INVESTIGATION OF THE PROPERTIES OF OPTICAL FIBERS (IN THE UV SPECTRAL REGION) AND OPTOELECTRONIC COMPONENTS OPERATING IN RADIATION FIELDS OF FUSION INSTALLATIONS

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1. Subtask objectives

Our mission within the subtask is to evaluate:

- the modifications induced by the radiation present in fusion installations in some optoelectronic semiconductor components, such as semiconductor lasers and detectors,
- the changes produced by irradiation and temperature on the optical transmission in the UV and visible spectral ranges, in optical fibers likely to be used in plasma diagnostics.

2. Investigations on semiconductor lasers

2.1 Introduction

We focused our research on component-of-the-shelf (COTS), so, several commercially available laser diodes were evaluated, after gamma-ray and electron beam irradiation. Their operating wavelengths vary from visible (635 nm, 650 nm, 670 nm) to near-IR (780 nm, 805 nm, 850 nm). Their rated output power covers the 5 – 8 mW range. The irradiation conditions were:

- gamma-ray irradiation was done at the *Department of Applied Nuclear Physics* facility of the National Institute of R&D for Physics and Nuclear Engineering – "Horia Hulubei": Co^{60} gamma source, with a dose rate of 0.3 kGray/h +/- 5%, the sample was placed at 3 m under water, where it is surrounded by the Co^{60} rods, with a distance of about 40 cm between them. In-situ dosimetry was used based on ethanol-chloride benzene vials, delivered with the equipment by the Hungarian producer – KFKI Budapest. The dosimetry is based on the spectrophotometric evaluation of color changes (red) induced in the above-mentioned substance by gamma irradiation. The irradiation was carried out at room temperature. For gamma-rays a cylindrical irradiation geometry was used, and the total dose was 30 Mrad.
- electron beam irradiation was performed at the Electron Accelerator Laboratory of the National Institute for Lasers, Plasma and Radiation Physics. Electron irradiation was done under the following conditions: medium electron energy: 6 MeV; electron beam current 3 - 4 μA; pulse repetition rate 100 Hz; pulse duration 3.5 μs; beam transversal area 100 cm^2; spot uniformity ± 5 %; dose rate = 200 - 220 krad/min; ambient temperature 20 ^oC. Electron irradiation was done from the front side of the laser diodes, in an axial geometry, and the total dose was 16 Mrad.

The measured parameters refer both to the emitter (compliance voltage, driving current, case temperature, emitted optical power, wavelength, mode structure), as well as the embedded detector (photodiode current), as they are affected by the total dose received. For all these parameters the appropriate curves were plotted, as function of the laser diode driving conditions (forward current, case temperature) and the total dose [1]-[4]. From the experimental data, several characteristics were derived: the external quantum efficiency, the laser diode serial resistance, the detector responsivity, the laser threshold current. All the lasers employed in our research were fundamental transverse mode devices, and only one was single longitudinal mode (that emitting at 635 nm), too. The measurements were carried out off-line, in the laboratory, before and after the irradiation, within a time interval from one to several days from the irradiation moment. No thermal or current stress was applied to the devices, neither during the irradiation, nor during the measurements.

2.2 The experimental set-up

In order to control the driving conditions for the laser under test, a laser diode controller with a 500 mA current driver module (7.6 nA resolution, 3.5 µA ripple noise, photodiode monitoring current up to 5 mA, and compliant voltage of 7 V) and a 32 W temperature controller (from – 20 ^{o}C to + 80 ^{o}C, 0.01 ^{o}C resolution, with variable slope and setting time) were used. The laser diodes were mounted during the tests in a temperature controlled mount equipped with a collimating three lens system offering three axis micro-positioning. In this way, collimated beams can be obtained from quite divergent laser diodes. For our experiments, a 100 µA thermistor was used as temperature sensor, matching well the operating temperature range we cover during investigations. All functions can be addressed either through the instrument front panel soft-key, or can be remotely accessed through the general purpose interface bus (GPIB) interface, based on the LabVIEW virtual instruments (VIs) we developed [5]; The driver has the possibility to bias the laser's photodiode up to 5 V, non-programmatically. All tests were carried out under DC driving conditions, no modulation signal was applied.

The laser wavelength was measured by two methods:

a) with a wavelength meter, based on two optical detectors having slightly different spectral response, which when exposed to the laser beam produces an unbalanced signal proportional to the incoming radiation wavelength,

b) with a mini spectrometer, with optical fiber input, case when the spectral components of the incident laser radiation are displayed over the spectrum.

The first instrument has a 4 mm aperture, in front of which a variable neutral density filter can be moved to obtain a variable attenuation. The detector head is sensitive from 450 nm to 1100 nm, with an over all accuracy of 0.5 nm and 0.1 nm resolution, under DC operation. The remote control of the equipment with a PC can be done through the serial port.

The mini spectrometer has a two channels configuration: 190 nm – 650 nm (spectral resolution of 1.5 nm), 650 – 850 nm (spectral resolution of 0.5 nm). It accommodates integration time intervals from 3 ms to 60 s and accepts averaging and boxcar operation. The signal is coupled to each channel separately through a 400 µm diameter optical fiber. A 12-bit analog-to-digital converter is included in the spectrometer case to avoid signal-to-noise degradation in electrically noisy environments. Signals for the laser diodes are coupled to the spectrometer via an optical fiber link terminated with an integrating sphere, which offer an appropriate means for the collection of divergent laser beams.

The transversal beam structure was evaluated with two laser beam analyzers, a standalone instrument or a PC single board device. Either of them derives its signal from a professional b/w CCD camera, while mode distribution can be represented as pseudo-color images. We developed special Virtual Instruments to control the laser beam analyzer with a PC. Programmes were also based on the LabVIEW software.
The optical power of the laser diodes was measured with a two channel power meter. In our investigation on laser diodes we used an integrating sphere/ silicon detector head and a thermopile, spectrally-flat-response detector. The power meter can be operated through a serial port connection or alternatively through a pseudo-GPIB link. Several VIs were designed to remotely control the instrument.

2.3 The research results

2.3.1 The emitted optical power vs. the driving current characteristics

Figure 1 shows an example of optical power versus the threshold current, at different driving temperatures and after the device received various radiation doses.

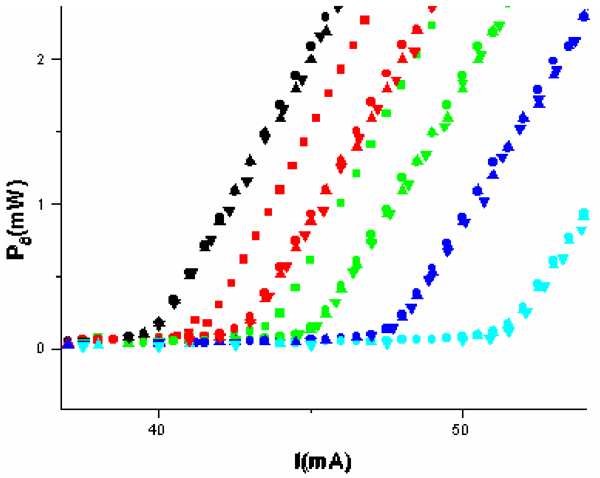

Figure 1. The optical power vs. the driving current curve, with the detail of the threshold current zone, for SLD1, at different case temperatures and total irradiation doses: black - 16 °C, red - 22 °C, green – 26 °C, blue - 30 °C, cyan - 35 °C; square - 0 Mrad, circle - 1 Mrad, up-triangle - 2 Mrad, down-triangle - 4 Mrad (gamma-ray).

The threshold current change depends on the laser diode type, its basic material, operating temperature and total dose. For the investigated semiconductor lasers, at the total doses used, the maximum relative modification of the threshold current equal to an increase of 3.8 %, was observed for the device SLD4 (index guided structure). All other lasers exhibit changes up to 2 %, for gamma-ray irradiation. Quantum-well (QW) devices proved to be less sensitive to irradiation as it concerns the modification of the threshold current, as compared to heterostructure devices. If, for example, we compare the modification of the threshold current upon gamma and electron irradiation, for the same device and total dose, the maximum value of the changes induced by electron irradiation are slightly higher (1.9 %) than those produced by gamma-ray (1.8 %), i.e. for the case of SLD2.
The calculus performed on the measuring results indicated a higher degradation of the external quantum efficiency for QW and index guide structures, a relative decrease between 5.7 % and 10.4 %, as compared to double heterostructure, to which corresponds a relative decrease of

3.7 % to 5.7 %, after gamma-ray irradiation. A comparison between the relative changes in the external quantum efficiency of the same type of semiconductor laser (i.e. SLD2) subjected to gamma and electron irradiation indicates a slightly higher modification of this parameter after gamma-ray irradiation, 9.7 % versus 6.7 % for electron irradiation.

2.3.2 The compliance voltage vs. the driving current characteristics

The next characteristic investigated on laser diodes was the V(I) curve, as a function of the diode case temperature and irradiation conditions. Figure 2 illustrates the modifications induced by electron and gamma-ray irradiation on the mentioned devices.

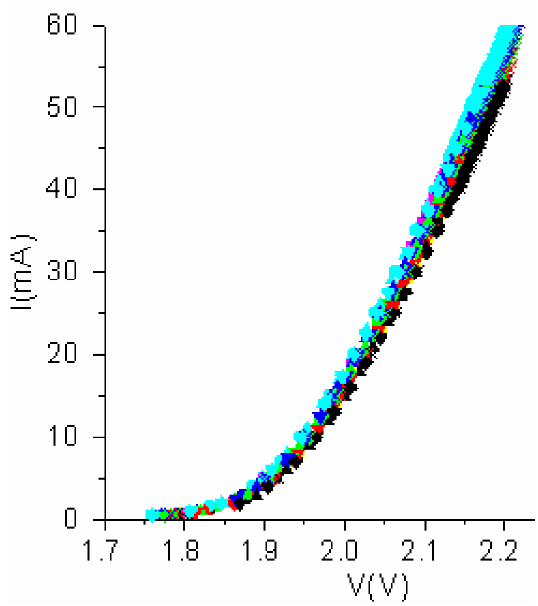

Figure 2. The laser voltage/ driving current curves for SLD1, for different case temperature, after gamma-ray irradiation at: square - 0 Mrad; circle - 1 Mrad; up-triangle - 2 Mrad; down-triangle - 4 Mrad; diamond - 6 Mrad; plus (+) - 9 Mrad; cross (X) - 14 Mrad.

These curves were used to compute the laser serial resistance for various conditions. Higher modification of the serial resistance were observed for QW devices subjected to electron irradiation, a maximum increase of 13.2 %, as compared to maximum change of 6.5 % for the double heterostructure devices, subjected to gamma irradiation.

2.3.3 The embedded photodiode responsivity

We also carried out investigations on the response of the photodiode associated with each semiconductor laser. We measured the photodiode monitoring current as a function of the laser emitted optical power and the device case temperature, for different total doses. An example of these characteristics is given in Figure 3. From these curves the photodiode responsivity was calculated, for different case temperatures and total radiation doses. The laser diode embedded monitoring detector proved to be the most sensitive part of the device, as far as its responsivity deteriorated more as compared to the emitter parameters. A relative decrease of 8 % to 10 % was observed for gamma-ray irradiation; while relative changes of up to 21 % appeared after electron irradiation in some laser diodes.

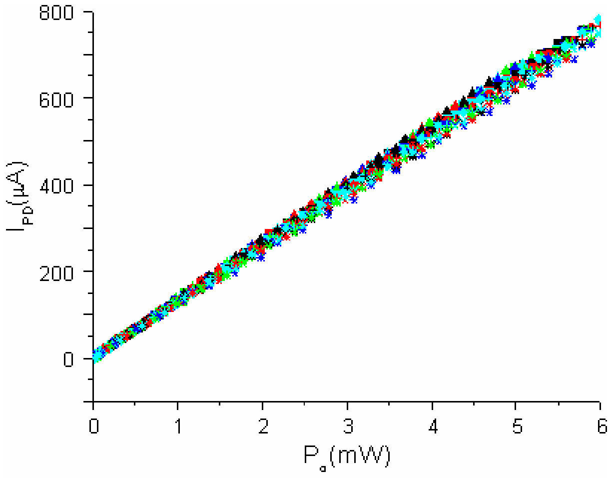

Figure 3. The variation of the photodiode monitoring current vs. the laser optical power for SLD4, at different case temperatures: black - 16 °C; red - 20 °C, green - 24 °C; blue - 28 °C, cyan -32 °C; after gamma-ray irradiation at: square - 0 Mrad; up-triangle - 1 Mrad; down-triangle - 2 Mrad; diamond - 4 Mrad; plus (+) - 6 Mrad; cross (X) - 9 Mrad; star (*) - 14 Mrad.

2.3.4 The laser diode wavelength changes

The modifications induced in the laser diodes emitted radiation wavelength are illustrated in Figure 4 with one example. Our investigations deal with the wavelength dependence on the driving conditions (case temperature and laser forward current) and the total dose to which the device was subjected.

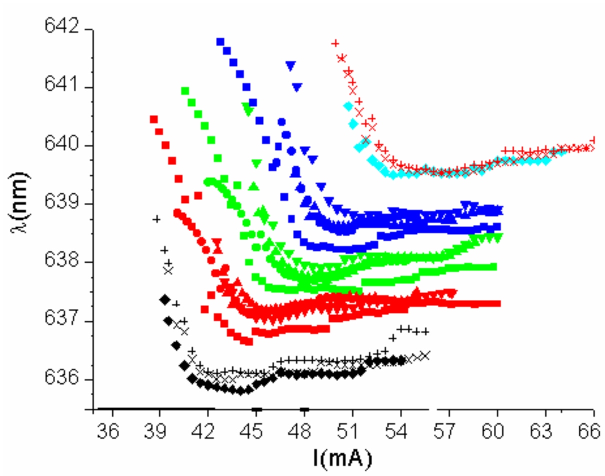

Figure 4. The variation of the emitted radiation wavelength for SLD1, for currents below and above the threshold current, at case temperature: black - 16 °C; red - 18 °C; green - 22 °C; blue - 26 °C; cyan – 30 °C, following gamma-ray irradiation, at: square - 0 Mrad; circle - 1 Mrad; up-trianlge - 2 Mrad; down-triangle - 4 Mrad; diamond - 6 Mrad; plus (+) - 9 Mrad; cross (X) - 14 Mrad.

We evaluated the wavelength both below and above the value of the threshold current. The general trend above the lasing point is a blue shift for the QW structures, of about 0.5 nm. The index guided and heterostructure laser diodes exhibit a high immunity to irradiation, at least for the total doses involved up to now. The SLD6 emerged as the most radiation-hardened device from this point of view.

2.3.5 The laser diode emitted spectra changes

The most notable modification of the emitted radiation spectral content was noticed for the two laser diodes emitting in the near-IR range (SLD5 and SLD6). As they are subjected to irradiation, their spectral bands modify (Figure 5, the broadening of the emitted spectrum) and, in one case, a multi mode longitudinal structure appears, as indicated in Figure 6.

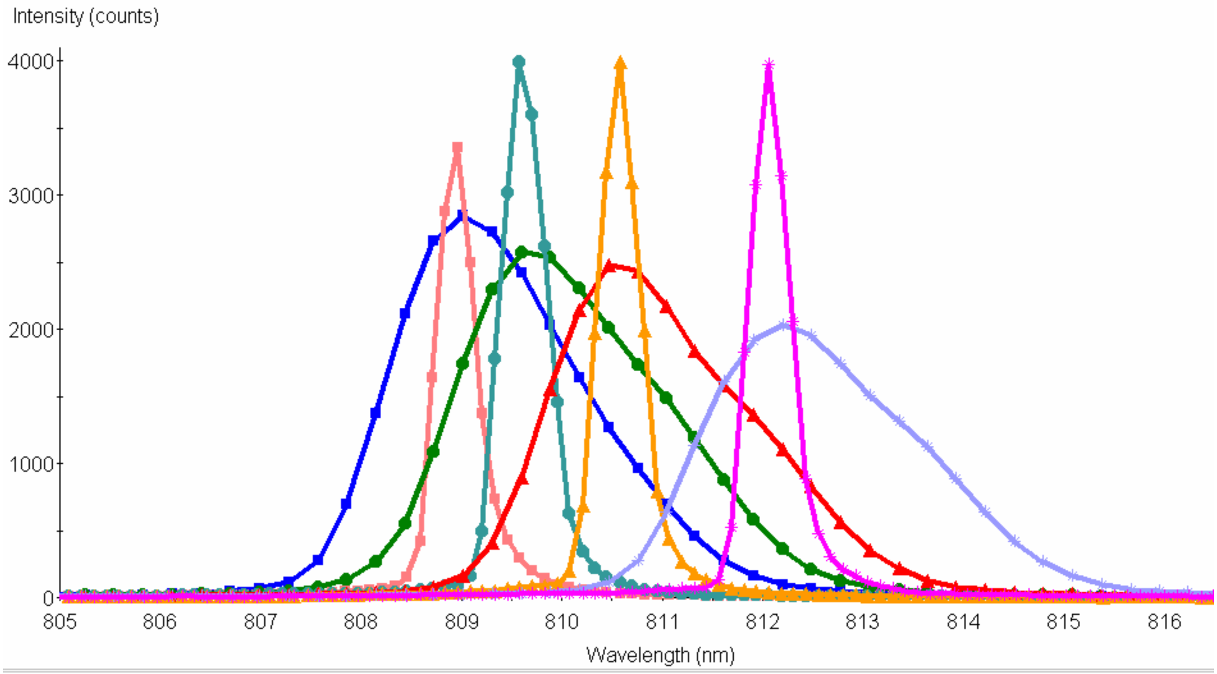

Figure 5. The narrowing of the spectral bandwidth of SLD5 after gamma-ray irradiation.

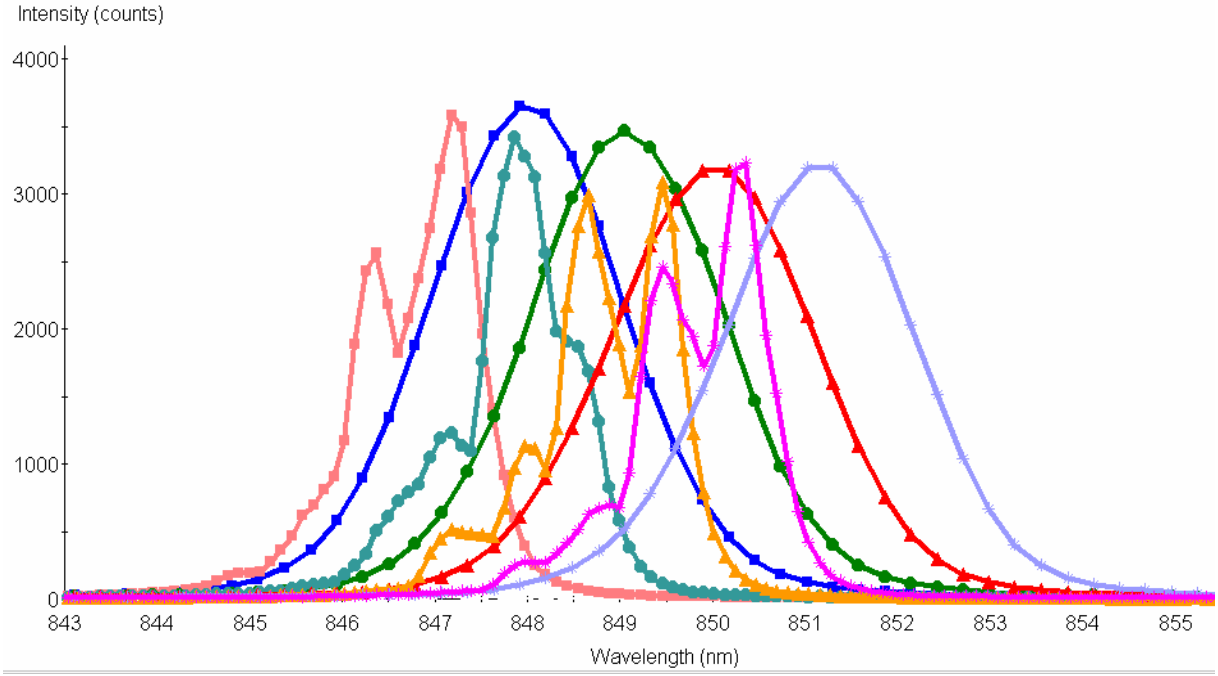

Figure 6. The build-up of multi mode longitudinal structure in SLD6 after gamma-ray irradiation.

2.3.6 The transversal mode structure

For the total irradiation doses we have used until now, no significant modification of the transversal mode structure was observed.

3. Investigations on UV optical fibers

3.1 The experimental set-up

The investigations carried out during 2002 were focused on the evaluation of the optical transmission of UV hardened optical fibers to be used in fusion installations as light guides for plasma diagnostics. Several types of commercially available UV enhanced optical fibers were investigated. The core diameter of these fibers is between 200 - 400 μm, with various cladding and jacket materials.

In our measurements we used a setup which includes: a broadband light source (deuterium/halogen) and an optical fiber mini spectrometer. The fiber can be subjected to UV, gamma-ray or temperature stress. All investigations were carried out at this stage before and after irradiation; no on-line measurements are now available. The optical fiber probes are 2 m long, solarization resistant optical fibers, of 400 μm core diameter. The samples are temporarily coupled to the probes through bare fiber terminators and appropriate SMA connectors. The heating is performed with a PC-controlled oven, with the maximum operating temperature of 300 ^{0}C, and the temperature resolution of 1 ^{0}C. The fibers subjected to temperature treatment were measured before and after the heating.

Each piece of optical fiber from the first set was gamma-ray irradiated with the following total dose steps: 20 krad, 40 krad, 80 krad, 230 krad, 480 krad. The fibers for the first set were also heated at 90 ^{o}C for half an hour, between the last two irradiation steps. Fibers from the second set were irradiated with gamma-rays at total doses: 80 krad, 250 krad and 500 krad. Between two subsequent irradiation processes all the optical fibers were kept at room temperature (23 ^{o}C).

For each measuring step, the evaluation of the characterization of the optical properties of fibers was performed according to the following procedure:

- the optical fibers were measured in the spectral range from 200 nm – 470 nm;
- this spectral band was divided into four sub-bands, in order to optimize the detection process, to obtain the maximum signal-to-noise ratio;
- for each step described above, 5 to 10 measurements were carried out, so that a mean value can be deduced. This method is mandatory as far as important errors are introduced by the temporary connectivity we are using. Any eccentricity of the fiber inside the connector, as well as a poor alignment of any two mating connectors results in a big bias in the measured attenuation.

The following figures illustrate some of the obtained results. All of the fibers used present an increase of the attenuation in the 230 nm - 250 nm spectral band. An exception constitutes the optical fiber denoted OF1-200, where no increase is noticed along the whole investigated range, for total irradiation doses up to 500 krad. It can be seen from the curves below, that the increase of the irradiation total dose implies more evident attenuation peaks. In the mean time, the dose rise induces in some cases a red shift of the absorption peak. The temperature stress generates in some cases a recovering effect, by reducing the spectral attenuation. The fibers most sensitive to this phenomenon are OF3-400 and OF4-400, while the fiber OF2-200 is quite insensitive to thermal recovery.

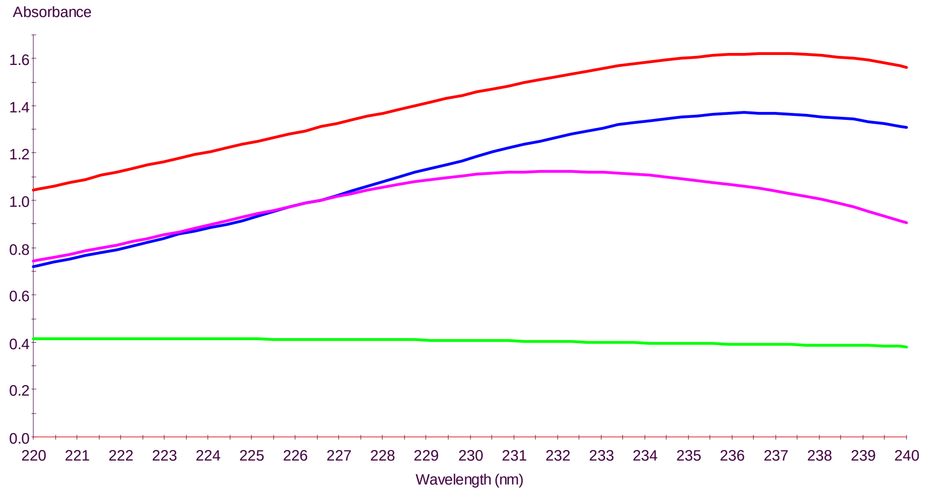

Figure 7. Fiber type OF2-400, spectral interval 220 – 240 nm, doses: green – 0 krad; magenta – 230 krad; red – 480 krad; blue – 480 krad/90°C.

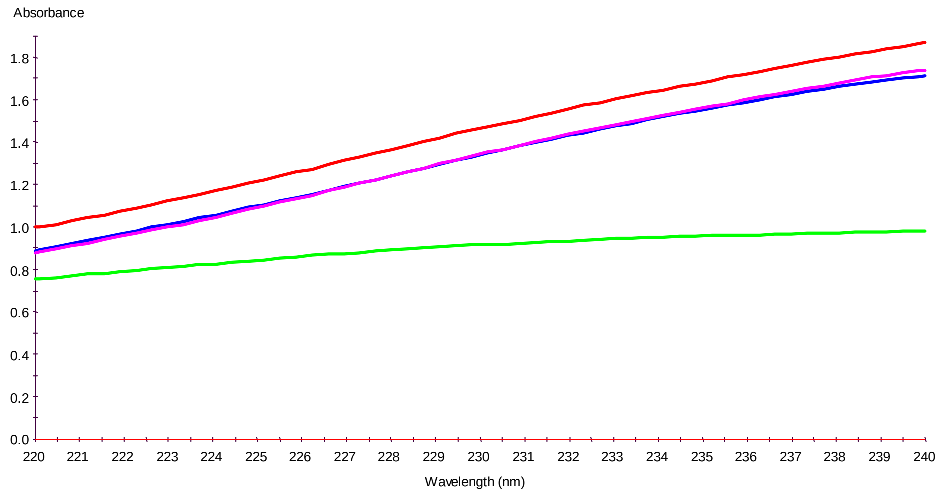

Figure 8. Fiber type OF3-200, spectral interval 220 – 240 nm, doses: green – 0 krad; magenta – 230 krad; red – 480 krad; blue – 480 krad/90 °C.

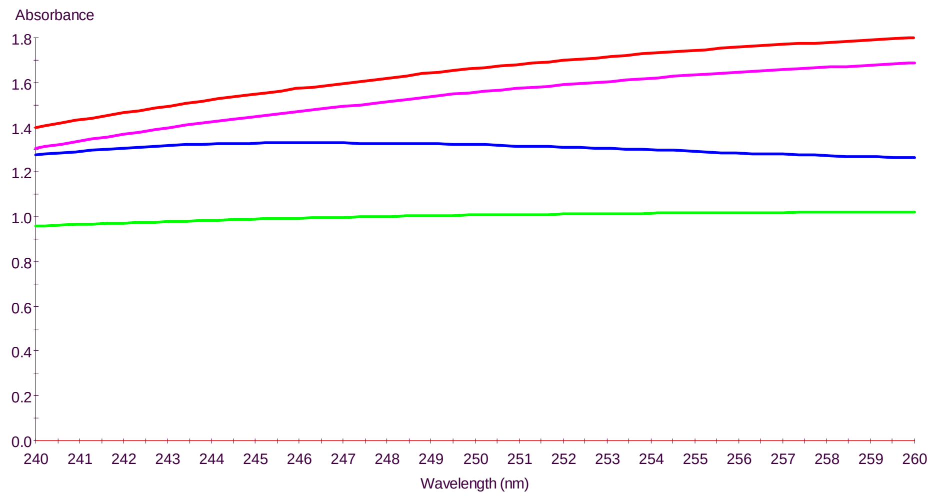

Figure 9. Fiber type OF3-200, spectral interval 240 – 260 nm, doses: green – 0 krad; magenta – 230 krad; red – 480 krad; blue – 480 krad/90 ° C.

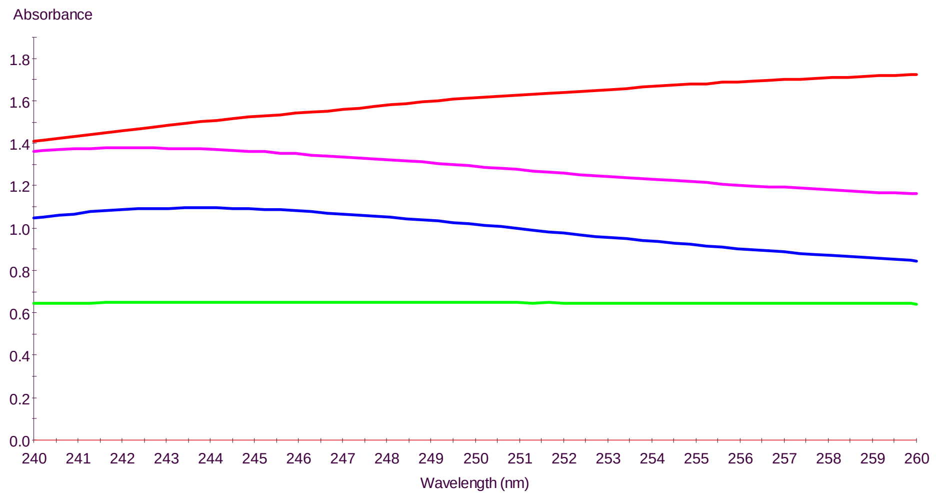

Figure 10. Fiber type OF3-400, spectral interval 240 – 260 nm, doses: green – 0 krad; magenta – 230 krad; red – 480 krad; blue – 480 krad/90 ° C.

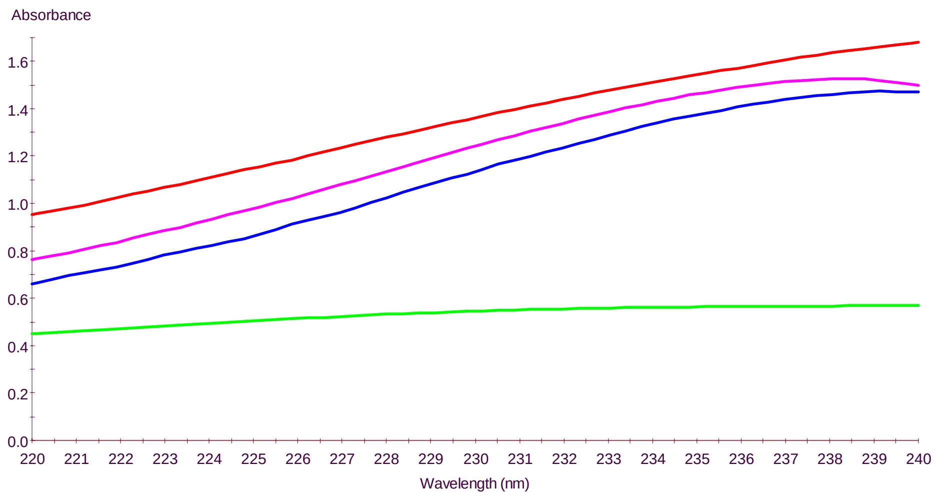

Figure 11. Fiber type OF4-400, spectral interval 220 – 240 nm, doses: green – 0 krad; magenta – 230 krad; red – 480 krad; blue – 480 krad/90 ° C.

Even if a bias is noticeable from spectral band to spectral band, the overall trends in the optical fiber attenuation is evident. So, the method makes possible the evaluation of RELATIVE CHANGES, NOT AN ABSOLUTE MEASUREMENT of the fiber's optical absorption/ transmission.

4. Conclusions

A. Six types of semiconductor laser diodes emitting in the visible and near-IR range were investigated, as they were subjected to gamma-ray and electron beam irradiation, at total doses up to 30 Mrad (gamma) and 16 Mrad (electron).

B. Up to this moment, the index guide structure seems to be more affected by irradiation concerning its threshold current (3% increase). QW and index guide devices present a high degradation of their external quantum efficiency. The change of the laser resistance is more noticeable for the QW lasers after electron irradiation.

C. A small (0.5 nm) blue shift of the emitted wavelength was observed for QW lasers, while the double heterostructure laser proved to be less affected by irradiation.

D. No major changes in the lasers transversal beam structure were proved for the total doses used.

E. Some of the semiconductor lasers exhibit a modification of the emitted spectra (broadening, multi mode structure) after irradiation.

F. For the studied lasers at the above mentioned doses, the photodiodes proved to be the most radiation sensitive component, as a responsivity degradation of 21 % was observed.

G. Seven types (as it concerns the technology/material used, core diameter, cladding dimension/thermal properties) of UV enhanced, commercially available optical fibers were studied. They were subjected to gamma-ray irradiation (up to 500 krad total dose) and thermal stress (up to 90 ^{o}C).

H. For one optical fiber, no degradation of the optical transmission was observed after gamma irradiation. All the other ones present a peak in the attenuation spectra at about 230 nm - 250 nm.

I. One optical fiber is insensitive to thermal recovery, while other two are very responsive to heating.

J. The investigations on optical fibers and semiconductor optoelectronic components will continue with: an increase of the total dose (both for gamma and electron irradiation) for the laser diodes; an evaluation of the temporal behavior of the semiconductor lasers; an extension of the radiation total doses and temperature stress limit for the UV enhanced optical fibers; an evaluation of the combined influence of ionizing radiation and UV radiation stress on the optical transmission of UV optical fibers.

Publications:

[1] **Sporea D. G.** **and** **Florean A.**, *"Investigations on the Degradation of Visible Lasers Diodes under Gamma-Ray Irradiation"*, 22nd Symposium on Fusion Technology, Helsinki, September, 2002.

[2] **Sporea D. G.** **and** **Florean A.**, *"Gamma-Ray Radiation Induced Changes in Near-IR Operating Semiconductor Laser Diodes"*, Radiation Effects on Components and Systems Conference, Padova, September, 2002.

[3] **Sporea D. G.** **and** **Florean A.**, **Oproiu C.** **and** **Constantinescu B.**, *"Evaluation of Visible and Near-IR Lasers Diodes subjected to Electron and Gamma-Ray Irradiation"*, International Semiconductor conference, Sinaia, October, 2002.

[4] **Sporea D. G.** **and** **Florean A.** **and** **Gherendi M.**, *"Heterojunction Laser Diodes Subjected to Ionizing Radiation"*, Advanced Topics in Optoelectronics Micro & Nanotechnologies International Conference, Bucharest, November, 2002.

[5] **Sporea D. G.** **and** **Sporea R. A.**, "Integrated Software Package for Laser Diodes Characterization", Advanced Topics in Optoelectronics Micro & Nanotechnologies International Conference, Bucharest, November, 2002.