Design of Deep-Etched, AlGaAs/GaAs Optical Waveguides with Reduced Fabrication Tolerance Sensitivity

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Abstract: Deep-etched GaAs/AlGaAs optical waveguides for use in integrated electrooptic devices were designed and simulated using the beam propagation method (BPM). Waveguides with a low fundamental mode loss (<0.1 dB/cm) but high second horizontal mode loss (>20 dB/cm) were achieved. This design is less susceptible to inaccuracies in the aluminium fraction in AlGaAs than other deep-etched waveguide designs. In practice it is difficult to accurately control the proportion of aluminium (value of x) in $Al_xGa_{1-x}As$ for low percentages of aluminium, hence this design will be easier to implement. Very small radius low-loss bends are simulated by BPM and low-loss multimode interference (MMI) structures are designed by the same method.

1. INTRODUCTION

Rib waveguides are commonly used for integrated electrooptic designs. The etch depth is normally shallow and the mode shape is therefore elliptical, being narrow in the vertical direction but broad in the horizontal direction, [1]. However, very deep-etched guides have recently been reported [2] which can have a more circular profile. Typical mode shapes for shallow- and deep-etched waveguides are shown in Fig. 1 and Fig. 2 respectively.

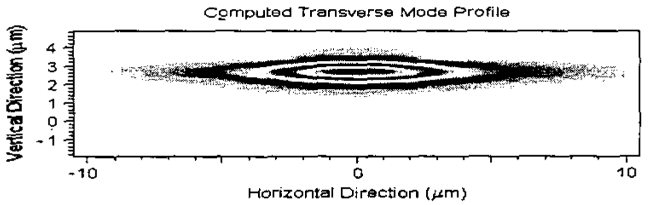

Figure 1: Mode profile for shallow-etched guide.

Whilst shallow-etched waveguides are relatively straightforward to design and implement, they have a number of disadvantages. Due to the weak horizontal confinement light can leak out at the sides so bend losses are often high. Coupling between the elliptical mode of the shallow-etched waveguide and the large, circular mode of a single mode fibre is difficult and the coupling loss is often very high. Finally, light is able to couple between waveguides so it is necessary to space waveguides and devices sufficiently so coupling does not take place. Small structures are therefore difficult to achieve.

Conversely, deep-etched waveguides have a more controllable mode shape so fibre to waveguide coupling is less lossy. The mode is very tightly confined so waveguides

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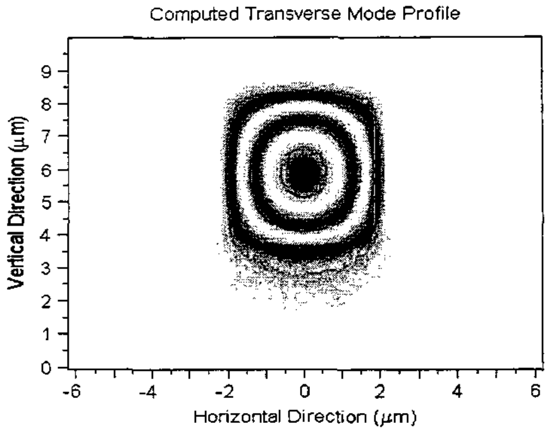

Figure 2: Mode profile for deep-etched guide.

can be placed very close together, leading to very compact devices. Bend losses may be very small and very tight bends can be designed. Finally, much smaller splitter/ combiner structures can be achieved.

The disadvantage of deep-etched waveguides is that they are more difficult to fabricate than shallow-etched designs. The waveguides analysed here are designed using GaAs/ AlGaAs epitaxial structures. One of the AlGaAs layers requires a much lower fraction of aluminium than is required for shallow-etched designs. In practice it is difficult to accurately obtain a low aluminium fraction by either MBE or MOCVD methods. A waveguide has therefore been designed that is less sensitive to the aluminium fraction in this layer and has a more simple epitaxial structure than previous waveguide designs. In addition, the design is less sensitive to the etch depth accuracy. A 90° bend, a multimode interference (MMI) splitter and a waveguide taper have also been simulated and the fibre-waveguide coupling loss has been investigated.

2. DEEP-ETCHED WAVEGUIDE DESIGN

Deep-etched waveguides support a number of modes. In order to achieve single mode operation it is necessary for the higher order modes to be lossy but the fundamental mode to have a low loss. The higher order modes leak into the substrate and are referred to as 'leaky-modes'. In the deep-etched designs presented by Heaton *et al.* [2] the guide is etched through the core and into the lower cladding layers, so that light is guided in the rib only. The guide consists of two lower cladding layers, the core layer, one upper cladding layer and a cap layer (Fig. 3). Lower cladding layer 1 controls the rate at which the light leaks from all the modes whereas lower cladding layer 2 acts as the mode filter. For the higher order modes to leak into the substrate they must have effective refractive indices lower than that of the second cladding layer. To reduce or increase the mode leakage the layer refractive indices or layer thickneses can be altered.

The designs formulated by Heaton *et al.* were analysed using the beam propagation method (BPM). This program calculated the propagation constant of the waveguides, from which the effective refractive index and loss for each guided mode was found. The effective index was given simply by the real part of the propagation constant and the loss was calculated from the imaginary part, using the formula [2]:

$$\text{loss} = 10^5\,\alpha\log_{10}(e) \quad \text{dB/cm} \tag{1}$$

where $\alpha=(4\times\pi)/\lambda$.

Heaton *et al.* designed and fabricated a range of deep-etched waveguides with lossy higher order modes but low fundamental guide loss. However, lower cladding layer 2

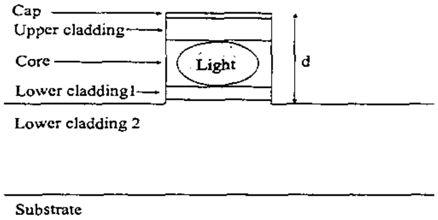

Figure 3: Schematic of a deep-etched rib waveguide. After [2]

required aluminium concentrations as low as 1% to obtain the small difference in refractive index which was required for this type of waveguide design. The effect of having an inaccurate aluminium fraction was to move the mode cutoff widths. This meant that to fabricate a guide with the required loss characteristics it was necessary to fabricate and measure a range of guide widths. The waveguide design was therefore not very reproducible.

3. WAVEGUIDE WITH REDUCED FABRICATION TOLERANCE

A new deep-etched waveguide was designed and simulated. The structure had a single lower cladding layer hence the epitaxial structure was more simple. The operation of the waveguide was predicted to be much less sensitive to the fraction of aluminium in this cladding layer than previous waveguide designs [2].

The core was GaAs and the upper cladding layer was AlGaAs with an aluminium fraction of 20%, which is high enough to enable accurate fabrication. Whilst the lower cladding layer still required a smaller aluminium fraction, simulations predicted that good operation would be achieved for an aluminium fraction between 6 and 9%. The thicknesses and concentrations of the epitaxial layers are listed in Table 1, and the waveguide structure is shown in Fig. 4.

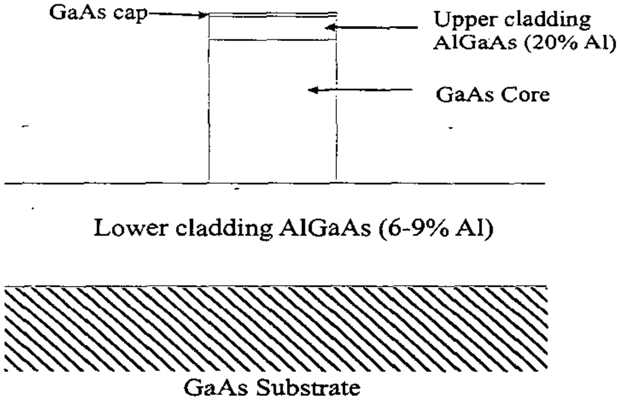

Figure 4: Structure of new waveguide design.

The operation of this design was compared to that of waveguide design B presented by Heaton *et al.* which has a similar rib width (2.2 μm). The losses in the fundamental and first horizontal modes were calculated for the two waveguide designs for different aluminium fractions in the lower cladding layer. The highlighted figures show the waveguide operation when the loss in the fundamental mode was less than 0.1 dB/cm and the loss in the first horizontal mode was greater than 20 dB/cm.

From the tables, it is clear the the new waveguide design has a very low fundamental mode loss and high TE_{10} mode loss for an aluminium concentration in the cladding layer

Layer	New Design
Cap Layer	0.1 μm GaAs
Upper Cladding	1 μm 20%
Core Layer	3.9 μm GaAs
Lower Cladding	3.4 μm 6-9%
Rib Width	2.4 μm
Etch Depth	5.0 μm ± 0.1 μm

Table 1: Design parameters of new deep-etched waveguide

Al fraction in lower cladding (%)	**TE_{00} mode loss (dB/cm)**	**TE_{10} mode loss (dB/cm)**
5	-0.396	-196.6
6	**-0.085**	**-123.2**
7	**-0.042**	**-85.0**
8	**-0.004**	**-55.9**
9	**-0.002**	**-27.3**
10	-0.011	-5.02

Table 2: Variation of waveguide performance with refractive index for the new design

of 6-9% However, waveguide design B only has good characterisitics for an aluminium fraction of 5%.

The computed mode size for this guide was 1.9μm in the horizontal direction and 3.5μm in the vertical direction. The simulated mode profile of the guide is shown in Fig. 5.

The new waveguide design required an etch depth of 5 μm ± 0.1 μm, whereas waveguide design B required an etch depth of 3.27 μm ± 0.05 μm. The etch depth accuracy for the new design was therefore required to be within 4% but that for design B required the etch depth to be within 1.5%, hence a greater etch depth accuracy was required for waveguide design B.

4. WAVEGUIDE TAPER

A further advantage of the new waveguide design was that it had a relatively large vertical mode size but narrow horizontal dimension. The mode would therefore be well confined and hence suitable for electrooptic devices. However, the horizontal mode size could be expanded easily by use of a lateral taper to reduce the fibre to waveguide coupling loss. A vertical taper is more difficult to design than a lateral taper.

A standard single mode fibre has a circular mode of approximately 9 μm. A taper was therefore designed to expand the horizontal waveguide dimension from 1.9 μm to 9 μm. The taper had a length of 500 μm and simultions were performed for an input mode with a width of 9 μm and varying mode hights. The results of these simulations are shown in Fig. 7 and the X-Z field pattern for the taper is shown in Fig. 6.

The lowest coupling loss is achieved for an input mode with a height of 4.3 μm as this has the best match to the height of the waveguide mode. In this case the predicted loss is

Al fraction in lower cladding 2 (%)	**TE_{00} mode loss (dB/cm)**	**TE_{10} mode loss (dB/cm)**
4	-0.223	-52.677
5	**-0.0315**	**-32.489**
6	-2.454	-55.6

Table 3: Variation of waveguide performance with refractive index for waveguide design B

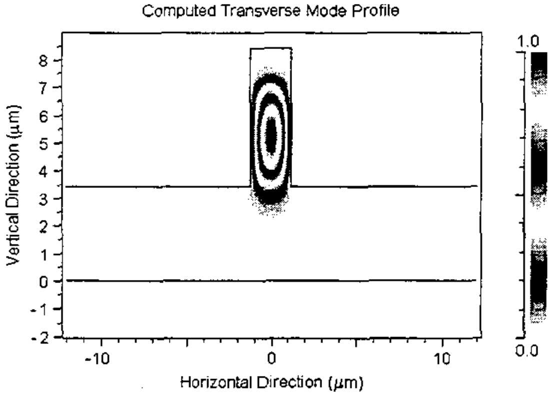

Figure 5: Mode profile for new waveguide design.

only 0.06dB. For an input mode with a height of 9 μm (i.e. similar to a single mode fibre mode profile) the predicted coupling loss was 1.3dB.

For a waveguide with no lateral taper, the coupling loss was predicted to be 5.4 dB when the input mode had horizontal and vertical dimensions of 9μm. This shows that even if the vertical mode dimensions are not matched, the simple lateral taper provides a great improvement in coupling efficiency for this waveguide, and relatively low coupling losses can be achieved.

5. BEND LOSS

Both the new waveguide design and design B had very low bend losses. A 90° bend with a 500 μm radius was simulated. The predicted bend loss for the new design was between 0.05 dB and 0.0007 dB, depending on the aluminium fraction in the lower cladding. The predicted loss for waveguide design B was 0.009 dB for an aluminium fraction of 5% in the lower cladding layer (optimised value).

The shallow-etched design was not capable of guiding light in such a tight bend. A 45° bend with a 50,000 μm bend radius was simulated for this design and was found to have an excess bend loss of 4.7 dB. These bend loss simulations show that much tighter low-loss bends can be designed for deep-etched waveguides than for shallow-etched waveguides.

6. MULTI-MODE INTERFERENCE DEVICES

Multi-mode interference (MMI) splitters and combiners are based on the principle of self-imaging. Self-imaging in slab waveguides was first suggested by Bryngdahl [3]. The principle of self imaging is as follows: an input optical field is reproduced in single or multiple images at periodic intervals along the direction of propagation of the waveguide. This guide must be wide enough to support a number of modes (generally greater than three [4]). The access waveguides are placed at the beginning and end of the length of waveguide. The output guides must be positioned at the point at which the required number of images are produced.

MMI 1 × 2 splitters have been designed for the new deep-etched design and for a shallow-etched design with an etch depth of 0.75 μm. It was found that the self-imaging interference pattern for the deep-etched design was more well-defined than that for the shallow etched guide. The light intensity patterns generated by BPM are given in Fig. 8 and 9. Fig. 8 shows the predicted power for an MMI device with the deep-etched waveguide design and Fig. 9 shows the power for a device with the shallow-etched design. It is clear that the areas of high light intensity are more closely confined in Fig. 8 than Fig. 9.

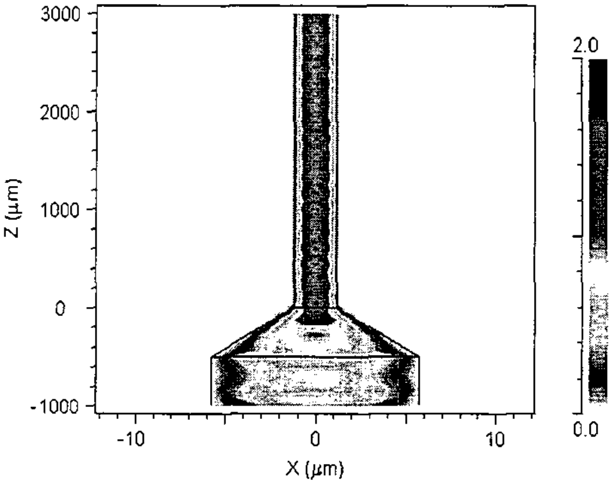

Figure 6: X-Z field pattern for simulated taper.

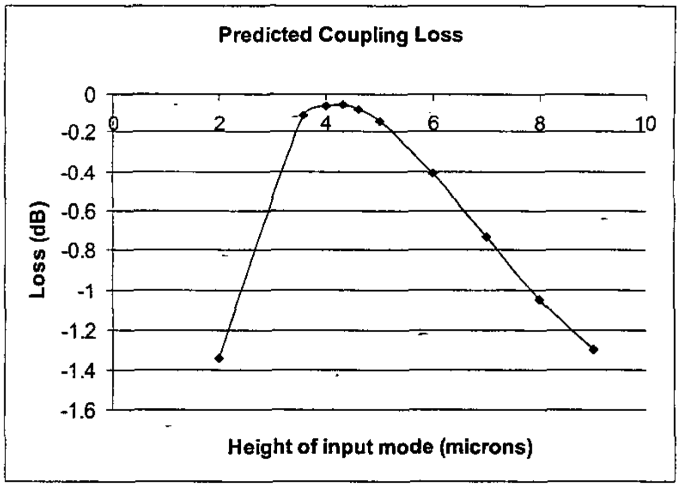

Figure 7: Predicted coupling loss.

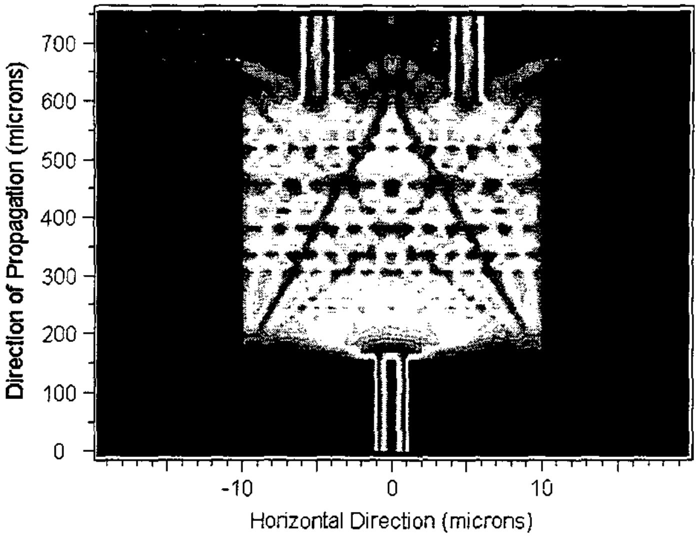

Figure 8: Predicted guided power in MMI device with new deep-etched waveguide design

Since the MMI splitter using the deep-etched design had a well-defined light intensity pattern it could be made very small. A device was simulated which had a width of only 10 μm and a corresponding length of only 111 μm. The power in each output waveguide was predicted to be 49% (-3.12 dB), corresponding to a 0.12 dB excess loss in each output guide. Conversely, the minimum size for the MMI splitter based on the shallow-etched design had a width of 40 μm and a corresponding length of 830 μm. The power in each output waveguide was predicted to be 45%, equivalent to an excess loss of 0.45 dB in each output guide.

A major advantage of using deep-etched waveguides for MMI designs is that the devices can be made very small. Although the output waveguides will be very close together there will not be coupling between the guides as the modes are very tightly confined. For shallow-etched waveguides in which the mode is weakly confined in the horizontal direction care must be taken to separate the waveguides sufficiently to ensure that coupling does not occur.

7. CONCLUSIONS

It has been shown that deep-etched waveguides have a number of important advantages over shallow-etched guides. However, deep-etched guides are difficult to fabricate because low aluminium fractions are required in the lower cladding layer. It is difficult to accurately achieve the low aluminium fractions by fabrication methods such as MBE or MOVPD. A waveguide has therefore been designed whose operation is much less sensitive to the fraction of aluminium in the lower cladding layer. This design should allow repeatable waveguides to be fabricated. The guides will have excellent bending loss properties and allow more compact devices to be fabricated. Finally, by implementing a lateral taper it will be possible to achieve low fibre to waveguide coupling losses.

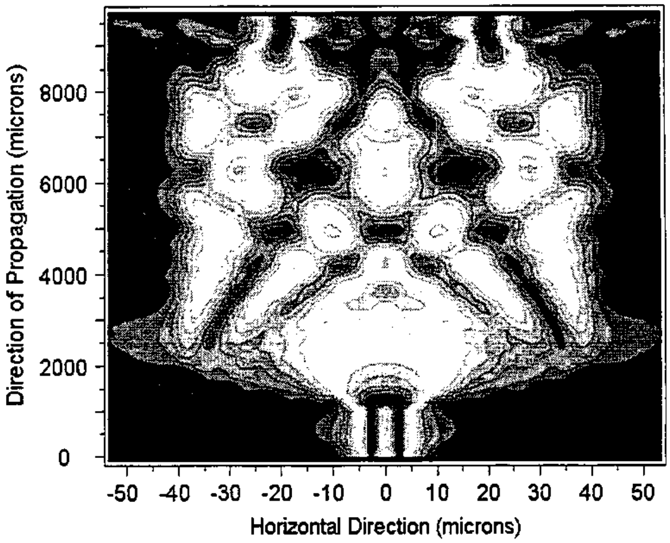

Figure 9: Predicted self-imaging pattern in MMI device with shallow waveguides.

ACKNOWLEDGEMENT

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REFERENCES

[1] M. W Austin, "Theoretical and experimental investigation of GaAs/GaAlAs and n/n+ GaAs rib waveguides," *J. Lightwave Technol.*, vol. LT-2, no. 5, pp. 688–694, 1984.

[2] J. M. Heaton, M. M. Bourke, S. B. Jones, B. H. Smith, K. P. Hilton, G. W. Smith, C. H. Birbeck, G. Berry, S. V. Dewar, and D. R. Wight, "Optimization of deep-etched, single-mode GaAs/AlGaAs optical waveguides using controlled leakage into the substrate," *J. Lightwave Technol.*, vol. 17, no. 2, pp. 267–281, 1999.

[3] O Bryngdahl, "Image formation using self-imaging techniques," *J. Opt. Soc. Amer.*, vol. 63, no. 4, pp. 416–419, 1973.

[4] L. B. Soldano and E. C. M. Pennings, "Optical multi-mode interference based devices based on self-imaging: principles and applications," *J. Lightwave Technol.*, vol. 13, no. 4, pp. 615–627, 1995.