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

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1 Introduction

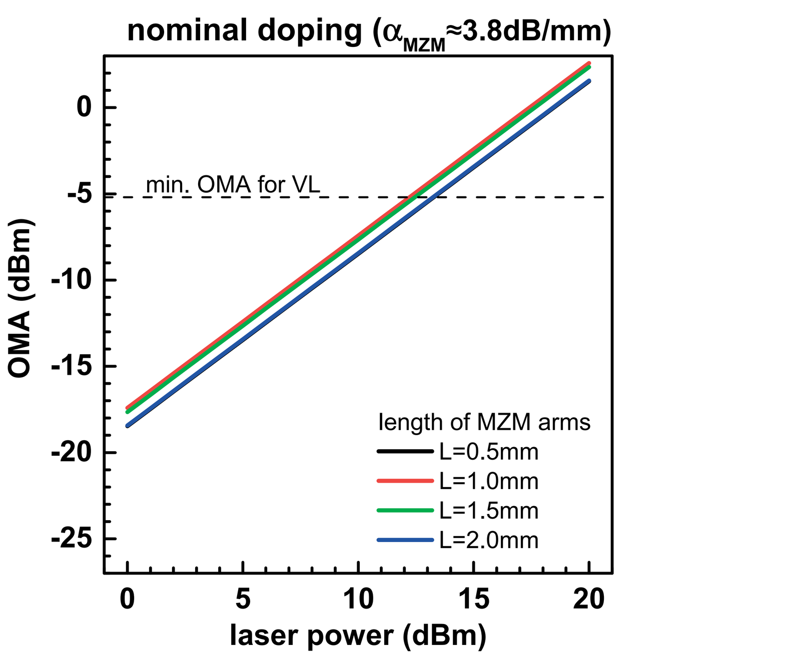
Silicon Photonics (SiPh) is currently being investigated as an alternative to directly modulated laser-based radiation-hard optical links [1]. The possibility of integrating SiPh devices with electronics and/or silicon particle sensors and an insensitivity of SiPh to a neutron fluence of above $3 \times 10^{16}\ n/cm^2$ make this technology particularly interesting for potential use close to the interaction points in future High Energy Physics (HEP) experiments.

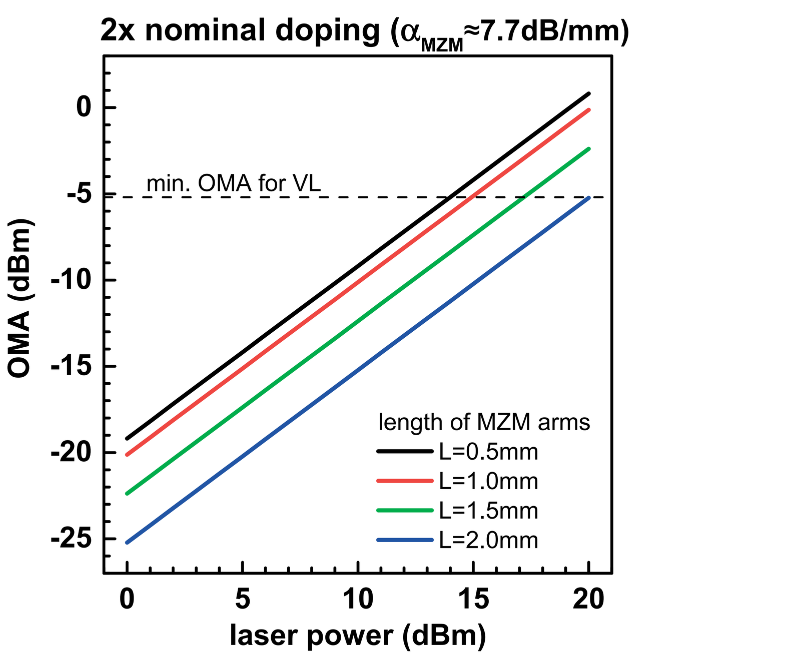
In addition to the high tolerance to displacement damage, silicon Mach-Zehnder Modulators (MZMs) resistant to a total ionizing dose of greater than $1MGy$ have recently been demonstrated [2]. As external light sources are required for implementing SiPh MZMs into a system, it will differ from existing directly modulated laser-based optical link systems.

A proposal for radiation-hard SiPh-based optical links is presented along with an analytical model to evaluate the system performance before- and after irradiation and an estimation for the electrical power consumption. The proposed link is compared to the specifications of the Versatile Link project [3].

3 Optical Power Budget

The length of the MZM arms and the minimal laser output power required to obtain an OMA of at least $-5.2dBm$, as specified for the Versatile Link Tx, has been determined for MZMs with a design like those tested in [2] (shallow etch waveguides with 2 different doping concentrations) and values for the optical losses of passive components as indicated in the schematic on the right.



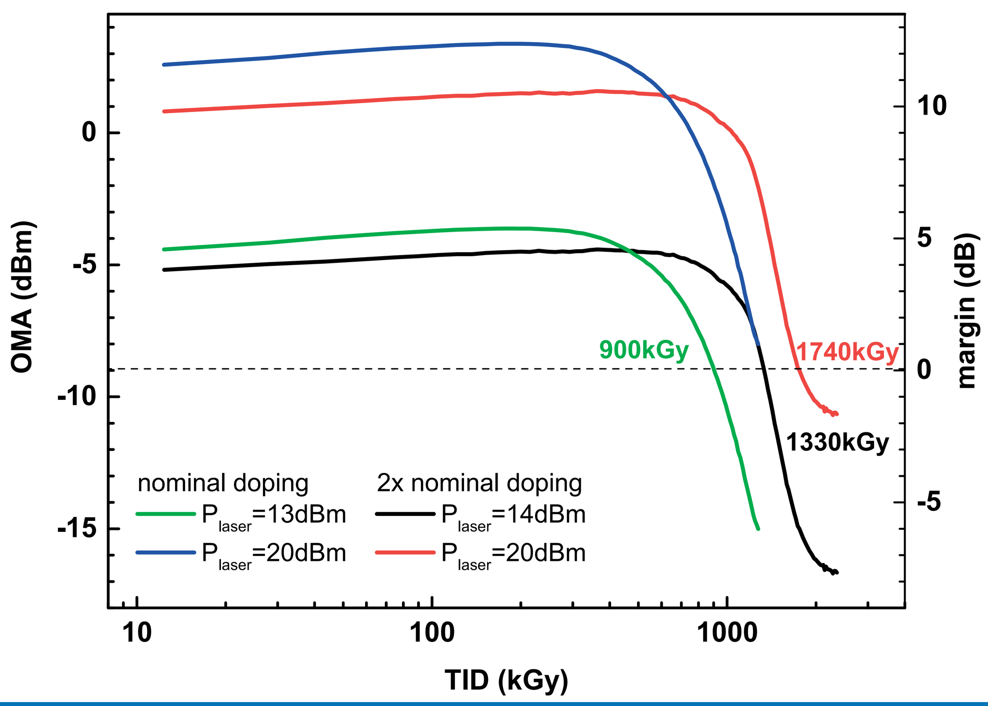


A laser with a minimal output power of $13dBm$ and $14dBm$ for an MZM with nominal doping and twice the nominal doping, respectively, has to be used for a radiation hard SiPh-based optical link. The corresponding margins of the optical power budget are then greater than $3dB$. They could be further increased by using higher power lasers or a larger V_{pp}.

	nominal doping, L=1.0mm		2x nominal doping, L=0.5mm		Versatile Link
	P_{Las}=13dBm	P_{Las}=20dBm	P_{Las}=14dBm	P_{Las}=20dBm	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**

The OMA and the margin of the power budget as a function of TID is calculated based on the MZM's phase shift degradation as obtained during an online x-ray irradiation test [4].

The failure dose at which the margin falls below zero and the system thus stops working reliably can go as high as $1.7MGy$ for a system with a high power laser and MZMs with 2x nominal doping.



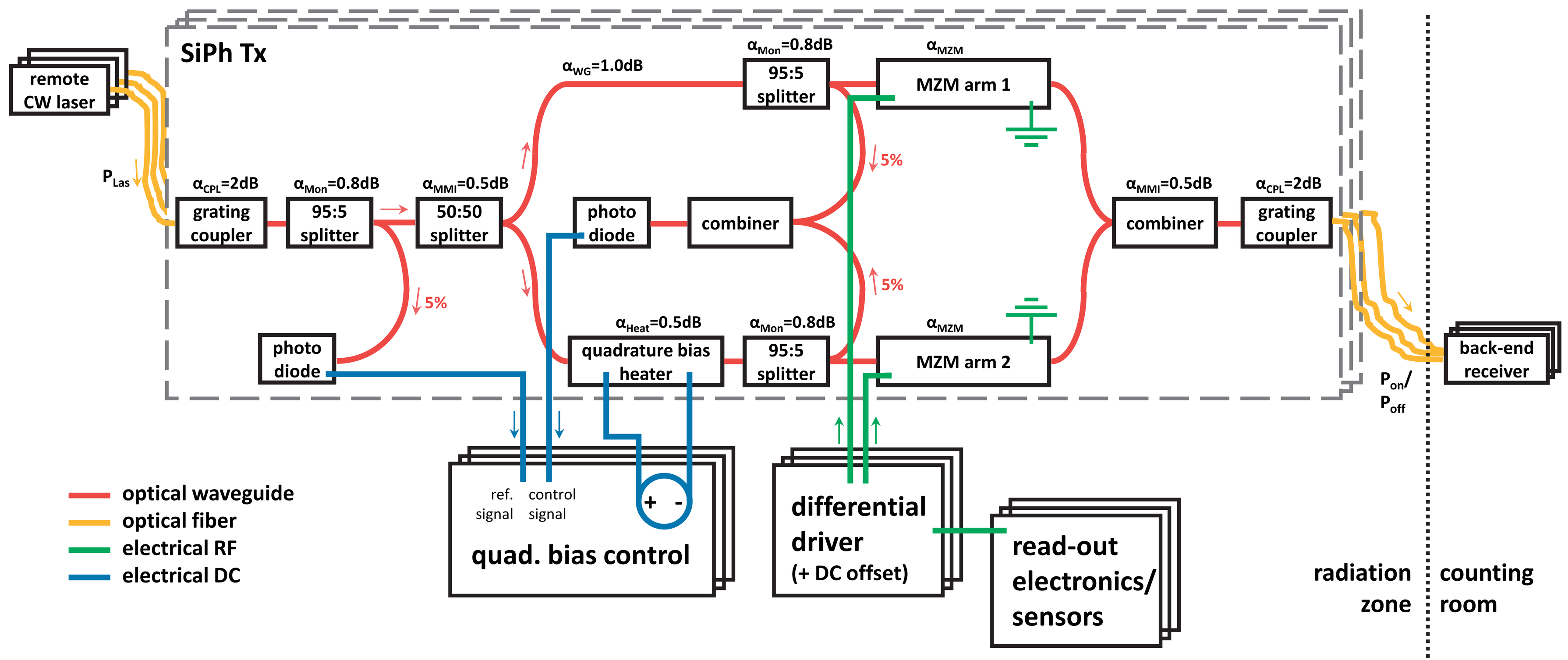
5 Polarization & Fiber Cabling

As typical grating couplers (GCs) and waveguides are inherently polarization-sensitive and laser diodes typically emit TE-polarized light, penalties due to the varying polarization state of light have to be taken into account when designing the system. Three scenarios can be envisioned:

- Use of polarization-maintaining optical fibers and TE-polarization MZMs
  - ➔ Costs for optical fiber doubles; radiation hardness has to be tested
- Use of standard optical fibers with dual-polarization GCs and polarization-independent waveguides
  - ➔ Thicker waveguides with potentially lower radiation hardness needed; dual-polarization GC and extra combiner add 1-2dB loss; radiation hardness of dual-polarization GCs has to be tested
- Use of standard optical fibers with dual-polarization GCs and a TM/TE-polarization converter and TE-polarization MZMs
  - ➔ dual-polarization GC, polarization converter and extra combiner add 2-3dB loss; radiation hardness of dual-polarization GCs and polarization converter has to be tested

2 System Model

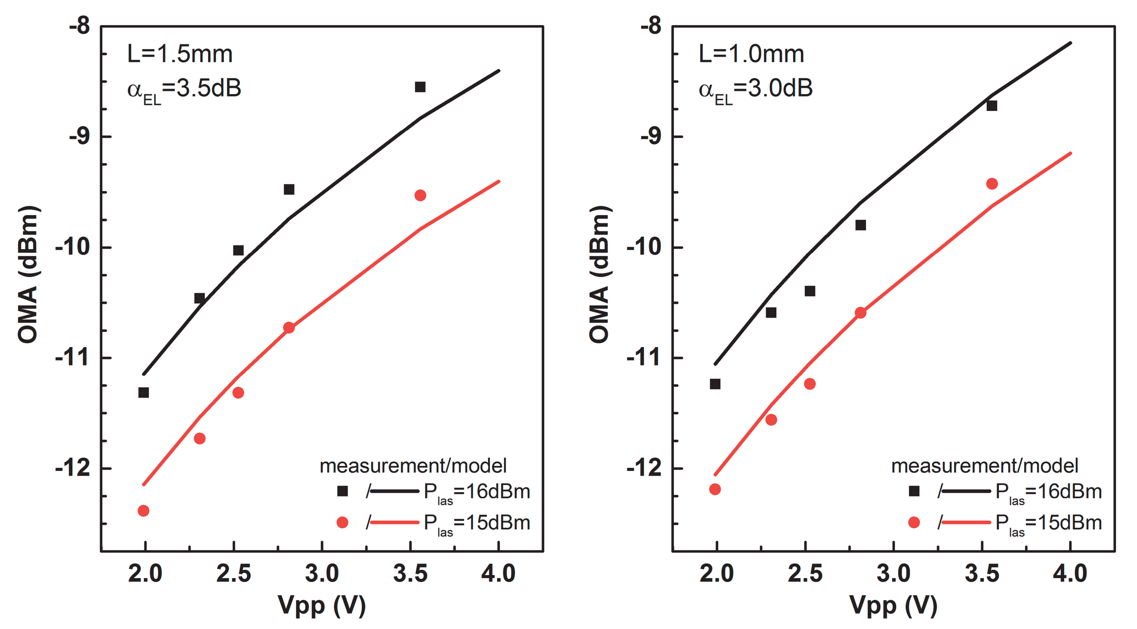
The system model for the upstream path is based on a MZM transmitter (Tx) biased at its quadrature point and modulated with a single-ended voltage swing of $V_{pp} = 4V$. This would be the same as applying a differential driving signal of half the amplitude to both modulator arms. The external light source with power P_{Las} is placed in a region with lower radiation levels. Values for the optical losses of optimized passive components are indicated in the schematic below.



The Tx Optical Modulation Amplitude (OMA) is calculated based on the difference in the optical power levels between the on- and off-state and the voltage-induced phase shift $\Delta\phi$ in the two MZM arms.

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

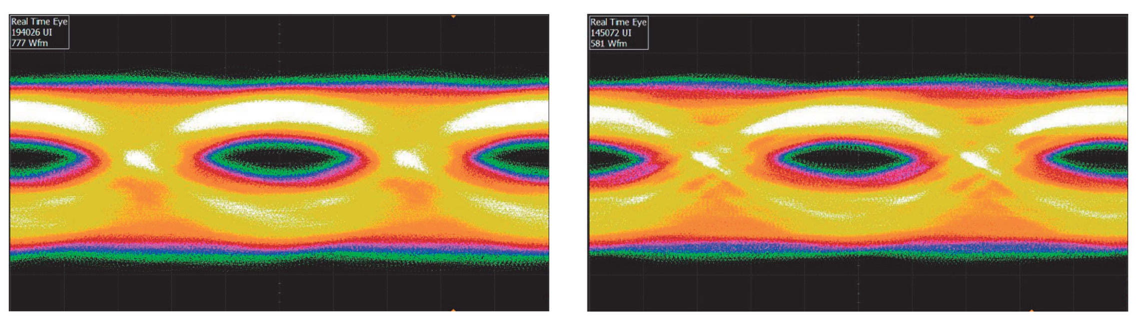
$$P_{in} = P_{Las} - \left(\alpha_{CPL} + \alpha_{MMI} + \frac{1}{2}\alpha_{WG} + \alpha_{Heat} + 2 * \alpha_{Mon} + \alpha_{MZM}\right)$$



Modelled OMAs for MZMs with different lengths and a deep etch waveguide [2] are compared to values measured at different V_{pp}'s and laser powers. As the measurements were done at die-level, an additional insertion loss factor α_{EL} was added in the model and used as a fitting parameter. α_{CPL}, α_{MMI} and α_{WG} of the actual test chip were used. The good agreement between measurement and model confirms its validity.

4 System performance

Comparison of measured eye diagrams obtained at $10Gb/s$ with a PRBS of 2^7-1, $V_{pp} = 3.56V$ and a laser power of $16dBm$ before irradiation and after exposure to x-rays and annealing at room temperature. The DC-performance degraded to 34% after irradiation and recovered to 85% after annealing. No significant change in AC-performance could be observed. MZMs with other design parameters showed a recovery of the DC-performance but did not show open eyes after annealing. The design of the tested devices was not optimized for high-speed testing. Better eye diagrams can be expected for a revised device design and larger driving voltage.



pre-irradiation after 2655kGy + annealing

6 Electrical power consumption

The total electrical power consumption of a SiPh Tx link 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 as well as the power required by the remote laser.

The power consumption of an MZM driver can be as high as $520mW$ [5], especially for large V_{pp}. A phase shift of π in a silicon thermo-optic heater for quadrature-biasing can be achieved with a heating power of approx. $25mW$ [6]. The power consumption of the heater control unit is assumed to be $10mW$.

The resulting power consumption per channel is summarized in the table on the right. The laser power has been excluded from the total sum because it would not be placed close to the interaction point. Its power is thus dissipated outside the sensitive volume.

The MZM driver is by far the biggest consumer. Therefore, research to improve its efficiency is needed to bring down the total power of the link.

	SiPh Tx (single-mode)	Versatile Link single-mode Tx	Versatile Link+ multi-mode Tx
laser power [mW]	300		
MZM power [mW]	40		
photodiode power [mW]	2*30		
MZM driver power [mW]	520		
heater power [mW]	25		
heater controller [mW]	10		
total power [mW]	**655**	**415**	**50**
bit-rate [Gb/s]	10	4.8	10
energy per bit [pJ/bit]	66	87	5

7 Conclusions

A system model for a radiation hard silicon photonics-based optical link was developed. The calculated optical modulation amplitude agrees well with measured values and predicts a working system, according to the Versatile Link requirements, up to a dose of 1.7MGy. Eye diagram measurements verify that radiation hardened Mach-Zehnder modulators can maintain their high-speed performance even after exposure to 2.6MGy. In spite of the high laser power and large elec. driving signal 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 is similar to a Versatile Link single-mode transmitter but much higher than in a multi-mode Versatile Link+ transmitter. In a next step, before a prototype for such a system can be built, components required for the control of the polarization of light and Germanium-on-Silicon photo diodes have to be tested for their tolerance to displacement damage and ionizing radiation.

References

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