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rPOL2V5 a compact radiation-hard resonant switched-capacitor DC-DC converter for the CMS HGCAL

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Abstract

A radiation-tolerant resonant switched-capacitor DC-DC converter (rPOL2V5) has been developed to supply the front-end analog and digital circuits for the detectors used in the LHC High Luminosity upgrades. It has been of particular interest to the CMS High-Granularity Calorimeter (HGCAL) community due to its lower volume compared to existing radiation-hard buck converters. rPOL2V5 is based on an ASIC developed using 130 nm CMOS technology. It is powered by a 2.5V input and it can supply a maximum current from 2A to 5A, depending on the output voltage value, which can range from 1V to 1.5V. This work presents the strategies adopted at the ASIC and PCB level to bring the converter to maturity, and its electrical and radiation characterisation results.

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rPOL2V5: a compact radiation-hard resonant switched-capacitor DC-DC converter for the CMS HGCAL

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ABSTRACT: A radiation-tolerant resonant switched-capacitor DC-DC converter (rPOL2V5) has been developed to supply the front-end analog and digital circuits for the detectors used in the LHC High Luminosity upgrades. It has been of particular interest to the CMS High-Granularity Calorimeter (HGCAL) community due to its lower volume compared to existing radiation-hard buck converters. rPOL2V5 is based on an ASIC developed using 130 nm CMOS technology. It is powered by a 2.5 V input and it can supply a maximum current from 2 A to 5 A, depending on the output voltage value, which can range from 1 V to 1.5 V. This work presents the strategies adopted at the ASIC and PCB level to bring the converter to maturity, and its electrical and radiation characterisation results.

KEYWORDS: Radiation-hard electronics, Analogue electronic circuits, Voltage distributions

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1 Introduction

rPOL2V5 is a radiation-hard resonant switched-capacitor DC-DC converter, which can be adopted in a two-stages power distribution scheme proposed for the High-Luminosity Large Hadron Collider experiments [1]. It is a second-stage converter that steps down the voltage from 2.5 V to an adjustable output voltage in the range 1-1.5 V, providing a maximum output current that depends on the output voltage value, in the range 2-5 A. The converter's module hosts an ASIC designed using 130 nm CMOS (which includes the power switches and the control circuitry) and discrete components such as capacitors and inductors [2].

Resonant switched-capacitor (ReSC) converters are derived from switched-capacitor (SC) converters. Compared to their SC counterparts, they feature an additional inductor to suppress the charge redistribution losses and therefore boost the efficiency [3–6]. Compared to inductor-based solutions such as a buck converter, ReSC converters exploit the high energy density of capacitors to allow a reduction in the converter volume. Indeed, the area occupied by both rPOL2V5 and bPOL2V5 (its radiation-tolerant buck counterpart) is about 250 mm², yet rPOL2V5 features a small 12 nH inductor (1.83 mm high), while bPOL2V5 uses a 100 nH inductor whose profile height is of 4.2 mm. Thanks to its compactness, rPOL2V5 is of interest for environments with challenging space constraints, such as the CMS High-Granularity Calorimeter [7].

The harsh environment of HGCAL is characterized by a large magnetic field (up to 3.8 T) and challenging radiation levels, with a total ionizing dose (TID) exceeding 200 Mrad and a neutron fluence up to $8 \cdot 10^{15}$ 1 MeV neq cm⁻². Therefore, the converter is equipped with an air-core inductor to be compliant with the magnetic field, while hardening by design techniques have been adopted for the ASIC design. In particular, enclosed layout transistors have been used to avoid TID-induced leakage currents, while triplication of the most important control circuitry has been adopted to protect the ASIC from single event effects up to a linear energy transfer of 40 MeV cm² mg⁻¹.

The first prototype of rPOL2V5 proved the effectiveness of its novel multi-mode control strategy and the tolerance of the converter to a TID of 220 Mrad [2, 8, 9]. Those studies revealed that the initial version of the rPOL2V5 did not always operate reliably and it had a sub-optimal efficiency in certain operating conditions. The work described in this paper focuses on the second prototype of rPOL2V5, which has been designed to improve these aspects and bring the converter to maturity.

The design strategies adopted at the ASIC and PCB level are presented, as well as the electrical and radiation characterisation results of this new prototype.

2 Prototype development

The rPOL2V5 ASIC features four power switches that are controlled by two signals, PWMH and PWML, which are generated by the control circuitry, see Figure 1a. To achieve output voltage regulation, the controller tunes the phase shift between PWMH and PWML, which in turn leads to a change in the switching frequency of the converter in the range 200 kHz – 10 MHz. In order to achieve output voltage regulation for a wide range of conversion ratios and to boost the light-load efficiency, the controller uses different modes of operation (more details are presented in [2, 9]).

Figure 1: (a) Schematic of the power stage of rPOL2V5 including the parasitic inductances, (b) picture of the rPOL2V5 test module and of the flip chip ASIC, and (c) parasitic inductance values extracted from the different PCB designs described in this paper.

Due to the pulsed nature of the currents flowing in the input and output of the converter, at each switching cycle the parasitic inductances associated to the $V_{in} - GND$ and $V_{out} - GND$ paths (see Figure 1a) experience large current variations, $\frac{dI}{dt}$, thus generating large voltage spikes on the power transistors. Since these spikes might exceed the voltage rating of the power devices, it is important to minimize the parasitic inductances associated with the PCB and the chip connections (L_{par}). For this reason, the ASIC adopts a flip chip assembly (see Figure 1b) and the PCB has been carefully designed to minimize unwanted inductances.

During the characterisation of the first rPOL2V5 prototype (rPOL2V5_V1), several issues were highlighted: unreliable transitions between the different operation modes of the controller; a malfunctioning of the controller that prevented the converter from working properly for $V_{out} > \frac{V_{in}}{2}$; and overshoots on V_{out} during the startup at light loads. These issues have been addressed in this work by designing an improved controller for the second prototype ASIC (rPOL2V5_V2).

In addition, the PCB design of the test module has been optimised. Two different variants of the PCB have been designed. The first features the same technology as the original test board (copper filled laser drilled microvias in pad) to achieve an optimal reduction of the parasitics, while the second features only simple mechanically drilled through vias to ease manufacturing constraints and decrease production cost. Mechanical vias result in a reduction of cost by 30% and ensure

higher production yields. Figure 1c compares the parasitic inductance values extracted from the different PCB designs. The laser microvia test board variant achieved almost a 50% reduction of the parasitic inductances as compared to the original design. However, the mechanical via variant still shows a significant reduction of the parasitic inductances, while also ensuring a lower cost of production.

3 Experimental results

During the electrical characterisation of rPOL2V5_V2, both variants of the module were successfully tested. The main changes introduced in the controller guarantee a safe operation of the converter and smooth transitions between the operating modes. The control circuitry is still affected by a malfunctioning that can be solved by introducing a minor modification.

The ASIC controller features a protection that limits the amplitude of the current flowing in the power stage to ensure the reliability of the chip. The triggering of this protection reduces V_{out} and the converter stops regulating. Since the protection intervenes at different load current points depending on the conversion ratio ($\frac{V_{out}}{V_{in}}$), the maximum current provided by the converter depends on V_{out} and V_{in} , as shown in Figures 2, 3.

Figure 2: Efficiencies measured at room temperature with $V_{in} = 2.5$ V for various V_{out} , for (a) the variant featuring laser microvias and (b) the variant using mechanical vias.

Due to its architecture, rPOL2V5 ensures the best performances when the conversion ratio ($\frac{V_{out}}{V_{in}}$) is equal to 0.5 or slightly lower. Therefore, considering $V_{in} = 2.5$ V, the converter achieves higher efficiency and reaches a higher maximum load current when $V_{out} < 1.2$ V, as shown in Figure 2. Indeed, as shown in Figure 2a, the laser microvia module can regulate the output voltage up to $I_{out} = 4$ A with an efficiency of 79.6% when $V_{out} = 1.1$ V, and up to $I_{out} = 5$ A with an efficiency of 78.3% when $V_{out} = 1$ V, while it cannot achieve output voltage regulation at $I_{out} = 3$ A when $V_{out} > 1.2$ V. A comparison of Figures 2a and 2b shows that the test module featuring the laser microvia PCB variant achieves higher efficiencies at high load currents as compared to the mechanical via variant. Still, the mechanical via variant module achieves output voltage regulation in a similar range of load currents and comparable peak efficiencies: 89% at $I_{out} = 1.4$ A, $V_{out} = 1.2$ V and 86.5% efficiency at $I_{out} = 1.9$ A, $V_{out} = 1.1$ V.

Figure 3: Efficiencies measured on a laser microvia module at room temperature for various V_{in} with (a) $V_{out} = 1V$ and (b) $V_{out} = 1.4V$.

As shown in Figure 3a, when $V_{out} = 1V$, the converter achieves high efficiency and high maximum load current also for $V_{in} < 2.5V$, since the conversion ratio is < 0.5 . Indeed, the tested laser microvia module ensures output voltage regulation above 3 A even for $V_{in} = 2.2V$, while reaching 87.1% efficiency at $I_{out} = 2.5A$, $V_{in} = 2.3V$ and 84.4% efficiency at $I_{out} = 3.5A$, $V_{in} = 2.4V$. For $V_{out} = 1.4V$ (see Figure 3b), the efficiency and the maximum load current drop critically when $V_{in} < 2.5V$, due to the high conversion ratio.

Figure 4: (a) Output voltage monitoring during the TID irradiation at room temperature on a laser microvia module with $I_{out} = 2A$. (b) Efficiency measurements done before and after the irradiation with $V_{in} = 2.5V$, $V_{out} = 1.2V$.

A TID irradiation campaign has been performed by exposing the rPOL2V5_V2 ASIC to X-rays. Two modules have been irradiated, one for each PCB variant. Both converters were fully functional after an exposure to 200 Mrad of TID. Figure 4a shows that during the irradiation the output voltage regulation has not been affected by the TID. Measurements presented in Figure 4b show that TID induces a strong degradation of the converter efficiency immediately after the end of the irradiation (red curve), in particular for high load currents. Nevertheless, the efficiency curves obtained after 1 week and 1 month of annealing at room temperature highlight that the converter recovers more than 50% of its performance.

4 Outlook and conclusion

rPOL2V5 is a radiation-tolerant 2.5V step down resonant switched-capacitor converter that has been developed to supply the front-end electronics of the HL-LHC experiments. This work presents the development as well as the characterisation results of the second prototype of this converter. The characterisation campaign highlighted how the modifications introduced at the ASIC design level in the controller contributed to guarantee a safe and reliable operation of the converter. Although a few minor modifications are still required, this second prototype brings rPOL2V5_V2 close to production readiness. Moreover, the PCB hosting the ASIC has been studied and improved to guarantee the chip reliability. Two different variants of the module have been successfully tested. The laser microvia module guarantees an optimal reduction of the parasitic inductances and reaches the best result in terms of efficiency, while the mechanical via PCB represents a cheaper, still fully functional solution. rPOL2V5 achieves the best results when $V_{out} < 1.2$ V, even at high load current (above 3 A), reaching an efficiency of 81.5% at $V_{out} = 1$ V, $I_{out} = 4.5$ A, and 83% at $V_{out} = 1.1$ V, $I_{out} = 3.5$ A with $V_{in} = 2.5$ V. Even at lower input voltages, when $V_{out} = 1$ V the converter achieves 84.7% efficiency at $I_{out} = 3$ A, $V_{in} = 2.4$ V and 87.1% at $I_{out} = 2.5$ A, $V_{in} = 2.3$ V. The converter has been successfully tested with TID up to 200 Mrad, and it shows a significant recovery of the damage induced by TID after one month of annealing. In order to complete the radiation characterisation, it remains necessary to perform displacement damage and SEE tests.

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