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All Optical Switching Operation in a Semiconductor Optical Amplifier based Mach-Zehnder Interferometer

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ABSTRACT

Optics has been used in computing for a number of years but the main emphasis has been and continues to be to link portions of computers, for communications, or more intrinsically in devices that have some optical application or component. Optical digital computers are still some years away; however a number of devices that can ultimately lead to real optical computers have already been manufactured. The most likely near-term optical computer will really be a hybrid composed of traditional architectural design along with some portions that can perform some functional operations in optical mode. In this paper design of Mach-Zehnder interferometer is shown which works as a switch. This switch can be used in designing the optical memories as well as in add-drop multiplexers. The interferometer employs bidirectional couplers and semiconductor optical amplifier in one of its arms. Interferometer acts as a very high speed switch, since it does not need any conversation from optical to electronic and vice versa.

1. INTRODUCTION

For many years, optics scientists have been looking for all-optical signal processing materials that enable one light beam to be controlled by another. However, most optical materials are linear and allow light beams to pass through without alteration.

The key to achieving all-optical processing functions is to use a nonlinear optical material where different light beams can interact. Of the many nonlinear materials investigated, one device has emerged as a practical solution for all-optical signal processing — the semiconductor optical amplifier (SOA).

All-optical signal processing is particularly of interest in telecommunications applications, where the benefits of the optical approach in terms of power and cost are becoming important. Today's telecom networks are based entirely on electronic data handling, but now the core network data speeds are at 40 Gb/s (40 billion bits per second), and, instead of the cheap CMOS silicon devices that formerly handled these signals, specialist electronic materials and sophisticated radio- frequency techniques are required. The electrical signals are also more difficult to route and transmit at these speeds, which require more power and cost more.

Modern high-speed electronic switching equipment (such as an IP router rack) can consume more than 10 kW and can require an equivalent power to remove the heat generated by the rack of equipment. In contrast, all-optical signal processing is intrinsically high speed and can easily handle complex signals and data rates of 40 Gb/s. SOA-based optical processing devices can require much less power (~1 W) than the electronic equivalent (approximately tens of watts) and can be readily integrated to scale to arrays of devices that have smaller footprints. Although the individual tasks that can currently be accomplished with optical processing are relatively straightforward, these tasks — such as wavelength conversion and signal regeneration are valuable in telecom networks.

It is important to understand that all-optical signal processing is not necessarily a replacement for all electronics, but it can greatly increase the effectiveness and capacity scalability of the overall optoelectronic system. Integrated Mach-Zehnder interferometers (MZIs) incorporating semiconductor optical amplifiers SOAs in the interferometer arms have recently been developed as very high-speed all-optical switching devices. Switches of course, are the vital component of a fibre optic communication network. Since electronic switching is a well develop technology, it would seem natural to use these switches in fibre optic networks. However the price for using this mature technology is optical to electrical (O/E) conversion with all the associated draw backs mentioned above of this method.

We shall discuss in later part of this paper that the function of light output by an MZI (with a constant bias light injected) versus the light injected into the MZI can also have the characteristics suitable for designing a flip-flop. Optical bi-stable devices, and in particular all-optical flip-flops, can have many uses in optical telecommunications and computing, such as threshold functions, 3R regeneration, de-multiplexing and rate conversion of telecommunication data [1], and temporary storage of decisions made on telecommunication data packets [2].

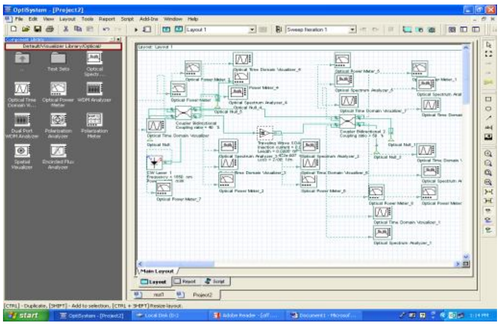

Figure 1: Mach-Zehnder Interferometer on Optiwave

2. OPERATING PRINCIPLE

A Mach-Zehnder interferometer incorporate a phase shifter in one of its arms, this phase shifter should have at least one parameter so that we can control the amount of phase shift.

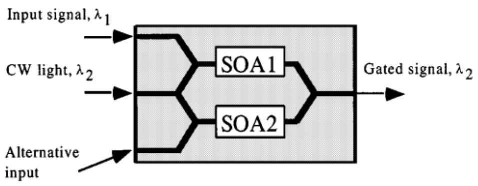

Figure2: Optical Gate using MZI with SOAs in the interferometer arms

A continuous-wave CW bias light input of power P enters on the left of the MZI. In one of the MZI arms, an SOA provides gain and a phase shift to the rightward-flowing CW light. This phase shift can be controlled through the injection current in the SOA and the input optical power. The MZI can be modelled by the following set of equations (with i set to 1). Equations (1), (2) and (4) model the SOA, and (3) models the interferometeric effect at MZI output [5]:

$$\frac{dN_i}{dt} = \frac{I}{q} - \frac{N_i}{\tau_e} - G_i\frac{e^{(G_i-\alpha_{int})L}-1}{(G_i-\alpha_{int})E}\left(rP_{bias} + \frac{P_{ini}}{2}\right) \quad (1)$$

$$G_i = \frac{\Gamma a}{V}(N_i - N_0) \quad (2)$$

$$P_{out\,i} = \frac{P_{bias}}{2}\Big(1 - r + re^{(G_i-\alpha_{int})L}$$
$$+2\sqrt{r(1-r)}\,e^{(G_i-\alpha_{int})L}\cos\left(\theta_i - \frac{\pi}{2}\right)\Big) \quad (3)$$

$$\theta_i = \theta_x + \frac{2\pi L\Gamma n_{eh}}{\lambda V}(N_x - N_i) \quad (4)$$

where I is the SOA injection current, q is the electronic charge, τ_e is the carrier lifetime, Γ is the confinement factor, L is the SOA length, V is the SOA active region volume, αint is the SOA intrinsic losses, a is the gain coefficient, neh is the refractive index change per carrier pair, N0 is the carrier number at transparency, λ is the wavelength of the light source used, and E is the energy of a photon at wavelength λ [2].

3. COMPONENT DESCRIPTION

Two basic components used in the designing of Mach-Zehnder interferometer are as follows.

1) Semiconductor optical amplifier (SOA)
2) Bidirectional coupler

3.1 Theory of Semiconductor Optical Amplifier

A schematic diagram of an SOA is shown in Fig3. The device is driven by an electrical current [4]. The active region in the device imparts gain, via stimulated emission, to an input signal. The output signal is accompanied by noise. This additive noise, amplified spontaneous emission (ASE), is produced by the amplification process.

SOAs are polarisation sensitive. This is due to a number of factors including the waveguide structure and the gain material. Polarisation sensitivity can be improved by the use of square-cross section waveguides and strained quantum-well material.

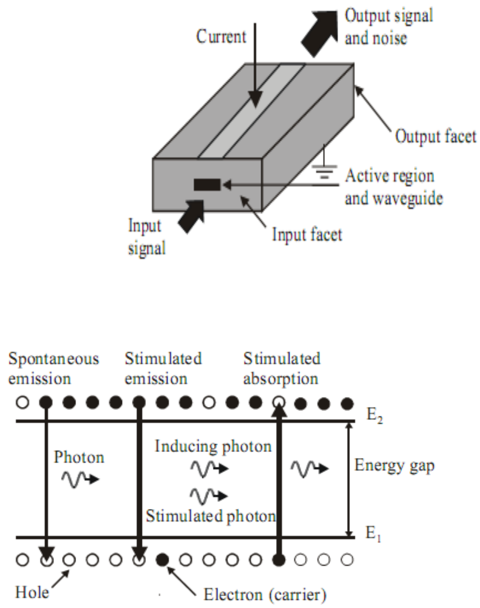

Figure 3: Semiconductor Optical Amplifier and stimulated emission

The gain of an SOA is influenced by the input signal power and internal noise generated by the amplification process [4]. As the input signal power increases the gain decreases as shown in Fig.

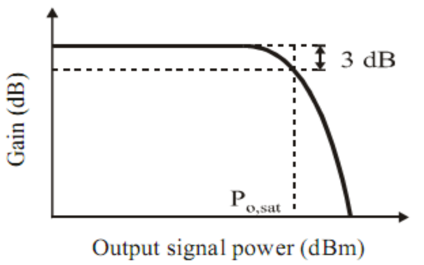

Figure 4: Gain Power Charecteristics

This gain saturation can cause significant signal distortion. It can also limit the gain achievable when SOAs are used as multi-channel amplifiers in wavelength division (WDM) multiplexed systems.

SOAs are normally used to amplify modulated light signals. If the signal power is high then gain saturation will occur. This would not be a serious problem if the amplifier gain dynamics were a slow process.

However in SOAs the gain dynamics are determined by the carrier recombination lifetime (few hundred picoseconds). This means that the amplifier gain will react relatively quickly to changes in the input signal power. This dynamic gain can cause signal distortion, which becomes more severe as the modulated signal bandwidth increases. These effects are even more important in multi-channel systems where the dynamic gain leads to inter-channel crosstalk. This is in contrast to optical fibre amplifiers, which have recombination lifetimes of the order of milliseconds leading to negligible signal distortion. SOAs also exhibit nonlinear behaviour. These nonlinearities can cause problems such as frequency chirping and generation of inter-modulation products. However, nonlinearities can also be of use in using SOAs as functional devices such as wavelength converters.

As its name suggests, an SOA is made from semiconductor optoelectronic material (Indium Ohosphide-based) and is pumped electrically to create a population inversion that generates optical gain via stimulated emission.

The devices are similar to the familiar semiconductor lasers used in consumer applications (for CD and DVD players) and to the specialist semiconductor lasers that power the optical fibre communications networks worldwide. However, they are designed to be purely amplifiers, not oscillators.

One reason that the device is practical is that they are tiny (volume~0.1 mm3). A second reason is their high gain (~30 dB), which means that small energy— less than 100 fJ — are required to generate nonlinear effects. For optical communications applications, the device has additional attractive properties, such as being able to couple efficiently to optical fibre and being insensitive to the polarization of incoming signals. The latter is required for operation in real telecom networks because the signal polarization changes as it is transmitted over optical fibre.

3.2 Bidirectional couplers

A fibre optic coupler is a device that can distribute the optical signal (power) from one fibre among two or more fibres. A fibre optic coupler can also combine the optical signal from two or more fibres into a single fibre. Fibre optic couplers attenuate the signal much more than a connector or splice because the input signal is divided among the output ports. For example, with a 1 X 2 fibre optic coupler, each output is less than one-half the power of the input signal (over a 3 dB loss).

Fibre optic couplers can be either active or passive devices. The difference between active and passive couplers is that a passive coupler redistributes the optical signal without optical-to-electrical conversion. Active couplers are electronic devices that split or combine the signal electrically and use fibre optic detectors and sources for input and output.

Optical couplers, also referred to as optocouplers, are well known devices used to direct light from one light source to a light receiving member. Optical couplers are the heart of an optical communication network. Optical fibre technology is used in a variety of applications such as telecommunication, computer, and medical applications. In the past, optical fibre communication technology and optical fibre communication elements mainly were used on backbone networks. These days they are widely used in metropolitan optical communication networks. An important aspect of optical fibre technology is the coupling of an optical fibre to an optoelectronic device for transmitting information conducted by the optical fibre.

An optical coupler is a passive device for branching or coupling an optical signal. Generally, a coupler is centralized by joining the two fibres together so that the light can pass from the sender unit to the two receivers, or else it can be made by joining the two "receiver" fibres which will then be aligned and positioned so as to face the "sender" fibre. The function of branching or coupling an optical signal in optical communications can be simply performed by various photomechanical connections, similar to branching or coupling in electric communications. Optical couplers are key components in optical networks. Optical couplers, optical switches, and optical power splitters are needed in many optical applications. In fibre optical transmission systems the light beams travelling in two or more fibres must often be combined into a single fibre, a device which accomplishes this is called a combiner or multiplexer. Similarly, in such systems one beam must frequently be split into two or more beams, a device which accomplishes this is called a splitter or divider. The optical fibre coupler, also called optical fibre splitter, is an essential element to implement Fibre-To-The-Home (FTTH), to connect planar arrangements of waveguides, for routing signals from one waveguide to another and/or for splitting optical signals into two independent signals at a predetermined power ratio to be transmitted over two different waveguides.

4. SIMULATIONS AND EXPERIMENTAL RESULTS

The main practical physical mechanisms used for optical nonlinearity in SOAs are cross-gain and cross phase modulation. There are other useful physical mechanisms, such as four-wave mixing and nonlinear polarization rotation, but these are less favoured because of their intrinsic polarization dependence.

Cross-gain modulation operates as shown in Figure 5.

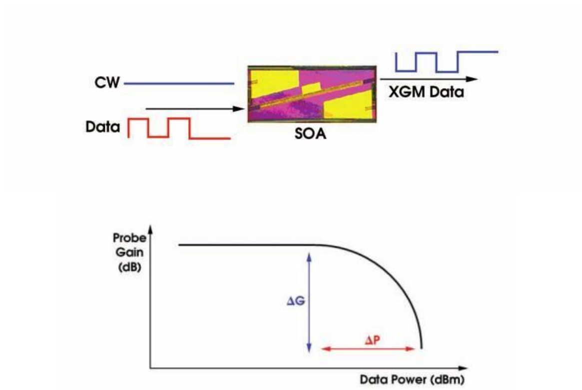

Figure 5. The incoming information carried on one wavelength (represented here in red) is transferred via cross gain modulation to another wavelength (left). The SOA's gain at the blue wavelength is saturated by the presence of signal at the red wavelength (bottom) (XGM = cross-gain modulation).

In this simple scheme, the power (ΔP) of the input data signal (red wavelength) causes the gain (ΔG) of the SOA to saturate, and, thus, output power of the second optical input (CW probe beam with blue wavelength) drops. If an optical filter is placed at the output of the amplifier's output to pass only the blue wavelength, the output signal becomes the logical inverse of the input data. The information on the incoming red wavelength has been converted to the blue wavelength. The speed is limited by the gain recovery time of the SOA. This timescale depends on several physical parameters of the device, but recent improvements have shortened the time to less than 25 ps so that wavelength conversion via bit-by-bit cross-gain modulation can be implemented at 40 Gb/s. phase modulation is a slightly more complex arrangement than cross-gain modulation, but it is the most widely used because of its potential for higher speed and better performance. In an SOA, whenever the gain is changed, the refractive index of the material changes as well. The change in index is exploited to achieve optical switching by placing the device in an optical interferometer such as the Mach-Zehnder interferometer shown in the Figure 1 and its simulation results is shown in figure6.

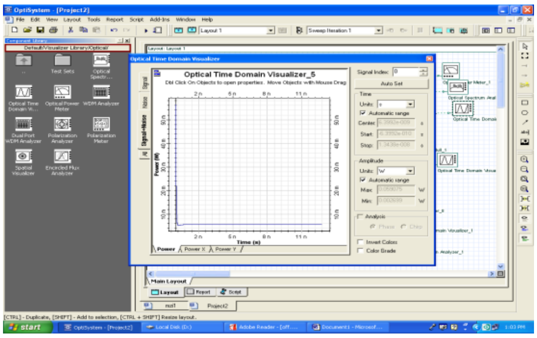

Figure 6: by altering the phase change in one arm of a Mach-Zehnder interferometer, cross-phase modulation can switch the output from one spatial port to the other). (Upper output shows the ON state and lower one shows OFF state)

The input data signal (red) changes the gain of the SOA as well as its refractive index. If the cross-phase modulation experienced by the blue input beam is radians, the output light at the blue wavelength is switched from one spatial port to the other. In addition, the interferometer can provide a much higher extinction ratio on the output data because the amplitude and phase of the light beams interfering at the output can be optimized.

As with cross-gain modulation, the speed of cross-phase modulation effects is limited by the recovery time of the SOA — that is, the time it takes the gain to unsaturated. If higher speeds are required, advanced techniques can be invoked to overcome the device's gain recovery time. One method, as shown in the lower part of Figure 1, is to time-delay a copy of the input data and to apply that signal to an SOA in the other arm of the Mach-Zehnder. Thus, switching in both directions occurs at the speed of gain saturation. This results in a speed improvement because the gain saturates faster than it is unsaturated.

Because of their small physical size, SOAs can be readily fabricated into compact interferometers with a variety of photonic integration approaches. Among these technologies, hybrid integration of the optimized nonlinear SOAs with low-loss silica waveguides (planar lightwave circuits) has been demonstrated to produce high-performance results.

5. APPLICATIONS

Designed Mach-Zehnder using SOA can be integrated for producing arrays of these devices. Currently there are four main applications for SOA MZI-based all-optical signal processing in telecommunication networks:

- Wavelength conversion.
- Optical regeneration.
- Optical Boolean logic.
- Advanced optical processing circuits.

Wavelength conversion (as shown in Figures 2) and optical regeneration are useful functions for optical communications systems. Wavelength conversion enables instantaneous wavelength reconfiguration, and regeneration allows transmission over long distances. Most wavelength division multiplexing fibre systems use in-line optical amplifiers (erbium-doped fibre amplifiers) to overcome the optical loss of the fibre and to increase the distance that data can be sent. However, the noise added by the amplifiers also ultimately limits the signal transmission distance. Regeneration with SOA, Mach-Zehnders reduces this noise and allows the optical signals to propagate farther. Research is going on to understand how various regenerators using all-optical signal processing can increase the performance and reduce the cost of high-speed optical communications systems.

The ability of all-optical signal processing to scale to more complex processing schemes ultimately depends on using the SOA-based devices to perform combinational optical logic. This application has advanced over recent years, and relatively complex optical circuits using several SOA based gates have been demonstrated [6][7]. In parallel, the operation speed of the basic SOA-based Boolean gate functions have increased, and up to 85 Gb/s NAND operation has been shown [6].

MZI switches incorporating SOAs can also be used as ADMs [4]. Many configurations are possible, one of which is shown in Fig. 7. In this configuration the input data signal at 40 Gb/s is split into two drive signals. One of the drive signals is delayed by a half a bit period. The interferometer is configured such that when an undelayed signal pulse is present in the upper arm of the interferometer an input 10 GHz pulse is directed to the drop port. At the same time the 3 x 10 GHz pulse stream is directed to the through port. When the delayed signal pulse is present in the lower arm of the interferometer the data is directed away from the drop port. The amplitudes of the drop and through pulses are modified by the SOA gain saturation induced by the input data pulses thus pulse amplification and reshaping also occurs, i.e. the device functions as a 2R regenerator. If it is combined with optical clock recovery for retiming it will function as a 3R regenerator. Data can be added to the vacant time slot in the output data simply by sending the add channel data pulses to the add port.

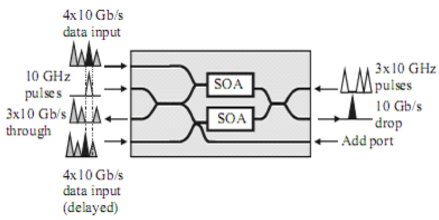

Figure 7: MZI Add Drop Multiplexer

Future high-speed WDM and TDM optical communication networks require high-speed optical switches (or gates) that can either be optically or electrically controlled. Such optical switches can be constructed using SOAs. The simplest method to control an SOA gate is by turning the device current ON or OFF. The great advantage of SOA gates is that they can be integrated to form gate arrays, such as 2 x 2 hybrid switch module shown in Fig. 8 [4]

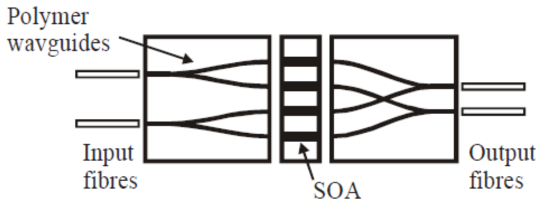

Figure 8: 2X2 hybrid SOA switch module

An incoming data packet can be routed to any output port by switching on the appropriate SOA. The switching time of a current switched SOA is of the order of 100 ps. Much faster switching times can be achieved using SOAs placed in non-linear loop mirrors as shown in Fig. 9.

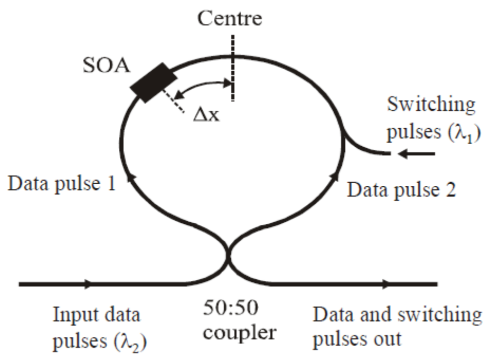

Figure 9: Optical Switch using TODA

Switching is achieved by placing an SOA offset from the centre of an optical fibre loop mirror and injecting data into the loop via a 50:50 coupler. The two counter-propagating data pulse streams arrive asynchronously at the SOA. A switching pulse is timed to arrive after one data pulse but just before its replica. The switching pulse power is adjusted to impart a phase change of π radians onto the replica, so the data pulse is switched out when the two counter-propagating components interfere on their return to the coupler. This device is also known as a TOAD (Terahertz Optical Asymmetric Demultiplexer) [4] because it can also be used to demultiplex high-speed TDM pulse streams.

6. CONCLUSION

SOA-MZI technology is capable of realising many of the all optical functions required in emerging optical networks. As optoelectronic integrated circuit technology advances and manufacturing cost fall, the use of SOA-MZI as a basic switch and as a component in functional subsystems will expand.

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