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A system-level model for high-speed, radiation-hard optical links in HEP experiments based on silicon Mach-Zehnder modulators

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ABSTRACT: Silicon Mach-Zehnder modulators have been shown to be relatively insensitive to displacement damage beyond a 1-MeV-equivalent neutron fluence of $3 \cdot 10^{16}$ n/cm^2. Recent investigations on optimized device designs have also led to a high resistance against total ionizing dose levels of above 1 MGy. Such devices could potentially replace electrical and/or optical links close to the particle interaction points in future high energy physics experiments. Since they require an external continuous-wave light source, radiation-hard optical links based on silicon Mach-Zehnder modulators need to have a different system design when compared to existing directly modulated laser-based optical links. 10 Gb/s eye diagrams of irradiated Mach-Zehnder modulators were measured. The outcomes demonstrate the suitability for using these components in harsh radiation environments. A proposal for the implementation of silicon Mach-Zehnder modulators in CERN's particle detectors was developed and a model to calculate the system performance is presented. The optical power budget and the electrical power dissipation of the proposed link is compared to that of the upcoming Versatile Link system that will be installed in 2018.

KEYWORDS: Optical detector readout concepts; Radiation damage to electronic components; Radiation-hard electronics

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Contents

1 Introduction

Silicon Photonics (SiPh) is currently being investigated as an alternative to directly modulated laser-based radiation-hard optical links [1]. The possibility of integrating SiPh devices with electronics and/or silicon particle sensors and an insensitivity of SiPh transmitters to a 1-MeV-equivalent neutron fluence of above $3 \cdot 10^{16}$ n/cm^2 makes this technology particularly interesting for potential use close to the paticle interaction points in future High Energy Physics (HEP) experiments. In addition to the high tolerance to displacement damage, results on silicon Mach-Zehnder Modulators (MZMs) resistant to a Total Ionizing Dose (TID) of greater than 1 MGy have recently been published [2]. This progress demonstrates that SiPh devices can withstand the expected harsh radiation levels in future HEP experiments.

Considerations regarding how SiPh-based optical links could be implemented into a system therefore need to be addressed, particularly because they will significantly differ from the existing systems. The main difference will be that instead of using directly modulated lasers, SiPh-based systems will employ an indirect modulation scheme for which an external light source is required to feed light into the MZMs.

In this paper, we demonstrate first that previously designed SiPh MZMs can support a 10 Gb/s data transmission rate after having been irradiated and we propose a revised MZM design on which radiation-hard SiPh-based optical links for the upstream path in HEP experiments could be built upon. We introduce an analytical model to evaluate the system performance with and without taking radiation into account and we estimate the electrical power consumption of such a link. The proposed link is compared to the specifications of the Versatile Link project [3], for which radiation-hard directly modulated laser-based optical links were used.

2 Dynamic performance

SiPh MZMs with different design parameters were designed [4] and statically tested for their radiation hardness [2]. The radiation hardness of SiPh MZMs can be improved by reducing the etch depth of the optical waveguide from "deep etch" to "shallow etch". In addition, samples having a 2× higher doping concentration in the pn-junction incorporated into the waveguide also resist to higher TID levels than MZMs with nominal doping.

Now, the high-speed performance of irradiated SiPh MZMs was tested and compared to results obtained from reference samples in order to assess how the radiation-induced phase shift degradation affects the transmitted data signal. It is important to note that due to lack of time, the design of the tested MZMs has not been optimized for high-speed performance, i.e. no impedance- and velocity-matched high-speed electrodes nor a $50\,\Omega$-termination load were incorporated in the MZM designs. The measured absolute performance thus is not representative for a device as it would be installed in an actual link. However, a qualitative comparison between identical devices before and after irradiation can nonetheless be carried out.

A PRBS7 signal created with an *Agilent N4903B J-BERT* was used for the optical eye diagram measurements. The MZMs were driven with a single-ended drive signal boosted by an RF amplifier to an amplitude of $V_{\text{pp}} = 3.5\,\text{V}$. A bias-tee was inserted after the RF amplifier to set the DC-bias voltage to $-3\,\text{V}$ and ensure reverse bias during modulation. The signal was applied to the MZMs through a *Cascade Infinity* RF probe. The wavelength of the optical carrier signal was set to the quadrature point of the MZM under test. The modulated optical signal was detected with a *New Focus 1544-A* photo diode connected to an *Agilent DSA 91204A Digital Signal Analyzer*.

Measured eye diagrams at $10\,\text{Gb/s}$ of a reference and irradiated shallow etch MZM with nominal doping are shown in figure 1. No significant change in the eye opening after irradiation can be observed. The irradiated sample received an accumulated TID of 2655 kGy. At the end of the irradiation, its phase shift reduced to 34 % of its pre-irradiation value. Afterwards it recovered to 85 % at room-temperature annealing before the eye measurement was performed. In contrast,
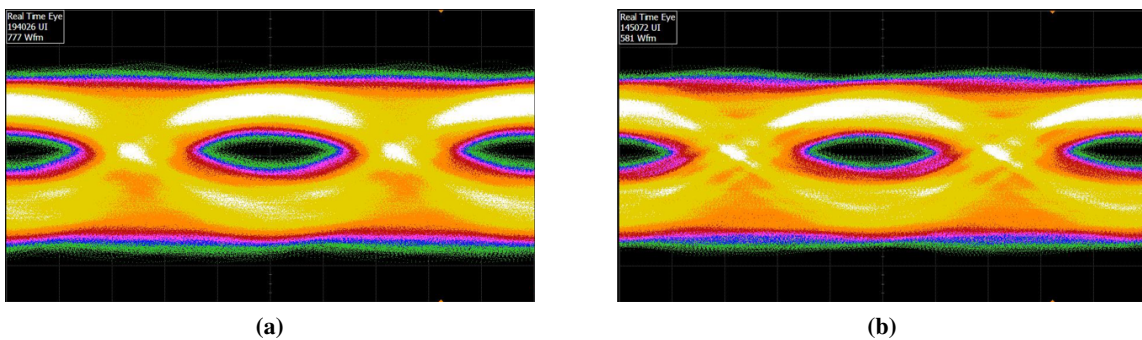

<div align="center">(a)   (b)</div>

Figure 1. Measured eye diagrams at $10\,\text{Gb/s}$ of a reference (a) and irradiated (b) shallow etch MZM with nominal doping concentration. The corresponding Optical Modulation Amplitude for both eye diagrams was calculated to be approx. $-10\,\text{dBm}$. Note that this particular MZM design was not optimized for high-speed performance. Representative eye diagrams for high-speed-optimzied building blocks are shown in the inset of figure 3.

it was not possible to measure an open eye after irradiation and annealing of a deep etch MZM with nominal doping even though its phase shift recovered from zero to 96 % compared to the pre-irradiation value. We conclude that although the DC-performance of MZMs anneals after irradiation, their post-irradiation RF-performance depends on whether the phase shift dropped to zero or not during irradiation. One can thus infer that the data transmission signal of an MZM does not critically degrade as long as the phase shift of the device is not entirely eliminated by radiation.

3 Proposal for revised MZM design and system model

The eye diagram measurements showed that SiPh MZMs can support a 10 Gb/s data rate after irradiation. As the tested MZMs were neither optimized for high-speed operation nor for a system implementation, another MZM design will be required before an actual link based on these devices can be tested. A schematic of the proposed MZM design is shown in figure 2. In particular, a revised MZM design will need to include properly designed high-speed electrodes, an on-chip termination load as well as a biasing control mechanism. The latter is necessary in order to be able to set and maintain the quadrature point of the MZM in case of temperature variations or drifts in the lasing wavelength during operation. The quadrature point can be set by an extra phase shift that is continuously adjusted through a feedback-loop depending on two control signals, one tapped where the light enters the MZM and one tapped after the heater. In commercial devices, this phase shifter is often realized by implementing a pin-diode. In a radiation environment, however, the intrinsic region of a pin-diode will become p-type [5] and thus lose its phase shifter function. For this reason, we propose to employ a thermo-optic heater as additional phase shifter as it should not be affected
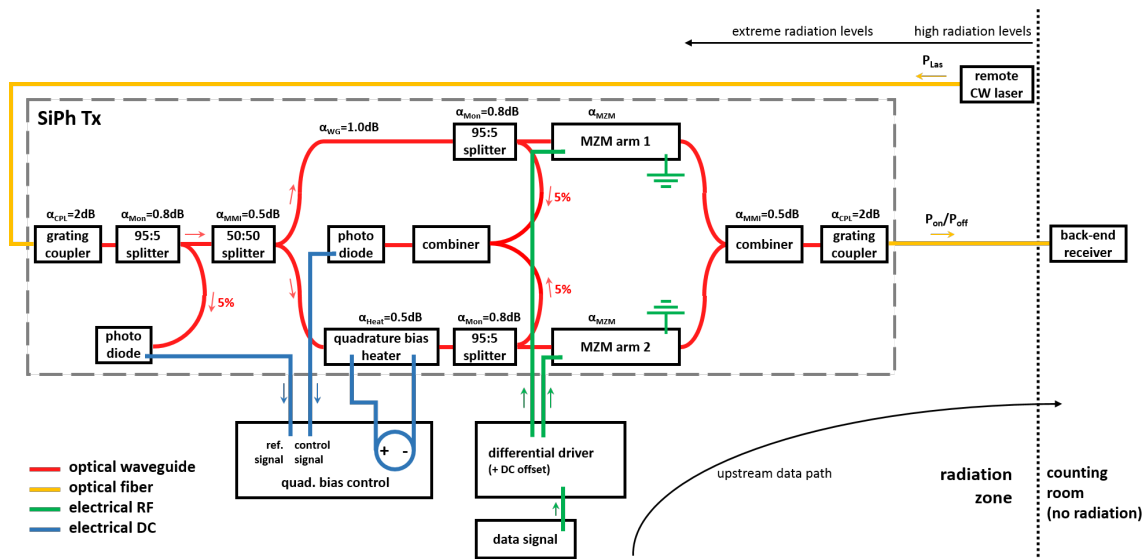

Figure 2. Proposed design for radiation-hard optical links based on a remotely located laser source and a differentially driven MZM that is biased at quadrature with a thermo-optic heater. The remote laser would be placed a few meters away from the SiPh Tx in a region in the HEP detector where the radiation levels are lower than where the MZM would be installed.

by radiation. Moreover, it can also be much shorter than a radiation-hard pn-junction-based phase shifter as used for modulation.

Radiation-hardened MZMs, realized either through implementing higher doping concentrations or employing shallow etch waveguides, generally exhibit higher losses than MZMs optimized for commercial purposes. Consequently, all passive components in a revised MZM design, e.g. grating couplers or splitters, will need to have lower optical losses than in the current device design in order to keep the overall device losses to a minimum. Target values for the losses of passive components that a revised MZM design should have are indicated above the respective components in figure 2. The same values were also used for the calculations presented in section 4. The remotely-located laser source will be placed a few meters away from the MZMs in a region in the HEP experiments where the radiation levels are lower. In this way, radiation-induced degradation of the laser source [6] can be minimized.

The MZMs in such a system implementation will be differentially driven with an amplitude of $V_{pp} = 2$ V, which would correspond to a single-ended drive signal of $V_{pp} = 4$ V. The Optical Modulation Amplitude (OMA) of SiPh MZM-based transmitters (Tx) modulated with V_{pp} is the difference between the transmitted optical power level of the on- and off-state given through the voltage-induced phase shift $\Delta\phi\left(\frac{V_{pp}}{2}\right)$ in the two MZM arms. If an MZM is biased at quadrature, the optical power levels at the output of the Tx are given by

$$P_{\text{on/off}} = \frac{P_{\text{in}}}{2}\left(1 + \cos\left[\frac{\pi}{2} \mp \Delta\phi\left(\frac{V_{pp}}{2}\right)\right]\right) - \left(\alpha_{\text{MMI}} + \alpha_{\text{CPL}} + \frac{1}{2}\alpha_{\text{WG}}\right), \quad (3.1)$$

$$P_{\text{in}} = P_{\text{Las}} - \left(\alpha_{\text{MMI}} + \alpha_{\text{CPL}} + \frac{1}{2}\alpha_{\text{WG}} + \alpha_{\text{Heat}} + 2\cdot\alpha_{\text{Mon}} + \alpha_{\text{MZM}}\right), \quad (3.2)$$

with P_{Las} being the optical power of the remote laser and α_{MMI}, α_{CPL}, α_{WG}, α_{Heat}, α_{Mon} and α_{MZM} being the losses of the 50:50 splitter/combiner, grating coupler, routing waveguides, thermo-optic heater, taps for the monitor photodiodes and the phase shifters, respectively. It is assumed for the model that there is no modulation bandwidth limitation imposed by the device design, i.e. the MZM's frequency response is flat up to a 3 dB-cutoff frequency that supports 10 Gb/s-operation without significant RF-power being reflected.

Modeled and measured OMAs for different V_{pp}'s, MZM lengths and laser powers are compared in figure 3. The measured values were taken from a similar test as the one described in section 2 but obtained from un-irradiated deep etch building block MZMs designed by imec. These MZM have properly designed transmission lines and were terminated with a 50 Ω off-chip load to support high-speed operation. The modeled values were obtained from eqs. (3.1) and (3.2) where instead of the loss values for the passive components indicated in figure 2, loss values of the actual MZMs at hand were used. These were $\alpha_{\text{MMI}} = 1$ dB, $\alpha_{\text{CPL}} = 4$ dB, $\alpha_{\text{WG}} = 1.7$ dB. Since no bias control was included on the test chip, α_{Heat} and α_{Mon} were set zero. However, an additional loss term α_{EL} was added and used as fitting parameter for the comparison to account for the varying coupling loss that occurred during the manual alignment of the optical fibers to the grating couplers for each tested MZM. The good agreement between the measured and modeled values confirms the validity of the model for MZMs that have been designed for high-speed operation.
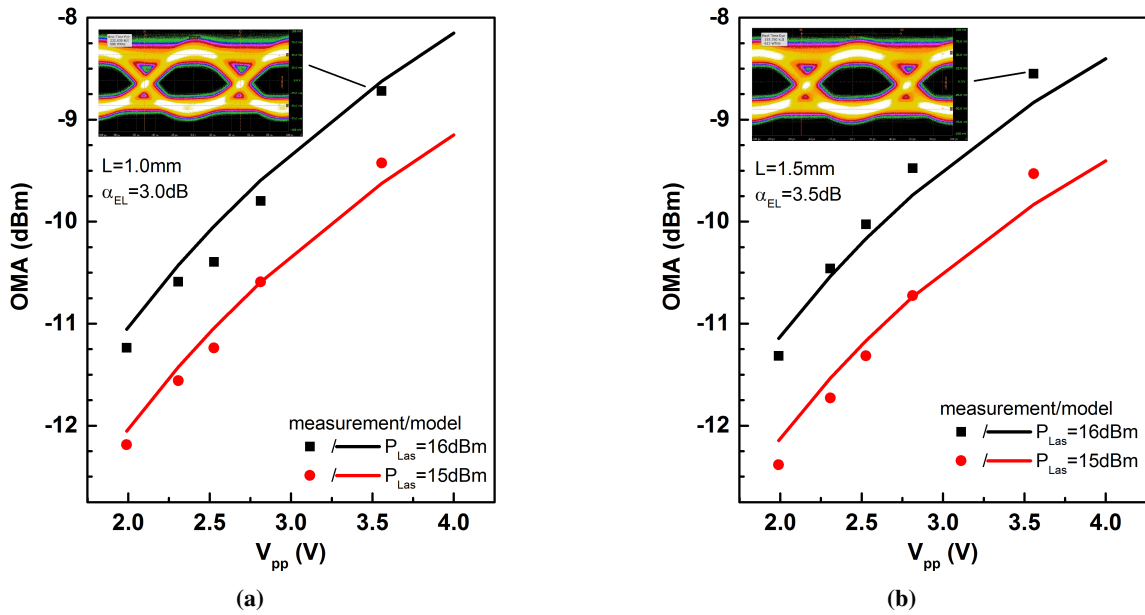
Figure 3. Measured (10 Gb/s) and modeled OMA for two deep etch MZMs designed by imec with nominal doping and a phase shifter length of 1.0 mm (a) and 1.5 mm (b). The insets show the measured eye diagrams for the indicated measurement point.

4 Laser power requirement and optical power budget

In order to minimize the number of transmitted bit errors, optical links need to operate above a minimum OMA. For single-mode transmitters in the Versatile Link project [3] this would be an OMA of at least −5.2 dBm. The model introduced above is used to find the minimum laser power required to feed into a SiPh Tx based on the revised MZM design with a shallow etch waveguide and either nominal or 2× nominal doping and different phase shifter lengths. The results shown in figure 4 indicate that P_{Las} has to be greater than 13 dBm for nominally doped MZMs with a length between 1.0–1.5 mm. This high laser power requirement is a direct consequence of the substantial additional losses in the radiation-hardened MZM design. This becomes more pronounced for 2× nominally doped MZMs where the losses are even higher. In this case, the phase shifter has to be shorter (0.5 mm) in order to minimize absorption losses, while at the same time a higher minimum laser power (14 dBm) is needed.

Knowing the minimum laser powers required to operate a radiation-hard SiPh optical link, the optical power budget can be determined. The power budget calculations and a comparison to the optical power budget of a Versatile Link single-mode transmitter are summarized in table 1. The calculations have also been done for a laser input power of 20 dBm to demonstrate how the link's power budget margin can be enhanced at the cost of higher optical input power. The values for the worst case receiver (Rx) sensitivity of −12.6 dBm and the total loss per link of 3.6 dB were taken from the calculations done for the optical power budget of a Versatile Link single-mode transmitter [7]. The resulting link margins can be as low as 3.8 dB for 2× nominally doped MZMs fed by a 14 dBm laser or as high as 11.6 dB for nominally doped MZMs fed by a 20 dBm laser.
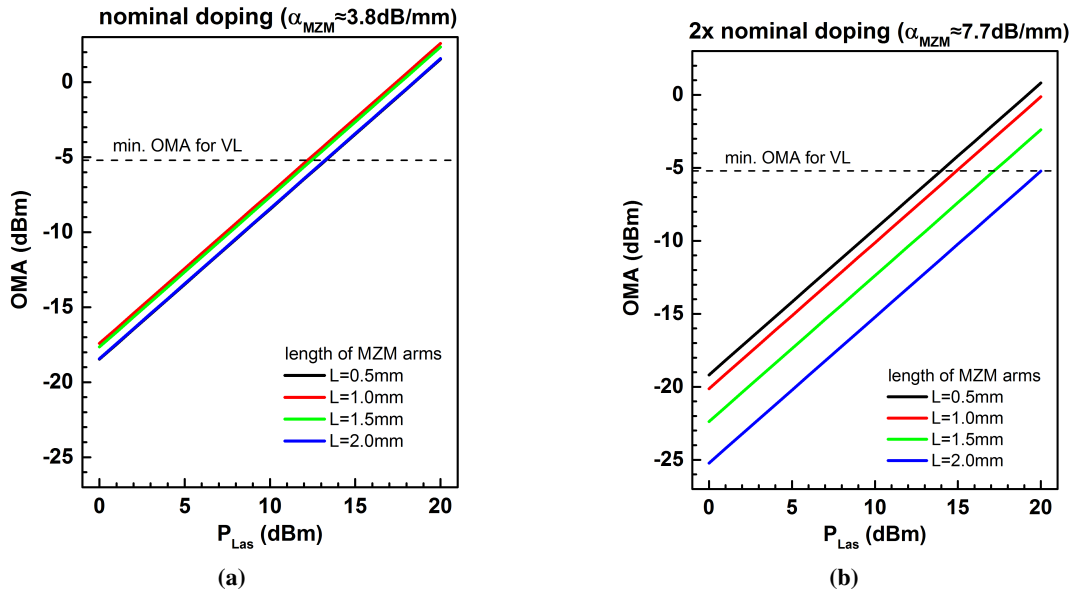
Figure 4. Determination of minimum laser power required to obtain an OMA of at least $-5.2\,\text{dBm}$ as specified for the Versatile Link (VL) project. A differential driving signal of $V_{\text{pp}} = 2\,\text{V}$ was used for the calculations.

Table 1. Optical power budget for radiation-hard optical links based on SiPh MZMs with different doping levels and laser input powers. The values are compared to a single-mode Tx from the Versatile Link project.

	nominal doping, $L = 1.0\,\text{mm}$		$2\times$ nominal doping, $L = 0.5\,\text{mm}$		Versatile Link [3]
	$P_{\text{Las}} = 13\,\text{dBm}$	$P_{\text{Las}} = 20\,\text{dBm}$	$P_{\text{Las}} = 14\,\text{dBm}$	$P_{\text{Las}} = 20\,\text{dBm}$	single-mode
Tx OMA [dBm]	−4.4	2.6	−5.2	0.8	−5.2
max. Rx sensitivity [dBm]	−12.6	−12.6	−12.6	−12.6	−12.6
power budget [dB]	8.2	15.2	7.4	13.4	7.4
fiber attenuation [dB]	0.1	0.1	0.1	0.1	0.1
connector insertion loss [dB]	2	2	2	2	2
link penalty [dB]	1.5	1.5	1.5	1.5	1.5
margin [dB]	**4.6**	**11.6**	**3.8**	**9.8**	**3.8**

Although the best link margin can be obtained for a system with a nominally doped MZM, the OMA of such a system would degrade faster in a radiation environment than if a $2\times$ nominally doped MZM was used. This can be readily noticed when the MZMs' pre-irradiation phase shift values in eq. (3.1) are replaced by phase shift values as a function of TID (figure 5). These phase shift values were measured during an online X-ray irradiation test [8] and are representative for the evolution of the phase shift in an actual system implementation where an MZM would be biased during exposure to radiation. In this case, the TIDs at which the system would fail range from 900 kGy (nominally doped MZM and low power laser) to 1300 kGy (nominally doped MZM and high power laser as well as $2\times$ nominally doped MZM with low power laser) and 1700 kGy ($2\times$ nominally doped MZM with high power laser). Apart from the first case, the link failure dose of the other three scenarios is high enough to meet the target TID requirements of ($> 1\,\text{MGy}$).
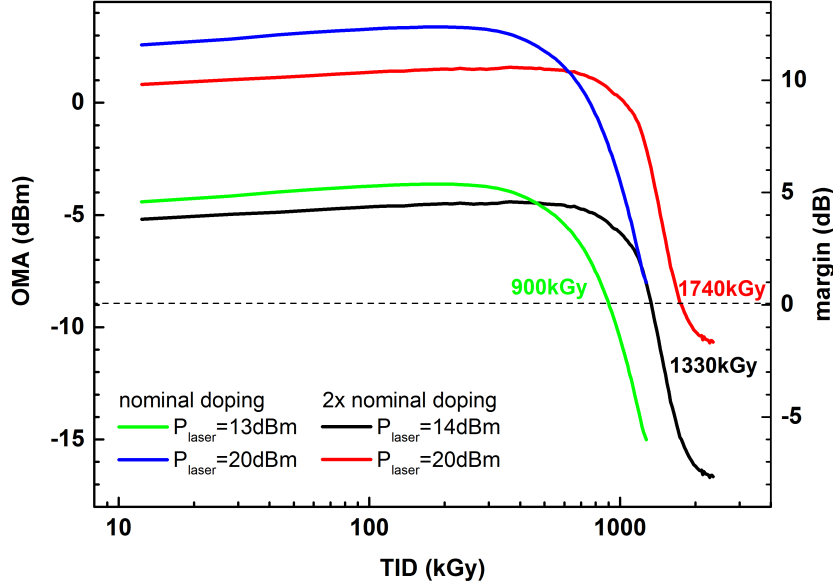
Figure 5. OMA and link margin as a function of Total Ionizing Dose (TID) for links with low and high power input lasers and MZMs with nominal and 2× nominal doping calculated for a (differential) $V_{\mathrm{pp}} = 2\,\mathrm{V}$.

5 Electrical power consumption

The total electrical power consumption of a SiPh Tx consists of the power dissipated in the MZM, the modulator driver, the monitor photodiodes and the heater and control unit used for biasing the MZM at its quadrature point as well as the power required by the remote laser. The DC-power consumption of the MZM is negligible as it is a reverse-biased diode. The RF-power consumption of the MZM, given by a $50\,\Omega$ system impedance and a peak voltage of $V_{\mathrm{p}} = {}^{1}\!/_{2}V_{\mathrm{pp}} = 1\,\mathrm{V}$ in both MZM arms, would be $40\,\mathrm{mW}$. The power consumption of an MZM driver is estimated to be around $320\,\mathrm{mW}$ [9]. The power required to quadrature-bias the MZM would be approx. $95\,\mathrm{mW}$, including $30\,\mathrm{mW}$ for a single monitor photodiode [10], $25\,\mathrm{mW}$ heating power in the silicon thermo-optic heater — which is enough to achieve a phase shift of π [11] — and an assumed power consumption of $10\,\mathrm{mW}$ for the heater control unit.

The total power consumption of $455\,\mathrm{mW}$ per Tx channel and the individual contributions are summarized in table 2. The power consumption of the remote laser, assumed to be given by a laser current of $100\,\mathrm{mA}$ at a voltage of $1.3\,\mathrm{V}$, was excluded from the total sum because the laser would not be placed close to the particle interaction point. Its power is thus dissipated outside the sensitive volume of the particle detector that needs to be cooled and the heat generated by the laser thus does not need to be transfered away. Obviously, the power still needs to be provided to run the link but it is not as critical as if it was dissipated in the innermost detector regions.

The total power consumption per channel of a single-mode SiPh Tx is about the same as for the Versatile Link counterparts. Still, due to the higher bit-rate the energy needed to transmit one bit is lower. In comparison with a Versatile Link+ (radiation-hard optical links developed as successors of the Versatile Link project) multi-mode Tx [12], a SiPh Tx clearly need much more power per channel and energy per bit. However, the power specified for the MZM driver, which is by far the

Table 2. Electrical power consumption for a radiation-hard SiPh MZM-based optical link in comparison to a single-mode Tx from the Versatile Link project and a multi-mode Tx from the Versatile Link+ project.

	SiPh Tx (single-mode)	Versatile Link single-mode Tx	Versatile Link+ multi-mode Tx
laser power [mW]	130		
MZM power [mW]	40		
MZM driver power [mW]	320		
photodiode power [mW]	2×30		
heater power [mW]	25		
heater controller [mW]	10		
total power [mW]	**455**	**415**	**50**
bit-rate [Gb/s]	10	4.8	10
energy per bit [pJ/bit]	46	87	5

biggest consumer, can be regarded as an upper estimate. More efficient MZM driver designs with power consumptions below 100 mW have already been published [13]. If similar values can be reached for a radiation-hard MZM driver, the power consumption per channel of a SiPh Tx could be reduced considerably.

6 Conclusions

Optical eye diagrams of Silicon Photonics (SiPh) Mach-Zehnder Modulators (MZMs) at 10 Gb/s were measured. The tests verify that the large-signal response of radiation-hardened MZMs does not critically change after exposure to 2.6 MGy as long as the MZMs' phase shift does not completely vanish during irradiation. A system model for a radiation-hard optical link based on a revised MZM design was developed. The optical modulation amplitudes calculated with this model agree well with measured values. Based on measurement results it is possible to predict a working system up to a dose of more than 1 MGy. If needed, the system's tolerance against ionizing radiation could be further increased at the expense of a higher power consumption, driven through a higher power laser and/or a larger driving signal. The electrical power consumption of a SiPh-based optical link is higher than that of components from the Versatile Link or Versatile Link+ developments, however such components could not be installed in regions with extreme radiation levels. As a next step, the resistance of Germanium-on-Silicon photodiodes, which would be needed for a revised MZM design, has to be tested for their tolerance to displacement damage and ionizing radiation. Later, a prototype based on the revised MZM design, including a radiation-hard driver, has to be built.

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