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Integrated Optics—Some Aspects

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ABSTRACT

Status of some key individual integrated optics components, their application in the field of telecommunications, integrated optoelectronic circuits, fibre optics sensors, optical interconnects and logic devices are highlighted in this paper. Possibilities of opto-opto processors in the computers field are also outlined.

1. INTRODUCTION

The field of integrated optics (IO) has been now active for more than 15 years with a number of institutions diverting more and more of their resources to this emerging area and forming new groups. The research got its main momentum from a basic conception to develop miniature optical components or their equivalents in planar form so that the size and power consumption is reduced, their performance and reliability improved and production guaranteed in larger numbers while functionally acting as replacement devices for electronic integrated circuits. As soon as it was realised that photons could be manipulated as has been the case with electrons, a new concept emerged where the aim was to use photons for all practical purposes including signal processing and making photonic circuits. The much superior performance, higher bandwidth (multi Gbit/s) and possibility of all optical circuits has now become the driving force to develop integrated optical circuits (IOCs) for almost all applications not only for communication but also for sensor development, signal processing, in parallel processing and utilization in the computer field.

Starting on a dull note, the field of IO grew somewhat slowly in the beginning but has now picked up following successful developments in fibre optics, material sciences and semiconductor devices to emerge as a technology of the future. The

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technology is not only based on new concepts but also calls for innovations in design, fabrication and material technology; for example, fabrication of source and detector on the same chip, design of waveguide bends, development of room temperature frequency-stabilized sources and increasing the level of optical component integration to result in an independent device utilizing multiplexers, sources, detectors, modulators, filters, etc. as the case may be on a single chip.

The list of IO devices so far successfully demonstrated is quite impressive and includes broad band phase/intensity/polarisation modulators, switches, muxers and demuxers, tunable filters, frequency shifters, polarisation controllers, switching matrices, etc. On the circuit side we have multifunction chips for sensors, integrated optoelectronic circuits (IOECs) for communication, real-time spectrum analysers, digital-to-analog and analog-to-digital (A/D) electrooptic converters, etc. In all the cases $LiNbO_3$ has been the first choice due to its excellent piezoelectric and electrooptic characteristics, ease of device fabrication and low loss of waveguides. The ultimate material, however, should be a semiconductor like *GaAs/GaAlAs* which can support (a) fabrication of detector as well source, (b) fabrication of high speed components, and (c) their integration with electronic components/circuits.

To begin with, it would be interesting to look at the status of some of the key individual IO components, for example :

Phase modulator : Operates at 1.3 μm wavelength with half-wave voltage ~ 6.2 V and a bandwidth of 5 GHz.

Mach-Zehnder interferometer : Operates at 1.3 μm wavelength with half-wave voltage of 11 V for an interaction length of 10 mm with a bandwidth greater than 20 GHz.

Directional coupler : For interaction length of 13 mm, wavelength 1.3 μm and drive voltage of 4.5 V, 3 dB, bandwidth reported is greater than 4 GHz. Directional couplers with 22 GHz equivalent bandwidth have also been reported.

Switching matrix : One of the switching matrices reported is 8×8 non-blocking type, having drive voltage of 30 V and is made up of 64 directional couplers of 2 mm active length.

Frequency shifter : Using concepts of transverse electric-transverse magnetic mode coupling via a synthetic propagating index wave, the frequency shift realised by applying multiphase signal to generate unidirectional coupling wave reported 90 per cent efficiency for 13 V for an optical bandwidth of 13 nm.

Tunable lasers : Using electrooptical tunable bandpass filter in conjunction to a *GaInAsP* laser diode single mode tunable emission of over 7 nm band has been reported.

2. APPLICATIONS OF IO DEVICES

2.1 Fibre Optics and Telecommunications

Fibre optics, because of its photonic character, is the first application area that attracted the workers to develop IO devices. This has been mainly because of the majority of IO components are single mode devices and hence there exists the potential of an immense bandwidth which could be exploited utilizing single mode optical fibres. Optical fibres are also the solution to the required input output connections for IO devices, though it is not yet an ideal solution. While the discrete planar components like intensity modulators, channel couplers, muxers, A/D converters can find direct applications, directional couplers and switching arrays can find applications in telecommunication networks to build complex network nodes with electrooptic control, in distribution rings, stars or exchange configurations. The technology of directional couplers can also be used for time division multiplexing and demultiplexing. This has been demonstrated to a bandwidth of serveral GHz and is comparable to the bandwidth of intensity and phase modulators. A bottleneck in A/D conversion also seems to be getting under control as IO 4/6-bit device operating at GHz sample rates, has been demonstrated.

2.2 Application of IOECs

The integrated optoelectronic circuits wherein optical and electronic functions are combined on the same chip is another area of importance and liklely to find applications in future systems for communication, instrumentation, sensor, data processing and optical computer interconnects. The idea in this case is to use the best of the integrated optics and integrated electronics available to improve the performance. Some of the telecommunication IOECs like integrated transmitter and detector have been demonstrated in the laboratory all around the world. One monolithic transmitter consisted of an *AlGaAs* laser integrated to *GaAs* Gunn oscillator, another is an integrated optoelectronic transmitter containing a multiple quantum well laser, monitor photodiodes and drive circuits, while still another is a transverse junction stripe laser integrated to 4 : 1 multiplexer (containing 36 NOR gates made up of approximately 150 *D*-mode MESFET) tested upto 160 MHz. These devices are yet in infancy.

Challenging areas of work include the following :

(i) Processing compatibility of optoelectronic and electronic components.

(ii) The threshold of laser diodes must be brought down and hence multiple quantum well lasers must be grown.

(iii) Combining the transmitter and receiver chip on a single substrate.

2.3 Applications in Fibre Optic Sensors

Fibre optic sensors is yet another area of IO device/component application and is poised for a relatively bigger market in the near future. The integration of IO devices with fibres has resulted in the successful development of many fibre optic sensors. Fibre rotation sensor or fibre gyro using a single mode fibre coupled to laser diode and detector via an integrated optics $LiNbO_3$ chip is now available commercially. The chip is used to couple, route, combine, phase modulate and polarisation control of a wave. The incorporation of IO in fibre gyro has given the opportunity of producing a practical device of high performance. Reports from several laboratories indicate that a waveguide microoptic gyro based on resonator principle may be developed in future. The technology is expected to integrate a laser diode, frequency shifters, drive circuits, waveguide ring, polarisers and 3 dB couplers on a single chip to facilitate the mass production using microcircuit technology.

2.4 Integrated Optics in Optical Interconnects

This application refers to free space optical interconnects and optical fibre interconnects in a high speed processor and computer, be it electrical or futuristic optical, to increase the throughput and speed by adopting parallel computing architecture, higher density of ICs and new computing architecture, The conventional electrical interconnects which have been pushed to the possible maximum get restricted due to their speed, area occupied, or capacitive loading effects.

Optical interconnects are best suited for data rates over and above 2 GHz and would help in reducing interconnecting pins by using optical data bus (optical fibre) to send multiplexed data. These fibre optic-integrated optics coupled transmitter/ receivers would also be suitable for (a) connecting distributed microprocessors separated by 1 km or even more, (b) connecting optical back planes within each processors to boards, (c) chip-to-chip interconnects, (d) CPU to memory on a board, and (e) board-to-board connection via multiplexing and demultiplexing the data.

These devices would use either a silicon or *GaAs* technology and would be at their best with *GaAs* devices provided optical coupling is improved. These will (a) outperform electrical interconnects, (b) need less volume, (c) be benefited from *GaAs* technology, and (d) be almost instantaneous in nature.

2.5 Integrated Optics Logic Devices

Optical transmission takes place at extremely high speeds. Reports from laboratories on two key components for high speed operation—the laser diodes and photo detectors—indicate that their operation even beyond 20 GHz would be possible in future. Thus we are ensured for high speed electrooptic (EO) and optoelectronic (OE) conversion. The state-of-the-art of optical fibres now promise link fibres of ultra low loss (0.18 dB/km @ 1.5 μm) and ultra high bandwidth (20-100 GHz) over a span of $\sim$ 100 km. It is therefore interesting to see what is holding up the true high speed device development.

At present signal processing is done in electronic domain since only electrical signal processing architecture is available. These devices have speed limitations of 1 Gbit/s for *Si* and 10 Gbit/s for *GaAs*. Since IO devices offer possibility of being operated as much higher speeds, these are very relevant for high speed signal processors with switching time $\sim$ picoseconds and switching energy $\sim$ picojouls; advantages of immunity from EMI, RFI and ground loop problem are of course the bonus features of IOCs. Logical operation in optical domain will enhance the system flexibility also because many EO and OE conversions would be eased out. While some of IO logic devices are almost ready for use at operations $\sim$ 1 Gbit/s, other devices having potential of being operated in sub-picosecond time with only picojoules of energy still require many years of research to become a reality.

Normal IO devices are operated in linear mode, but for logical operations its output must vary nonlinearly with input data; for example, for switching, gates, etc. This goal can be achieved by using any of the following phenomena.

(i) By applying electrical signals and using the electrooptic effect.

(ii) By conversion of coherent optical fields using a fast photo-detector.

(iii) By resorting to optically-excited material effects like Kerr effect, i.e., by forcing an index change via an intense optical field.

2.6 Electrooptic Effect Devices

These are now the most experimented devices since some materials like $LiNbO_3$ show large EO coefficient and waveguide fabrication methods have been almost perfected. In this case while the change in index is a linear function of applied electric field, the device is so biased that the output intensity is a nonlinear function of change of signal value. If input data is in the optical form, an overlay layer of appropriate photoconductor can be used to produce an electrical signal.

$\Delta\beta$ reversal switch and Mach-Zehnder interferometer have been the most sought-for configurations. The speed of these devices is limited by electrical drive circuit time constant. Switching speeds as high as 20 GHz have been demonstrated for $\Delta\beta$ switches. AND, OR, EOR, inverting and A/D conversion functions have been demonstrated successfully. 4/6-bit A/D converter operating at GHz sample rates has been reported by several laboratories.

Optical logic devices based on homodyne of coherent optical fields on a photo detector and conversion into electrical output have been tried out with the aim of producing optically-formatted input data devices. OR, inverter, EOR, etc. functions have been demonstrated the output depending on the phase relations of two fields.

2.7 Purely Optical Logic Devices

Less than a decade back it was realised that standard IO devices could take the advantage of nonlinear properties of optical waveguide material so as to be operated with optical signals both at input and output, without the need of any electronics support, thus the possibility of opto-opto processors. This thought was derived as a consequence of the following facts :

(i) Waveguide cross-sections involved in IO structures are small hence one can create high power density by using a moderate power source.

(ii) Propagation in waveguides is without diffraction losses.

(iii) Long, low loss interaction can be maintained to accumulate the phase shifts, hence high efficiency can be achieved.

(iv) Nonlinearity of μ with optical intensity at high power density can be taken into advantage.

The growing interest in these devices is due to the following facts :

(i) They can lead to opto-opto processors.

(ii) Their switching time (on/off) could be less than sub-picosecond depending on the material.

(iii) Switching can be done by using a different wavelength.

(iv) They can work with coherent/incoherent fields.

(v) They can be optically cascaded to form a chain of circuits using optical amplifiers wherever needed.

From theoretical point of view, almost all IO devices like the gratings, reflectors, directional couplers, Mach-Zehnder interferometers, and mode sorters have been analysed. Directional coupler is the most studied device since it is most suitable for switching matrices due to its four-port characteristic.

In case of small nonlinear changes in waveguide effective index, the performance is a function of accumulative phase shift. However, if the input fields are too large to disturb the low power index difference defining the waveguide structure, self focusing of a wave may occur as also the guiding characteristics may change and power may leave the device to be coupled to an adjacent guide.

The successful implementation of all these optical devices is totally dependent on the availability of proper nonlinear materials that will dictate the speed of the device, operating power, switched fraction of power, cascading stages and thermal characteristics of the circuit. *InSb* and *GaAs* seem to be the best materials at present at the wavelengths of interest. Nonlinear saturable absorption (absorption of material decreasing with intensity increase) can also be exploited for these devices.

2.8 Bistable Logic Devices

Bistable logic devices have received lot of attention because of their sub-picosecond switching speeds and very low power requirement. It basically consists of an optical element whose optical output is sampled and used as a feedback to alter the operating characteristics. These devices are of two types.

2.8.1 Extrinsic Bistable Devices

In this case the signal is generated by an optoelectrical converter and is applied appropriately on the device as a feedback. Since this artificial nonlinearity can be very high (several orders higher than intrinsic), these are quite efficient though circuit time constants reduce the speed of the device. Optical limiter, pulse shaper, optical triode, optical switch, differential amplifier and logics have been reported in $LiNbO_3$ waveguide structures with switching times < 50 nanoseconds at switching energies ~ 0.5 picojouls.

2.8.2 Intrinsic Bistable Devices

These utilize optically-induced feedback effects and most commonly use a nonlinear material between a Fabry-Perot cavity. The smallest successful device to date is a 4.9 μm thick *GaAs/GaAlAs* 61 layer quantum well structure showing a holding optical intensity ~ kW/cm^2 and was probed with a *HeNe* laser; rise time of 1 picosecond has been predicted.

2.9 Nonlinear Integrated Optics

Nonlinear mixing of optical beams has resulted into the generation of new frequencies by the interactions of two or more waves and experiments on phase conjugation, optical bistability and optical switching have been reported. The nonlinear interactions occur when optical beams propagating in a media are strong enough to produce polarisation of material fields. These polarisation fields radiate at frequencies other than input and the radiated power grows linearly with the propagation distance under optimum conditions of phase matching. Though almost all nonlinear interactions have been observed in bulk materials, their efficiency is poor (< 0.1 per cent at tens of mW input power). The waveguides are ideal medium for observing these effects since (a) large input powers can be maintained with small total output powers, (b) diffractionless propagation leads to long interaction lengths if waveguide losses are low, and (c) phase matching can easily be obtained using waveguide dispersion and modal dispersion characteristics.

Since these phenomena depend on nonlinear intensity dependence of refractive index via the third order succeptibility, materials suitable for making low loss stable waveguides are required.

Despite the difficulties of materials and fabrication of high quality waveguides, developments are still taking place world over. Second harmonic generation is the most studied phenomenon with the aim of producing coherent radiation in blue and ultra violet region. Frequency doubling experiments using 0.80, 1.06, 1.15 and 1.09 μm wavelengths have been successfully reported to conversion efficiency better than ~ 1 per cent at few mW powers. $LiNbO_3$ is generally the preferred material, but *GaAs* and some nonlinear organic materials have also been studied. These devices can be used for (a) second harmonic generation, (b) sum/difference frequency generation, (c) sum frequency generation with counter propagating waves, (d) degenerate four-wave mixing, and (e) coherent anti-Stokes Raman scattering (CARS).

These interactions have been used for the following experiments/signal processing applications.

(i) Picosecond transient digitizer based on the mixing of two counter propagating beams and observing the normally radiated field which is convolution of two input fields.

(ii) Bistable devices based on degenerate four-wave mixing in IO circuits.

(iii) Study of monolayers on surface using CARS.

(iv) Nonlinear directional couplers for optical logic using intensity-dependent refractive index.

(v) Gratings on thin films from intensity-dependent refractive index materials for optical logics, thus producing distributed feedback bistability.

3. CONCLUSION

In conclusion one can state that as a current and futuristic field, integrated optics is an area which will revolutionise, the twenty-first century outlook in science and technology and make the 'photon' do all that the 'electron' is doing at present, and much more, and at faster speeds. The relevance of the field to India is that it continues to be an 'intelligence intensive' rather than 'capital intensive' and could result in a much higher industrial return per rupee of the research and development investment.

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