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Design of a Radiation-Tolerant Thermal Control Unit for Silicon Photonics Modulators in 28-nm CMOS Technology

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High-energy physics experiments require radiation-tolerant optical links for high-speed data communication. Ring modulators offer high bandwidth but are sensitive to temperature and process variations, necessitating thermal control to stabilize their resonant wavelengths. This work presents a radiation-tolerant thermal control unit designed for micro-ring modulators. The system integrates a first-order delta-sigma ADC to monitor photodiode current, a digital controller, and a high-resolution delta-sigma DAC driving a micro-heater. Simulations demonstrate that the ADC achieves over 60 dB SNR, while the DAC enables temperature control with 0.38 °C resolution. These results establish a foundation for reliable thermal management in high-speed, radiation-tolerant optical links.

Summary (500 words)

Optical communication systems have been essential to the operation of LHC detectors and will remain critical in future high-energy physics (HEP) experiments. Next-generation detectors will demand significantly higher data transmission rates and greater radiation tolerance. Meeting these requirements calls for optoelectronic components with radiation tolerance levels comparable to those of the readout circuits. While vertical-cavity surface-emitting lasers (VCSELs) and edge-emitting lasers (EELs) offer limited radiation tolerance (approximately 1 MGy), Silicon Photonics (SiPh) devices, such as ring modulators, are emerging as promising alternatives offering improved radiation hardness, higher bandwidth, and greater data throughput per fiber.

However, the resonant wavelength of ring modulators is sensitive to process and temperature variations. Therefore, ring modulators are typically designed with integrated heaters to control the temperature around the ring and stabilize its resonant wavelength. Furthermore, photodetectors are required to sense the optical power absorbed by the ring modulator.

In this work, we present a radiation-tolerant thermal control unit for micro-ring modulators. A block diagram of the temperature control unit is shown in Fig. 1. It includes a current-input analog-to-digital converter (ADC) to sense the output current of the photodetector and an output driver to inject a current through the heater, thereby controlling the resonant wavelength of the ring modulator. Closed-loop temperature control is necessary to compensate for dynamic resonance shifts due to circuit operation and total ionizing dose (TID). The temperature control is implemented in the digital domain using a proportional-integral-derivative (PID) controller and a digital-to-analog converter (DAC) to regulate the output power. The purpose of this unit is to ensure a well-defined and stable resonant frequency of the ring modulators, compensating for their intrinsic temperature sensitivity.

The architecture in Fig. 1 has been studied through mathematical modeling and simulations. The analog-to-digital converter is implemented as a first-order 1-bit delta-sigma modulator and includes a custom input stage for signal conditioning and anti-aliasing filtering.

The signal conditioning block can accept a maximum input current of 1 mA and can be configured to provide a tunable current gain to match the full-scale range of the delta-sigma modulator. The ADC achieves a signal-to-noise ratio (SNR) exceeding 60 dB, corresponding to approximately 10-bit effective resolution.

The DAC and output driver should supply a maximum output power of 80 mW to cover the full spectral range of the ring modulators with a resolution of at least 100 μ W, corresponding to a 0.38 °C temperature resolution.

The DAC also employs delta-sigma modulation to enhance resolution using a 6-bit quantizer, and the output driver provides an output power proportional to the DAC digital input.

This work lays the foundation for robust, high-precision thermal control in future radiation-tolerant, high-speed optical links for HEP applications.

Author: ATZENI, Gabriele

Co-authors: KLEKOTKO, Adam; CIARPI, Gabriele (CERN); RODRIGUES SIMOES MOREIRA, Paulo (CERN); BIEREIGEL, Stefan (CERN); KULIS, Szymon (CERN)

Presenters: ATZENI, Gabriele; CIARPI, Gabriele (CERN)

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