Design and Radiation Assessment of Optoelectronic Transceiver Circuits for ITER

P. Leroux\textsuperscript{a}, W. De Cock\textsuperscript{b}, M. Van Uffelen\textsuperscript{a}, M. Steyaert\textsuperscript{c}

\textsuperscript{a}Katholieke Hogeschool Kempen, ICT-RELIC, Kleinhoefstraat 4, B-2440 Geel, Belgium.
\textsuperscript{b}SCK-CEN, the Belgian Nuclear Research Centre, Boeretang 200, B-2400 Mol, Belgium.
\textsuperscript{c}Katholieke Universiteit Leuven, ESAT-MICAS, Kasteelpark Arenberg 10, B-3001 Heverlee, Belgium.

Abstract

The presented work describes the design and characterization results of different electronic building blocks for a MGy gamma radiation tolerant optoelectronic transceiver aiming at ITER applications. The circuits are implemented using the 70GHz f\textsubscript{T} SiGe HBT in a 0.35µm BiCMOS technology. A VCSEL driver circuit has been designed and measured up to a TID of 1.6 MGy and up to a bit rate of 622Mbps. No significant degradation is seen in the eye opening of the output signal. On the receiver side, both a 1GHz, 3kΩ transimpedance and a 5GHz Cherry-Hooper amplifier with over 20dB voltage gain have been designed.

I. INTRODUCTION

One of the most challenging environments with respect to ionizing radiation current electronic designers are facing is ITER (International Thermonuclear Experimental Reactor). In this nuclear fusion reactor, the requirements of integrated electronic circuits with respect to radiation tolerance are very severe. One of the applications in ITER where the radiation conditions are extreme is the maintenance of the diverter. This periodic task will need to be performed by remotely operated robots and its functionality could be improved by adopting a significant amount of on-board electronics. Several systems and circuits will need to remain operational even after exposure to a TID (Total Ionizing Dose) in the order of MGy. The anticipated gamma radiation levels are similar to those expected in the S-LHC. The design of these circuits is clearly very challenging. This paper will focus on the potential use of a bidirectional fiber optic communication link between the robotics operated inside the reactor vessel and the control room. More specifically we will present and discuss our recent results on the design and assessment of the radiation hard optical transceiver electronics. All circuits are designed in a 0.35µm BiCMOS technology.

Fig. 1 shows the schematic of a typical fibre optic link including the analogue front-end circuitry for both the transmitter and the receiver side. In previous work we designed and assessed a discrete driver for a VCSEL [6] on the transmitter side of the link. Even though this driver was sufficiently tolerant to radiation, it featured several shortcomings owing to its discrete nature: the inherent frequency performance is limited due to large circuit board parasitics, the complete circuit is rather area consuming which may complicate the mounting of the transmitter and the poor matching performance between the devices in circuit blocks like a differential pair and a current mirror limits the predictability and hence, the reliability of the driver.

The following transmitter section describes the design, simulation and measurement of a new and integrated VCSEL driver in a 0.35µm SiGe BiCMOS technology which no longer suffers previous shortcomings. The driver will operate at a power supply of 3.3 V and is intended to be used in combination with a 1550 nm VCSEL. The design is based on SPICE simulations using the model provided by the manufacturer but modified to include the dose dependent effects of gamma irradiation on the devices’ DC parameters. In the case of the driver, where only HBT’s are used, the model describes the influence of radiation on the base current of the SiGe HBT. Details on the model adaptations for this device are available in [12]. The model itself is based on a similar approach for a discrete SiGe HBT presented in [5].

On the receiver side several electronic building blocks have been designed in the same 0.35µm BiCMOS technology. The TIA (TransImpedance Amplifier) is the first block after the photodiode and converts the diode current into a voltage, sufficiently high above the noise floor of the subsequent PA (PostAmplifier). The TIA features a transimpedance gain of 3kΩ for a 1GHz bandwidth. The equivalent input noise current given by the integrated output noise voltage divided by the transimpedance gain is 0.6µA. The circuit was
designed taking transistor radiation effects into account. We included the previously measured degradation in the simulation via a DC SPICE model extension of the bipolar transistors. For the PA a sequence of differential bipolar Cherry-Hooper amplifiers was designed with a simulated bandwidth of 5GHz and a gain of 20dB per stage. These receiver circuits are currently being processed.

II. OPTICAL TRANSMITTER

For the transmitter side a driver was implemented for a long wavelength (1550 nm) VCSEL (Vertical Cavity Surface Emitting Laser). The schematic of the integrated VCSEL driver circuit is shown in Fig. 2 and is based on the discrete driver presented in [6]. The current through the VCSEL is composed of a constant DC current, to which we add a pulsed modulation current provided by the driver. A dummy resistor is placed symmetrically with respect to the VCSEL which improves the AC balance of the circuit since Q1a and Q1b now drive a similar load. Transistor Q2 acts as a current source which is biased by Q3 in diode configuration, hence creating a current mirror. R3 is an external potentiometer which allows to set the modulation current to the required level. This was done only once and no adjustment during irradiation is required. The supply is set at 3.3 V.

![Fig. 2: Schematic of the integrated SiGe VCSEL driver.](image)

The circuit was monitored before, during and after several Co60 gamma irradiation experiments up to a TID of 1.6 MGy. Fig. 3 shows the relative increase of the modulation current as a function of the accumulated dose. The modulation current displays a limited variation in the order of 0.1 % up to a dose of 600 kGy. The initial decrease is attributed to an increase in base current for the different transistors as evidenced by separate measurements on identical stand-alone transistors. For Q3 and Q2 the additional base current reduces the collector current for both transistors and hence decreases the modulation current through the driver.

The output current through the VCSEL is not only degraded by changes in the base current of Q2 and Q3. A fraction of the current is also lost in the base of Q1b. The initial decrease in modulation current is followed by an increase which is caused by the observed in-situ recovery of the devices during irradiation [12].

The design of the driver could principally be improved to render an even more stable output current, even during irradiation. The influence of the base current of Q2 and Q3 on the output current can be reduced by using an extra emitter follower Q4 in the current mirror to deliver the base current of both Q2 and Q3. This solution is depicted in Fig. 4. The influence of the base current changes of Q1a and Q1b could be counteracted by using a Darlington pair to substitute both transistors. The obvious downside of this solution is the effective doubling of the input transistors base-emitter voltage.

![Fig. 4: Improved current mirror topology with reduced current degradation under radiation.](image)

The measurement data have been confirmed with SPICE simulations based on the model described in [12]. The same initial decrease and subsequent increase in modulation current is observed. Note that the minimum in the modulation current, occurring at a dose of 80 kGy does not correspond to the maximum in base current, just before the onset of recovery. This difference may be attributed to a difference in measurement conditions. For the separate devices the pins were grounded between two consecutive measurements during irradiation. This was not possible for the driver where the connections to the different contact switches are much more complex. Also the driver continuously draws a current of a few mA when it is being measured where the devices were measured for a large current range which makes the
average current lower.

Fig. 5: Eye diagram of modulation current through the VCSEL after a dose of 1.6 MGy at 622 Mbps.

A second irradiation experiment has been performed to verify the operation of the driver up to a TID of 1.6 MGy and up to a bitrate of 622 Mbps. The resulting eye diagram is shown in Fig. 5. A photograph of the integrated driver, within a ceramic DIL40 package is depicted in Fig. 6.

Fig. 6: Photograph of an integrated SiGe VCSEL driver.

III. OPTICAL RECEIVER

Two crucial building blocks in the design of the receiver (Fig. 1) will be discussed: a differential bipolar transimpedance amplifier and a differential bipolar Cherry-Hooper amplifier which is used to construct the postamplifier.

Fig. 7 shows a simplified schematic of the transimpedance amplifier. It consists of a common-base input stage, formed by Q1, which decouples the input capacitance (including the diode capacitance and parasitic capacitance related to the connections to the IC) from the transimpedance feedback loop. This stage presents a current gain of almost 1. The second stage consists of a common-emitter stage formed by Q2 with shunt-shunt feedback resistor Rf. The transimpedance gain of the circuit can be approximated by 2Rf. The bandwidth of the circuit is determined by the base node of Q2. On this node, the resistance needs to be sufficiently high to keep the GBW (gain bandwidth) of the loop sufficiently below the output pole of the open loop system in order to guarantee the system stability:

$$BW = \frac{1 + g_{m2}R_2}{2\pi C_{gs} \left( R_f \parallel R_f \right)}.$$  

(1)

Notice that both for achieving high gain and good stability the value of Rf will be chosen sufficiently high. The low frequency noise contributions referred to the input of the circuit are given by

$$\overline{i_{n,in}^2} = 2kT\Delta f \left( \frac{1}{R_1} + \frac{1}{R_1} + \frac{R_{b1}}{R_f} + \frac{1}{R_f} \right),$$  

(2)

where rb1 is the parasitic base resistance of Q1. This expression shows the main drawback of adding a common base input stage as it reduces the noise performance by the first three terms in equation (2). Even though Rf can be chosen larger the overall noise performance will still be degraded.

Fig. 7: Differential bipolar transimpedance amplifier.
A combined noise transient simulation was used to verify the behavior of the driver at different dose levels and for different currents. No significant degradation is observed in these simulations. An eye diagram of the output signal is shown in Fig. 10, where the input was a 1 Gbps 2^7-1 PRBS current of 30 µA.

Fig. 11: Differential bipolar Cherry-Hooper amplifier stage.

A combined noise transient simulation was used to verify the behavior of the driver at different dose levels and for different currents. No significant degradation is observed in these simulations. An eye diagram of the output signal is shown in Fig. 10, where the input was a 1 Gbps 2^7-1 PRBS current of 30 µA.

Fig. 11: Differential bipolar Cherry-Hooper amplifier stage.

A combined noise transient simulation was used to verify the behavior of the driver at different dose levels and for different currents. No significant degradation is observed in these simulations. An eye diagram of the output signal is shown in Fig. 10, where the input was a 1 Gbps 2^7-1 PRBS current of 30 µA.

Fig. 11: Differential bipolar Cherry-Hooper amplifier stage.

A combined noise transient simulation was used to verify the behavior of the driver at different dose levels and for different currents. No significant degradation is observed in these simulations. An eye diagram of the output signal is shown in Fig. 10, where the input was a 1 Gbps 2^7-1 PRBS current of 30 µA.

Fig. 11: Differential bipolar Cherry-Hooper amplifier stage.

A combined noise transient simulation was used to verify the behavior of the driver at different dose levels and for different currents. No significant degradation is observed in these simulations. An eye diagram of the output signal is shown in Fig. 10, where the input was a 1 Gbps 2^7-1 PRBS current of 30 µA.
Fig. 12 shows the voltage gain of the amplifier stage as a function of frequency for total ionizing dose levels from 0 Gy up to 300 kGy. With respect to the bandwidth of the circuit, the same behavior is observed as described for the transimpedance amplifier, i.e. an initial reduction followed by recovery owing to a reduced current through the amplifying device. In this circuit however also a minor gain degradation is observed owing to the dependence of the gain on $g_{ml}$ and hence on the current through $Q_1$ which is degraded in the same manner as $Q_2$. The gain remains between 21.5 dB and 22 dB and the bandwidth stays larger than 5 GHz inspite of radiation.

A noise transient analysis was performed on the cascade of the transimpedance and Cherry-Hooper amplifier and a typical result is shown in Fig. 13. The same input current of $30 \mu A$ was used as for the TIA alone. Notice by comparison with Fig. 10 that the SNR of the signal is almost not degraded by the post-amplifier owing to the large gain of the TIA. Results with increasing dose levels are similar.

IV. CONCLUSION

We have presented recent design and characterization results on the most critical electronic building blocks in a MGy radiation tolerant optoelectronic transceiver for application in ITER. All circuits were designed in a 0.35µm SiGe BiCMOS technology using only the nnp HBT devices. Simulations were performed using the model provided by the manufacturer but adapted to include their radiation dependent current gain degradation.

At the transmitter side, a VCSEL driver has been designed, simulated and measured before, during and after irradiation up to 1.6 MGy. No significant degradation is seen up to these dose levels and for a bitrate up to 622 Mbps.

At the receiver side a fully differential transimpedance amplifier has been designed and simulated. The circuit features a gain of 3.2 kΩ, a bandwidth of 1 GHz and an input current sensitivity of 2 µA at an SNR of 10. The TIA is followed by a Cherry-Hooper based differential amplifier with a voltage gain of more than 21 dB and a bandwidth surpassing 5 GHz. Both circuits feature a degradation of only a few percent for a gamma dose up to 600 kGy.

V. REFERENCES