Low-loss, single-mode GaAs/AlGaAs waveguides with large core thickness

A.D. Ferguson, A. Kuver, J.M. Heaton, Y. Zhou, C.M. Snowden and S. Iezekiel

Abstract: Low-loss, single-mode waveguides with a large core thickness have been designed and fabricated in gallium arsenide/aluminium gallium arsenide waveguides. Detailed beam propagation method simulations were carried out to investigate the modal properties of the waveguides and were compared with measured results. For lengths of 2 cm, insertion losses of $\leq$3.5 dB were achieved when coupled to conical lensed fibre. This demonstrates a simple method of achieving minimal coupling losses without the need for complex structures such as waveguide tapers. In addition, the propagation loss was measured to have a low value of 0.2 ± 0.09 dB/cm.

1 Introduction

Gallium arsenide/aluminium gallium arsenide (GaAs/AlGaAs) rib waveguides are useful for many optical and electro-optical devices such as switches, modulators and filters. Many of these devices are required to be single mode. However, efficient coupling between an optical fibre and a single-mode GaAs/AlGaAs waveguide is difficult to achieve and it is often necessary to resort to waveguide tapers to reduce the coupling loss. This paper describes a simple method to obtain a single-mode GaAs/AlGaAs waveguide that has a fundamental mode with dimensions well matched to that of the optical fibre.

Rib waveguides in GaAs/AlGaAs are usually designed to have a core thickness <1 μm in order to obtain single-mode operation. However, it has been suggested that single-mode waveguides with core thicknesses of several micrometres can be achieved if the dimensions of the waveguide are chosen carefully [1]. In the literature, both Si/Ge/Si and Si/SiO_2 thick-core waveguides have been analysed [1] and Si/SiO_2 waveguides have been realised [2, 3]. The relationship between the waveguide dimensions to ensure that the higher-order horizontal modes (e.g. the TE_{10} mode) are cut off is given as [1]:

$$\frac{a}{b} \leq C + \frac{r}{\sqrt{1 - r^2}} \quad (1)$$

where the dimensions refer to those in Fig. 1, C is the correction factor and $r \geq 0.5$. This formula was derived by Soref *et al.* [1] using results from mode-matching techniques given by Petermann [4]. Here, the numerical correction factor is given as 0.3. However, Pogossian *et al.* [5] proposed a correction factor of zero in order to give a more conservative design and stated that the effective index method is a better method of designing these thick-core waveguides than using (1). These two approaches will be compared with reference to the fabricated GaAs/AlGaAs waveguides described in this work, which have been analysed using the beam propagation method (BPM) [6].

It is found for these waveguides that the higher-order modes in the vertical direction (e.g. the TE_{01} mode) leak laterally into the rib-side regions and will therefore not propagate [1]. This will occur if the effective refractive indices of the modes are lower than the effective refractive index of the fundamental mode of the slab waveguide in the etched regions outside the waveguide rib. The effective refractive indices of the modes have been simulated for different etch depths and the results are given in Section 2.

Finally, the modal properties of the fabricated GaAs/AlGaAs waveguides have been measured and are discussed in Section 3. In addition, the insertion losses when the waveguides are coupled to conical lensed fibre have been measured, and the waveguide propagation losses have been measured using the Fabry–Perot method.

2 Design and simulation

A set of waveguides with the cross-section in Fig. 1 were designed. The thickness ($2b\lambda$) of the GaAs waveguide core was chosen to be 4 μm, making it suitable for a range of integrated waveguide applications. The lower cladding was AlGaAs with an aluminium fraction of 30% and the thickness of this layer was 1.5 μm.

The correlation BPM method was used to determine whether the higher-order modes would be supported. The correlation method is slower than the imaginary distance BPM but has the advantage that it is more applicable to leaky-mode problems than the imaginary distance method.

A three-dimensional waveguide model was set up, which allowed the waveguide width and etch depth to be varied. The refractive indices of the layers were calculated using the formulae given by Gehrsitz *et al.* [7] and were found to be 3.374 for GaAs and 3.214 for AlGaAs with an aluminium fraction of 30%. Gehrsitz *et al.* present data for the refractive index of AlGaAs to wavelengths below the bandgap of AlGaAs.

Once the model was set up, a fibre mode was launched into the waveguide model. This was offset in the horizontal direction in order to excite the higher-order horizontal modes. The computed step sizes and propagation lengths

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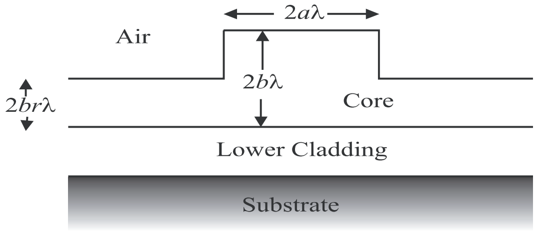

Fig. 1 *Cross-section of the thick-core waveguide*
Modified from Soref *et al.* [1]

were adjusted in order to achieve 'convergence' of the simulation. The simulation was taken to have converged when physically realistic modes were found, for example, when the modes were not asymmetrical. In order for convergence to be achieved, it was necessary for the waveguide model to have a length >10 mm. The modes were identified by considering their shapes. For example, the TE_{10} mode has two lobes separated at the centre of the waveguide rib. Table 1 lists the guide geometries that were found to support the TE_{10} mode for etch depths of 1.1 and 1.5 μm.

The higher-order vertical modes were also analysed, again using BPM. In this case, a fibre mode was launched into the waveguide model with a vertical offset in order to excite these 'leaky' modes. The rate of loss of the higher order horizontal and vertical modes could be estimated from the imaginary effective refractive index for the mode using the following equation [8]:

$$\text{loss} = 10^5 \alpha \log_{10}(e)\, \text{dB/cm} \quad (2)$$

where $\alpha = (4\pi n_{imag})/\lambda$ and n_{imag} is a predicted value.

The loss of the TE_{01} mode was found to be very high (nearly 300 dB/cm for an etch depth of 1.5 μm). However, this was difficult to simulate accurately, as the effective refractive index of the mode varied with the boundary conditions of the simulation. In this simulation, the horizontal dimension used was ± 23 μm. The TE_{01} mode leaking laterally into the regions surrounding the waveguide rib is shown in Fig. 2.

To analyse the operation of the waveguide in more detail, the effective indices of the TE_{10} and TE_{01} modes were simulated for different waveguide widths (Figs. 3 and 4). For a waveguide with an etch depth of 1.5 μm, the effective indices of the TE_{20} and TE_{02} modes were also simulated. In addition, the effective refractive index of the fundamental mode of the slab waveguide region (the region outside the rib) was calculated. It was predicted that a mode would not be supported if its effective refractive index was lower than that of the fundamental mode of the slab region, as it would leak laterally into this region. To support this prediction, the loss of the TE_{10} mode was calculated from (2), using the imaginary effective refractive index found using BPM. For the waveguide with an etch depth of 1.5 μm

Table 1: GaAs/AlGaAs rib waveguides

Width (μm)	Etch depth (μm) 1.1	1.5
3	•	•
4	•	•
5	•	×
6	•	×

•, does not support TE_{10} mode
×, supports TE_{10} mode

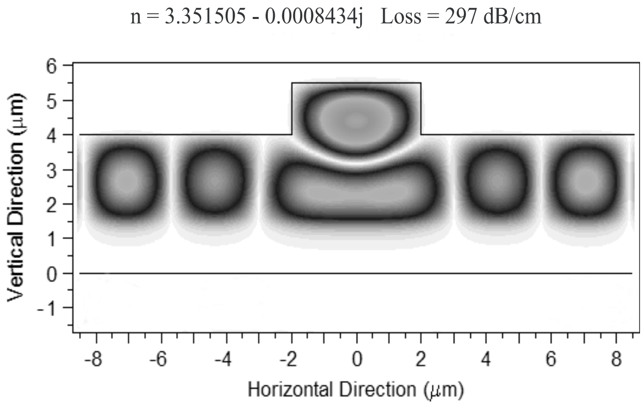

Fig. 2 *BPM simulation of the field intensity of the TE_{01} leaky mode, with the peak at 0 μm in the horizontal direction*

and width of 4 μm, the imaginary refractive index was -0.0005558, giving a very large loss of 195 dB/cm.

From Fig. 3, it can be seen that the effective refractive index of the TE_{01} mode lies well below that of the fundamental mode of the waveguide slab region, and hence this mode will be very leaky, as was predicted from the imaginary refractive index of this mode (Fig. 2). According to the figure, the effective refractive index of the TE_{10} mode becomes equal to that of the fundamental mode of the slab region when the waveguide width is 5 μm. It is therefore predicted that this mode will be cut off when the waveguide width is <5 μm, therefore providing further evidence that guides with widths of 3 and 4 μm and an etch depth of 1.5 μm will not support this mode (Table 1).

The effective index of the TE_{20} mode lies below that of the TE_{10} mode. Its effective refractive index was computed for waveguide widths ≥ 7.5 μm. For a waveguide width of 7.5 μm, its effective refractive index is below that of the fundamental region. However, for smaller waveguide widths, this mode was not found to be supported by the waveguide; hence, here it is assumed that this mode is cut off. In addition, for a waveguide width of 7.5 μm, the loss

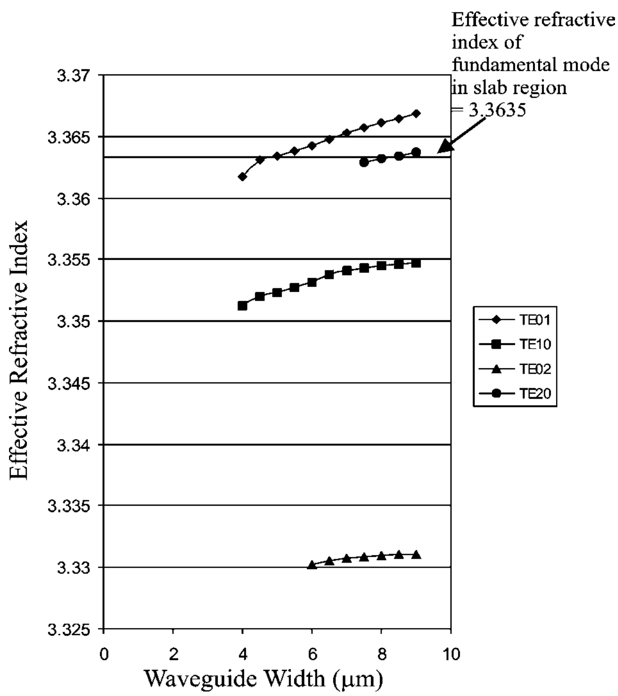

Fig. 3 *Predicted values of the effective refractive indices for the TE_{10}, TE_{01}, TE_{20} and TE_{02} modes against waveguide width for a guide with an etch depth of 1.5 μm*

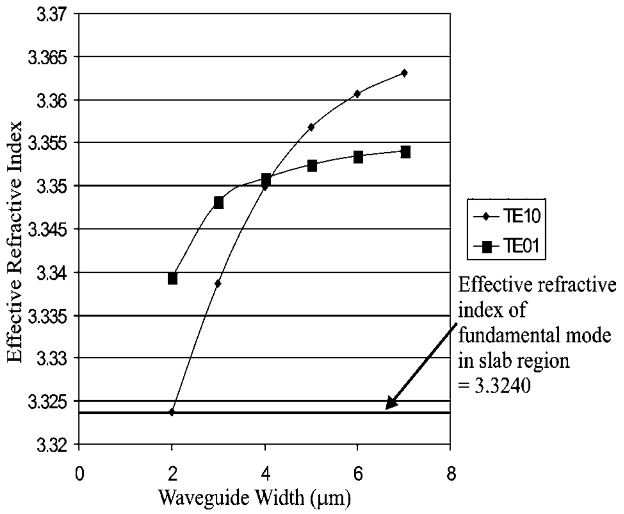

Fig. 4 *Predicted values of the effective refractive indices for the TE_{10} and TE_{01} modes against waveguide width for a guide with an etch depth of 3 μm*

of the TE_{20} mode was calculated from the imaginary refractive index to be 30 dB/cm, which is a significant loss.

A waveguide with an etch depth of 3 μm was also analysed (although these guides were not fabricated) and again the predicted effective refractive indices of the TE_{10} and TE_{01} modes were plotted against the waveguide width (Fig. 4). Here, the TE_{10} mode would be cut off when the waveguide width was <2 μm. However, the TE_{01} mode would be supported over the range of waveguide widths, as its effective refractive index lies above the effective refractive index of the slab region. This analysis shows that it would be difficult to obtain single-mode waveguides with large etch depths for this type of waveguide.

For both the waveguide with an etch depth of 1.5 μm and the waveguide with an etch depth of 3 μm, the effective refractive index of the TE_{10} mode crosses the line of the slab mode effective refractive index when the rib width is exactly twice the dimension of the GaAs core in the etched region, that is, $2 \times 2br\lambda$. In Fig. 3, the value of $2br\lambda$ is 2.5 and the TE_{10} mode becomes cut off at 5 μm. In Fig. 4, the value of $2br\lambda$ is 1 μm and the TE_{10} becomes cut off at 2 μm.

Therefore an approximate formula giving the cut-off point of the higher-order horizontal modes may be stated as follows

$$2a\lambda \leq (m+1)2br\lambda \qquad (3)$$

hence

$$\frac{a}{b} \leq (m+1)r \qquad (4)$$

where m is the mode number.

The mode shapes and sizes were simulated for the different geometries. The fundamental modes for the guides with a width of 4 μm and etch depths of 1.1 and 1.5 μm are given in Fig. 5.

It is clear that the fundamental mode for the guide with an etch depth of 1.5 μm is more confined in the horizontal direction than that for the guide with an etch depth of 1.1 μm. The predicted $1/e$ mode widths are 4.6 and 6 μm, respectively, and the predicted mode heights are 3.2 and 3.1 μm, respectively.

It is stated by Soref *et al.* [1] that a 'square' aspect ratio of $a/b = 1$ will produce a nearly circular profile, as required for efficient coupling to a conical lensed optical fibre.

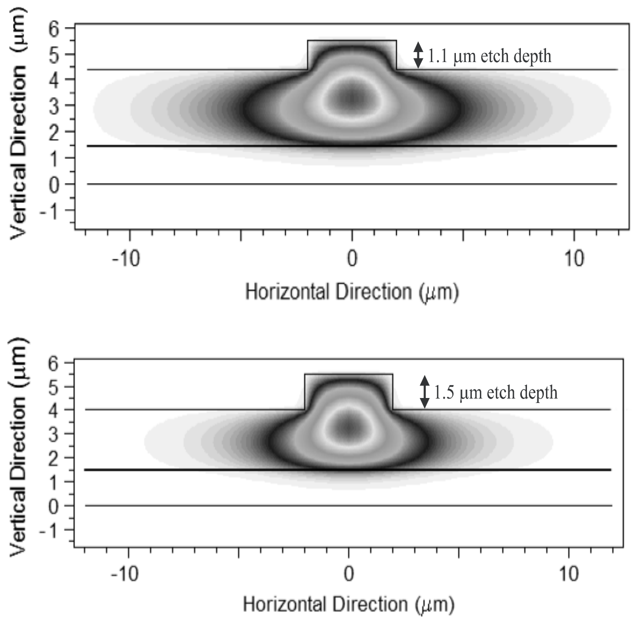

Fig. 5 *BPM simulation of the field intensity of the fundamental mode of a guide with a width of 4 μm and an etch depth of 1.1 μm and a guide with a width of 4 μm and an etch depth of 1.5 μm*

However, by considering Fig. 5, it can be seen that choosing the maximum waveguide etch depth (while retaining single-mode operation) is also important in order to obtain the most circular mode.

3 Experimental results

Sets of waveguides with widths of 3, 4, 5 and 6 μm and etch depths of 1.1 and 1.5 μm were fabricated. The material was grown by molecular beam epitaxy, and a reactive ion etch (dry etch) process was used to form the waveguides, yielding rib guides with smooth, straight sidewalls. A picture of a waveguide facet is given in Fig. 6. The waveguide cross-section was produced using a focused ion beam (FIB) system and then the sectioned sample was imaged using a scanning electron microscope. It can be seen from the figure that there is some re-deposited material on the top of the facet, and vertical lines can be seen extending from the guide sidewalls. This occurred because the FIB

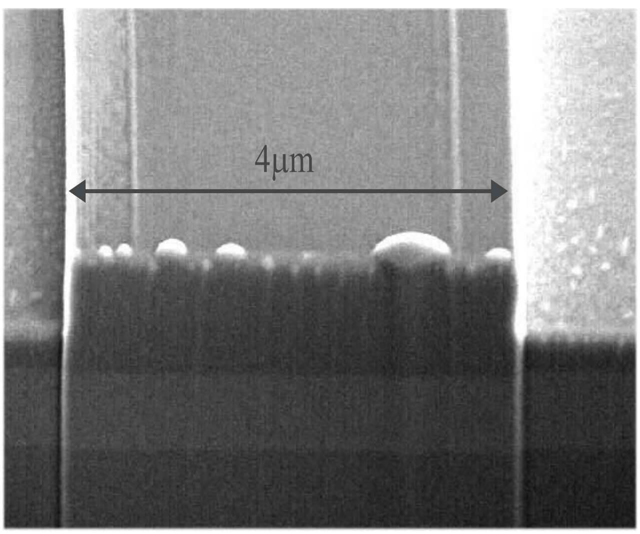

Fig. 6 *FIB picture of a waveguide facet*

system was used to produce the cross-section, which involved material removal by ion bombardment. However, more damage is likely to be caused to the sample if the cross-section is produced manually.

A single-mode fibre was used to launch TE-polarised light with a wavelength of 1.55 μm into the waveguides from the tunable laser source of an Agilent 8164A lightwave measurement system. Between 5 and 15 waveguide samples were measured for each waveguide geometry, and the results were found to be very consistent. The input was offset vertically, horizontally and at an angle to the sample in order to excite the higher-order modes. As predicted, the TE_{10} mode was supported for the guides with an etch depth of 1.5 μm and widths of 5 and 6 μm. The modes were observed using a Hamamatsu C2741-03 infrared vidicon camera and controller and captured using frame-grabbing software. Figure 7 shows the measured and simulated TE_{10} mode for the 1.5 μm etch depth, 5 μm width guide. If the high field intensity parts of the simulated mode are considered, then the placement of the lobes is similar to those of the measured result.

In order to observe the vertical modes, very short lengths of the waveguides (<3 mm) were cleaved. However, the vertical modes were not observed for any of these waveguides. The most likely explanation for this is that the leakage of the vertical modes is so rapid that it is not detected even after relatively short distances. It was therefore concluded that the waveguides that did not support the TE_{10} mode operated as single-mode guides. From the simulations, the estimated leakage for the TE_{10} mode for a waveguide with a width of 4 mm was 195 dB/cm, which is equivalent to a loss of nearly 60 dB over a 3 mm length, which would be very difficult to detect.

The insertion losses were measured when the waveguide input and output were coupled to a conical lensed single-mode fibre. These lensed fibres had dimensions well-matched to the waveguide mode. A calibration was first made by connecting an optical fibre to bypass the conical fibres and the waveguide sample. This eliminated the other losses in the measurement system, for example, losses in the fibre connectors. Using the tunable laser source, the power through the device was measured over a range of wavelength intervals. This enabled the Fabry–Perot resonances to be observed. A typical plot of the transmitted power for wavelengths from 1550 to 1551 nm, at 0.001 nm intervals, is given in Fig. 8. The amplitude of the resonances was found to be consistent across a wide range.

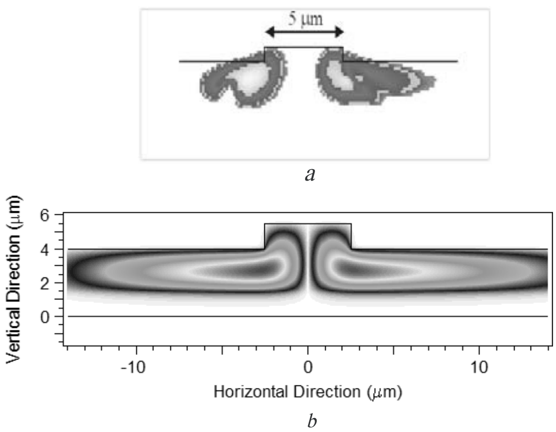

Fig. 7 *Images of the TE_{10} mode with a waveguide width of 5 μm and an etch depth of 1.5 μm*

a Measured
b Simulated

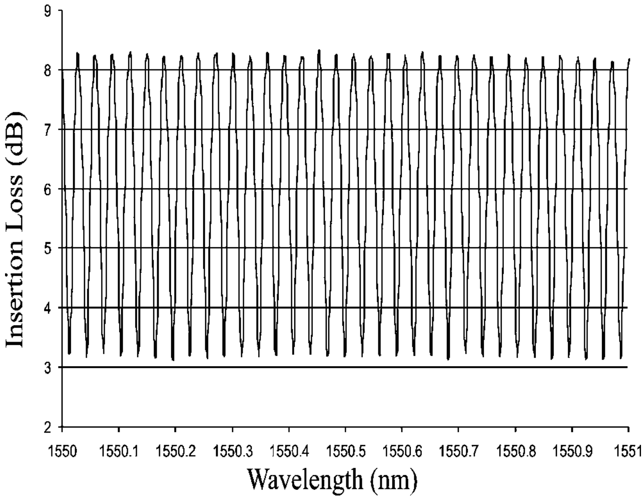

Fig. 8 *Measured power through a waveguide with an etch depth of 1.5 μm and a width of 4 μm*

The waveguides were not anti-reflection coated, therefore reflection from the end facets affected the insertion loss measurement. For this waveguide, the maximum and minimum insertion losses were 3.1 and 8.3 dB, respectively, for a length of 11.1 mm. If the end facets of the waveguide were anti-reflection coated, it is therefore predicted that the waveguide insertion loss would be 3.1 dB or slightly better. For a waveguide length of 20 mm, the best measured insertion loss was 3.0 dB.

The lowest insertion loss (for a single-mode guide) was measured for the waveguide with an etch depth of 1.5 μm and a width of 4 μm. This was attributed to the fact that its fundamental mode profile was the closest to being circular and would therefore achieve a good match to a conical lensed optical fibre. A comparison of the measured fundamental modes of a guide with an etch depth of 1.1 μm and a guide with an etch depth of 1.5 μm is shown in Fig. 9. The figure shows that the mode of the guide with an etch depth of 1.5 μm is better confined and is therefore more circular than that of the guide with an etch depth of 1.1 μm. This result was predicted by the BPM simulations, showing the importance of designing the waveguide to achieve a mode profile with the most circular shape possible.

The propagation loss was measured using the Fabry–Perot method. As with the insertion loss measurement, the power through the waveguide was measured at intervals of 0.001 nm and the maximum and minimum transmitted powers were found. To find the waveguide propagation loss, the following equations were used [9]:

$$K = \frac{T_{\max} - T_{\min}}{T_{\max} + T_{\min}} \tag{5}$$

$$\ln\left[\frac{1 - \sqrt{1 - K^2}}{K}\right] = \ln R - \alpha l \tag{6}$$

Fig. 9 *Measured images of the fundamental modes for rib widths of 4 μm*

The image on the left is for an etch depth of 1.1 μm and that on the right is for an etch depth of 1.5 μm

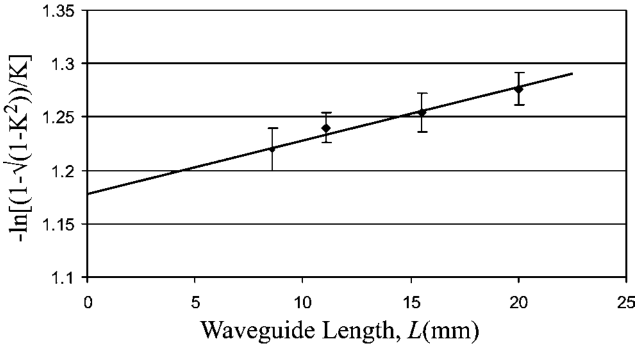

Fig. 10 *Fabry–Perot measurements for four different waveguide lengths*

where T_{max} and T_{min} are the maximum and minimum transmitted powers, respectively, R the facet reflectivity, L the waveguide length and α the propagation loss per centimetre.

Repeating the measurement for four different waveguide lengths and plotting the left-hand side of (6), the reflectivity and loss of the sample were determined. This is given in Fig. 10. The value of reflectivity was found to be 0.308 ± 0.013, and the propagation loss was 0.2 ± 0.09 dB/cm. The low propagation loss was attributed to the high quality of the material growth and waveguide fabrication. The surface roughness is estimated to be much less than 25 nm rms on the side walls and less than 15 nm rms on the top surface.

4 Correction factor for single-mode operation

The correction factor, C, in (1) was given as 0.3 by Soref *et al.* [1]. However, a modified value of zero was proposed by Pogossian *et al.* [5]. In this paper, GaAs/AlGaAs thick-core waveguides have been designed using BPM. Using the waveguide dimensions that were found (both by simulation and experimentally) to produce single-mode guides, this correction factor has been investigated.

The waveguide with an etch depth of 1.5 μm and a width of 4 μm was single mode. Substituting values for r and a/b into (1) shows that the value of C should be >0.2. However, the 5 μm waveguide with this etch depth was found to be multimode. Again, substituting the geometrical parameters into (1), it is found that C must be <0.45 for the formula to show that this would be a multimode guide. The value of 0.3 suggested by Soref *et al.* would therefore be a reasonable value to use in this case.

All the waveguides measured with an etch depth of 1.1 μm were found to be single mode. Substituting the values into (1) for a guide width of 6 μm, it is found that the correction factor should be >0.45.

Therefore if the correction factor of 0.3 had been used in the design of the waveguides with an etch depth of 1.5 μm, the maximum waveguide width would have been estimated to be between 4 and 5 μm. Simulating the waveguides, the maximum waveguide width was also found to be between 4 and 5 μm. However, in the case of the waveguides with an etch depth of 1.1 μm, the maximum waveguide width would have been estimated to be between 5 and 6 μm if the correction factor of 0.3 had been used. In practice, a waveguide with a width of 6 μm was found to be single mode. Alternatively, if a waveguide with a width of 6 μm had been selected, its maximum etch depth would have been calculated to be 1.0 μm using the correction factor of 0.3. This would not have allowed the etch depth to be maximised and would have resulted in a less tightly confined waveguide mode.

It is difficult to apply a single correction factor to all waveguide geometries: the required correction factor will vary depending on the waveguide geometry. This investigation shows that the empirical approach to the design of these waveguides is limited and that a numerical approach such as BPM provides a more efficient design method.

5 Higher order TE_{n0} modes with $n > 1$

Recent work by Lousteau *et al.* [10] predicts that for some rib waveguide structures, higher order TE_{n0} $(n > 1)$ are guided with low loss; therefore the waveguides are effectively multimode. However, simulations of the TE_{20} presented here (4) predict that this mode is more leaky than the TE_{10} mode. In addition, measurements have shown that single mode waveguides are achieved when the TE_{10} mode becomes leaky. Therefore in this case at least, it seems that single-mode waveguides can be achieved by consideration of only the TE_{10} mode.

6 Conclusions

Very low-loss thick-core GaAs/AlGaAs waveguides have been demonstrated. They have been analysed in detail using BPM and the measured results compare well with the simulations. BPM has been shown to be a more efficient method of designing these waveguides than simply using (1). It is very important that the waveguide should have as great an etch depth as possible before the guide becomes multimode. This ensures that the mode is as tightly confined as possible (and therefore has a smaller horizontal dimension), which improves the coupling efficiency to cleaved single-mode fibre and to conical lensed fibre.

This work has demonstrated that the method used to achieve thick-core Si/SiO_2 single-mode waveguides is also valid for thick-core GaAs/AlGaAs waveguides. The thick-core design presents a simple solution for low-loss coupling to single-mode optical fibre. In addition, the propagation loss of the guides has been found to have a very low value of 0.2 ± 0.09 dB/cm.

Finally, single-mode waveguides with a large core thickness have been simulated extensively using BPM, and the results compared with empirical approaches. The validity of these approaches has been studied and discussed. The cut-off points of the higher order horizontal and vertical modes have been investigated by predicting their effective refractive indices, and an approximate formula for estimating when the higher-order horizontal modes will become cut off has been suggested.

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