SiPhoSpace – Radiation-tolerant high-speed optical data transmission for space applications

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ABSTRACT

The feasibility of a compact, radiation tolerant 100 Gb/s optical data link based on Silicon Photonics technology for integration into future aerospace platforms and satellite payloads has been studied. Crucial for such applications is sufficient radiation tolerance to ionizing and non-ionizing radiation, a challenge completely unaddressed by currently available commercial components at such high data-rate. We show that the concept is feasible by describing the simulation of electronic and photonic components as well as the full system. Radiation testing results show that the components are sufficiently radiation tolerant.

Keywords: Optical Data Transmission, Silicon Photonics, Satellite Link, Radiation effects, Radiation tolerance.

1. INTRODUCTION

The idea of global, low earth orbit satellite constellations delivering high data rate free-space communication from and to any point in the world is reaching maturity. Projects by SpaceX, OneWeb, Facebook and Google are only a few examples of many initiatives which have recently been publicized. Key to the success of such deployments is the availability of compact, radiation tolerant electro-optic transceivers in the satellite payload which enable error free transfer of data with minimum impact on weight, volume and power dissipation.

The ATTRACT SiPhoSpace has evaluated the feasibility of radiation tolerant optical data links for such aerospace applications. The target data rate per fiber is 100 Gb/s. The proposed transceiver is a hybrid assembly of photonic and electronic CMOS integrated circuits. Existing optical link systems that have been qualified for operation in radiation environments do not exceed 5 Gb/s per optical fibre. In addition to this significant increase in speed, the SiPhoSpace technology offers superior radiation tolerance with respect to existing commercial components, thus opening up new applications in spacecraft on more challenging missions.

We have designed and fabricated Silicon Photonics components that will enable future integration into an optical transceiver. These components have been exposed to ionising radiation to validate their radiation tolerance. Device and system-level simulations have been carried out, as well as simulations of the impact of temperature on the performance of the silicon photonics modulators. The simulation results show that the SiPhoSpace transceiver concept is valid, paving the way to full implementation in a second phase of the project. Driver circuits have also been investigated as part of the project, with a promising architecture having been identified that will be submitted for fabrication again in a second project phase.

2. STATE OF THE ART

Existing optical link systems that have been qualified for operation in radiation environments do not exceed 5 Gb/s per optical fibre. This is equally true of those developed for High Energy Physics (HEP), e.g. the Versatile Link [1], and those developed for Aerospace applications (e.g. SpaceFibre [2]). There are ongoing developments to extend this to 10 Gb/s per fibre (e.g. the Versatile Link Plus [3]), which are expected to reach production maturity in 2020. This project targets at least one order of magnitude increases in throughput per optical fibre and radiation tolerance. Such high levels of radiation tolerance becoming available for space applications will reduce the need for spacecraft

shielding, thus bringing down the overall spacecraft weight and associated launch and production costs.
The constituent Silicon Photonics components that will make up the proposed data transmission system, as well as the concepts for control and tuning of ring modulators, have been described in the literature [4,5]. These components need to be studied for their radiation hardness and, if necessary, be modified to increase their radiation tolerance. Similarly, the control methods and algorithms required to stabilise the operation of the link need to be validated and possibly extended to meet the requirements of operation in a radiation environment.

3. Breakthrough Character of the Project

The SiPhoSpace project will provide substantial increases in both data-rate and radiation tolerance. Availability of optical transceivers enabling at least an order of magnitude increase in the data rate that can be sustained over a single optical fibre will significantly reduce spacecraft mass and simplify the wiring harness compared to current designs. Alternatively, new spacecraft designs with greatly expanded capabilities could be within reach. Radiation tolerance of spacecraft electronics is critical to mission success. Different orbits and mission trajectories can have very different requirements that can currently lead to difficult design decisions due to a lack of sufficiently robust data transfer systems. Increasing the radiation tolerance of the optical transceiver to hundreds of kGy or even MGy levels will bring the freedom to design spacecraft for complex missions with high bandwidth requirements.

4. Project Results

A Silicon Photonics test chip (PIC) was designed at CERN and submitted for fabrication to IMEC. Fig. 1 shows the fabricated chip. The PIC integrates several photonics building blocks and circuits for Datacom applications. The design leverages the CERN know-how on radiation hard Silicon Photonics for high energy physics (HEP) to design optical high-speed links for the back-plane of satellites payloads. The PIC integrates a variety of devices (modulators, photodiodes, couplers, waveguides, etc.) for experimental evaluation of the radiation hardness of the selected Silicon Photonics platform. All the implemented active components (modulators and photodiodes) present frequency response above 25 GHz and some of them exceed 50 GHz bandwidth.
The main objective of the SiPhoSpace project is the feasibility study of a 100 Gb/s link based on micro-ring modulators. Simulations of a four channel WDM transmitter (Tx) and a receiver (Rx) based on ring resonators have been carried out. The simulations show that the proposed design will be capable of achieving good levels of Transmission Penalty and Extinction Ratio (see Fig. 2).

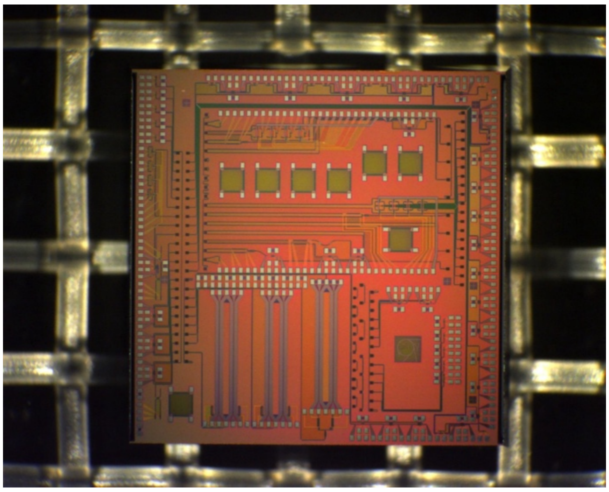

Fig. 1. Photograph of the Silicon Photonics Test Chip.

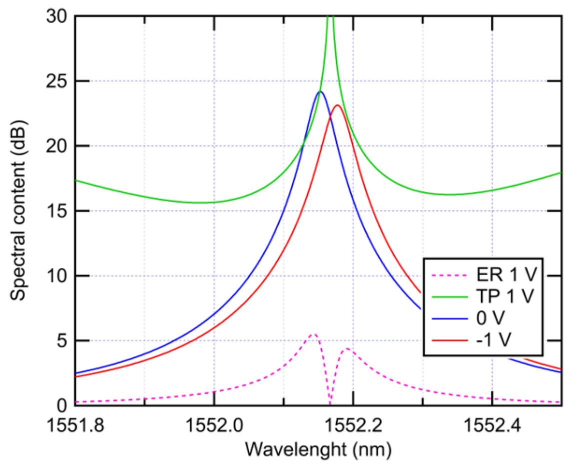

Fig. 2. Transmission penalty (TP) and extinction ratio (ER) simulation of the Ring Modulator design for a modulation signal with 1 V amplitude.

Radiation tolerance testing has shown that Silicon Photonics devices are most sensitive to ionising radiation. This is consistent with results on electronic circuits designed in similar Silicon-On-Insulator (SOI) processes. We have shown that targeted design changes can dramatically increase the radiation tolerance of Mach-Zehnder Modulators (MZMs), see the difference between the green- and blue traces of Fig. 3. Our results have also shown that Ring Modulators (RMs) are more radiation tolerant than MZMs in the same technology. This represents a proof of principle that the targeted technology will deliver the desired level of radiation tolerance.

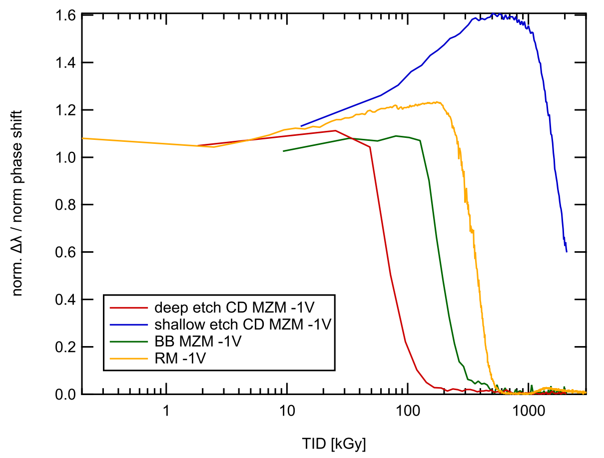

Fig. 3. Change in modulator phase shift for different device designs. We target the application of the design changes for the shallow etch device to the Ring Modulator (RM) shown.

RMs are sensitive to production tolerances and ambient temperature variations. An ohmic heater is typically placed on top of the ring structure to allow thermal tuning of the resonance wavelength to the desired value. To evaluate the effect of electro-thermal tuning, the required power, the achievable wavelength shift, the temperature distribution, and potential optimizations of the waveguide position were evaluated by coupled electrical-thermal-optical simulations. These simulations showed an inhomogeneous temperature distribution around the waveguide with a steep gradient (Fig. 4). The average temperature of the waveguide of a 10 µm diameter ring resonator can be changed by 8.1 K per milliwatt of electrical power. The resonance wavelength can be tuned in the C-band by 1 nm per 3.3 mW of electrical power. Better thermal insulation near the waveguide will further lower the power requirements, lower the heater peak temperature, and smooth the temperature distribution.

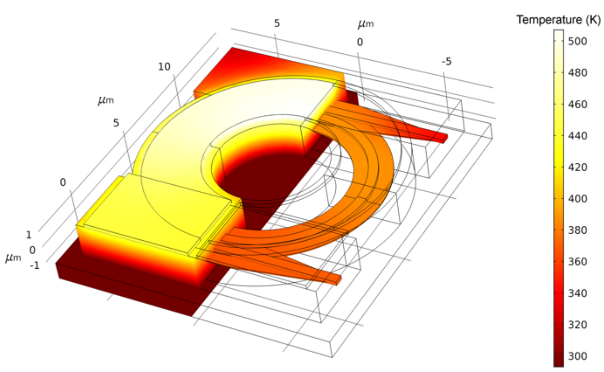

Fig. 4. Simulated temperature distribution of ring resonator at 10.8 mW heating power in aluminium heater on top and a silicon substrate held on 293 K. The silicon waveguide shows an average temperature of 381 K.

In order to guarantee the operation of the ring modulators at 25 Gb/s in a radiation environment a 28-nm CMOS technology has been chosen. The small feature-size process guarantees the required high-speed performance and provides better radiation tolerance than the 65-nm process used to date [6] (due mainly to the thinner gate oxide).

A modulator driver has been designed, consisting of a 3-stage tapered chain of standard CML (Current Mode Logic) buffers, followed by pseudo-differential output stage capable of delivering ±0.5 V at 25 Gb/s. As well as the driver design, particular care has been taken in the design of the pads, ESD (Electro-Static Discharge) protection and EIC-to-PIC wire bonds, because they can severely limit the performance. Therefore, a 1 kV and 2 kV HBM (Human Body Model) compatible ESD protection circuit with low parasitic capacitance has been designed to improve the driver testability without impacting the high-speed performance. A simulated Eye Diagram of the driver output is shown in Fig. 5.

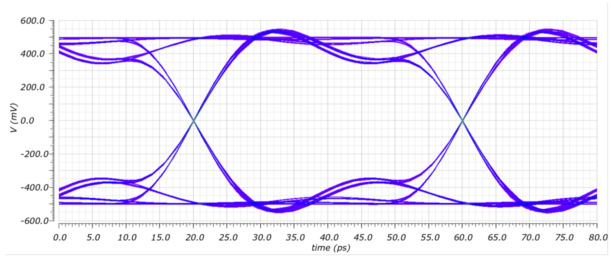

Fig. 5. Simulated 25 Gb/s Eye Diagram for the 28-nm driver design.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

The ATTRACT Phase 1 SiPhoSpace project provides the basis scaling up the technology to TRL 7 in Phase 2. The Phase 2 objective will be enabling the commercial adoption of an innovative high speed (100 Gb/s) link product targeting the aerospace industry for both on-board satellite and EGSE (Electrical Ground Support Equipment) markets. This will be achieved in the following steps:

- Increased monitoring, diagnostic and control/feedback features to enable inclusion in real systems;
- Providing a plug-and-play 100 Gb/s module;
- Full characterization for the aerospace market including electrical, temperature, electromagnetic interference (EMI), vibration, radiation (SEEs and TID);
- Full characterization of life-time and aging, industrial scale manufacturability, including electronic-photonic packaging.

Beside these R&D activities, the ATTRACT Phase 2 SiPhoSpace project will undertake:
- Market analysis, potential customer network set up, pre-commercial demonstration;
- Dissemination and commercialization planning for on-board satellite and EGSE applications.

5.2. **Project Synergies and Outreach**

In ATTRACT Phase 2 the original Phase 1 consortium made up of CERN, INFN, Bristol University, and KIT will be reinforced to a total of 7 partners: adding an engineering R&D center with strong technology transfer capability (the Department of Information Engineering, UniPisa); IngeniArs (www.ingeniars.com), an aerospace SME; and Thales Alenia Space that will act as end-user. The partnership may be further extended with other aerospace companies (e.g. Leonardo, Airbus, Sener, OHB, Sitael). Moreover, the network of partners and customers in the aerospace fields of UniPisa, IngeniArs and Thales Alenia Space will be contacted to invest and/or find synergies with SiPhoSpace. This network includes the main European stakeholders: ASI, ESA, CNES, DLR agencies in addition to the prime contractors mentioned above.

Planned satellite launches in the coming 10 years, with the explosion of the small satellite and constellation market [7], as well as the inter-satellites [8] and satellite-to-ground market, will create large opportunities for SiPhoSpace.

5.3. Technology application and demonstration cases

The ATTRACT Phase 2 SiPhoSpace project will support European industry in maintaining its leading position while reducing dependence on non-European component suppliers. In terms of demonstrated applications for industry and society, ATTRACT Phase2 SiPhoSpace will provide enabling technologies for multiple applications:
- 100 Gbps on-board satellite connectivity (beyond state-of-art of 6.25 Gb/s SpaceFibre and 1 Gb/s Space Ethernet) for high-speed sensors & detectors, lasers, data handling equipment in scientific, surveillance, remote sensing and telecom missions, including optical inter-satellite and satellite-ground connections;
- 100 Gbps connectivity for reliable EGSE used in the aerospace industry for test.

5.4. Technology commercialization

The path to commercialization foresees two steps: first the ATTRACT Phase 2 SiPhoSpace project will increase the TRL up to level 7 with a pre-commercial prototype. This will provide a proof-of-concept high-speed (100 Gb/s) link demonstrator – an innovative product targeting the aerospace industry's on-board satellite and EGSE markets. This pre-commercial prototype will be made available to EU space stakeholders (named in Section 5.2) in order to test the technology, thus easing its market adoption and further TRL improvement up to TRL 8-9 after the end of SiPhoSpace Phase 2 project. A full IPR licensing scheme will be defined within the partners of SiPhoSpace Phase 2 for the commercial exploitation of the technology.

A preliminary market analysis carried on in collaboration with IngeniArs has identified a potential market of at least 5 M€ in the next 3-5 years, rising to 50-100 M€ in 5-10 years thanks to several factors:
- next 10 years of planned satellites and growing market of small-satellites/constellations [7];
- the need for optical inter-satellite communication [8] and optical satellite-to-ground communication in telecom systems;
- the need for multi-Gb/s links and Silicon Photonics technology for Space identified by the EC-EDA-ESA Joint Task Force for EU non-dependence [9].

To reach the goal a Phase 2 project of at about 30 months and an estimated budget of 2 M€ is foreseen.

5.5. Envisioned risks

As external risks, SiPhoSpace can face the threat of a contracting aerospace market, as well as potential competition from similar developments by other groups. These risks have been mitigated by already carrying out a preliminary competitor analysis and a market and business plan analysis with Ingeniars, and considering both on-board (satellites, spacecraft, exploration rovers) and ground (EGSE) applications as well as non-space applications. Examples of the latter are high reliability HPC standards like OCP [10,11] that could benefit from single-event immune links such as ours.

SiPhoSpace can face also internal administrative risk (e.g. partner resignation) and technical risk (e.g. delays or technology higher prototyping cost). To mitigate these issues Ingeniars has already been involved in the market and business plan analysis, and if the initial end-user partner resigns then several alternate aerospace industries (see Section 5.2) could be contacted as a replacement. Technical delays will be mitigated thanks to the synergies with other project activities carried out by the partners.

5.6. Liaison with Student Teams and Socio-Economic Study

In ATTRACT Phase 2 SiPhoSpace will involve activities with MSc and PhD level student teams by organizing: (i) a 1-week full immersion summer school organized for each of the 2 project years on "Silicon Photonics for Aerospace and HEP applications"; (ii) a call for ideas where student teams will be asked to propose applications, based on SiPhoSpace output technology, that will be discussed in a final project workshop. Moreover, SiPhoSpace will contribute to the ATTRACT Phase 2 expert-driven socio-economic study via interviews, business planning and market analysis.

Finally, since SiPhoSpace addresses the requirements of the EC-ESA-EDA Joint Task Force for EU technology non-dependence, and the themes of 25 Gb/s link for space and of integrated SiPho are key requirements, we expect synergies among activities in ATTRACT Phase 2 and co-funding from ESA RP & ESA ScyLight [8] programs and from prime aerospace companies.

6. ACKNOWLEDGEMENT

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