INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

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WINTER COLLEGE ON
LASER PHYSICS: SEMICONDUCTOR LASERS
AND INTEGRATED OPTICS

(22 February - 11 March 1988)

CHARACTERIZATION TECHNIQUES FOR INTEGRATED OPTICS

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Torino, Italy

CHARACTERIZATION TECHNIQUES

FOR INTEGRATED OPTICS

- WAVEGUIDES
- COMPONENTS
- DEVICES

CHARACTERISTICS TO BE MEASURED

FOR PLANAR AND STRIPE GUIDES

- MODAL STRUCTURE
- REFRACTIVE INDEX PROFILE
- SCATTERING LEVELS
- NEAR FIELD
- FAR FIELD
- ATTENUATION
- COUPLING EFFICIENCY
- COMPOSITION

. . . .

DIRECT METHODS

- [redacted] : CUMBERSOME, TIME-CONSUMING, DIFFICULT FOR MANY STRUCTURES & MATERIALS

- REFLECT[redacted] : VERY SENSITIVE TO SURFACE CLEANLINESS, LOW-RELIABILITY

INDIRECT [redacted]

- [redacted] OF MODAL EFFECTIVE INDICES (INVERSE WKB METHOD):
  - GOOD PRECISION FOR PLANAR, MULTIMODE GUIDES
  - DIFFICULT FOR STRIPE GUIDES
  - IMPOSSIBLE FOR BURIED AND MONOMODE GUIDES

- QUANTIT[redacted] :
  - GOOD FOR SINGLE MODE WAVEGUIDES
  - SENSITIVE TO GUIDE TERMINATION QUALITY
  - UNRELIABLE FOR MULTIMODE GUIDES
  - [redacted] FOR DETECTORS

INDIRECT METHODS (CONT.)

[redacted]:

- GOOD PRECISION FOR STEP-INDEX GUIDES, EVEN BURIED ONES
- USEFUL FOR GUIDES WITH 2-3 MODES AND GRADED INDEX
- APPLICABLE TO HIGH-INDEX GUIDES WHERE PRISM COUPLING NOT POSSIBLE

CHEMICAL [redacted]:

- APPLICABLE TO ALL GUIDES IF RELATIONSHIP BETWEEN COMPOSITION AND INDEX IS KNOWN
- UNRELIABLE WHEN OTHER EFFECTS PRESENT (STRESS, CRYSTALLINE STRUCTURE, ...)

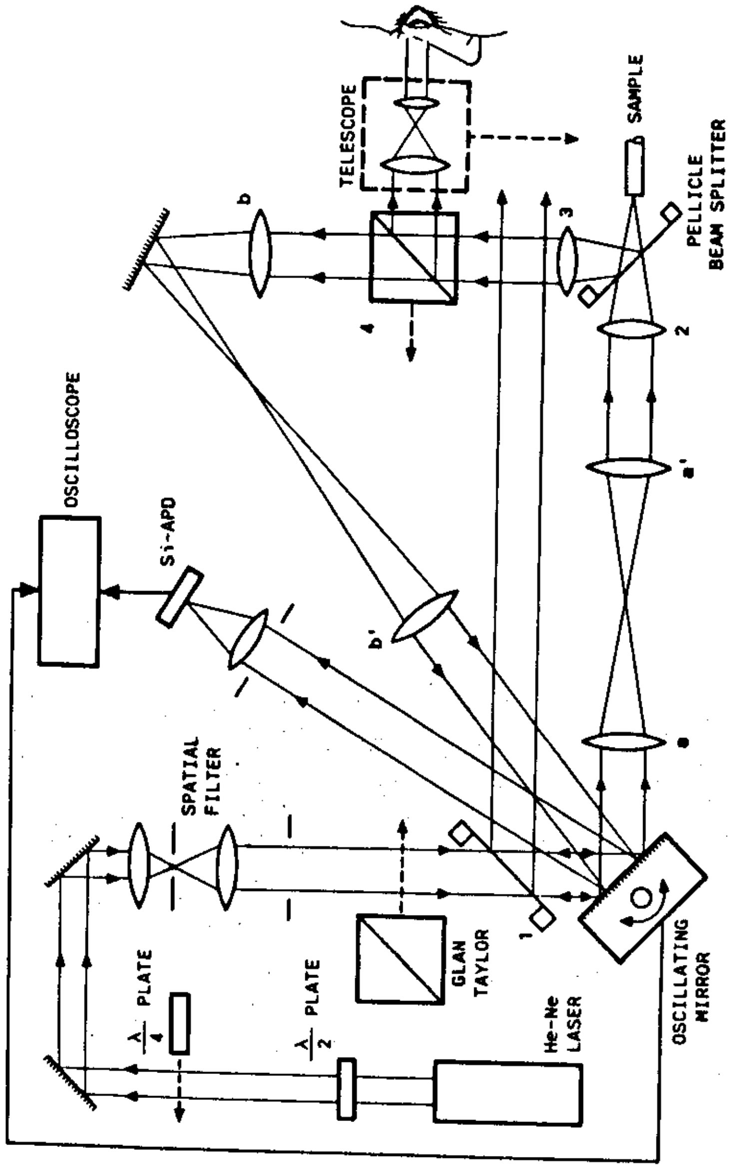
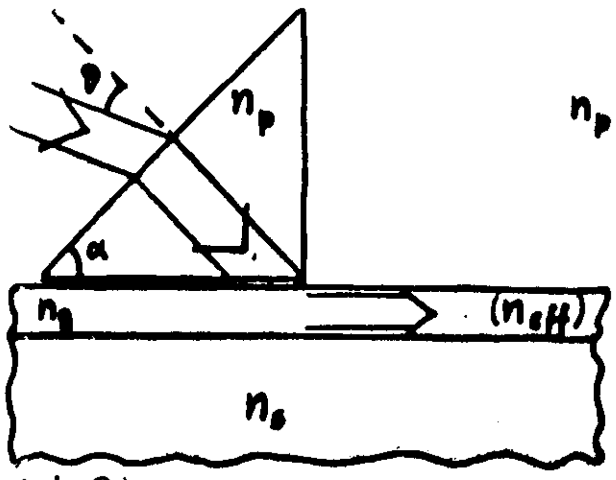


Fig. 1 : Schematic configuration of the experimental set-up. Description in the text

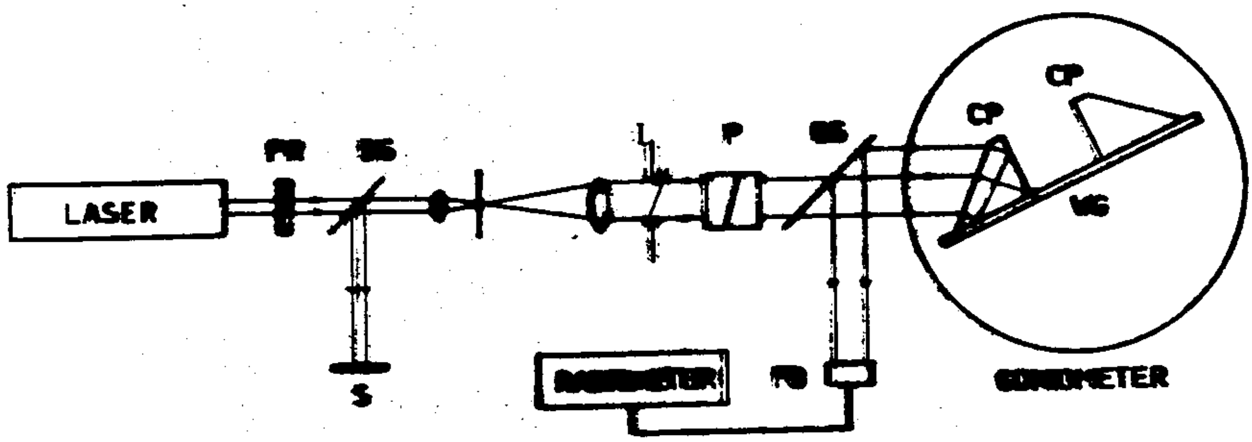
REFLECTOMETRIC INDEX PROFILING

ACCOPPIAMENTO A PRISMA
PRISM COUPLING



$n_p > n_g$

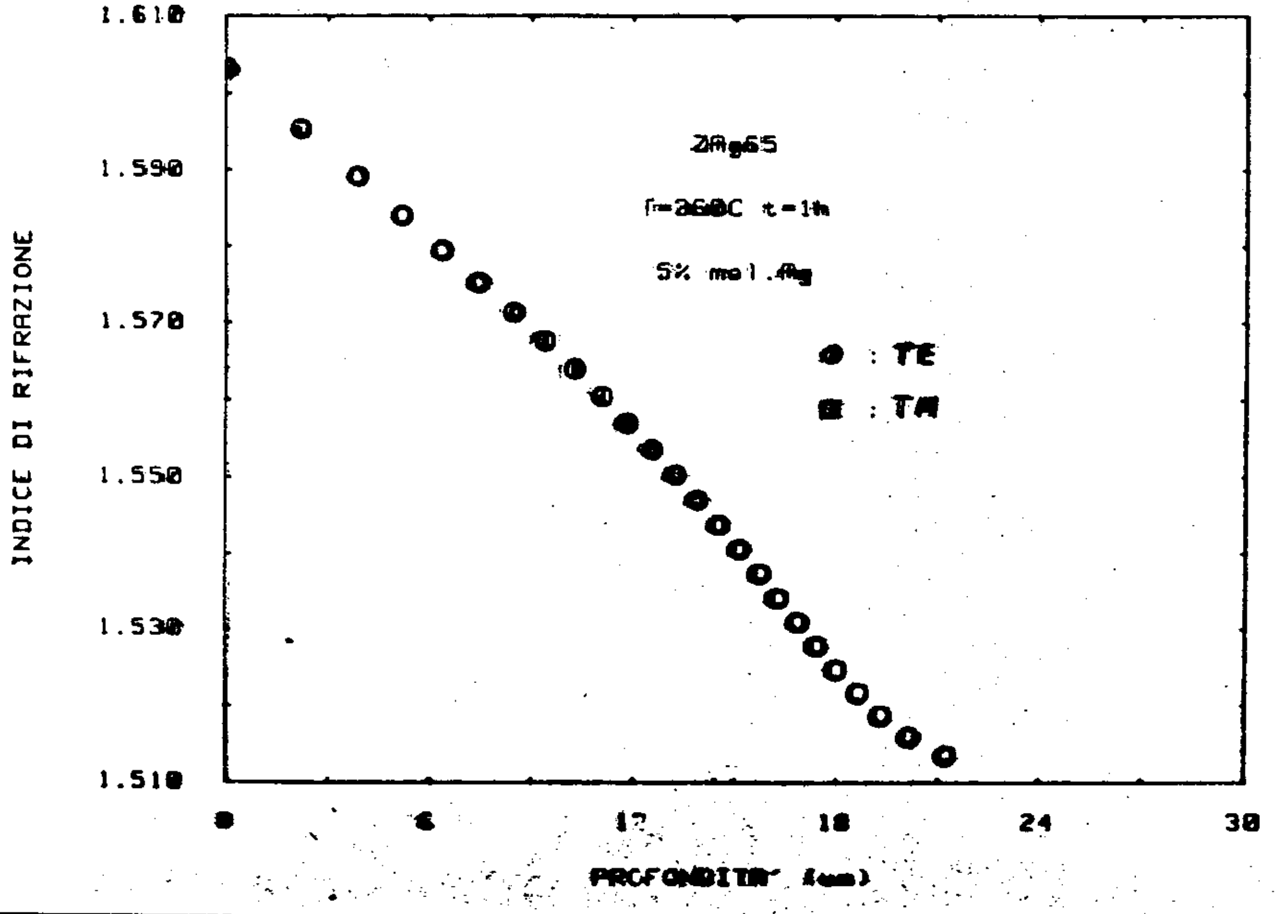
$$\arcsin\left(\frac{\sin\theta}{n_p}\right) = \arcsin\frac{n_{eff}}{n_p} - \alpha$$

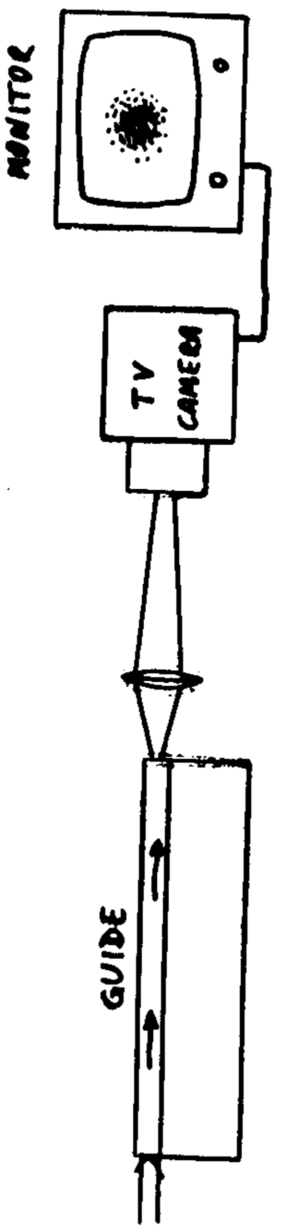


PRISM COUPLING MEASUREMENT

EXPERIMENTAL SET-UP

REFRACTIVE INDEX PROFILE OF Ag^+-Na^+ EXCHANGED GUIDE RECONSTRUCTED BY INVERSE WKB METHOD



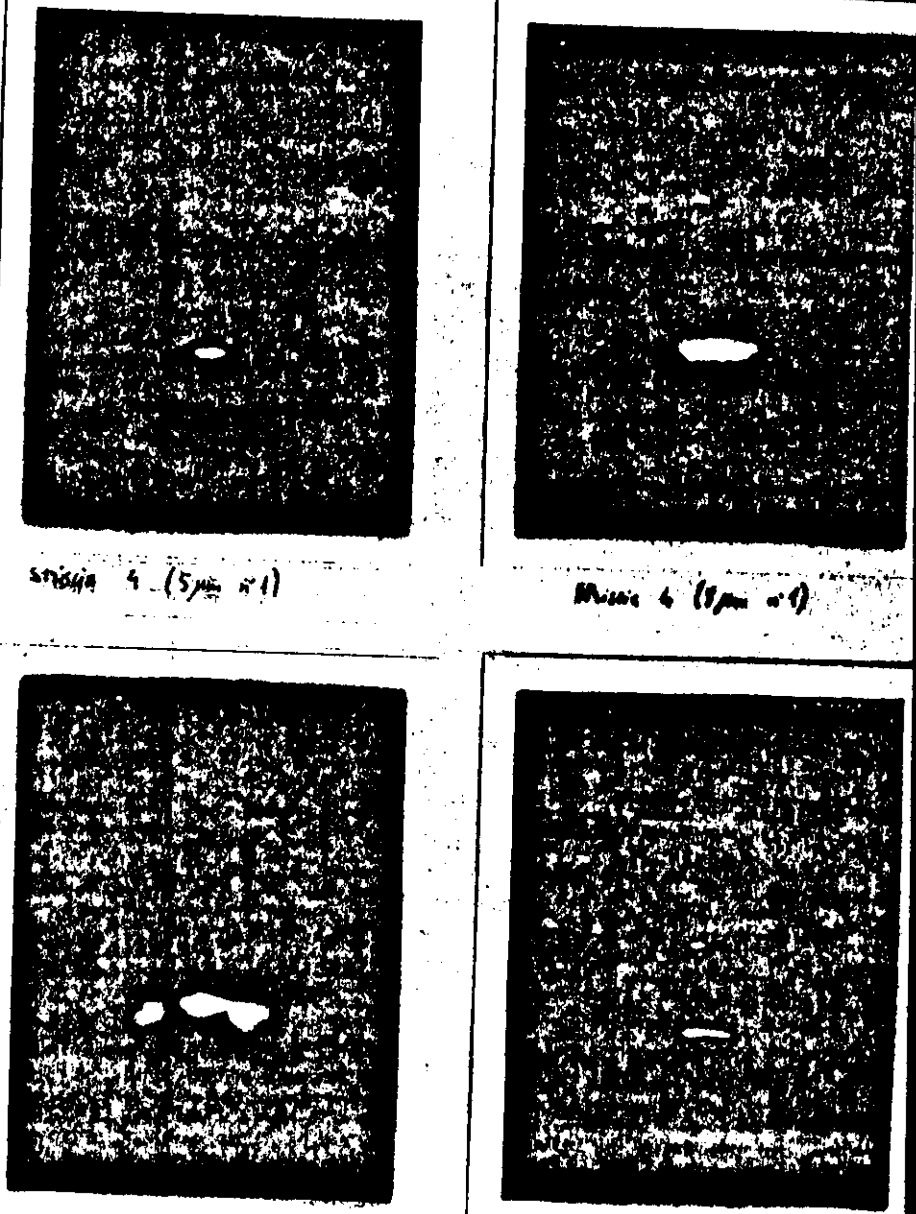


SCHEMATIC OF NEAR FIELD MEASUREMENT

- QUALITATIVE (INSPECTION OF PATTERN): MODAL STRUCTURE
- QUANTITATIVE ANALYSIS: INDEX PROFILE (WITH LIMITATIONS)

Centro Studi e Laboratori Telecomunicazioni S.p.A.

NEAR FIELD OF $Ti:LiNbO_3$ STRIPE GUIDE



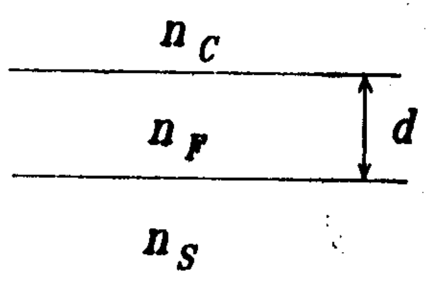
Striscia 4 (5 μm n°1)   Striscia 4 (5 μm n°1)

Striscia 4 (5 μm n°1)   Striscia 4 (5 μm n°1)

Step–index waveguide

(analysis from waveguide theory)

planar waveguide:



boundary equation for cut–off spectrum

$$\frac{d}{\lambda} = \frac{m\pi + \operatorname{atan}\sqrt{a}}{2\pi\sqrt{n_F^2 - n_S^2}}$$

a = asymmetry constant

TE polarization

$$a = \frac{n_S^2 - n_C^2}{n_F^2 - n_S^2}$$

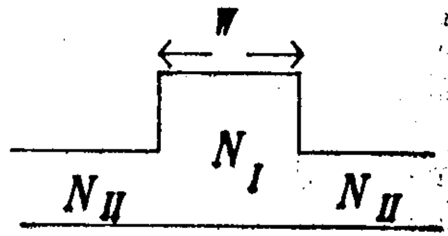
TM polarization

$$a = \frac{n_F^4}{n_C^4}\,\frac{n_S^2 - n_C^2}{n_F^2 - n_S^2}$$

Step–index waveguide

(using effective index method)

2–dim waveguide

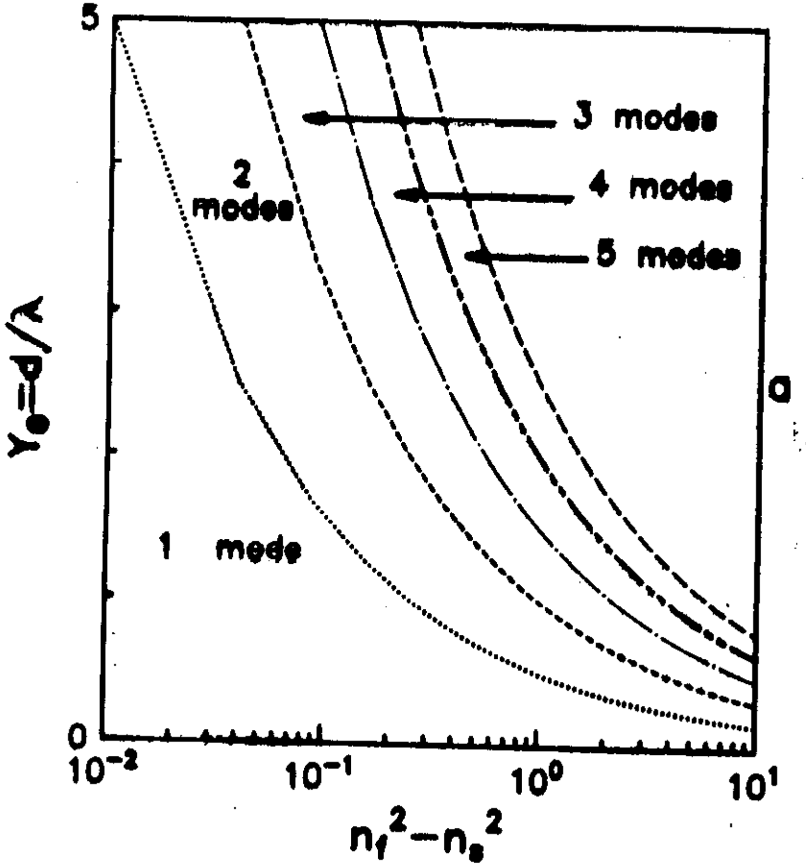


boundary equation for cut–off spectrum

$$\frac{W}{\lambda} = \frac{m\,\pi}{2\pi\sqrt{N_I^2 - N_{II}^2}}$$

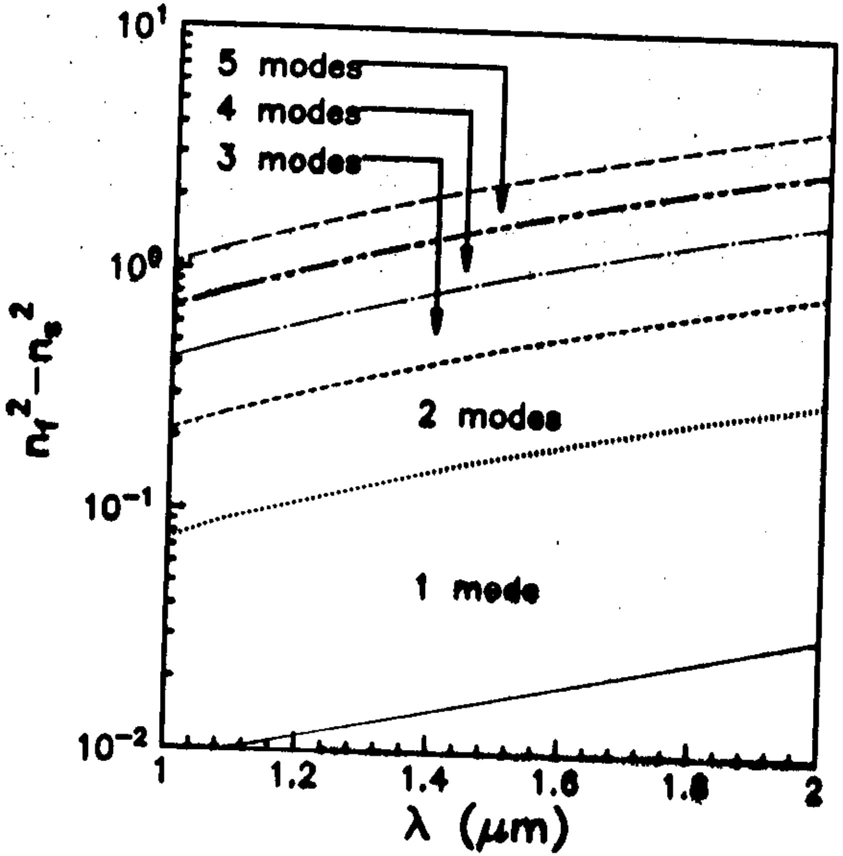
W = waveguide width
N_I = effective index in the waveguide region
N_{II} = effective index outside the waveguide region
m = mode number

Step-index waveguide: normalized cut-off chart



a = 0

Cut-off chart calculated for an actual step-index waveguide 2.7 μm thick



TM polarization
a = 2340

$Ti:LiNbO_3$ graded-index waveguide

planar waveguide

boundary equation for cut-off waveguide

$$\frac{D}{\lambda} = \frac{(m + 3/4)\,\pi}{2\pi\sqrt{n(0)^2 - n_s^2}\int_0^\infty f(x)dx}$$

x = depth coordinate
D = diffusion lenght
$n(0)$ = surface refractive index
n_s = substrate refractive index
$f(x)$ = refractive index profile shape
m = mode number

$Ti:LiNbO_3$ graded-index waveguide

(effective index method)

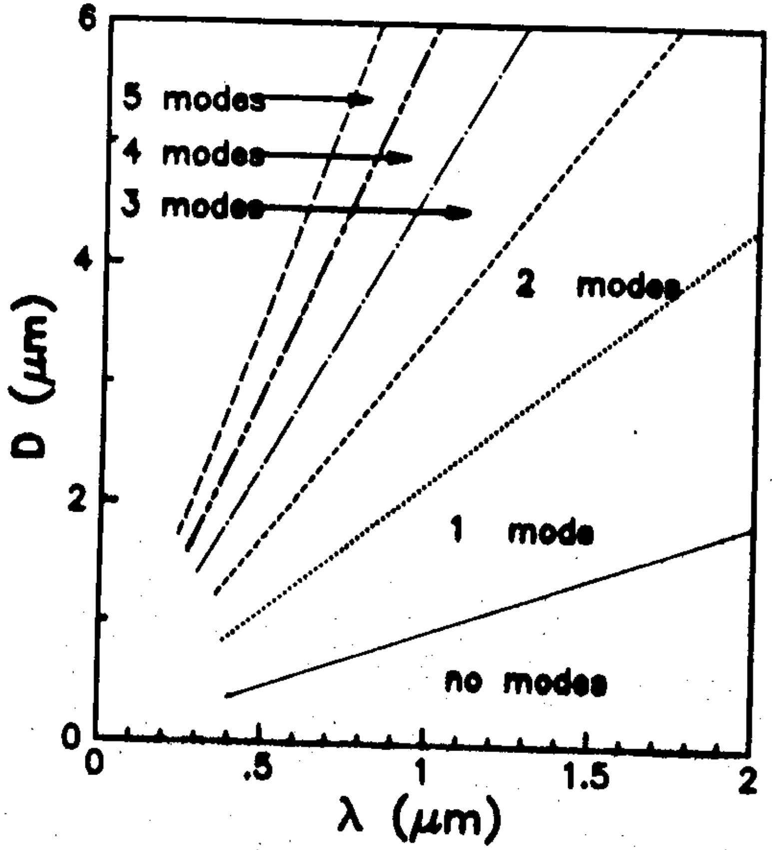
2-dim waveguide

boundary equation for cut-off spectrum

$$\frac{w}{\lambda} = \frac{(m + 1/2)\,\pi}{2\pi\sqrt{n_{eff}^2 - n_s^2}\int_0^\infty h(u)du}$$

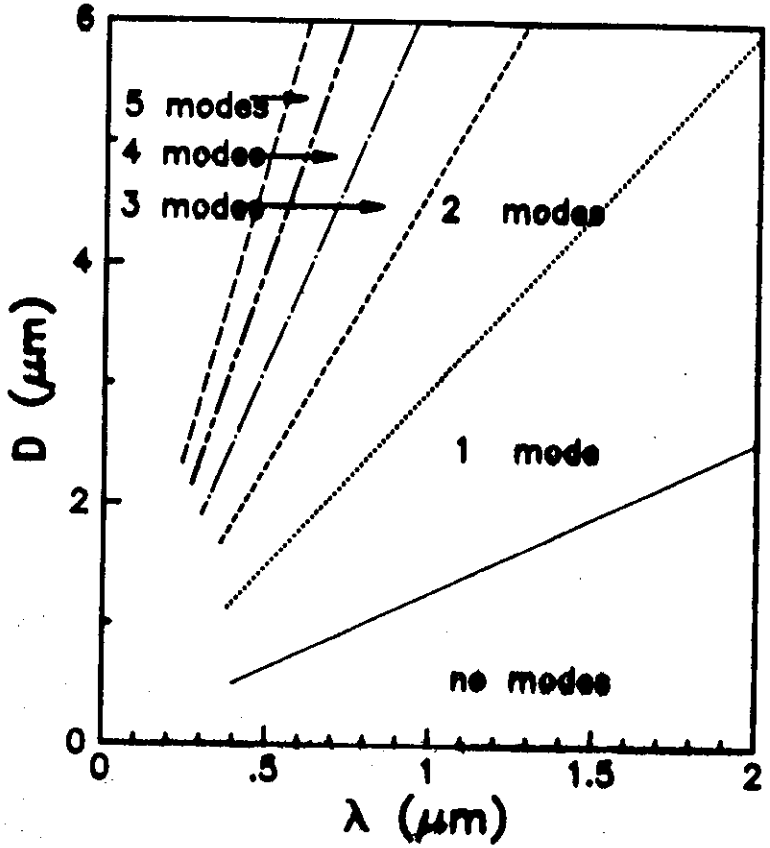
u = normalized lateral coordinate : $2y/w$
w = Ti strip width
n_{eff} = modal index for depth mode
n_s = substrate refractive index
$h(u)$ = index profile shape of the equivalent 1-dim graded guide (function of the ratio w/D)

Cut–off chart for graded index waveguide calculated for Δn^2 = 0.103 and TE modes

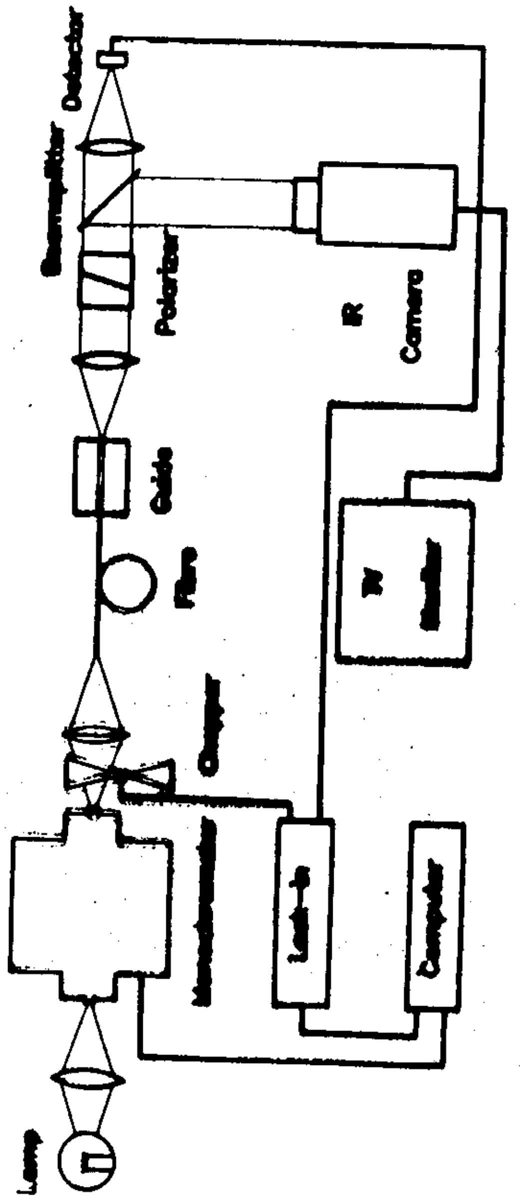


profile shape:
gauss function

Cut–off chart for graded index waveguide calculated for Δn^2 = 0.103 and TE modes

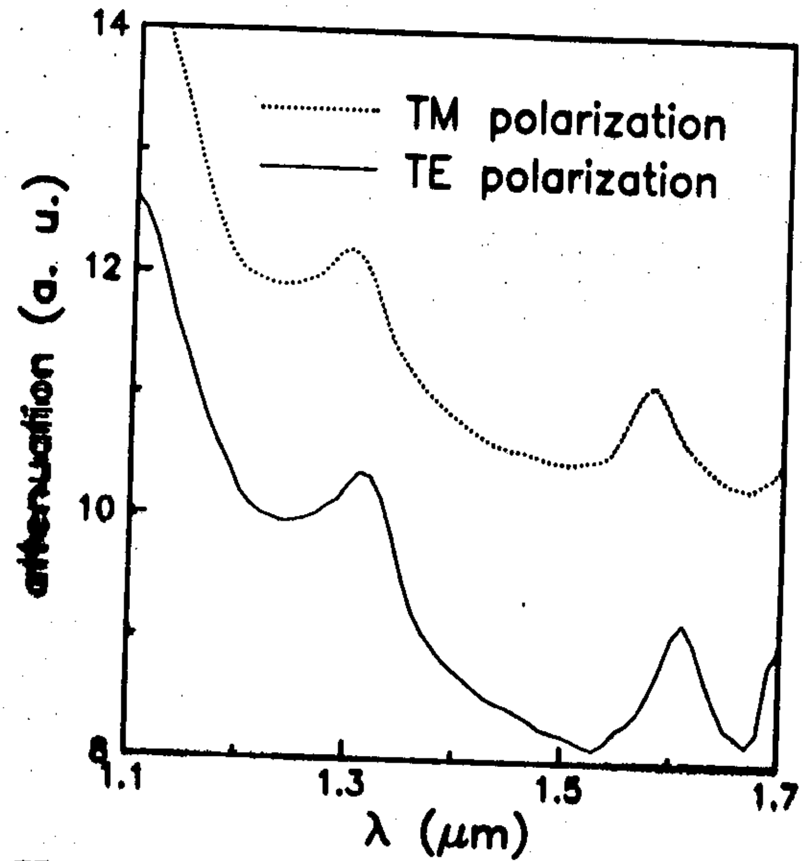


profile shape:
erfc function



MODAL CUT-OFF SPECTROSCOPY:
EXPERIMENTAL SET-UP

Cut-off spectra on a InGaAsP/InP ridge waveguide, 3.6 μm thick, 10μm wide, TE and TM polarization: experimental values

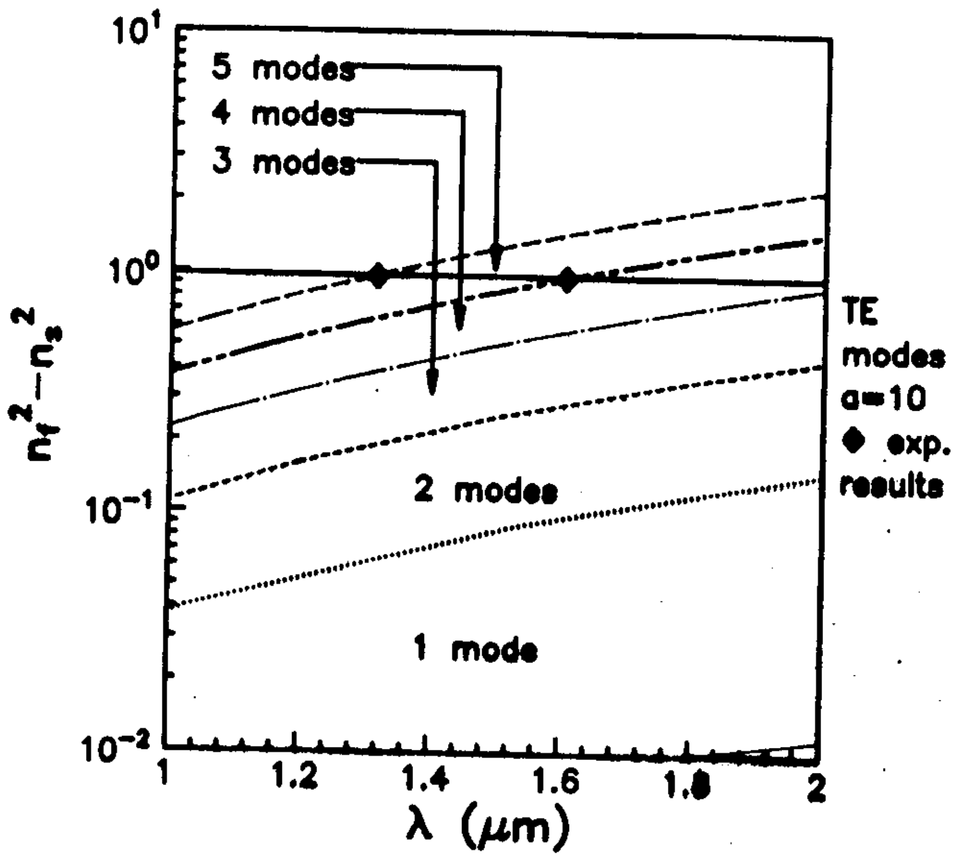


TE polarization: cut-off at $\lambda = 1.315\ \mu m$
$\lambda = 1.605\ \mu m$

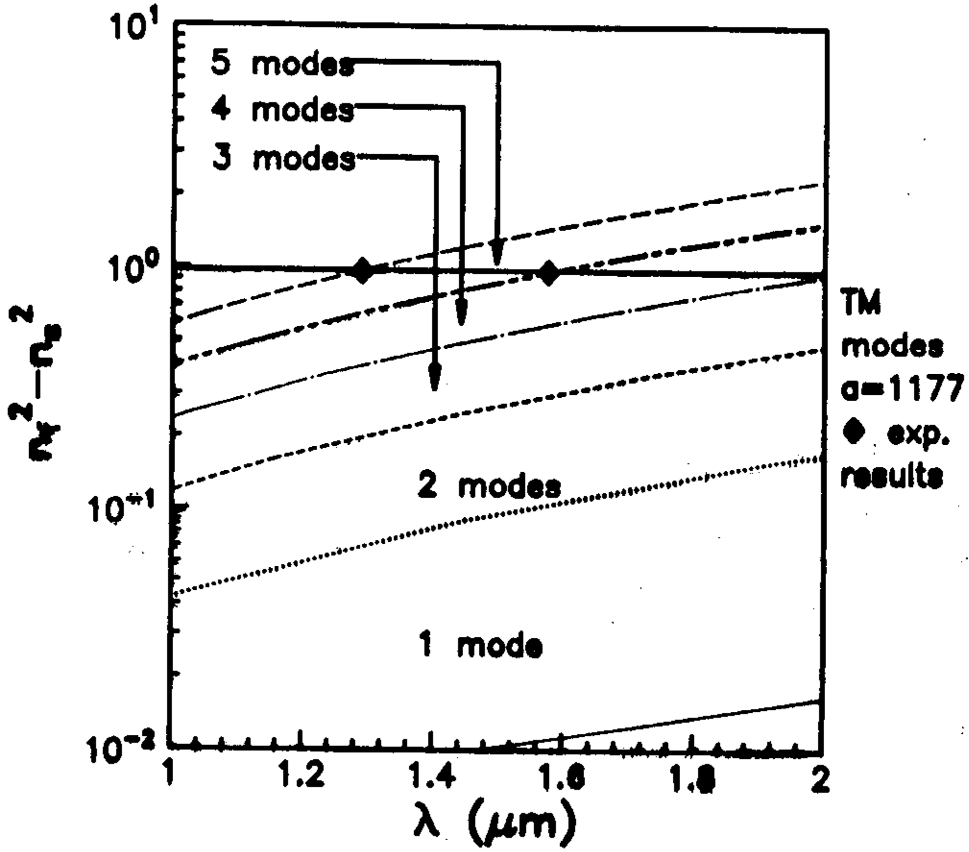
TM polarization: cut-off at $\lambda = 1.295\ \mu m$
$\lambda = 1.575\ \mu m$

$\Delta = ^{+-}.010$

LPE grown (InGaAsP λ_{em}=1.1μm)waveguide 3.6μm thick: experimental results



LPE grown (InGaAsP λ_{em}=1.1μm)waveguide 3.6μm thick: experimental results

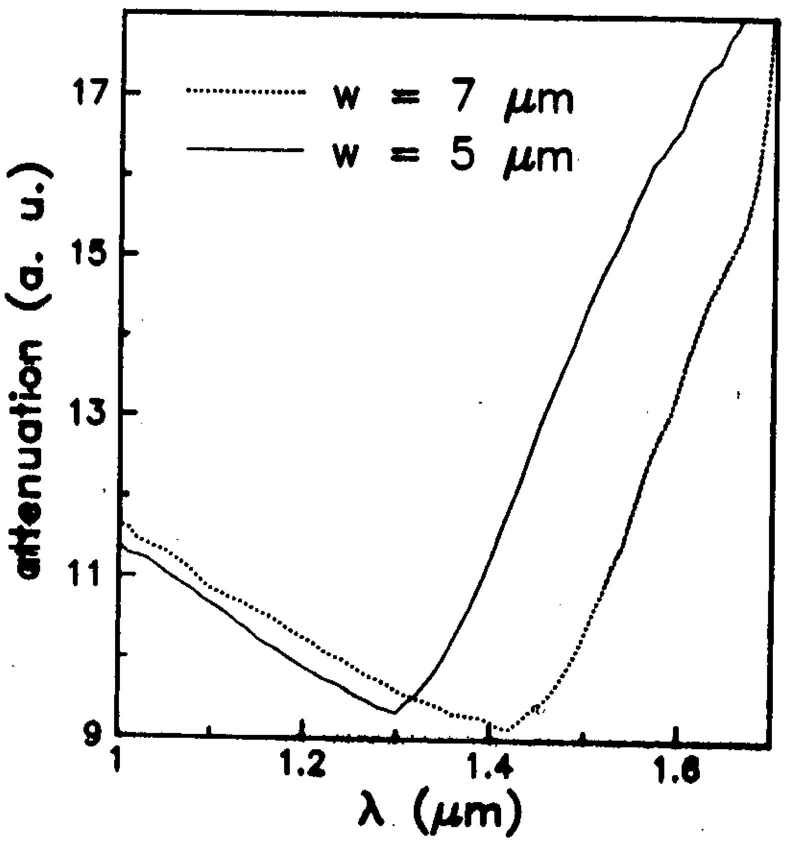


$n_f(\lambda=1.3\mu m)=3.325^{+-}.001$

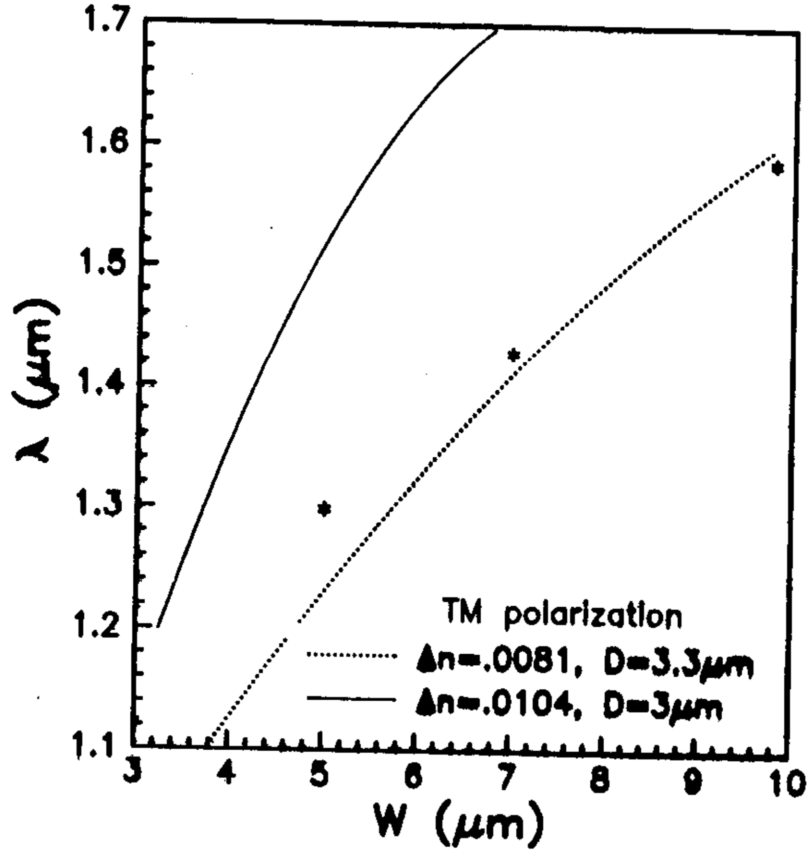
$n_f^2-n_s^2$ =.967^{+-}.003

$n_f(\lambda=1.6\mu m)=3.280^{+-}.001$

measured cut-off spectra of Ti:LiNbO$_3$ waveguide of different width w, Ti thickness 62 nm diffusion time 7h at 1000 °C



Ti:LiNbO$_3$ waveguide, diffusion time=7h, Ti thickness=62 nm: experimental results



Use of the spectral cut-off measurements

a) step-index semiconductor waveguide:

refractive index measurement with an accuracy < 2×10^{-3}

b) graded-index $Ti:LiNbO_3$ 2-dim waveguide

choice between different:
diffusion profile shapes
diffusion lengths
refractive index jumps
(i.e. using at the same time planar waveguide analysis)

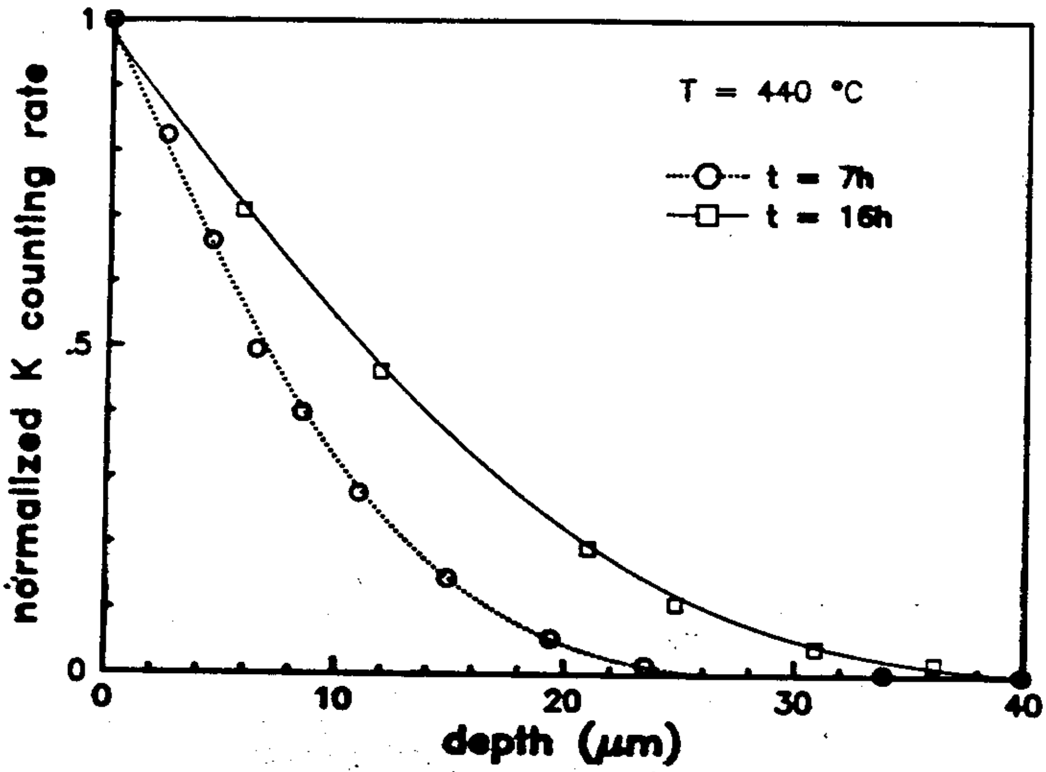
ADVANTAGES

- measurement apparatus normally available in the laboratory
- fast and easy measurement
- better precision than reflectometric method
- possibility to measure refractive index of buried waveguide

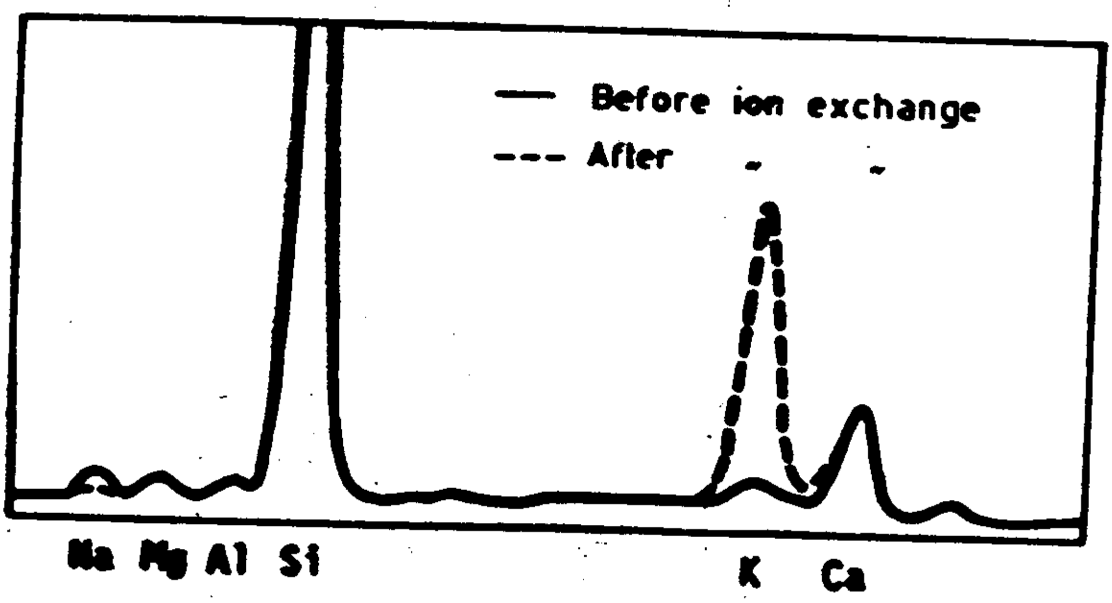
DISADVANTAGES

- refractive index measurement impossible near the material gap wavelength
- lower precision than ellipsometric method

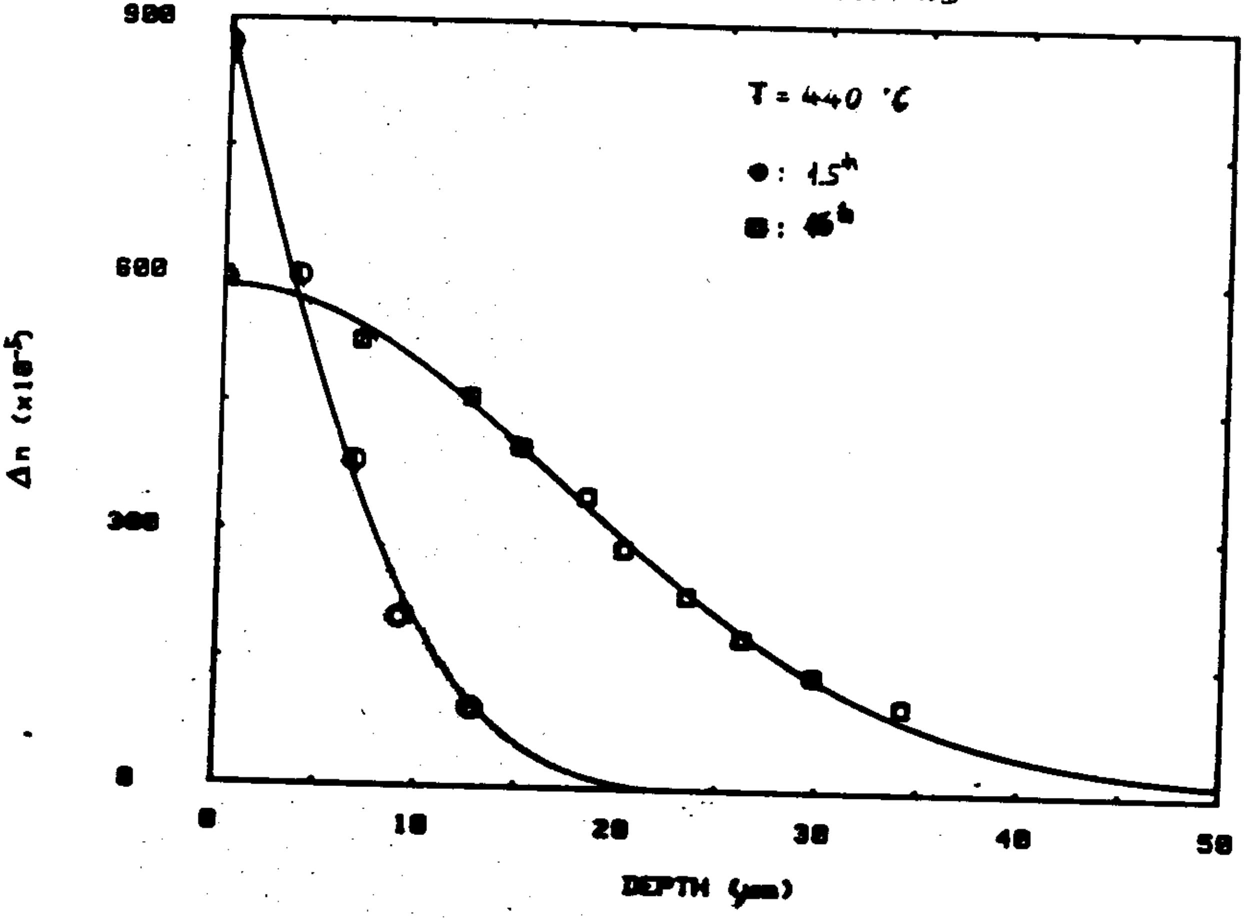
K concentration profile



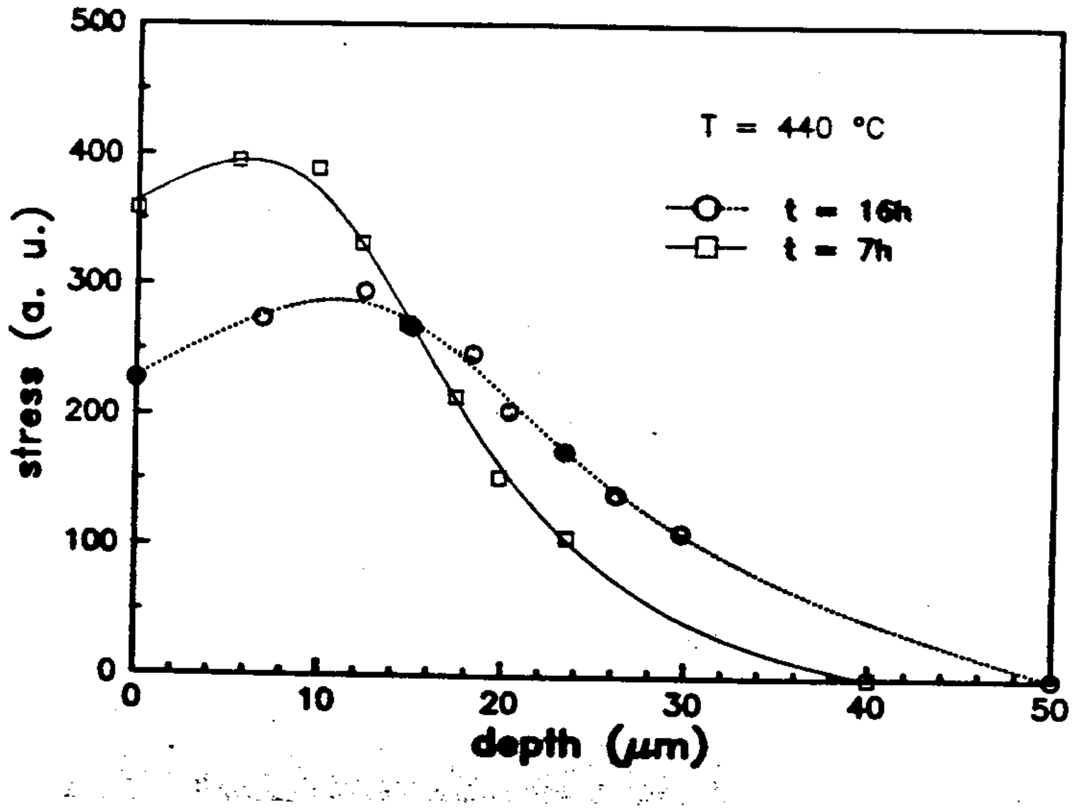
EDX SPECTRA OF GLASS



REFRACTIVE INDEX PROFILE OF K^+-Na^+ EXCHANGED GUIDES BY INVERSE WKB METHOD



Evolution of stress profile



TECHNIQUES FOR GUIDE LOSS DETERMINATIONS

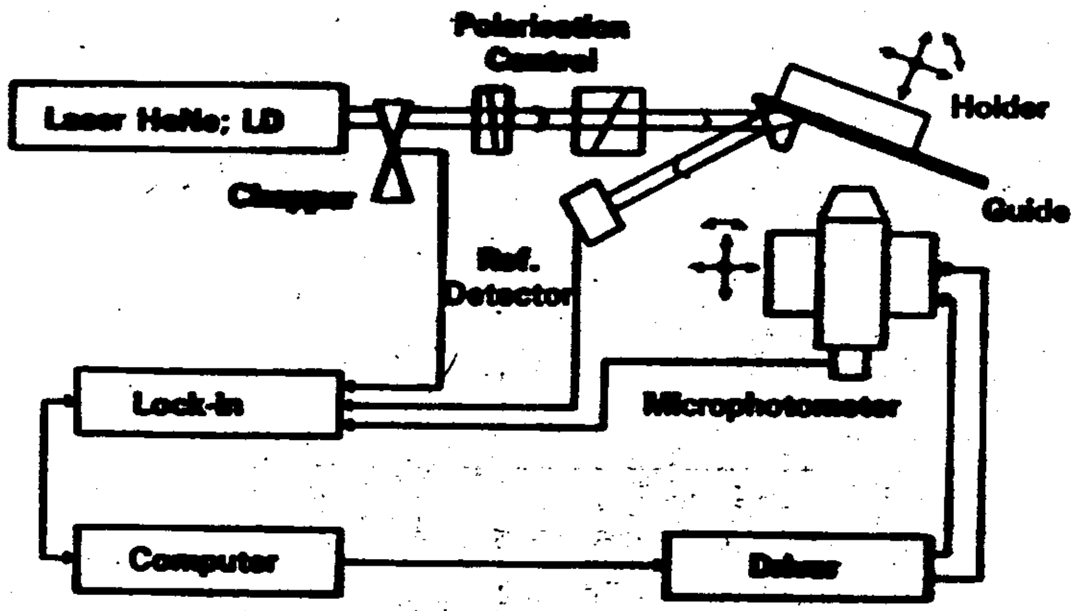
- MEASUREMENT OF LATERAL SCATTERED POWER: WIDE APPLICABILITY
  GOOD PRECISION
  NON DESTRUCTIVE

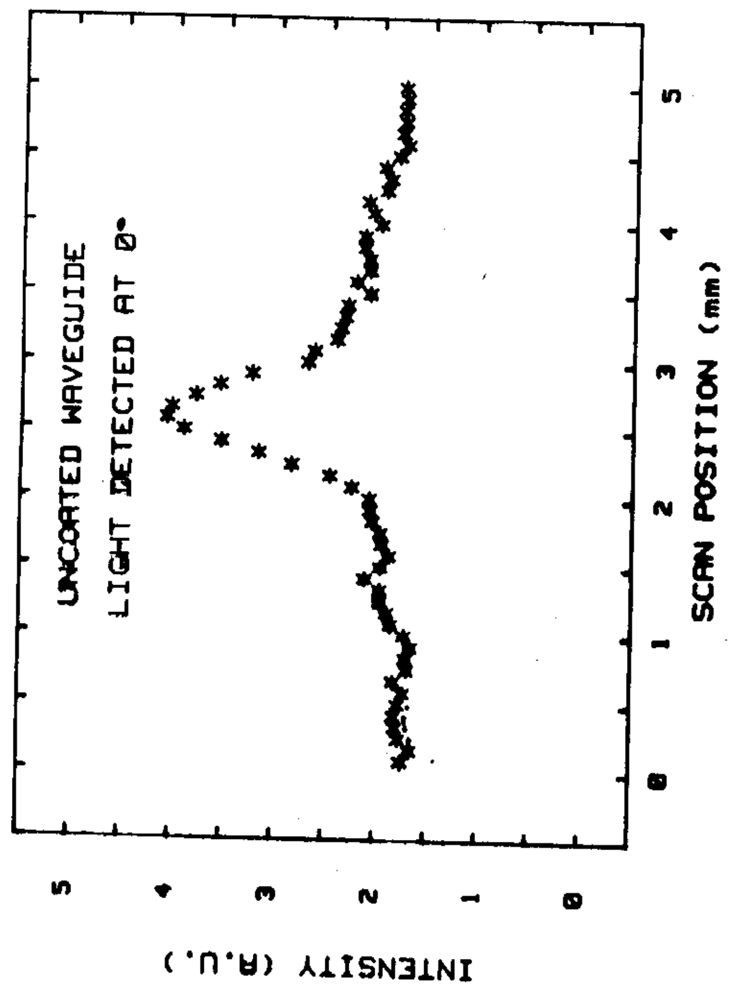
- POWER EXTRACTION BY SLIDING PRISM: POOR REPRODUCIBILITY
  RISK OF DAMAGING GUIDE
  NOT APPLICABLE TO BURIED GUIDES

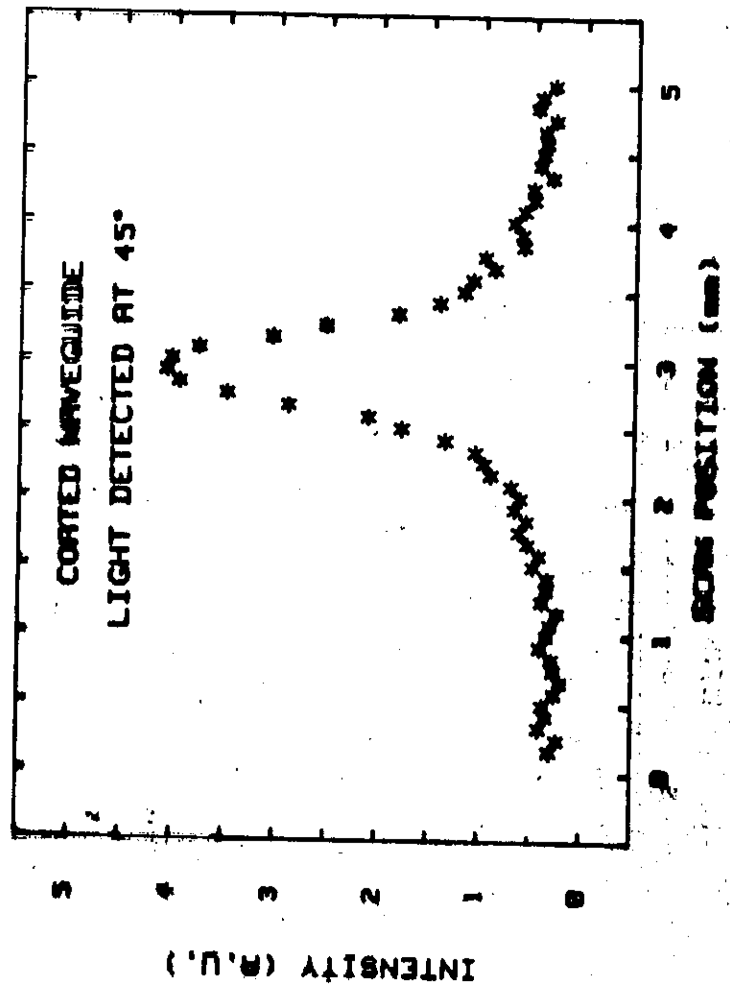
- DETERMINATION OF CHARACTERISTICS OF A RESONATOR CONTAINING THE GUIDE:
  CUMBERSOME, DELICATE EDGE PREPARATION
  GOOD ACCURACY FOR VERY LOW LOSS GUIDES

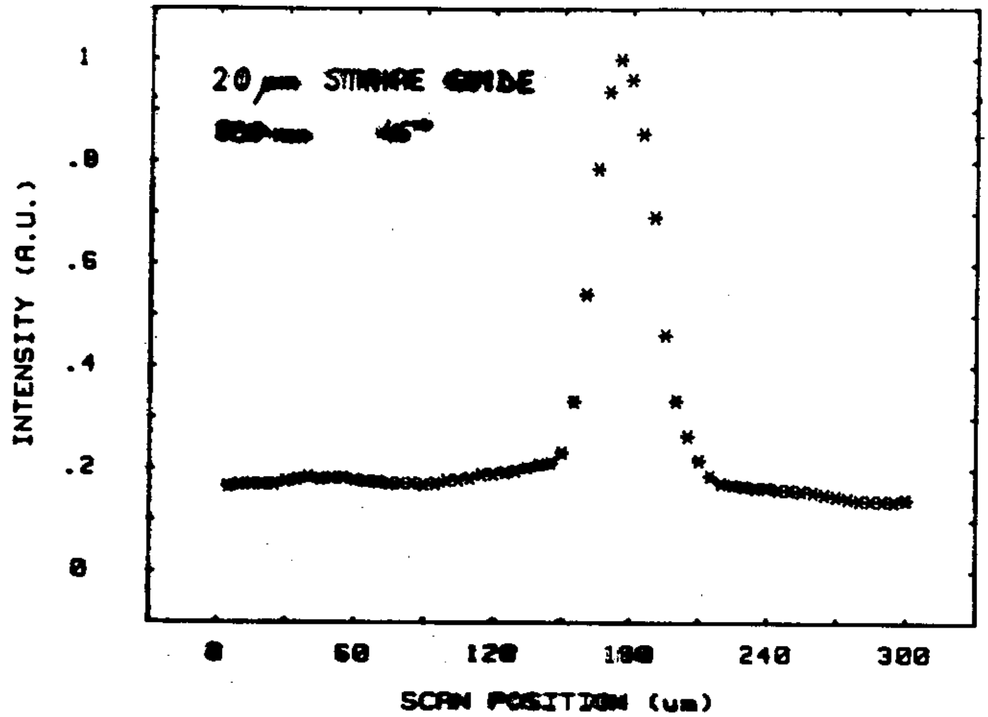
- DETERMINATION OF INSERTION LOSS OF PROGRESSIVELY SHORTENED GUIDE (CUT-BACK):
  DESTRUCTIVE
  GOOD RESULTS FOR CLEAVED-END GUIDES
  COUPLING EFFICIENCY AS BY-PRODUCT

SET-UP FOR SCATTERED LIGHT DETECTION

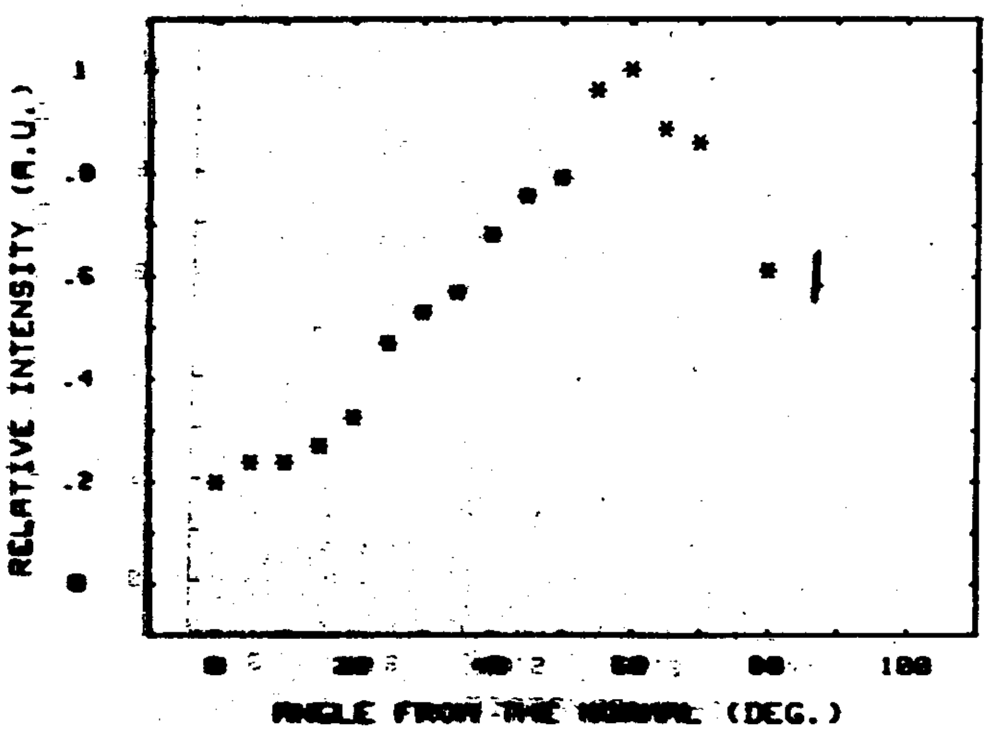


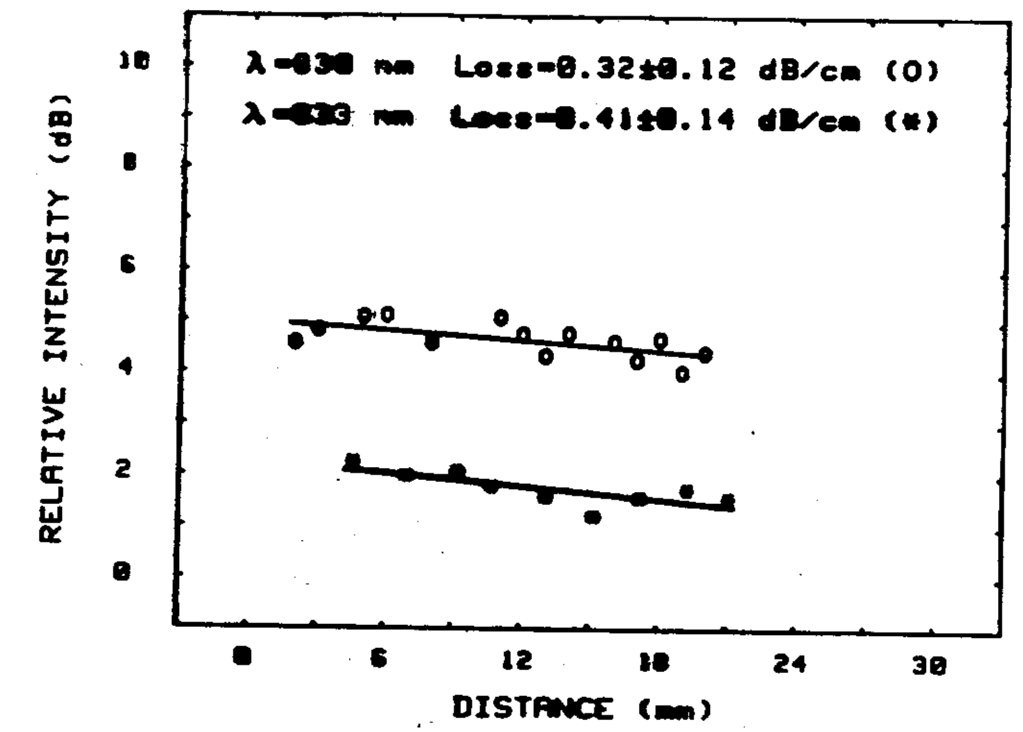

UNCOATED WAVEGUIDE
LIGHT DETECTED AT 0°
SCAN POSITION (mm)
INTENSITY (A.U.)
0
1
2
3
4
5

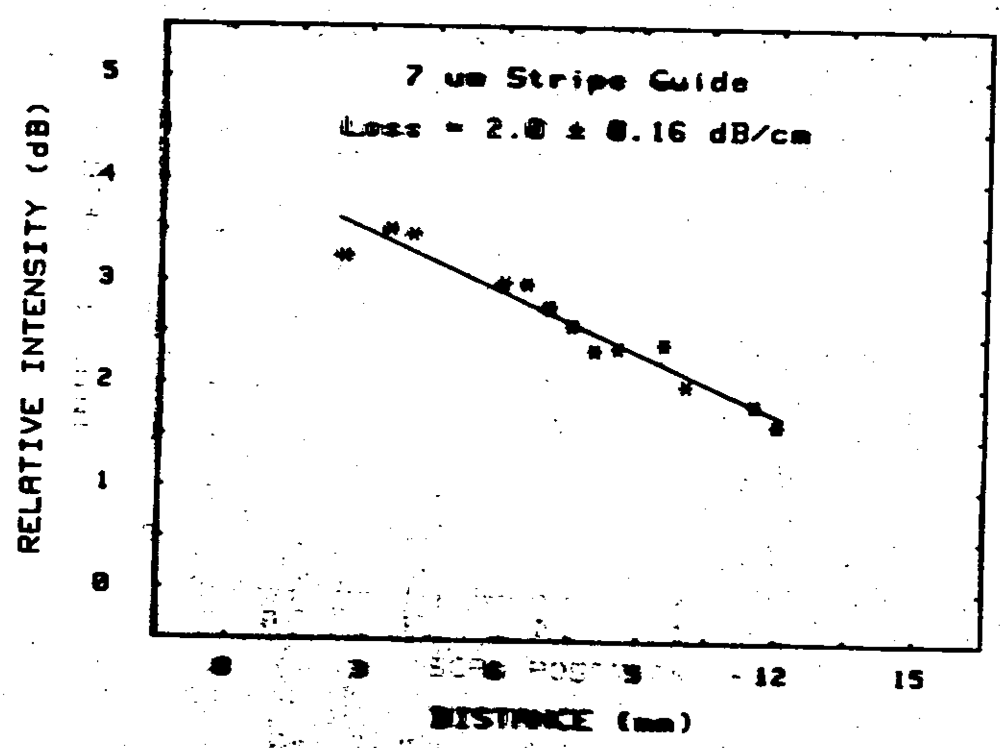

COATED WAVEGUIDE
LIGHT DETECTED AT 45°
SCAN POSITION (mm)
INTENSITY (A.U.)
0
1
2
3
4
5



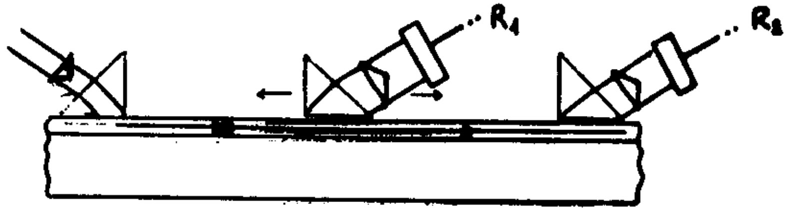
SHAPE OF SCATTERED RADIATION LOBE
($Ti:LiNbO_3$ GUIDES)



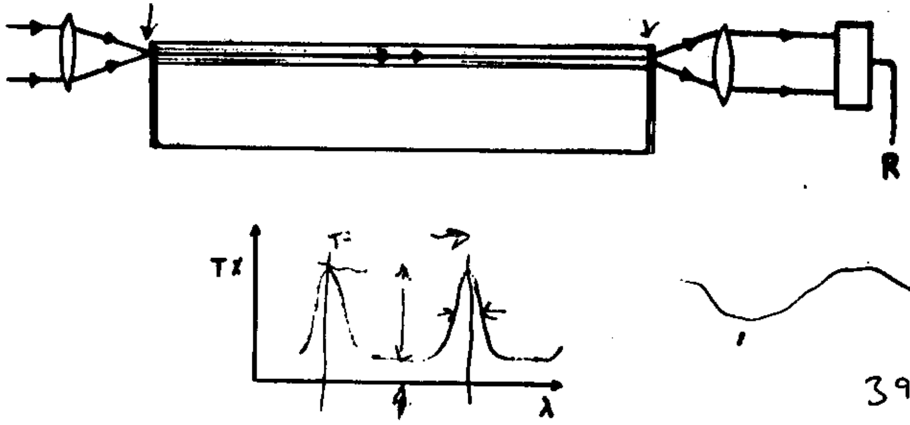

λ=830 nm Loss=0.32±0.12 dB/cm (O)
λ=633 nm Loss=0.41±0.14 dB/cm (*)
RELATIVE INTENSITY (dB)
DISTANCE (mm)
0
2
4
6
8
10
0
6
12
18
24
30


7 um Stripe Guide
Loss = 2.0 ± 0.16 dB/cm
RELATIVE INTENSITY (dB)
DISTANCE (mm)
0
1
2
3
4
5
0
3
12
15

SCHEMATIC OF GUIDE LOSS MEASUREMENT BY SLIDING PRISM POWER EXTRACTION



DETERMINATION OF F-P RESONATOR SPECTRUM



CHARACTERISTICS TO BE MEASURED FOR INTEGRATED OPTICAL COMPONENTS

- COUPLERS:
  - PARTITION RATIO
  - EXCESS LOSS
  - SPECTRAL BEHAVIOUR
  - POLARIZATION "

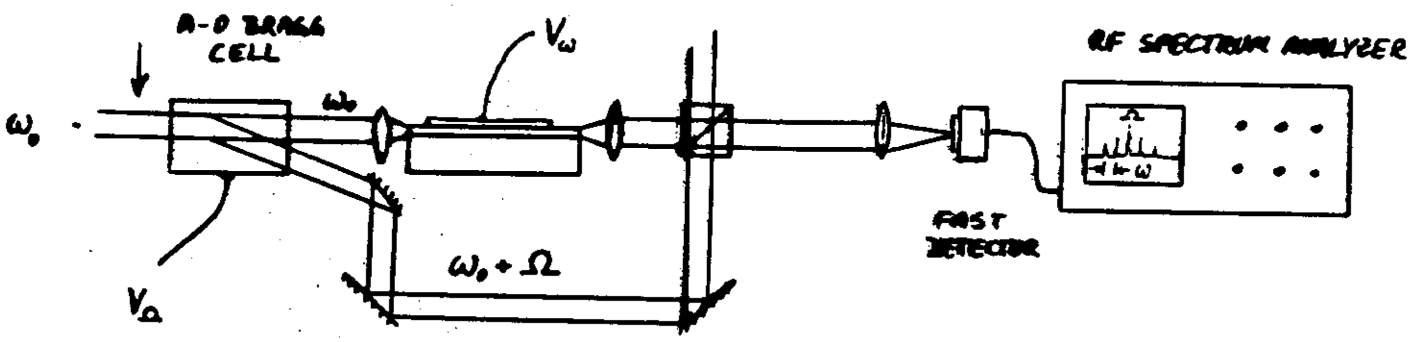
  } RADIOMETRIC MEASUREMENTS

- FILTERS, WAVELENGTH MULTI/DEMULTIPLEXERS:
  - SPECTRAL BEHAVIOUR
  - POLARIZATION "
  - CROSSTALK

  } RADIOMETRIC MEAS.

- SWITCHES:
  - ON/OFF RATIO
  - SWITCHING TIME
  - ELECTRO-OPTIC EFFICIENCY
  - CROSSTALK
  - SPECTRAL & POLARIZATION BEHAVIOUR

- MODULATORS:
  - BANDWIDTH
  - EFFICIENCY
  - SPECTRAL & POLAR. BEHAVIOUR



OPTICAL HETERODYNE SET-UP FOR CHARACTERIZATION OF INTEGRATED PHASE MODULATORS