Radiation Hardness of Silicon Integrated Nano Photonic Devices

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Integrated Nano Photonic (INP) sensors will be used in medical and space applications in the near future. Therefore, these devices must also be able to withstand harsh environments without failure. For space and medical applications radiation hardness is a very important issue. At TNO we have investigated the radiation hardness of nano photonic devices using electro-magnetic radiation and high energy particles. We have bombarded various ring resonators and couplers with gamma rays, protons and electrons. After the tests the device operation is verified and compared to non-radiated devices.

Introduction

Research is being performed to investigate what the most extreme environments are in which the INP sensors can be used, and how exposure to these environments influences the proper operation of the sensors.

In this paper, we report on the INP sensors performance after exposure to different kinds of ionizing radiation. This can be useful for the medical industry and space industry. Some examples of applications in these fields are:

- Intravascular temperature-, pressure- or chemical sensing while the patient is being exposed to x-rays / gamma rays for radiation therapy or x-ray picture
- Temperature/pressure sensing inside or outside a spacecraft in orbit around the Earth, exposed to high energy electrons/protons/other high energy particles.

For this experiment we use a number of identical chips which contain a large number of photonic devices. The chips will be exposed to different radiation sources, after which we verify if the devices have suffered from the radiation by measuring their optical responses. The devices are different types of micro ring resonators (RRs) and 2x2 MMI couplers from which the response is known. We expect possible changes in output transmission intensity and free spectral range (FSR) due to radiation induced changes in the material.

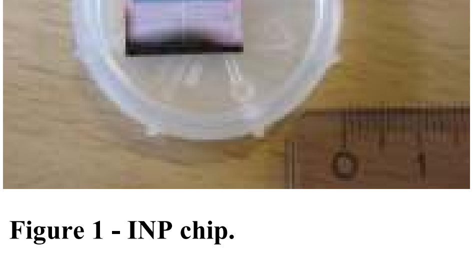

Figure 1 - INP chip.

An example of the chip is shown in Figure 1. The devices are fabricated using standard SOI CMOS techniques as offered by ePIXfab. The structures have a height of 220 nm and waveguide widths vary between 0.45 um and 3.0 um. Vertical grating couplers (VGCs) are used for the coupling of the read-out fibers to the chip. As a light source we use a broadband amplified spontaneous emission (ASE) source with a center frequency of 1550 nm and bandwidth of 50 nm. Reading the signal is done with an optical spectrum analyzer (OSA).

Gamma Radiation

If EM radiation is energetic enough, it is able to remove electrons from atoms or molecules, thus ionizing them. Ionizing radiation can be used for cancer treatment. The high energy rays ionize atoms and destroy molecular bonds, killing the target tissue. For this purpose gamma ray radiation is used. Typical (maximum) gamma ray doses administered to patients of a particular type of lymphoma is 1.8 – 2.0 Gy per day [1].

To determine at which dose of gamma radiation the device fails, 5 chips are used for a radiation experiment, which were performed using a gamma radiation device at the Catharina Hospital in Eindhoven. Each chip received a different dose of 1 MeV gamma radiation, with a highest dose equivalent to a (lethal) treatment of 100 Gy. A number of devices on each chip are measured before the experiment. After the experiment, the same devices are measured for the 100 Gy treated chip. An example of a response from a ring resonator before and after the experiment is shown in Figure 2.

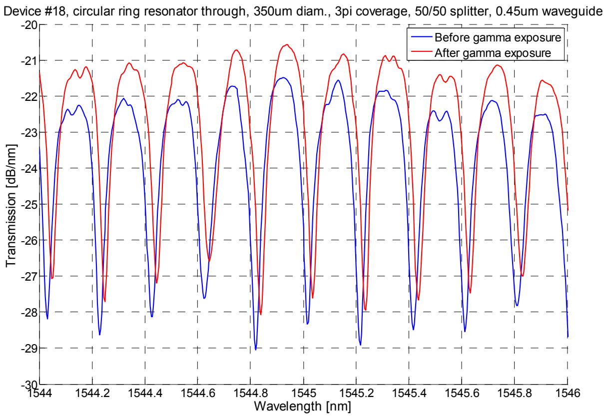

Figure 2 - Response ring resonator before and after radiation experiment.

Here the blue response is measured before the 100 Gy gamma ray exposure, the red line is measured after the experiment. From all measured devices, plotted in Figure 3, we can conclude that the ring resonator gives the same response as before. The intensity is a little higher, however this has to do with uncertainty in fiber coupling losses. The shape and free spectral range (FSR) of the signal is unchanged.

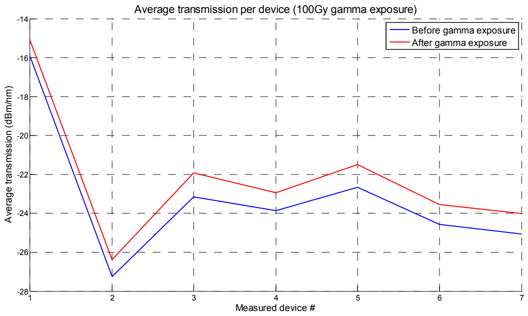

Figure 3 - Average transmission vs. device number.

Based on the experimental results, we can conclude that the devices still operate after receiving a large medical gamma ray dose. The general response and FSR are unchanged. The observed intensity variation is well within measurement uncertainty (±1.5dB).

Electron Particle Radiation

As with gamma radiation, high energy electrons are able to ionize matter. Electrons deliver between 90% – 100% of their energy relatively uniform (compared to EM radiation) after entering tissue/material, after which the dose deposition curve drops rapidly [2]. High energy electrons are used for surface cancer treatments, also with a daily maximum dose of 2 Gy. When assuming 1 MeV electrons with a penetration depth of approximately 1 cm, this is an exposure in the order of 10^{10} electrons/cm^2. For space applications, the amount of electrons/cm^2 is much larger. As a reference we take the O3B space mission, which has a constellation of satellites with an orbit in the radiation rich Van Allen belt. For this 10 year space mission FSS windows are tested to withstand $3*10^{16}$ electrons/cm^2 [3].

An electron radiation experiment is performed at the Radiation Institute Delft (RID, formerly known as IRI) in Delft, where a van de Graaff generator is used to generate electrons of 1 MeV. Five chips are bombarded by electrons with different electron fluencies, from 10^{12} e$^-$/cm^2 up to $3*10^{15}$ e$^-$/cm^2.

Since no measurements are performed with the chips before the exposure to electrons, we can only compare average transmission powers and FSR. The average transmission power per chip (thus electron fluency) is shown in Figure 4. Error bars are added, with an estimated fiber coupling error of ± 1.5 dB. The variations in average transmission fall within this error. FSR is the same for all devices. We can conclude that high energy electrons have no influence on the general functioning of the INP devices on the chip.

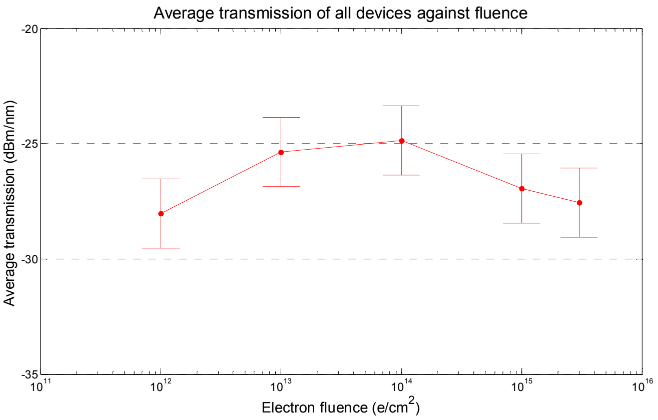

Figure 4 - Average transmission for all measured devices for different electron fluencies.

Proton Particle Radiation

Protons are massive particles compared to electrons. Their interaction cross section with other matter is larger and therefore, they interact faster than electrons, and their interaction increases with decreasing kinetic energy. As a result, protons release most energy at the Bragg-peak location, dependent on the proton energy at entry of a material. For medical applications, protons can be used to release most energy inside a tumor, rather than the surface and surrounding tissue. In space protons are present in large amounts. Therefore, if INP devices are used in medical and space applications they have to be able to withstand large proton fluencies without failing.

As a reference we take the O3B space mission again, since the Van Allen belt contains a large amount of protons. The solar panels for this space mission are tested with $7*10^{15}$

protons/cm^2 with an energy of 1 MeV. We performed a proton irradiation experiment using the AccTec singletron accelerator in Eindhoven, where 1 MeV protons are generated to bombard five INP chips. The protons have an average penetration depth of 40 microns in silicon. Most energy is thus deposited in the top layer of the chip. Fluencies vary from 10^{12} p/cm^2 up to 10^{16} p/cm^2, thus equivalent to the 10 year O3B space mission. This also covers the medical needs, where much lower fluencies are used.

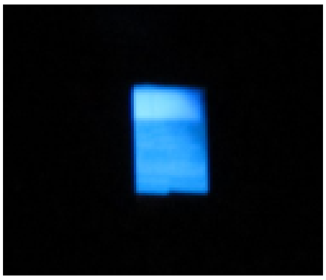

Figure 5 - INP chip glowing due to proton induced fluorescence.

In Figure 5 one of the INP chips is shown during proton irradiation, glowing due to fluorescence of the silicon. As with the electrons, no measurements are performed with the chips before exposure. Therefore, we look at average transmission and FSR again. The average transmission is plotted in Figure 6. The drop is due to protons sputtering, thus doping of the Si which is known to cause additional loss to PICs. Also we notice a decrease of the FSR with respect to the increasing proton fluency. The change in FSR for one selected device is determined at approximately -1.2 % per decade proton fluency starting from 10^{13} p/cm^2. This is also explained by the doping of the Si, after which the index of refraction of the material changes.

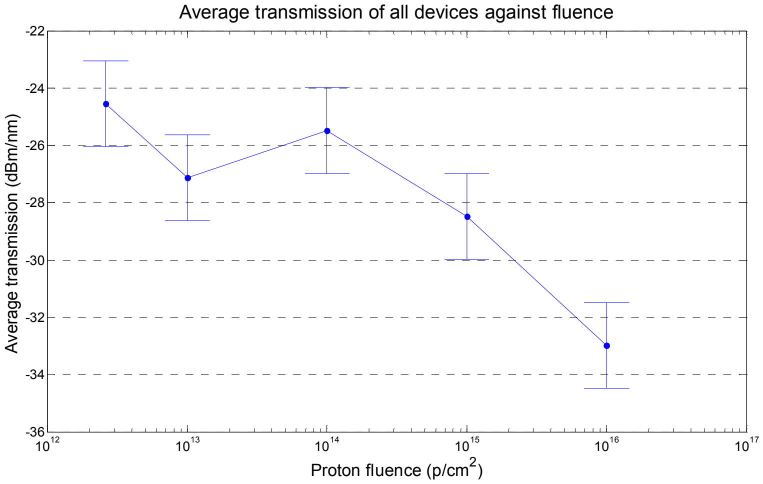

Figure 6 - Average transmission against proton fluency.

Conclusions

We have shown that the general operation of INP devices does not change after being exposed to medical and space levels of gamma and electron radiation. The devices which are exposed to large levels of proton radiation do give a slight decay in transmission. Also the FSR decreases with approximately 1.2% per decade of proton fluency starting from 10^{13} p/cm^2. Depending on the application, this effect should be taken into account. More detailed effects of radiation will be investigated by TNO in future research, with the addition of exposure of radiation during operation.

References

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