INTEGRATED OPTICAL CIRCUITS

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ABSTRACT

This paper describes in detail the materials and fabrication processes demonstrated for integrated optics applications. The loss mechanism of integrated optical waveguides are also discussed.

1.0 INTRODUCTION

The field of integrated optics is devoted to the development of systems components for use in optical communications, instrumentation, signal processing and sensor applications. The fundamental waveguiding mechanism is achieved by total internal reflection in a similar manner to optical fibres. This requires the creation of a region with a higher refractive index than that of its surroundings. The small optical wavelengths mean that the guiding region will have dimensions typically of the order of a few microns. Control of the guided radiation requires the ability to induce local refractive index changes. This has been achieved via· electro-optic, acousto-optic and magneto-optic effects i.e. by the application of electrical, magnetic or acoustic energy. Of these the electro-optic effect is the most popular being relatively easy to control and efficient. Recent work on non-linear effects (i.e. refractive index dependent upon light intensity) has opened up the possibility of optical control and the prospect of all-optical logic.

There are two basic groups of materials in current use for integrated optical circuits; ferroelectric material (particularly lithium niobate) and the III-V semiconductors. At first sight of III-V semiconductor integrated optics appears to have a number of disadvantages; in particular a lower electro-optic coefficient than lithium niobate and a larger refractive index which will increase reflection losses at fibre/device interfaces. However, semiconductors offer the unique prospect of true integration on a single chip (monolithic integration) with sources, detectors and electronic components.

A study of III-V semiconductor devices can conveniently be broken into four distinct areas; electronic circuits (e.g. MESFET's), transducers (e.g. LED's lasers, APD's), guided wave devices and all optical components. This contribution is concerned principally with semiconductor guided optical wave devices but will also consider all optical devices involving guided waves. It is important to bear in mind the parallel advances made in the small scale integration of electronic devices and optical transducers i.e. in optoelectronic integration.

A study of semiconductors guided wave devices requires many problems to be addressed including the fundamentals of guided optical wave theory, semiconductor growth technology and microfabrication techniques.

2.0 THE MATERIALS

The ability to guide radiation in an integrated optical waveguide requires the effective refractive refraction index of the guiding region to be increased relative to that of its surroundings. In the Ill-V semiconductors this is most popularly achieved by a combination of geometry and material compositional or dopant changes although proton bombardment to reduce free carrier concentrations [1], ion implantation and strain-induced effects have also been utilised [2],[3].

The common starting point for fabrication was until few years ago a dielectric slab waveguide formed by the growth of an epitaxial n^- GaAs guiding layer on n^+ GaAs substrate.

The presence of free carriers in the substrate depresses the refractive index there resulting in a planar film of refractive index n_2 sandwiched between two regions with lower refractive indices n_1 and n_3 as illustrated in Figure 1.

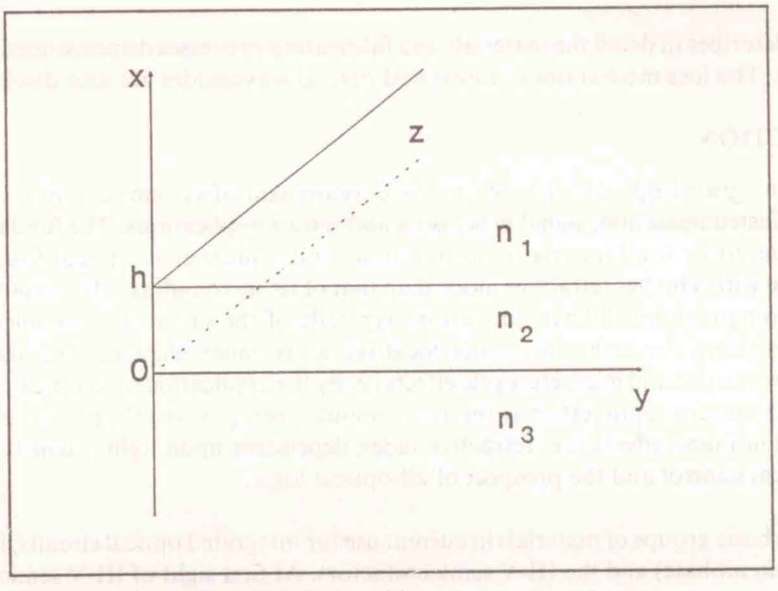

Figure 1: Generalised Slab Waveguide.

The simple geometry of this structure enables the finite number of guided modes and the infinite number of radiation modes to be found as solutions of Maxwell's equations subject to relative boundary conditions [4],[5].

A guiding (epitaxial) layer thickness of about $3\mu m$ is found sufficient to allow one propagating TE and one propagating TM mode [6]. The magnitude of the refractive index depression is relatively small $\triangle n = -3x10^{-3}$ for an operating wavelength of $1.3\mu m$ and a substrate doping density of $n = 10^{18}$ cm^{-3} [6].

If a metal Schottky electrode is deposited on to the epitaxial layer and reverse bias applied to it the epitaxial layer quickly becomes punched-through. A large electric field then fills the region under the electrode and for reverse bias voltage Vb greater than punch through the electric field in the epilayer is given to a good approximation by [7]

$$E_b(x) = \frac{V_b}{h} \tag{1}$$

For TE waves the refractive index change produced through the electro-optic effect by an electric field in the (100) direction is

$$\frac{+n_0^3 r_{41} E_b}{2}$$

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where r_{41} is the non-zero electro-optic coefficient in the reduced notation of Nye [18]. For GaAs $r_{41} = 1.4\text{x}10^{-12}\ \text{mV}^{-1}$. There is no electro-optic interaction with TM modes.

More recent attention has focused on GaAs/GaA1As heterostructure planar waveguides for the starting material. There are several reasons for this shift. n/n^+ GaAs devices show relatively high optical losses, due on the main to the presence of free carriers and the electrode metallisation in the vicinity of the guided radiation [6]. Further, the required switching voltages in n/n^+ devices are relatively high, often exceeding −30V.

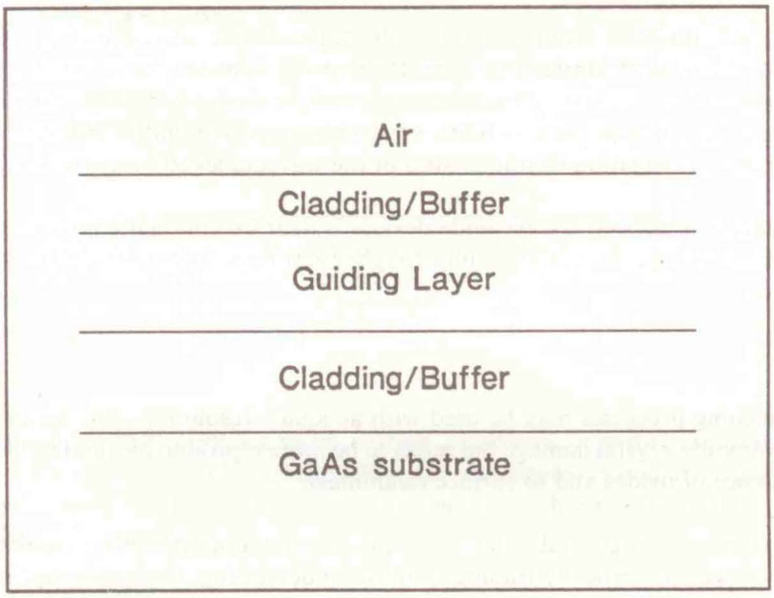

Figure 2: GaAs/GaAlAs Layer Structure Suitable for Waveguide Fabrication.

In GaAlAs the refractive index is depressed as the Al fraction x is increased [9]. The depression $\triangle n$ is = 0.4x. Planar optical confinement is considerably improved and losses can be minimised with the use of buffer layers. Further, it is the doping of the material which determines the profile of an applied electric field whereas compositional changes now dominate the refractive index profile. Thus the use of the heterostructure allows for reduced switching voltages. A typical GaAs/GaAIAs heterostructure used for waveguide fabrication is illustrated in Figure 2. The growth of this slice was realised by the MOCVD process and supplied by the SERC Gentral Facility at Sheffield.

The recent popularity of heterostructure devices is coupled to the development of MBE and MOCVD growth techniques capable of yielding large are slices of the desired composition (and which are not primarily ear-marked for laser/photodiode work!). The author would still recommend the characterisation of each wafer individually before processing.

Silica monomode optical fibres show low attenuation windows at 1.3μm (= 0.8 dB km^{-1}) and and 1.55μm (= 0.2 dBkm^{-1}) wavelengths with minimum material dispersion normally at 1.3μm. GaAs/GaAIAs devices could be utilised at these wavelengths. However, monolthic integration at these wavelengths calls for the use of quaternary (InGaAsP) or ternary (InGaAs) material grown on InP substrates. In work aimed towards this aim processing technol gies and much of the guided wave work has concentrated on n/n^+ InP material [10] [11] [12].

Integration of components is not simple and the material layers required for the different devices will often prove incompatitable. Thus the development of localised growth processes so that devices fabricated on different areas of the wafer can be optimised, may be necessary.

3.0 LATERAL CONFINEMENT (FABRICATION TECHNOLOGY)

Additional confinement so confining guided radiation to a pencil beam, is most popularly achieved by forming rib structures. These rib waveguides are formed by etching away parts of the substrate between mask line(s) formed photolithographically [13].

The popularity of ribs stem from a readily adjustable degree of confinement determined by their geometry, the ability to control fabrication precisely and the relatively easy extension to derive devices. Two problems addressed here are the etching processes and the analysis of the guiding which can no longer be performed analytically. It is required to define a waveguide shape with sufficient control and reproducibility to enable design for the propagation characteristics of the waveguides to be applied with confidence.

A particular feature of dielectric waveguide devices is their exceptionally large aspect ration (typically 1000:1). Good rib edge definition with minimum roughness is important. Lift-off techniques [14] help etch mask edge definition.

3.1 ETCHING

Both dry and wet etching processes may be used with adequate resolution. The former requires expensive equipment and may involve crystal damage but tends to be more reproducible than wet etching which proves sensitive to the presence of oxides and to surface cleanliness.

Wet chemical etching is in general either isotropic or crystallographically selective. An isotropic etch etches horizontally as well as vertically leading to mask undercutting. Crystallographically selective etches are useful but dry etching will be required for say waveguide sectional changes. Wet GaAs etches reported include $HCl : H_2O_2 : H_2O$ [15], $H_2SO_4 : H_2O : H_2O_2$ [16] and $H_3PO_4 : H_2O$ [17] systems.

Dry etching process technologies are described in [15] and [18]. Amongst those utilised for GaAs based waveguide formation are ion beam milling [19], reactive ion beam etching [21], ion beam assisted etching [21] and plasma etching. In general, greater selectivity may be obtained using R.I.B.E. with freon or I.B.A.E. with chlorine than with ion beam etching. However, although selectivity between mask and substrate is important etching is not in general required to be selective between the various heterostructure layers as it is rarely required to terminate an etch at a particular interface. Knowledge of etch rate for particular etching conditions is most important.

One point of note is that wet etched devices are found to have smaller reverse leakage current and higher breakdown voltages than similar ion beam etched ones. This may be due to damage [22] or edge effects being minimised by undercutting effects of the wet etchants.

With careful thought prior to fabrication, an etch mask formed using metallisation can subsequently form the control electrode so assuring self alignment. This is illustrated in Figure 3. It should be noted that electric bias field is largely confined to the unetched rib region so the effects of crystal damage should be minimised.

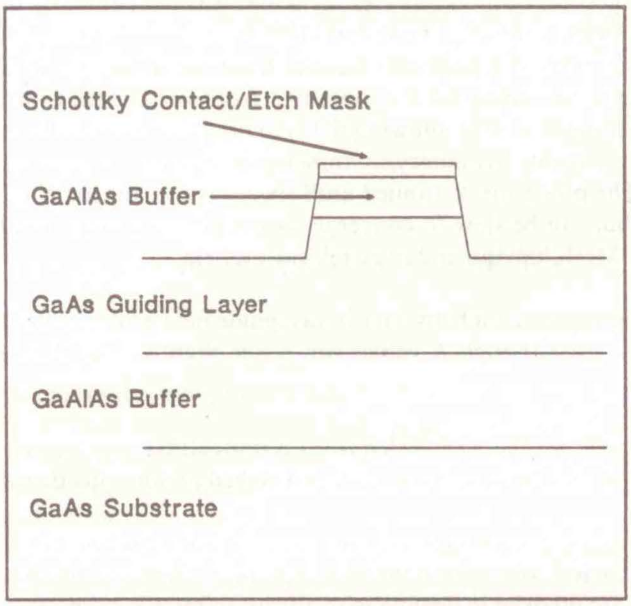

Figure 3: Schematic Diagram of a GaAs/GaAIAs Rib Waveguide Phase Modulator Structure with Self Aligned Electrode formed using the material of Figu↑O↑C.

The ion beam etching of InP produces much surface roughness, reported as being due to In cones [18]. R.I.B.E. with Ar_2/O_2 leaves smooth surfaces. For wet chemically etched InP ribs the use of HCl : H_3PO_4 system gives promising results when used in conjunction with an SiO_2 masking layer [12]. Other InP etches have also been investigated [23].

3.2 DESIGN AND ANALYSIS

An exact analytical solution to Maxwell's equation is not possible for rib structure and recourse must be made to approximate [24][25], or numerical analysis based on finite elements [26][27], the construction and optimisation of a series trial function [28] and finite difference techniques. This last approach is described in some detail here by means of illustration.

All solve the scalar TE wave equation

$$\frac{d^2E}{dx^2} + \frac{d^2E}{dy^2} + (k_0^2 n^2(x, y) - \beta^2)E = 0 \tag{2}$$

for a waveguide whose cross-section remains constant along its length. These are "quasi-TE" solution.

Rib waveguides offer many design opposabilities all attainable by altering the geometry and/or refractive index profiles. Common choices are tightly confined structures particularly useful for curved waveguide section [19], a structure tightly guided vertically but weakly so horizontally suitable for devices relying on the coupling between radiation in two or more guides fabricated in close proximity and relatively weakly guiding ribs offering good coupling to a monomode fibre [29] with typically a 5μm core diameter.

The finite difference method of solution replaces the scalar wave equation by finite difference relations in terms of fields at discrete mesh points E_{ij}. An initial guess is made for propagation constant and the E_{ij} and updated values of E_{ij} computed in a pagewise manner from the difference form of the wave equation [6][25]. After one or more scans an improved *B* is obtained from variational expression. Condition at oo are approximated either by setting $E = 0$ or allowing fields to decay exponentially at a "sufficient distance" determined by numerical experiment. Symmetry/asymmetry is invoked so only half the waveguide cross section need be considered. The process is continued until successive values for *B* agree to within a specified limit. The method is robust but can be slow to converge particularly if a large number of mesh points and a poor initial guess are used. Mesh halving and over-relaxation help.

Robertson et al found good agreement between rib waveguide field profiles calculated by finite difference and function fitting methods [29] although *B* values can differ slightly. The discrepancy is the subject of current interest.

Figure 4 shows guided mode profiles calculated using a finite difference technique for the fundamental quasi-TE mode in a GaAs/GaAIAs rib waveguide with two etched depths outside the lateral guiding region.

The accuracy of the finite difference method has recently been studied by its application to special waveguide structures with analytical solutions to the wave equation. These studies show excellent and versatile performance although errors are invoked in dealing with abrupt refractive index changes such as those found in rib walls [30].

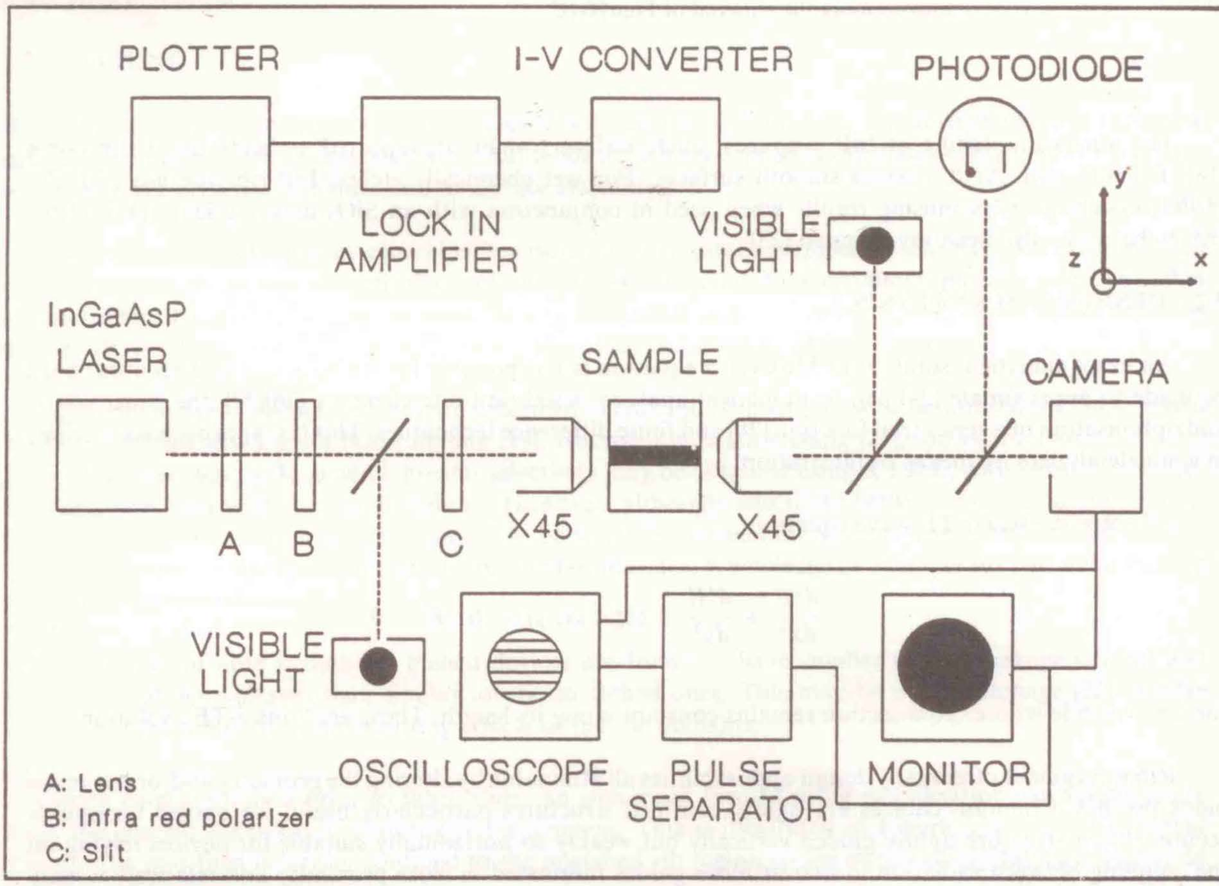

Figure 4: Block diagram of an Optical System suitable for the Evaluation of Discrete Integrated Optical Devices.

The analysis of waveguide section whose cross section varies along its length (e.g. a tapered waveguide or a Y junction) requires more complex analysis using, for example, a beam propagation method [31][32] which essentially models the scalar wave equation in a paraxial approximation and neglects the influence of the forward propagating beam.

4.0 DEVICES

4.1 GaAs/GaAIAs HETEROSTRUCTURE GUIDED WAVE DEVICES

(a) Low loss monomode waveguides.

Low attenuation is a required pre-requisite owing to the relatively long path lengths required (typically several millimetres). Several such waveguides have been reported [33] [34]. The simplest method of attenuation measurement is to compare transmission over a length of sample reduced by successive cleaving. A typical experiment arrangement is shown in Figure 5. Low losses are particularly difficult to assess by this method and accuracy is limited by the need of constant coupling to the waveguide from an external sources. Walker [33] suggests observation of resonances in the natural cavity formed by reflections from the cleaved sample ends as being particularly useful for low loss samples.

Recently reported semiconductor waveguide propagation losses have been in the range 1 to 2 dB cm^{-1}. As the fabrication procedures and material growth techniques become established, losses of < 1 dB cm^{-1} should become routine.

Suitably biased rib waveguides act as phase modulators and GaAs/GaAIAs have reported shifts of about 5° V^{-1}mm^{-1}, approximately twice that measured for n/n^{+} GaAs in the early 1980's [35].

(b) Directional couplers

The directional coupler switch provides for the modulation of radiation in a waveguide by the transfer of the guided light to a similar adjacent waveguide. When power is fed into a guide, all or a fraction of the power is transferred to the second waveguide because of coupling. The power exchange depends on interaction length, coupling length and phase mismatch. Coupling between parallel guides is constant and power fed into one guide will pass in a periodic manner from one guide to the other.

Analysis can be performed either by expressing the coupling of energy between individual primary guides (coupled mode approach) or by directly studying a structure consisting of the two guides as a composite using, for example, the finite difference method (normal mode approach) [36].

Complete transfer should occur with perfect synchronisation and an interaction length of one coupling length. Amongst problems to be addressed is that of cross talk, which recent work [37] suggests may arise even in a perfectly constructed device.

Switching between the two parallel waveguides can be achieved by destroying the phase synchronism of the coupled guides via the electro-optic effect. The (011) and (011) dependence of the sign of the refractive index change involved is interesting. The directional coupler switch proposed by Kogelnik and Schmidt [38,39] in which the sign of $\triangle \mathbf{B}$ is reversed midway along the sample length, allows for electro-optic control of the cross-over state (i.e. light at the output of the device is confined to the non-excited or coupled waveguide) for a broad range of sample lengths greater than L_c. This can only be achieved for a sample length of $(n + 1)\ L_c$ where n is an integer for normal biasing. In principle, both switches states can be achieved using reversed $\triangle B$ configuration but in practice, uniform biasing requires a lower value of $\triangle B$ to achieve eth straight through state [6]. Extinction ratios of between 14 and 20 dB have recently been reported for both states with and without recourse to $\triangle B$ electrodes. 10 V is a typical switching voltage. Published work suggests a 10 Gbit/s bit rate is feasible using such "lumped-parameter" devices.

Travelling wave electrode designs such as those already in use on $LiNbO_3$ guides may be the key to higher bit rates still [40]. The use of non-parallel coupled guides, asynchronous guides and multiple guide couplers provide interesting possibilities [41] [42][43].

For dielectric waveguides, the coupling lengths are typically many thousands of wavelengths (i.e. of the order of millimetres whereas the wavelength is around $1\mu m$). Wilkinson recently outlined the possibility of devices only a few wavelengths long as in microwave circuits using metal clad optical waveguides (CAPS) [44]. The dimensional tolerances called for are of the order of I0nm but this is feasible with state of the art electron beam lithography and reactive ion etching methods.

(c) Waveguide bends

In order to provide fibre coupling to a device such as a directional coupler, it is necessary to separate the two interacting guides buy at least $200\mu m$ away from the coupled interaction region. One way of avoiding this is to use curved waveguide sections. Such sections have been the subject of much practical [19] and theoretical study [45][46].

Rib waveguide bends require relatively large radii of curvature in order to keep radiation losses to an acceptable level. Abrupt directional changes allow for small displacement angles [47]. A very successful alternative is to reflect light guided in a single mode waveguide into an identical perpendicular guide using a vertical etched "totally reflection" mirror [48]. Right angled bends with losses as low as 1 dB have been achieved, using both wet chemically and dry etched mirrors. This limit may well be a fundamental one although mirror roughness is a contributing factor. Dry etching allows the technique to be extended to other angles.

(d) Y Junctions and interferometers

As already outlined the localised modification of refractive index by application of an electric field provides for phase modulation. This may be combined with equal power division by means of a Y junction with adjustment to the relative phase between the two arms. Subsequent recombination of the two arms at another Y junction gives rise to destructive or constructive interference depending on the relative phase and thus converts phase modulation. Switching voltages are about 7 V fpr 6 mm long electrodes [17]. Y junction quality is essentially for good performance.

4.2 InP BASED GUIDED WAVE DEVICES

The development of InP based waveguide devices lags behind GaAs based structures due in the main to a limited supply of material for development work. This situation should soon change however, with MOCVD and MBE techniques. InP based work suffers from a further disadvantage because Schottley contacts to the material prove leaky [6]. Oxidation helps [6][49] but its use does not lend itself to low switching voltages. Grown or diffused $p/n/n^+$ devices therefore appear to be the most promising for active InP devices. The electro-optic effect is similar in magnitude to [10][50]. InGaAsP/InP material will provide for lower optical losses and switching voltages in the same manner demonstrated for GaAs/GaAIAs heterostructures. Similar design procedures may be used.

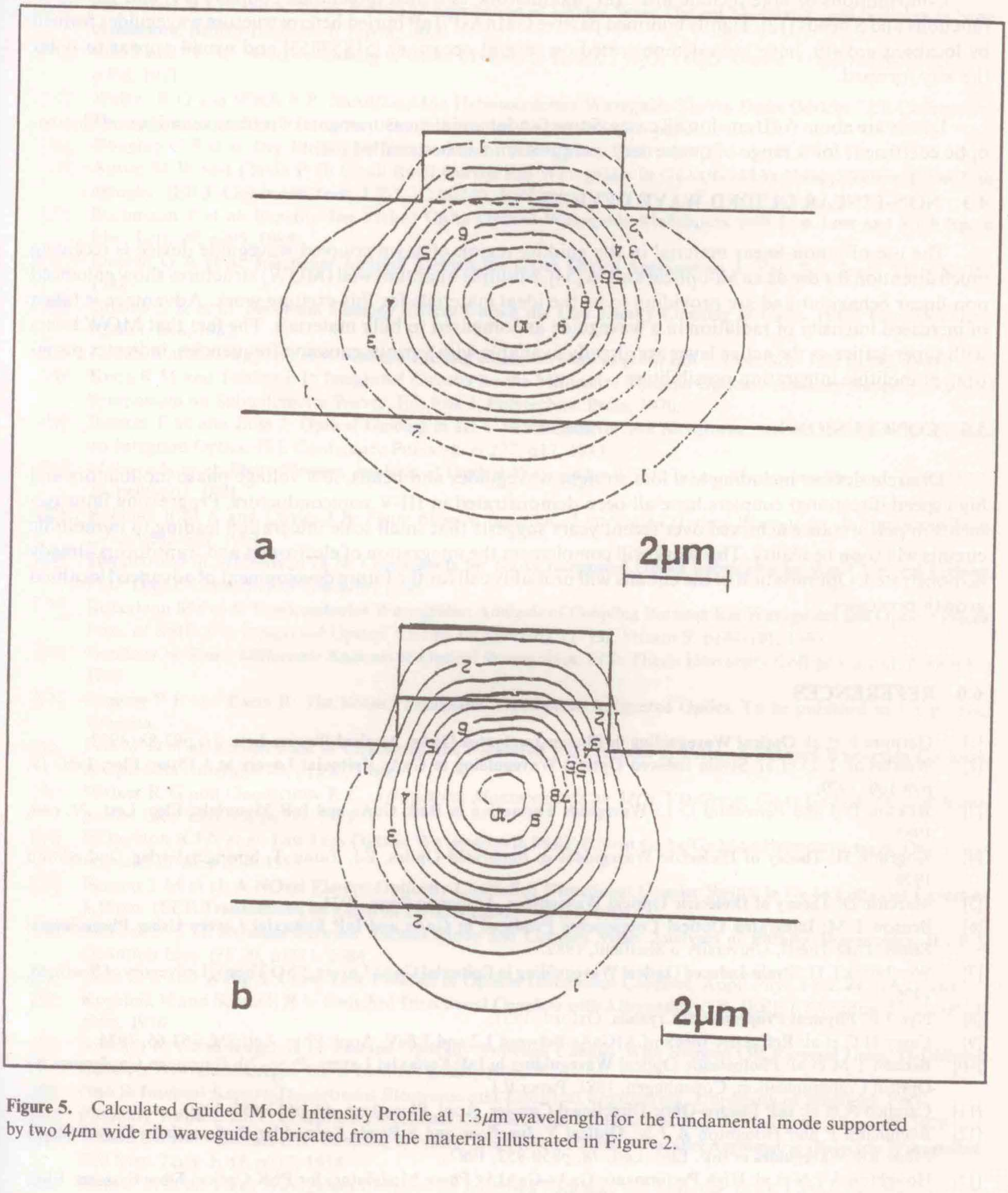

Figure 5. Calculated Guided Mode Intensity Profile at 1.3μm wavelength for the fundamental mode supported by two 4μm wide rib waveguide fabricated from the material illustrated in Figure 2.

Contributions of note include n/n$^+$ InP modulators, switched directional couplers [11] and passive Y functions and S bends [12]. Tightly confined passive GaInAsP/InP buried heterostructure waveguides formed by localised growth, have been demonstrated on several occasions [51][52][53] and would appear to point the way forward.

Losses are about 6 dB cm-1 in all cases. Some fundamental measurements of refractive index and electro-optic coefficient for a range of quaternary composition has been called for.

4.3 NON-LINEAR GUIDED WAVE DEVICES

The use of a non-linear material in the guiding region of say a coupled waveguide device is receiving much attention for use as an all-optical switch [54]. Multiple quantum well (MQW) structures show enhanced non-linear behaviour and are providing to be the ideal materials for this exciting work. Advantage is taken of increased intensity of radiation in a waveguide as compared to bulk materials. The fact that MQW lasers with super-lattice as the active layer are already available with various emission frequencies, indicates promising monolithic integration possibilities.

5.0 CONCLUSIONS

Discrete devices including low loss straight waveguides and bends, low voltage phase modulators and high speed directional couplers have all been demonstrated in III-V semiconductors. Progressing improvements in performance achieved over recent years suggests that small scale integration leading to monolithic circuits will soon be reality. This work will complement the integration of electronics and transducers already demonstrated. Optimisation of the circuits will probably call for the future development of advanced localised growth processes.

6.0 REFERENCES

[1] Garmire E et al: **Optical Waveguiding in Photon-Implanted GaAs**. Applied Physics Lett. *21*, p87-88, 1972.

[2] Westbrook L D et al: **Strain Induced Optical Waveguiding in GaAs Epitaxial Layers at 1.15μm. Elec. Lett.** *15*, p99-100, 1979.

[3] Jackson D J and Persechini D L: **Waveguide Formation in Bulk GaAs and InP Materials**. Elec. Lett. *21*, p44, 1985.

[4] Kogelnik H: **Theory of Dielectric Waveguides in Integrated Optics**. Ed. Tamir T, Springer-Verlag, 2nd edition 1979.

[5] Marcuse D: **Theory of Dielectric Optical Waveguides**. Academic Press, 1974.

[6] Benson T M: **Integrated Optical Components Produced in GaAs and InP Eoitaxial Layers Using Photoeleastic Effect**. PhD Thesis, University o Sheffieid, 1982.

[7] Westbrook L D: **Strain-Induced Optical Waveguiding in Epitaxial GaAs Layers**. PhD Thesis, University of Sheffield, 1979.

[8] Nye J F: **Physical Properties of Crystals**. Oxford, 1957.

[9] Casey H C et al: **Refractive Index of AIGaAs Between 1.2 and 1.8eV**. Appl. Phys. Lett. *24*, p63-65, 1974.

[10] Benson T M et al: **Photoelastic Optical Waveguiding in InP Epitaxial Layers**. Proc. 7th European Conference on Optical Communication, Copenhagen, 1981. Paper 9.1.

[11] Carenco A et al: **InP Electro-Optic Directional Coupler**. Appl. Phys. Lett. *40*, p653-655, 1980.

[12] Buchmann P and Houghton A J N: **Optical Y Junctions and S-Bends Formed by Preferentially Etvhed Single Mode Rib Waveguides in InP**. Elec. Lett. *18*, p850-852, 1982.

[13] Houghton A J N et al: **High Performance GaAs-GaAIAs Phase Modulators for PSK Optical Fibre Systems**. Elec. Lett. *20*, p479, 1984.

[14] Donzelli G P: **High-Yield Self Alignment Method for Submicrometer GaAs MESFETS**. Elec. Lett. *14*, p523-524, 1978.

[15] Houghton A J N and Rodgers P M: **The Fabrication of Guided Wave Optical Modulators and Switches in Semiconductors**. British Telecom. J. *1*, p78, 1983.

[16] Iida S and Ho K: **Selective Etching in GaAs Crystals in $H_2SO_4 : H_2O_2 : H_2O$ System**. J. Electrochem. Soc. *118*, p768, 1971.

[17] Walker R G and Webb A P: **GaAd/GaAIAs Heterostructure Waveguide Electro-Optic Devices**. IEE Colloquium-Towards Semiconductor Integrated Optoelectronics. Digest 1985/29, paper 1.

[18] Doughty G F et al: **Dry Etching for Semiconductor Waveguides**. Ibid, paper 8.

[19] Austin M W and Flavin P G: **Small Radii Curved Rib Waveguides in GaAs/GaAIAs Using Electron Beam Lithography**. IEE J. Lightwave Tech. LT-1, p236-240, 1983.

[20] Buchmann P et al: **Reactive Ion Etched GaAs Optical Waveguide Modulators with Low Loss and High Speed**. Elec. Lett. *20*, p295, 1984.

[21] Lincoln G A et al: **Ion Beam Assisted Etching for GaAs Device Applications** J. Vac. Sci. Tech. *20*, p786-789, 1982.

[22] Ghandi S K et al: **Ion Beam Damage Effects During the Low Energy Cleaning of GaAs**. IEEE Elec. Dev. Lett. EDL-3, P48, 1982.

[23] Adachi S and Kawaguchi H: **Chemican Etching Characteristics of (100) InP** J. Elec. Soc. *128*, p1342, 1981.

[24] Knox R M and Toulios P P: **Integrated Circuits for the Millimetre Through Optical Frequancy Range**. Proc. MRI Symposium on Submillimetre Waves. Ed. Fox J, Polytechnic Press, 1970.

[25] Benson T M and Buss J: **Optical Guiding in III-V Semiconductor Rib Structures**. Second European Conference on Integrted Optics. IEE Conference Publication *227*, p17, 1983.

[26] Mabaya N et al: **Finite Element Analysis of Optical Waveguides**. IEEE Trans. Microwave Th. and Tech. *MTT-29*, p600-605, 1981.

[27] Rahman B M A and Davies J B: *Finite Element Solution of Integrated Optical Waveguides*. J. Lightwave Tech. *LT-2*, p682-688, 1984.

[28] Summarised in Macfadyen D N: **Components for GaAs Integrated Optics Fabricated by Wet Chemical Etching**. PhD Thesis, University of Glasgow, 1980.

[29] Robertson M J et al: **Semiconductor Waveguides: Analysis of Coupling Between Rib Waveguides and Optical Fibres**. Proc. of SPIE *578*, Integrated Optical Circuit Engineering 11. Ed. Sriram S, p184-191, 1985.

[30] Dandacy N: **Finite Difference Analysis of Optical Waveguides**. MSc Thesis University College Cardiff, November 1985.

[31] Lagasse P E and Baets R: **The Beam Propagatinf Menthod in Integrated Optics**. To be pubished in J. Cpt. Soc. America.

[32] Feit M D et al: **Comparision of Calculated and Measured Performance of Diffused Channel-Waveguide Couplers**. J. Opt. Soc. Ameriaca *73*, p1296, 1983.

[33] Walker R G and Goodfeilow R C: *Attenuation Measurements on MOCVD-Grown GaAs/GaAIAs Optical Waveguides*. Eiec. Lett. *19*, ps590, 1983.

[34] HOughton A J N et al: **Low Loss Optical Waveguides in MBE Grown GaAs/GaAIAs Heterostructures**. Opt. Communication *46*, p1G4, 1983.

[35] Benson T M et al: **A NOvel Electro-Optically Controlled Directional Coupler Switch in GaAs Lpitaxial Layers at 1.15μm. IEEE Transactions on Electron Devices** *ED-19*, p1477, 1982.

[36] Marom E et al: **Relation Between Normal Mode and Coupled Mode Analyses of Parallel Waveguides**. IEEE j. Quantum Elec. *QE.20*, p1311, 1984.

[37] Chen K L and Wang S: **Cross Talk Problem in Optical Directional Couplers**. Appl. Phys. Lett. *44*, pl65, 1984.

[38] Kogelnik H and Schmidt R V: **Switched Directional Couplers with Alternating △R**. IEEE 1. Quantum Elec. *OE.12*, p396, 1976

[39] Schmidt R V and Kogelnik H: **Electro-Optically Switched Coupler With Stepped OR Reversal Using Ti-Diffused $LiNbO_3$, Waveguides. Appl. Phys. Lett.** *28*, ps503, 1976.

[40] Ono S: Internal Report, Department Electronic and Electrical Engineering, University of Sheffield, 1981.

[41] Findakly T and Chen C L: **Optical Directional Couplers with Variable Spacing**. Appl. Optics *17*, p 769, 1978.

[42] Wilson L 0 and Reinhart F K: **Coupling of Nearly Degenerate Modes in Parallel Asymmetric Dielectric Waveguides**. Bell Syst. Tech. J. *53*, p717, 1974.

[43] Haus H A et al: **Three Waveguides Couplers for Improved Sampling and Filtering**. IEEE J. Quantum Elec. *QE.17*, p2321, 1981.

[44] Wilkinson C D W and MacGregor C: **Metal Clad Optical Waveguides (CAPS)**. IEEE Colloquium – Electromagnetic Aspects of Optical Devices. Digest No. 1985/19, 1985.

[45] Yoneyama Y et al: **Bends In Nonradiative Dielectric Waveguides**. IEEE Trans. Microwave Th. and Tech. *MTT-30*, p2146, 1982.

[46] Kendall P C et al: **Rib Waveguide Curvature Loss: The Scalar Problem**. IEE Proc. J. *132*, p140, 1985.

[47] Taylor H F: **Power Loss at Directional Change in Dielectric Waveguides**. Appl. Optics *13*, p642, 1974.

[48] Benson T M: **Etched Wall Bent Guide Structure for Integrated Optics in the III-V Semiconductors**. IEEE J. Lightwave Tech. *LT-2*, p31, 1984.

[49] Wada O and Majerfeld A: **Low Leakage Nearly Ideal Schottky Barriers to n-InP**. Llec. Lett. *14*, p125, 1978.

[50] Tada K and Suzuki N: **Linear Electro-Optic Properties of InP**. Japan J. Appl. Phys. *19*, p11, 1980.

[51] Benson T M et al: **Single mode InGaAsP/InP Buried Waveguide Structures Grown on Channeled (111)B InP Substrates**. Elec. Lett. *18*, p812, 1992.

[52] Mikami O et al: **GainAsP/InP B.H Optical Waveguides at a 1.5μm Wavelength**. Llec. Lett. *19*, ps593, 1983.

[53] Bornholdt C et al: **Passive Optical GaInAsP/InP Waveguides**. Elec. Lett. *19*, p81, 1983.

[54] Li P Kam Wa et al: **All Optical Multiple Quantum Well Waveguide Switch**. Elec. Lett. *21*, p26, 1985.