Development of a radiation tolerant VCSEL-based transmitter with discrete COTS components

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Radiation tolerant fibre optic transmission links are considered for possible applications in future thermonuclear fusion reactors. We design and test a radiation resistant transmitter based on 840 nm VCSELs and dedicated driver electronics with discrete commercial-off-the-shelf (COTS) bipolar transistors. We experimentally confirm the high radiation acceptance level of VCSELs up to a 10 MGy total dose. Both SPICE simulations and experiments show that the driver still delivers a sufficient forward current to the VCSEL, in spite of the radiation induced degradation of the transistors. Hence, a robust optical transmitter for use in nuclear environments can be fabricated using commercially available bipolar transistors, VCSELs and optical fibres.

Introduction

The successful remote operation of equipment for maintenance and diagnostics tasks in the future Iternational Thermonuclear Experimental Reactor (ITER) requires the development of transmission links that can withstand high total doses, ranging from 1 to 100 MGy, depending on the particular working conditions [1]. Fibre-optic technology has seen a growing interest from this community and from the nuclear industry in general, since it could offer a radiation tolerant, electromagnetic insensitive transmission medium for both data-communication and sensing purposes with multiplexing possibilities. The transmission of multiplexed data over optical fibres would be an essential asset to ease the management of the umbilical cabling between the handling tools and the remote control equipment [2].

Most reported data on radiation tolerance of opto-electronic components concern only individual optical parts (fibres, emitter, receivers, etc). Very often, however, the driving electronics for controlling the optical link is omitted. Commercial-off-the-shelf drivers are usually sensitive to radiation and compromise the possible application of optical fibre communication systems in harsh nuclear radiation environments, particularly when high total dose levels are of concern. In this paper, we therefore attempted to design a complete radiation tolerant transmitter, using the vertical-cavity surface-emitting laser (VCSEL) and a dedicated electronic driver circuit.

Radiation tolerant VCSEL driver

A driver is required to convert sensor information, which we will assume to consist of TTL-type signals, to appropriate forward current pulses for a VCSEL to emit the optical signals which can then be transmitted over an optical fibre link outside the radiation field. Such an integrated circuit able to withstand a total dose in excess of 1 MGy is not commercially available. Therefore, we chose to design a VCSEL driver circuit, based on discrete COTS bipolar transistors, allowing very high radiation hardness at the cost of limited but acceptable bandwidth of several MHz. In addition, VCSELs can be easily driven without pre-bias at such a frequency. The changes of the transistor parameters with total dose are introduced in a SPICE transistor model by adding time dependent elements.

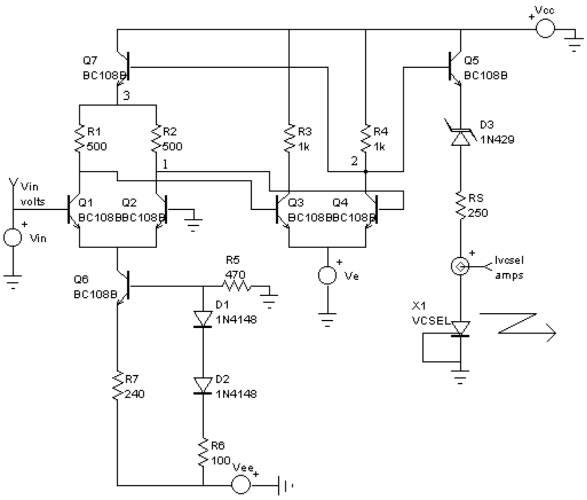

Figure 1 : VCSEL driver circuit scheme consisting of a current source and a differential amplifier stage.

Our driver scheme consists of a current source and a two-stage differential amplifier with a positive feedback, as shown in Figure 1. The values of the different elements were calculated such that a TTL-type input to the driver would generate a forward current delivered to the VCSEL of about 12 mA, as specified by the manufacturer. The operation of the circuit was simulated with SPICE software. According to these results, the forward current delivered to the VCSEL decreases by about 20 % at a cumulated dose of a about 20 kGy and remains constant for higher doses. This decrease can be anticipated into the initial design, without exceeding the driving specifications of the VCSELs. Three identical driver circuits (cf. Figure 2) were then irradiated in a ^{60}Co gamma facility (SCK·CEN, Belgium). The forward current I_f delivered to the VCSELs was measured off-line after subsequent total dose steps of 9 kGy, 92 kGy, 505 kGy and 1 MGy. The dose-rate was 5 kGy·h^{-1} for the first two and 10 kGy·h^{-1} for the two last dose steps. During the subsequent irradiations, the driver components were left unbiased and ungrounded. After a total dose of 1 MGy, I_f dropped by about 8 % (cf. Figure 3), which is better than the estimate given by the SPICE simulation. At a cumulated dose of 10 MGy, however, we observe a further decrease of the delivered current, down to a loss of about 35 %.

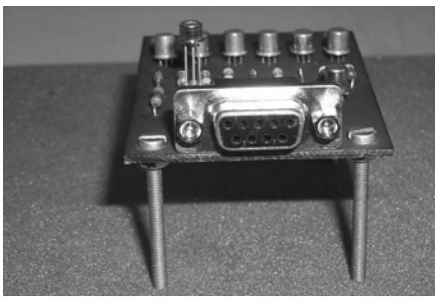

Figure 2 : Driver circuit on polyimide backed PCB

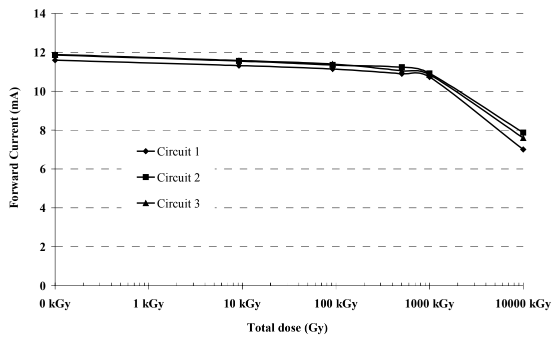

Figure 3 : Forward current measured at 1 MHz on three identical VCSEL driver circuits as a function of total dose at specific total dose values.

The difference between the simulation and the experiment can be explained by the difference in the experimental conditions for which the individual transistor degradation data (used as simulation parameters) were collected and those for which our results are valid (off-line measurements, unbiased components during irradiation and different dose-rate). From these results, one can also conclude that the bandwidth of these driving circuits remains practically unchanged, even at 10 MGy (not shown here), as the pulse with is unaffected upon these total doses.

Radiation tolerant transmitter assembly

In literature, different reports indicate the excellent resistance of VCSELs exposed to a variety of radiation conditions (see e.g. [3]). This can be explained by their small active area, the large operating current density and the short carrier lifetime, which limit the effect of radiation induced defects. Packaging of these devices might be an important issue. The use of a lens to optimise the coupling of the VCSEL optical power into an optical fibre connector has shown to be detrimental in terms of radiation induced loss [4]. Therefore, we believe that such devices pigtailed with COTS radiation resistant optical fibres might be a valid alternative to construct a radiation-hardened optical emitter assembly.

Four MITEL 1A440® VCSELs were packaged in a metal housing containing a 2 mm diameter glass ball lens that couples the optical power emitted by the VCSEL into a 100 μm core SPECTRAN TCG®-type pure silica fibre. The selection of this fibre follows from its well-established radiation tolerance [5]. These assemblies were irradiated in a ^{60}Co gamma facility (SCK·CEN, Belgium) at a dose-rate of 15 kGy·h^{-1} up to a total dose of 10 MGy(H_2O) and a constant temperature of 60 °C ± 1 °C.

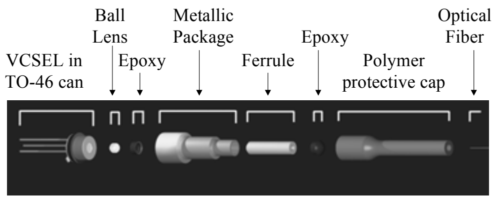

Figure 4 : Exploded view of a pigtailed VCSEL under test, showing the different parts of the assembly.

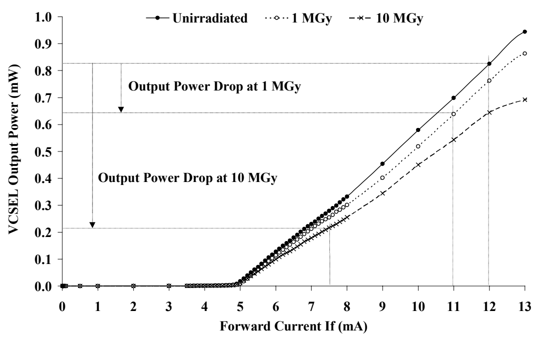

Figure 5 : P-I characteristics of a VCSEL assembly at 0 Gy, 1 MGy and 10 MGy (60 °C). The arrows show the total optical output power decrease due to the radiation effects on both the driver current and the VCSEL.

Figure 5 shows the P-I characteristic of a VCSEL at a number of total dose values. The measured output powers, which are compensated for the induced loss in the optical fibre leads, remain limited to a few percent. After a relatively rapid growth of the radiation induced loss at the early stages of the irradiation (< 100 kGy), which is ascribed to the induced attenuation in the ball lens, the output power monotonously decreases with dose. Within the measurement uncertainty of ± 0.1 mA, the threshold current remains constant even at total doses in excess of 6 MGy, which contradicts the results of earlier off-line measurements [6]. The electrical characteristics of the VCSELs were found to be very stable, even at the highest total dose. Hence, we do not expect an important degradation of their high speed performances. From the limited power loss, the acceptable decrease of the slope efficiency, the stability of the threshold current and the unchanged voltage - forward current characteristics, we confirm that these pigtailed devices are radiation tolerant up to a total dose of 10 MGy.

To estimate the effect of a total gamma dose on a transmitter consisting of our driver and a pigtailed VCSEL, we can rely on the characteristics measured at that dose for both sub-assemblies (cf. Figure 5). For example, a radiation induced forward current drop combined with the optical power loss of a VCSEL, results in a decrease of 22 % (1.1 dB) of optical power injected in the fibre at a cumulated dose of 1 MGy. Such optical output power drops can still be taken into account in the power budget of the transmission link. Removing the focusing lens in the emitter assembly could further limit the radiation induced losses and render it more robust, yet at the expense of a serious reduction of available output power – only about 1 % of the available optical power would be injected in the 100 µm core. At a total dose of 10 MGy, we expect a total decrease of the transmitter output of 75 % (6.1 dB). Hence, at these total dose levels, the signal-to-noise level of this assembly becomes seriously degraded. The contribution of the optical losses in the laser assembly becomes small compared to the loss of forward current in the driving circuit. One should therefore redesign the laser driver circuit if a higher dose acceptance level is required [7].

Summary

We designed a gamma radiation tolerant driver circuit for 840 nm VCSELs, based on discrete bipolar transistors. Considering the limited influence of gamma rays on both the driver circuit and the VCSELs, we can conclude that it is feasible to construct an elementary optical transmitter using COTS devices with a resistance to gamma radiation levels in excess of 1 MGy and a satisfactory bandwidth of several MHz for operation in many nuclear instrumentation schemes. Moreover, SPICE simulations on an adapted circuit design have already shown the feasibility to exceed a dose tolerance of 10 MGy and obtain a (theoretical) GHz bandwidth.

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