PL-TN--91-1067

PL-TN--
91-1067

②

$LiTaO_3$ AND $LiNbO_3$:Ti RESPONSES TO IONIZING RADIATION

R. J. Padden
E. W. Taylor
A. D. Sanchez
J. N. Berry
S. P. Chapman
S. A. DeWalt
K. K. Wong

November 1991

Final Report

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

PHILLIPS LABORATORY
Directorate of Space and Missile Technologies
AIR FORCE SYSTEMS COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-6008

PL-TN-91-1067

This final report was prepared by the Phillips Laboratory, Kirtland Air Force Base, New Mexico, under Job Order ILIR8906. The Laboratory Project Officer-in-Charge was Capt Richard J. Padden (STET).

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

If your address has changed, if you wish to be removed from our mailing list, or if your organization no longer employs the addressee, please notify PL/STET, Kirtland AFB, NM 87117-6008 to help us maintain a current mailing list.

This report has been reviewed and is approved for publication.

Richard J Padden
RICHARD J. PADDEN, Capt, USAF
Project Officer

FOR THE COMMANDER

Mark V. Tollefson

JAMES P. CARRIE, Maj, USAF
Chief, Test and Simulation Br

MARK V. TOLLEFSON, Lt Col, USAF
Chief, Space Electronics Div

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
November 1991

3. REPORT TYPE AND DATES COVERED
Final, 11 January 1989 - 30 April 1991

4. TITLE AND SUBTITLE
$LiTaO_3$ AND $LiNbO_3$:TI RESPONSES TO IONIZING RADIATION

5. FUNDING NUMBERS
PE: 61101F
PR: ILIR
TA: 89
WU: 06

6. AUTHOR(S)
R. J. Padden, E. W. Taylor, A. D. Sanchez, J. N. Berry, S. P. Chapman, S. A. DeWalt, K. K. Wong *

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Phillips Laboratory
Kirtland AFB, NM 87117-6008

8. PERFORMING ORGANIZATION REPORT NUMBER
PL-TN--91-1067

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
*Allied-Signal, Inc., Morristown, New Jersey

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Optical guided wave devices can experience crosstalk and mode-switching in the presence of ionizing radiation. This technical note discusses the responses of $LiTaO_3$ and $LiNbO_3$:Ti directional coupler waveguides to exposures of linearly accelerated electrons. A comparison of the waveguides in terms of sensitivity to the ionizing radiation is made.

14. SUBJECT TERMS
Integrated Optic Devices, Photorefractive Effect, $LiNbO_3$, $LiTaO_3$, Radiation Effects

15. NUMBER OF PAGES
24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
SAR

ACKNOWLEDGEMENT

This research was performed in part through funds provided under the Laboratory Independent Research Program of the USAF Phillips Laboratory.

CONTENTS

FIGURES

1.0 INTRODUCTION

A number of materials and structures for optical waveguides are currently on the market or in development. Two of the more established types of materials, in terms of substrates, are $LiNbO_3$ and $LiTaO_3$. Although these technologies are well-established, a recurring problem, particularly for the scientific community, is the relative lack of information on the responses to ionizing radiation of these materials and the devices made from them. Some interesting work, however, has been performed using $LiNbO_3$:Ti directional coupler waveguides, and the results have been reported (Refs. 1-5).

The work performed for this report builds upon the earlier work done on $LiNbO_3$:Ti directional couplers, and also examines a proton exchanged $LiTaO_3$ directional coupler. The data from these devices were gathered during two separate experiments using 15 MeV accelerated electrons and various doses and dose rates. Previously reported ionization-induced refractive index and polarization effects in $LiNbO_3$:Ti are confirmed here (Ref. 3), at least for specific test conditions. In addition, these effects are also noted, but to a lesser degree, in the $LiTaO_3$ device response.

These initial experiments represent only a small portion of the possible radiation environments and system configurations these devices could experience. Also, the different physical makeup of the two devices somewhat clouds the comparison of results. Nevertheless, for the conditions of our tests, the $LiTaO_3$ proton exchange directional coupler appears significantly less sensitive to ionizing radiation (accelerated electrons in particular) than its $LiNbO_3$:Ti counterpart.

2.0 $LiNbO_3$:Ti RESPONSE

2.1 SETUP

The first of two $LiNbO_3$:Ti transient radiation measurements was performed using the setup of Figure 1. The directional coupler was composed of Z-cut $LiNbO_3$:Ti operating at λ = 1300 nm, using a polarization preserving pigtailed

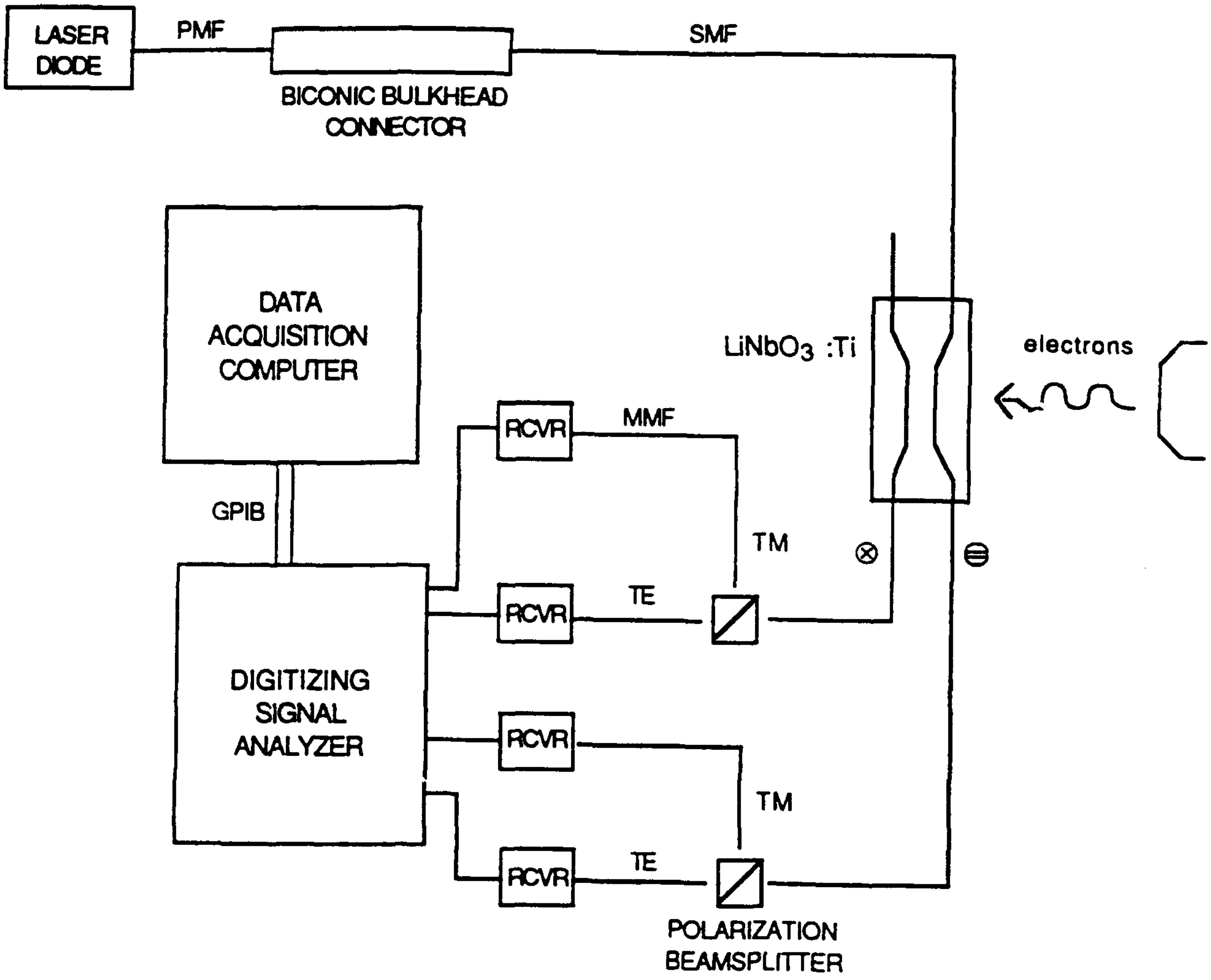


Figure 1. The setup for the first $LiNbO_3$:Ti measurements.

injection laser diode. With no bias applied to the device, transverse magnetic (TM) polarization was favored in the through channel (θ). The device was pigtailed with 1-m lengths of single-mode fiber. Outputs of both the through θ and cross ⊗ channels were sent to polarization beamsplitting cubes so both transverse electric (TE) and TM components could be monitored separately. The receivers used were avalanche photodiodes whose outputs were recorded by a digitizing signal analyzer.

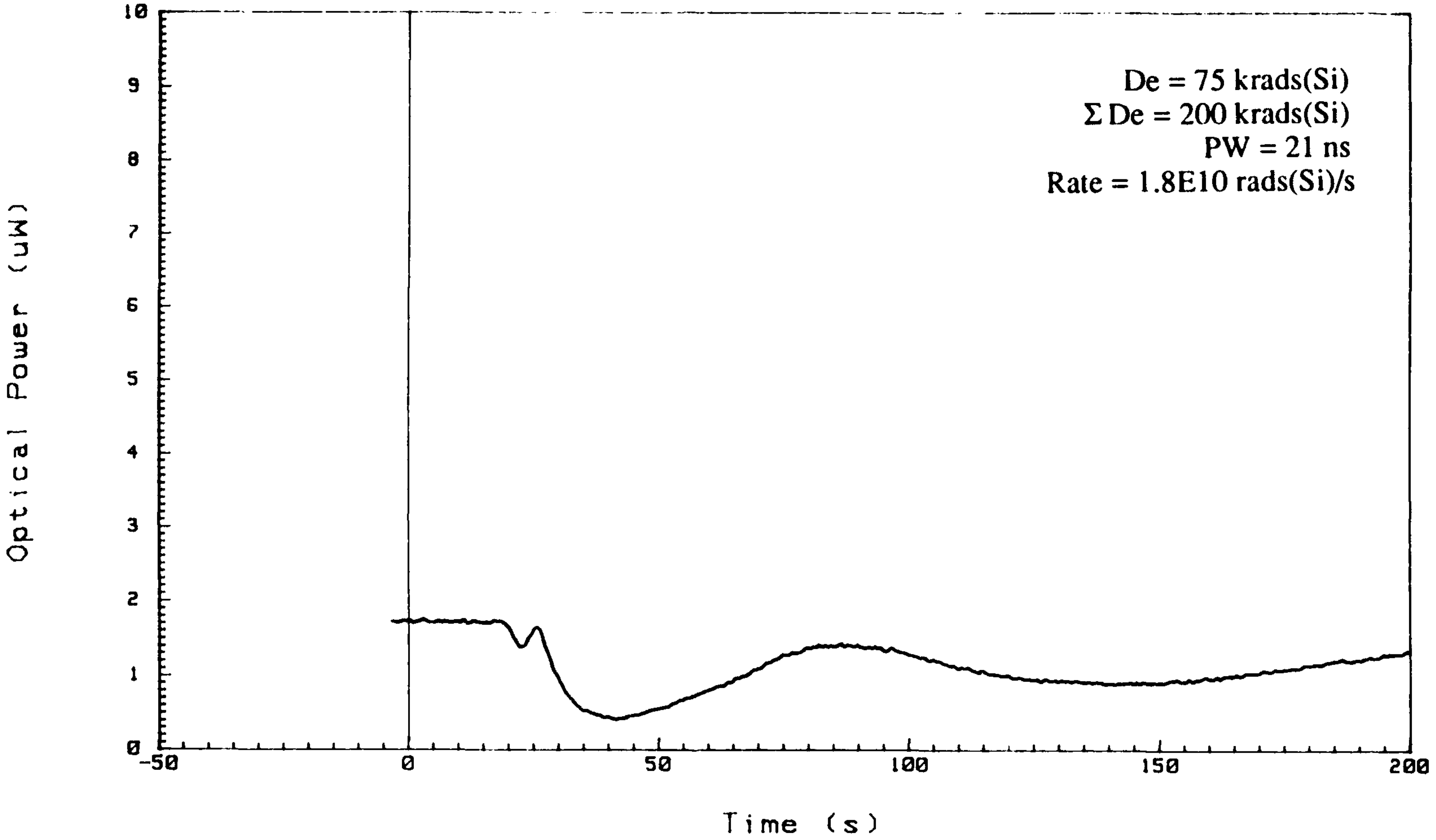
The ionizing radiation source used was a linear electron accelerator. The pulse width for the first measurements was 20 ns full width at half maximum (FWHM) for a dose of 375 rads(Si)/pulse and a dose rate of 1.8×10^{10} rads(Si)/s for each pulse. The electron energy was 15 MeV. The maximum pulse repetition rate for the source was 60 pulses/s, but was typically run at 30 pulses/s. The beam divergence was such that only the interaction region of the waveguide, where optical coupling between the channels takes place, was irradiated.

2.2 EXPERIMENT RESULTS

The laser power for Figure 1 was set at 1.50 mW. The dose rate was kept constant, but total dose was increased with each succeeding shot. The acquisition equipment was set to capture up to 200 s of data for long term recovery information.

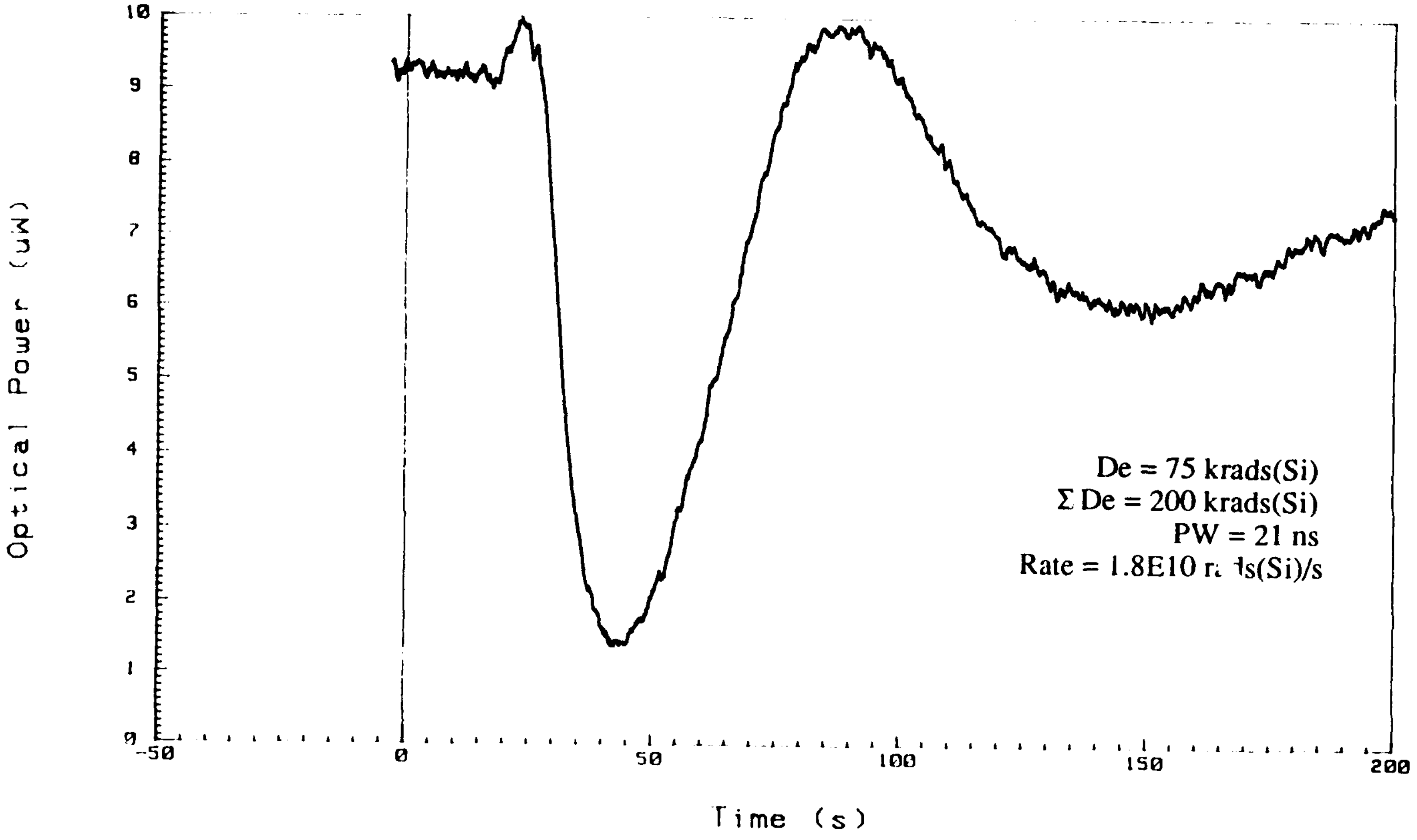
An indicative type of response of the $LiNbO_3$:Ti device is shown in Figure 2. This particular case consisted of 75 krads(Si) incident on the device, while cumulative total dose was 200 krads(Si).

It is interesting to see that once the electrons impinge on the device, there are obviously some types of polarization mode conversion effects happening. One explanation of this could be the coupling coefficients of the two channels being changed so that the phase matching condition is disturbed and the coupling length for TE and TM modes are altered. This can be brought about by changes in the effective indices of the channels and surrounding substrate through deposition of electrons into the material. Drift of these electrons



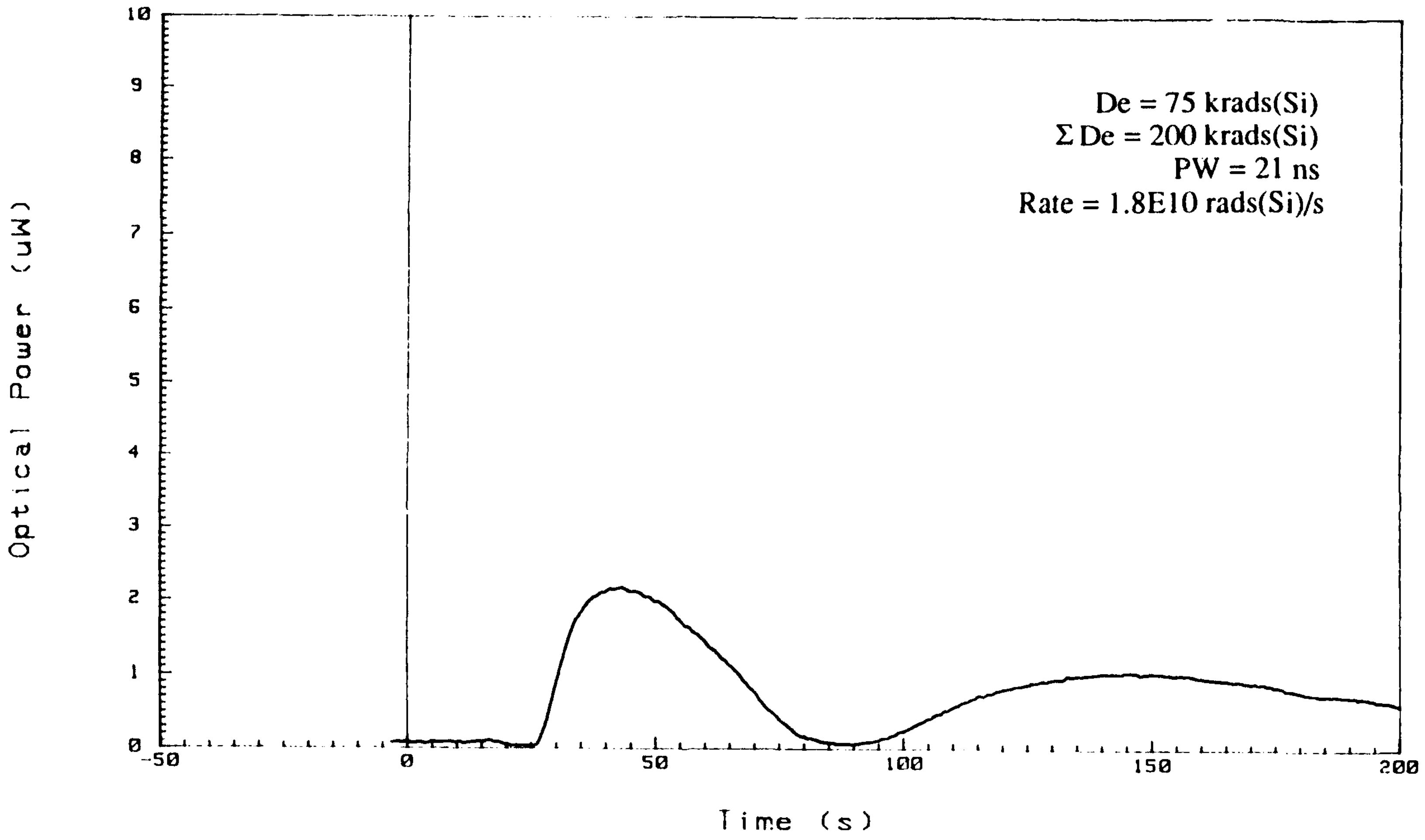
(a) TE through channel.

Figure 2. $LiNbO_3$:Ti directional coupler response of first experiment. No power was detected in the TE cross channel.



(b) TM through channel.

Figure 2. Continued.



(c) TM cross channel.

Figure 2. Concluded.

leads to the creation of space charge fields and subsequently the refractive index change via the linear electro-optic effect. In essence, this is photorefractive-like damage which has been discussed by Taylor (Ref. 3).

It is also observed that there is a significant loss of total power in the waveguide channels during the first instance of mode switching. While absorption/attenuation is evident, scattering is the most probable cause of this. The waveguides are not destroyed, however, because transfer of energy from one mode to another (and channel to channel) indicates that, though degraded, the fundamental switching operation of the device is still intact. Indeed, after the first "cycle" (≈90 s) of the mode switching, power in each channel has essentially returned to the baseline values.

It is important to note some comments on the data based on experimental constraints. This particular study needs to be qualified in two aspects. The first is that no reference on the laser source was used to detect any drift that might be occurring. The second is that no power was seen in the cross channel TM axis (Fig. 2). The laser drift problem was a valid concern until a subsequent exposure of the device was conducted, where a reference channel was set up to detect both TE and TM modes. As will be seen later, the laser drift does not appear to be a factor in the crosstalk occurring between the device channels. It is believed that the problem of no power in the cross channel TM axis was caused by the misalignment of the optical train set up to detect that particular output. However, the trend of the crosstalk is evident in the responses of the other three channels, and it seems reasonable to expect that the fourth channel would show similar behavior.

The second $LiNbO_3$:Ti study (Fig. 3) had a similar configuration to that of Figure 1, with the following exceptions: (1) A polarization maintaining 2 x 2 fiber optic coupler was used between the laser diode source and the input of the device. The coupler was roughly a -3 dB splitter with the first output going to the device and the second output sent through a polarization beamsplitting cube to detect reference TE and TM modes. (2) A higher power pigtailed laser diode (λ = 1320 nm) was used to compensate for the power loss experienced through the 2 x 2 coupler. (3) A fiber polarizer was placed

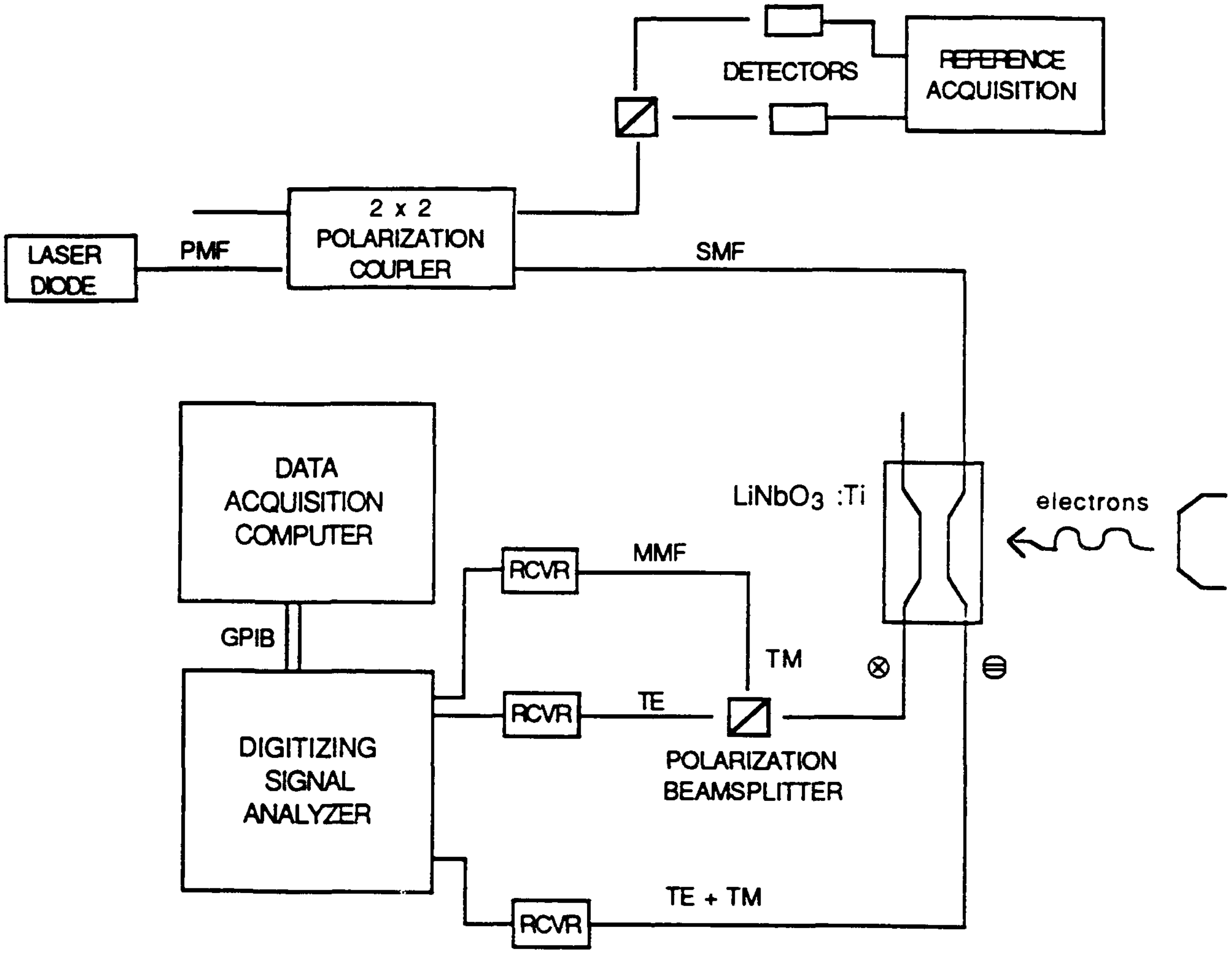


Figure 3. The setup for the second $LiNbO_3$:Ti measurements. (Due to equipment limitations, only three receivers were used so total optical power only was detected on the through channel.)

between the laser and the device input to better control input polarization. (4) A mechanical coupling problem in one optical receiver resulted in foregoing detection of TM and TE modes in the through channel, so we detected strictly total optical power from that channel.

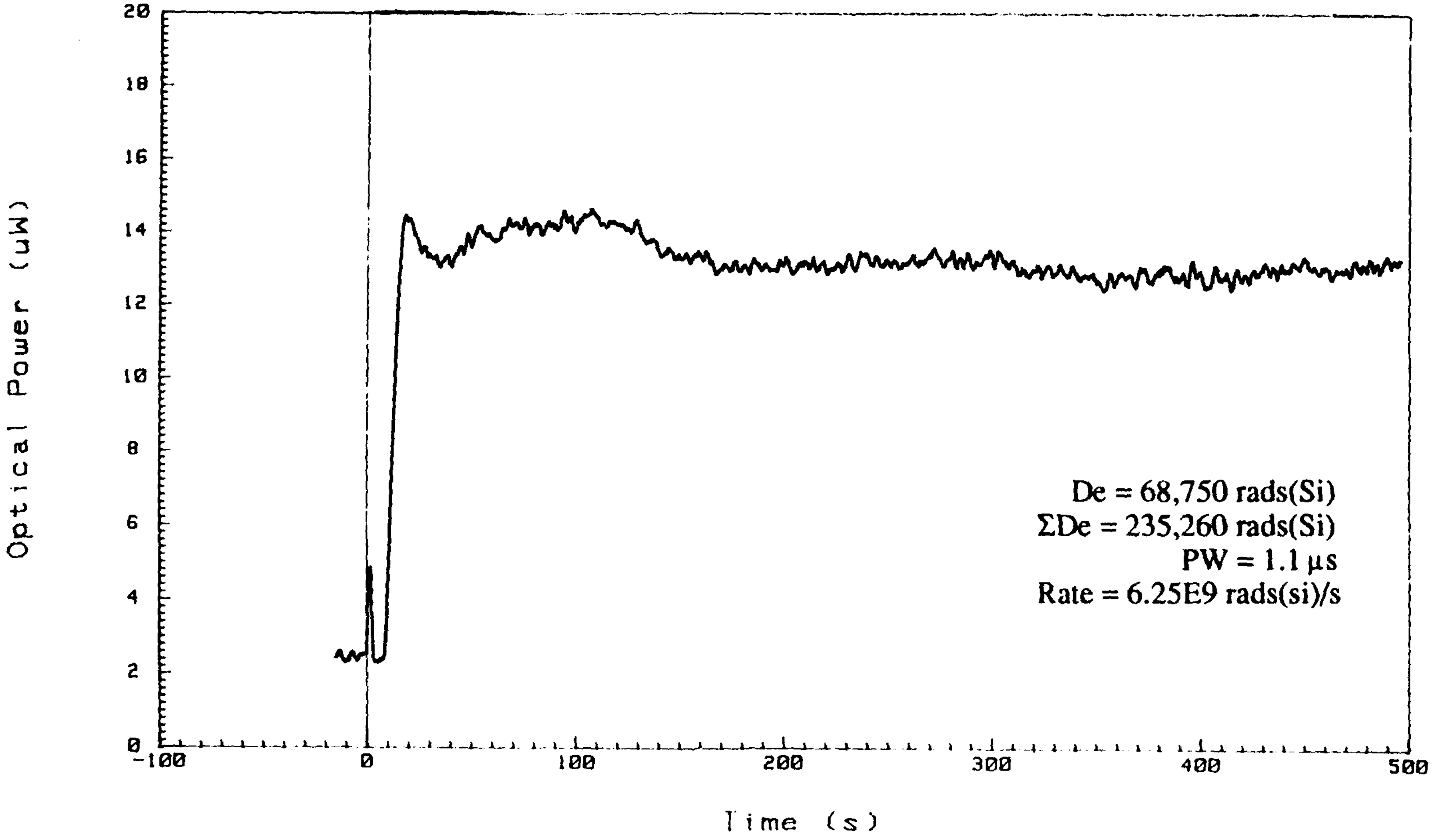
The same radiation source was used in this second setup. However, there were a number of different pulse widths used to provide varying amounts of dose and dose rates. The particular case examined in Figure 4 used a 1.1 μs FWHM pulse width for a dose of 6875 rads(Si)/pulse and a dose rate of 6.25×10^9 rads(Si)/s per pulse. The dose for the results in Figure 4 was 68,750 rads(Si), and the cumulative total dose was 235,260 rads(Si).

The results shown in Figure 4 confirm that mode switching is occurring. This is evident in the two cross ⊗ channel traces, where the "symmetry" of the two curves about the horizontal axis shows power transfer between the TM and TE axes. Another interesting point about the device response is that the total power gained in the through θ channel is more than the combined loss of the cross ⊗ channel axes. A possible reason for this could be that the reflectivity of the channel, which is a function of the refractive index, is decreasing because of the induced effects in the device. This hypothesis is being advanced and reported.[*]

Finally, Figure 5 shows the output of the laser reference channel used in Figure 3. It is apparent that, although the laser power noise is evident, the long term drift (over hundreds of seconds) is fairly constant and does not manifest itself in the characteristic curves of Figure 4.

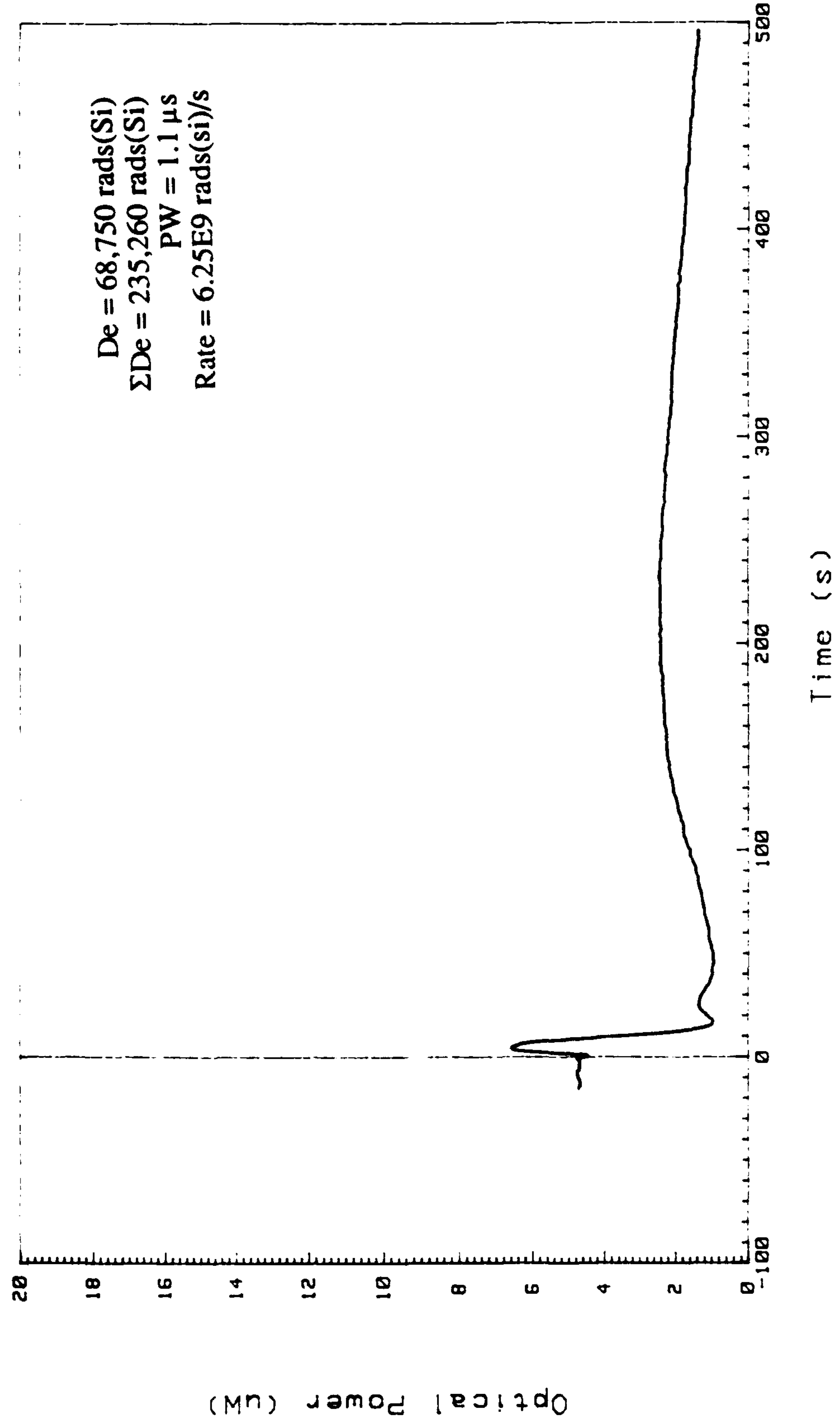
---

[*] Taylor, E. W., et al, "Radiation-induced Crosstalk in Polarization Maintaining Fibers and Directional Coupler Waveguides," to be submitted for publication, April 1991.



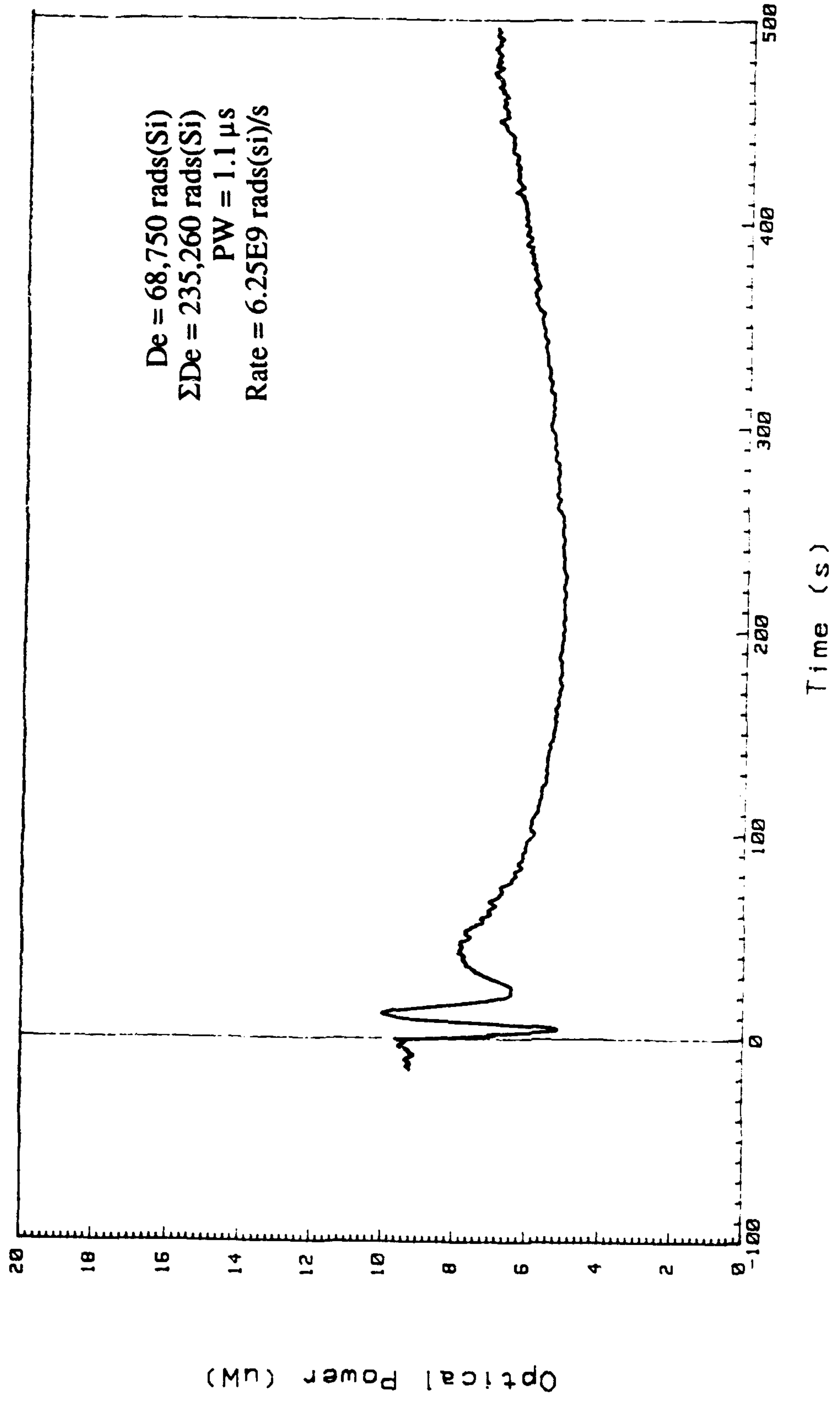
(a) $LiNbO_3$:Ti TM and TE channel.

Figure 4. $LiNbO_3$:Ti directional coupler response of second experiment.



(b) $LiNbO_3$:Ti TM cross channel.

Figure 4. Continued.



(c) $LiNbO_3$:Ti TE cross channel.

Figure 4. Concluded.

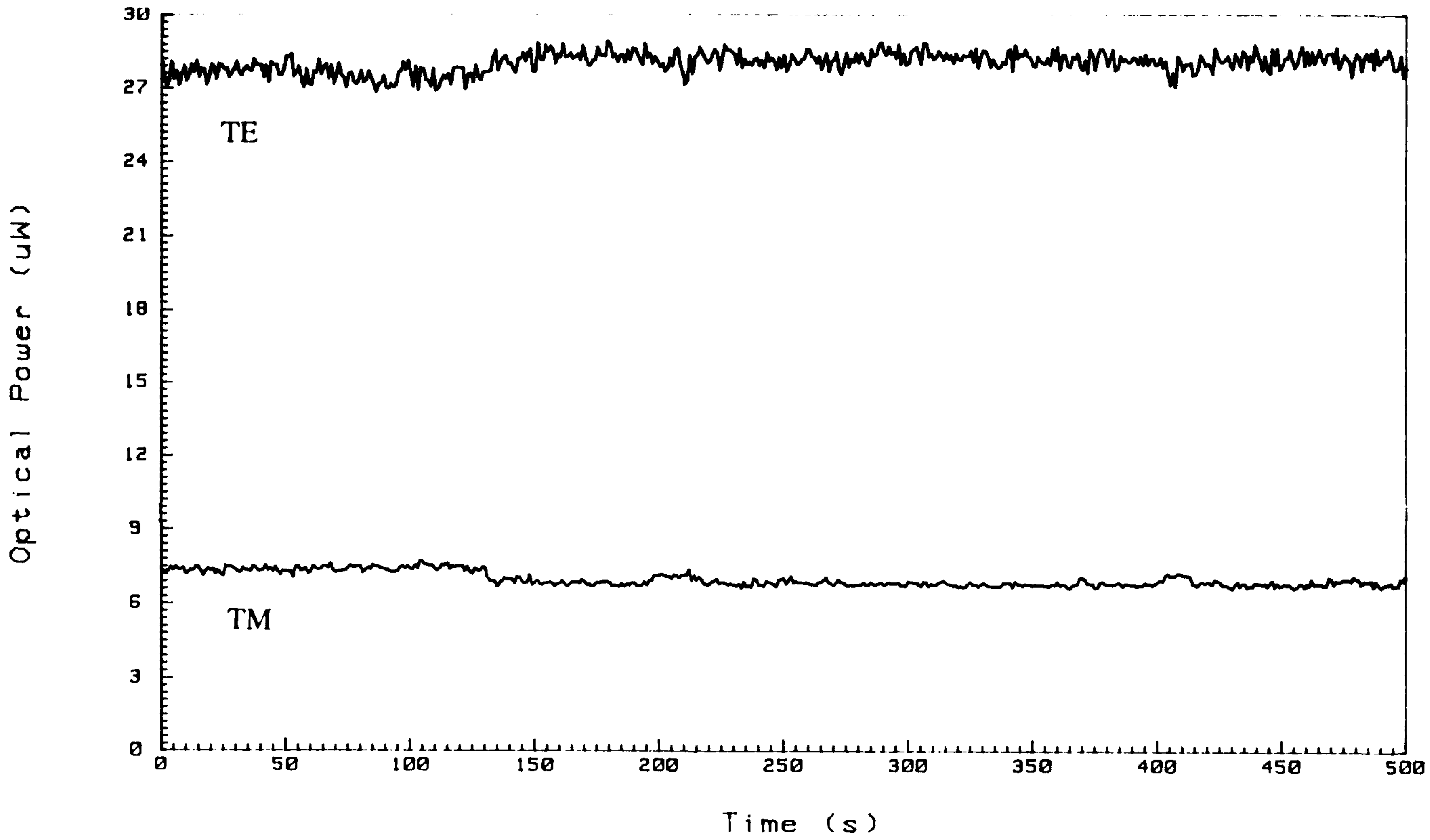


Figure 5. Laser drift for the second $LiNbO_3$:Ti experiment. It is apparent that the mode switching and crosstalk exhibited in Figure 4 are not a result of laser mode hopping.

3.0 $LiTaO_3$ RESPONSE

3.1 SETUP

The $LiTaO_3$ directional coupler used was a proton-exchanged X-cut device operating passively at $\lambda = 1320$ nm and pigtailed with polarization preserving fiber. The device characteristics were such that only TE modes were allowed to propagate in the waveguides (45 dB rejection of TM modes), so that the TE ⊗, TM ⊗, and TE θ channels were monitored by the three available receivers (Fig. 6). For this study, as in the previous $LiNbO_3$:Ti investigation, the radiation source pulse width and energy density was varied to provide different dose and dose rates.

3.2 EXPERIMENT RESULTS

A representative response of the $LiTaO_3$ device is shown in Figure 7. The radiation pulse width was 2.0 μs, with 18.2 krads(Si)/pulse. The dose for this case was 1.29 Mrads(Si) with a cumulative total dose of 2.52 Mrads(Si). The single pulse dose rate was 9.1 x 10^9 *rads(Si)/s*.

Figure 7 shows that again there is an altering of the coupling length occurring based on the responses of the TE θ and TE ⊗ channels. The TM ⊗ channel throughout the entire acquisition period shows no discernible power loss, gain, or mode coupling. Notice that the TE ⊗ channel, which under passive conditions most of the input power is transferred to, has seen significant power gain. Reflectivity in the device may be the explanation here also, although the lack of TM θ detection does not allow this to be confirmed. Another important observation in these data is that, for such a large dose received, the TE power in both channels recovered (to a point of residual damage) in a relatively short time as compared with the $LiNbO_3$:Ti device. (As a comparison of the two technologies under similar doses, the $LiTaO_3$ device under a dose of $\approx$40 krads(Si) showed recovery in both TE channels in roughly 200 ms.)

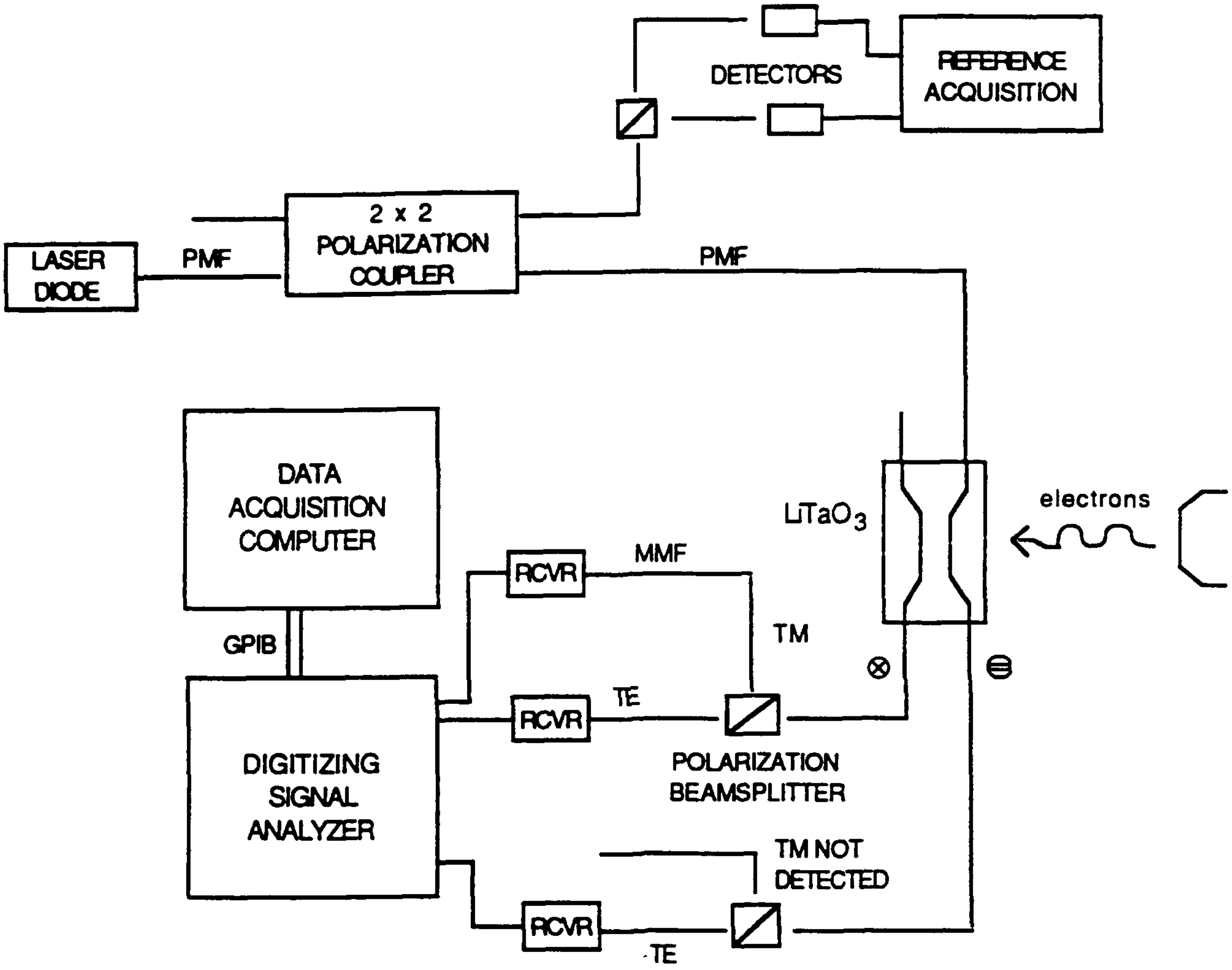
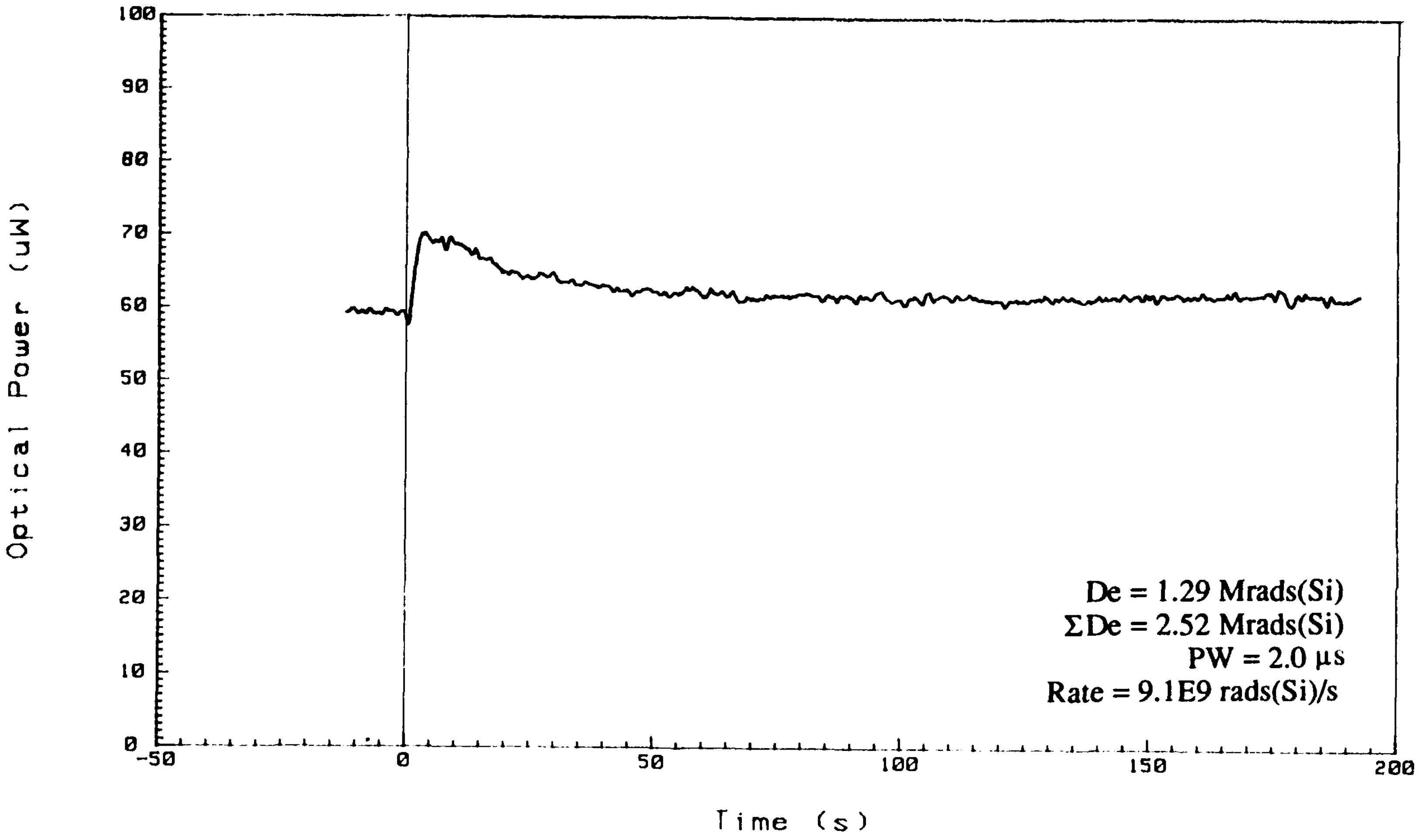
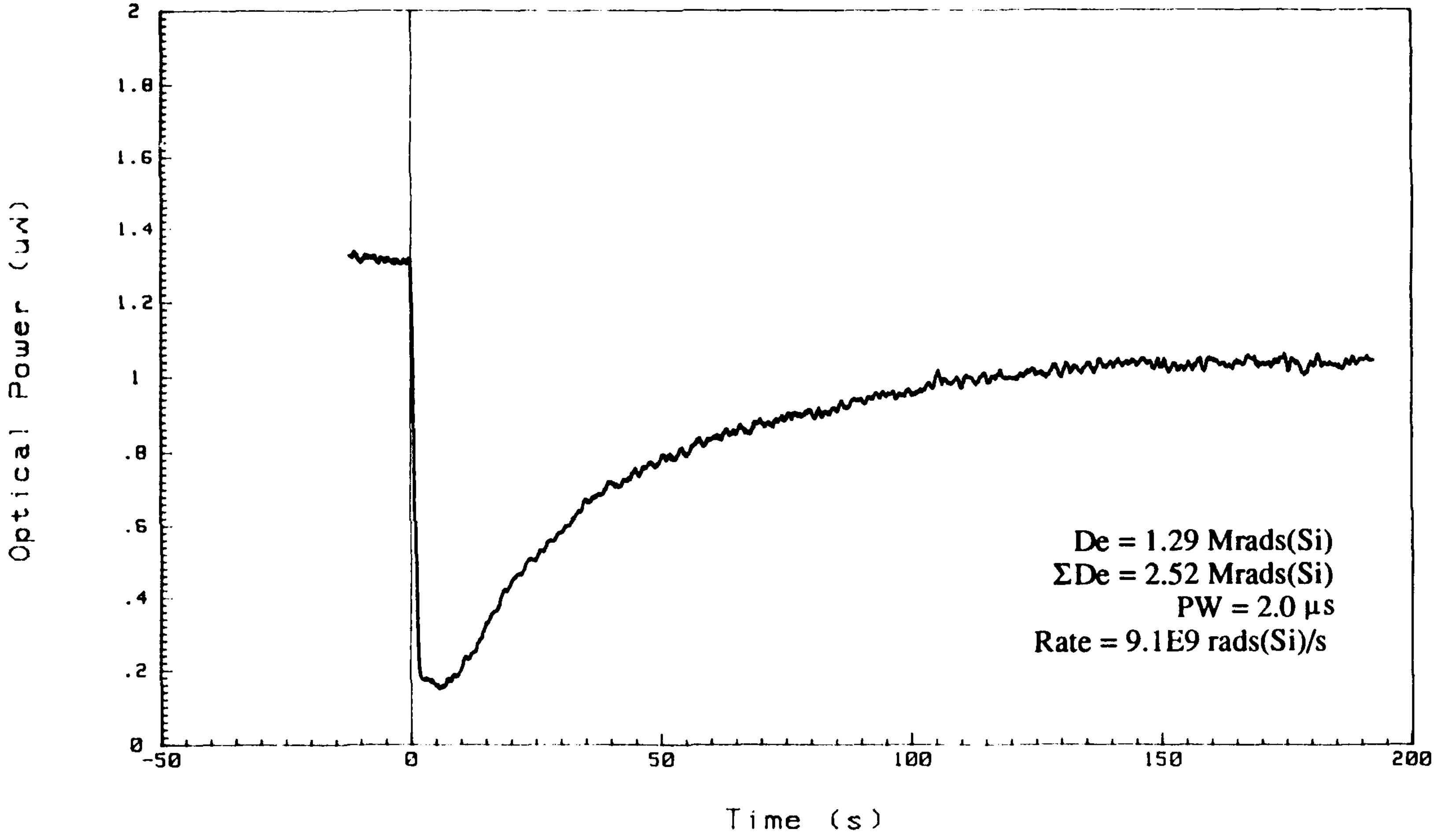


Figure 6. The setup for the $LiTaO_3$ measurements. In this experiment a 2 x 2 polarization maintaining fiber coupler was used also. Since the device rejects such a high ratio of TM to TE, the receivers were set to monitor both TE channels and the TM cross channel.



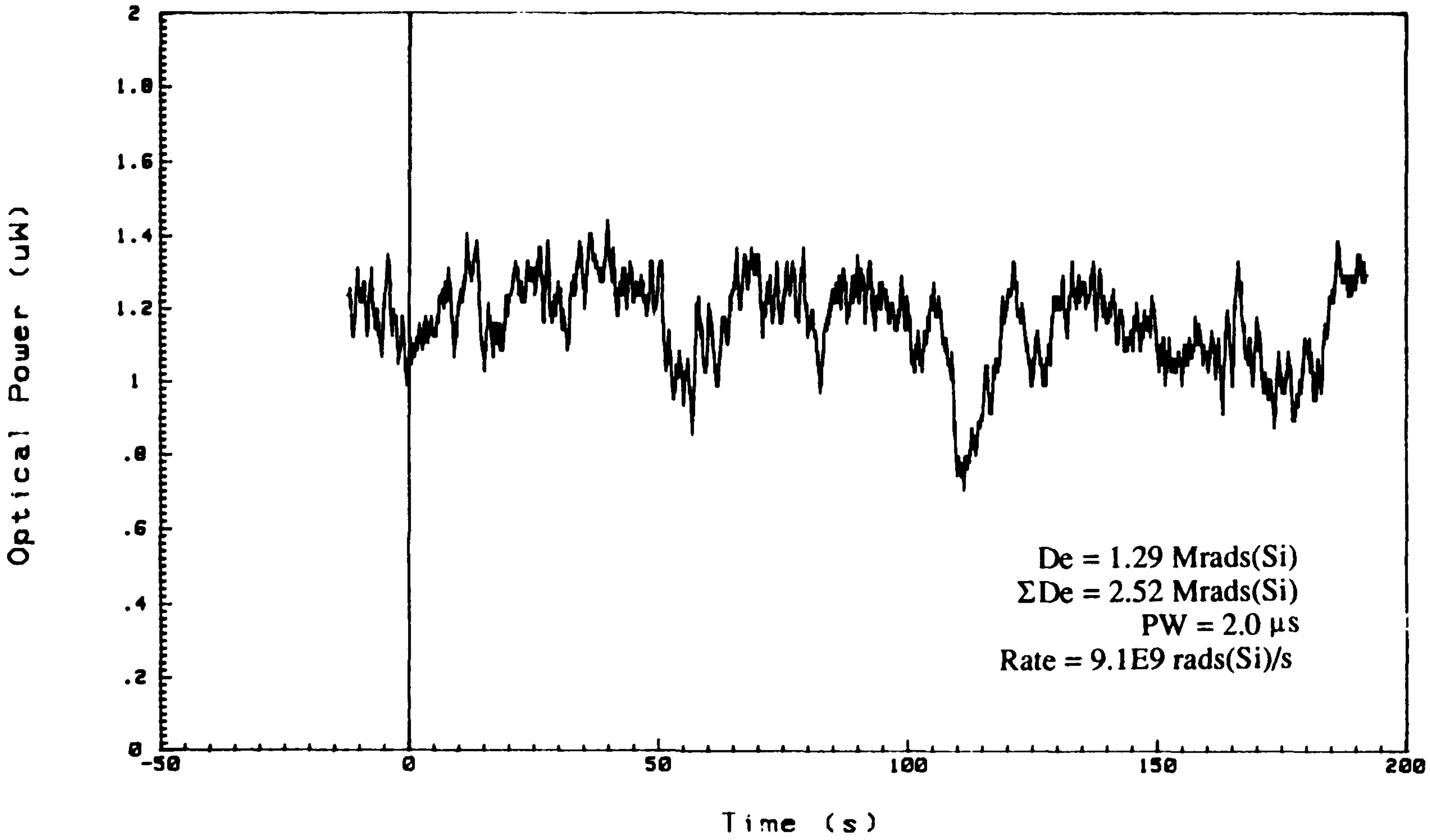
(a) The TE cross channel exhibits gain after the radiation event before starting to recover in a short time (~5 s).

Figure 7. $LiTaO_3$ directional coupler response. Note here that the power gained in (a) is not totally explained by the loss in (b).



(b) The TE through channel exhibits the classic transient radiation damage curve.

Figure 7. Continued.



(c) The TM cross channel shows no particular trend in the response.

Figure 7. Concluded.

4.0 CONCLUSIONS

Based on the experimental results herein, two important findings are apparent. Keeping in mind the conditions placed on the data within this report, it is clear that transient ionizing radiation causes crosstalk between channel guides in $LiNbO_3$:Ti and $LiTaO_3$ and at significantly smaller optical power levels than where optical damage or crosstalk are known to occur. There appear to be ways to reduce the crosstalk problem (Ref. 3), but further study needs to be done. Finally, it is apparent that the $LiTaO_3$ proton-exchange technology is significantly less sensitive to ionizing radiation than $LiNbO_3$:Ti, based on the comparison of polarization responses and the amount of radiation dose received.

REFERENCES

1. Roske, F., et al, "Preliminary Radiation Hardness Testing of $LiNbO_3$:Ti Optical Directional Couplers Operating at 810 nm," <u>SPIE</u>, Vol. 787, 1987.

2. Taylor, E. W., Wilson, V. R., Sanchez, A. D., Coughenour, M., and Chapman, S. P., "A Comparison of Integrated and Fiber Optic Responses in the Presence of Nuclear Fields," <u>SPIE</u>, Vol. 898, pp. 42-45, 1988.

3. Taylor, E. W., "Ionization-induced Refractive Index and Polarization Effects in $LiNbO_3$:Ti Directional Coupler Waveguides," <u>IEEE/OSA J. Light. Tech.</u>, Vol. 9 No. 3, March 1991.

4. Taylor, E. W., Wilson, V. R., et al, "Nuclear-induced Refractive Index Effects Observed in Typical Guided Wave Devices," <u>SPIE</u>, Vol. 1177, pp. 287-292, September 1989.

5. Taylor, E. W., "Behavior of Coupled Waveguide Devices in Adverse Environments," <u>SPIE</u>, Vol. 1314, pp. 155-166, April 1990.