# GAMMA-RAY VULNERABILITY OF LIGHT-EMITTING DIODES INJECTION-LASER DIODES AND PIN-PHOTODIODES FOR 1.3 µm WAVELENGTH-FIBER OPTICS

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## INTRODUCTION

With the increasing use of optical data links, it becomes essential to test for radiation vulnerability not only the transmission support - fiber and cable - but also fiber-end electro-optical components that could be exposed to hostile environment.

Presently there is a significant number of radiation tests of optical fibers [1, 2, 3]. Here are only given a few results obtained on gradient index multimode fibers with and without phosphor. These data provide an important contribution to the improvement of all standard electro-optical pigtailed components working on the 1.3 µm wavelength : light-emitting diodes (LED), injection-laser diode modules (LDM) and pin-photodiodes (PD). Multicomponent LDM behavior under $Co^{60}$ exposure was extensively tested. Hardened optical data links allow now to ensure medium data transmission rates on appreciable fiber - lengths despite medium steady - state gamma-ray exposure.

## EXPERIMENTAL

Irradiation facility used was the "SIGMA cell" located at DEIN on Saclay Nuclear Center site (FIG.1). Axial $^{60}Co$ sources of irradiation volume had a total activity of about 250 Ci tests along. Exposure conditions of optical fibers were already described [4]. Important is the small dose-rate gradient along fiber windings : ± 5 %. Fiber lengths from 5 to 100 m were exposed up to 10 kGy $h^{-1}$ with different dose-rates from 2 Gy $h^{-1}$ to 120 Gy $h^{-1}$. Injected light was given by stabilized laser diode modules (LDM) set outside of "SIGMA". High stability photometers and "1-to-2" couplers were used to monitor continuous light received by photodetectors.

Fiber-end optical components were exposed to gamma-rays with a mean dose-rate of 80 Gy $h^{-1}$. Some care was taken to irradiate standard components and improved components with the same dose-rate (± 10 %).

All tests were made at the natural temperature of the "SIGMA" irradiation room (22-24°C).

## RESULTS AND DISCUSSION

Results for 850 nm - electro-optical components (Al Ga As LED and silicon PIN) were already given previously [5]. In this paper, we provide an up-to-date summary of radiation vulnerability of III-V compounds emitter and detector components designed for 1.3 μm multimode fiber (MMGI) applications.

### 1. - FIBER FOR PIGTAILED COMPONENTS

All the commercialy available components are pigtailed with the MMGI 50/125 fiber which is standardized over the world. As known, heavily doped core of this fiber and presence of phosphor make it very sensitive to radiation : a radiation-induced attenuation at 1.3 μm can be as high as 40-50 dB/km following a moderate radiation dose of 10 Gy [6]. FIG.2 shows the growth data of the Ge-P doped standard-telecom fiber : for a moderate dose-rate of 2 Gy $h^{-1}$, the induced attenuation presents no saturation level beyond 1 kGy and reaches the very high value of 40-50 dB/m for 10 kGy (as given in [6] induced attenuation versus total dose follows a nearly linear law). Therefore, such a fiber is quite bad to be used as the pigtail of hardened electro-optical components.

Another MMGI large bandwith fiber made by another process than Ge-P doped core fiber was widely tested. Typical growth data of induced attenuation is given fig.2 for the dose-rate of 120 Gy $h^{-1}$. A saturation level appears beyond a total dose of 2-3 kGy (for this dose-rate) and the saturation value remains rather restricted for 10 kGy : about 100 dB/km. This last value is compatible with that from [6] : about 300 dB/km obtained with a much higher dose-rate of 7200 kGy $h^{-1}$.

These results show the bad incidence of phosphor in fiber cores on radiation resistance ; such an effect was fundamentaly studied [7].

Finally, the present summary of tests on silica-core fibers is shown by table 1 . $\Delta$L (dB/km) example is given for 10 kGy-total dose with a medium dose-rate nearly 100 Gy $h^{-1}$. Note best results are obtained with SI hard polymer-clad silica-core fiber (a few dB/km for $\Delta$ L).

## 2. - Ga In As P LED

The gamma-ray tolerance in 820-900 nm-wavelength fiber optic systems is mainly determined by light output degradation of Al Ga As LEDs [8, 9]. Presently not many results were published for 1.3 μm-LEDs.

The ALCATEL-CIT tested device is a double heterojunction light-emitting diode (DH-LED) made with Ga In As P/In P. With an active area diameter of 40 μm, typical radiance is 30 $W.cm^{-2}$ for a current density of 20,000 $A.cm^{-2}$. Optical rise and decay times are about 10 ns for a forward current of 150 mA. Fiber output power is 18-22 μW.

We compared two batches of ten Ga In As P - LEDs, the first with standard LEDs, the other with LEDs especially pigtailed with the fiber having no phosphor in core. The new pigtail is a 100/140 fiber to enhance the light output.

Fig.3 shows before exposure the caracteristics power versus forward current of both types. At typical current of 150 mA, fiber output power of new DEL is about 10 times that of standard one : -10 -12 dBm instead of -20 -21 dBm.

Fig.4 shows for extreme samples of each LED type, total dose-dependence of the light output power for a 100 mA forward bias. Some degradation in the light output appears for standard LED while new pigtailed LED present a good behavior up to nearly 50 kGy. No defects seem induce by gamma ray exposure up to that total dose. This result is consistent with data for japanese Ga In As P DH-LEDs [9] which show optical degradation occurs beyond 100 kGy.

The summary of our previous and present tests on Ga Al As - LED and Ga In As P - LED is shown by table 2. $\Delta$ P (dB) example is given for 10 kGy-total dose with a medium dose-rate of 100 Gy $h^{-1}$. The maximal -2 dB value is dealt with Ga Al As - DH-LEDs.

### 3. - Ga In As P LD

The ALCATEL-CIT tested device is a double buried heterojunction injection-laser (DBH-LD) with a low threshold current. Active material is the quarternary semiconductor Ga In As P epitaxied on a InP substrate. Standard pigtail fiber is the 50/125 telecom fiber emitting 3 mW for a forward current of 50 mA. Mean value of emission wavelength is 1310 $\pm$ 10 nm and spectral width less than 1,6 nm. Typical response times are about 300 ps.

Table 3 gives the main caracteristics at 20°C of tested laser-diodes.

In the aim of aiding efficiently the design of hardened fiber optic links, complete laser-diode modules (LDM) were chosen for irradiation testing. Fig.5 shows the other elements currently used with pigtailed injection-LD : a monitor photodiode adhering to laser-diode rear-face, a thermoelectric element cooler and a thermistor matted to the device substrate.

First work to test correctly under exposure such operating modules is to perfect a current-source network showing an excellent tolerance to gamma-rays. Several networks were designed and tested under exposure. All were based on IC with bipolar transistors. Fig.6 gives main results obtained with two different networks and especially that of a very stable current-source up to 5 kGy (125 Gy $h^{-1}$) and even beyond.

Irradiation tests were made on LDMs with laser current-source laying on cards (two LDMs a card) themselves set in the SIGMA room along an isodose circle. All components withstood the same dose-rate : 74 $\pm$ 5 Gy $h^{-1}$.

Fig.7 shows the Ge-pin photodiode of modules has a constant sensitivity versus exposure up to 50 kGy [9, 10] (Load resistance was 10 k$\Omega$ ). Consequently photodiode output can be used to monitor irradiated laser-diode itself.

Fig.8 presents data obtained with four modules differently pigtailed. Optical behavior of new pigtailed LDs is clearly the best while standard modules are unusable beyond 1 kGy only. Nevertheless a serious decrease in output power appears as early as 3,5 kGy, effect especially strong for one of tested LDs : Fig. 9 - 10.

For this device, operating mode changes to no-lasing emission at about 6 kGy, althougth case temperature remains stable up to the total dose of 7,6 kGy. Also forward current and case temperature being kept constant all over exposure, this optical degradation could be caused by threshold current increase of injection-laser diodes, the internal quantum efficiency decreasing with increasing radiation - induced non-radiative recombination [11].

That point of view is proved in a second part. Before going on exposure of LDMs it was possible to regenerate initial output power of LDs by increasing drive currents of a few mA. Example is given for the previous "best" and "wrong" devices.

Fig.11 shows data obtained during the second exposure from 7.5 to 16.5 kGy. If the same forward current in LDs remains quite constant it is not like case temperature (Fig.12). Beyond a cumulated dose of about 10 kGy, temperature grows gradually to + 3°C until exposure end. It is probably a slight damage of the Peltier element cooler (made also with a semiconductor) and not that of the passive thermistor because temperature increase leads optical power to decrease (Fig.12). Nevertheless it remains some degradation of optical output power especially for the "wrong" LDs which have highest threshold currents (table 3). On the other hand, the "best" LDs are those having lowest threshold currents and consequently highest drive currents. It would be of great interest to operate these devices with higher controled case temperature.

LED and LD radiation vulnerability is due to displacement damage in the semiconductor light-producing region [11] althougth that region has a small volume in the double heterojunction devices tested here.

### 4. - <u>In Ga As p-i-n PD</u>

In a photodiode the same physical process is responsable of producing photocurrent whether the photon comes from a light signal or an energetic gamma-ray. But gamma-ray interaction is a bulk effect (electron-holes pairs generated in the whole volume of the semiconductor) while optical signal creates carriers only in the small active region.

Also the ALCATEL-CIT choiced p-i-n PD is a homojunction In Ga As epitaxied on a InP substrate, having a very small volume. Active area diameter is 70 $\mu$m with thickness less than 1 $\mu$m. Responsitivity is maintained high (0.7 - 0.9 $A.W^{-1}$ at 1,3 $\mu$m) by an antireflection coating and a quarter - wavelength laid on the device rear - face. A few volts (-5 to -6 V) is sufficient for complete depletion and full collection of optically-produced carriers. Typical dark current is 10 nA and pulse response times are fast (~ 400 ps) for a load resistance of 50$\Omega$ parallel with 0,5 pF device capacitance.

Photodiode behavior under exposure was tested with 1,3 μm wavelength-LEDs (three PDs a LED) through "2-to-1" couplers (Fig.13). Stability of LED continous light was monitored by radiometers. Receveid level on PDs was about 1 μw. Photocurrents were measured by low-noise operational amplifiers set outside of "SIGMA" room and followed by a multiway-recorder. All PDs were biased to -6 V during exposure and dark currents measured during a short time of switching off LEDs. Temperature in irradiation room was about 25°C. Constant dose-rate was 65 Gy $h^{-1}$ and cumulated dose 40 kGy.

Fig.14 - 15 show data of four photodiodes issued from a same batch. Their optical sensitivity normalized at 0.9 $A.W^{-1}$ remains at a constant value until exposure end. In the contrary, a vulnerability mecanism occuring in all devices is the increase of initial dark currents (X 50). Generally, this effect is mainly caused by surface leakage effects, but because sensitivity is not affected by radiation exposure it can be thought some defects are created in the bulk of the devices.

Table 4 gives the resultant variation of signal-to-noise ratio $\Delta$(S/N) for $Co^{60}$ - 10 kGy exposure : about -3 dB.

This value was previously obtained for THOMSON-CSF hardened silicon PD [5]. It seems PD-S/N degradation should be the smallest contribution in the budget of long-term medium dose-rate exposed optical links.

## CONCLUSION

Some 1.3 μm wavelength-pigtailed LED and p-i-n PD made in III-V semiconductors show a weak vulnerability to gamma-ray steady-state exposure at medium dose-rates of a few tens Gy $h^{-1}$. Optical performances degradation remains small up to 40-50 kGy. These components are suitable to be used in hardened medium-length low-transmission-rate data links for future robotics in harsh environment. (Well fitted as transmission support is the new pure silica-core fiber with hard polymer-cladding. Radiation - induced 1.3 μm - wavelength attenuation is low up to several tens of kGy).

Tested DBH laser-diode modules offers a lower tolerance than DH-DEL. Two degradation processes clearly appear : - an optical decrease of the stimulated light emission beyond 3 - 4 kGy (with no-lasing operation for 6-7 kGy in worse case) - a bad operation of the thermoelectric element cooler beyond about 10 kGy.

Further tests have to be made for evaluating gamma-ray vulnerability of 1.55 μm-wavelength monomode fiber optics.

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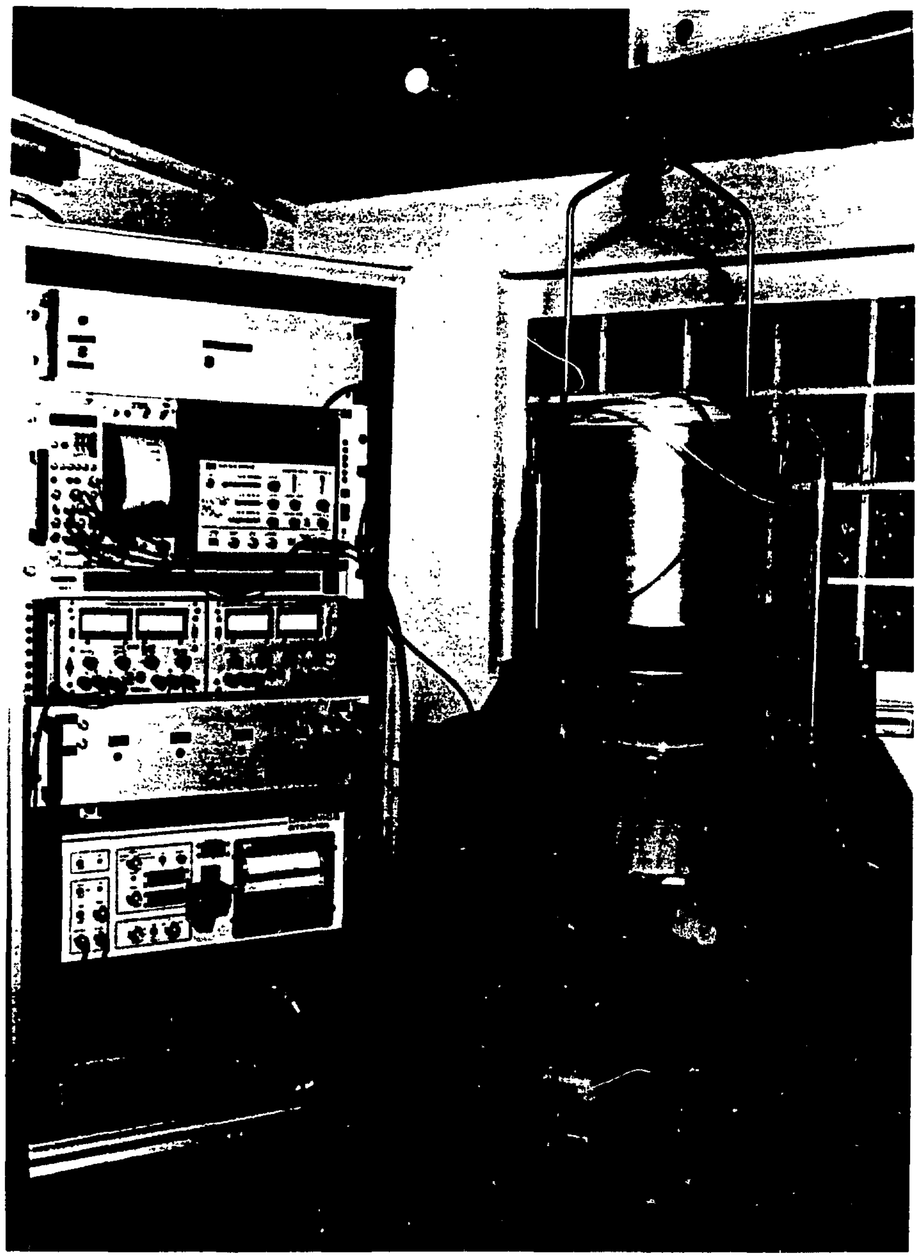
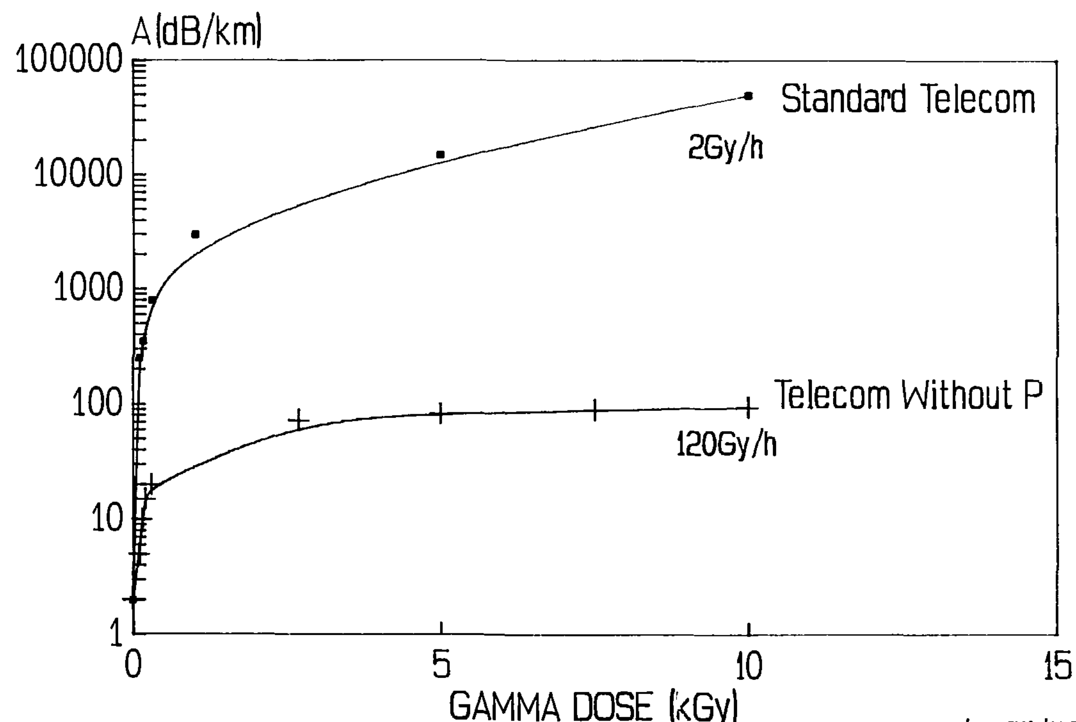


Fig. 1
SIGMA $^{60}Co$ FACILITY

# IRRADIATION OF MM GI FIBERS

1300 nm LASER DIODE




No parasite photobleaching

FIG.2

DTA/LETI/DEIN

# OPTICAL FIBERS IN NUCLEAR ENVIRONMENT

| MULTIMODE FIBERS | CORE MATERIAL | BW MHz.km | INTRINSIC LOSS L dB.km−1 | ΔLdB.km−1 $Co^{60}$_1Mrad(Si) optical fibers | |
|---|---|---|---|---|---|
| | | | | old | new |
| step index profile | pure silica | <25 | $\leqslant$10 | <100 | <10 |
| gradient index profile | doped silica | >250 | $\leqslant$1 | <500 | <100 |

TABLE 1

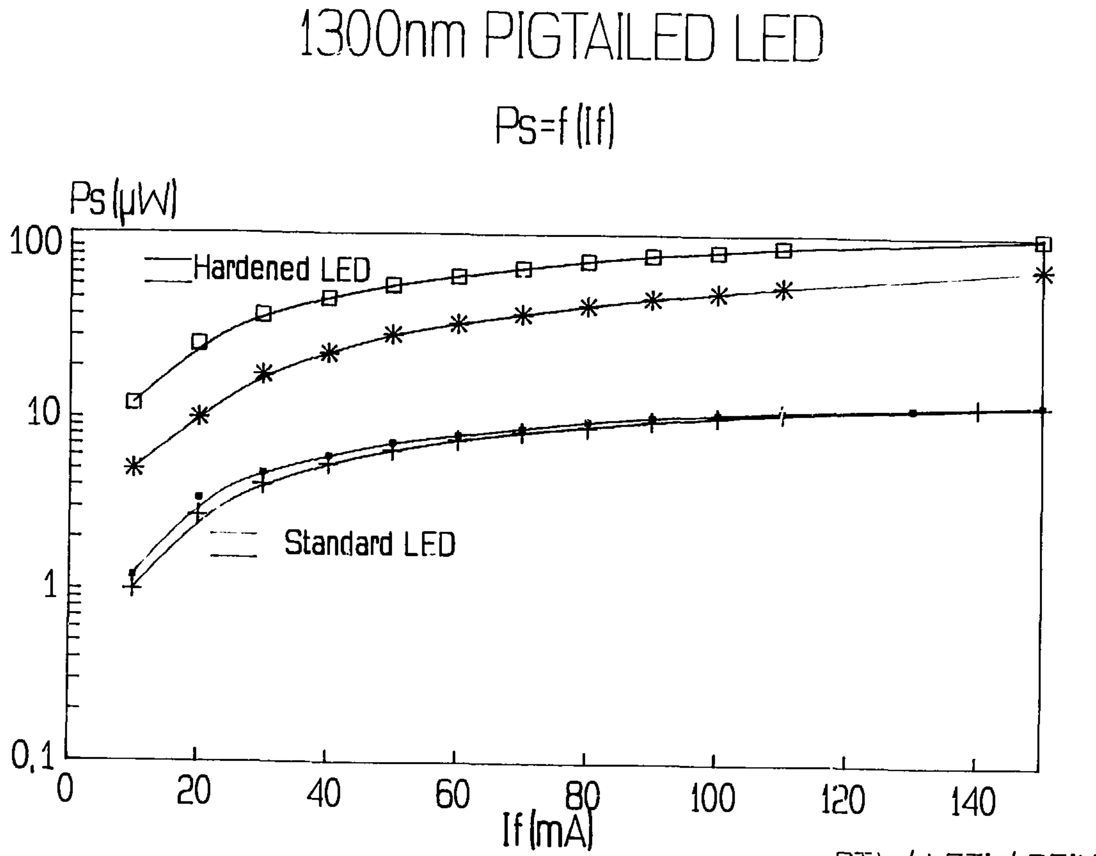



FIG.3

DTA / LETI / DEIN

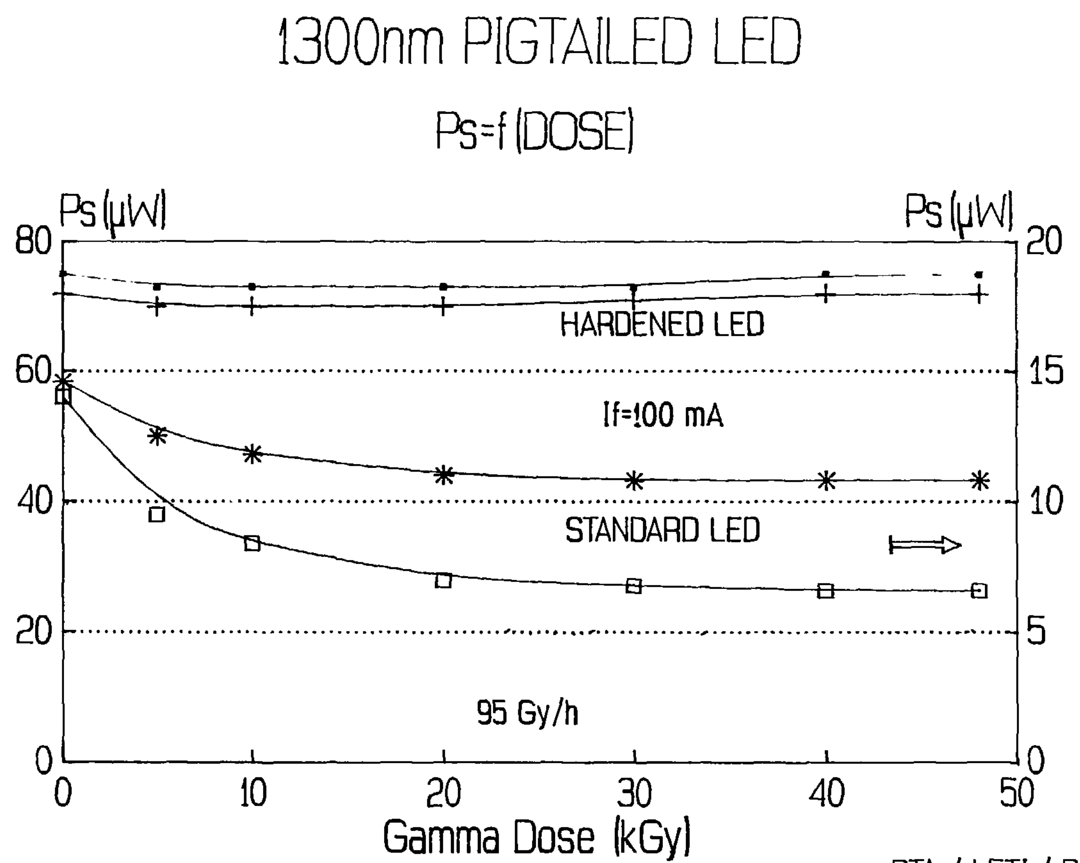



FIG.4

DTA / LETI / DEIN

## RADIATION RESPONSE OF FIBER-END OPTICAL SOURCES

| LIGHT SOURCES | SEMI CONDUCTOR | Modulation capacity MHZ | Mean optical power P mW | ΔP dB $Co^{60}$ – 1Mrad(Si) components standard | improved |
|---|---|---|---|---|---|
| LED | Ga Al As 830 nm | <50 | 0.25 | – 10 | – 2 |
| LDM | In Ga AsP 1300 nm | <2000 | 1.5 | – 30 | – 6 |

**LED : light emitting diode**

**LDM : laser diode module**

TABLE 2

| Type Number | TL2005/61610 | | | TL2005/61640 | | | |
|---|---|---|---|---|---|---|---|
| | 69 | 94 | 191 | 350 | 367 | 382 | 414 |
| Threshold current (mA) | 44.20 | 36.00 | 28.70 | 37.90 | 16.30 | 36.70 | 16.50 |
| Mean value * (nm) | 1309 | 1296.6 | 1311.3 | 1309.4 | 1321.8 | 1312.1 | 1315.7 |
| Spectral * Width (nm) | 1.82 | 1.59 | 0.663 | 1.27 | 1.08 | 1.53 | 1.57 |
| Mode number * | 4 | 4 | 3 | 5 | 3 | 6 | 2 |
| Pigtail fiber | 50/125 standard telecom | | | 100/140 Telecom without phosphor | | | |
| Drive current | 17.50 | 18.90 | 18.00 | 15.70 | 21.30 | 23.30 | 17.30 |
| Fiber output power (mW) | 4.02 | 3.75 | 3.57 | 3.13 | 3.18 | 3.01 | 2.72 |

* at a drive current frequency of 200 MHz

Table 3

MAIN CARACTERISTICS OF ALCATEL-CIT DBH - LASER DIODES

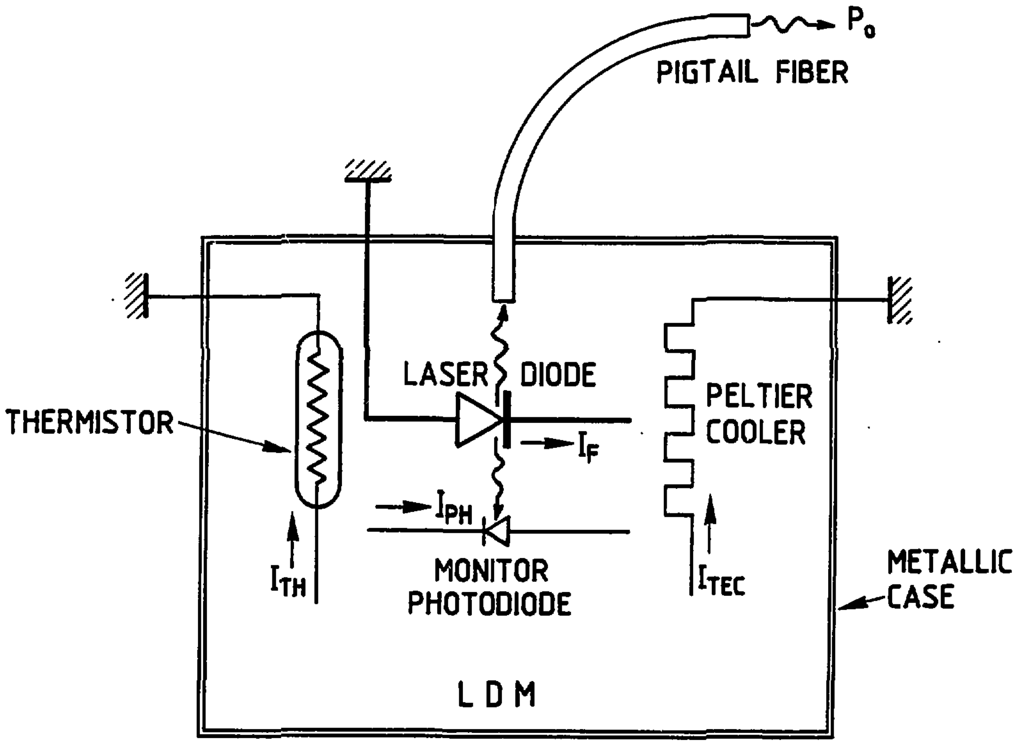



**Fig. 5**

**GENERAL DIAGRAM**

**OF A LASER DIODE MODULE**

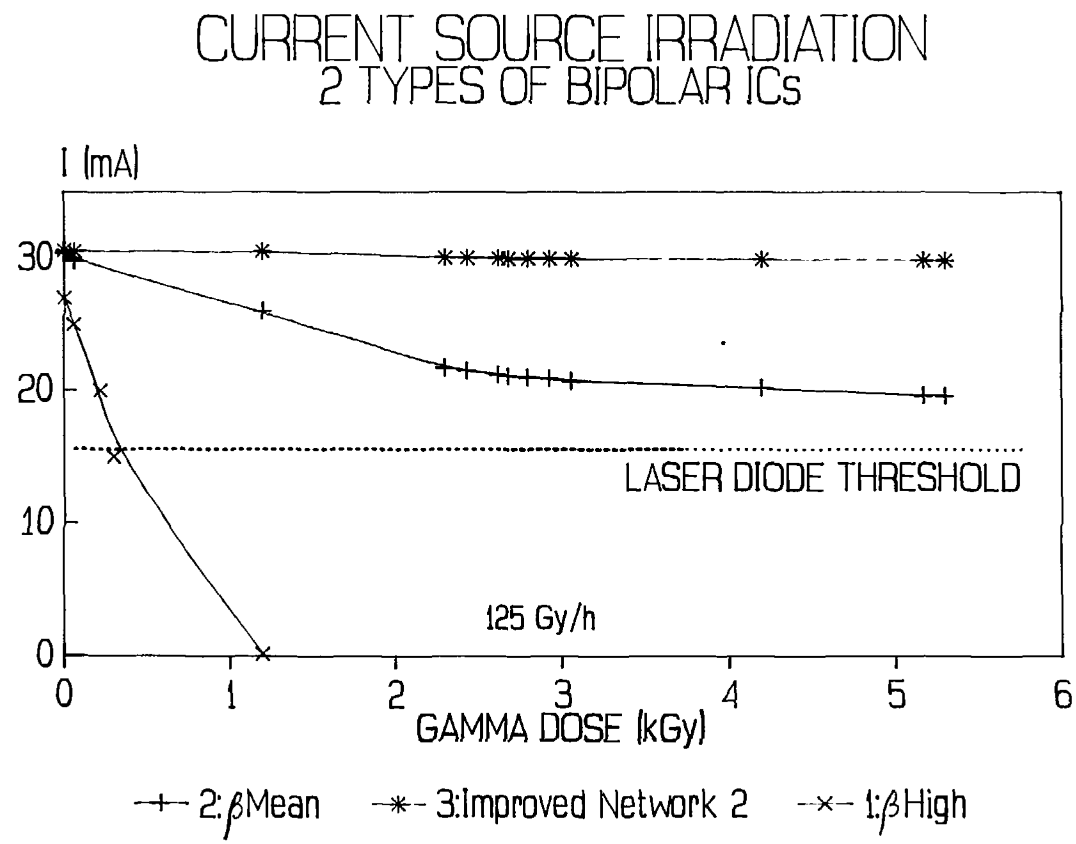
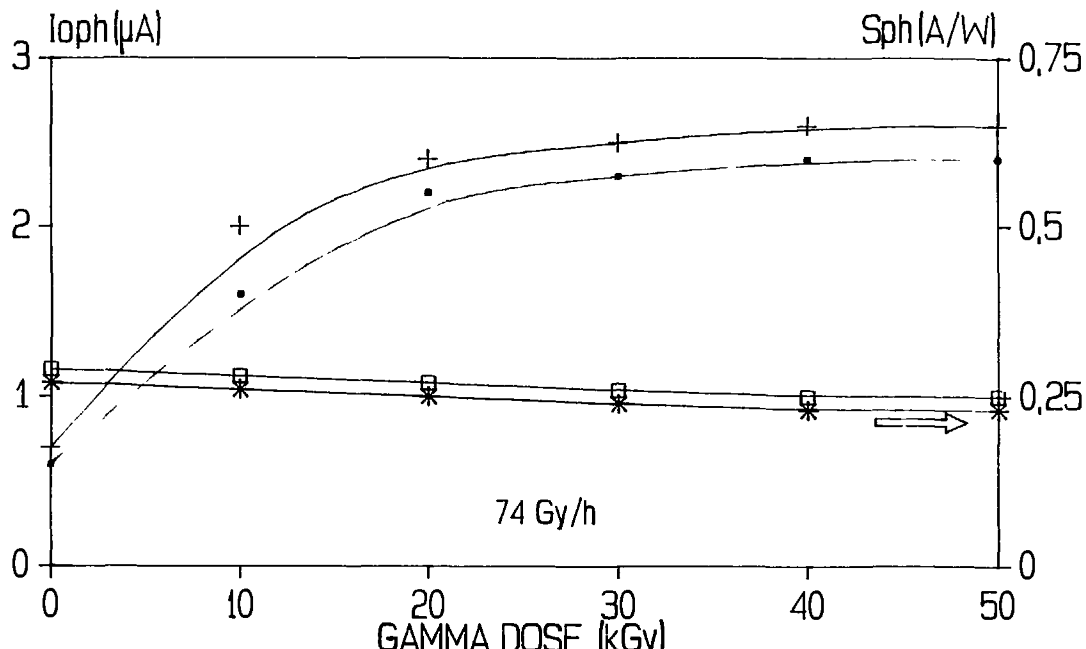



FIG.6

DTA/LETI/DEIN

# 1300nm PIGTAILED LDM

## PHOTODIODE OF MODULE




DTA / LETI / DEIN

FIG.7

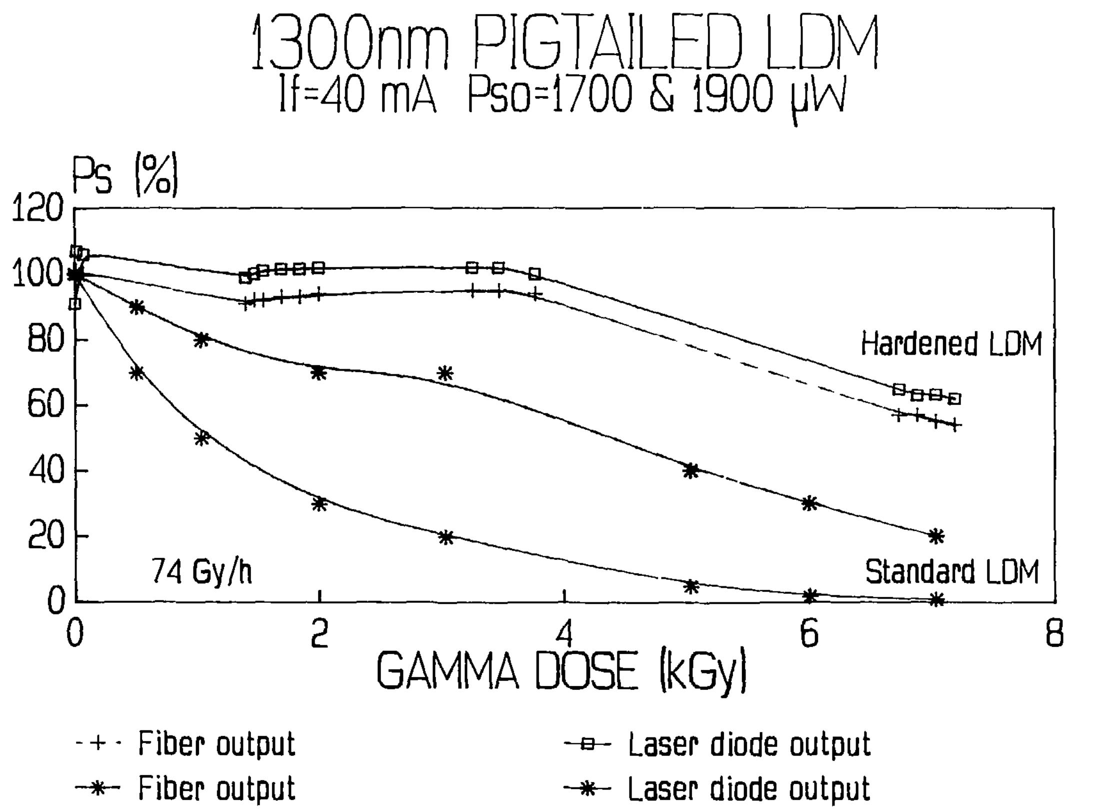
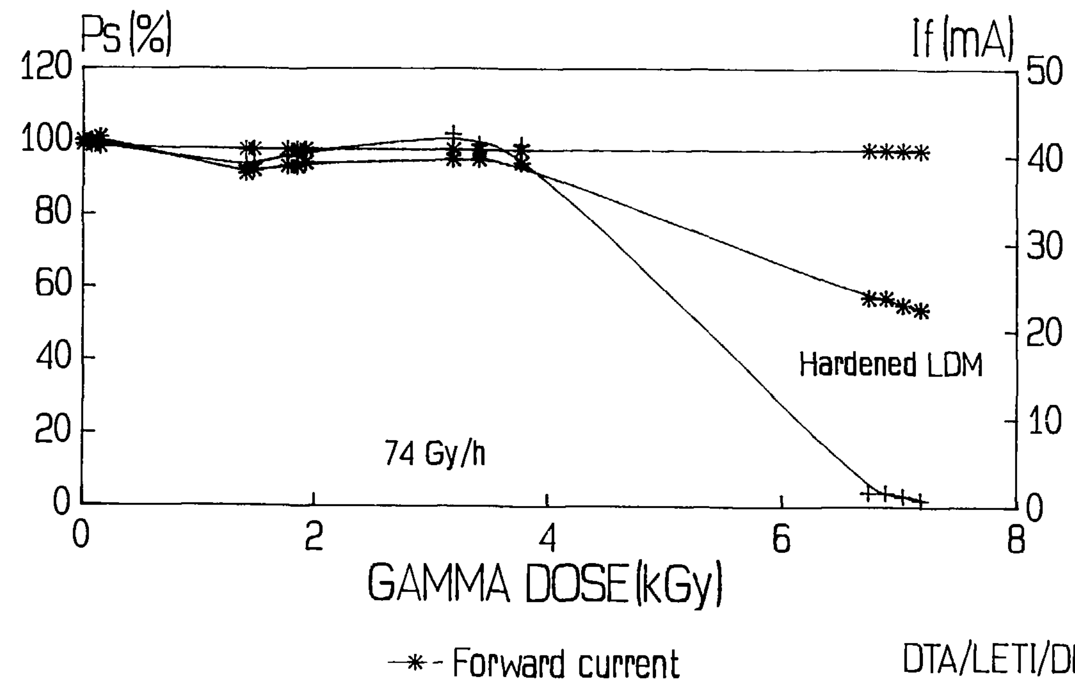



FIG.8

DTA / LETI / DEIN

# 1300nm PIGTAILED LDM
Pso=1700 & 1900μW




DTA/LETI/DEIN

FIG.9

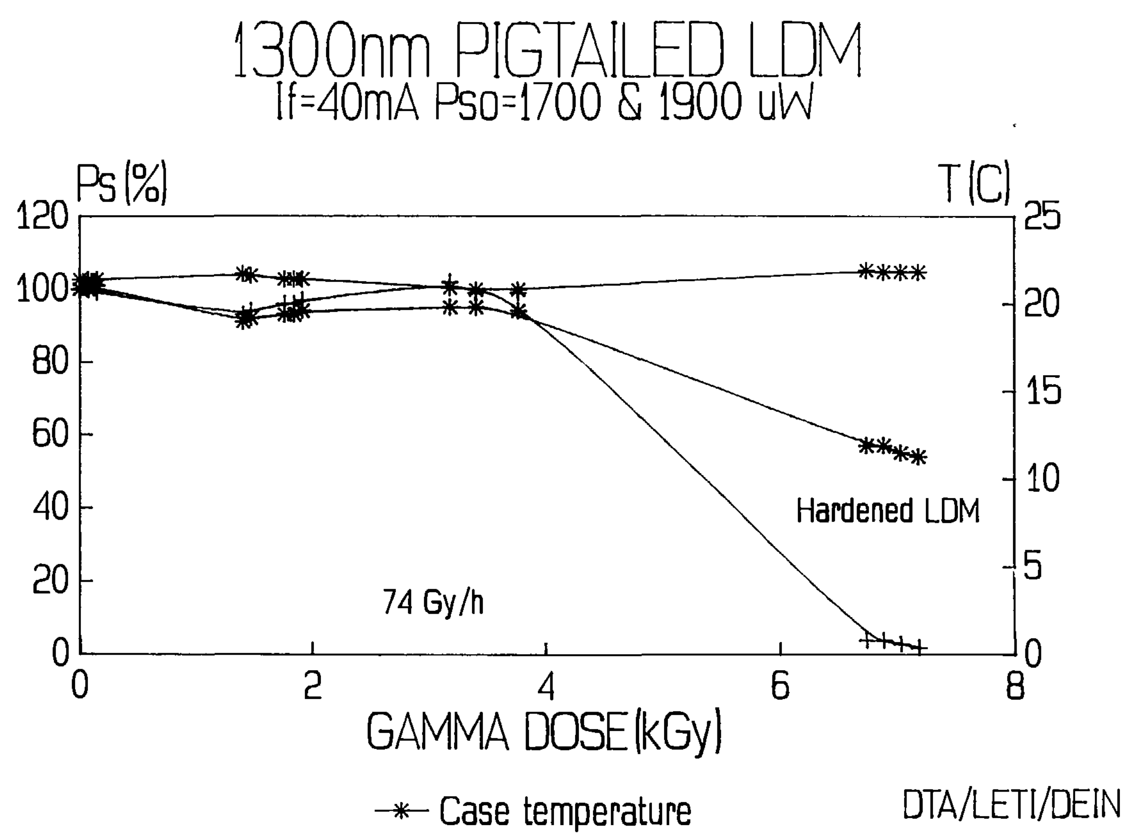

1300nm PIGTAILED LDM
If=40mA Pso=1700 & 1900 uW
Ps (%)
T (C)
120
100
80
60
40
20
0
25
20
15
10
5
0
0
2
4
6
8
GAMMA DOSE (kGy)
Hardened LDM
74 Gy/h
Case temperature
DTA/LETI/DEIN

FIG.10

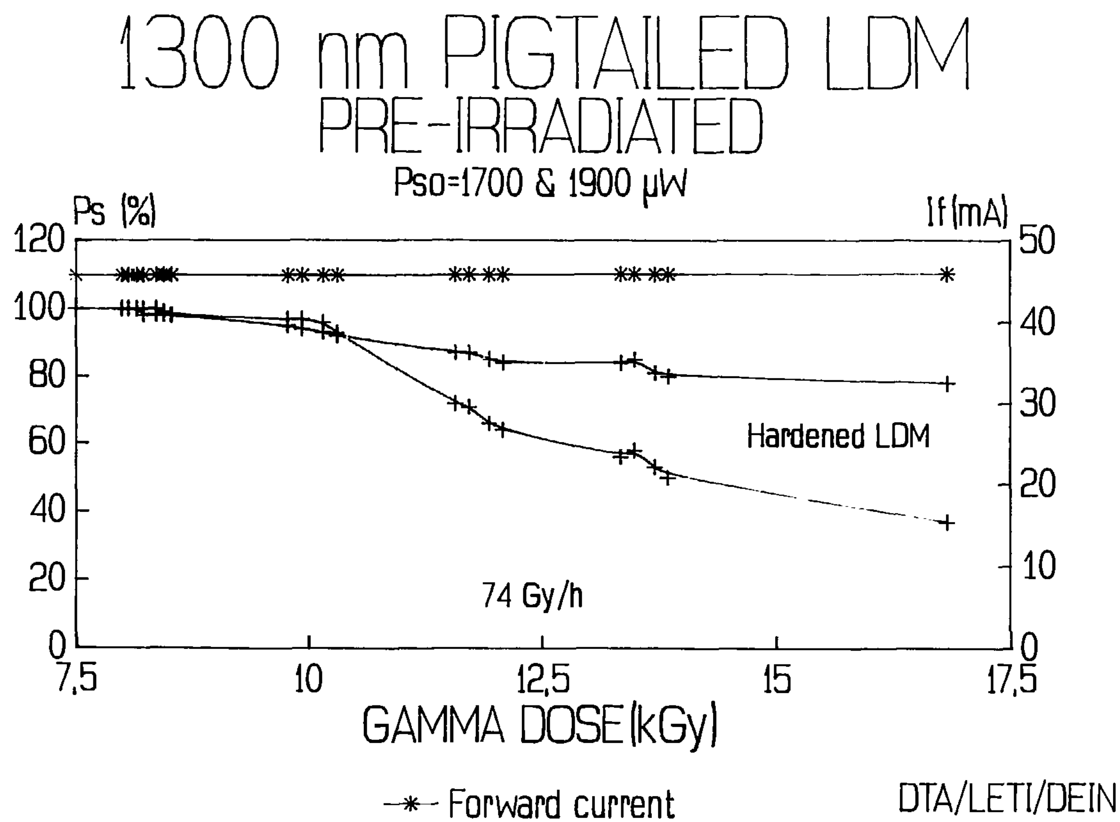

1300 nm PIGTAILED LDM
PRE-IRRADIATED
Pso=1700 & 1900 μW
Ps (%)
If (mA)
120
100
80
60
40
20
0
50
40
30
20
10
0
7,5
10
12,5
15
17,5
GAMMA DOSE (kGy)
Hardened LDM
74 Gy/h
Forward current
DTA/LETI/DEIN

FIG.11

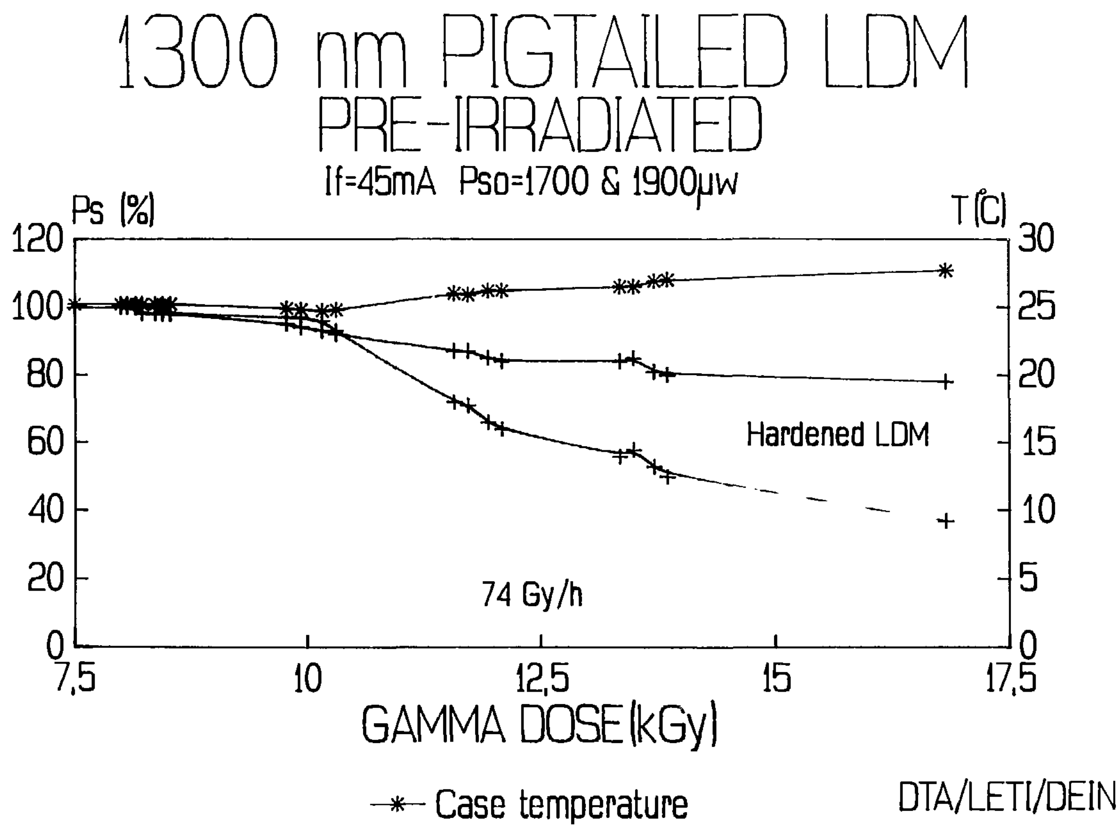



FIG.12

SIGMA $^{60}$Co FACILITY

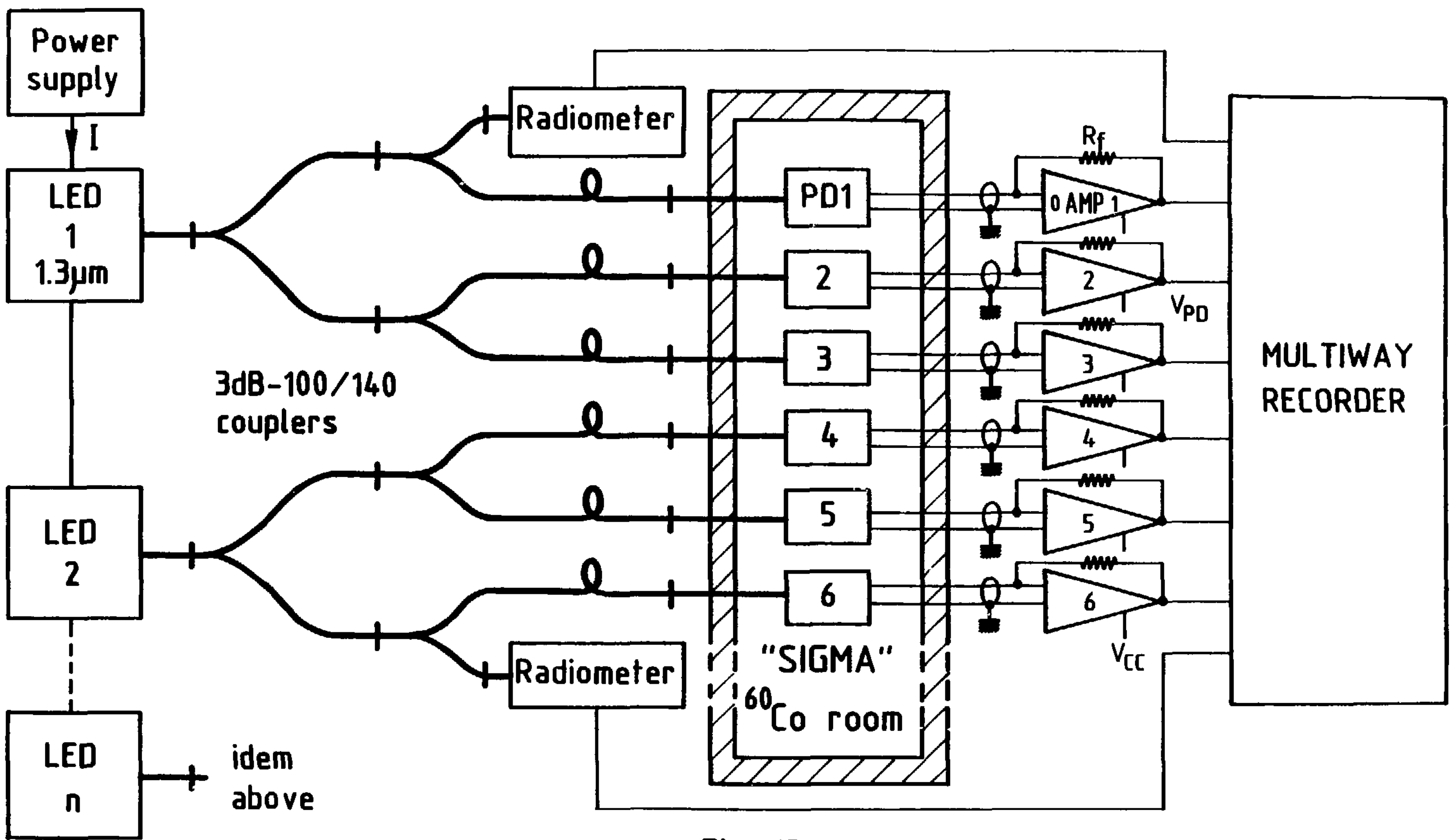



Fig. 13

GAMMA-RAY IRRADIATION APPARATUS OF PIN-PHOTODIODES

# 1300nm PIGTAILED PIN PHOTODIODE

Sph=f (DOSE)

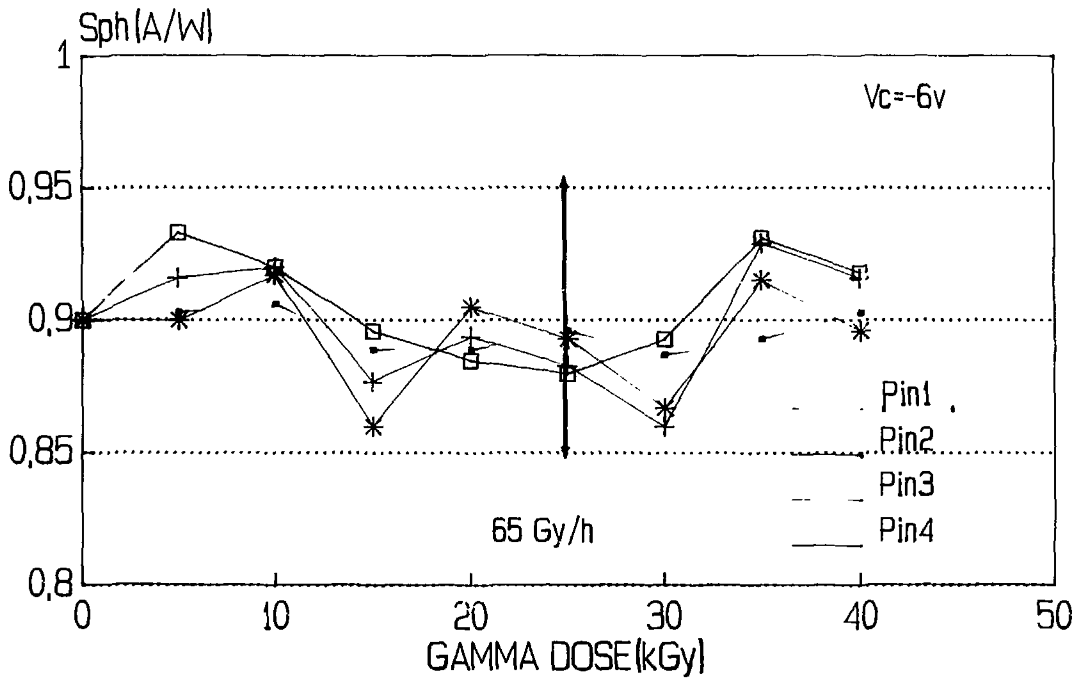



FIG.14

DTA / LETI / DEIN

# 1300nm PIGTAILED PIN PHOTODIODE

Io=f (DOSE)

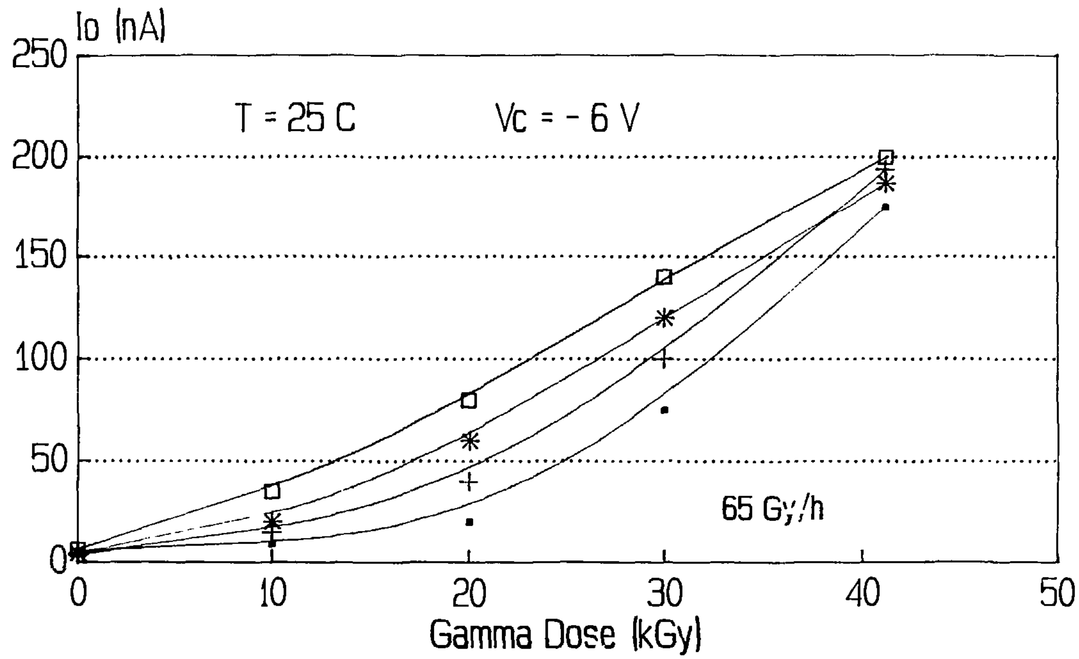



FIG.15

DTA / LETI / DEIN

# RADIATION RESPONSE OF FIBER-END PHOTODETECTORS

| OPTICAL DETECTOR | MATERIAL | RISE TIME ns | SENSITIVITY A.W-1 | Δ(S/N) dB $Co^{60}$ 1Mrad(Si) components | |
|---|---|---|---|---|---|
| | | | | standard | improved |
| pin PD | Si 830 nm | <1 | 0.5 | − 20 | − 3 |
| | In Ga As 1300 nm | | 0.9 | − 30 | − 3 |

PD : PHOTODIODE S/N : SIGNAL TO NOISE RATIO

TABLE 4