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SPACE RADIATION EFFECTS ON OPTICAL TRANSCEIVER SYSTEM OF SATELLITE AT NEAR EQUATORIAL LOW EARTH ORBIT

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14. ABSTRACT
Satellite communications are now embarking on a new paradigm as they integrate space, aerial, and terrestrial networks to create a three-dimensional framework for 5G connectivity. However, spacecraft, space stations, satellites, and astronauts are exposed to an increased level of radiation when in space. Therefore, it is important to evaluate risks and performance effects associated with extended radiation exposures in missions and space travel. This research proposal focuses on Low Earth Orbit (LEO), especially at the near-equatorial radiation environment and how the radiation particles in it interact with materials in general and with inter-satellite optical wireless communication systems in particular.

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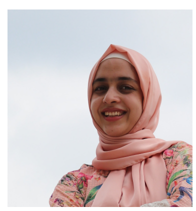
Principle Researcher: Prof. Dr. Nurul Fadzlin Hasbullah	Co-Researcher: Asst. prof. Dr. Norazlina Saidin
Postdoc and Postgraduate Students	
1. Name: Dr Abdouraouf Said Youssouf Nationality: Comoros Island Post doc	
2. Name: Tamana Baba Matric number: G2218500 Nationality: Indian PhD (Full time)	
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1. ABSTRACT:

Satellite communications are now embarking on a new paradigm as they integrate space, aerial, and terrestrial networks to create a three-dimensional framework for 5G connectivity. However, spacecraft, space stations, satellites, and astronauts are exposed to an increased level of radiation when in space. Therefore, it is important to evaluate risks and performance effects associated with extended radiation exposures in missions and space travel. This research proposal focuses on Low Earth Orbit (LEO), especially at the near-equatorial radiation environment and how the radiation particles in it interact with materials in general and with inter-satellite optical wireless communication systems in particular.

The research will include exposing the transmitter (laser) and receiver (photodetector) to space radiation i.e. the electron radiation and study the degradation effects on the devices with varying dose. The data from the characterisation of devices before and after radiation will be used as input to simulate the optical communication link of the satellites using OptiSystem. The performance of the optical link with transreceiver subjected to space radiation will be investigated using different methods of modulation techniques and analytical modelling of the optical system will be performed.

2. RESEARCH OBJECTIVES

1- To characterize the electrical and optical performance parameters of the IsOWC transceiver before radiation.
2- To simulate the performance degradation of the IsOWC transceiver under electron radiation
3- To model the performance degradation of the IsOWC transceiver under electron radiation with different wavelengths and modulation techniques.

3. Methodology

The experimental setup of the irradiation process encompasses two stages. Firstly, the irradiation process of the optoelectronics devices with the EPS – 3000 electron beam machine facility in Nuclear Malaysia. Considering the worst-case scenario with reference to Suparta [28], the lasers and photodiodes will be irradiated with 1.5 MeV electrons of energy with five iterations of radiation exposure of electron-equivalent doses ranging from 50 kGy to 250 kGy, at the Malaysian Nuclear Agency.

The electrical and optical characterization of all devices were performed before and after the irradiation process and was carried out in the photonics and optoelectronics labs at University Malaya and IIUM respectively. The selected optoelectronics components are from the transmitters and the receivers' sub-systems, namely the laser source and the photodiodes. The lasers and photodiodes are the commercial on the shelf (COTS), where they are selected based on their manufacturing materials and wavelengths.

Another stage will be at the system level, which is characterized by the simulation of the performance of the IsOWC link system in incorporating the radiation-induced degradation of the devices. The IsOWC link system will be designed using OptiSystem software, based on the different types of modulation techniques such as On-Off Keying (OOK) and homodyne Binary Phase Shift Keying (BPSK) modulation techniques. The simulated results will be obtained by importing experimental data of devices into the communication links established in OptiSystem software. The analytical model will be derived using the Q factor and Bit Error Rate (BER) of the system with the degradation from the noise figure of the optoelectronic devices.

4. PUBLICATIONS:

PUBLISHED AND ACCEPTED WORK:

1. A. S. Youssouf *et al.*, "Induced electron radiation effect on the performance of inter-satellite optical wireless communication," *PLoS ONE*, vol. 16, no. 12 December. 2021, doi: 10.1371/journal.pone.0259649.
2. T. Baba, N. F. Hasbullah, and N. B. Saidin, "Degradation of InGaN LEDs by Proton Radiation," pp. 932–936, 2023, doi: 10.1109/icbir57571.2023.10147696, May 2023.
3. T. Baba, M. Hazeeq, N. B. Saidin, and N. F. Hasbullah, "Effect of Proton Radiation on Gallium Nitride LEDs," vol. 99, no. 1, pp. 1–8, doi: 10.11591/eei.v99i1.paperID (February 2024)
4. Radiation-induced Degradation of Silicon Carbide MOSFETs -A Review

5. FINDINGS OF THE RESEARCH

In the published paper titled "Induced Electron Radiation Effect on The Performance of Inter-satellite Optical Wireless Communication", the irradiation experiment of the selected optoelectronics components, namely the laser and the photodiodes for the electron radiation, has been carried out successfully. Electron radiation has made a significant impact on devices. The characterization of the devices demonstrates the magnitude of the radiation effect, where the laser diodes threshold current density increased, and the output power decreased with the increase of irradiation doses by more than 40%. The decrease of quantum efficiency translates this degradation by creating non-radiative recombination centres that compete with radiative recombination sites. For the photodiode, the dark current increases by 40 nA, which lead the responsivity to decrease. At the system level, the simulation of the IsOWC system using the homodyne BPSK modulation technique has been reported. The magnitude degradation of the lasers and photodiodes are fed to the IsOWC system and simulated. The impact of radiation can be seen along with the degradation of the system performance with radiation doses. The combined effect of irradiation on both Tx and Rx at the performance level has been modelled analytically and by simulation. After the fourth dose of the irradiation process, the system performance degraded by 70% in electron approximately, where the Q factor decreases by more than 80% approximately and the system BER increase by more than 20 orders of magnitude and reach1×10^{-3}, which indicates that further irradiation processes were not necessary. This fact has been translated in the analytical and simulation modelling, where the combined radiation effect on the Tx and Rx has been reported and compared with the state of art investigations. Figure 2 shows the degradation of output power with radiation.

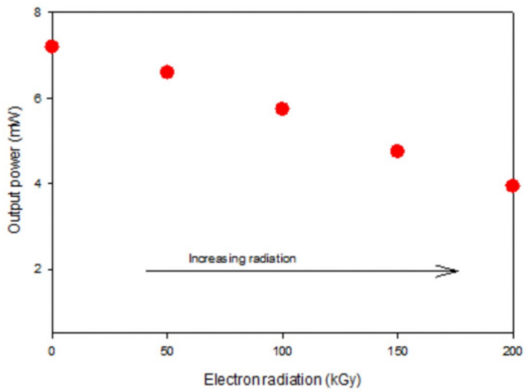

Figure 2. Degradation of the 980 nm laser diode: Radiation-induced optical power loss at 30 mA.

The dark current has been used as the parameter to investigate the electron radiation effect on the InGaAs Photodiode for the photodiodes. Figure 3. shows the characterization of the dark current. By analyzing closely, before radiation, the dark current was 1.35 nA, which is typical to a photodiode operating at this particular wavelength.

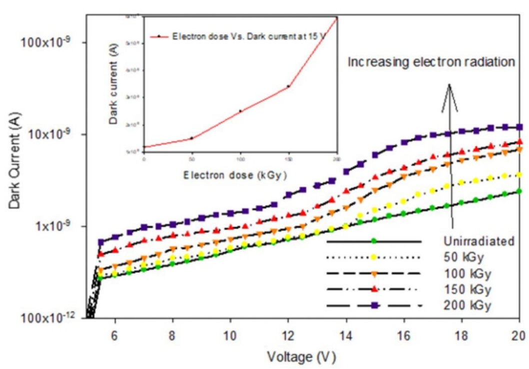

Figure 3 . Electron irradiation of dark current versus voltage.

Figure 4 represents the Q factor of the inter-satellite optical communication links performance that implements the 980 nm laser in the transmitter under different irradiation doses. Before irradiation, the Q factor of the system was 26 with a BER of 1.5×10^{-26}.

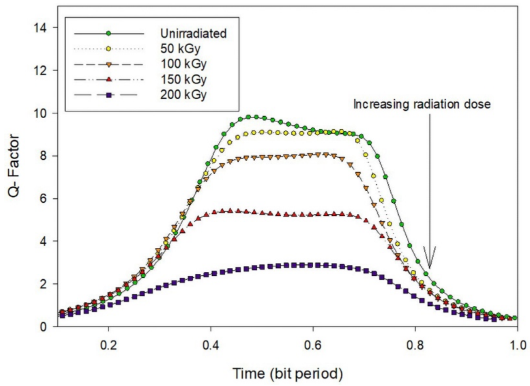

Figure 4. Electron radiation effect on Tx, with 980 nm laser.

The degradation of the normalized Q factor of the homodyne BPSK based system, as a function of both Tx and Rx dose, is obtained as reported in Figure 5. It shows the normalized Q factor versus the electron radiation dose model. The normalized Q factor is one before irradiation, as can be shown. The Q factor drops by 20% when the radiation effect of 50 kGy is combined on the Tx and Rx. The degradation of the system deteriorating as the electron radiation dose was increasing. After 200 kGy of electron irradiation, the Q factor decreases by more than 80%, an indicator of system failure.

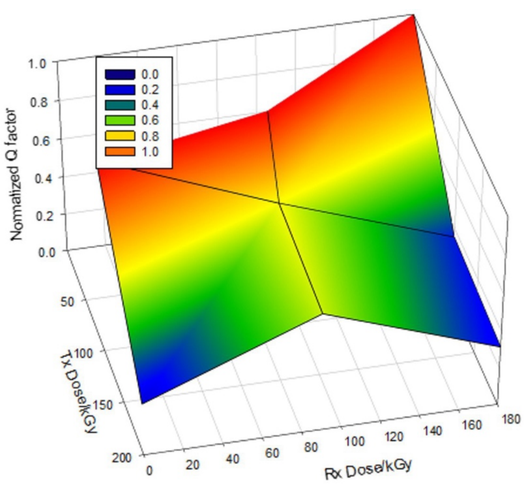

Figure 5. Normalized Q factor versus electron radiation dose on Tx and Rx–BPSK.

This can be further illustrated in Figure 6, where the BER is increased to 1×10^{-3}, which is below the threshold of the accepted range of BER.

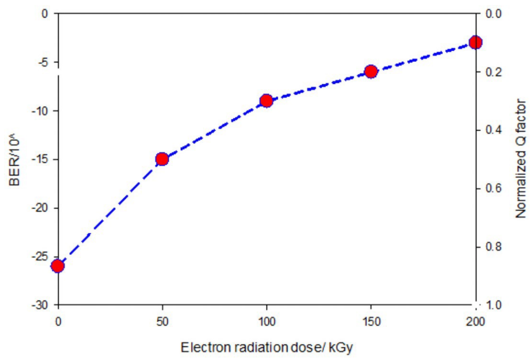

Figure 6. BER and Q factor versus electron radiation dose on Tx and Rx -BPSK.

The research in the paper titled "Effect of Proton Radiation on Gallium Nitride LEDs" studied the effect of proton radiation on Indium Gallium Nitride LEDs. The electrical and optical characteristics of the LEDs were compared before and after radiation. When using electrical devices based on GaN in harsh conditions or open spaces, the degradation characteristics described in the present study can assist scientists and engineers in making well-informed decisions. However, the impact of radiation on InGaN LED devices appears complicated and was influenced by several variables. While the electrical characteristics show degradation, an improvement in the optical characteristics post-irradiation can be noticed. This is attributed to oxygen related defects that can be optically active.

Electrical characterization results of the LEDs found in "Degradation of InGaN LEDs by Proton Radiation" appears to show that the diodes are not much affected by radiation when it is forward biased. However, the effect of radiation on Indium Gallium Nitride LEDs was found to be significant in the reverse bias characteristics of the devices. The results show an increase in the reverse current for most of the devices. This increase in current is attributed to the rise in the bulk density of traps. Apart from the reverse current, optical intensity has also increased after radiation. This increase is attributed to radiation-induced annealing or healing of defects leading to increased optical intensity. Figure 6 shows the optical intensity of the LEDs after radiation.

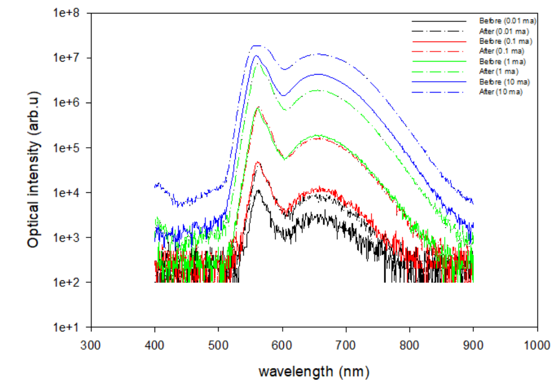

Figure 6. Optical intensity of LED

The findings of the study titled “Degradation in Silicon Carbide Schottky Diodes Induced by 8 MeV Proton Radiation” demonstrate that silicon carbide Schottky diodes' reverse current and ideality factor suffer significantly from 8 MeV proton radiation. While the ideality factor has increased up to 17%, the reverse current was reduced to 90%. The forward current also showed a very slight rise, but this was not statistically significant as compared to the change in reverse current. The radiation had little to no impact on the diodes' capacitance. These findings are in line with the flaws in silicon carbide caused by radiations that are well-known. Defects such as vacancies, interstitials and trap charge carriers are caused by proton radiation. This may result in fewer free charge carriers, which in turn raises the diode's reverse current and ideality factor. The slight increase in forward current may be the result of the flaws opening new tunnelling routes.

The results of the paper titled “Investigation of Proton Radiation Effect on InGaN LEDs”, show that the forward current and capacitance remain mostly unaffected after radiation. However, the reverse current and light intensity increase, indicating a deviation in the device performance. While InGaN LEDs are known to be relatively radiation-resistant compared to other semiconductor materials, this study highlights the importance of considering radiation effects when designing and operating devices in harsh environments such as space or high-energy particle accelerator facilities.

Adding to all these research papers, a review paper titled “Radiation-induced Degradation of Silicon Carbide MOSFETs -A Review” has also been published under this grant. This review provides an overview of what is currently known about the degradation and failure of SiC MOSFETs due to radiation. Published work has demonstrated that the properties of the SiC MOSFET were altered after irradiation. Radiation causes a decrease in the threshold voltage of a MOSFET. In addition to the threshold voltage, the capacitance and resistance also decrease after irradiation. Meanwhile, the leakage current and mobility mainly increase due to radiation. The primary method by which radiation can damage these devices is by causing flaws in the SiC crystal structure. Radiation can also alter the interface states and thickness of the gate oxide, which can worsen the device's performance. Despite these challenges, it has been demonstrated that SiC MOSFETs are found to be relatively radiation-hard, making them acceptable to.be use in high-radiation environments like space and nuclear power applications. The findings of this review are crucial for a comprehensive understanding of radiation degradation in Silicon Carbide MOSFETs. This knowledge can be used during device manufacturing and applications to mitigate the effects of radiation on SiC MOSFETs.

6. IMPACTS

The findings of the projects shows the limitation of the Inter-satellite Optical Wireless Communication (IsOWC) performance with electron radiation. It has been demonstrated experimentally the degradation of the transceiver and transmitter with various magnitude of electron radiation dose which translated into the bit-error-rate and and the Q factor of the communication link performance. This findings may assist engineers/scientist to estimate the possible risk of using AlGaAs and InGaAs lasers and photodiodes for satellite link communication with respect to electron radiation, thus make informed decision on the type of transmitter and receiver used. This will also encourage further research on better, radiation hardened transmitter and receiver when designing the the Inter-satellite Optical Wireless Communication link.

This project has allowed postgraduate students, postdoctoral fellow and undergraduate students to learn the technique and methodology of scientific research in particular on the Inter-satellite Optical Wireless Communication (IsOWC) performance and degradation of devices with radiation. The project also giving opportunities for the PI and coinvestigator to research more on the subjects and developing new knowledge in the areas.

The project did not apply for funding to buy equipment, only research consumables and paying for the human resource. In future, hopefully we can apply for funding to repair our aging photoluminescent setup which has broken recently. Nevertheless, the funding given is sufficient to ensure the completion of the project. We would like to express our heartfelt gratitude for funding this project.

6. CHANGES

We followed the methodology mentioned in the original proposal. We additionally add some publications related to the topic as can be seen in the list of publications. This is due to the postgraduate students are funded by AOARD. Some complications/problems faced during the project is that since the timing is during COVID/Post-Covid era, we have difficulty in finding the suitable research assistants for this project, particularly due to the nature of the project which requires knowledge in semiconductor/radiation physics and communication engineering. Many candidates are deterred due to this; however, we manage to find good students for completion of the project.

7. CONCLUSION

In conclusion, IsOWC systems are promising for future space missions due to their high data rates and low latency. However, they are susceptible to the effects of space radiation, which can cause damage to the semiconductor devices used in these systems. In this project, we investigated the effects of different types of radiation on IsOWC systems and semiconductor devices used. We found that radiation can cause significant degradation in the performance of IsOWC devices. The degradation in performance caused by radiation can lead to several problems for IsOWC systems including reduced data rates, increased bit error rates, and even a complete failure. Therefore, it is important to design IsOWC systems with radiation hardening in mind. This can be done by using radiation-tolerant devices, shielding the devices from radiation, and developing fault-tolerant system architectures. Our findings suggest that further research is needed to develop radiation hardened IsOWC systems and semiconductor devices for future space missions. Such research should focus on developing new radiation-tolerant semiconductor devices as well as new system architectures that are more resilient to radiation.