmission system employing SLA/ISA

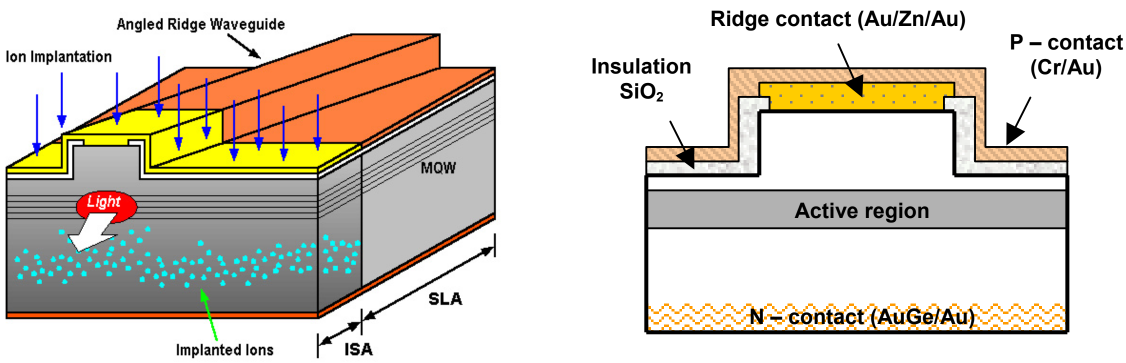
2. Saturable Absorbers

A simpler approach is the use of fast saturable absorbers (SAs) in the optical transmission line to form a 2R regenerator which whilst not retiming the pulses removes additive noise and cross talk. This eliminates the need for clock extraction and ultra-wide bandwidth modulators [10, 11]. Semiconductor saturable absorbers are devices with a non-linear absorption characteristic, which decreases with high input power. SAs therefore selectively absorb the low power noise, while they are almost transparent for the main signal pulse, offering the potential for elimination of the unwanted low power distortion induced by a signal transmitted over a long span of fiber. Simulations carried out at UCL demonstrated the feasibility of 80 Gb/s channel rate transmission over trans-oceanic distance with SAs [12]. Semiconductor SAs are compact, passive devices, and can be integrated with other optical devices, but the maximum bit-rate is limited by the saturation absorption recovery time. This problem however can be overcome by ion implantation of the device [13].

3. Ion Implantation

Ion implantation is based on the introduction of point defect centers in the semiconductor material, to create additional levels in the material's energy gap and reduce the carrier recombination time. Thus, the lifetimes of free carriers are significantly reduced by defect centers from the nanosecond time scale down to picoseconds or femtoseconds [14]. Ion implantation of SAs therefore enables fast recovery SAs to be realised and is advantageous over other method such as carrier sweep-out or low-temperature molecular beam epitaxy (LT-MBE), as it reduces the complexity of the device fabrication process.

Essiambre *et al.* [15], showed that the system performance can be considerably improved if an SA was inserted after each in-line amplifier, simply because it can remove low-power dispersive waves. Previously, it was found that the main performance limitations of the ion implanted SAs is the noise penalty arising from the unsaturated loss of the normal incidence device [13], and the long recovery time of the ion implanted semiconductor optical amplifier device [16]. Therefore, we propose here an all-optical semiconductor laser amplifier/integrated saturable absorber (SLA/ISA), to overcome the unsaturated loss and recovery time limits. Our design (Figure 2) incorporates an angled ridge waveguide to enable the device to obtain pure travelling wave operation with only single layer facet coating. The SLA/ISA is realised by ion implantation normal to the junction plane rather than through the laser facet, as has been used in all previously reported work [17].



(a) SLA/ISA device structure ***(b) Cross-sectional***

Figure 2: Semiconductor laser amplifier/integrated saturable absorber (SLA/ISA)

4. Simulations

Simulations were carried out using SRIM (The Stopping and Range of Ions in Matter) 2003 simulator [18] to analyse the damage characteristic of several ions on the wafer we use. Figure 3 shows the plot of the damage distribution of the respective ions versus the penetration depth in the wafer structure use to fabricate the SLA/ISAs. This enables us to estimate the type of ions and energy that could be used to implant our device. The results shows that heavier ions O^+ and N^+ have a shorter stopping range which is in the vicinity of around 3 μm to 4 μm, but create higher damages hence introducing more recombination centers in the MQW. Whereas, lighter ions such as He^+ and H^+ would be able to penetrate deeper into the wafer substrate, but creating less vacancies. Ideally, the implant species and parameters are chosen so that the ions would stop deep inside the substrate, creating a trail of defect centers in the MQW but leaving the region free of any implanted ions.

A modelling program, FWave IV has also been used to calculate the guided propagation modes in the ridge waveguide design for the epitaxial wafers used for this work. The waveguide modelling results is presented in Figure 4. The program solves explicitly the horizontal and vertical components of the electric field, and calculates the effective index of the waveguide corresponding to each mode, which is used to relate to the optical confinement and light propagation in the SLA/ISA waveguide.

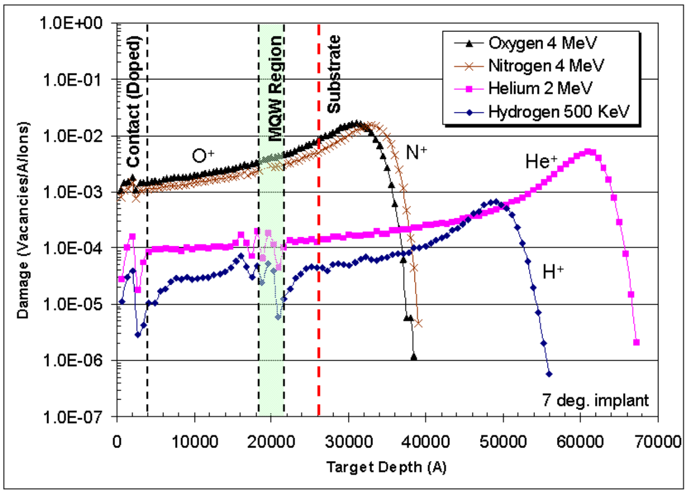


Figure 3: Damage distribution for implantation of $O^+/N^+/He^+/H^+$ ions in the wafer structure used for fabrication of the SLA/ISAs

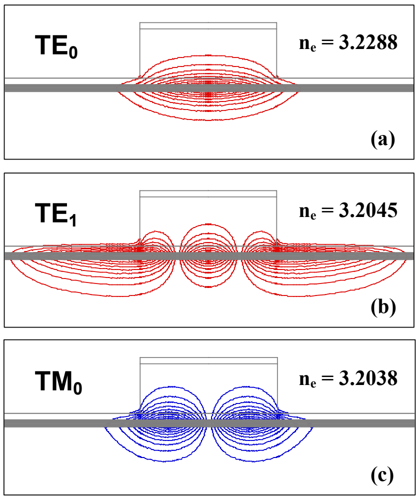


Figure 4: Guided wave modelling results for our ridge waveguide design; (a) & (b) horizontally polarised field, (c) vertically polarised field

5. Experiment and results

The samples used in this study were wafers incorporating a 60-period InGaAsP/InGaAsP MQW on n-InP substrate. The samples were implanted with nitrogen ions at 4 MeV energy using a High Voltage Engineering Europa (HVEE) implanter at the University of Surrey. Doses investigated were $1\text{x } 10^{12}$ cm^{-2}, $3 \text{ x } 10^{12}$ cm^{-2}, and $6 \text{ x } 10^{12}$ cm^{-2}. During implantation, the samples were tilted by 7 degrees from normal incidence to minimise channelling effects. After implantation, the time response of the MQW absorption was determined by pump-probe measurements using 2 ps pulses at 4 MHz repetition rate and 1560 nm wavelength. A pump energy of 17 pJ was focused on a ~ 5 µm spot radius on the device, while the power ratio between the pump and the probe was 50:1. The 1/e decay time of the pump-probe measurement was extracted from exponential fitting to the measurements and is defined as the value of the recovery time. From an initial recovery time of 3 ns prior to implantation, a decrease to 15 ps, 7 ps, and ~3.7 ps after implantation at doses of $1\text{x } 10^{12}$ cm^{-2}, $3 \text{ x } 10^{12}$ cm^{-2}, and $6 \text{ x } 10^{12}$ cm^{-2} respectively was observed (Figure 5). This results indicate that implantation generates defects along the ion trail that act as additional traps in the bandgap, thereby reducing the time response of the SA via fast emptying of the conduction band.

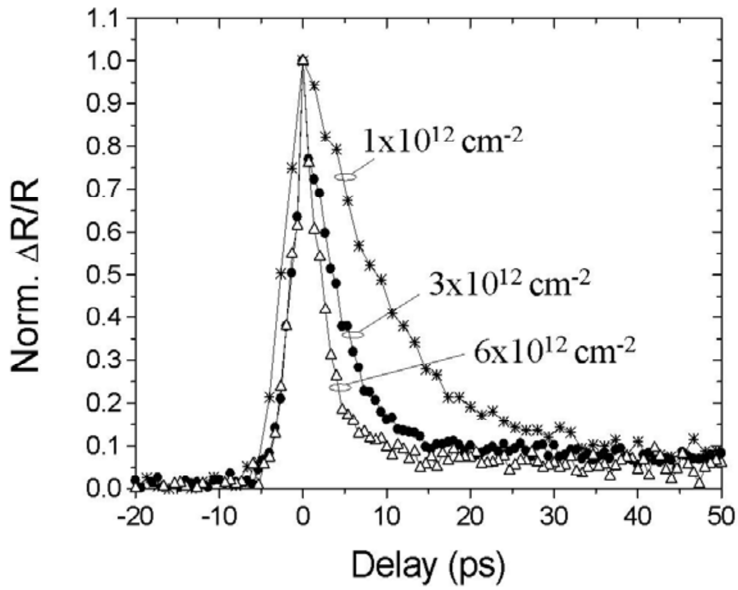


Figure 5: Time-resolved measurements of normal incidence ISA for three implantation doses using Nitrogen ions at 4 MeV

7. Summary

This project represents a change in direction from much of current optical communications research, which aims to maximise the number of relatively low bit rate channels through WDM to obtain increased throughput. The approach here, by contrast, aims to achieve the increased capacity by using integrated devices in a non-linear supported transmission system, enabling a reduced number of WDM channels to be used for a given throughput. This offers large system benefits, through reduced error-rate, improved spectral efficiency, and reduced terminal, router and regenerator complexity. Therefore, employing this SLA/ISA has good potential to achieve practically all-optical global networks with high-bandwidth and unlimited transmission distance.

Acknowledgments

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