Optimization of Optical Characteristics of Travelling Wave Modulators

by

Steven Hung-Che Lin

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Abstract

The advent of electro-optic modulators has made possible the conception of many high-speed optical devices and systems. Unfortunately, these modulators generally have intolerably high insertion loss which reduces their throughtput and makes them impractical to use. In this work, an integrated GaAs optical waveguide has been fabricated and is butt-coupled to a single-mode fiber to reduce the high coupling loss that typically exists in using bulk optic components. Theoretical calculations have been carried out to characterize the fiber-to-waveguide coupling. They show a maximum of 69% coupling efficiency is possible if single-mode operation is to be maintained in the waveguide. Experimental results show that a maximum of 70% (1.55 dB coupling loss) fiber-to-waveguide coupling has been achieved. To our knowledge, 1.55dB is the lowest number ever reported in the literature for fiber-to-GaAs ridge waveguide coupling loss. The propagation loss of 2 dB/cm is also comparable to the lowest number reported for GaAs waveguides. Furthermore, this is the first attempt to demonstrate that the use of single-mode fibers for input coupling to GaAs ridge waveguides is realizable and definitely promises a great potential to make a high throughput, low driving voltage, high bandwidth and reliable electro-optic modulator in the future.

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Finally, I'd like to thank my mother, Enid, and my sister, Sai-Sen, for their love and support for the last 22 years. Without them, my dream of attending MIT would not have become a reality.

To

my mother, Enid

&

my sister, Sai-Sen

Table of Contents

Abstract 2

Acknowledgements 3

Chapter 1 Introduction 7

1.1 Why Single-mode Fibers ? 11

1.2 Why GaAs Ridge Waveguides ? 15

Chapter 2 Review of Previous Work 17

Chapter 3 Theory 21

3.1 Single-mode Fibers 23

3.2 Single-mode GaAs Channel Waveguides 29

Chapter 4 Modelling - Gaussian Approximation 41

Chapter 5 Experiments and Results 55

Conclusion 73

Appendix A Computer Program Listing - Fibers 75

Appendix B Computer Program Listing - GaAs Waveguides 88

References 112

Chapter 1

INTRODUCTION

The development of low-loss integrated optical devices and low-loss coupling between these devices is required before the many proposed applications of integrated optical systems can become practical and usable. Most research in the past on travelling wave modulators has ignored these vital points, instead emphasizing device performance characteristics such as high bandwidth, compactness, low driving voltage, and modulation depth. Although these are important parameters of an electro-optic modulator, the insertion loss of such a modulator, which comes from the propagation loss in the device itself as well as the input and output coupling losses, has been so high that the system performance has been largely impractical. Furthermore, the use of bulk optic components, such as quarter-wave plates, polarizers, and microscope objectives has introduced more losses into the system and thus degraded the performance of the system even more. For example, an input power of few milliwatts from the laser typically produces an output power, measured after the modulator, on the order of hundred microwatts, which is useless for most practical system applications.

Despite the compact size of the modulator, the whole system, which is illustrated in Fig. 1, may be large in size and inflexible in structure. The problems of mechanical alignment and stability are also disadvantages that result from the use of bulk optic components.

In the last few years, single-mode fibers butt-coupled directly to the facets of a modulator have been proposed as a replacement for bulk optics. The coupling efficiency and mechanism, which depend on how well the modes in single-mode fiber and in channel waveguide overlap spatially, will be described in detail in this thesis.

With the exception of custom-made fibers, fibers of different parameters are limited and difficult to obtain. Therefore, channel waveguide will have to be designed such that the waveguide is single-moded and its modal field best overlaps the fiber modal field.

Chapter 1 provides a general background of the problem concerned and proposes a new scheme to overcome such problem.

Chapter 2 reviews the previous work on this problem. The results are presented and compared.

Chapter 3 shows the detailed theoretical analyses of the fiber mode and waveguide mode. The eigenvalue equation for the single-mode fiber is solved analytically to obtain the field and intensity profile of the fundamental mode propagating in the fiber. The effective index method is applied to the strip-loaded GaAs waveguide. With some reasonable assumptions and

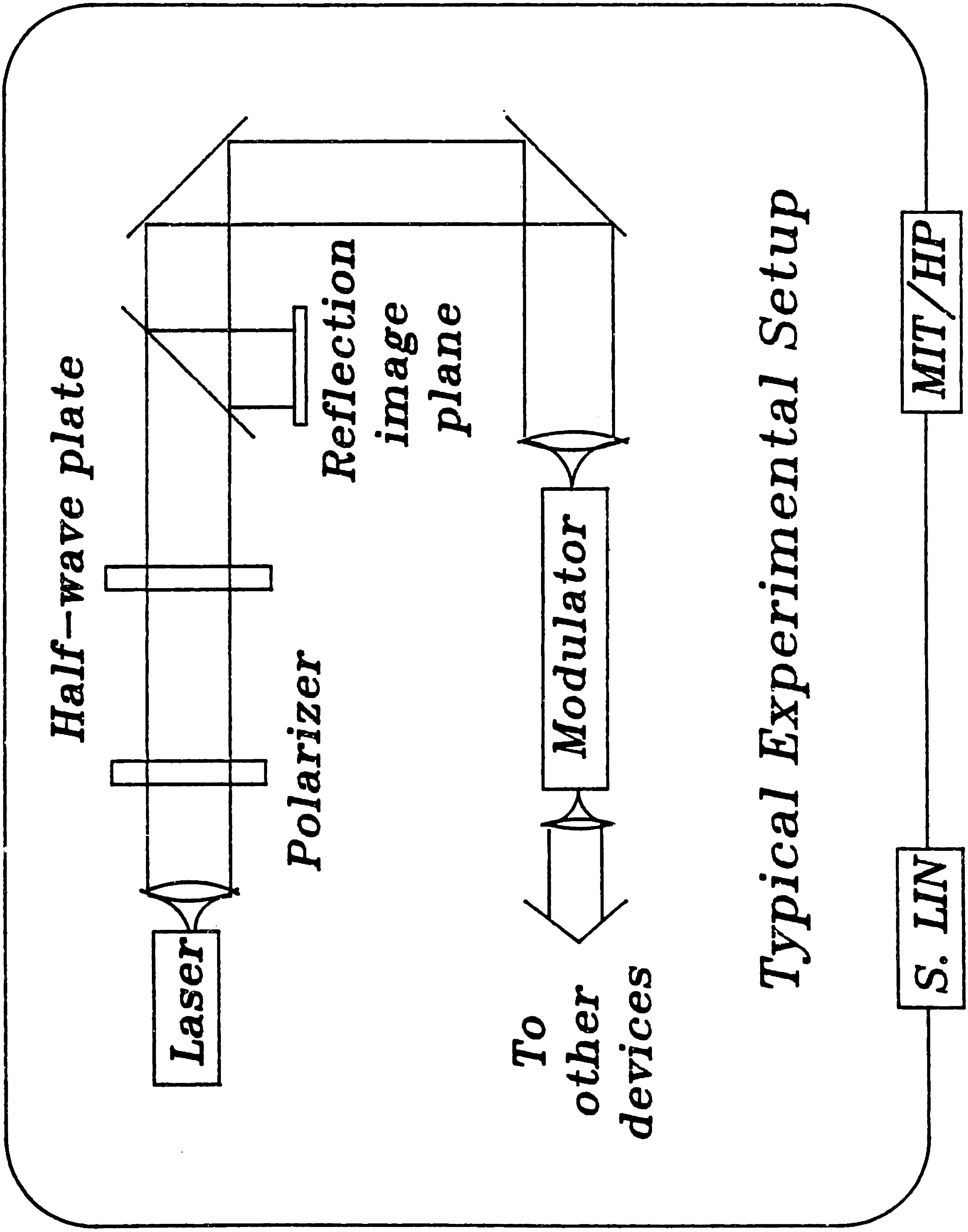
Half-wave plate
Polarizer
Laser
Reflection image plane
Modulator
To other devices
Typical Experimental Setup
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Figure 1

approximations, the field and intensity profile are also obtained for the fundamental mode of the waveguide.

Chapter 4 deals with applying the gaussian approximations to the fiber and waveguide modes found in chapter 3 and explains the advantage and procedure of such approximations. The issues of coupling efficiency and alignment tolerances are also addressed based on the gaussian approximations.

Chapter 5 describes the actual experiments. The setup, instruments used, calibration procedures and data obtained are presented. The data are compared against the theoretical predictions to check the validity of the theoretical model and justify why under certain conditions this model would fail. The design and the experimental results of the optimal waveguide are described. Some of the trade-offs of such a design are also discussed.

Appendices A and B list the computer programs which are used to design the optimal waveguide. It is menu-driven and comments are given throughout the program listings in detail to aid the reader in understanding the programs.

1.1 Why Single-mode Fibers ?

Because there are many disadvantages in using bulk optic components to couple the light into the waveguide, interest in replacing these bulk optic components with a single-mode fiber has increased tremendously. There are basically 6 reasons to justify the use of a single-mode fiber.

1) Loss
2) Alignment and stability
3) Packaging
4) Flexibility
5) Pigtailed laser
6) Development of in-line fiber optic components

The first, and also one of the most important reasons, is the issue of loss in the system. With the low-loss property of single-mode fiber available commercially nowadays, propagation loss between the laser and the waveguide can be reduced to a minimum. Compared with bulk optics, losses due to microscope objectives, polarizers and quarter-wave plates have been eliminated. In addition, the propagating mode in the single-mode fiber has a very well defined and stable mode shape. Consequently, waveguides can be designed to best match this fiber mode thus reducing the coupling loss.

Fiber also offers the advantage of easy alignment by simply butting the fiber to the waveguide facet followed by some minute adjustment to optimize the waveguide output intensity. However, tremendous efforts are required if one uses a lens to couple the light into the waveguide, particularly for infrared light, because it is difficult to determine whether or not the light is hitting the waveguide facet perpendicularly. Furthermore, due to lens imperfections, the focusing beam entering the waveguide would have slightly different mode shape if lens is oriented differently or the waveguide is translated axially by a little bit. Therefore, the coupling is not stable and the loss can not be easily minimized.

Ease of packaging is one of the features that makes single-mode fibers look attractive. With all of the bulk optic components shown in Figure 1, it is impossible to package the whole system into a small, compact box because certain components, such as microscope objectives, require certain working distances. However, with the single-mode fibers, which are flexible and occupy little space, light can be guided in any arbitrary direction, which, in turn, will make the packaging problem more flexible and easier to accomplish.

The wide spread use of pigtailed lasers is another reason why fiber is preferred over bulk optics because light can go from the laser directly to the fiber and then to the waveguide without any interruptions. All the intermediate bulk optic components can be eliminated and replaced by the equivalent fiber optic in-line components. One example is the fiber polarization controller, which is essentially two quarter-wave plates, capable of changing any input state of polarization to any output state of polarization.

Fig. 2 shows the experimental setup using in-line fiber optic components and direct butting of fibers to the waveguides. Clearly, fibers offer the advantages of structural simplicity and flexibility that bulk optics doesn't have. However, one should be aware of the requirements involved in using fibers, which include :

1) accurate horizontal and vertical positioning of fibers and channel waveguides.
2) flat, defect-free waveguide and fiber end surfaces.
3) overlapping of field distributions in fibers and in channel waveguides.

The fiber-to-waveguide coupling depends on the spatial overlap between the transverse fields of the optical modes in the fibers and in the channel waveguides. Optimization and theoretical calculations to characterize the field coupling will be described in detail in this thesis.

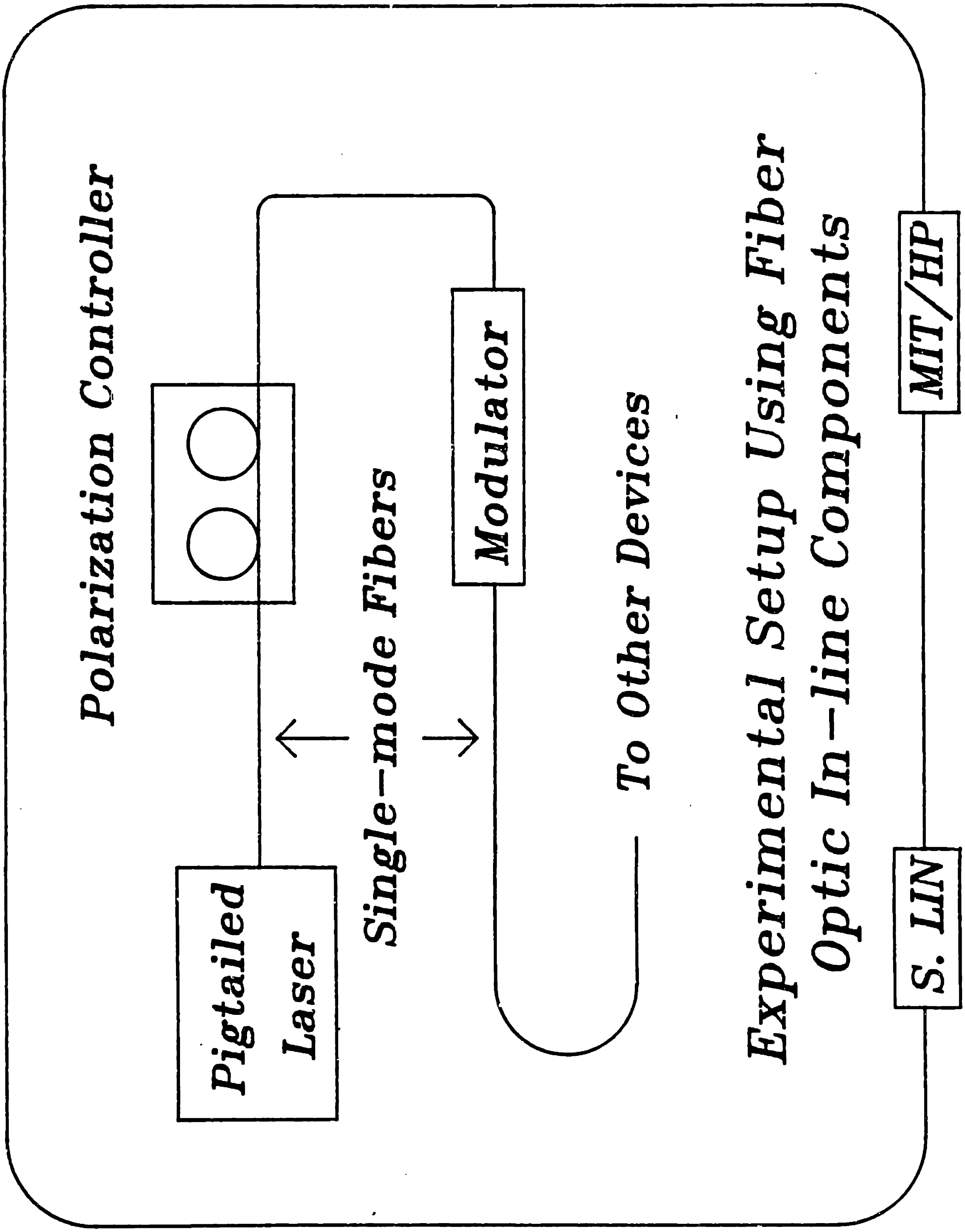
Polarization Controller
Pigtailed Laser
Single-mode Fibers
Modulator
To Other Devices
Experimental Setup Using Fiber Optic In-line Components
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Figure 2

1.2 Why GaAs Ridge Waveguides ?

Most investigations of travelling wave modulators in the past have been on $LiNbO_3$ modulators with strong emphasis on higher bandwidth and lower driving voltage [32,33]. This is usually achieved at the expense of smaller channel waveguide dimensions, which are responsible for most of the coupling losses due to a poor match to the mode of the incoming light. In order to reduce the coupling loss, larger channel waveguide dimensions will have to be fabricated to allow better match of the waveguide mode to the fiber mode. This would require either an increase in driving voltage or longer electrodes in the modulator in order for the optical fields to experience the same amount of electro-optic effect. Since increasing driving voltage is not desirable, longer electrodes must be used to compensate the large waveguide dimensions. Long electrodes, however, mean that device must suffer more velocity walk-off between the optical and microwave fields, which, in turn, reduces the bandwidth of the modulator. This is why a different material with a smaller velocity mismatch must be used if coupling losses are to be reduced and high bandwidth and low driving voltage maintained.

GaAs travelling wave modulators have thus been proposed to accomplish these goals. Because velocity mismatch between the optical and the microwave fields is less severe in GaAs than in $LiNbO_3$, longer electrodes can be fabricated in GaAs modulators to allow larger waveguide dimensions. Higher bandwidth can also be achieved at the same time in GaAs modulators. In addition, potential integrability with semiconductor lasers and ease of manufacturability have made the future of GaAs look very promising. Thus, the use of fibers as input and output coupling to GaAs waveguides may be the way to build a high throughput, high bandwidth, low driving voltage and compact electro-optic modulator in the future.

Chapter 2

REVIEW OF PREVIOUS WORK

The history of using fibers as input and output couplings to the modulators has not been long. Since late 70's, more and more research efforts have been devoted to solve the problem of high-loss coupling which has hindered the performance of a modulator. In 1979, Keil and Auracher reported a total insertion loss of about 7 - 9.4 dB for 1 cm long single-mode Ti-diffused $LiNbO_3$ waveguides (c-cut) inserted between 2 single-mode fibers [1]. The coupling loss at each face of the waveguide was about 3 dB for TE polarization and 1.55 dB for TM polarization. Coupling loss of 1 dB at each face was also obtained for a y-cut substrate and TM polarization. However, the propagation loss associated with it was 6.6 dB/cm, which contributed to a higher overall insertion loss.

Fukuma and Noda improved the coupling loss to 2.5 dB and 1 dB for coupling from single-mode fibers to Ti-diffused strip waveguides fabricated in y-plate and z-plate $LiNbO_3$ in 1980 [2]. The overall insertion losses were 5.5 dB and 2.5 dB respectively for 1 cm long waveguides.

Similar results were also obtained by Bulmer et al. [3] in the same year except that the best coupling efficiency had improved to 0.6 dB for each end of the waveguide, contributing to a total of 1.7 dB insertion loss. The coupling structure consisted of a Si V-groove in the longitudinal direction to stabilize the mechanical alignment of the fibers to the waveguides. Tapered fibers in deep transverse grooves provided a more precise alignment of the coupling fibers. The schematic is shown in Fig. 3.

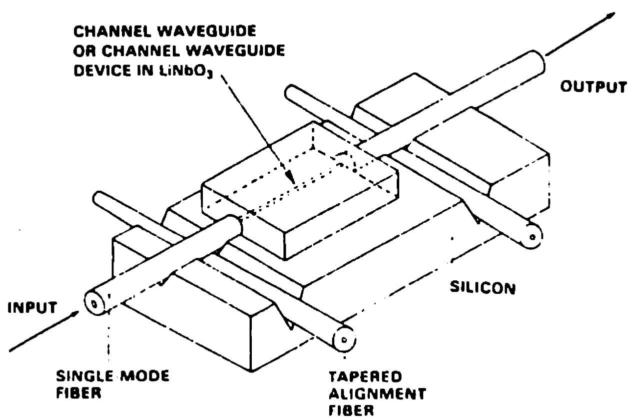

Fig. 3 Schematic of Si V-groove / flip-chip coupling structure

In 1981, Ramer [4] reported a coupling loss of definitely less than 1 dB using the same V-groove structure as that used by

Bulmer et al. except that tapered fibers were not used in the transverse direction. Theoretical calculations of coupling efficiency were given. Alignment tolerances in the transverse and angular directions were also considered with analytical expressions stated.

Ramaswamy, Alferness, and Divino [6] reported in 1982 a total insertion loss as low as 1 dB with a single-mode fiber coupled to a 1 cm long Ti-diffused $LiNbO_3$ waveguide. The coupling loss, however, was not specifically given.

Table 1 summarizes all the results reported in the literatures. The overall insertion loss shown in the table includes the coupling loss from both ends of the waveguide and the waveguide propagation loss. It assumes zero Fresnel reflection loss because waveguide facets can be anti-reflection coated to achieve a high transmission coefficient.

All of the work mentioned above were done on $LiNbO_3$ waveguides. There has been very little work done on GaAs waveguides in the past [31,34] and no work done specifically on the coupling problem between single-mode fibers and GaAs ridge waveguides. Thus, the work reported in this thesis would be the first effort to demonstrate the feasibility of using fibers as input coupling to GaAs ridge waveguides.

	Coupling Loss(dB)	Propagation Loss(dB/cm)	Insertion Loss(dB)
Keil et al.	3 (TE) 1.55 (TM)	3.4 (TE) 3.9 (TM)	9.4 (TE) 7.0 (TM)
Noda et al.	2.5 1.0	0.5(y-plate) 0.5(z-plate)	5.5 2.5
Bulmer et al.	0.6-1.5	0.5	1.7-3.5
Ramer	< 1	< 1	< 3
Alferness et al.			> 1

Table 1 – Insertion Loss Summary

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Table 1

Chapter 3

THEORY

The optical coupling efficiency [1-8] between single-mode fibers and single-mode channel waveguides is given by the overlap integral which measures how well the two field distributions overlap spatially. This overlap integral can be expressed by

$$\epsilon_p = \frac{\left| \iint E_1 E_2^* \, dxdy \right|^2}{\iint E_1 E_1^* \, dxdy \iint E_2 E_2^* \, dxdy} \qquad \text{--(1)}$$

where E_1 and E_2 are the fundamental mode electric field distributions in the fiber and in the channel waveguide respectively.

For wave functions with constant phase such as those in fibers and waveguides, the complex conjugate can simply be omitted to yield

$$\epsilon_p = \frac{\left| \iint E_1 E_2 \, dxdy \right|^2}{\iint |E_1|^2 \, dxdy \iint |E_2|^2 \, dxdy} \qquad \text{--(2)}$$

An alternative way to interpret this coupling efficiency is that, since all the guided modes and radiation modes in the waveguide are orthogonal and form a complete set, it is possible to expand the fiber mode in terms of all these modes in the channel waveguide as shown below [9] :

$$E_1 = \sum_i (a_i E_i)_{\substack{\text{guided} \\ \text{modes}}} + \sum_j (b_j E_j)_{\substack{\text{radiation} \\ \text{modes}}} \quad \text{--(3)}$$

Thus, the coefficient a_i associated with the lowest order guided mode would correspond to the overlap integral expressed in (1).

3.1 Single-mode fibers

Figure 4 shows the geometry of a single-mode fiber of core radius a, core index n_c, and cladding index n where $n_c > n$.

Assuming a field distribution of [10,11]

$$E(r,\theta) = R(r) \cos (n\theta) \qquad \text{--(4)}$$

which must satisfy the wave equation

$$\nabla^2 E(r,\theta) + (n^2(r) K_0^2 - \beta^2) E(r,\theta) = 0, \qquad \text{--(5)}$$

where K_0 is the wave number in the air and β is the propagation constant in the fiber.

R(r) can be analytically solved to yield

$$R(r) = \begin{cases} A J_n (ur/a) + B Y_n (ur/a) & r < a \\ C K_n (wr/a) + D I_n (wr/a) & r >= a \end{cases} \qquad \text{--(6)}$$

where J_n, Y_n, K_n, and I_n denote the n-th order Bessel functions of the first and second kind and the n-th order modified Bessel functions of the first and second kind, respectively. u is the normalized transverse propagation constant in the core defined by

$$u = a (K_c^2 - \beta^2)^{1/2} \qquad \text{--(7)}$$

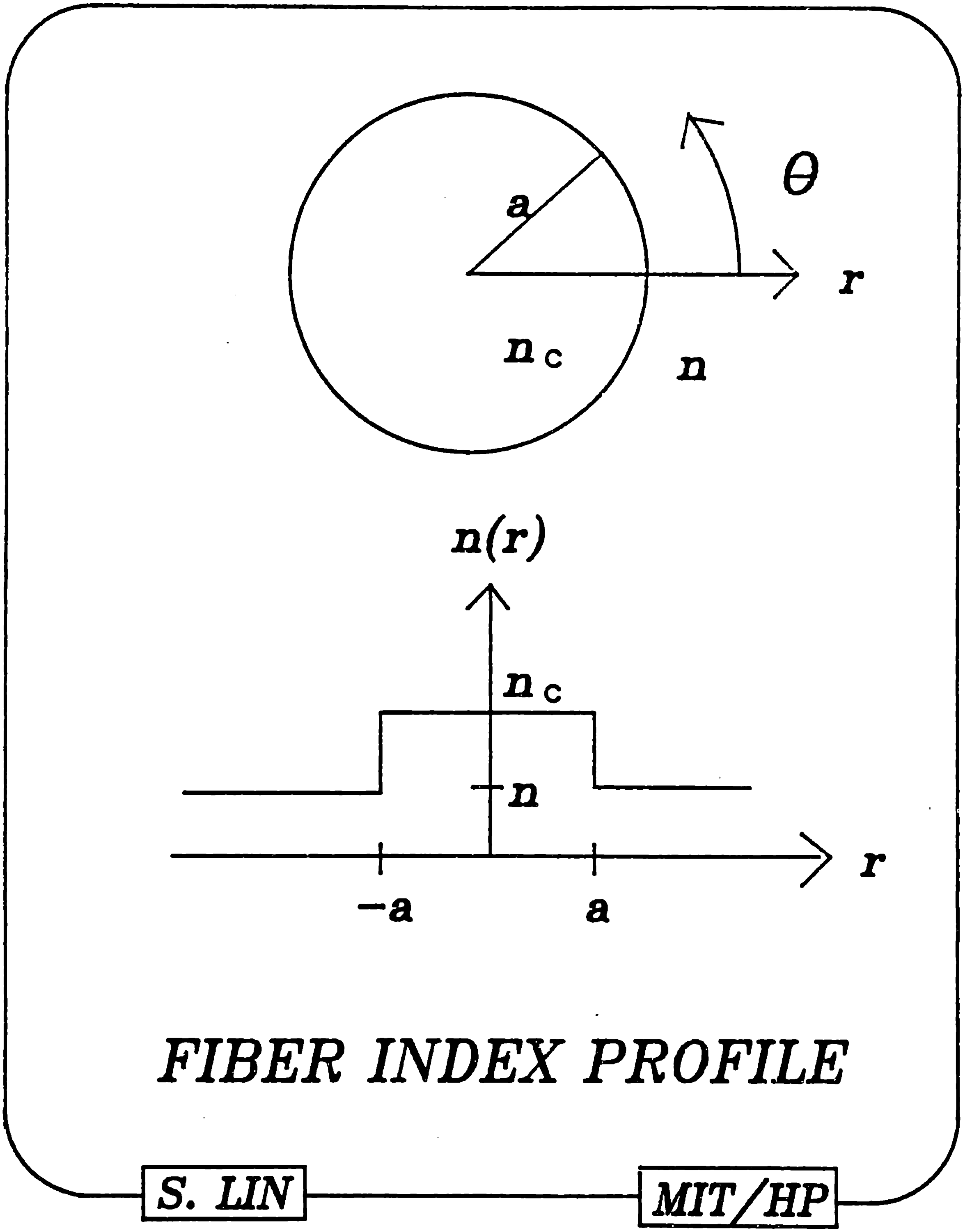


Figure 4

and w is the normalized decay constant in the cladding defined by

$$w = a (\beta^2 - K^2)^{1/2} \qquad \text{--(8)}$$

A solution that approaches infinity as r approaches infinity can not be acceptable to the real physical situation. Thus, B and D are forced to be zero. Therefore,

$$R(r) = \begin{cases} A J_n (ur/a) & r < a \\ C K_n (wr/a) & r > a \end{cases} \qquad \text{--(9)}$$

Applying the boundary conditions that R(r) and its derivative are continuous across the core-cladding interface, one obtains

$$A J_n (u) = C K_n (w) \qquad \text{--(10)}$$

$$\frac{A u}{a} J_n' (u) = \frac{C w}{a} K_n' (w) \qquad \text{--(11)}$$

(10) and (11) can be combined to give the eigenvalue equation for the propagation constant :

$$\frac{J_n (u)}{u J_{n+1} (u)} = \frac{K_n (w)}{w K_{n+1} (w)} \qquad \text{--(12)}$$

which together with

$$u^2 + w^2 = V^2 \qquad \text{--(13)}$$

where V is the normalized frequency defined by

$$V = \frac{2 \pi a}{\lambda} (n_c^2 - n^2)^{1/2} \qquad \text{--(14)}$$

completely determine the fiber modal dispersion and the propagation constant.

For single-mode fibers, the fundamental mode, which is designated as HE_{11} or LP_{01} mode, is the only allowed propagating mode. The cut-off frequency for the next higher order mode is V = 2.405. Therefore, to ensure single-mode operation,

$$\frac{2 \pi a}{\lambda} (n_c^2 - n^2)^{1/2} < 2.405 \qquad \text{--(15)}$$

has to be satisfied.

Careful approximations can be further made to simplify the eigenvalue equation (12),

$$\frac{J_0 (u)}{u J_1 (u)} = \frac{K_0 (w)}{w K_1 (w)} \qquad \text{--(16)}$$

where n = 0 has been substituted to specify HE_{11} mode. The result is [12,13] :

$$u (V) = \frac{(1 + 2^{1/2}) V}{1 + (4 + V^4)^{1/4}} \qquad --(17)$$

The propagation constant can be found, independent of the fiber configuration, by defining

$$b (V) = \frac{(\beta / K)^2 - n^2}{n_c^2 - n^2} \qquad --(18)$$

For a small index difference, (18) can be approximated by

$$b (V) = \frac{(\beta / K) - n}{n_c - n} \qquad --(19)$$

or $\beta (V) = n_c K (b \Delta + 1)$

$$= n_c K (1 + \Delta - \Delta (u/V)^2) \qquad --(20)$$

where Δ is the index difference in percent.

Equations (17) and (20) describe HE_{11} mode with maximum error of 2%. Its intensity profile is shown in Fig. 5 on next page using the parameters of the single-mode fibers used in our experiments.

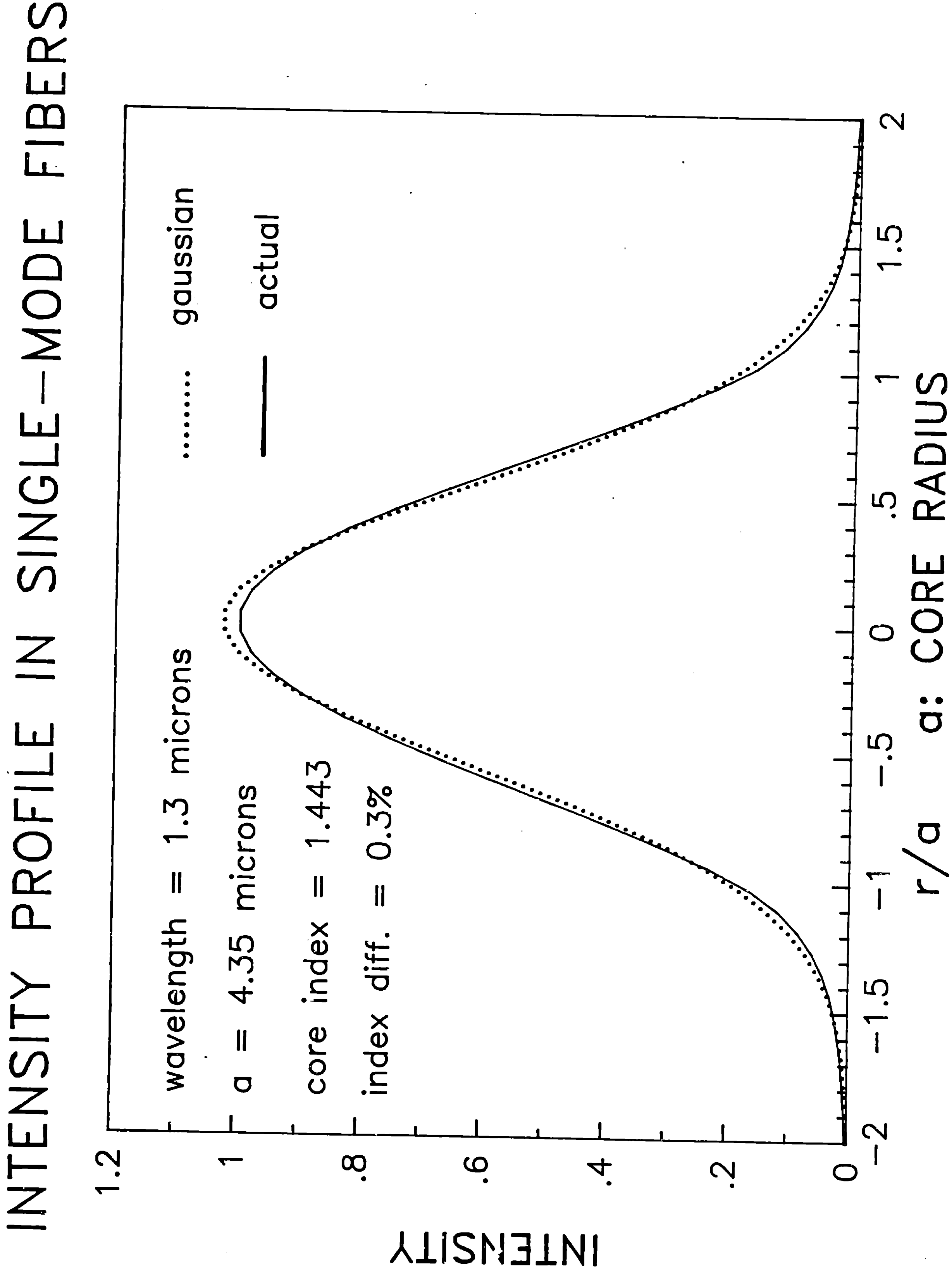

INTENSITY PROFILE IN SINGLE-MODE FIBERS
wavelength = 1.3 microns
a = 4.35 microns
core index = 1.443
index diff. = 0.3%
gaussian
actual
INTENSITY
1.2
1
.8
.6
.4
.2
0
-2
-1.5
-1
-.5
0
.5
1
1.5
2
r/a a: CORE RADIUS

Figure 5

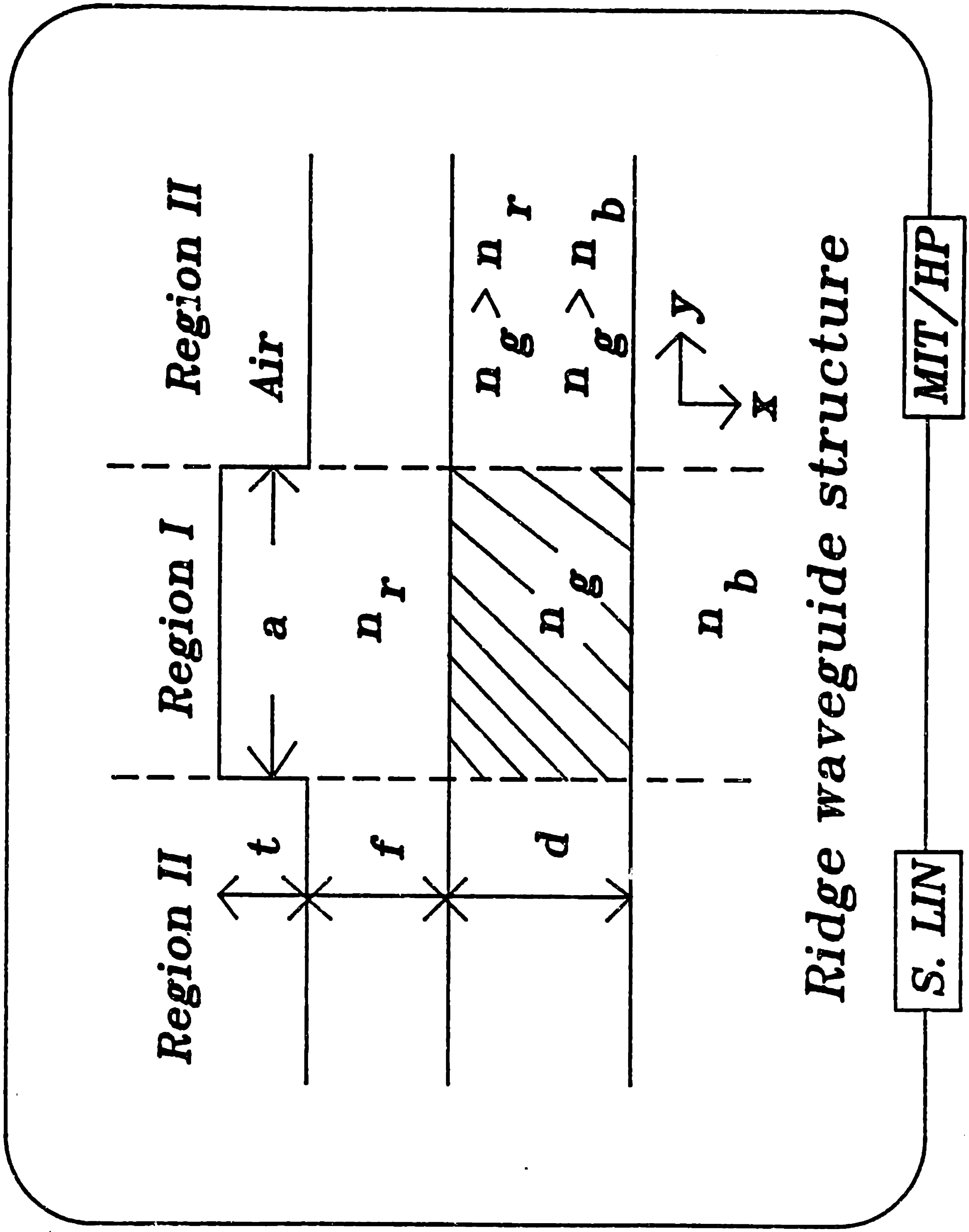
3.2 Single-mode GaAs channel waveguides

Low-loss, and high-bandwidth modulators are of great importance to lightwave technology today. Ways of accomplishing these goals have been investigated in GaAs strip-loaded waveguides. Fig. 6 shows the configuration of the waveguide being studied.

Guiding of light in the shaded region is possible in this structure because the guiding layer, which has the largest refractive index, supports the vertical modes. The lateral mode is supported due to the ridge, which contributes to a higher effective index in the region bounded by the ridge [14-18]. Depending on the relative material refractive indices and the thickness of each layer, the vertical mode may be slightly asymmetric with respect to the guiding layer. However, the geometrical symmetry in the lateral direction guarantees that the lateral mode will be symmetric. To fully understand how this strip-loaded waveguide guides light, the effective index method will be applied to region I and II as if they were 4-layer slab waveguides with infinite lateral dimensions (d/dy = 0).

Shown in Fig. 7 is the structure of a 4-layer slab waveguide [19-23]. To eliminate the possibility of cladding modes propagating in the waveguide, the propagation constant, β , must be restricted between $K_0 n_1$ and $K_0 n_2$.

For TE modes, the electric field can be expressed as :



Ridge waveguide structure
Region II
Region I
Region II
Air
t
f
d
a
n_r
n_g
n_b
$n_g > n_r$
$n_g > n_b$
x
y
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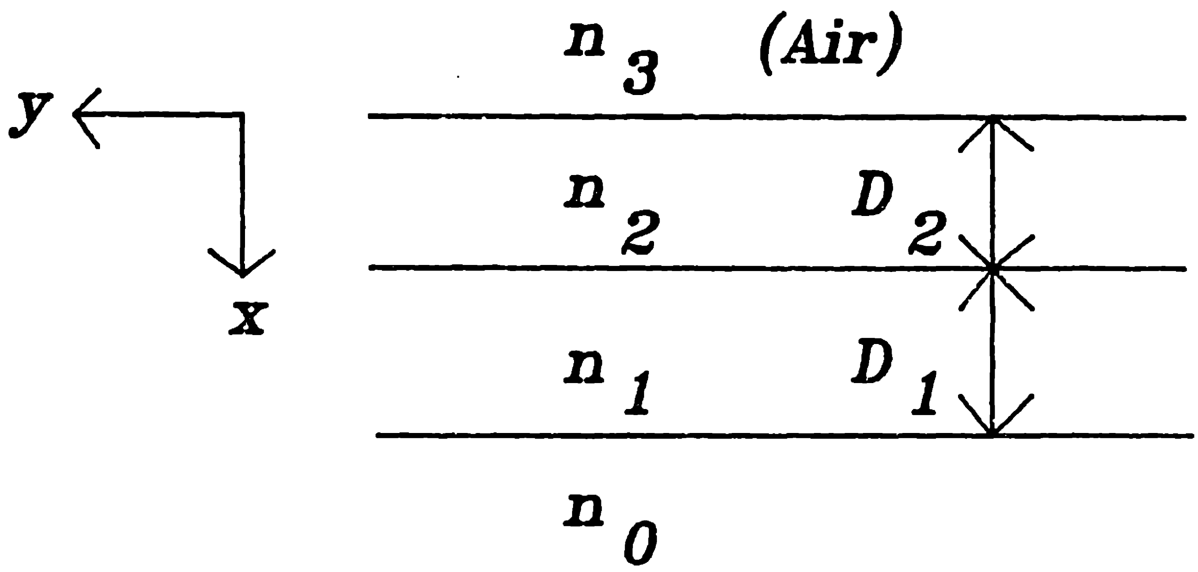
Figure 6



$$n_1 > n_2 \geq n_0 > n_3$$

4-layer dielectric slab

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Figure 7

$$E_y(x) = \begin{cases} A \cos(r) \exp\{-q_0(x-D_1-D_2)\} & D_1 + D_2 <= x \\ A \cos\{h_1 x - h_1(D_1+D_2)+r\} & D_2 <= x < D_1 + D_2 \\ A\ G \sinh(q_2 x+s) & 0 <= x < D_2 \\ A\ G \sinh(s) \exp(q_3 x) & x <= 0 \end{cases} \quad \text{--(21)}$$

where

$$\begin{aligned} \beta^2 - q_0^2 &= (n_0 K_0)^2, \\ \beta^2 + h_1^2 &= (n_1 K_0)^2, \\ \beta^2 - q_2^2 &= (n_2 K_0)^2, \\ \beta^2 - q_3^2 &= (n_3 K_0)^2. \end{aligned} \quad \text{--(22)}$$

r and s are phase shifts reqiured to match the boundary conditions.

Continuity of E-field requires :

$$G = \frac{\cos(h_1 D_1 - r)}{\sinh(q_2 D_2 + s)} \quad \text{--(23)}$$

Continuity of dE_y/dx also requires :

i) At $x = D_1 + D_2$

$$-q_0 \cos(r) = -h_1 \sin(r)$$

$$\tan(r) = q_0/h_1$$

$$\text{or} \quad r = \tan^{-1}(q_0/h_1) \quad \text{--(24)}$$

ii) At $x = D_2$

$$-h_1 \sin(r - h_1D_1) = G\, q_2 \cosh(q_2D_2 + s)$$

$$h_1 \sin(h_1D_1 - r) = \frac{\cos(h_1D_1 - r)}{\sinh(q_2D_2 + s)} q_2 \cosh(q_2D_2 + s)$$

or $$h_1 \tan(h_1D_1 - r) = q_2 \coth(q_2D_2 + s) \qquad \text{--(25)}$$

iii) At $x = 0$

$$q_2 \cosh(s) = q_3 \sinh(s)$$

or $$s = \tanh^{-1}(q_2/q_3) \qquad \text{--(26)}$$

Equations (24), (25), (26) can be combined to form a single eigenvalue equation for the propagation constant β . Substituting (24) and (26) into (25) yields :

$$h_1 \tan\{h_1D_1 - \tan^{-1}(q_0/h_1) + m\pi\} = q_2 \coth\{q_2D_2 + \tanh^{-1}(q_2/q_3)\} \qquad \text{--(27)}$$

Re-arranging (27), one obtains

$$h_1D_1 = m\pi + \tan^{-1}(q_0/h_1) + \tan^{-1}\{(q_2/h_1) \coth(q_2D_2 + \tanh^{-1}(q_2/q_3))\} \qquad \text{--(28)}$$

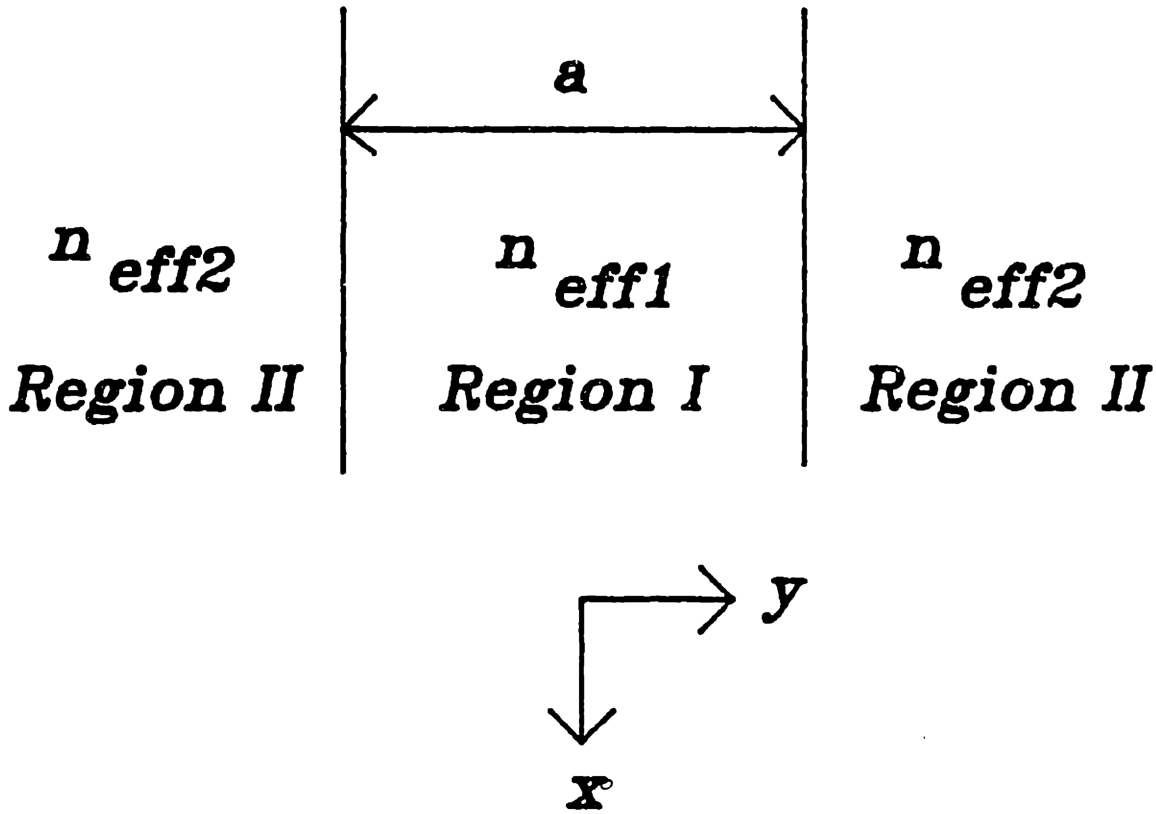
where $m = 0, 1, 2, 3, \ldots\ldots$, the mode number.

It is worth noting that equation (28) can be interpreted as stating thε the totai phase shifts due to propagation and reflections at $x = D_2$ and $x = D_1 + D_2$ have to add up to integer multiple of π in order for the modes to propagate. By solving equation (28) together with equation (22) numerically to obtain β and thus the rest of the parameters, one can characterize this 4-layer guiding structure by an effective index, which is defined by

$$N_{eff} = \beta / K_0 \qquad \text{--(29)}$$

Using this procedure, one can predict the effective indices associated with the 4-layer slab of the region bounded by the ridge and the region outside the ridge as if each region were infinite in the lateral direction. The result is illustrated in Fig. 8 in which the region bounded by the ridge is characterized by n_{eff1} and region outside the ridge is characterized by n_{eff2}.

Because the region bounded by the ridge has a thicker upper buffer layer than that of the region outside the ridge, the asymmetry factor in index profile is less for the region bounded by the ridge, which implies more modes will be supported in this region at the same driving frequency. In other words, the fundamental mode propagating in the region bounded by the ridge will have a higher propagation constant than that in the region outside the ridge. This is why n_{eff1} will always be greater than



Equivalent waveguide model

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n_{eff2} to support the lateral modes.

The new simplified waveguide structure shown in fig. 8 can be very easily solved. The electric field is

$$E_y(y) = \begin{cases} \cos(u)\exp(w)\exp(2wy/a) & y < -a/2 \\ \cos(2uy/a) & 0 <= |y| <= a/2 \\ \cos(u)\exp(w)\exp(-2wy/a) & a/2 <= y \end{cases} \quad \text{--(30)}$$

where $u^2 = (a/2)^2 ((n_{eff1}K_0)^2 - \beta^2)$ --(31)

$w^2 = (a/2)^2 (\beta^2 - (n_{eff2}K_0)^2)$ --(32)

Boundary conditions require

$$-(2u/a)\sin(u) = -(2w/a)\cos(u)$$

or $w = u\tan(u)$ --(33)

u and w can be solved by knowing,

$$u^2 + w^2 = V^2 \quad \text{--(34)}$$

where V is the lateral normalized frequency defined by

$$V = (\pi a/\lambda)(n_{eff1}^2 - n_{eff2}^2)^{1/2}$$

Assuming the electric field does not extend too far from the guiding region and the sharp corner effects can be neglected, the total electric field is simply the product of the vertical modes and lateral modes found earlier. Plots of vertical and lateral modes are shown in Figures 10 and 11 on the next few pages for the waveguide structure illustrated in Figure 9. Cautions must be taken that the effective index method is valid only if the mode is not near cut-off. Furthermore, the assumption of the total electric field being the product of the vertical and lateral modes implies the modes are well confined in the guiding region and the evanescent field of the optical mode has practically diminished at the edges of the ridge. Otherwise, the effects of the ridge's side edges will create some undesirable and complicated TE-TM mode conversion as discussed in Peng and Oliner's paper [24-28].

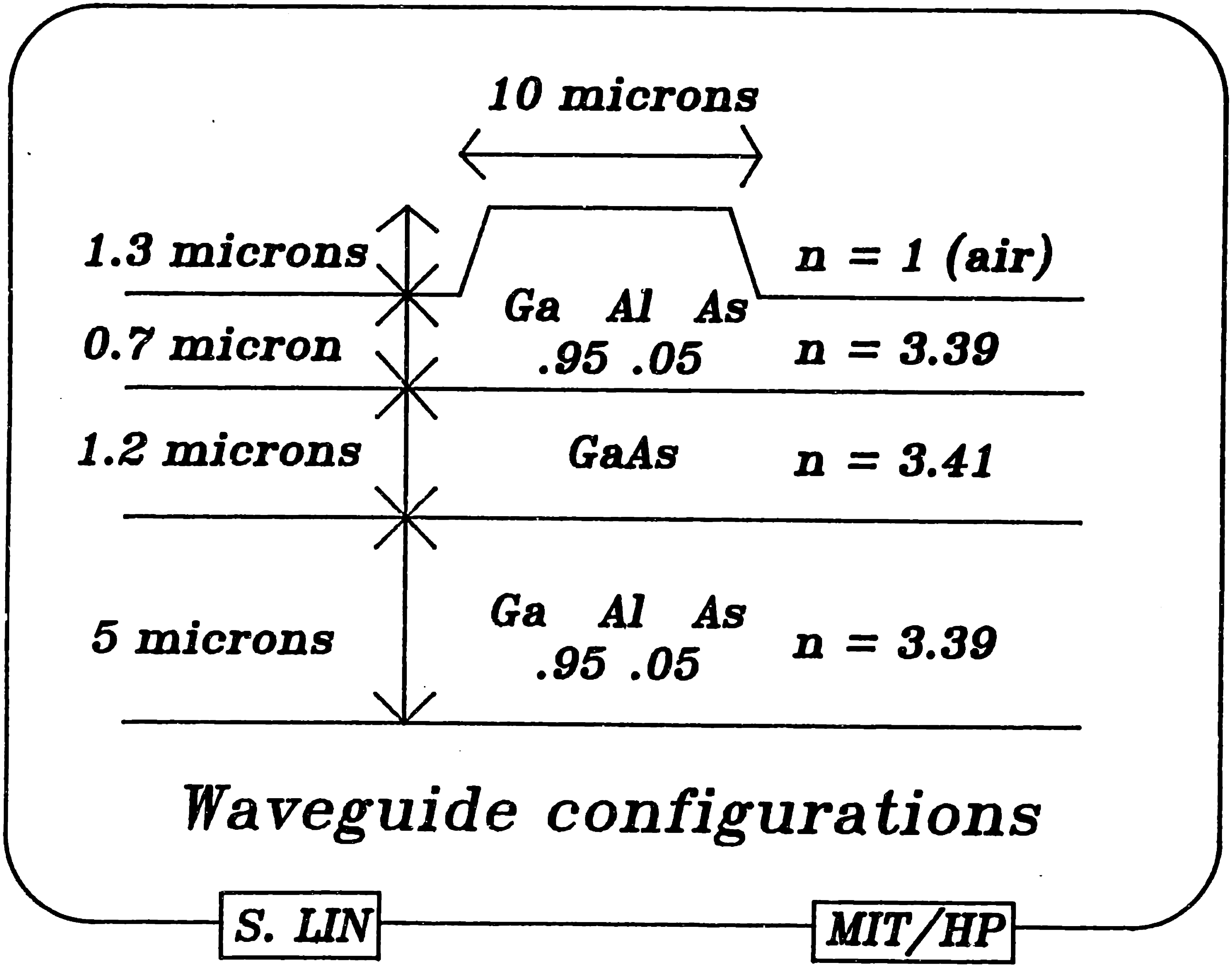
10 microns
1.3 microns
n = 1 (air)
Ga Al As
.95 .05
0.7 micron
n = 3.39
1.2 microns
GaAs
n = 3.41
5 microns
Ga Al As
.95 .05
n = 3.39
Waveguide configurations
S. LIN
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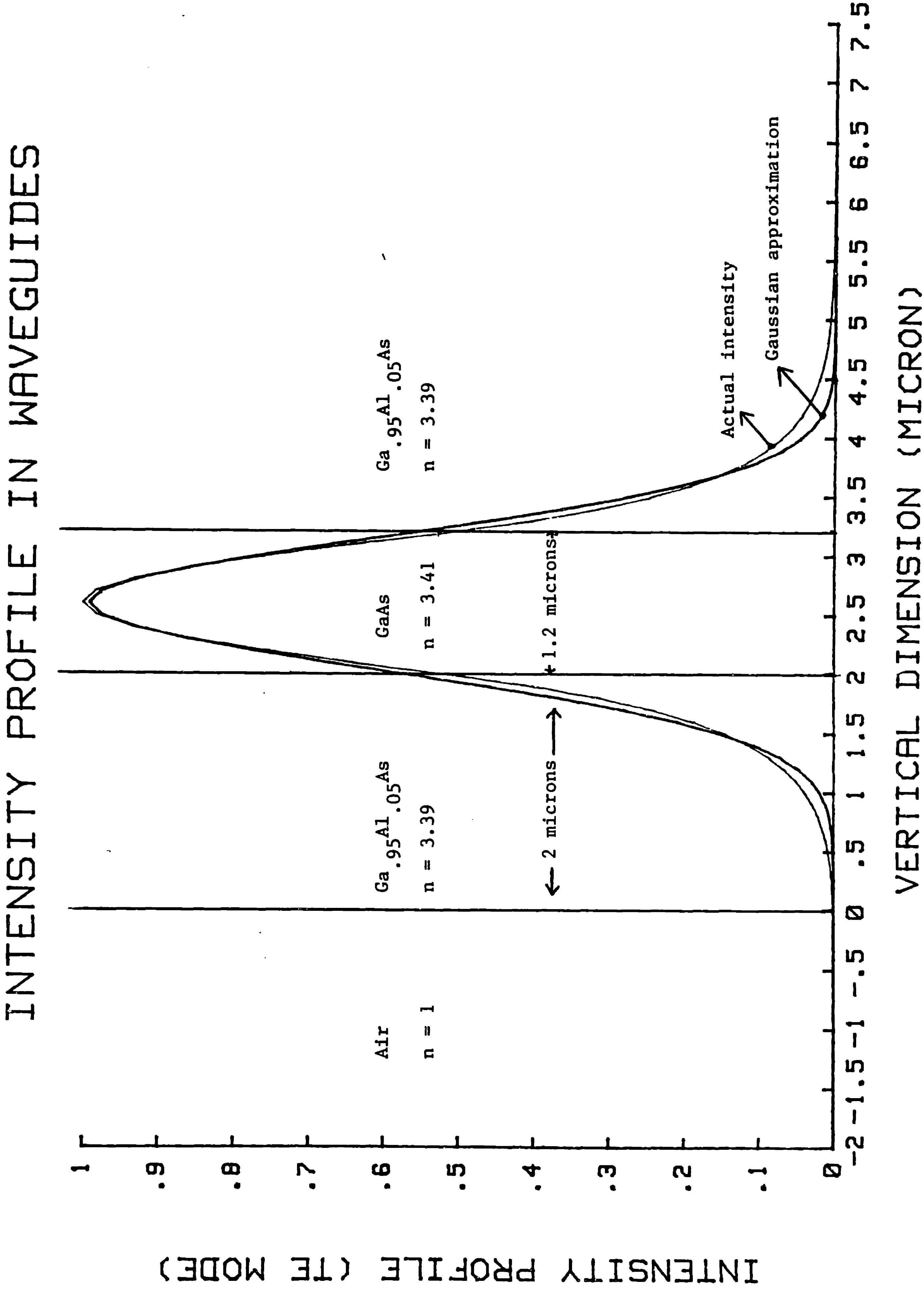
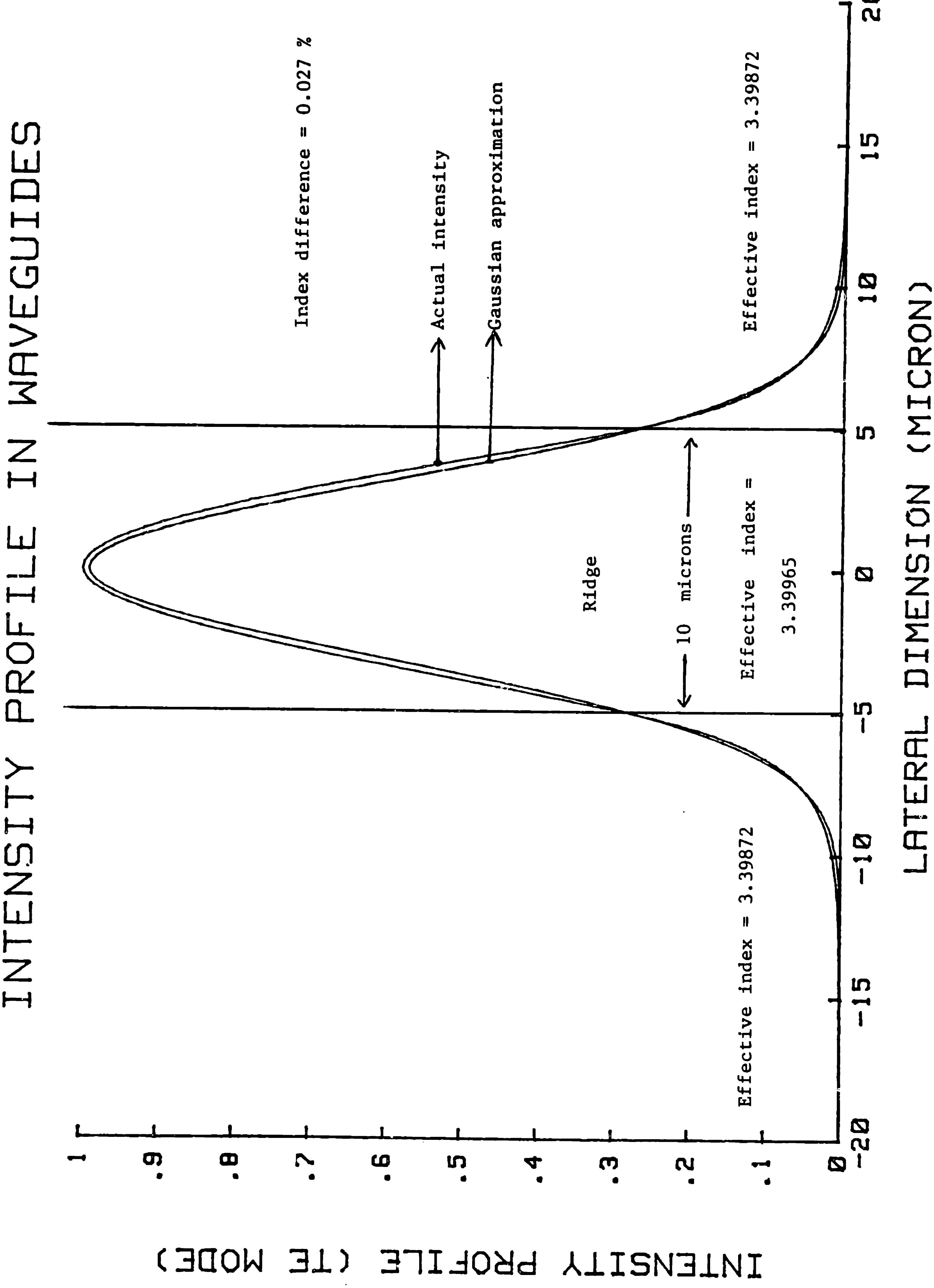
Figure 9


INTENSITY PROFILE IN WAVEGUIDES
Air
n = 1
Ga.95Al.05As
n = 3.39
GaAs
n = 3.41
Ga.95Al.05As
n = 3.39
2 microns
1.2 microns
Actual intensity
Gaussian approximation
VERTICAL DIMENSION (MICRON)
INTENSITY PROFILE (TE MODE)
-2 -1.5 -1 -.5 0 .5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1

Figur 10



INTENSITY PROFILE IN WAVEGUIDES
Index difference = 0.027 %
Actual intensity
Gaussian approximation
Effective index = 3.39872
Ridge
10 microns
Effective index = 3.39965
Effective index = 3.39872
LATERAL DIMENSION (MICRON)
INTENSITY PROFILE (TE MODE)
-20
-15
-10
-5
0
5
10
15
20
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1

Figure 11

Chapter 4

MODELLING - GAUSSIAN APPROXIMATIONS

Knowing the analytic field functions in the fibers and in the waveguides enables one to evaluate the overlap integral directly. However, this is not always the best strategy since the field functions of the fibers involve Bessel and modified Bessel functions, which, when multiplied by the waveguide field functions of sin, sinh or exponential, may make the overlap integral impossible to carry out analytically. Therefore, a gaussian approximation has been proposed to resolve the difficulties encountered by using Bessel functions [3,4,7].

Restating the overlap integral formula :

$$\epsilon_p = \frac{\left| \iint E_1 \, E_2 \, dxdy \right|^2}{\iint |E_1|^2 \, dxdy \iint |E_2|^2 \, dxdy} ,$$

and assuming fiber mode E_1 can be approximated by

$$g_1 (r) = A_1 \exp(-r^2/2a^2) , \qquad \text{--(35)}$$

and waveguide mode E_2 can be approximated by

$$g_2(x,y) = A_2 \exp(-(x^2/2w_x^2 + y^2/2w_y^2)) \quad , \qquad \text{--(36)}$$

where a is the mode size of the fiber, and w_x and w_y are the mode sizes of the waveguide in the vertical and lateral directions respectively, substitution of (35) and (36) into the overlap integral shows (assuming perfect alignment) :

$$p = \frac{4}{\left(\frac{w_x}{a} + \frac{a}{w_x}\right)\left(\frac{w_y}{a} + \frac{a}{w_y}\right)} \quad . \qquad \text{--(37)}$$

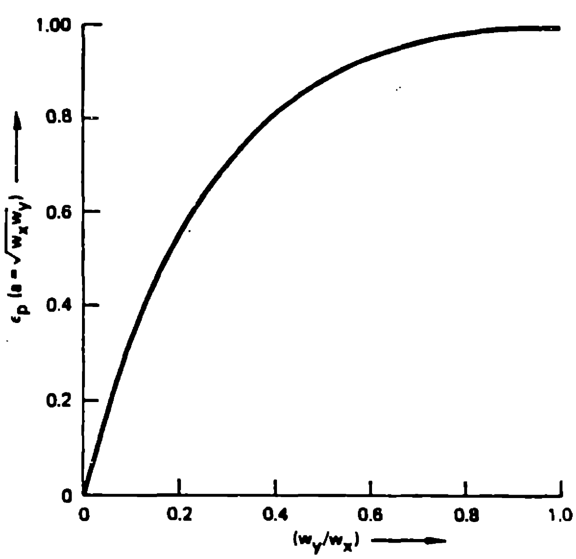


Fig. 12

This coupling efficiency, ϵ_p, is maximized ($d\epsilon_p/da = 0$) when $a = (w_x w_y)^{1/2}$. Fig. 12 shows ϵ_p, under the condition

$a = (w_x w_y)^{1/2}$, as a function of ratio w_y/w_x.

There are several things to note :

1. In order to maintain the coupling loss of less than 1 dB, w_y/w_x must be greater than 0.4.

2. Given w_y and w_x are known, figure 10 implies that the best coupling efficiency can be achieved if the mode size of the fibers is chosen to be $(w_x w_y)^{1/2}$. Unless the fibers are custom-made, this would be difficult to achieve. Furthermore, this optimized coupling efficiency is limited and may be very low.

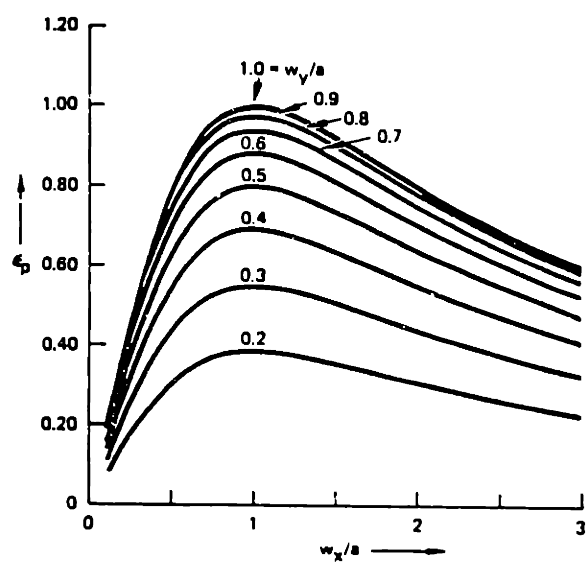


Fig. 13

Thus, a better way to optimize the coupling efficiency is to custom-make the waveguides. Fig. 13 illustrates the principles behind it.

Again, there are several things to note :

1. The coupling efficiency is maximized ($d\epsilon_p/dw_x, dw_y = 0$) if w_x, $w_y = a$. This allows waveguides to be made such the vertical and lateral mode sizes are as close to the fiber mode size as possible.
2. The steeper slopes in the region of $w_x/a < 1$ implies the coupling efficiency is more sensitive to the fluctuations in the waveguide mode size, which may be caused by the imperfections from the fabrication or any uncertainty in waveguide indices and dimensions. Therefore, larger waveguide mode sizes would be perferred over smaller waveguide mode sizes (as compared to the fiber mode size) in order to reduce the sensitivity of coupling efficiency due to any uncertainty.

Under the gaussian approximations, $\epsilon_p = 100\%$ can be achieved only if $w_x = w_y = a$. In practice, this would require a very thick guiding layer in order to have comparable mode sizes in the vertical and the lateral directions. However, a thick guiding layer may make the channel waveguide become multi-moded in the vertical direction and thus reduce the coupling efficiency. Thick layers are difficult to grow and require very fine control over the index difference between layers if the resulting waveguide is to be single-moded. Therefore, 100% coupling efficiency will never be realized.

The analysis presented above assumes perfect alignment of the fiber to the waveguide. (The peaks of the two modes match up) Generally, this may be difficult to accomplish. Thus, the alignment tolerances on coupling efficiency need to be carefully investigated.

Assuming displacements of l_x and l_y in the vertical and lateral directions exist between the fiber and the waveguide, equation (36) of the approximated gaussian function for the waveguide mode will have to be modified by :

$$g_2\ (x,y) = A_2 \exp\{-[(x-l_x)^2/2w_x^2 + (y-l_y)^2/2w_y^2]\} \quad \text{--(38)}$$

Substitution of (38) and (35) into the overlap integral yields a a new expression with a correction factor multiplied by the old coupling efficiency shown in (37) :

$$\frac{\epsilon_{new}}{\epsilon_p} = \mathrm{Exp}\left(\frac{-l_x^2}{w_x^2 + a^2}\right) \mathrm{Exp}\left(\frac{-l_y^2}{w_y^2 + a^2}\right) \quad \text{--(39)}$$

Some dependencies should be pointed out :

1) The correction factor is unity if there are no vertical or lateral displacements, $l_x = l_y = 0$.

2) The losses increase with increasing displacements, l_x and l_y.

3) The losses decrease with increasing fiber and waveguide mode sizes, a, w_x, and w_y.

If there exist angular misalignments θ_x and θ_y, which are measured from the propagation axis (z) toward the vertical (x) and the lateral (y) axes respectively, then the coupling efficiency is modified by a correction factor as shown below (assuming small θ_x and θ_y):

$$\frac{\epsilon_{new}}{\epsilon_p} = \mathrm{Exp}\left(\frac{-k^2a^2w_x^2\sin^2\theta_x}{2(a^2 + w_x^2)}\right) \mathrm{Exp}\left(\frac{-k^2a^2w_y^2\sin^2\theta_y}{2(a^2 + w_y^2)}\right) \quad \text{--(40)}$$

In this case,

1) The correction is unity if there are no angular misalignments, $\theta_x = \theta_y = 0$.

2) For a given modal configuration, the loss will decrease for an increase in wavelength.

3) For a given wavelength, the loss will increase for an increase in the mode sizes.

Notice that in both cases of transverse and angular misalignments, the coupling tolerance factor is a gaussian function of the misaligning parameter, and the sensitivity of this coupling tolerance factor depends on the fiber and waveguide mode sizes, a, w_x, and w_y.

Since the choices of a, w_x, and w_y are very sensitive and critical in certain ranges, care must be taken to pick the values that are valid and correctly approximate the actual field profile. As a result, two criteria are necessary :

$$\text{i)} \quad \iint |E_i|^2 \, dxdy = \iint |g_i|^2 \, dxdy \qquad \text{--(41)}$$

$$\text{ii)} \quad \text{minimize} \quad \iint (E_i - g_i)^2 \, dxdy, \qquad \text{--(42)}$$

$$i = 1, 2$$

Criterion i) states the actual field function and the approximated gaussian function have the same energy across the cross seciton of the fiber or waveguide. This criterion will impose a constraint on the relationship between the height and beam waist(s) of the gaussian function. Criterion ii) states the error between the actual field function and the approximated gaussian function should be minimized across the fiber or waveguide cross section.

To illustrate how this procedure works, let's examine the fiber mode. Because of fiber's circular symmetry, the double integral is reduced to single integral and the integrand is integrated along the radial direction from zero to infinity.

Criterion i)

$$\int_0^\infty |E_1|^2 \, r \, dr = \int_0^\infty |g_1|^2 \, r \, dr$$
$$= A_1^2 \int_0^\infty \exp(-(r/a)^2) \, r \, dr$$
$$= (A_1 a)^2 / 2$$

Therefore,

$$A_1 = \left(\frac{2 \int_0^\infty |E_1|^2 \, r \, dr}{a^2} \right)^{1/2} \quad \text{<------ a known quantity} \qquad \text{--(40)}$$

Criterion ii)

By picking an initial value of a, A_1 can be calculated by (40). Knowing the values of A_1 and a, square error between the actual field function and approximated gaussian function can be computed. By adjusting the value of A_1 slowly and appropriately, one can find a particular value of A_1 and the corresponding a that minimizes the square error.

The reason criterion i) is necessary is because the approximated gaussian function has to have the same amount of energy as that of the actual field funciton. Otherwise, the gaussian approximation would not make any physical sense. It will also ensure the denominator of the overlap integral stays unchanged when gaussian functions are substituted for the actual functions. However, there will be a slight error in the numerator when the substitutions of gaussian functions are made.

This is why criterion ii) is essential to further minimize the errors due to the modelling of the actual optical modes in fibers and in waveguides by gaussian functions.

The advantage of the gaussian approximation is that it approximates a very complicated wave function by a gaussian function that is characterized by only two parameters, the waist and the height. Furthermore, the coupling efficiency can be completely determined just by knowing three parameters, the waist of the fiber mode, a and the waists of the waveguide mode in the vertical and lateral directions, w_x and w_y. As long as these three parameters are known, the details of the actual wave functions would not be of concern to the coupling efficiency.

Figures 14, 15 and 16 are duplicates of Figures 5, 10, and 11 shown earlier. They clearly illustrate how exactly the fiber and the waveguide modes can be approximated by the appropriate gaussian functions.

Figures 17 and 18 demonstrate how the vertical and lateral mode sizes of the waveguide and the optical coupling efficiency respond to various buffer indices using the gaussian approximation model. The numbers obtained are based on the waveguide configuration shown in Figure 9, i.e. a pure GaAs guiding layer buffered by GaAlAs layers below and above.

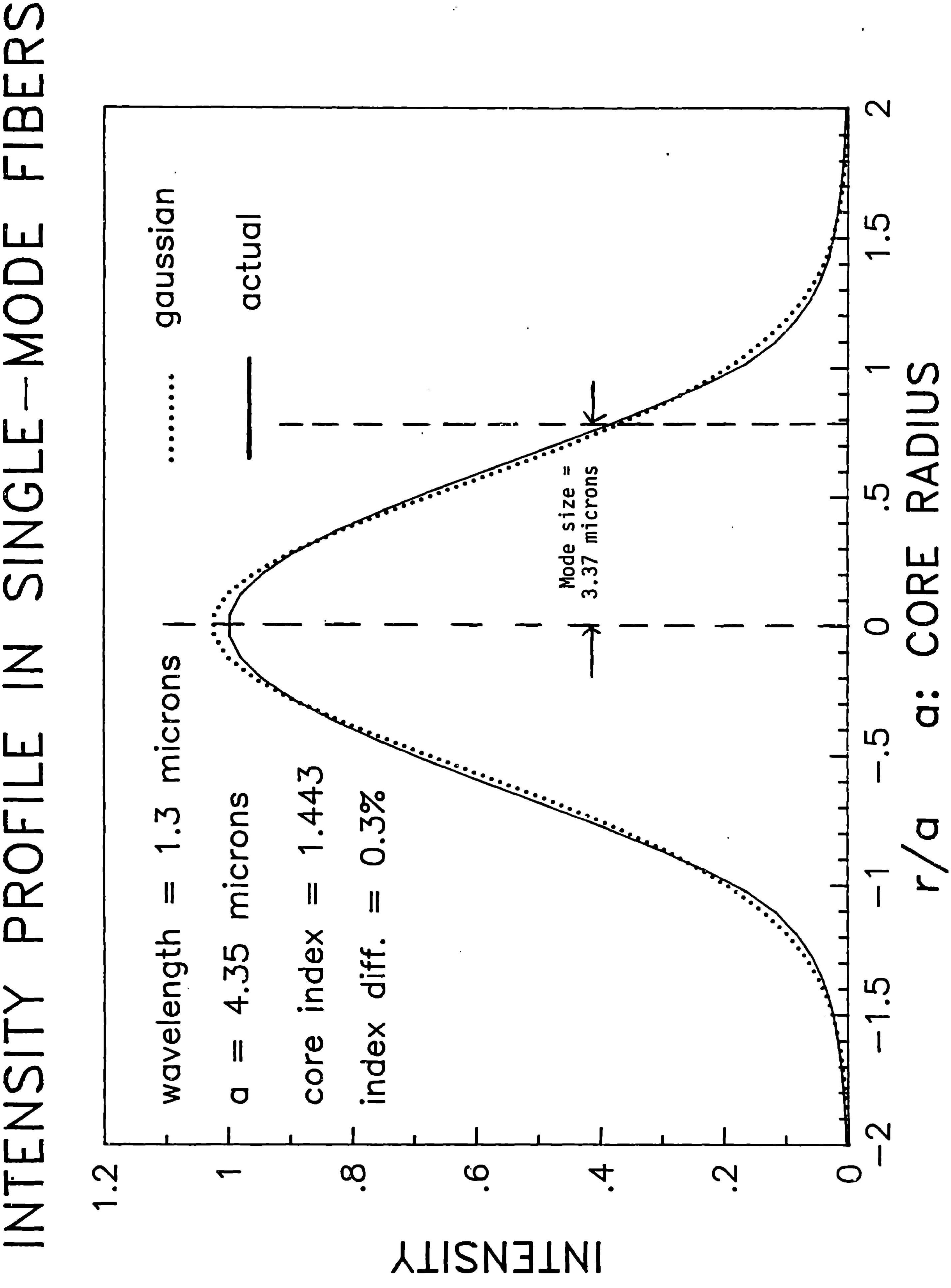
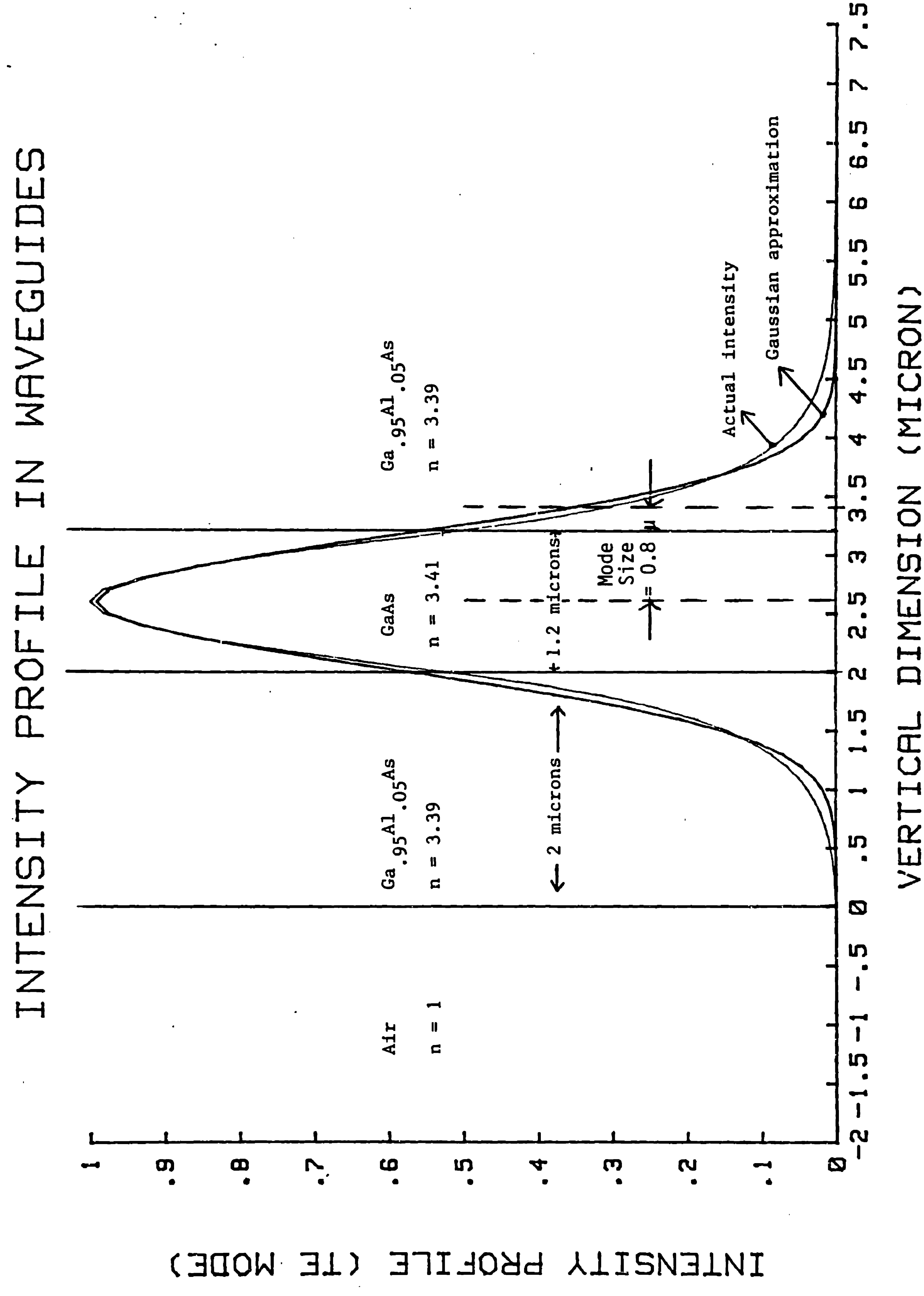

INTENSITY PROFILE IN SINGLE-MODE FIBERS
wavelength = 1.3 microns
a = 4.35 microns
core index = 1.443
index diff. = 0.3%
gaussian
actual
Mode size =
3.37 microns
INTENSITY
r/a   a: CORE RADIUS
1.2
1
.8
.6
.4
.2
0
-2
-1.5
-1
-.5
0
.5
1
1.5
2

Figure 14



INTENSITY PROFILE IN WAVEGUIDES
Air
n = 1
Ga.95Al.05As
n = 3.39
GaAs
n = 3.41
Ga.95Al.05As
n = 3.39
2 microns
1.2 microns
Mode Size = 0.8 μ
Actual intensity
Gaussian approximation
VERTICAL DIMENSION (MICRON)
INTENSITY PROFILE (TE MODE)

Figure 15

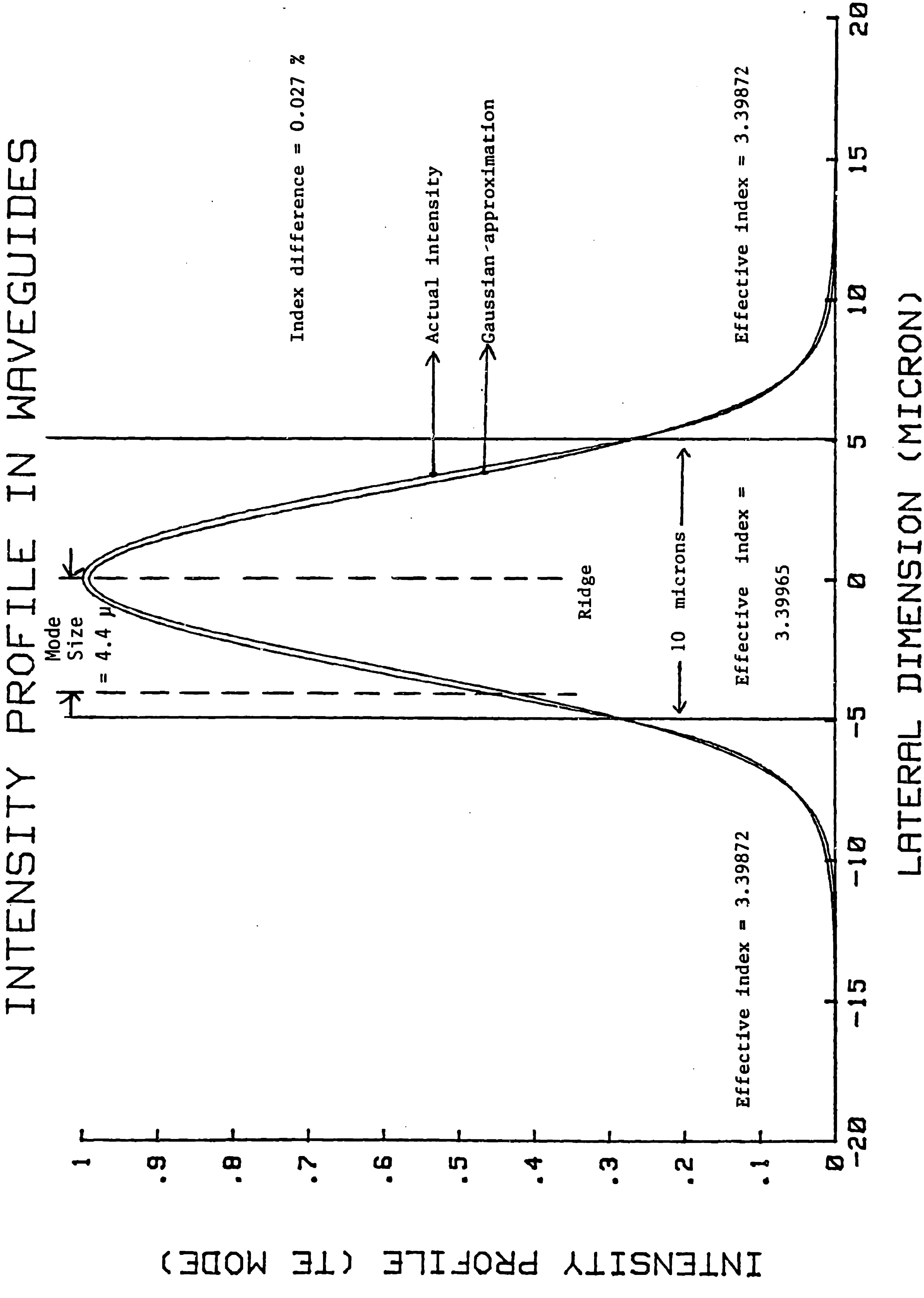

INTENSITY PROFILE IN WAVEGUIDES
Index difference = 0.027 %
Actual intensity
Gaussian approximation
Effective index = 3.39872
Effective index = 3.39872
Effective index = 3.39965
10 microns
Ridge
Mode Size = 4.4 μ
LATERAL DIMENSION (MICRON)
INTENSITY PROFILE (TE MODE)
-20
-15
-10
-5
0
5
10
15
20
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1

Figure 16

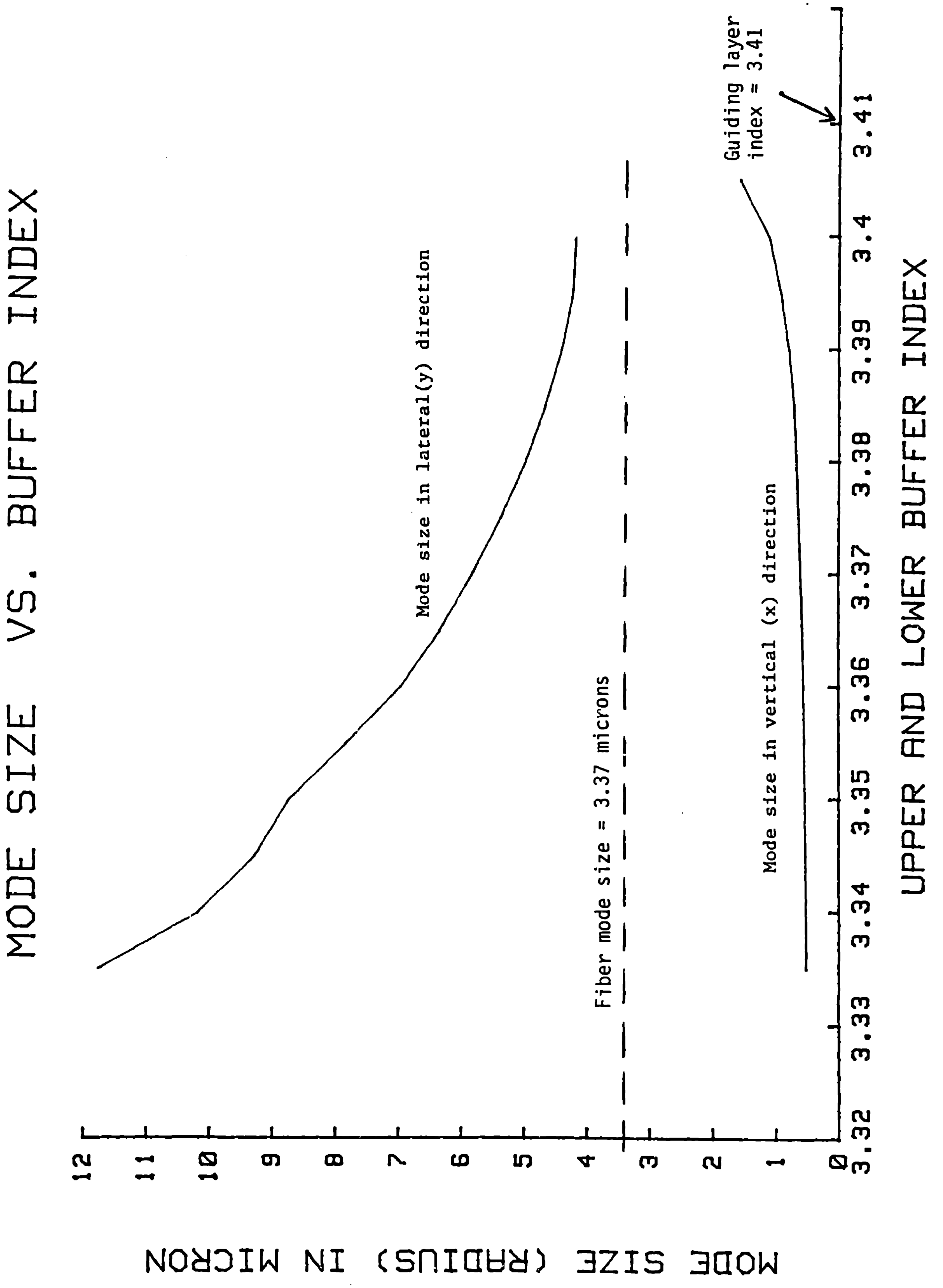
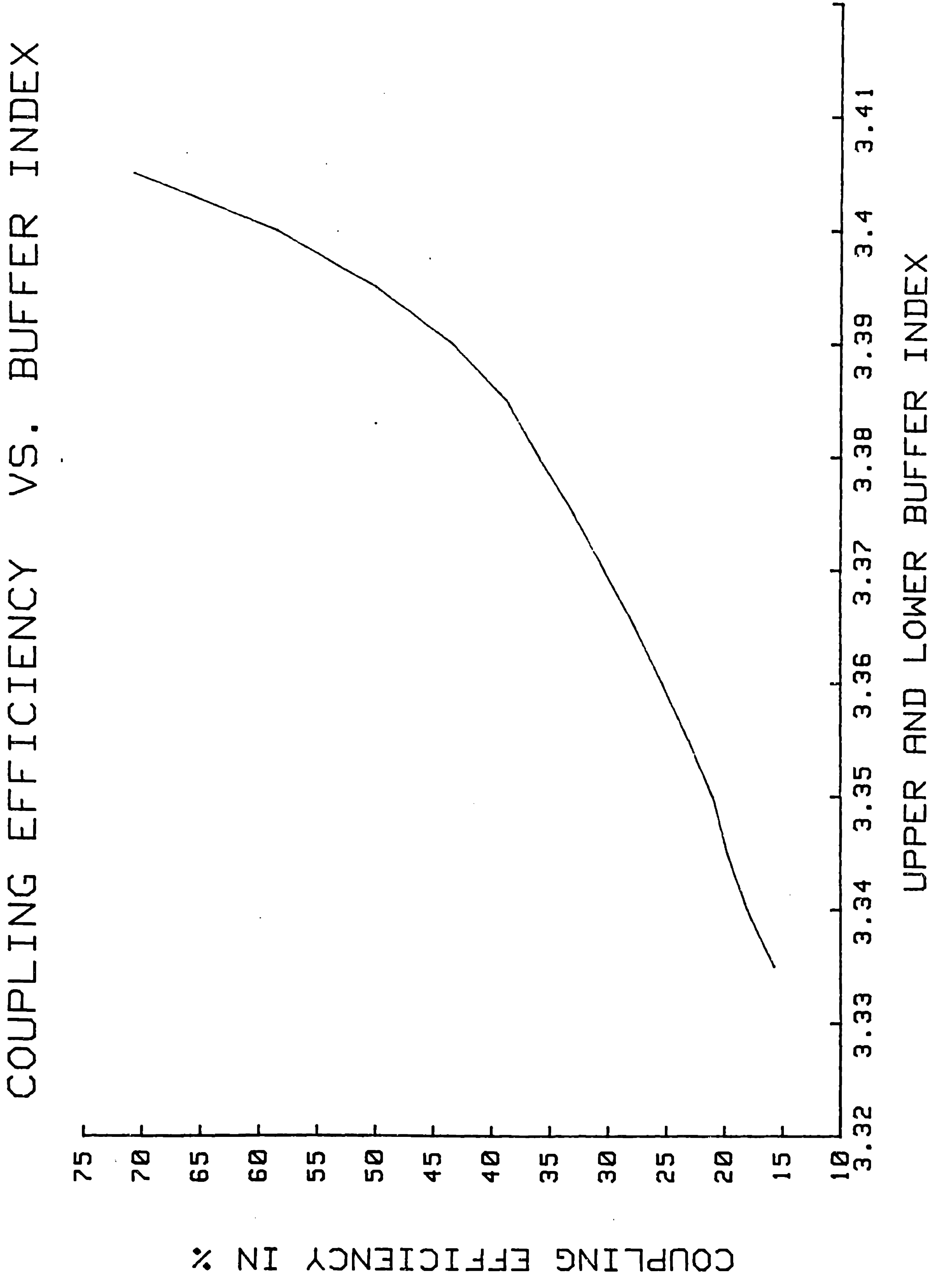

MODE SIZE VS. BUFFER INDEX
MODE SIZE (RADIUS) IN MICRON
UPPER AND LOWER BUFFER INDEX
12
11
10
9
8
7
6
5
4
3
2
1
0
3.32
3.33
3.34
3.35
3.36
3.37
3.38
3.39
3.4
3.41
Mode size in lateral(y) direction
Fiber mode size = 3.37 microns
Mode size in vertical (x) direction
Guiding layer
index = 3.41

Figure 17



COUPLING EFFICIENCY VS. BUFFER INDEX
UPPER AND LOWER BUFFER INDEX
3.32
3.33
3.34
3.35
3.36
3.37
3.38
3.39
3.4
3.41
COUPLING EFFICIENCY IN %
10
15
20
25
30
35
40
45
50
55
60
65
70
75

Figure 18

Chapter 5

EXPERIMENTS AND RESULTS

Figure 19 shows the setup of the optical coupling measurement experiments.

The original waveguides tested consisted of a GaAs (n = 3.41) guiding layer of 1.2 microns thickness neighbored by upper and lower buffer layers, which were GaAlAs with 5% Al doping (n = 3.39) [29,30]. The upper buffer layer thickness was 2 microns and the lower buffer layer thickness was 5 microns. Waveguides of ridge width from 3 to 10 microns, and etch depth of 0.7, 1.3, and 2.2 microns were fabricated in order to obtain a variety of waveguide dimensions. The process of etching the waveguides is illustrated in Figure 20. The case of 2.2 microns etch depth corresponded to etching past the guiding layer by 0.2 micron. Figure 21 shows the cross sectional sketch of the waveguide whose ridge width is 10 microns and etch depth is 1.3 microns. Photographs of the waveguide taken through a microscope are shown in Figures 22 and 23. Figure 22 is the top view of the waveguides and Figure 23 is the cross sectional view of the same waveguides shown in Figure 22.

Because of the unavailability of a pigtailed laser during the course of this work, bulk optic components were used to

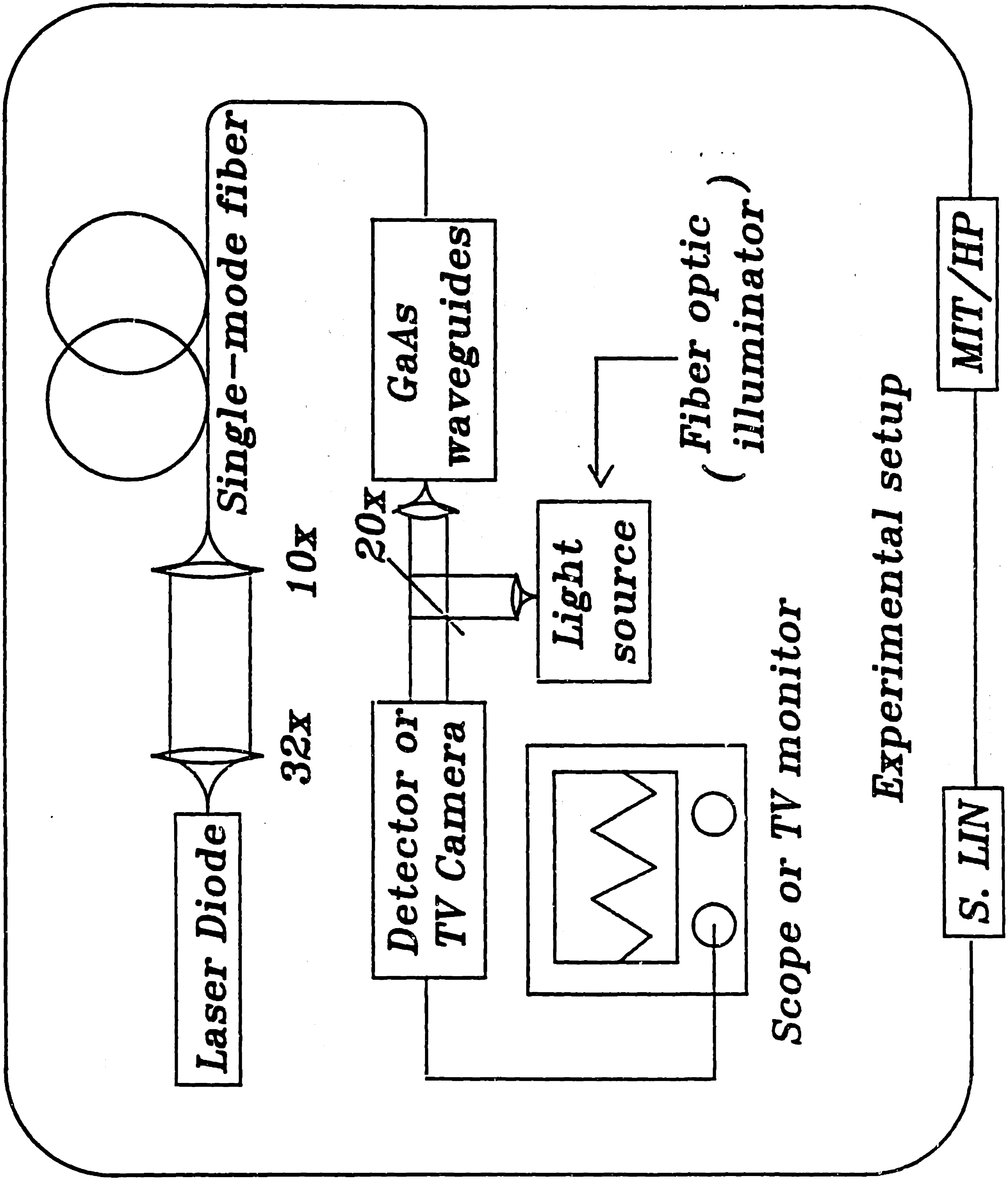
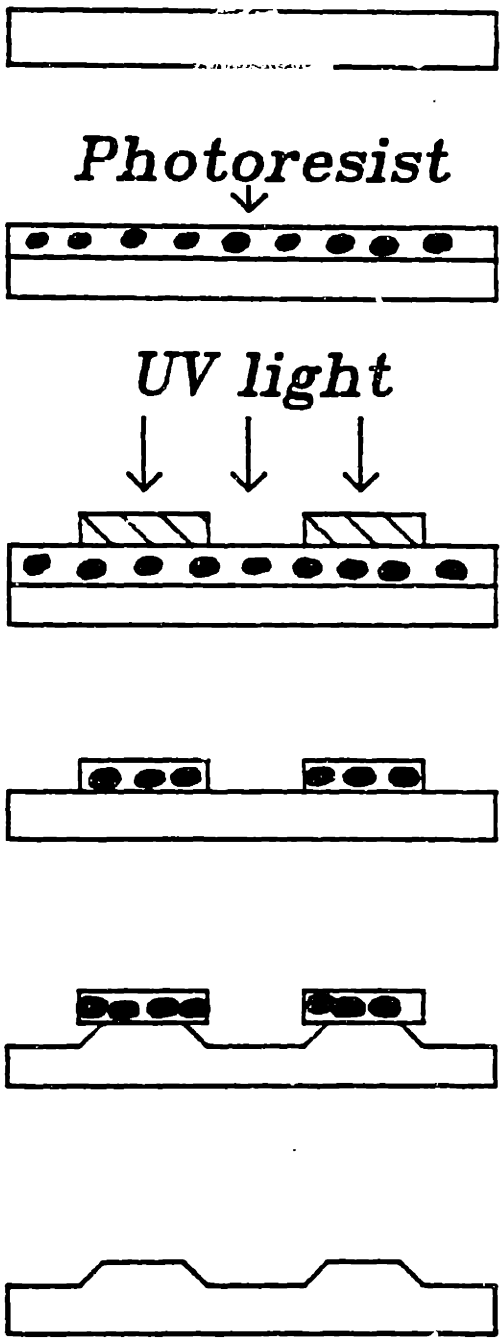

Laser Diode
32x
10x
Single-mode fiber
GaAs
waveguides
20x
Light
source
Fiber optic
(illuminator)
Detector or
TV Camera
Scope or TV monitor
Experimental setup
S. LIN
MIT/HP

Figure 19



Inspect, clean & orient the wafer

Spin on positive photoresist(AZ1350J)

Lay the mask on & expose the wafer to ultraviolet light

Develop photoresist using KOH developer

Etch the waveguides using H_2SO_4 + H_2O_2 + H_2O

Strip photoresist by acetone

Waveguide Fabrication Process

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Figure 20

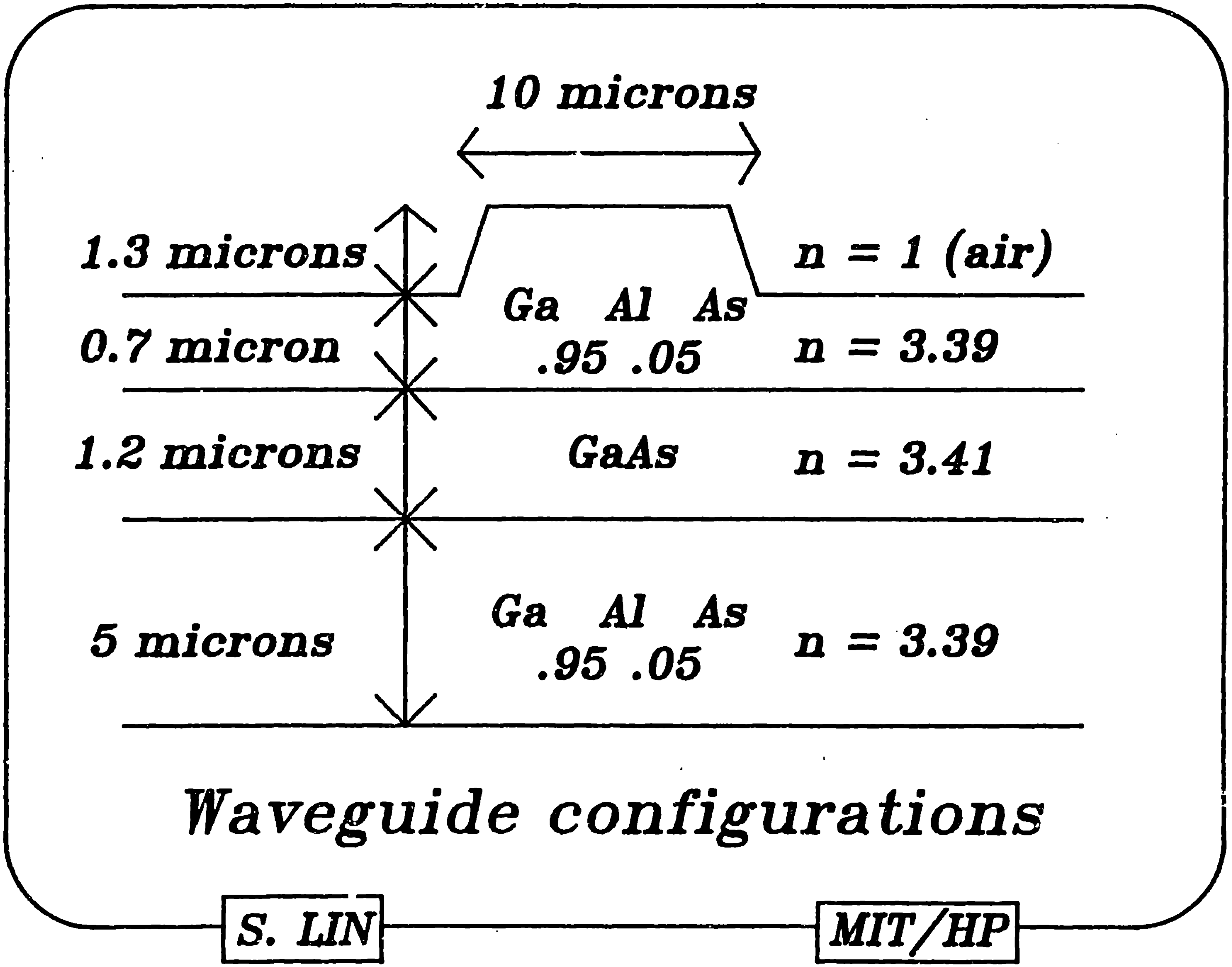
10 microns
1.3 microns
0.7 micron
1.2 microns
5 microns
Ga Al As
.95 .05
GaAs
Ga Al As
.95 .05
n = 1 (air)
n = 3.39
n = 3.41
n = 3.39
Waveguide configurations
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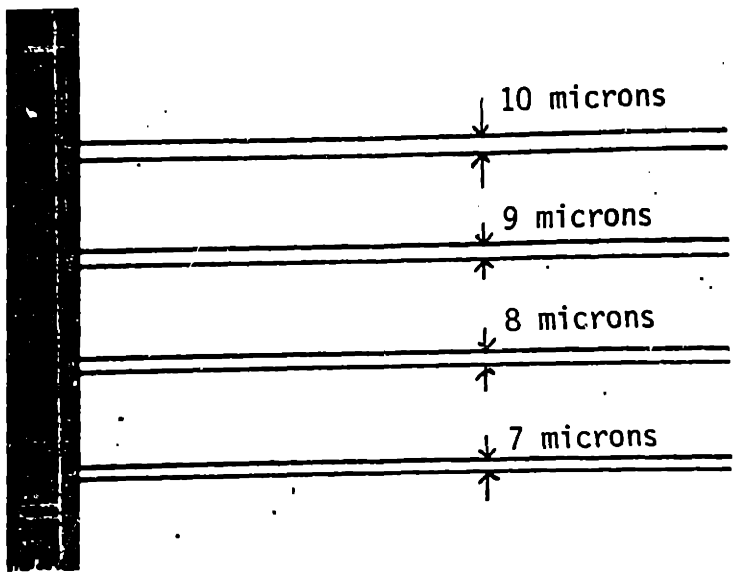
Figure 21



Top view of the waveguides

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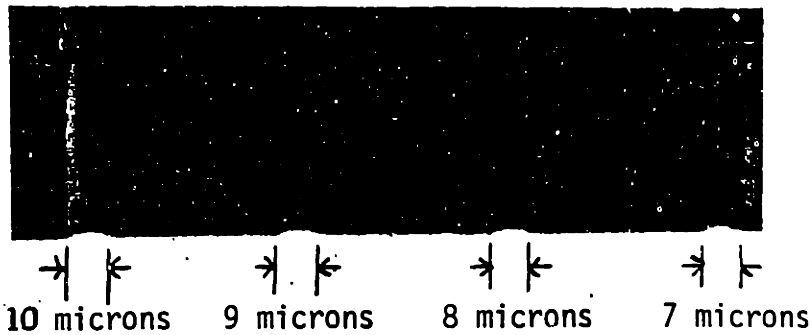
Figure 22



Side view of the waveguides

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Figure 23

collimate the laser light in the input stage. A laser diode of wavelength 1.3 microns was used as the source of the light. It was collimated by a 32x microscope objective and focused by a 10x microscope objective into a piece of single-mode fiber whose core radius was 4.35 microns and core and cladding indices were 1.443 and 1.439 respectively. The other end of the fiber was butted to the waveguide under test. XYZ stages with submicron resolution were used to position the fiber such that light could be transmitted into the waveguide. The light coming out of the waveguide was focused by a 20x microscope objective and was then imaged onto a large-area Ge detector and a TV camera sensitive at 1.3 microns. The TV camera was hooked up to a TV monitor for viewing the general two dimensional intensity profile of the waveguide mode and to a scope to trace out its exact intensity profiles in the vertical and lateral directions. Thus, any ambiguity of the mode pattern or whether or not the higher order modes existed in the waveguide due to the saturation or nonlinear effects in the TV camera could be excluded.

The waveguide insertion loss consisted of both coupling loss and propagation loss. It was determined by taking the difference between the light intensities measured before the waveguide and after the microscope objective and compensating for the loss due the microscope objective (about 2 dB). Then the waveguide was cleaved and its insertion loss was measured again. With this technique of successively cleaving the waveguides and measuring the length and the insertion loss of the waveguide, we were able to calculate the propagation loss the waveguide, which is shown in Figure 24. Assuming a linear relationship between the propagation loss and the length of the waveguide, a straight line was fitted to the 4 data points obtained. The slope of the straight line corresponded to the propagation loss of the waveguide and the intercept with the vertical axis, which was extrapolated, corresponded to the coupling loss between the fiber and the waveguide, including the Fresnel reflection loss at both ends of the waveguide. From the data, about 1 dB/cm propagation loss and 3 dB loss due to mode mismatch were deduced. These numbers were for the waveguide with ridge width 10 microns and etch depth 1.3 microns.

3 dB (50%) loss due to the mismatch between the fiber mode and the waveguide mode was not far from the theorectical prediction of 42% with perfect alignment. However, experimental errors inevitably existed and accounted for some of the discrepancies. For instance, the fiber may have been placed at an angle or offset compared to the waveguide, which, in turn, would introduce more loss due to the mechanical misalignments analyzed earlier in chapter 4. A Fabry-Perot type of resonator [31] may have been formed in the waveguides due to certain reflections at the fiber-waveguide and waveguide-air boundaries, which could be eliminated if the facets of the waveguide were properly anti-reflection coated.

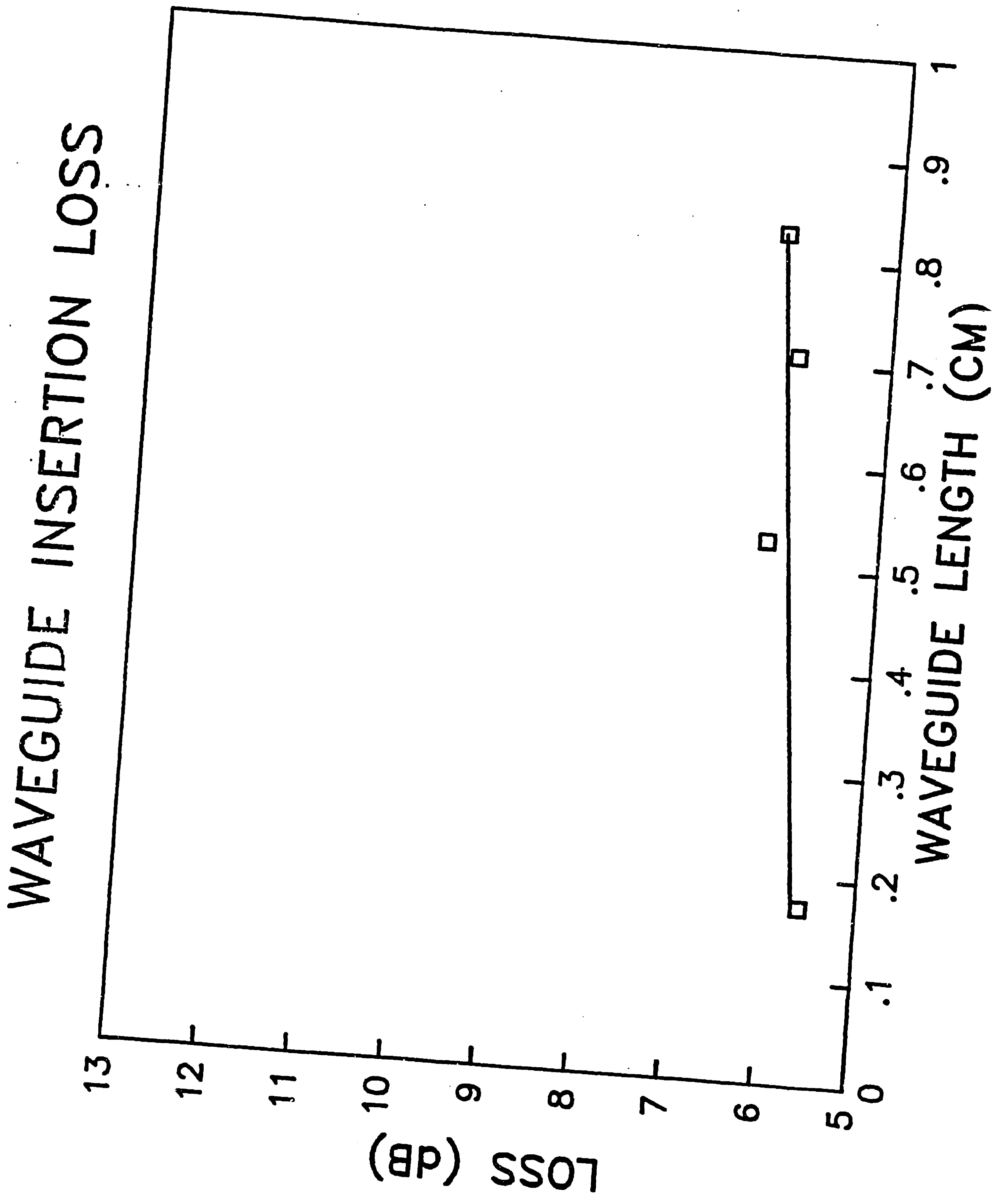
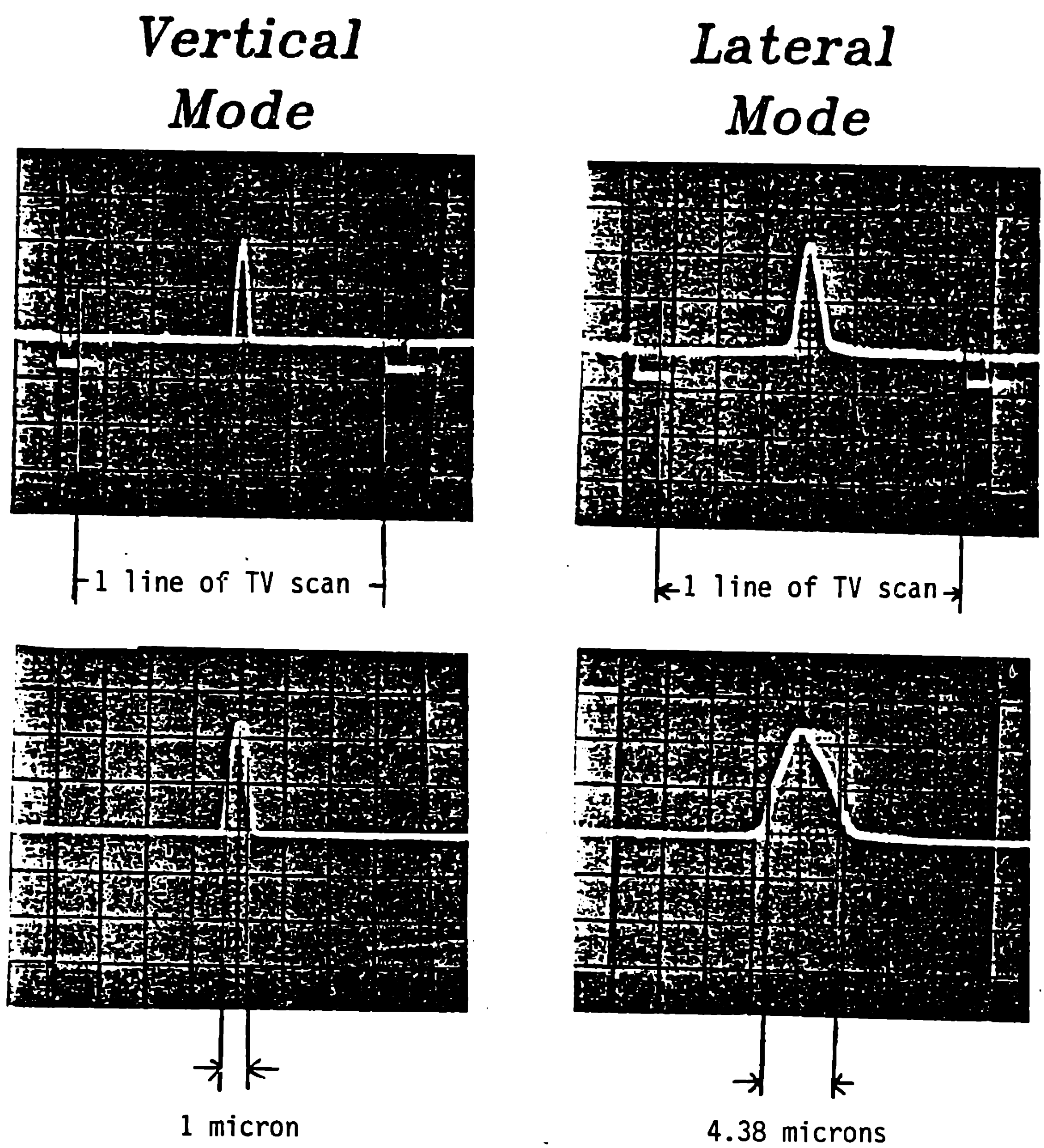

WAVEGUIDE INSERTION LOSS
LOSS (dB)
13
12
11
10
9
8
7
6
5
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
WAVEGUIDE LENGTH (CM)

Figure 24

The single-mode pattern of the waveguide mode as predicted by the theoretical model is confirmed in Figure 25. These pictures were taken with ND filters to avoid any ambiguity of whether or not the higher order modes propagated in the channel waveguide. Notice the mode sizes in the vertical and lateral directions were quite different. This was why the optical coupling loss due to mode mismatch between fibers and waveguides was high.

By illuminating the waveguide facets by a fiber optic illuminator from the output end of the waveguides to image the reflection off the facets onto the TV camera, we were able to display the waveguide mode and the ridge profile at the same time. Thus, the vertical and lateral mode sizes were calculated with reference to the dimension of the ridge. Results were shown in Table 2. Apparently, the discrepancy between the measured coupling efficiency of 50% and predicted 42% was due to the mismatch in the vertical mode. However, if the observed mode sizes were substituted into the gaussian overlap integral formula as shown in equation (37), coupling efficiency of 52% would have been predicted. This proved the validity of the gaussian approximations.

The same apparatus was used to test the 'optimal' waveguide which was designed by computer simulations. The configurations of the 'optimal' waveguide is illustrated in Figure 26. The lower and upper buffer layer's index was designed to be as close



Mode size measurements

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Figure 25

	Vertical mode size	Lateral mode size
Theory	0.8 micron	4.4 microns
Experiment	1.0 micron	4.38 microns

Mode size comparison

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Table 2

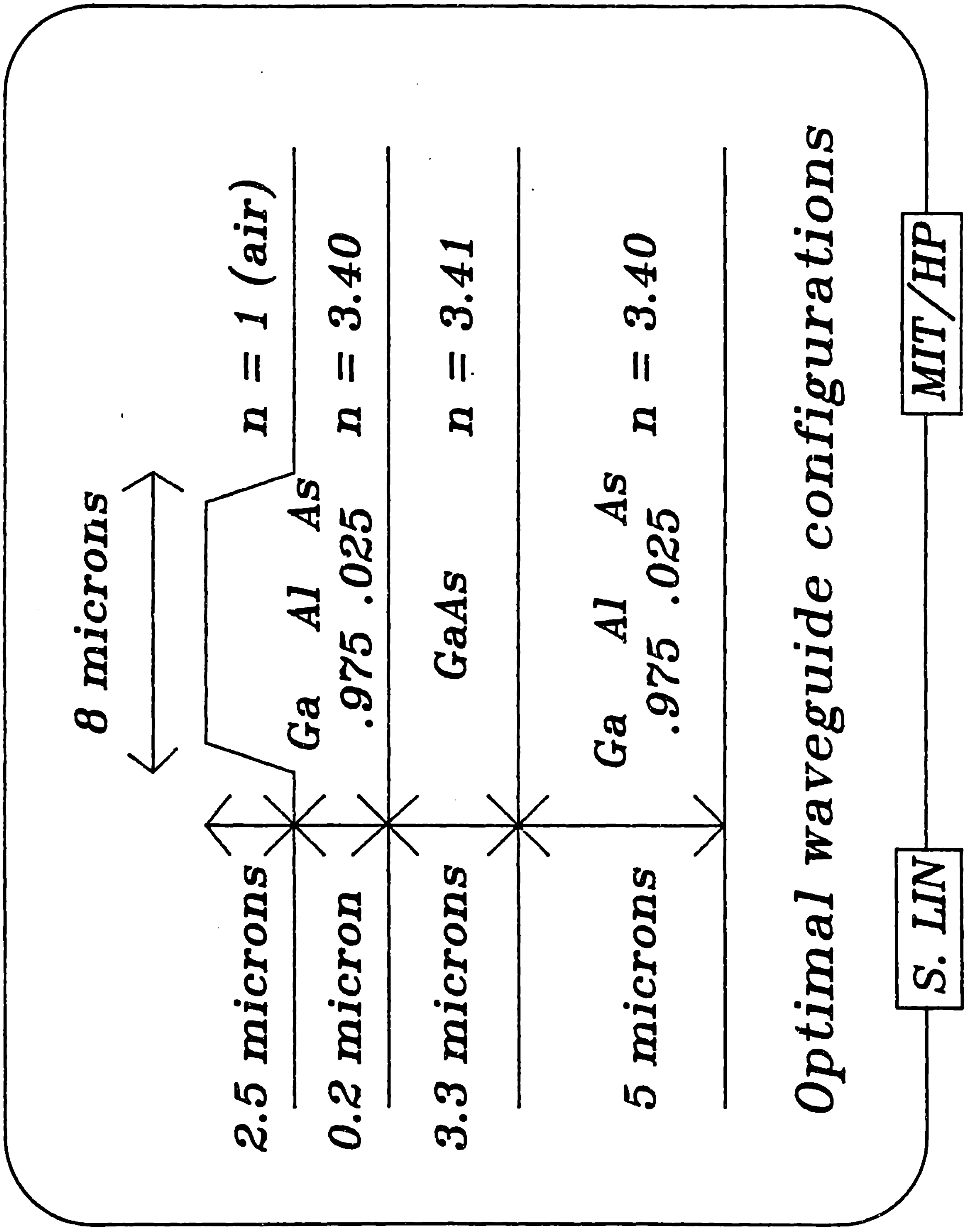
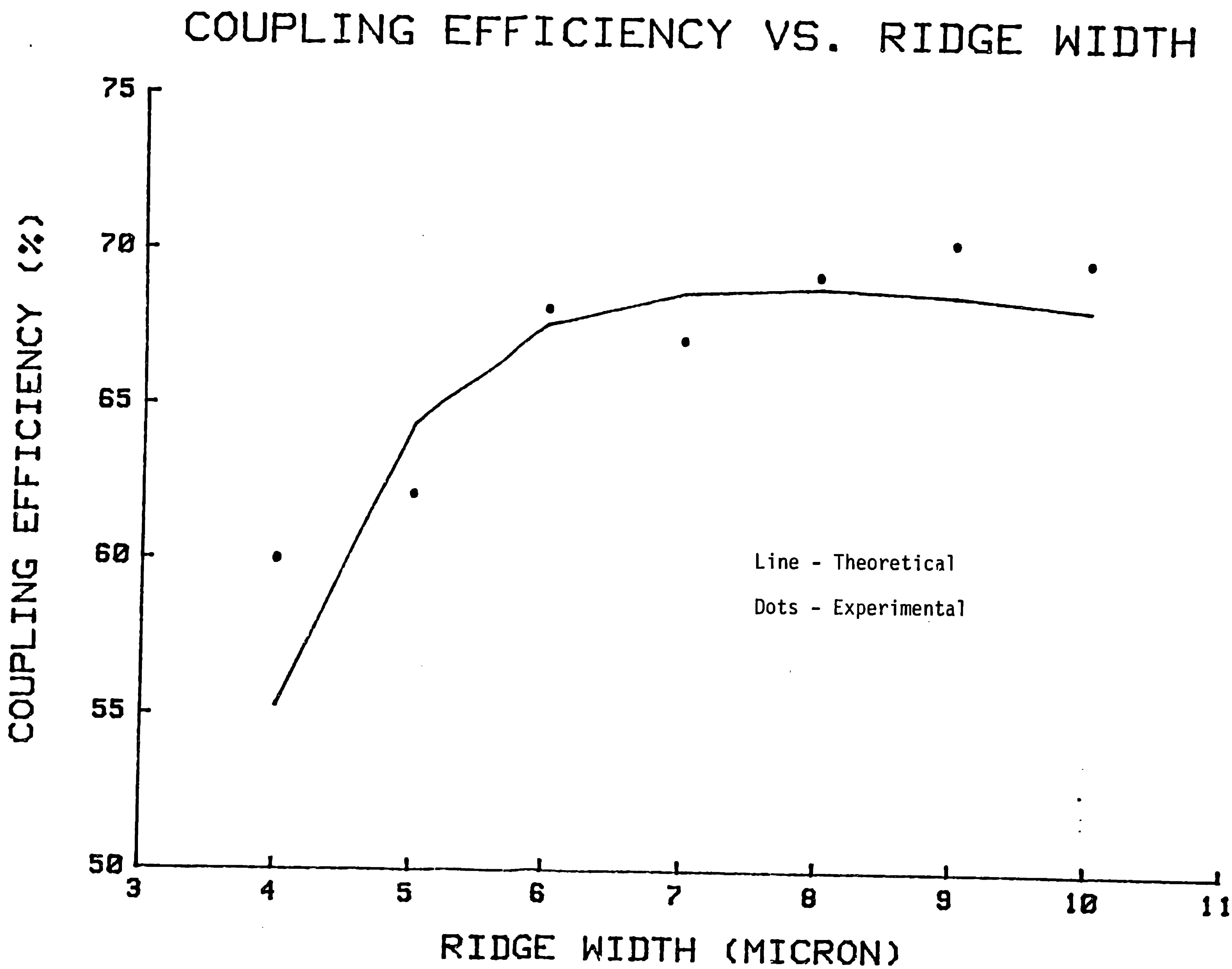

8 microns
2.5 microns
n = 1 (air)
0.2 micron
Ga .975 Al .025 As
n = 3.40
3.3 microns
GaAs
n = 3.41
5 microns
Ga .975 Al .025 As
n = 3.40
Optimal waveguide configurations
S. LIN
MIT/HP

Figure 26

to the guiding layer's index as possible to allow a thicker guiding layer, which would support a larger vertical mode to better match the fiber mode. Due to the practical limitations, the Al concentration in GaAs could only be made as small as 2.5%, which corresponded to refractive index difference of 0.01 or 1% ($\Delta n = 0.4 \ \Delta[Al]$) [29,30]. Thus, the index of the guiding layer was 3.41 and that of the buffer layers was 3.4. With these indices, guiding layer thickness of 3.3 microns, ridge height of 2.7 microns and etch depth of 2.5 microns were the best compromise to maximize the coupling efficiency and at the same time maintain the single-mode profile in the waveguide.

Results showed that there was an impressive improvement in the coupling efficiency. About 70% coupling efficiency was measured for the larger waveguides of ridge width from 6 to 10 microns and 60% coupling efficiency was measured for the smaller waveguides of ridge width 4 or 5 microns. Figure 27 shows the experimental results compared to the theoretical predictions. The agreements between the two were very strong except for the the waveguide of 4 microns ridge width. This was an indication of theoretical model breaking down due to assumption of the total field being the product of the vertical mode and the lateral mode. Because of the small ridge width and large etch depth, the evanescent fields of the guided mode effectively saw the ridge edges, which meant the wave equation needed to be re-solved with more stringent boundary conditions [25,26]. Thus the product of


COUPLING EFFICIENCY VS. RIDGE WIDTH
COUPLING EFFICIENCY (%)
75
70
65
60
55
50
3
4
5
6
7
8
9
10
11
RIDGE WIDTH (MICRON)
Line - Theoretical
Dots - Experimental

the vertical and lateral modes would not describe the actual mode adequately if substantial evanescent fields were present at the edges of the ridge.

Figure 28 shows the vertical and lateral intensity profile of the guided mode in the optimal waveguide. The results agreed with the model's prediction of a single-mode pattern in both vertical and lateral directions. Table 3 draws a comparison between the predicted and measured mode sizes in the vertical and lateral directions for this waveguide. Again, the agreements were astonishingly good.

One thing that should have been pointed out was that, despite the high coupling efficiency obtained for these waveguides, the propagation loss inevitably went up due to the large etch depth, which introduced more scattering loss. Large etch depth was, however, necessary in order to have a thicker guiding layer and still maintain the single-moded pattern. For the waveguide sample tested, the propagation loss was about 2 dB/cm for the large waveguides and up to 3 dB/cm for the small waveguides. As can be seen, there was a trade-off between the coupling efficiency and the propagation loss. Compromise between the two will have to be made in the future in order to minimize the overall insertion loss of the waveguides.

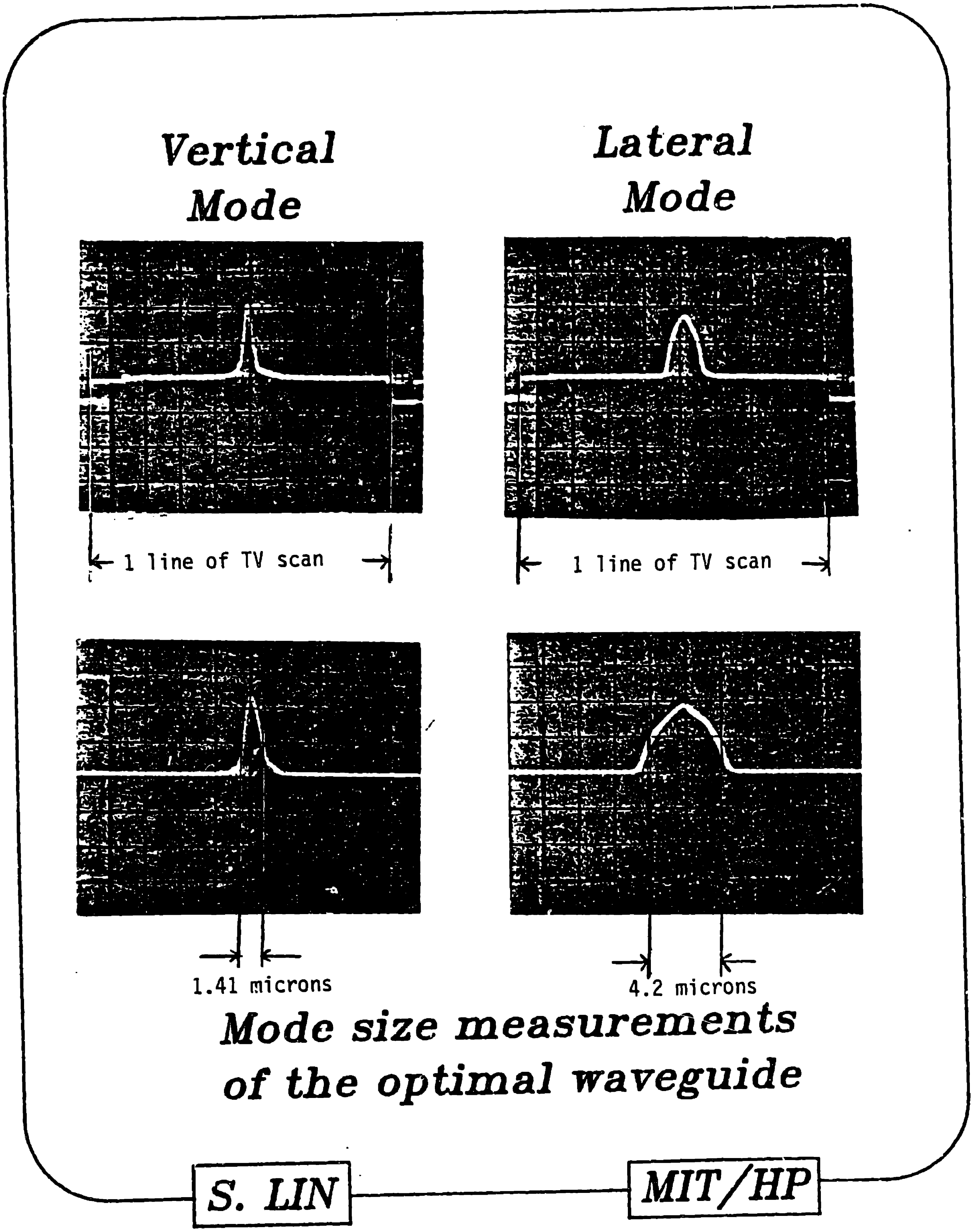

Vertical Mode
Lateral Mode
1 line of TV scan
1 line of TV scan
1.41 microns
4.2 microns
Mode size measurements of the optimal waveguide
S. LIN
MIT/HP

Figure 28

	Vertical mode size	Lateral mode size
Theory	1.39 microns	4.2 microns
Experiment	1.41 microns	4.2 microns

Mode size comparison for the optimal waveguide

S. LIN

MIT/HP

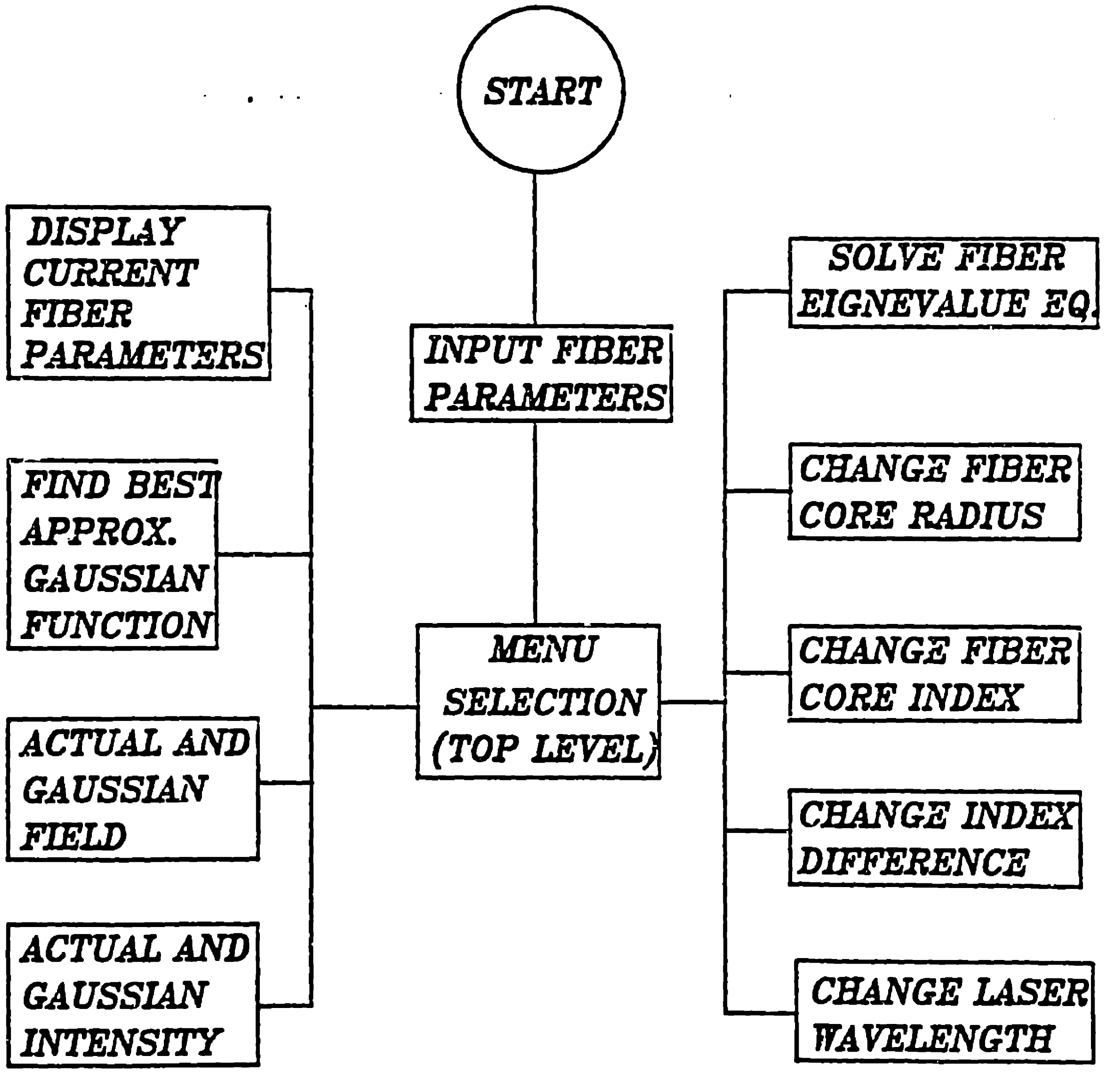
Table 3

CONCLUSION

A new coupling scheme for the electro-optic travelling wave modulator has been proposed, fabricated, and tested with the experimental results fully analyzed and compared to the theoretical predictions. The new scheme uses a piece of single-mode fiber to couple the laser light into the GaAs ridge waveguide. The coupling loss, which is due to the mismatch between the fiber mode and the waveguide mode, has been completely characterized by a model that utilizes the effective index method to solve for the parameters associated with the propagating waveguide mode. The assumption is also made that the waveguide mode is the product of the vertical mode obtained by solving a 4-layer slab waveguide independently and the lateral mode which comes from a 3-layer slab waveguide with refractive indices being the effective indices of the 4-layer slab waveguides solved earlier. The assumption has been proved to be valid as long as the optical mode is well confined in the guiding region and its evanescent field does not extend all the way to the edges of the ridge. Using this model, we have designed an optimal waveguide which should achieve 69% coupling efficiency and yet still maintain the single-mode profile. Experimental results have indeed verified the single-mode pattern in the waveguide and the coupling efficiency has been measured to be 70%. Because of the large etch depth of this waveguide, propagation loss rises due to the optical field being more easily scattered at the edges of the ridge. Thus, compromise will have to be made in the future design in order to keep the overall insertion loss of the waveguide as low as possible. However, at the present moment, the model developed to describe the coupling characteristics between the fiber and the waveguide is sufficient and adequate for predicting the coupling loss for most situations.

APPENDIX A :

THIS FIBER PROGRAM SOLVES THE EIGENVALUE EQUATION FOR THE FUNDAMENTAL PROPAGATING MODE IN A SINGLE-MODE FIBER WHOSE PARAMETERS ARE TYPED IN BY THE USER AT THE BEGINNING OF THE PROGRAM. IT IS ALSO CAPABLE OF CALCULATING THE FIELD AND INTENSITY PROFILE OF THE FUNDAMENTAL MODE. GAUSSIAN APPROXIMATION IS APPLIED SUCH THAT THE ACTUAL MODE IS APPROXIMATED BY A CIRCULARLY SYMMETRIC GAUSSIAN WHOSE ENERGY IS THE SAME AS THAT OF THE ACTUAL MODE. PARAMETERS OF THE FIBERS CAN BE CHANGED BY TYPING IN THE NEW NUMBERS AT THE TOP LEVEL WHERE THE MENU IS DISPLAYED. THE STRUCTURE OF THE PROGRAM IS ILLUSTRATED IN THE FLOW CHART SHOWN ON NEXT PAGE.



STRUCTURE OF THE PROGRAM

```
{------------------------------------------------------------------------
 THIS PROGRAM ASKS THE USER FOR THE FIBER PARAMETERS NEEDED TO CALCULATE
 THE LIGHT PROPAGATION BEHAVIORS IN SINGLE-MODE FIBERS. THEN. THE PROGRAM
 WILL ALSO SEARCHES FOR A OPTIMAL GAUSSIAN FUNCTION THAT BEST OVERLAPS THE
 FIBER MODE PROFILE WITH MINIMUN ERROR.
 ------------------------------------------------------------------------}
$UCSD$
PROGRAM FIBER (INPUT, OUTPUT);

VAR
  U ,            {NORMALIZED TRANSVERSE PROGPAGATION CONSTANT IN THE CORE}
  W ,            {NORMALIZED DECAYING CONSTANT IN THE CLADDING}
  A ,            {CORE RADIUS}
  N_CORE,        {CORE REFRACTIVE INDEX}
  N_CLADDING,    {CLADDING REFRACTIVE INDEX}
  N_DIFF,        {INDEX DIFFERENCE, DEFINED AS :

                            2                 2
                   (N_CORE)  - (N_CLADDING)       N_CORE - N_CLADDING
                   ------------------------   =   -------------------
                                  2                     N_CORE
                        2*(N_CORE)                                     }

  NA,            {NUMERICAL APERTURE}
  HEIGHT,        {HEIGHT OF THE GAUSSIAN CURVE}
  SS,            {SPOT SIZE OF THE APPROXIMATED GAUSSIAN}
  B,             {AXIAL PROPAGATION CONSTANT}
  AREA,          {AREA UNDER THE SQUARE OF J0 AND K0 CURVE FROM 0 TO
                  POSITIVE INFINITY}
  AMPLITUDE,     {AMPLITUDE FACTOR NECESSARY TO MATCH THE BOUNDARY CONDITION AT
                  THE CORE-CLADDING INTERFACE}
  LAMBDA,        {WAVELENGTH OF LIGHT}
  V              {NORMALIZED FREQUENCY}
     :   REAL ;


  GAUSSIAN,      {ARRAY TO STORE THE APPROXIMATED FIBER MODE PROFILE}
  BESSEL         {ARRAY OF 80 ELEMENTS TO STORE THE FIBER MODE PROFILE}
     :   ARRAY [0..80] OF REAL ;


  ARRAY_FILLED   {TRUE IF BOTH GAUSSIAN AND BESSEL ARRAYS ARE FULL}
     :   BOOLEAN;


CONST
  PI = 3.14159 ;
  C  = 3E8;            {SPEED OF LIGHT IN M/SEC}


{-----------------------------------------------------------------------
 THE WAIT PROCEDURE PUASES THE EXECUTION OF PROGRAM, WAITS FOR A KEY TO
 BE STRUCK FROM THE KEYBOARD, THEN CONTINUES EXECUTING ON A NEW PAGE.
 -----------------------------------------------------------------------}
 PROCEDURE WAIT;

 VAR
   REPLY  :  CHAR :

 BEGIN
```

```
   WRITE ('HIT ANY KEY TO CONTINUE');
   REPLY := ' ';
   REPEAT                          {INITIALIZATION}
     READ (REPLY);                 {KEEP READING UNTIL A KEY IS STRUCK}
   UNTIL UNITBUSY(1);              {"1" IS THE KEYBOARD UNIT}
   WRITE ( CHR ( HEX ('08')), CHR ( HEX ('20')));
                                   {CLEAR THE CHARACTER ENTERED BY THE USER BY
   WRITELN;                         EXECUTING A BACK_SPACE AND A SPACE COMMAND}
   UNITCLEAR(1);
 END;                              {RESET THE KEYBOARD UNIT}


{---------------------------------------------------------------------------
 THE FACT FUNCTION COMPUTES THE FACTORIAL OF AN INTEGER.
 ---------------------------------------------------------------------------
 FUNCTION FACT ( X : INTEGER ) : INTEGER ;

 VAR
    FACT_TEMP : INTEGER;

 BEGIN
   IF ((X = 0) OR (X = 1))
     THEN FACT := 1
     ELSE BEGIN                        { FACT(0) = FACT(1) = 1 }
            FACT_TEMP := 1;            {INITIALIZE TEMPORARY VARIABLE}
            REPEAT
              FACT_TEMP := FACT_TEMP * X;
              X := X - 1;
            UNTIL (X = 1);
            FACT := FACT_TEMP;
          END;
 END;


{---------------------------------------------------------------------------
 THE FOLLOWING J0 FUNCTION COMPUTES THE VALUE OF BESSEL FUNCTION OF ORDER
 ZERO GIVEN A PARAMETER FROM ITS INFINITE SERIES REPRESENTATION. REFERENCE
 CAN BE FOUND IN BUTKOV'S "MATHEMATICAL PHYSICS"  PAGE 139, AND A. SNYDER'S
 "THEORY OF OPTICAL WAVEGUIDE", EQ. 37-63.

                                    N        X     2N
                               (-1)  *  ( ------- )
                 INFINITY                   2
   J0 (X) =    SUMMATION    -------------------------------
                  N = 0                        2
                                    FACT ( N )

 ---------------------------------------------------------------------------
 FUNCTION J0 ( X : REAL ) : REAL;

 VAR
   N         {LOOPING INDEX IN COMPUTING BESSEL FUNCTION AS THE SUM OF
               INFINITE SERIES}
      :  INTEGER ;

   TEMP,     {TEMPORARY VALUE}
   J0_TEMP   {TEMPORARY SUM FOR BESSEL FUNCTION}
      : REAL ;
```

```
BEGIN
  IF (X=0)
    THEN J0 := 1                     { J0(0) = 1 }
    ELSE BEGIN
           J0_TEMP := 0;             {INITIALIZE TEMPORARY SUM}
           FOR N := 0 TO 5  DO       {SERIES CONVERGES AFTER N=5}
             BEGIN
               TEMP := (EXP(2*N*LN(X/2))) / (SQR(FACT(N)));
               IF (N MOD 2) = 1 THEN TEMP := -(TEMP);
               J0_TEMP := J0_TEMP + TEMP;
             END;
           J0 := J0_TEMP;
         END;
END;

{-----------------------------------------------------------------------------
 THE K0 FUNCTION RETURNS THE VALUE OF HANKEL FUNCTION FOR A GIVEN PARAMETER.
 THIS IS BASED ON THE INTEGRAL FORMULA FOR HANKEL, K0, FUNCTION GIVEN BY
 A. SNYDER IN HIS BOOK OF "THEORY OF OPTICAL WAVEGUIDE", EQ. 37-66.


                infinity      -x * cosh (t)
  K0 (x) =   INTEGRAL     ( e               ) dt
                 t = 0


 THE TRAPEZOID APPROXIMATION METHOD IS USED IN NUMERICALLY INTEGRATING
 THIS INTEGRAL BECAUSE OF ITS COMPARATIVELY FASTER CONVERGENCE THAN
 APPROXIMATING THE INTEGRAL BY SUCCESSIVE RECTANGLES.
 -----------------------------------------------------------------------------}
FUNCTION K0 ( X : REAL ) : REAL ;

VAR
  K0_SUM              {TEMPORARY SUM OF HANKEL FUNCTION}
     :  REAL ;

  SAMPLE,             {NUMBER OF SAMPLES IN NUMERICAL INTEGRATION OF K0 FUNCTION
                       IN ONE UNIT OF X}
  K_UPPERLIMIT,       {UPPER LIMIT OF K0 NUMERICAL INTEGRATION. INTEGRATION AFTER
                       THIS UPPER LIMIT IS IGNORED BECAUSE THE INTEGRAL HAS
                       CONVERGED TO A FINITE NUMBER.}

  K                   {COUNTING INDEX}
     :  INTEGER ;

          {IF THE ARGUMENT OF K0 FUNCTION IS SMALL, THEN THE CONVERGENCE
           RATE IS SLOW, THUS A LARGER K_UPPERLIMIT IS REQUIRED. HOWEVER,
           BECAUSE THE FUNCTION IS NOT CHANGING VERY FAST FOR SMALL ARGUMENT,
           FEWER NUMBER OF SAMPLES PER UNIT OF ARGUMENT WILL BE SUFFICIENT
           TO ENSURE ACCURACY.
           FOR LARGE ARGUMENT OF K0 FUNCTION, SMALLER K_UPPERLIMIT IS
           SUFFICIENT AND NECESSARY BECAUSE CONVERGENCE RATE IS SO FAST THAT
           INTEGRAL CONVERGES ALMOST IMMEDIATELY AND TO AVOID THE PROBLEM OF
           REAL NUMBER UNDERFLOW IMPLEMENTED IN THE PASCAL LANGUAGE STRUCTURE
           THE INTEGRAL HAS TO BE TRUNCATED AS SOON AS IT CONVERGES.
           HOWEVER, BECAUSE THE INTEGRAND IS CHANGING VERY DRASTICALLY WITHIN
```

```
          THE CONVERGING RANGE, MORE NUMBER OF SAMPLES PER UNIT OF ARGUMENT
          IS REQUIRED TO ENSURE ACCURACY AS IS IN THE CASE OF X>10.
          THE PRODUCT OF K_UPPERLIMIT AND SAMPLE IS KEPT AS SMALL AS
          POSSIBLE TO REDUCE THE NUMBER OF COMPUTATION ITERATIONS REQUIRED.

BEGIN
  IF (X < 0.0001 )
     THEN BEGIN
            K_UPPERLIMIT := 16;
            SAMPLE := 2;
          END;
  IF ( (X < 0.001) AND (X >= 0.0001))
     THEN BEGIN
            K_UPPERLIMIT := 14;
            SAMPLE := 2;
          END;
  IF ( (X < 0.01) AND (X >= 0.001))
     THEN BEGIN
            K_UPPERLIMIT := 12;
            SAMPLE := 2;
          END;
  IF ( (X < 0.1) AND (X >= 0.01))
     THEN BEGIN
            K_UPPERLIMIT := 9;
            SAMPLE := 2;
          END;
  IF ( (X < 1) AND (X >= 0.1))
     THEN BEGIN
            K_UPPERLIMIT := 7;
            SAMPLE := 2;
          END;
  IF ( (X < 10) AND (X >= 1))
     THEN BEGIN
            K_UPPERLIMIT := 4;
            SAMPLE := 3;
          END;
  IF ( X >= 10 )
     THEN BEGIN
            K_UPPERLIMIT := 2;
            SAMPLE := 4;
          END;


  K0_SUM := 0;
  K := K_UPPERLIMIT * SAMPLE;
  K0_SUM := K0_SUM + (EXP (-X * (EXP( K/SAMPLE )+ EXP( -K/SAMPLE ))/2)
                     + EXP(-X)/(2*SAMPLE));
  FOR K := 1 TO (K_UPPERLIMIT*SAMPLE-1) DO
    BEGIN
      K0_SUM := K0_SUM + EXP(-X*(EXP(K/SAMPLE)+EXP(-K/SAMPLE))/2)/SAMPLE;
    END;
  K0 := K0_SUM;
END;


{-----------------------------------------------------------------------
 THE GLOGE FUNCTION COMPUTES THE NORMALIZED TRANSVERSE PROPAGATION
 CONSTANT FROM A GIVEN NORMALIZED FREQUENCY. THIS FUNCTION IS BASED ON
 THE FORMULA GIVEN BY GLOGE IN APPLIED OPTICS, VOL. 10, PAGE 2252-2258,
 EQUATOIN # 18 FOR HE11 MODE.
```

```
 ------------------------------------------------------------------------}

FUNCTION GLOGE ( FREQUENCY : REAL ) : REAL;

BEGIN
  GLOGE := (1+SQRT(2))*FREQUENCY/(1+EXP(0.25*LN(4+EXP(4*LN(FREQUENCY)))));
END;


{------------------------------------------------------------------------
 STATUS PROCEDURE INFORMS THE USER THE CURRENT FIBER PARAMETERS.
 ------------------------------------------------------------------------}
PROCEDURE STATUS;

BEGIN
  PAGE;
  NA := SQRT (2*N_DIFF) * N_CORE;             {COMPUTES NUMERICAL APERTURE}
  N_CLADDING := N_CORE * SQRT(1 - 2*N_DIFF);  {COMPUTES CLADDING INDEX}
  WRITELN ('CURRENT FIBER PARAMETERS ARE AS FOLLOWS :');
  WRITELN ('=========================================================');
  WRITELN ('FIBER CORE RADIUS ------------>', A*1E6:3:2, ' MICRONS');
  WRITELN ('FIBER CORE INDEX ------------->', N_CORE:4:3);
  WRITELN ('CLADDING INDEX---------------->', N_CLADDING:4:3);
  WRITELN ('FIBER INDEX DIFF ------------->', N_DIFF*100:3:2, ' %');
  WRITELN ('NUMERICAL APERTURE ----------->', NA:4:3);
  WRITELN ('WAVELENGTH ------------------->', LAMBDA*1E6:3:2, ' MICRONS');
  WRITELN ('=========================================================');
  WRITELN;
  WAIT;
END;


{------------------------------------------------------------------------
 FUNCTION INIT_SS SEARCHES FOR THE APPROXIMATE MODE SIZE OF THE ACTUAL
 FIBER MODE.  MODE SIZE IS DEFINED AS THE WIDTH (RADIUS) WHERE THE INTENSITY
 DROPS TO 1/e (OR FIELD DROPS TO 1/SQRT(e)).
 ------------------------------------------------------------------------}
FUNCTION INIT_SS : REAL;

VAR
  COUNT      : INTEGER ;

BEGIN
  COUNT := 0;
  REPEAT
    COUNT := COUNT + 1;
  UNTIL ( BESSEL [COUNT] <= 0.6 );
  INIT_SS := TRUNC((COUNT/20)*A*1E8)/1E8;  {CONVERSION FROM MEASUREMENT IN
                                             IN UNIT OF CORE RAIUS TO MICRON}
END;


 {------------------------------------------------------------------------
  LIST_FIELD PROCEDURE LISTS THE VALUES OF THE ACTUAL AND GAUSSIAN FIELD.
  ------------------------------------------------------------------------}
 PROCEDURE LIST_FIELD;

 VAR
   COUNT : INTEGER ;
   B,D   : REAL;
```

```
BEGIN
  IF ARRAY_FILLED                                {MAKE SURE THE ARRAYS ARE FILLED}
    THEN
      BEGIN
        PAGE;
        FOR COUNT := 0 TO 4*20 DO
          BEGIN
            D := BESSEL [COUNT];            {RETRIEVE FIBER MODE PROFILE FROM THE
                                             ARRAY}
            B := GAUSSIAN [COUNT];
            IF (((COUNT/23) = TRUNC(COUNT/23)) AND (COUNT <> 0))
                                     {CHECK IF THE SCREEN IS FULL}
              THEN WAIT;             {IF YES, HIT A KEY TO CONTINUE NEXT PAGE}
            WRITELN('COUNT = ',COUNT,' GAUSSIAN = ',B,' ACTUAL = ',D);
          END;
      END
    ELSE
      WRITELN ('FIELD PROFILE NOT STORED IN ARRAY YET !');
  WRITELN;
  WAIT;
END;


{------------------------------------------------------------------------------
 LIST_INTENSITY PROCEDURE LISTS THE VALUES OF THE ACTUAL AND GAUSSIAN FIELD
 -----------------------------------------------------------------------------}
PROCEDURE LIST_INTENSITY;

VAR
  COUNT  : INTEGER ;
  B,D    : REAL;


BEGIN
  IF ARRAY_FILLED                                {MAKE SURE THE ARRAYS ARE FILLED}
    THEN
      BEGIN
        PAGE;
        FOR COUNT := 0 TO 4*20 DO
          BEGIN
            D := BESSEL [COUNT];            {RETRIEVE FIBER MODE PROFILE FROM THE
                                             ARRAY}
            B := GAUSSIAN [COUNT];
            IF (((COUNT/23) = TRUNC(COUNT/23)) AND (COUNT <> 0))
                                     {CHECK IF THE SCREEN IS FULL}
              THEN WAIT;             {IF YES, HIT A KEY TO CONTINUE NEXT PAGE}
            WRITELN('COUNT = ',COUNT,
                    ' GAUSSIAN = ',SQR(B),' ACTUAL = ',SQR(D));
          END;
      END
    ELSE
      WRITELN ('INTENSITY PROFILE NOT STORED IN ARRAY YET !');
  WRITELN;
  WAIT;
END;

{------------------------------------------------------------------------
```

```
THE FUNCTION ERROR CALCULATES THE TOTAL ERROR BETWEEN THE ACTUAL
FIELD PROFILE AND THE APPROXIMATED GAUSSIAN PROFILE.
---------------------------------------------------------------------}
FUNCTION ERROR (SPOTSIZE, HEIGHT : REAL) : REAL;

VAR
  B,D,          {AMPLITUDES ASSOCIATED WITH BESSEL AND HANKEL FUNCTIONS}
  ERROR_SUM     {SUM OF THE ERRORS}
      : REAL ;

  COUNT         {TEMPORARY COUNTING INDEX}
      : INTEGER ;

BEGIN
  ERROR_SUM := 0;                       {INITIALIZATION}
  FOR COUNT := 0 TO 4*20 DO             {SUM UP THE ERRORS IN THE REGION FROM
                                         CORE CENTER TO 4 UNITS OF CORE RADIUS
                                         AWAY.}
    BEGIN
      D := BESSEL [COUNT];              {RETRIEVE FIBER MODE PROFILE FROM THE
                                         ARRAY}
      B := HEIGHT*EXP(-(SQR(COUNT*A/SPOTSIZE)/800));
                                        {CALCULATES THE GAUSSIAN MODE PROFILE}
      ERROR_SUM := ERROR_SUM + SQR( D  -  B ) * (COUNT*A/20);
                                        {SUM UP THE ERROR IN THE CORE REGION
                                         BETWEEN GAUSSIAN AND BESSEL FUNCTIONS
                                         AND IN THE CLADDING REGION BETWEEN
                                         GAUSSIAN AND HANKEL FUNCTIONS}
    END;
  ERROR := ERROR_SUM;
END;


{---------------------------------------------------------------------
THE PROCEDURE STORE_GAUSSIAN STORES AWAY THE VALUES OF FIBER FIELD PROFILE
IN AN ARRAY OF 80 ELEMENTS. ONE UNIT OF RADIUS CONSISTS OF 20 SAMPLES,
THUS THE ARRAY STORES THE VALUES OF ELECTRIC FIELD FROM CORE CENTER TO
4 UNITS OF RADIUS AWAY.
---------------------------------------------------------------------}
PROCEDURE STORE_GAUSSIAN;

VAR
  INDEX            {INDEX OF THE ARRAY}
    :  INTEGER;

BEGIN
  FOR INDEX := 0 TO 80
    DO GAUSSIAN [INDEX] := HEIGHT*EXP(-(SQR(INDEX*A/SS)/800));
  ARRAY_FILLED := TRUE;
END;


{---------------------------------------------------------------------
THE PROCEDURE STORE_BESSEL STORES AWAY THE VALUES OF FIBER FIELD PROFILE
IN AN ARRAY OF 80 ELEMENTS. ONE UNIT OF RADIUS CONSISTS OF 20 SAMPLES,
THUS THE ARRAY STORES THE VALUES OF ELECTRIC FIELD FROM CORE CENTER TO
4 UNITS OF RADIUS AWAY.
---------------------------------------------------------------------}
PROCEDURE STORE_BESSEL;
```

```
VAR
  INDEX              {INDEX OF THE ARRAY}
    :  INTEGER;

BEGIN
  FOR INDEX := 0 TO 80
    DO IF INDEX <= 20
              THEN BESSEL [INDEX] :=  J0(U*INDEX/20)
                                      {BESSEL FUNCTION IN THE CORE REGION}
              ELSE BESSEL [INDEX] :=  AMPLITUDE*K0(W*INDEX/20):
                                      {MODIFIED BESSEL FUNCTION IN THE CLADDING
                                       REGION}
END;

{-----------------------------------------------------------------------
THE FIND_AREA PROCEDURE CALCULATES THE AREA OF THE SQUARE OF FIBER MODE
PROFILE (J0 AND K0 FUNCTIONS) FROM ZERO TO POSITIVE INFINITY. TRAPEZOID
APPROXIMATION IS USED TO CARRY OUT THE NUMERICAL INTEGRATION.
-----------------------------------------------------------------------}
PROCEDURE FIND_AREA;

VAR
  COUNT          {TEMPORARY INDEX IN KEEPING TRACK OF THE AREA}
      : INTEGER ;

  X              {TEMPORARY VARIABLE}
      : REAL ;

BEGIN
   COUNT := 0;                          {INITIALIZATION}
   AREA := 0;                           {INITIALIZATION}
   X := 0;                              {R*dR = 0 FOR THE FIRST POINT}
   REPEAT
     AREA := AREA + X;
     COUNT := COUNT + 1;
     IF (COUNT <= 80)                   {IF WITHIN THE REGION OF 4 UNITS OF CORE
                                         RADIUS, READ THE VALUE FROM THE ARRAY.
                                         OTHERWISE GO AHEAD TO CALCULATE THE
                                         VALUES NOT STORED IN THE ARRAY.}
       THEN X := SQR(BESSEL[COUNT])*COUNT*SQR(A/20)
       ELSE X := SQR(AMPLITUDE*K0(W*COUNT/20))*COUNT*SQR(A/20);
   UNTIL (X <= 0.0000002 * AREA);     {CHECK IF THE AREA HAS CONVERGED}
   AREA := AREA + X/2;
   WRITELN ('COUNT =',COUNT,'  AREA = ',AREA);
END;

{-----------------------------------------------------------------------
PROCEDURE GAUSSIAN_FIT WILL FIND A GAUSSIAN CURVE THAT BEST FITS THE ACTUAL
FIBER MODE AND HAS THE SAME AMOUNT OF ENERGY.
-----------------------------------------------------------------------}
PROCEDURE GAUSSIAN_FIT;

  VAR
    INCREMENT,           {STEP INCREMENT OF SPOT SIZE}
    HEIGHT0.HEIGHT1,     {TEMPORARY VARIABLES}
    NEW_ERROR,           {TOTAL NEW ERROR }
    OLD_ERROR            {TOTAL OLD ERROR }
```

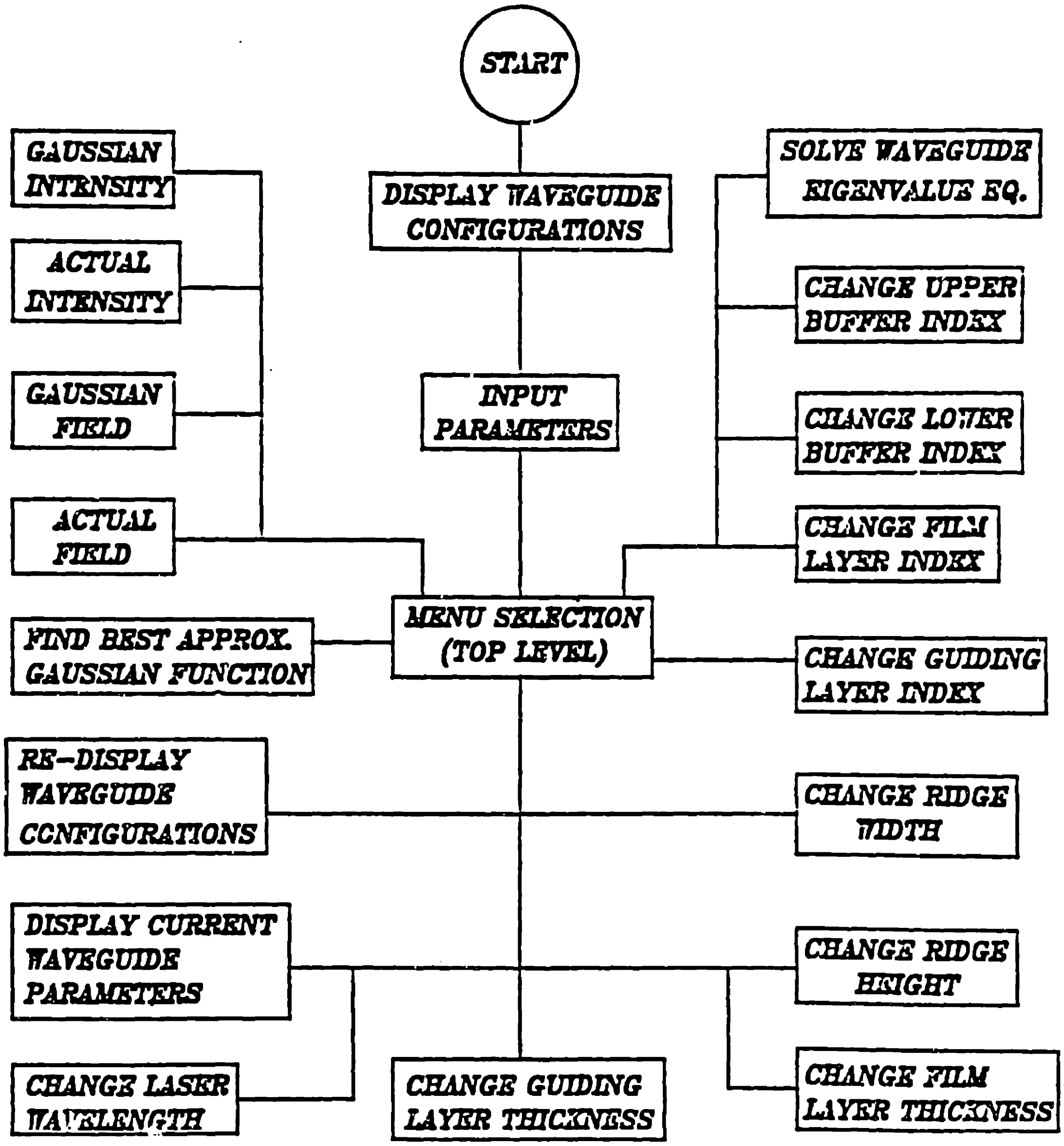
```
     : REAL ;


  BEGIN
    PAGE;
    WRITELN;
    WRITELN ('SEARCHING FOR THE BEST GAUSSIAN ...........');
    WRITELN ('==========================================================');
    SS := INIT_SS;
    INCREMENT := 1E-8;                 (INCREMENT STEP SIZE IN 0.01 MICRON)

    HEIGHT0 :=SQRT(2*AREA/(SQR(SS)));(INITIAL HEIGHT OF THE GAUSSIAN)
    NEW_ERROR := ERROR (SS, HEIGHT0);(INITIAL ERROR OF THE TRIAL GAUSSIAN)
    WRITELN ('FOR SPOT SIZE = ',SS*1E6,'  MICRONS');
    WRITELN ('HEIGHT = ',HEIGHT0,'      ERROR = ',NEW_ERROR);
    WRITELN;
                                       (DETERMINE WHETHER THE STEP SIZE
                                        SHOULD BE INCREMENTED OR DECREMENTED
                                        TO MINIMIZE THE ERROR)

    HEIGHT1 :=SQRT(2*AREA/(SQR(SS+INCREMENT)));(HEIGHT OF THE NEW GAUSSIAN)
    IF ERROR (SS+INCREMENT,HEIGHT1) > NEW_ERROR(CHECK WHICH GAUSSIAN RESULTS)
       THEN INCREMENT := -INCREMENT;            (IN GREATER ERROR)
    REPEAT                             (SEARCH FOR THE SPOT SIZE WHICH MINIMIZES
                                        THE ERROR BY TRYING DIFFERENT VALUES OF
                                        SPOT SIZE STEPPED BY THE INCREMENT)
      SS := SS + INCREMENT;
      HEIGHT := SQRT(2*AREA/(SQR(SS)));
      OLD_ERROR := NEW_ERROR;
      NEW_ERROR := ERROR(SS,HEIGHT);
      WRITELN ('FOR SPOT SIZE = ',SS*1E6,'  MICRONS');
      WRITELN ('HEIGHT = ',HEIGHT,'      ERROR = ',NEW_ERROR);
      WRITELN;
    UNTIL (NEW_ERROR>OLD_ERROR);       (KEEP DOING THIS UNTIL THE ERROR HAS
                                        REACHED THE MINIMUN AND THUS THE BEST
                                        SPOT SIZE HAS BEEN FOUND.)
    SS := SS - INCREMENT;              (PRINT OUT THE FINAL RESULTS)
    HEIGHT := SQRT(2*AREA/(SQR(SS)));
    WRITELN ('==========================================================');
    WRITELN ('PREDICTED GAUSSIAN BEST APPROXIMATING THE FIBER MODE :');
    WRITELN ('SPOT SIZE = ',SS*1E6:3:2,'  MICRONS      HEIGHT = ',HEIGHT);
    WRITELN ('==========================================================');
    STORE_GAUSSIAN;                    (STORE THE OPTIMAL GAUSSIAN IN ARRAY)
    WRITELN;
    WAIT;
  END;


{-----------------------------------------------------------------------------
 PROCEDURE SOLVE SOLVES THE EIGENVALUE EQUATION FOR THE FIBER PROPAGATION
 CONSTATN AND OTHER RELEVANT PARAMETERS.
 ----------------------------------------------------------------------------}
PROCEDURE SOLVE;

BEGIN
   PAGE;
   WRITELN;
   WRITELN;
   WRITELN ('==========================================================');
   V := (2)*(PI)*(A)*(N_CORE)*(SQRT(2*N_DIFF))/(LAMBDA);
```

```
                                        {COMPUTES NORMALIZED FREQUENCY}
   U := GLOGE (V);                      {COMPUTES U BY GLOGE'S FORMULA}
   W := SQRT (SQR(V) - SQR(U));         {COMPUTES DECAYING CONSTANT}
   B := N_CLADDING*2*PI*(1+N_DIFF-N_DIFF*(SQR(U/V)))/LAMBDA;
                                        {COMPUTES THE AXIAL PROPAGATION CONSTANT}
   WRITELN ('NORMALIZED FREQUENCY,             V  =  ',V);
   WRITELN ('TRANSVERSE PROPAGATION CONSTANT,  U  =  ',U);
   WRITELN ('DECAY CONSTANT,                   W  =  ',W);
   WRITELN ('PROPAGATION CONSTANT,             B  =  ',B);
   WRITELN ('===========================================================');
   AMPLITUDE:= J0(U)/K0(W);             {AMPLITUDE FACTOR MULTIPLIED BY
                                         K0 FUNCTION TO MATCH UP J0 FUNCTION
                                         AT THE CORE-CLADDING INTERFACE}
   STORE_BESSEL;                        {STORE THE FIBER FIELD VALUES INTO ARRAY}
   FIND_AREA;                           {FIND THE AREA UNDER THE SQUARE OF THE
                                         FIBER FIELD PROFILE}
   WRITELN;
   WAIT;
END;


{-----------------------------------------------------------------------
 CHANGE PROCEDURE CHANGES THE FIBER PARAMETERS OR EXECUTES THE COMMAND
 RECEIVED FROM THE USER.
 ----------------------------------------------------------------------}
PROCEDURE CHANGE (NUMBER : INTEGER);

BEGIN
  CASE NUMBER OF
    0 : SOLVE;
    1 : BEGIN
          WRITE ('FIBER CORE RADIUS ( IN MICRONS ) ---> ');
          READLN (A);
          A := A * 0.000001;            {UNIT CONVERSION FROM MICRON TO METER}
        END;
    2:  BEGIN
          WRITE ('FIBER CORE INDEX -------------------> ');
          READLN (N_CORE);
        END;
    3 : BEGIN
          WRITE ('FIBER INDEX DIFF ( IN % ) ----------> ');
          READLN (N_DIFF);
          N_DIFF := N_DIFF/100;         {CONVERSION FROM PERCENTAGE}
        END;
    4 : BEGIN
          WRITE ('WAVELENGTH ( IN MICRONS ) ---------> ');
          READLN (LAMBDA);
          LAMBDA := LAMBDA * 0.000001;  {UNIT CONVERSION FROM MICRON TO METER}
        END;
    5 : STATUS;
    6 : GAUSSIAN_FIT;
    7 : LIST_FIELD;
    8 : LIST_INTENSITY;
    OTHERWISE
  END;
END;

{-----------------------------------------------------------------------
 MENU PROCEDURE LET THE USER TO SELECT THE NEXT EXECUTION.
 ----------------------------------------------------------------------}
```

```
PROCEDURE MENU;

VAR
  SELECTION : INTEGER;

BEGIN
 REPEAT
  PAGE;
  WRITELN ('MENU IS AS FOLLOWS :');
  WRITELN ('=======================================================');
  WRITELN ('0. SOLVE THE FIBER EIGENVALUE EQUATION.');
  WRITELN ('1. CHANGE THE FIBER RADIUS.');
  WRITELN ('2. CHANGE THE FIBER CORE INDEX.');
  WRITELN ('3. CHANGE THE FIBER INDEX DIFFERENCE.');
  WRITELN ('4. CHANGE THE LASER WAVELENGTH.');
  WRITELN ('5. LIST THE PRESENT FIBER PARAMETERS.');
  WRITELN ('6. PROCEED TO GAUSSIAN APPROXIMATION.');
  WRITELN ('7. LIST THE ELECTRIC FIELD PROFILE.');
  WRITELN ('8. LIST THE INTENSITY PROFILE.');
  WRITELN ('=======================================================');
  WRITE ('SELECTION PLEASE  -------> ');
  READLN (SELECTION);
  WRITELN;
  WRITELN;
  CHANGE (SELECTION);
 UNTIL FALSE;
END;

{-----------------------------------------------------------------------
 THE FOLLOWING PROCEDURE ASKS THE USER FOR THE FIBER PARAMETERS
 ----------------------------------------------------------------------}
PROCEDURE INITIALIZATION;

BEGIN
  ARRAY_FILLED := FALSE;
  CHANGE ( 1 );
  CHANGE ( 2 );
  CHANGE ( 3 );
  CHANGE ( 4 );
  PAGE;
END;


 {----------------------------------------------------------------------
                            MAIN PROGRAM
 ---------------------------------------------------------------------}

 BEGIN
   INITIALIZATION;                 {USER INPUTS FIBER PARAMETERS}
   MENU;
 END.
```

APPENDIX B :

THIS PROGRAM ALLOWS THE USER TO INPUT THE WAVEGUIDE PARAMETERS AND TO CALCULATE THE WAVEGUIDE MODE PROFILE. THE EFFECTIVE INDEX METHOD IS USED TO ANALYZE AND CHARACTERIZE THE PROPAGATION BEHAVIOR. THE ACTUAL MODE IS ASSUMED TO BE THE PRODUCT OF THE VERTICAL MODE AND LATERAL MODE. THIS ASSUMPTION IS VALID ONLY IF THE ACTUAL MODE IS WELL CONFINED IN THE GUIDING REGION AND THE TAILS OF THE FIELDS DO NOT EXTEND INTO THE REGION WHERE SHARP EDGES OR DISCONTINUITY HAVE SUBSTANTIAL EFFECTS ON THE PROPAGATING MODES. THIS PROGRAM ALSO ALLOWS THE USER TO APPLY THE GAUSSIAN APPROXIMATION TO THE ACTUAL MODE BY FINDING A TWO DIMENSIONAL GAUSSIAN FUNCTION THAT BEST APPROXIMATES THE ACTUAL MODE AND YET HAS THE SAME ENERGY AS THAT OF THE ACTUAL MODE. AT THE END OF EXECUTION OF THE PROGRAM, THE USER WILL BE GIVEN ALL THE PERTINENT INFORMATION ABOUT THE BEST APPROXIMATING GAUSSIAN FUNCTION AND THE CORRESPONDING COUPLING EFFICIENCY TO THE FIBER. CERTAIN PARAMETERS OF THE WAVEGUIDE CAN BE CHANGED BY SIMPLY TYPING IN THE NEW NUMBERS IN THE TOP LEVEL WHERE THE MENU OF THE PROGRAM IS DISPLAYED. THIS FEATURE ENABLES THE USER TO SIMULATE THE WAVEGUIDE PERFORMANCE AS A FUNCTION OF A CERTAIN WAVEGUIDE PARAMETER WHILE ALL OTHER PARAMETERS ARE HELD CONSTANT. THEREFORE, THIS PROGRAM CAN BE USED AS A DESIGN TOOL TO DESIGN A RIDGE WAVEGUIDE THAT MEETS SOME SPECIFIC REQUIREMENTS.



STRUCTURE OF THE PROGRAM

```
$REF 75$
$UCSD$
PROGRAM WG (INPUT, OUTPUT);

VAR
  N_HIBFR,          {INDEX OF UPPER BUFFER LAYER}
  N_LOBFR,          {INDEX OF LOWER BUFFER LAYER}
  N_FILM,           {INDEX OF FILM LAYER}
  N_GUIDE,          {INDEX OF GUIDING LAYER}
  RW,               {RIDGE WIDTH}
  RH,               {RIDGE HEIGHT}
  FT,               {FILM THICKNESS}
  GT,               {GUIDING LAYER THICKNESS}
  BETA_1,           {AXIAL PROPAGATION CONSTANT IN REGION 1 (OUTSIDE REGION)}
  BETA_2,           {AXIAL PROPAGATION CONSTANT IN REGION 2 (INSIDE REGION)}
  EFF_N1_HI,        {EFFECTIVE INDEX OF REGION 1 FOR HIGHER ORDER MODES}
  EFF_N2_HI,        {EFFECTIVE INDEX OF REGION 2 FOR HIGHER ORDER MODES}
  EFF_INDEX_1,      {EFFECTIVE INDEX OF REGION 1 FOR THE LOWEST ORDER MODE}
  EFF_INDEX_2,      {EFFECTIVE INDEX OF REGION 2 FOR THE LOWEST ORDER MODE}
  U_GUIDE_1,        {TRANSVERSE PROPAGATION CONSTANT IN REGION 1 GUIDING LAYER}
  U_GUIDE_2,        {TRANSVERSE PROPAGATION CONSTANT IN REGION 2 GUIDING LAYER}
  W_HIBFR_1,        {DECAY CONSTANT IN UPPER BUFFER LAYER OF REGION 1}
  W_HIBFR_2,        {DECAY CONSTANT IN UPPER BUFFER LAYER OF REGION 2}
  W_LOBFR_1,        {DECAY CONSTANT IN LOWER BUFFER LAYER OF REGION 1}
  W_LOBFR_2,        {DECAY CONSTANT IN LOWER BUFFER LAYER OF REGION 2}
  W_FILM_1,         {DECAY CONSTANT IN THE FILM LAYER OF REGION 1}
  W_FILM_2,         {DECAY CONSTANT IN THE FILM LAYER OF REGION 2}
  PHI_1,            {PHASE SHIFT FACTOR IN REGION 1 AS DEFINED BY SUN AND MULLER}
  PHI_2,            {PHASE SHIFT FACTOR IN REGION 2 AS DEFINED BY SUN AND MULLER}
  KI_1,             {PHASE SHIFT FACTOR IN REGION 1 AS DEFINED BY SUN AND MULLER}
  KI_2,             {PHASE SHIFT FACTOR IN REGION 2 AS DEFINED BY SUN AND MULLER}
  G_1,              {AMPLITUDE FACTOR IN REGION 1 AS DEFINED BY SUN AND MULLER}
  G_2,              {AMPLITUDE FACTOR IN REGION 2 AS DEFINED BY SUN AND MULLER}
  G_LAT,            {AMPLITUDE FACTOR IN THE LATERAL WAVEGUIDE MODEL}
  BETA_EFF,         {EFFECTIVE AXIAL PROPAGATION CONSTANT IN WHOLE WAVEGUIDE}
  U_LATERAL,        {TRANSVERSE PROPAGATION CONSTANT IN LATERAL DIRECTION}
  W_LATERAL,        {DECAY CONSTANT IN THE LATERAL DIRECTION}
  WX,               {MODE SIZE IN THE X DIRECTION}
  WY,               {MODE SIZE IN THE Y DIRECTION}
  HEIGHT,           {HEIGHT OF THE GAUSSIAN CURVE}
  X_LIMIT,          {VERTICAL MODE SIZE OF THE ACTUAL PROFILE AS DEFINED BY 1/e}
  Y_LIMIT,          {LATERAL MODE SIZE OF THE ACTUAL PROFILE AS DEFINED BY 1/e}
  ACTUAL_SUM,       {SUM OF THE SQUARE OF THE FIELD IN THE GUIDING REGION}
  WAVELENGTH        {WAVELENGTH OF LASER}
        : REAL ;

  PROP_MODE,        {TOTAL PROPAGATING MODES IN THE WAVEGUIDE}
  TOTAL_MODE_1,     {TOTAL NUMBER OF MODES SUPPORTED VERTICALLY IN REGION 1}
  TOTAL_MODE_2,     {TOTAL NUMBER OF MODES SUPPORTED VERTICALLY IN REGION 2}
  MODE              {THE MODE NUMBER THAT IS CURRENTLY BEING CALCULATED}
        :INTEGER ;

  RH_GREATER_THAN_FT,
                    {TRUE IF RIDGE HEIGHT IS GREATER THAN THE FILM THICKNESS}
  GAUSSIAN_EMPTY,{TRUE IF ARRAYS OF GAUSSIAN PROFILE ARE EMPTY}
  ARRAY_EMPTY       {TRUE IF ARRAYS OF ACTUAL FIELD PROFILE ARE EMPTY}
        : BOOLEAN ;

  FIELD_1,          {VERTICAL ELECTRIC FIELD PROFILE OF OUTSIDE(1) REGION}
  FIELD_2,          {VERTICAL ELECTRIC FIELD PROFILE OF INSIDE(2) REGION}
```

```
  GAUSSIAN_X      {GAUSSIAN FIELD APPROXIMATION IN THE VERTICAL DIRECTION}
        : ARRAY[-40..200] OF REAL ;

  FIELD_LAT,      {LATERAL ELECTRIC FIELD PROFILE}
  GAUSSIAN_Y      {GAUSSIAN FIELD APPROXIMATION IN THE LATERAL DIRECTION}
        : ARRAY[0..200] OF REAL ;

CONST
  PI = 3.14159;

{----------------------------------------------------------------------------
 THE TANH FUNCTION COMPUTES THE HYPERBOLIC TANGENT OF A REAL NUMBER.
 ---------------------------------------------------------------------------}
FUNCTION TANH ( X : REAL ) : REAL, ;

BEGIN
  TANH := (EXP(X)-EXP(-X)) / (EXP(X)+EXP(-X));
END;

{----------------------------------------------------------------------------
 THE INV_TANH FUNCTION COMPUTES THE INVERSE OF HYPERBOLIC TANGENT. NOTE THE
 ABSOLUTE VALUE OF THE ARGUMENT HAS TO BE LESS THAN ONE.
 ---------------------------------------------------------------------------}
FUNCTION INV_TANH ( X : REAL ) : REAL ;

BEGIN
  INV_TANH := 0.5 * LN ((1+X)/(1-X));
END;

{----------------------------------------------------------------------------
 SINH FUNCITON COMPUTES THE HYPERBOLIC SINE OF A REAL NUMBER.
 ---------------------------------------------------------------------------}
FUNCTION SINH ( X : REAL ) : REAL ;

BEGIN
  SINH := (EXP(X) - EXP(-X))/2;
END;

{----------------------------------------------------------------------------
 THE FUNCTION SMALLER RETURNS THE PARAMETER OF SMALLER VALUE.
 ---------------------------------------------------------------------------}
FUNCTION SMALLER ( X, Y : INTEGER ) : INTEGER ;

BEGIN
  IF (X > Y) THEN SMALLER := Y
             ELSE SMALLER := X;
END;

{----------------------------------------------------------------------------
 THE FUNCTION GREATER RETURNS THE PARAMETER OF LARGER VALUE.
 ---------------------------------------------------------------------------}
FUNCTION GREATER ( X, Y : REAL ) : REAL ;

BEGIN
  IF (X > Y) THEN GREATER := X
```

```
                ELSE GREATER := Y;
END;

{-----------------------------------------------------------------------------
 FUNCTION ROUND ROUNDS THE NUMBER UP OR DOWN DEPENDING ON THE FIRST DECIMAL
 DIGIT.
 ----------------------------------------------------------------------------}
FUNCTION ROUND ( X : REAL ) : INTEGER ;

BEGIN
  IF ((X - TRUNC(X)) < 0.5)
    THEN ROUND := TRUNC(X)
    ELSE ROUND := TRUNC(X) + 1;
END;


{-----------------------------------------------------------------------------
 THE WAIT PROCEDURE PUASES THE EXECUTION OF PROGRAM, WAITS FOR A KEY TO
 BE STRUCK FROM THE KEYBOARD, THEN CONTINUES EXECUTING ON A NEW PAGE.
 ----------------------------------------------------------------------------}
 PROCEDURE WAIT;

 VAR
   REPLY
      : CHAR ;

 BEGIN
   REPLY := ' ';                     {INITIALIZATION}
   WRITELN;
   WRITE ('HIT ANY KEY TO CONTINUE');
   REPEAT
     READ (REPLY);                   {KEEP READING UNTIL A KEY IS STRUCK}
   UNTIL UNITBUSY(1);                {"1" IS THE KEYBOARD UNIT}
   WRITE ( CHR ( HEX ('08')), CHR ( HEX ('20')));
                                     {CLEAR THE CHARACTER ENTERED BY THE USER BY
                                      EXECUTING A BACK_SPACE AND A SPACE COMMAND}
   WRITELN;
   UNITCLEAR(1);                     {RESET THE KEYBOARD UNIT}
 END;


{-----------------------------------------------------------------------------
 THIS PROCEDURE PRINTS OUT THE STRUCTURE OF THE CHANNEL WAVEGUIDE.
 ----------------------------------------------------------------------------}
PROCEDURE PRINT_WAVEGUIDE;

BEGIN
  PAGE;
  WRITELN ('WAVEGUIDE STRUCTURE : ');
  WRITELN ('=============================================================');
  WRITELN ('                                                             ');
  WRITELN ('                          <- RIDGE WIDTH ->                  ');
  WRITELN ('                          ------------------                 ');
  WRITELN ('              RIDGE HEIGHT !        ^        !  N_UPPER_BUFFER ');
  WRITELN (' BOUNDARY 1  --------------- FILM THICKNESS ----------------- ');
  WRITELN ('                                    !           N_FILM        ');
  WRITELN (' BOUNDARY 2  ----------------------------------------------- ');
  WRITELN ('             GUIDE THICKNESS                    N_GUIDE       ');
  WRITELN (' BOUNDARY 3  ----------------------------------------------- ');
```

```
  WRITELN ('                                                N_LOWER_BUFFER  ');
  WRITELN ('                                                                ');
  WRITELN ('================================================================');
  WRITELN;
END;


{-------------------------------------------------------------------------
 PRESENT_STATUS PROCEDURE INFORMS THE USER ON CURRENT STATUS OF WAVEGUIDE
 PARAMETERS. THIS IS INTENDED TO HELP THE USER KEEPING TRACK OF WHAT IS GOING
 ON ESPECIALLY IF THE USER INTENDS TO DO A LOT OF SIMULATIONS.
 -------------------------------------------------------------------------}
 PROCEDURE PRESENT_STATUS;

 BEGIN
   PAGE;
   WRITELN ('PRESENT STATUS IS AS FOLLOWS :');
   WRITELN ('==================================================================');
   WRITELN ('1. INDEX OF UPPER BUFFER LAYER  ------> ',N_HIBFR:4:3);
   WRITELN ('2. INDEX OF LOWER BUFFER LAYER  ------> ',N_LOBFR:4:3);
   WRITELN ('3. INDEX OF FILM  LAYER         ------> ',N_FILM:4:3);
   WRITELN ('4. INDEX OF GUIDING LAYER       ------> ',N_GUIDE:4:3);
   WRITELN ('5. RIDGE WIDTH                  ------> ',RW*1E6:4:2,' MICRONS');
   WRITELN ('6. RIDGE HEIGHT                 ------> ',RH*1E6:4:2,' MICRONS');
   WRITELN ('7. FILM LAYER THICKNESS         ------> ',FT*1E6:4:2,' MICRONS');
   WRITELN ('8. GUIDING LAYER THICKNESS      ------> ',GT*1E6:4:2,' MICRONS');
   WRITELN ('9. WAVELENGTH OF LASER          ------> ',WAVELENGTH*1E6:4:2,
                                                               ' MICRONS');
   WAIT;
 END;


{-------------------------------------------------------------------------
 THE PROCEDURE INIT_WX LOOKS FOR AN INITIAL MODE SIZE IN THE X DIRECTION.
 THIS INITIAL MODE SIZE IS DEFINED BY THE WIDTH OF THE MODE WHERE ITS
 INTENSITY HAS DECAYED TO 1/e OF ITS PEAK VALUE, OR EQUIVALENTLY THE E-FIELD
 HAS DECAYED TO 1/SQR(e), WHICH IS 60%, OF ITS PEAK VALUE.
 -------------------------------------------------------------------------}
PROCEDURE INIT_WX ;

VAR
  I          {TEMPORARY COUNTING INDEX, IN UNIT OF 0.1 MICRON}
     : INTEGER ;

BEGIN
  I := -20;
  REPEAT
    I := I + 1;
  UNTIL ( FIELD_2[I] >= 0.6);
  WX := (FT+GT/2) - I/1E7;      {CONVERSION TO METER}
END;


{-------------------------------------------------------------------------
 THE PROCEDURE INIT_WY LOOKS FOR AN INITIAL MODE SIZE IN THE Y DIRECTION.
 THIS INITIAL MODE SIZE IS DEFINED BY THE WIDTH OF THE MODE WHERE ITS
 INTENSITY HAS DECAYED TO 1/e OF ITS PEAK VALUE, OR EQUIVALENTLY THE E-FIELD
 HAS DECAYED TO 1/SQR(e), WHICH IS 60%, OF ITS PEAK VALUE.
```

```
-------------------------------------------------------------------------------
PROCEDURE INIT_WY ;

VAR
  I           {TEMPORARY COUNTING INDEX, IN UNIT OF 0.1 MICRON}
      : INTEGER ;

BEGIN
  I := 0;
  REPEAT
    I := I + 1;
  UNTIL ( FIELD_LAT[I] <= 0.6);
  WY := I/1E7;                         {CONVERSION TO METER}
END;


{------------------------------------------------------------------------------
 FIELD_PROFILE PROCEDURE RETRIEVES THE FIELD PROFILE IN A PARTICULAR REGION
 FROM THE ARRAY AND PRINTS THEM OUT ON THE SCREEN.
 ------------------------------------------------------------------------------}
PROCEDURE FIELD_PROFILE ;

VAR
  REGION,
  UPPERLIMIT,
  LOWERLIMIT,
  X
        : INTEGER ;


BEGIN
  IF ARRAY_EMPTY
    THEN WRITELN ('NO FIELD PROFILE STORED IN THE ARRAY')
    ELSE
     BEGIN
       WRITELN ('REGION 1 : VERTICAL FIELD PROFILE OF OUTSIDE(1) REGION');
       WRITELN ('REGION 2 : VERTICAL FIELD PROFILE OF INSIDE(2) REGION');
       WRITELN ('REGION 3 : LATERAL ELECTRIC FIELD PROFILE ');
       WRITELN ('=================================================');
       WRITE ('WHICH REGION OF FIELD PROFILE ARE YOU INTERESTED ?   ---->');
       READLN (REGION);
       PAGE;
       CASE REGION OF
         1:
           BEGIN
             IF NOT RH_GREATER_THAN_FT
               THEN
                 BEGIN
                   LOWERLIMIT := -20;
                   UPPERLIMIT := ROUND((FT+GT-RH)*1E7) + 40;
                   FOR X := LOWERLIMIT TO UPPERLIMIT DO
                    BEGIN
                      IF ((X/22)=TRUNC(X/22)) AND (X>=0) THEN WAIT;
                      IF X = 0
                       THEN WRITELN ('X = ',X,'  BOUNDARY 1   E-FIELD = ',
                                FIELD_1[X])
                       ELSE
                        BEGIN
                         IF X = ROUND((FT-RH)*1E7)
```

```
                    THEN WRITELN ('X = ',X,'  BOUNDARY 2   E-FIELD = ',
                                  FIELD_1[X])
                    ELSE BEGIN
                           IF X = UPPERLIMIT - 40
                             THEN WRITELN ('X = ',X,
                                           '  BOUNBARY 3   E-FIELD = ',
                                           FIELD_1[X])
                             ELSE WRITELN ('X = ',X,
                                           '               E-FIELD = ',
                                           FIELD_1[X]);
                         END;
                END;
            ...D;
         END
        ELSE WRITELN(' RH > FT ,   NO FIELD PROFILE STORED.');
      END;

    2:
      BEGIN
        LOWERLIMIT := -20;
        UPPERLIMIT := ROUND((FT+GT)*1E7) + 40;
        FOR X := LOWERLIMIT TO UPPERLIMIT DO
         BEGIN
          IF ((X/22)=TRUNC(X/22)) AND (X>=0) THEN WAIT;
          IF X = 0
            THEN WRITELN ('X = ',X,'  BOUNDARY 1   E-FIELD = ',
                          FIELD_2[X])
            ELSE BEGIN
                   IF X = ROUND(FT*1E7)
                     THEN WRITELN ('X = ',X,'  BOUNDARY 2   E-FIELD = ',
                                   FIELD_2[X])
                     ELSE BEGIN
                            IF X = UPPERLIMIT - 40
                              THEN WRITELN ('X = ',X,
                                            '  BOUNBARY 3   E-FIELD = ',
                                            FIELD_2[X])
                              ELSE WRITELN ('X = ',X,
                                            '               E-FIELD = ',
                                            FIELD_2[X]);
                          END;
                 END;
         END;
      END;

    3:
      BEGIN
        LOWERLIMIT := 0;
        UPPERLIMIT := 200;
        FOR X := LOWERLIMIT TO UPPERLIMIT DO
         BEGIN
          IF ((X/22)=TRUNC(X/22)) AND (X>0) THEN WAIT;
          IF X=ROUND(RW*1E7/2)
            THEN WRITELN ('X = ',X,' BOUNDARY   E-FIELD = ',FIELD_LAT[X])
            ELSE WRITELN ('X = ',X,'            E-FIELD = ',FIELD_LAT[X]);
         END;
      END;
  END;
 END;
 WAIT;
END;
```

```
{---------------------------------------------------------------------------
 GAUSSIAN_PROFILE PROCEDURE RETRIEVES THE FIELD PROFILE IN A PARTICULAR
 REGION FROM THE ARRAY AND PRINTS THEM OUT ON THE SCREEN.
 ---------------------------------------------------------------------------}
PROCEDURE GAUSSIAN_PROFILE ;

VAR
  REGION,
  UPPERLIMIT,
  LOWERLIMIT,
  X
        : INTEGER ;


BEGIN
  IF GAUSSIAN_EMPTY
    THEN WRITELN ('NO GAUSSIAN FIELD PROFILE STORED IN THE ARRAY')
    ELSE
     BEGIN
       WRITELN ('REGION 2 : VERTICAL FIELD PROFILE OF INSIDE(2) REGION');
       WRITELN ('REGION 3 : LATERAL ELECTRIC FIELD PROFILE ');
       WRITELN ('==========================================================');
       WRITE ('WHICH REGION OF FIELD PROFILE ARE YOU INTERESTED ?   ---->');
       READLN (REGION);
       PAGE;
       CASE REGION OF
         2:
           BEGIN
             LOWERLIMIT := -20;
             UPPERLIMIT := ROUND((FT+GT)*1E7) + 40;
             FOR X := LOWERLIMIT TO UPPERLIMIT DO
              BEGIN
               IF ((X/22)=TRUNC(X/22)) AND (X>=0) THEN WAIT;
               IF X = 0
                 THEN WRITELN ('X = ',X,'  BOUNDARY 1   E-FIELD = ',
                                HEIGHT*GAUSSIAN_X[X])
                 ELSE BEGIN
                        IF X = ROUND(FT*1E7)
                          THEN WRITELN ('X = ',X,'  BOUNDARY 2   E-FIELD = ',
                                         HEIGHT*GAUSSIAN_X[X])
                          ELSE BEGIN
                                 IF X = UPPERLIMIT - 40
                                   THEN WRITELN ('X = ',X,
                                              '  BOUNBARY 3   E-FIELD = ',
                                              HEIGHT*GAUSSIAN_X[X])
                                   ELSE WRITELN ('X = ',X,
                                              '               E-FIELD = ',
                                              HEIGHT*GAUSSIAN_X[X]);
                               END;
                      END;
              END;
           END;

         3:
           BEGIN
             LOWERLIMIT := 0;
             UPPERLIMIT := 200;
             FOR X := LOWERLIMIT TO UPPERLIMIT DO
```

```
              BEGIN
               IF ((X/22)-TRUNC(X/22)) AND (X>0) THEN WAIT;
               IF X=ROUND(RH*1E7/2)
                THEN WRITELN ('X = ',X,' BOUNDARY   E-FIELD = ',
                                           HEIGHT-GAUSSIAN_Y[X])
                ELSE WRITELN ('X = ',X,'             E-FIELD = ',
                                           HEIGHT-GAUSSIAN_Y[X]);
              END;
           END;
       END;
     END;
  WAIT;
END;


{--------------------------------------------------------------------------
 INTENSITY_PROFILE PROCEDURE RETRIEVES THE FIELD PROFILE IN A PARTICULAR
 REGION FROM THE ARRAY AND PRINTS THEM OUT ON THE SCREEN.
 --------------------------------------------------------------------------}
PROCEDURE INTENSITY_PROFILE ;

VAR
  REGION,
  UPPERLIMIT,
  LOWERLIMIT,
  X
        : INTEGER ;


BEGIN
  IF ARRAY_EMPTY
    THEN WRITELN ('NO INTENSITY PROFILE STORED IN THE ARRAY')
    ELSE
     BEGIN
       WRITELN ('REGION 1 : VERTICAL INTENSITY PROFILE OF OUTSIDE(1) REGION');
       WRITELN ('REGION 2 : VERTICAL INTENSITY PROFILE OF INSIDE(2) REGION');
       WRITELN ('REGION 3 : LATERAL INTENSITY PROFILE ');
       WRITELN ('===========================================================');
       WRITE ('WHICH REGION OF FIELD PROFILE ARE YOU INTERESTED ?   ---->');
       READLN (REGION);
       PAGE;
       CASE REGION OF
         1:
           BEGIN
             IF NOT RH_GREATER_THAN_FT
               THEN
                 BEGIN
                   LOWERLIMIT := -20;
                   UPPERLIMIT := ROUND((FT+GT-RH)*1E7) + 40;
                   FOR X := LOWERLIMIT TO UPPERLIMIT DO
                    BEGIN
                     IF ((X/22)=TRUNC(X/22)) AND (X>=0) THEN WAIT;
                     IF X = 0
                       THEN WRITELN ('X = ',X,'  BOUNDARY 1   E-FIELD = ',
                                SQR(FIELD_1[X]))
                       ELSE
                         BEGIN
                           IF X = ROUND((FT-RH)*1E7)
                           THEN WRITELN ('X = ',X,'  BOUNDARY 2   E-FIELD = ',
                                          SQR(FIELD_1[X]))
```

```
                    ELSE BEGIN
                           IF X = UPPERLIMIT - 40
                             THEN WRITELN ('X = ',X,
                                           '   BOUNBARY 3   E-FIELD = ',
                                           SQR(FIELD_1[X]))
                             ELSE WRITELN ('X = ',X,
                                           '               E-FIELD = ',
                                           SQR(FIELD_1[X]));
                         END;
                   END;
              END;
           END
         ELSE WRITELN(' RH > FT ,   NO INTENSITY PROFILE STORED.');
     END;

   2:
     BEGIN
       LOWERLIMIT := -20;
       UPPERLIMIT := ROUND((FT+GT)*1E7) + 40;
       FOR X := LOWERLIMIT TO UPPERLIMIT DO
        BEGIN
         IF ((X/22)=TRUNC(X/22)) AND (X>=0) THEN WAIT;
         IF X = 0
           THEN WRITELN ('X = ',X,'  BOUNDARY 1   E-FIELD = ',
                             SQR(FIELD_2[X]))
           ELSE BEGIN
                  IF X = ROUND(FT*1E7)
                    THEN WRITELN ('X = ',X,'  BOUNDARY 2   E-FIELD = ',
                                      SQR(FIELD_2[X]))
                    ELSE BEGIN
                           IF X = UPPERLIMIT - 40
                             THEN WRITELN ('X = ',X,
                                           '   BOUNBARY 3   E-FIELD = ',
                                           SQR(FIELD_2[X]))
                             ELSE WRITELN ('X = ',X,
                                           '               E-FIELD = ',
                                           SQR(FIELD_2[X]));
                         END;
                END;
        END;
     END;

   3:
     BEGIN
       LOWERLIMIT := 0;
       UPPERLIMIT := 200;
       FOR X := LOWERLIMIT TO UPPERLIMIT DO
        BEGIN
         IF ((X/22)=TRUNC(X/22)) AND (X>0) THEN WAIT;
         IF X=ROUND(RW*1E7/2)
           THEN WRITELN ('X = ',X,' BOUNDARY   E-FIELD = ',
                                   SQR(FIELD_LAT[X]))
           ELSE WRITELN ('X = ',X,'              E-FIELD = ',
                                   SQR(FIELD_LAT[X]));
        END;
     END;
 END;
END;
WAIT;
END;
```

```
{---------------------------------------------------------------------------
 GAUSSIAN_INTENSITY PROCEDURE RETRIEVES THE FIELD PROFILE IN A PARTICULAR
 REGION FROM THE ARRAY AND PRINTS THEM OUT ON THE SCREEN.
 --------------------------------------------------------------------------}
PROCEDURE GAUSSIAN_INTENSITY ;

VAR
  REGION,
  UPPERLIMIT,
  LOWERLIMIT,
  X
        : INTEGER ;


BEGIN
  IF GAUSSIAN_EMPTY
    THEN WRITELN ('NO GAUSSIAN INTENSITY PROFILE STORED IN THE ARRAY')
    ELSE
     BEGIN
       WRITELN ('REGION 2 : VERTICAL INTENSITY PROFILE OF INSIDE(2) REGION');
       WRITELN ('REGION 3 : LATERAL I TNEISTY PROFILE ');
       WRITELN ('==========================================================');
       WRITE ('WHICH REGION OF INTENSITY PROFILE ARE YOU INTERESTED ?   ---->')
       READLN (REGION);
       PAGE;
       CASE REGION OF
         2:
           BEGIN
             LOWERLIMIT := -20;
             UPPERLIMIT := ROUND((FT+GT)*1E7) + 40;
             FOR X := LOWERLIMIT TO UPPERLIMIT DO
              BEGIN
               IF ((X/22)=TRUNC(X/22)) AND (X>=0) THEN WAIT;
               IF X = 0
                 THEN WRITELN ('X = ',X,'  BOUNDARY 1   E-FIELD = ',
                                SQR(HEIGHT*GAUSSIAN_X[X]))
                 ELSE BEGIN
                        IF X = ROUND(FT*1E7)
                          THEN WRITELN ('X = ',X,'  BOUNDARY 2   E-FIELD = ',
                                         SQR(HEIGHT*GAUSSIAN_X[X]))
                          ELSE BEGIN
                                 IF X = UPPERLIMIT - 40
                                   THEN WRITELN ('X = ',X,
                                                 '  BOUNBARY 3   E-FIELD = ',
                                                 SQR(HEIGHT*GAUSSIAN_X[X]))
                                   ELSE WRITELN ('X = ',X,
                                                 '               E-FIELD = ',
                                                 SQR(HEIGHT*GAUSSIAN_X[X]));
                               END;
                      END;
              END;
           END;

         3:
           BEGIN
             LOWERLIMIT := 0;
             UPPERLIMIT := 200;
             FOR X := LOWERLIMIT TO UPPERLIMIT DO
```

```
              BEGIN
               IF ((X/22)=TRUNC(X/22)) AND (X>0) THEN WAIT;
               IF X=ROUND(RW*1E7/2)
                THEN WRITELN ('X = ',X,' BOUNDARY   E-FIELD = ',
                                        SQR(HEIGHT*GAUSSIAN_Y[X]))
                ELSE WRITELN ('X = ',X,'            E-FIELD = ',
                                        SQR(HEIGHT*GAUSSIAN_Y[X]));
              END;
           END;
       END;
     END;
  WAIT;
END;


{-----------------------------------------------------------------------
 VER_FIELD FUNCTION RETURNS THE VALUE OF FIELD_1[X] IF X > 40. ELSE,
 FIELD_2[X] IS RETURNED.
 -----------------------------------------------------------------------}
FUNCTION VER_FIELD ( X, Y  : INTEGER ) : REAL ;

BEGIN
  IF Y > ROUND((RW/2)*1E7)  THEN VER_FIELD := FIELD_1[X-ROUND(RH*1E7)]
                            ELSE VER_FIELD := FIELD_2[X];
END;


{-----------------------------------------------------------------------------
 THE CW_ERROR FUNCTION COMPUTES THE ERROR BETWEEN THE ACTUAL ELECTRIC FIELD
 PROFILE AND THE GAUSSIAN APPROXIMATION IN THE GUIDING REGION OF INTEREST
 -----------------------------------------------------------------------------
FUNCTION CW_ERROR ( AMP : REAL ) : REAL;

VAR
  ERROR_TOTAL, {TOTAL ERROR ACCUMULATED}
  GAUSSIAN,    {AMPLITUDE ASSOCIATED WITH THE GAUSSIAN FUNCTION}
  ACTUAL_CW    {AMPLITUDE ASSOCIATED WITH THE ACTUAL FIELD PRODILE}
       : REAL ;

  X,Y           {TEMPORARY COUNTER}
       : INTEGER ;


BEGIN
  ERROR_TOTAL := 0;
  FOR X := ROUND(FT*1E7) TO ROUND((FT+GT/2+2*X_LIMIT)*1E7) DO
    FOR Y := 0 TO ROUND(2*Y_LIMIT*1E7) DO
      BEGIN
        GAUSSIAN := AMP*GAUSSIAN_X[X]*GAUSSIAN_Y[Y];
        ACTUAL_CW := VER_FIELD(X,Y)*FIELD_LAT[Y];
        ERROR_TOTAL := ERROR_TOTAL + SQR (GAUSSIAN - ACTUAL_CW);
      END;
  FOR X := ROUND((FT+GT/2-2*X_LIMIT)*1E7) TO ROUND(FT*1E7)-1 DO
    FOR Y := 0 TO ROUND((RW/2)*1E7) DO
      BEGIN
        GAUSSIAN := AMP*GAUSSIAN_X[X]*GAUSSIAN_Y[Y];
        ACTUAL_CW := FIELD_2[X]*FIELD_LAT[Y];
        ERROR_TOTAL := ERROR_TOTAL + SQR (GAUSSIAN - ACTUAL_CW);
```

```
      END;
    CW_ERROR := ERROR_TOTAL;
  END;

{------------------------------------------------------------------------------
 THE FUNCTION GAUSSIAN_AMP COMPUTES THE AMPLITUDE OF THE GAUSSIAN FUNCTION
 GIVEN THE MODE SIZES IN X AND Y DIRECTIONS AND THE ENERGY OF BOTH CURVES
 BEING EQUAL.
------------------------------------------------------------------------------}
FUNCTION GAUSSIAN_AMP ( X_MODESIZE, Y_MODESIZE : REAL ) : REAL ;

VAR
  GAUSSIAN_SUM
          : REAL ;

  X,Y
          : INTEGER ;


BEGIN                                   {INITIALIZATION}
  GAUSSIAN_SUM := 0;                    {INITIALIZE THE GAUSSIAN ARRAY}

  FOR X := -20 TO ROUND((FT+GT)*1E7) + 40 DO
    GAUSSIAN_X[X] := EXP(-0.5*SQR((X/1E7-FT-GT/2)/X_MODESIZE));
  FOR Y := 0 TO 200 DO
    GAUSSIAN_Y[Y] := EXP(-0.5*SQR(Y/(Y_MODESIZE*1E7)));

      {ADD UP THE SQUARE OF EACH GAUSSIAN ELEMENT IN THE SUMMING REGION}
  FOR X := ROUND(FT*1E7) TO ROUND((FT+GT/2+2*X_LIMIT)*1E7) DO
    FOR Y := 0 TO ROUND(2*Y_LIMIT*1E7) DO
        GAUSSIAN_SUM := GAUSSIAN_SUM + SQR(GAUSSIAN_X[X]*GAUSSIAN_Y[Y]);
  FOR X := ROUND((FT+GT/2-2*X_LIMIT)*1E7) TO ROUND(FT*1E7)-1 DO
    FOR Y := 0 TO ROUND((RW/2)*1E7) DO
        GAUSSIAN_SUM := GAUSSIAN_SUM + SQR(GAUSSIAN_X[X]*GAUSSIAN_Y[Y]);

  {WRITELN('G = ',GAUSSIAN_SUM, ' A = ',ACTUAL_SUM);}
  GAUSSIAN_AMP := SQRT(ACTUAL_SUM/GAUSSIAN_SUM);
END;


{------------------------------------------------------------------------------
 FIND_GAUSSAIN PROCEDURE FINDS THE GAUSSIAN FUNCTION THAT BEST APPROXIMATES
 THE ACTUAL FIELD PROFILE IN THE CHANNEL WAVEGUIDE BASED ON 2 CRITERIA :

 1. THE GAUSSIAN FUNCTION AND THE ACTUAL FUNCTION HAVE THE SAME AMOUNT OF
    ENERGY IN THE GUIDING REGION BOUNDED BY THE RIDGE BOUNDARIES.
    (AS OPPOSED TO HAVING THE SAME ENERGY THROUGHTOUT THE WHOLE CROSS SECTION)
 2. THE ERROR BETWEEN THE 2 CURVES IS MINIMIZED.
 3. THE PEAK OF THE GAUSSIAN FUNCTION IS POSITIONED AT THE CENTER OF THE
    GUIDING LAYER. (THIS ASSUMPTION WILL NOT BE TRUE IF THE FILM LAYER IS
    TOO THIN THAT THE OPTICAL FIELD SEES THE EXISTENCE OF THE UPPER BUFFER
    LAYER, WHICH IS AIR, IN WHICH CASE THE OPTICAL MODE WILL BE ASYMMETRIC)

 ASSUMPTION #1 WILL REMAIN VALID AS LONG AS MOST THE OPTICAL ENERGY IS
 RESTRICTED WITHIN THIS REGION.
------------------------------------------------------------------------------}
PROCEDURE FIND_GAUSSIAN ;
```

```
VAR
  REVERSAL,
  X,Y            {TEMPORARY COUNTER}
      :INTEGER ;

  DELTA_X,
  DELTA_Y,
    HEIGHT0,HEIGHT1,     {TEMPORARY VARIABLES}
    NEW_ERROR,           {TOTAL NEW ERROR }
    OLD_ERROR            {TOTAL OLD ERROR }
     : REAL ;


BEGIN
  PAGE;
  ACTUAL_SUM := 0;            {INITIALIZATION}
  DELTA_X := 1E-7;            {INCREMENT IN METER}
  DELTA_Y := 1E-7;
  {WX := TRUNC(1E7*SQRT(-SQR(FT)/(2*LN(COS(U_GUIDE_2*GT-PHI_2)))))/1E7;
   WY := TRUNC(1E7*SQRT(-SQR(RW)/(8*LN(COS(U_LATERAL*RW/2)))))/1E7;}
  INIT_WX;            {CALCULATE THE INITIAL MODE SIZE AND ASSIGN IT TO WX}
  INIT_WY;            {CALCULATE THE INITIAL MODE SIZE AND ASSIGN IT TO WY}
  X_LIMIT := WX;
  Y_LIMIT := WY;

      {ADD UP THE SQUARE OF EACH ACTUAL ELEMENT IN THE SUMMING REGION}
  FOR X := ROUND(FT*1E7) TO ROUND((FT+GT/2+2*X_LIMIT)*1E7) DO
    FOR Y := 0 TO ROUND(2*Y_LIMIT*1E7) DO
      ACTUAL_SUM := ACTUAL_SUM + SQR(VER_FIELD(X,Y)*FIELD_LAT[Y]);
  FOR X := ROUND((FT+GT/2-2*X_LIMIT)*1E7) TO ROUND(FT*1E7)-1 DO
    FOR Y := 0 TO ROUND((RW/2)*1E7) DO
      ACTUAL_SUM := ACTUAL_SUM + SQR(FIELD_2[X]*FIELD_LAT[Y]);
  WRITELN ('ACTUAL_SUM = ',ACTUAL_SUM);

  {----------- FIND THE BEST MODE SIZE IN THE VERTICAL DIRECTION --------}

  GAUSSIAN_EMPTY := FALSE;          {GAUSSIAN ARRAY WON'T BE EMPTY AFTER
                                     THE EXECUTION OF THIS PROCEDURE}
  REVERSAL := 0;                    {INITIALIZATION, NO REVERSAL YET}
  HEIGHT0 := GAUSSIAN_AMP(WX,WY);   {INITIAL HEIGHT OF THE GAUSSIAN}
  NEW_ERROR := CW_ERROR (HEIGHT0);  {INITIAL ERROR BASED ON HEIGHT0}
  WRITELN ('FOR WX = ',WX*1E6:4:2,' MICRONS',' WY = ',WY*1E6:4:2,' MICRONS');
  WRITELN ('HEIGHT = ',HEIGHT0,'       ERROR = ',NEW_ERROR);
                                    {TO DETERMINE WHETHER THE INITIAL GAUSSIAN
                                     IS TOO FAT OR TO THIN}
  HEIGHT1 := GAUSSIAN_AMP(WX+DELTA_X,WY);
  IF CW_ERROR (HEIGHT1) > NEW_ERROR{IF IT IS TOO FAT......}
       THEN DELTA_X := -DELTA_X;    {THEN REVERSE THE INCREMENT DIRECTION}

  REPEAT                            {SEARCH FOR THE SPOT SIZE WHICH MINIMIZES
                                     THE ERROR BY TRYING DIFFERENT VALUES OF
                                     SPOT SIZE STEPPED BY THE INCREMENT}
    WX := WX + DELTA_X;             {TRY A NEW MODE SIZE IN THE X DIRECTION}
    OLD_ERROR := NEW_ERROR;
    HEIGHT := GAUSSIAN_AMP(WX,WY); {CALCULATE THE HEIGHT OF THIS NEW GAUSSIAN}
    NEW_ERROR := CW_ERROR(HEIGHT); {CALCULATE THE NEW ERROR}
    IF (NEW_ERROR>OLD_ERROR)        {IF ERROR HAS REACHED A MINIMUM BASED ON
                                     THE CURRENT STEP SIZE, THEN....}
      THEN BEGIN
             DELTA_X := -DELTA_X/10;    {REVERSE THE STEP SIZE DIRECTION AND
```

```
                                        MAKE THE RESOLUTION FINER}
          REVERSAL := REVERSAL + 1;   {RECORD DOWN THE FIRST REVERSAL}
        END;
  WRITELN ('FOR WX = ',WX*1E6:4:2,' MICRONS',' WY = ',WY*1E6:4:2,' MICRONS');
  WRITELN ('HEIGHT = ',HEIGHT,'       ERROR = ',NEW_ERROR);
UNTIL (NEW_ERROR>OLD_ERROR) AND
      (REVERSAL = 2);                {KEEP DOING THIS UNTIL THE ERROR HAS
                                      REACHED THE MINIMUN AND THUS THE BEST
                                      SPOT SIZE HAS BEEN FOUND}

WX := WX + 10*DELTA_X;               {GO BACK ONE STEP TO RECORD THE BEST WX}
WAIT;

{------------- DO THE SAME THING IN THE LATERAL DIRECTION ---------------}

REVERSAL := 0;                      {INITIALIZATION, NO REVERSAL YET}
HEIGHT0 := GAUSSIAN_AMP(WX,WY);     {INITIAL HEIGHT OF THE GAUSSIAN}
NEW_ERROR := CW_ERROR (HEIGHT0);    {INITIAL ERROR BASED ON HEIGHT0}
WRITELN ('FOR WX = ',WX*1E6:4:2,' MICRONS',' WY = ',WY*1E6:4:2,' MICRONS');
WRITELN ('HEIGHT = ',HEIGHT0,'      ERROR = ',NEW_ERROR);
                                    {TO DETERMINE WHETHER THE INITIAL GAUSSIAN
                                     IS TOO FAT OR TO THIN}
HEIGHT1 := GAUSSIAN_AMP(WX,WY+DELTA_Y);
IF CW_ERROR (HEIGHT1) > NEW_ERROR
     THEN DELTA_Y := -DELTA_Y;      {THEN REVERSE THE INCREMENT DIRECTION}
REPEAT                              {SEARCH FOR THE SPOT SIZE WHICH MINIMIZES
                                     THE ERROR BY TRYING DIFFERENT VALUES OF
                                     SPOT SIZE STEPPED BY THE INCREMENT}
  WY := WY + DELTA_Y;               {TRY A NEW MODE SIZE IN THE Y DIRECTION}
  OLD_ERROR := NEW_ERROR;
  HEIGHT := GAUSSIAN_AMP(WX,WY);    {CALCULATE THE HEIGHT OF THIS NEW GAUSSIAN}
  NEW_ERROR := CW_ERROR(HEIGHT);    {CALCULATE THE NEW ERROR}
  IF (NEW_ERROR>OLD_ERROR)          {IF ERROR HAS REACHED A MINIMUM BASED ON
                                     THE CURRENT STEP SIZE, THEN....}
    THEN BEGIN
          DELTA_Y := -DELTA_Y/10;     {REVERSE THE STEP SIZE DIRECTION AND
                                       MAKE THE RESOLUTION FINER}
          REVERSAL := REVERSAL + 1;  {RECORD DOWN THE FIRST REVERSAL}
        END;
  WRITELN ('FOR WX = ',WX*1E6:4:2,' MICRONS',' WY = ',WY*1E6:4:2,' MICRONS');
  WRITELN ('HEIGHT = ',HEIGHT,'       ERROR = ',NEW_ERROR);
UNTIL (NEW_ERROR>OLD_ERROR) AND
      (REVERSAL = 2);                {KEEP DOING THIS UNTIL THE ERROR HAS
                                      REACHED THE MINIMUN AND THUS THE BEST
                                      SPOT SIZE HAS BEEN FOUND.}

WY := WY + 10*DELTA_Y;               {GO BACK ONE STEP TO RECORD THE BEST WY}
HEIGHT := GAUSSIAN_AMP(WX,WY);       {CALCULATE THE HEIGHT OF THE OPTIMAL
                                      GAUSSIAN JUST FOUND}

{------------------ PRINT OUT THE FIANL RESULTS ------------------------}

WRITELN;
WRITELN ('=============================================================');
WRITELN ('PREDICTED GAUSSIAN MODE SIZE :');
WRITELN ('VERTICAL = ',WX*1E6:4:2,' MICRONS');
WRITELN ('LATERAL  = ',WY*1E6:4:2,' MICRONS');
WRITE   ('OPTICAL COUPLING EFFICIENCY = ');
WRITELN (0.01*ROUND(1E4*(4/(((3.37/(WX*1E6))+(WX*1E6/3.37)) *
                        ((3.37/(WY*1E6))+(WY*1E6/3.37))))):4:2,' %');
```

```
                                         {FIBER MODE SIZE WAS 3.37 MICRONS}
  WRITELN ('================================================================');
  WAIT;
END;


{---------------------------------------------------------------------------
 THE PROCEDURE CHANGE_PARAMETER ALLOWS USER TO CHANGE ANY OF THE WAVEGUIDE
 PARAMETERS AFTER THE INITIAL PARAMETERS HAVE BEEN TYPED IN.
 ---------------------------------------------------------------------------}
PROCEDURE CHANGE_PARAMETER ( PARAMETER : INTEGER ) ;

BEGIN
  CASE PARAMETER OF
    1 : BEGIN
          WRITE ('1. INDEX OF UPPER BUFFER LAYER               ------> ');
          READLN (N_HIBFR);
        END;
    2 : BEGIN
          WRITE ('2. INDEX OF LOWER BUFFER LAYER               ------> ');
          READLN (N_LOBFR);
        END;
    3 : BEGIN
          WRITE ('3. INDEX OF FILM LAYER                       ------> ');
          READLN (N_FILM);
        END;
    4 : BEGIN
          WRITE ('4. INDEX OF GUIDING LAYER                    ------> ');
          READLN (N_GUIDE);
        END;
    5 : BEGIN
          WRITE ('5. RIDGE WIDTH                 (IN MICRON)   ------> ');
          READLN (RW);
          RW := RW/1000000;             {CONVERSION FROM MICRON TO METER}
        END;
    6 : BEGIN
          WRITE ('6. RIDGE HEIGHT                (IN MICRON)   ------> ');
          READLN (RH);
          RH := RH/1000000;             {CONVERSION FROM MICRON TO METER}
        END;
    7 : BEGIN
          WRITE ('7. FILM LAYER THICKNESS        (IN MICRON)   ------> ');
          READLN (FT);
          FT := FT/1000000;             {CONVERSION FROM MICRON TO METER}
        END;
    8 : BEGIN
          WRITE ('8. GUIDING LAYER THICKNESS     (IN MICRON)   ------> ');
          READLN (GT);
          GT := GT/1000000;             {CONVERSION FROM MICRON TO METER}
        END;
    9 : BEGIN
          WRITE ('9. WAVELENGTH OF LASER         (IN MICRON)   ------> ');
          READLN (WAVELENGTH);
          WAVELENGTH := WAVELENGTH/1000000; {CONVERSION FROM MICRON TO METER}
        END;
    10 : PRESENT_STATUS;
    11 : BEGIN
           PRINT_WAVEGUIDE;
           WAIT;
```

```
        END;
    12 : FIND_GAUSSIAN;
    13 : FIELD_PROFILE;
    14 : GAUSSIAN_PROFILE;
    15 : INTENSITY_PROFILE;
    16 : GAUSSIAN_INTENSITY;
    OTHERWISE;
  END;
END;


 {-----------------------------------------------------------------------------
  CHANGE PROCEDURE ALLOWS THE USER TO CHANGE THE CURRENT STATUS OF CHANNEL
  WAVEGUIDE BY MODIFYING ONE OR MORE OF THE WAVEGUIDE PARAMETERS.
  ----------------------------------------------------------------------------}
  PROCEDURE CHANGE;

  VAR
    NUMBER      {SELECTION OF WAVEGUIDE PARAMETER TO BE CHANGED}
        : INTEGER ;

  BEGIN
    REPEAT
      PAGE;
      WRITELN ('WHICH WAVEGUIDE PARAMETER WOULD YOU LIKE TO CHANGE ?');
      WRITELN ('============================================================');
      WRITELN (' 0. NO CHANGES (CONTINUE TO SOLVE THE EIGENVALUE EQUATION)');
      WRITELN (' 1. INDEX OF UPPER BUFFER LAYER');
      WRITELN (' 2. INDEX OF LOWER BUFFER LAYER ');
      WRITELN (' 3. INDEX OF FILM  LAYER ');
      WRITELN (' 4. INDEX OF GUIDING LAYER');
      WRITELN (' 5. RIDGE WIDTH');
      WRITELN (' 6. RIDGE HEIGHT');
      WRITELN (' 7. FILM LAYER THICKNESS');
      WRITELN (' 8. GUIDING LAYER THICKNESS');
      WRITELN (' 9. WAVELENGTH OF LASER');
      WRITELN ('10. DISPLAY CURRENT WAVEGUIDE PARAMETERS');
      WRITELN ('11. DISPLAY WAVEGUIDE GEOMETRY');
      WRITELN ('12. FIND THE BEST APPROXIMATING GAUSSIAN FUNCTION');
      WRITELN ('13. LIST ELECTRIC FIELD PROFILE OF THE FUNDAMENTAL MODE');
      WRITELN ('14. LIST APPROXIMATED GAUSSIAN FIELD PROFILE');
      WRITELN ('15. LIST INTENSITY PROFILE OF THE FUNDAMENTAL MODE');
      WRITELN ('16. LIST APPROXIMATED GAUSSIAN INTENSITY PROFILE');
      WRITELN ('============================================================');
      WRITELN;
      WRITE ('PLEASE INPUT A NUMBER ( 0 - 16 )   ------> ');
      READLN (NUMBER);
      WRITELN;
      CHANGE_PARAMETER (NUMBER);
    UNTIL (NUMBER = 0);
    IF RH > FT
      THEN RH_GREATER_THAN_FT := TRUE
      ELSE RH_GREATER_THAN_FT := FALSE;
  END;


 {-----------------------------------------------------------------------------
 THE INITIALIZATION PROCEDURE ASKS THE USER FOR WAVEGUIDE DIMEMSIONS AND THE
 REFRACTIVE INDICES IN EACH LAYER.
```

```
---------------------------------------------------------------------------;
PROCEDURE INITIALIZATION;

BEGIN
  GAUSSIAN_EMPTY := TRUE;
  ARRAY_EMPTY := TRUE;
  PRINT_WAVEGUIDE;
  CHANGE_PARAMETER (1);
  CHANGE_PARAMETER (2);
  CHANGE_PARAMETER (3);
  CHANGE_PARAMETER (4);
  CHANGE_PARAMETER (5);
  CHANGE_PARAMETER (6);
  CHANGE_PARAMETER (7);
  CHANGE_PARAMETER (8);
  CHANGE_PARAMETER (9);
  CHANGE;
END;


{--------------------------------------------------------------------------
 THE FUNCTION ERROR_4_LAYER COMPUTES THE ERROR RESULTED FROM A TRIAL SOLUTION
 IN SOLVING THE 4-LAYER-WAVEGUIDE TRANSCENDENTAL EQUATION. THIS IS TAKEN FROM
 EQ.(6.91), PAGE 192 OF ADAM'S "AN INTRODUCTION TO OPTICAL WAVEGUIDES". THE
 APPROACH USED IN THIS PROGRAM IS LARGELY BASED ON THE METHOD DESCRIBED
 IN ADAM'S BOOK. FOR REFERENCE, PLEASE CONSULT PAGE 192 AND 76 OF HIS BOOK.
 --------------------------------------------------------------------------}
FUNCTION ERROR_4_LAYER ( PROP_CONST,
                         FILM_DIMENSION, GUIDE_DIMENSION,
                         INDEX_HIBFR, INDEX_LOBFR,
                         INDEX_FILM, INDEX_GUIDE          : REAL ;
                         M : INTEGER                              ) : REAL ;

VAR
  U_GUIDE,          {TRANSVERSE PROPAGATION CONSTANT IN THE GUIDING LAYER}
  W_HIBFR,          {DECAY CONSTANT IN THE UPPER BUFFER LAYER}
  W_LOBFR,          {DECAY CONSTANT IN THE LOWER BUFFER LAYER}
  W_FILM            {DECAY CONSTANT IN THE FILM LAYER}
    : REAL ;

BEGIN
  U_GUIDE := SQRT (SQR(2*PI*INDEX_GUIDE/WAVELENGTH) - SQR(PROP_CONST));
  W_HIBFR := SQRT (SQR(PROP_CONST) - SQR(2*PI*INDEX_HIBFR/WAVELENGTH));
  W_LOBFR := SQRT (SQR(PROP_CONST) - SQR(2*PI*INDEX_LOBFR/WAVELENGTH));
  IF (FILM_DIMENSION > 0)
    THEN W_FILM := SQRT (SQR(PROP_CONST) - SQR(2*PI*INDEX_FILM/WAVELENGTH))
    ELSE W_FILM := W_HIBFR - 100;
  ERROR_4_LAYER := U_GUIDE*GUIDE_DIMENSION - M*PI - ARCTAN(W_LOBFR/U_GUIDE) -
                   ARCTAN(W_FILM/(U_GUIDE*TANH(W_FILM*FILM_DIMENSION +
                                          INV_TANH(W_FILM/W_HIBFR))));

                      {4-LAYER SLAB WAVEGUIDE TRANSCENDENTAL EQUATION NEEDED
                       TO BE SOLVED AS STATED IN EQ. (6.91) OF ADAM'S BOOK}

END;


{---------------------------------------------------------------------------
 FIELD_PROFILE_1 PROCEDURE DEFINES THE ANALYTIC FIELD EXPRESSIONS IN REGION 1
```

```
OF THE FOUR-LAYER SLAB WAVEGUIDE. THESE ANALYTIC FIELD EXPRESSIONS ARE BASED
ON THE PAPER BY SUN AND MULLER OF APPLIED OPTICS, VOL. 16, NO. 4, PAGE 814-
815. ONLY THE EXPRESSIONS FOR TE MODE ARE DERIVED HERE. FOR TM MODE, PLEASE
REFER TO THE PAPER DIRECTLY.
-------------------------------------------------------------------------}
PROCEDURE FIELD_PROFILE_1 (BETA : REAL; TOTAL_MODE : INTEGER);

VAR
  X,
  UPPERLIMIT,
  LOWERLIMIT
        : INTEGER ;

BEGIN
  IF (MODE = 0)                    {CHECK IF THIS IS THE FUNDAMENTAL MODE}
   THEN
    BEGIN
      BETA_1 := BETA;              {PROPAGATION CONSTANT IN THE OUTSIDE REGION}
      TOTAL_MODE_1 := TOTAL_MODE; {# OF ALLOWABLE MODES IN THE OUTSIDE REGION}
      EFF_INDEX_1 := BETA_1*WAVELENGTH/(2*PI); {CALCULATE THE EFFECTIVE INDEX}
       IF  NOT(RH_GREATER_THAN_FT) THEN      {IF THE RIDGE IS NOT OVER-ETCHED}
        BEGIN
         U_GUIDE_1 := SQRT (SQR(2*PI*N_GUIDE/WAVELENGTH) - SQR(BETA_1));
         W_HIBFR_1 := SQRT (SQR(BETA_1) - SQR(2*PI*N_HIBFR/WAVELENGTH));
         W_LOBFR_1 := SQRT (SQR(BETA_1) - SQR(2*PI*N_LOBFR/WAVELENGTH));
         W_FILM_1 := SQRT (SQR(BETA_1) - SQR(2*PI*N_FILM/WAVELENGTH));
         PHI_1 := ARCTAN (W_LOBFR_1/U_GUIDE_1);
         KI_1 := INV_TANH (W_FILM_1/W_HIBFR_1);
         G_1 := COS (U_GUIDE_1*GT - PHI_1) / SINH (W_FILM_1*(FT-RH) + KI_1);
         LOWERLIMIT := -20;
         UPPERLIMIT := TRUNC((FT+GT-RH)*1E7) + 40;
                                   {RECORD THE FIELD PROFILE IN THE ARRAY}
         FOR X := LOWERLIMIT TO UPPERLIMIT DO
           BEGIN
             IF (X<0) THEN
               FIELD_1[X] := G_1*SINH(KI_1)*EXP(W_HIBFR_1*X/1E7);
             IF (X>=0) AND (X<ROUND((FT-RH)*1E7)) THEN
               FIELD_1[X] := G_1*SINH(W_FILM_1*X/1E7 + KI_1);
             IF (X>=ROUND((FT-RH)*1E7))AND(X<ROUND((FT-RH+GT)*1E7)) THEN
               FIELD_1[X] := COS(U_GUIDE_1*(X/1E7-GT-FT+RH) + PHI_1);
             IF (X>=ROUND((FT-RH+GT)*1E7)) THEN
               FIELD_1[X] := COS(PHI_1)*EXP(-W_LOBFR_1*(X/1E7-FT-GT+RH));
           END;
        END;
    END
   ELSE EFF_N1_HI := BETA*WAVELENGTH/(2*PI);  {IF THIS IS A HIGHER ORDER MODE,
                                               JUST CALCULATE THE EFFECTIVE INDEX}

  WRITELN ('FOR OUTSIDE (1) REGION :');
  WRITELN ('     PROPAGATION CONSTANT    = ',BETA);
  WRITELN ('     EFFECTIVE INDEX(1)      = ',BETA*WAVELENGTH/(2*PI));
  WRITELN;
END;


{-------------------------------------------------------------------------
FIELD_PROFILE_2 PROCEDURE DEFINES THE ANALYTIC FIELD EXPRESSIONS IN REGION 2
OF THE FOUR-LAYER SLAB WAVEGUIDE. THESE ANALYTIC FIELD EXPRESSIONS ARE BASED
ON THE PAPER BY SUN AND MULLER OF APPLIED OPTICS, VOL. 16, NO. 4, PAGE 814-
815. ONLY THE EXPRESSIONS FOR TE MODE ARE DERIVED HERE. FOR TM MODE, PLEASE
```

```
 REFER TO THE PAPER DIRECTLY.
 -------------------------------------------------------------------------}
PROCEDURE FIELD_PROFILE_2 (BETA : REAL; TOTAL_MODE : INTEGER);

VAR
  X,
  UPPERLIMIT,
  LOWERLIMIT
        : INTEGER ;

BEGIN
  IF MODE = 0                        {CHECK IF THIS IS THE FUNDAMENTAL MODE}
   THEN
    BEGIN
      BETA_2 := BETA;
      TOTAL_MODE_2 := TOTAL_MODE;
      EFF_INDEX_2 := BETA_2*WAVELENGTH/(2*PI);
      U_GUIDE_2 := SQRT (SQR(2*PI*N_GUIDE/WAVELENGTH) - SQR(BETA_2));
      W_HIBFR_2 := SQRT (SQR(BETA_2) - SQR(2*PI*N_HIBFR/WAVELENGTH));
      W_LOBFR_2 := SQRT (SQR(BETA_2) - SQR(2*PI*N_LOBFR/WAVELENGTH));
      W_FILM_2 := SQRT (SQR(BETA_2) - SQR(2*PI*N_FILM/WAVELENGTH));
      PHI_2 := ARCTAN (W_LOBFR_2/U_GUIDE_2);
      KI_2 := INV_TANH (W_FILM_2/W_HIBFR_2);
      G_2 := COS (U_GUIDE_2*GT - PHI_2) / SINH (W_FILM_2*FT + KI_2);
      LOWERLIMIT := -20;
      UPPERLIMIT := TRUNC((FT+GT)*1E7) + 40;
                                      {RECORD THE FIELD PROFILE IN THE ARRAY}
      FOR X := LOWERLIMIT TO UPPERLIMIT DO
        BEGIN
          IF (X<0) THEN
            FIELD_2[X] := G_2*SINH(KI_2)*EXP(W_HIBFR_2*X/1E7);
          IF (X>=0) AND (X<TRUNC(FT*1E7)) THEN
            FIELD_2[X] := G_2*SINH(W_FILM_2*X/1E7 + KI_2);
          IF (X>=TRUNC(FT*1E7)) AND (X<TRUNC((FT+GT)*1E7)) THEN
            FIELD_2[X] := COS(U_GUIDE_2*(X/1E7-GT-FT) + PHI_2);
          IF (X>=TRUNC((FT+GT)*1E7)) THEN
            FIELD_2[X] := COS(PHI_2)*EXP(-W_LOBFR_2*(X/1E7-FT-GT));
        END;
    END
   ELSE EFF_N2_HI := BETA*WAVELENGTH/(2*PI);  {IF THIS IS A HIGHER ORDER MODE,
                                               JUST CALCULATE THE EFFECTIVE INDEX}
  WRITELN ('FOR CENTRAL (2) REGION :');
  WRITELN ('     PROPAGATION CONSTANT    = ',BETA);
  WRITELN ('     EFFECTIVE INDEX(2)      = ',BETA*WAVELENGTH/(2*PI));
  WRITELN;
END;


{--------------------------------------------------------------------------
 FIELD_PROFILE_LAT PROCEDURE DEFINES THE ANALYTIC FIELD EXPRESSIONS IN THE
 EQUIVALENT LATERAL WAVEGUIDE STRUCTURE CHARACTERIZED BY EFFECTIVE INDEX
 IN EACH REGION. THESE ANALYTIC FIELD EXPRESSIONS ARE BASED ON THE PAPER BY
 SUN AND MULLER OF APPLIED OPTICS, VOL. 16, NO. 4, PAGE 814-815. ONLY THE
 EXPRESSIONS FOR TE MODE ARE DERIVED HERE. FOR TM MODE, PLEASE REFER TO THE
 PAPER DIRECTLY.
 -------------------------------------------------------------------------}
PROCEDURE FIELD_PROFILE_LAT (BETA : REAL; TOTAL_MODE : INTEGER );

VAR
  X,
```

```
  UPPERLIMIT,
  LOWERLIMIT
        : INTEGER ;

  V                     (NORMALIZED FREQUENCY)
        : REAL ;


BEGIN
  IF MODE = 0 THEN                    (CHECK IF THIS IS THE FUNDAMENTAL MODE)
    BEGIN
      V := PI*RW*SQRT(SQR(EFF_INDEX_2)-SQR(EFF_INDEX_1))/WAVELENGTH;
      WRITELN ('INDEX DIFFERENCE                      = ',
                                    EFF_INDEX_2 - EFF_INDEX_1);
      BETA_EFF := BETA;
      U_LATERAL := SQRT(SQR(2*PI*EFF_INDEX_2/WAVELENGTH) - SQR(BETA_EFF));
      W_LATERAL := SQRT(SQR(BETA_EFF) - SQR(2*PI*EFF_INDEX_1/WAVELENGTH));
      G_LAT := COS(U_LATERAL*RW/2)/EXP(-W_LATERAL*RW/2);
      LOWERLIMIT := 0;
      UPPERLIMIT := 200;
                                     (RECORD THE FIELD PROFILE IN THE ARRAY)
      FOR X := LOWERLIMIT TO UPPERLIMIT DO
        IF X <= TRUNC(RW*1E7/2)
          THEN FIELD_LAT[X] := COS(U_LATERAL*X*1E-7)
          ELSE FIELD_LAT[X] := G_LAT*EXP(-W_LATERAL*X*1E-7);
    END
   ELSE             (IF THIS IS A HIGHER ORDER MODE, THEN .....)
    BEGIN
      V := PI*RW*SQRT(SQR(EFF_N2_HI)-SQR(EFF_N1_HI))/WAVELENGTH;
      WRITELN ('INDEX DIFFERENCE                      = ',
                                          EFF_N2_HI - EFF_N1_HI);
    END;
  PROP_MODE := PROP_MODE + TOTAL_MODE;
  WRITELN ('TRANSVERSE NORMALIZED FREQUENCY       = ',V);
  WRITELN ('TOTAL NUMBER OF MODES LATERALLY       = ',TOTAL_MODE);
  WRITELN ('==================================================');
  WRITELN ('TOTAL SUPPORTED PROPAGATING MODES     = ', PROP_MODE);
END;


{----------------------------------------------------------------------
FOUR_LAYER_EQ PROCEDURE SOLVES THE TRANSCENDENTAL EQUATION FOR A 4-LAYER
SLAB WAVEGUIDE STRUCTURE.
----------------------------------------------------------------------}
PROCEDURE FOUR_LAYER_EQ ( FILM_THICKNESS, GUIDE_THICKNESS,
                          N_UPPERBFR, N_LOWERBFR,
                          N_FILM_LAYER, N_GUIDE_LAYER      : REAL ;
                          REGION, MODE_NUMBER              : INTEGER );

VAR
  LO_ERROR, HI_ERROR,
  ERROR,                (TEMPORARY VARIABLES USED IN SOVLING THE EQUATION)
  BETA,                 (AXIAL PROPAGATION CONSTANT)
  HI_BETA, LO_BETA      (HIGHER AND LOWER LIMITS OF THE ALLOWED VALUES OF
                         PROPAGATION CONSTANT FOR SINCLE-MODE OPERATION)
       : REAL ;

  TOTAL_MODE            (TOTAL NUMBER OF MODES ALLOWED TO PROPAGATE)
       : INTEGER ;
```

```
BEGIN
  HI_BETA := 2*PI*N_GUIDE_LAYER/WAVELENGTH-1;
                        {HIGHER LIMIT OF PROPAGATION CONSTANT TO ENSURE SINGLE-
                         MODE PROPAGATION}
  LO_BETA := 2*PI*GREATER(N_LOWERBFR, N_FILM_LAYER)/WAVELENGTH+1;
                        {LOWER LIMIT OF PROPAGATION CONSTANT TO ENSURE SINGLE-
                         MODE PROPAGATION}
  HI_ERROR := ERROR_4_LAYER(HI_BETA,FILM_THICKNESS,GUIDE_THICKNESS,N_UPPERBFR,
                            N_LOWERBFR, N_FILM_LAYER, N_GUIDE_LAYER,MODE_NUMBER);
                        {ERROR DUE TO HI-LIMITING VALUE OF PROPAGATION CONSTANT}
  LO_ERROR := ERROR_4_LAYER(LO_BETA,FILM_THICKNESS,GUIDE_THICKNESS,N_UPPERBFR,
                            N_LOWERBFR, N_FILM_LAYER, N_GUIDE_LAYER,MODE_NUMBER);
                        {ERROR DUE TO LO-LIMITING VALUE OF PROPAGATION CONSTANT}
  WRITELN ('HI_ERROR = ',HI_ERROR,'   LO_ERROR = ',LO_ERROR);
  TOTAL_MODE := TRUNC(GREATER(LO_ERROR,HI_ERROR)/PI) + 1;

{THE FOLLOWING REPEAT-UNTIL ROUTINE SOLVES THE TRANSCENDENTAL EQUATION BY
 SUCCESSIVELY TRYING DIFFERENT VALUES OF PROPAGATION CONSTANT AND COMPARES
 THE ERRORS RESULTED FROM THEM. THE TECHNIQUE OF BISECTION METHOD IS USED
 TO SOLVE FOR THE PROPAGATION CONSTANT UNTIL THE ERROR HAS BEEN MINIMIZED
 TO LESS THAN 0.001}

  REPEAT
    BETA := (HI_BETA+LO_BETA)/2;  {FIRST TRIAL OF BETA}
    ERROR := ERROR_4_LAYER(BETA,FILM_THICKNESS,GUIDE_THICKNESS,N_UPPERBFR,
                    N_LOWERBFR, N_FILM_LAYER, N_GUIDE_LAYER,MODE_NUMBER);
    {WRITELN ('FOR BETA = ',BETA,'   ERROR = ',ERROR);}
    IF (ERROR-LO_ERROR)>0
     THEN BEGIN
            LO_BETA := BETA;
            LO_ERROR := ERROR;
          END
     ELSE BEGIN
            HI_BETA := BETA;
            HI_ERROR := ERROR;
          END;
  UNTIL (ABS(ERROR) < 0.001);

  CASE REGION OF
        1: FIELD_PROFILE_1 (BETA,TOTAL_MODE);    {REGION 1 IS OUTSIDE REGIONS}
        2: FIELD_PROFILE_2 (BETA,TOTAL_MODE);    {REGION 2 IS INSIDE REGION}
        3: FIELD_PROFILE_LAT (BETA,TOTAL_MODE); {REGION 3 IS THE LATERAL
                                                  WAVEGUIDE CHARACTERIZED BY
                                                  EFF_INDEX_1 AND EFF_INDEX_2
                                                  IN THE CENTRAL AND OUTSIDE
                                                  REGIONS}
  END;
  WRITELN;
END;


{--------------------------------------------------------------------------
 ----------------------- MAIN   PROGRAM -----------------------------
 ---------------------------------------------------------------------------}
BEGIN
  INITIALIZATION;
  REPEAT
   MODE := 0;           {STUDY THE FUNDAMENTAL MODE FIRST}
   PROP_MODE := 0;      {TOTAL PROPAGATING MODE = 0}
```

```
    REPEAT
     PAGE;
     WRITELN ('FOR VERTICAL MODE NUMBER ',MODE);
     WRITELN ('============================================');
     FOUR_LAYER_EQ (FT,GT,N_HIBFR,N_LOBFR,N_FILM,N_GUIDE,2,MODE);
                        {SOLVE THE EIGENVALUE EQUATION IN THE CENTRAL REGION}

     IF NOT RH_GREATER_THAN_FT  {IF FT>RW, THEN IT IS STILL A 4-LAYER PROBLEM}
       THEN FOUR_LAYER_EQ (FT-RH,GT,N_HIBFR,N_LOBFR,
                           N_FILM,N_GUIDE,1,MODE)
       ELSE BEGIN                {OTHERWISE, THE PROBLEM IS REDUCED TO A 3-LAYER
                                  DIELECTRIC PROBLEM. THUS, SOME PARAMETERS NEED
                                  TO BE RE-ADJUSTED}
              FOUR_LAYER_EQ (0,GT+FT-RH,N_HIBFR,N_LOBFR,
                             N_LOBFR,N_GUIDE,1,MODE);
              RH_GREATER_THAN_FT := TRUE;
            END;
                        {SOLVE THE EIGENVALUE EQUATION IN THE OUTSIDE REGION}

     IF ((EFF_INDEX_1 = EFF_INDEX_2) AND (MODE=0)) OR
        ((EFF_N1_HI = EFF_N2_HI) AND (MODE>0))
                                      {IF EFFECTIVE INDEX OF THE OUTSIDE AND
                                       INSIDE REGIONS ARE EQUAL, THEN THERE IS
                                       NO GUIDING IN THE LATERAL DIRECTION}
       THEN
         BEGIN
           WRITE ('EFF_INDEX_1 = EFF_INDEX_2 ----->');
           WRITELN ('NO GUIDING IN THE LATERAL DIRECTION');
         END
                                      {IF EFFECTIVE INDEX OF THE OUTSIDE AND
                                       INSIDE REGIONS AREN'T EQUAL, THEN
                                       SOLVE THE 3-LAYER DIELECTRIC PROBLEM}
       ELSE
         IF (MODE=0) THEN FOUR_LAYER_EQ (0,RW,EFF_INDEX_1,EFF_INDEX_1,
                           EFF_INDEX_1,EFF_INDEX_2,3,0)
                     ELSE FOUR_LAYER_EQ (0,RW,EFF_N1_HI,EFF_N1_HI,
                           EFF_N1_HI,EFF_N2_HI,3,0);
     ARRAY_EMPTY := FALSE;
     MODE := MODE + 1;                {ANALYZE THE NEXT HIGHER ORDER MODE}
     WAIT;
    UNTIL (MODE = SMALLER (TOTAL_MODE_2,TOTAL_MODE_1)) ;  {UNTIL CUTOFF}
    CHANGE;                           {GO BACK TO THE MENU (TOP) LEVEL}
  UNTIL (FALSE);
END.
```

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