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Testing silicon photonic Mach–Zehnder modulators versus total ionizing dose

Simone Cammarata [a,b,c,*], Serena Mattiazzo [d,e], Devis Pantano [d,e], Fabrizio Palla [a], Philippe Velha [f,g], Paolo Pintus [h,i], Sergio Saponara [c], Fabrizio Di Pasquale [b] Claudio J. Oton [b], Stefano Faralli [a,b,1]

[a] Istituto Nazionale di Fisica Nucleare - Sezione di Pisa, Largo B. Pontecorvo 3, 56127, Pisa, Italy
[b] Istituto di Intelligenza Meccanica - Scuola Superiore Sant'Anna, Via G. Moruzzi 1, 56124, Pisa, Italy
[c] Dipartimento di Ingegneria dell'Informazione - Università di Pisa, Via G. Caruso 16, 56122, Pisa, Italy
[d] Istituto Nazionale di Fisica Nucleare - Sezione di Padova, Via F. Marzolo 8, 35131, Padova, Italy
[e] Dipartimento di Fisica e Astronomia - Università di Padova, Via F. Marzolo 8, 35131, Padova, Italy
[f] Istituto Nazionale di Fisica Nucleare - Trento Institute for Fundamental Physics and Applications, Via Sommarive 14, 38123, Povo, Italy
[g] Dipartimento di Ingegneria e Scienze dell'Informazione - Università di Trento, Via Sommarive 9, 38123, Povo, Italy
[h] Dipartimento di Fisica - Università di Cagliari, Via Università 40, 09124, Cagliari, Italy
[i] Department of Electrical and Computer Engineering - University of California Santa Barbara, Santa Barbara, USA

A R T I C L E I N F O

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A B S T R A C T

Silicon photonics is emerging as a key technology for developing radiation-tolerant optical transceivers. In this work, we present the electro-optical characterization of two radiation-hardened shallow-etched Mach–Zehnder modulators with different doping configurations when exposed to 1.2 Grad(SiO_2) total ionizing dose. The trade-offs between radiation hardness and nominal performance metrics are highlighted to provide insights for optimizing SiPh devices for high-energy physics applications.

1. Introduction

Silicon photonics (SiPh) technologies are being evaluated to assist the evolution of the electro-optical (EO) transceivers (TRXs) in high-energy physics (HEP) experiments. Recent research aims to merge SiPh's of high-speed and power-efficient communication capabilities with the radiation tolerance requirements of HEP scenarios. SiPh modulators have been originally found to be highly sensitive to ionizing radiation. They are typically realized with high-speed PN junction-based phase shifters integrated into structures like Mach-Zhender modulators (MZMs) [1] or ring modulators (RMs) [2]. Radiation-induced charge accumulation near silicon-oxide interfaces can deplete the P-doped side of PN junctions, impairing their electrical operation and degrading EO modulation capabilities. However, adjusting design parameters such as dopant concentration and waveguide geometry (e.g., slab thickness) can enhance radiation hardness [3]. Following these radiation-hardening design techniques, preliminary findings indeed suggest that SiPh circuits can effectively operate in environments affected by both ionizing and non-ionizing radiation up to levels consistent with those expected in the upcoming HL-LHC experiments, respectively on the order of 1.2 Grad(SiO_2) total ionizing dose (TID) [4] and 3 $\cdot 10^{16}$ cm^{-2} 1 MeV-equivalent neutron fluences [5]. However, these radiation-hardening design choices also affect metrics like modulation efficiency ($V_\pi l_\pi$) and optical propagation losses, necessitating a trade-off between nominal performances and radiation tolerance to meet HEP links' communication standards, including optical and electrical power budgets. To explore this trade-off, two radiation-hardeneded MZMs with 1.5 mm-long shallow-etched phase shifters have been designed. They differ only in their PN junction doping configuration, with one device having a nearly tenfold increase in dopant compared to the other. Preliminary characterization results of these MZMs were reported in [6]. This paper focuses on the modification of their performance ratings after ionizing radiation exposure.

* Corresponding author at: Istituto Nazionale di Fisica Nucleare - Sezione di Pisa, Largo B. Pontecorvo 3, 56127, Pisa, Italy.
E-mail address: simone.cammarata@pi.infn.it (S. Cammarata).
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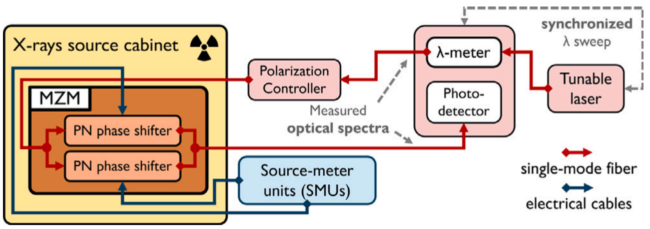

Fig. 1. Electro-optical characterization setup for measuring IV curves and optical spectra during X-rays irradiation.

Performance metrics	Pre-irradiation		1.2 Grad(SiO_2) TID	
	Low-doped MZM	High-doped MZM	Low-doped MZM	High-doped MZM
Optical insertion loss (0 V_{bias})	5.5 dB	20.4 dB	5.4 dB	18 dB
Modulation efficiency $V_\pi l_\pi$ (1 V_{bias})	2.45 V·cm	1.15 V·cm	10.70 V·cm	0.95 V·cm
Breakdown voltage V_{bd} (1 μA)	12.5 V	6.2 V	24.2 V	7.0 V

Fig. 2. MZM performance metrics extracted from IV curves and electro-optical spectra before irradiation and after exposure to 1.2 Grad(SiO_2) TID.

2. Results

The MZMs under test are irradiated up to 1.2 Grad(SiO_2) TID by means of a 10-keV X-rays source. The photonic integrated circuit (PIC) containing the MZMs is mounted on a printed circuit board (PCB) and positioned under the X-rays irradiator to obtain an average uniform dose-rate of approximately 1.5 krad/s on the devices under test (DUTs). Optical coupling to the PIC is achieved through on-chip grating couplers and low-profile fiber arrays. A closed-loop Peltier cell-based system controls the PIC temperature to ensure long-term measurement stability. Current–voltage (IV) relationships and optical spectra are measured during the irradiation for each MZM as a function of reverse bias voltage applied to the PN junction-based phase shifters. IV curves are recorded with source-meter units (SMUs), while optical spectra are acquired using a passive component analyzer (PCA) combined with a tunable laser source, as described in [6] (see Fig. 1).

The IV curves globally show an increase in the reverse breakdown voltage V_{bd} of the PN junctions, defined here as the reverse voltage at which the current reaches 1 μA. This is particularly evident for the low-doped MZM, where V_{bd} increase from 12.5 V to 24.2 V after exposure to 1.2 Grad(SiO_2) TID, as shown in Fig. 2. While the high-doped device also exhibits an increase in V_{bd}, the effect is much smaller. This behavior confirms that carrier depletion is occurring in the PN junction, supporting the understanding that TID-induced electrical pinch-off is affecting the P-doped section of SiPh modulators.

This is further evidenced by examining the optical insertion losses of the DUTs, as illustrated in Fig. 2. The high-doped MZM shows a reduction in loss by about 2.4 dB, likely due to decreased free-carrier losses from carrier depletion effects. In the low-doped MZM, the change in insertion loss is not as clear. This could be because the sensitive slab region of the phase shifter is not only depleted but has already been electrically inverted after 1.2 Grad(SiO_2) TID. The positive oxide-trapped charge may have attracted so many electrons in the originally P-doped slab region that it is now completely inverted, resulting in nearly unchanged insertion loss.

The electro-optical characterization complements these observations. The low-doped MZM shows a significant degradation in EO modulation efficiency, with the $V_\pi l_\pi$ metric increasing from 2.45 V·cm to 10.70 V·cm after full radiation exposure. In contrast, the high-doped MZM demonstrates outstanding radiation-hardness, maintaining performances beyond 1.2 Grad(SiO_2).

3. Conclusions

This contribution examined the impact of radiation hardening techniques on MZMs by correlating performance metrics with their degradation versus TID. Both low- and high-doped MZMs are shown to operate up to 1.2 Grad(SiO_2), highlighting, however, a trade-off between nominal performances and radiation tolerance. The low-doped device experiences a fourfold increase in its $V_\pi l_\pi$ metric after radiation exposure, making it inefficient for use in TRXs without ensuring annealing procedures during its operational lifetime, as the driving voltage cannot be scaled up accordingly. Conversely, the high-doped MZM exhibits excellent radiation tolerance but suffers from large optical insertion loss, likely failing to meet the optical power budget constraints of HEP communication links. Novel PN junction designs may be required to balance radiation-hardness with system-level modulation performances.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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