

DIGITAL PHOTONICS Track #3

Integrated Optical Switches based on Silicon Photonics for on-board space applications

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ABSTRACT

Optical switches are expected to become key components of future satellite-based laser communication systems or photonic telecom payloads, and to take place in on-board equipment and subsystems implementing fiber optic links, interconnections and/or routing solutions.

Thales Alenia Space- France and VTT of Finland have undertaken to investigate, develop and evaluate, new optical switches based on photonic integrated circuit (PIC) technology and optimized for such potential payload applications.

This paper reports on the development and complete test of a 1x8 Thermo-Optic optical switch based on Si photonic integrated circuit (PIC) designed and manufactured by VTT in Finland. System-validation carried out on an optical communication test-bed operating 25 Gbps DPSK modulation format, in particular with the objective to assess the impact of the optical switch isolation on BER performance of the entire system is also presented.

Keywords: Optical switches, photonic integrated circuit, Si Photonics, space applications

1. INTRODUCTION

Integrated optical switches could emerge as a key enabling technology for future space systems, promising to overcome long-standing limitations of Radio-Frequency and Electro-Mechanical approaches in high-data-rate, power- and mass-constrained environments. As satellite constellations expand and satellite payloads demand faster and more flexible connectivity, the ability to route optical signals dynamically—without converting continuously between optical and electrical domains—becomes increasingly attractive. So, this type of devices are especially relevant for future telecom payloads and satellite laser communication systems, where they could play a major role.

Integrated optical switches provide fast switching time, high bandwidth, galvanic isolation, and potentially lower power consumption, while also offering intrinsic compatibility with photonic integration for compact, robust space-qualified architectures. In addition, they could be integrated into complex optical link architectures, such as wavelength-division multiplexed (WDM) systems, coherent free-space optical communications, and onboard optical RF or digital interconnects for processing and routing large volumes of data. These use cases demand not only efficient switching but also careful consideration of system-level impacts such as polarization dependence, crosstalk, alignment sensitivity, and the ability to maintain stable performance over the mission lifetime.

Thales Alenia space France has identified such devices as being of great interest. Potential applications include routing, redundancy switching or RF antenna beam switching/hopping in photonic RF architectures with reduced SWaP (Size, Weight and Power), as well as all-optical routing capabilities, in a space-based optical transport network with Optical Inter-Satellite links (OISL) such as envisaged in the ESA HYDRON concept.

More details on the relevant applications are provided in Section 1. Section 2 focuses on integrated optical switches, describing the design and manufacturing of a 1x8 optical switch sample and presenting the measured functional performance of the packaged implementation. Section 3 reports temperature testing results for a packaged PIC 1x8 optical switch sample. Finally, Section 4 presents system-level validation results obtained when such a device was integrated into an optical communication test-bed operating with 25 Gbps DPSK modulation..

2. APPLICATIONS OF INTEGRATED OPTICAL SWITCHES

Thales Alenia Space, with support of space agencies (ESA & CNES), has been elaborating new Photonic RF payload concepts to deliver higher-performance, more functional, and lower-cost telecom systems. By transferring RF/microwave signals onto optical carriers, processing can be performed in the optical domain, leveraging photonics benefits such as broad bandwidth, small size/low mass, as well as multiplexing or switching capabilities.

A photonic RF repeater typically acts as a space/frequency switch, routing any RF sub-band from any input port to any output port and shifting its frequency position accordingly. It can take place in RF communication payloads - e.g., between the low-noise receive front-end and the high-power transmit amplification - and enable optical distribution of centralized RF local oscillators (LO) to electro-optical mixers over fiber, photonic multi-LO frequency conversion and optical cross-connection (circuit switching) of RF signals. This offers unique properties such as scalability to large port counts and RF frequency independence.

A simplified architecture is shown for a Forward multi-beam repeater and related RF photonic equipment developed by Thales Alenia Space in OMCU (Optical Multi-frequency Conversion Unit for broadband transparent analogue repeaters) and OWR-RFE (Optical Wideband Reconfigurable – Receiver Front-End) ESA projects.

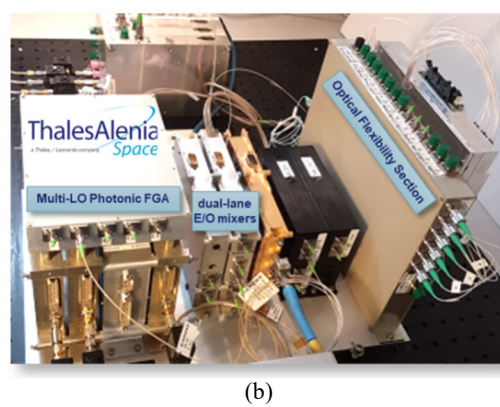
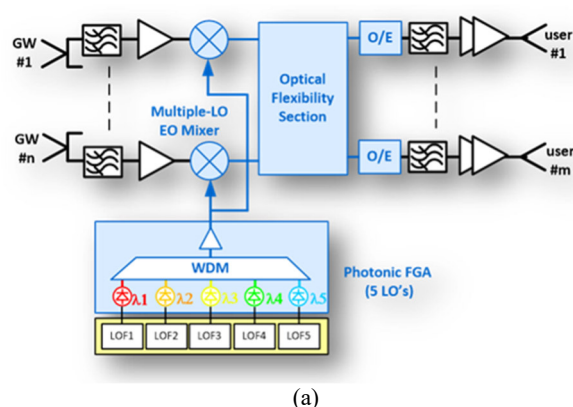


Figure 1. Architecture of a photonic repeater for the Forward multi-beam access mission (a) and associated RF/photonic equipment (b)

Photonic technologies were proven to offer substantial advantages in terms of hardware complexity, along with mass and power consumption savings of about 35% compared with RF solutions. The availability of photonic integrated circuits (PICs)—especially integrated optical switching devices—could further improve these benefits while enhancing reliability by enabling redundancy switching directly in the photonic domain. For this reason, TAS considers the possibility to include the integrated switch technology in its photonic equipment and payload architectures, particularly for redundancy schemes. Beyond redundancy, integrated optical switches may also support intra-satellite functions such as beam hopping and advanced reconfiguration of digital interconnects in next-generation photonic payloads.

Another key application for optical switching is satellite-based laser communication systems. Free-space optical links offer major benefits over RF by using much higher carrier frequencies (notably the 1.55 μm C-band), enabling very high capacity, while providing highly directional beams with very low divergence, making interference or interception unlikely. They also reduce regulatory constraints compared with RF licensing, and can allow smaller, lighter transmit/receive terminals than antenna-based systems. These benefits are driving growing interest for space applications such as LEO-to-ground telemetry, GEO feeder links, and inter-satellite communications. Innovative LEO/MEO telecom constellation concepts target worldwide coverage and low latency, using 100+ satellites to provide mesh connectivity at Gbps to ~100 Gbps. Optical inter-satellite links (OISLs) are critical to achieve these high capacities, and ~1.5 μm optical solutions are preferred for compatibility with ground technology and for WDM supports modularity, redundancy, and all-optical routing. However, strict mass, size, and power constraints apply to small-to-medium satellite platforms, while cost and manufacturability strongly influence design because many terminals must be produced quickly. Examples include Lighspeed™ LEO system with optical neighbor-to-neighbor crosslinks and RF ground access, and Laser Light™ using MEO optical crosslinks plus >100 Gbps satellite-to-ground links with all-optical routing that does not rely on RF spectrum.

Semi-transparent, optical communication and digital processing payload architectures could be particularly relevant in such cases. Such a payload concept is illustrated in Figure 3 below, showing the stages required to interface the optical ISL with the RF equipment through the digital on-board processor (OBP) and the optical cross-connect (OXC), with blue, orange and grey boxes respectively representing optical, RF and digital stages.

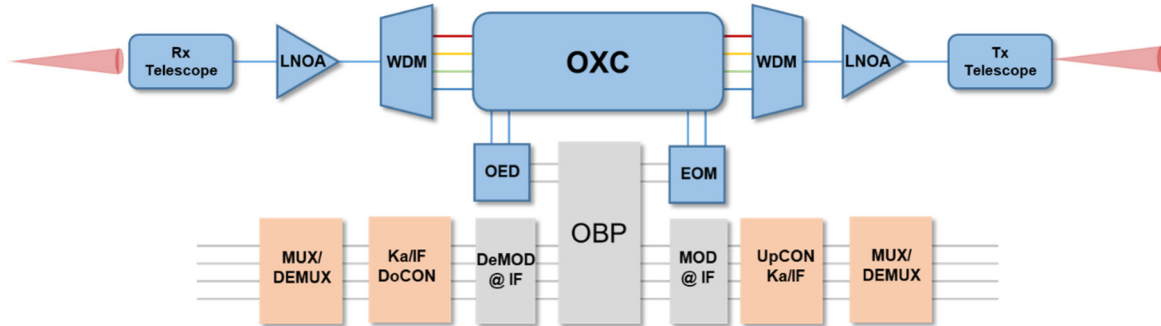


Figure 2. Semi-transparent P/L architecture for optically-linked satellite constellation

In this case, one part only of the optical link paths are terminated at the OBP, and the other part go through the P/L transparently via the OXC. While the OBP supports fine bandwidth routing, the OXC provides coarse routing capability. This requires that the OXC be reconfigured at each handover, which puts specific requirements to the optical switching technology in terms of switching speed and durability in number of switching cycles, in particular. Optical switching plays here a key role in routing in space optical transport network satellite.

3. INTEGRATED OPTICAL SWITCH

3.1 Design and manufacturing of a PIC TO 1x8 optical switch

As written in the previous section, integrated optical switches based on photonic integrated circuit (PIC) technology could be an attractive for satellite payloads thanks to their high integration density and lack of moving parts, among others. Integrated photonic switches were fabricated using VTT's 3 μm SOI technology guarantying propagation losses as low as 0.04 dB/cm. They are implemented using Mach-Zehnder interferometers (MZIs). The switch works by inducing a relative phase change between the two MZI arms so the light exits through one of two output ports. Typically, multi-mode interference (MMI) couplers are used to split the input light evenly between the arms and then recombine it at the output. Switch elements based on either 1x2 or 2x2 MMIs can be implemented depending on the device version.

Phase shifters can be based on two main physical mechanism: thermo-optic (TO) effect (exploiting the high thermo-optic coefficient of silicon), and carrier injection. So, TO switches are based on heaters, electro-optic (EO) switches on PIN junctions. As switching operation is based on phase shifting provided physically by these heaters (on each arm of MMI coupler, bias voltage may or may not be applied for switch on or switch off operations), the developed devices are commonly called thermo-optical silicon photonic integrated circuit (PIC) switch.

VTT used implanted silicon heaters that can be shorter than 100 μm instead of mm-long metal lines heater technology enabling more compact structures but requiring relatively higher voltages and producing higher local temperatures. Because heat release is affected by isolation, heater-based switching always involves a trade-off between speed and power consumption: better isolation slows heat dissipation. VTT's most power-efficient heaters consume about 25 mW for a π -shift (rise time $\sim 30 \mu\text{s}$, fall time $\sim 50 \mu\text{s}$), while achieving a faster $\sim 30 \mu\text{s}$ fall time typically increases power to $\sim 50 \text{mW}$. The dimensions of optical switch chips (up to 8 output ports) are approximatively $5 \times 5 \text{ mm}^2$ and all devices have been designed and manufactured for TE polarization and 1550 nm wavelength operation. During design phase, electrical contact pads have also been included in the layout (i.e. chip) to make wire-bonding and probing easier.

Generally, an optical switch, exhibiting a number of port counts higher than 2, consists in a PIC including 1x2 switch elements assembled in tree topology. The figure hereafter shows the PIC layout of Thermo-Optic 1x8 switch with 1x2 MMI and the manufactured chip by VTT.

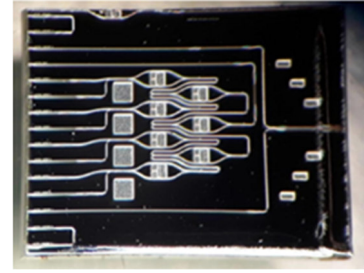
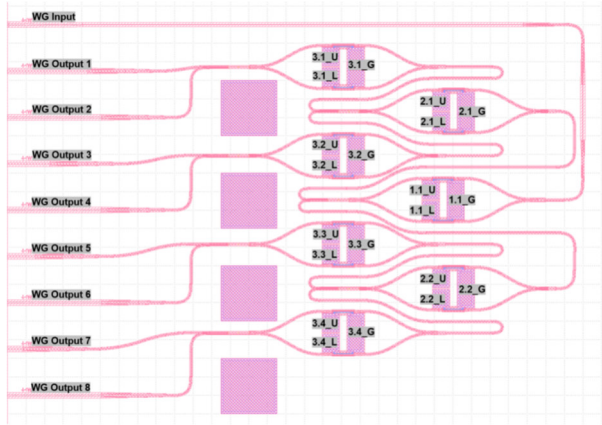


Figure 3. Layout of PIC TO 1x8 switch with 1x2 MMI (U- Upper heater/ L-Lower heater) and manufactured chip

After the manufacturing and probing test of all switch chip versions, a set of chips has been selected for packaging. The target was to package the chip versions showing the best functional performance. Only samples based on thermo-optic operation principle have been considered in the packaged devices.

A spot size converter (SSC), as shown in the figure below, was included in the module for enhancing fibre coupling efficiency. Indeed, as shown in the next section, fibre coupling losses are lower than 1 dB et insertion loss of modules are essentially due to splitting loss. The PIC chip is packaged into a 50x30 mm² 26-pin custom butterfly Kovar housing enabling hermetic sealing and polarization maintaining (PM) fiber arrays are used with FC/APC connectors for outputs ports. The following figure shows the packaged PIC TO 1x8 optical switch.

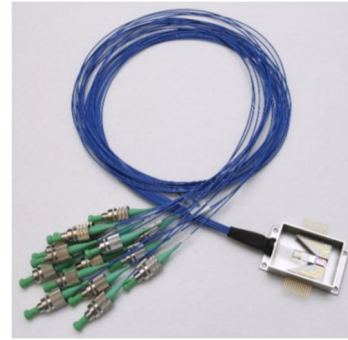
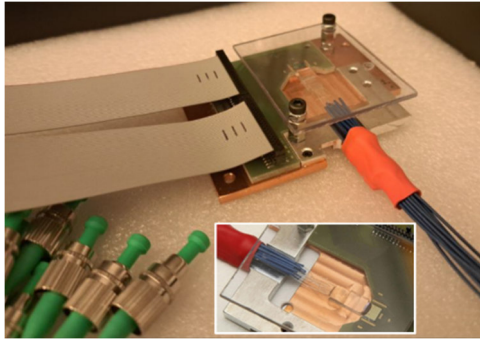


Figure 4. Spot size converter in a packaged PIC TO 1x2 switch device and packaged PIC TO 1x8 optical switch

3.2 Functional performance of a PIC TO 1x8 optical switch

Functional tests of a 1×8 switch device were performed to assess voltage/static response (IL, ER, crosstalk/optical isolation), wavelength and polarization dependence, as well as switching time and power consumption. The module uses a cascade architecture of 1×2 switches, implemented with seven interferometers across three splitting stages, where each interferometer is driven independently.

Voltage static response (IL, ER, X-talk): For each selected output channel, bias operating voltages of corresponding heaters is optimized to provide maximum transmission of optical power on the selected output channel. Indeed, for example for selecting output channel #1, voltages of respectively upper heater 1.1, upper heater 2.1 and upper heater 3.1 are adjusted for procuring maximum optical power transmission at the output.

Voltage static response is plotted for each output channel by varying bias voltage of the final heater. The figure hereafter shows it for channels #1/ #2.

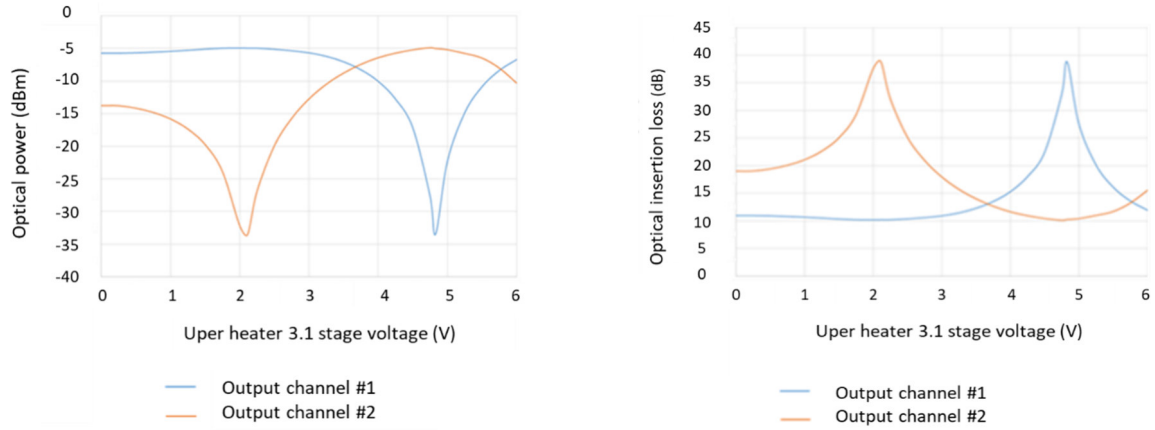


Figure 5. Voltage static response and insertion loss of channels #1/ #2

The functional performances in terms of optical insertion loss, Extinction Ratio and Crosstalk are given in the table below. Crosstalk is only evaluated on one pair of outputs in a same stage CH_n / CH_{n+1} for which measurement are performed simultaneously.

	Channel #1	Channel #2	Channel #3	Channel #4	Channel #5	Channel #6
Optical IL (dB)	10.23	10.15	11.3	11.75	10.45	10.36
ER (dB)	-27.36	-28.76	-29.04	-23.37	-28.96	-28.24
X-talk (dB)	-27.44	-28.67	-28.59	-23.82	-28.15	-29.06

Table 1. IL, ER & X-talk values of packaged PIC 1x8 TO switch sample

The measured optical insertion losses (IL) match well with the expected splitting loss from the required stages: selecting one output needs 3 stages, each with ~ 3.5 dB coupling loss, giving a theoretical total of about 10.5 dB. However, outputs #7 and #8 show higher IL (>13 dB) and very poor extinction ratios (ER) around -3 dB. This was due to a damage in the waveguide of one arm of the corresponding MZI. The damage had been accidentally caused by the wire bonding as the bond pads are very close to the waveguides. This prevented further characterizations using outputs #7 and #8 of that sample device.

Wavelength dependence: Assuming identical behavior across all output channels, the measurement is performed only on output channel #1. A voltage static response measurement is repeated by sweeping the input wavelength across the C-band (1535–1565 nm) in 5 nm steps, while recording the output optical power versus wavelength for a fixed heater bias voltage. The results show optical power variations of about 2.5 dB for the maximum transmission (“switch on”) bias and about 11.7 dB for the minimum transmission (“switch off”) bias. The device’s wavelength dependence changes strongly with the bias voltage applied to each heater.

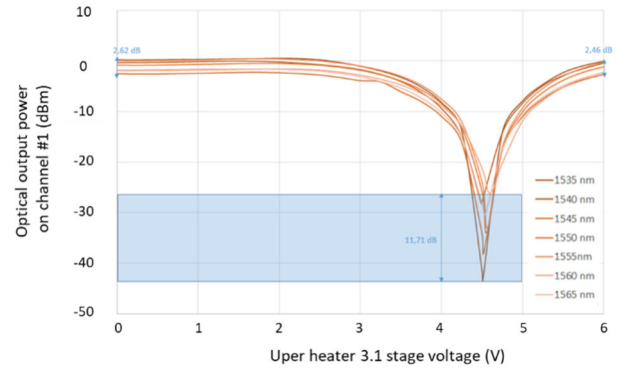


Figure 6. Wavelength dependence for output channel #1

Polarization dependence: PDL is measured separately for each optical output channel, with the goal of characterizing how polarization-dependent loss changes with switch position from minimum to maximum optical power transmission. After adjusting heater bias voltage for “switch on” and “switch off” states, a polarization controller at the switch input is used to quantify optical losses caused by changes in the input polarization state. Test are performed with an 8×1 optical switch exhibiting a worst-case specified PDL of 0.08 dB, which is much lower than expected. In practice, measured PDL values for channels #1 to #6 range from 2.5 (channel #5) to 3.4 dB (channel #1), mainly attributed to fiber-integrated guide coupling or transmission through the heater stages.

Switching time: The method implemented for measuring the switching time remains the same as the one used to assess the rise/fall time of a photodiode. First, a reference square-wave signal with the required amplitude is generated: then, high/low levels are observed on oscilloscope and tuned to correspond to maximum (“switch on”) and minimum (“switch off”). Next, the heater bias is replaced by the square-wave drive, switching is verified using an optical power meter, the signal is applied to a fast photodiode and oscilloscope, and the switching time is extracted as the difference between the rise time of the reference and the combined opto-electronic system.

Switching-time measurements are strongly affected by how the optical signal propagates through multiple heater stages. In the best configuration, switching between two paths within the same pair of outputs is achieved by changing the bias of the last heater stage, while the earlier stages are pre-biased to maximize transmission into that last stage. Switching times were measured separately for different output channels, but the full characterization of the switch was not completed due to limited time. For the channels tested, the switching time is quasi-constant at about 24–25 ps, slightly higher at the extreme outputs (~28–29 ps), and in all cases remains below 30 μ s.

Power consumption: An ammeter was placed between the heater power supply and the device under test to measure current consumption versus the last heater stage voltage for output channel #1 (3.1-Upper heater). Channel #1 is switched on at 5 V with a current of ~7 mA (~35 mW), and the current never exceeds ~8 mA, meaning each heater consumes less than ~48 mW.

4. TEMPERATURE TEST OF PACKAGED PIC TO 1×8 OPTICAL SWITCH

In order to evaluate the packaged PIC 1×8 TO optical switch sample vs. temperature, over a range from -15°C to $+65^\circ\text{C}$, the test focused on output pair channels #5/ #6, selected for its best trade-off in insertion loss and ER/X-talk. For each temperature, the voltage static transfer function of both channels #5 & #6 was measured by sweeping the upper heater last-stage (3.3-Upper heater) voltage, using a fixed +15 dBm CW laser as optical source. The figure below shows the experimental set-up implemented for measuring the variations of optical output power at both output channels #5 and #6 vs. temperature.

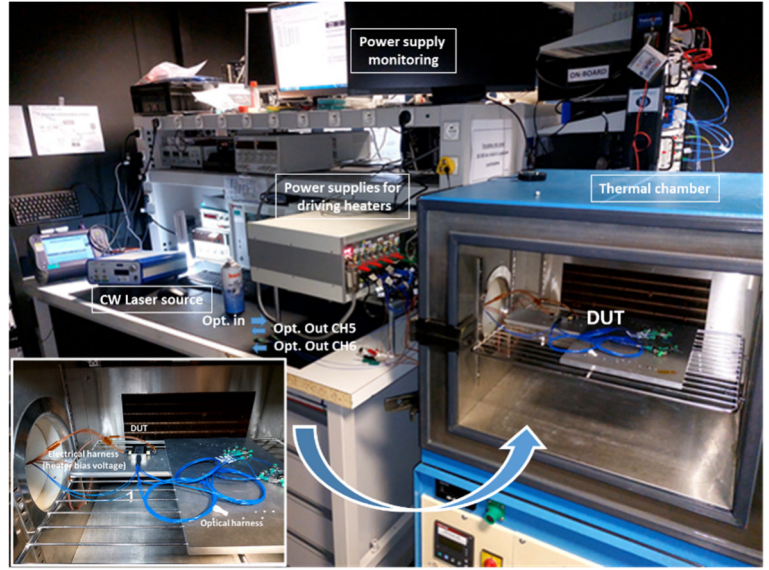


Figure 7. Experimental set-up for temperature tests of the PIC 1x8 TO optical switch sample

As shown in the figure below, up to +50°C, the maximum transmission changes by less than 1 dB and insertion loss remains relatively stable, but at +65°C the insertion loss increases sharply to 18.23 dB and crosstalk degrades (down to ~-21 dB), indicating the tested device cannot be reliably used above 50°C. The heater bias voltage required to achieve simultaneously maximum transmission on output channel #5 and minimum on output channel #6 also drifts slightly with temperature (about -3% at -15°C and +0.9% at +65°C), implying that a feedback loop would be required in real operation to maintain optimal performance.

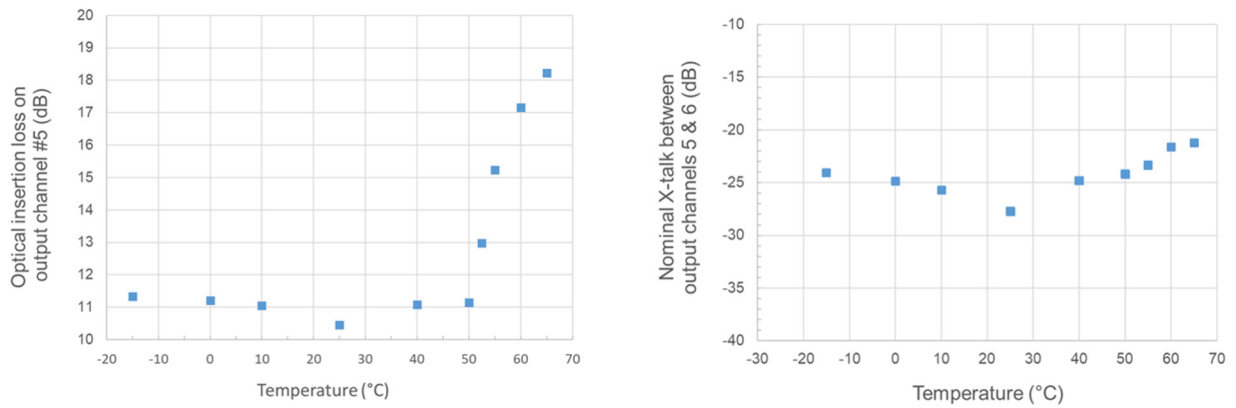


Figure 8. Optical IL and X-talk variations vs. temperature for output channel #5 of the PIC 1x8 TO optical switch

5. SYSTEM VALIDATION

For system validation, the packaged PIC 1×8 TO optical switch sample is implemented into an existing optical communications system test-bed to evaluate how crosstalk affects BER performance.

An overview of the experimental set-up is given in the next figure. The switch is used in a reversed 2×1 configuration, and the output pair channel #5/ channel #6 is selected because it provides the best insertion loss and crosstalk characteristics.

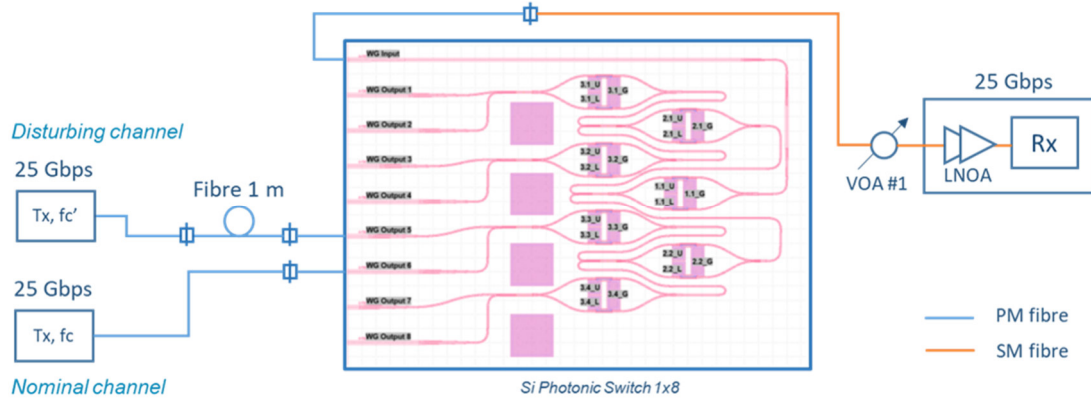


Figure 9. Overview of experimental set-up for system validation

Channel #6 serves as the nominal reference, carrying digitally modulated DPSK data at ~ 25.781 Gb/s (PRBS 15), while channel #5 sends a disturbing DPSK signal in parallel with a ~ 1 m optical patch cord to vary the signal phase vs. reference. The laser frequencies are aligned to about 1551.75 nm for a worst-case interferer scenario, and their optical powers are set respectively to quasi-equal values (+2.93 dBm & +2.65 dBm).

The switch optical input is routed through a VOA for adjusting input optical power on a low-noise optical amplifier increases with an output optical power close to +17 dBm. The amplified light is then sent to a digital optical receiver connected to a BER (bit error rate) tester. DPSK receiver includes a Delay Line Interferometer (DLI) for phase demodulation.

First, the last heater stage (i.e. 3.3 upper heater) bias voltage is set to provide minimum transmission on input channel#5 (switched off) and maximum transmission on input channel #6 (switched on), achieving a crosstalk near -29 dB. As shown in the figure hereafter, BER measurements show no significant degradation at the same wavelength on both nominal and disturbing channels or for a wavelength shifted by 100 GHz on the disturbing channel.

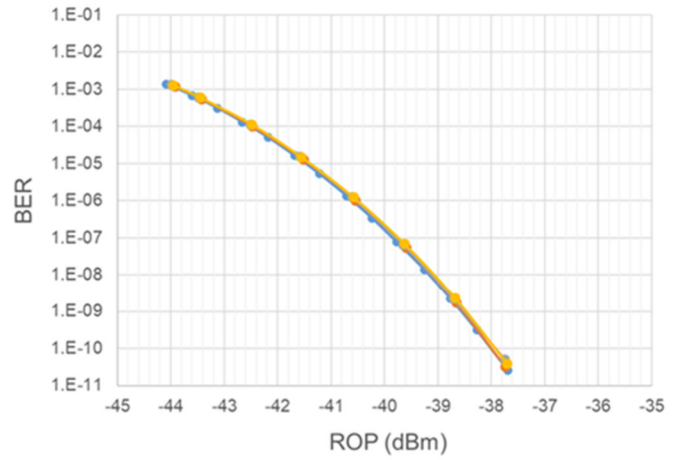


Figure 10. BER performances @ 25 Gbps DPSK vs. optical frequency variation between input channels (ROP: Received Optical Power)

Then, the heater bias voltage is adjusted to vary crosstalk while keeping the 100 GHz frequency offset between both wavelengths. The following figure shows modulated optical signals measured on OSA for different crosstalk between nominal and disturbing channels.

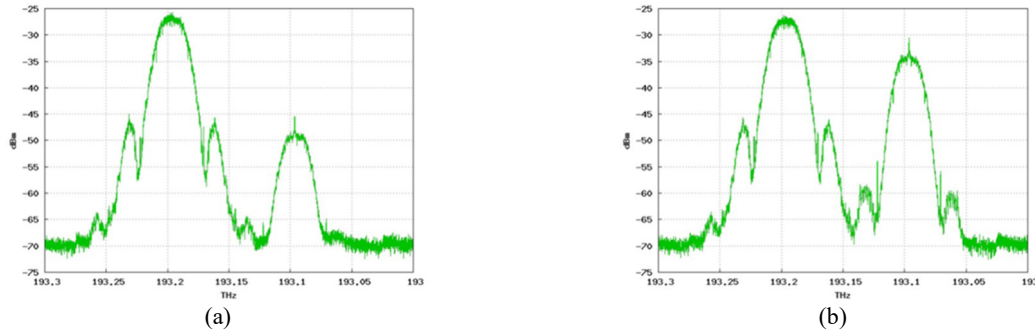


Figure 11. Test modulated optical signals in DPSK format for system validation w/ X-talk= 29 dB (a) and X-talk= 6 dB (b)

The figure below gives BER performance at 25 Gbps on channel #6 (switched on) vs. crosstalk level between the two optical input channels, where crosstalk is varied by adjusting the heater bias voltage.

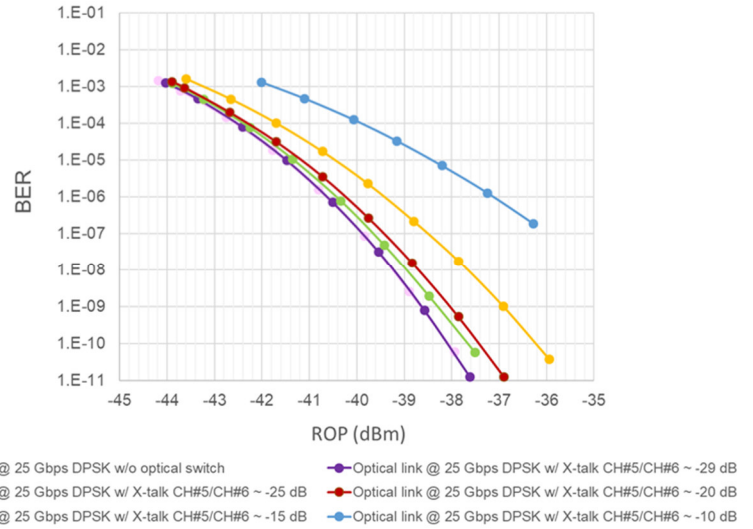


Figure 12. BER performances of optical link @ 25 Gbps DPSK vs. X-talk between optical input channels

The power-penalty curves hereafter show that keeping crosstalk better than -20 dB, the system remains largely robust, with less than 1 dB power penalty. Combined with the previous temperature characterization - where crosstalk remains relatively controlled up to +50°C - the optical switch is considered deployable in optical communications system without excessive performance loss.

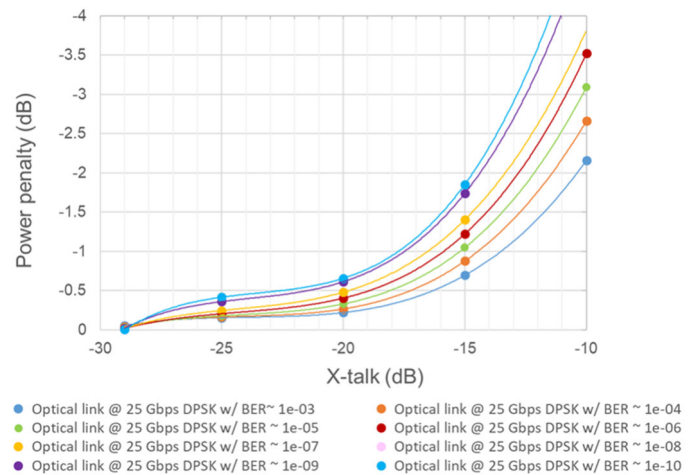


Figure 13. Power penalty of an optical link @ 25 Gbps DPSK vs. X-talk between input channels

6. CONCLUSION

This paper reports on the development and complete test of a 1x8 optical switch based on Si photonic integrated circuit (PIC) designed and manufactured by VTT in Finland. This device relies upon thermo-optical silicon switches including either 1x2 or 2x2 MMI couplers, cascaded in a tree-like architecture. Switching is based on phase shifting achieved via heaters, located on each arm of MMI couplers and each controlled by a bias voltage. Bias voltage may or may not be applied physically on heaters for switching on or off. For a 1x8 switch, seven 1x2 elementary switches need to be integrated in a 3-stage tree topology. The PICs was fabricated using VTT's 3 μm SOI technology guarantying propagation losses as low as 0.04 dB/cm. The TO 1x8 optical switch chip footprint was 5x5 mm² and was packaged into a 50x 30 mm² 26-pin custom butterfly Kovar housing, with polarization maintaining (PM) fiber arrays. A spot size converter (SSC) was included in the module for enhancing fibre coupling efficiency.

Packaged TO 1x8 optical switch sample was delivered to Thales Alenia Space for functional and thermal testing as well as for system validation. Achievements and test results of both the PIC-based optical switch and the whole sub-system for optical communications was presented. Optical performances of the packaged chip were measured at ambient temperature as well as under thermal conditions, and showed insertion losses around 10/11 dB, ER and crosstalk better than ~23 dB for output pairs, PDL between ~2.5 and 3.5 dB, switching times <30 μs , and nominal operation within the [-15 ; +50°C] temperature range. However, bias-voltage versus temperature behavior suggests that a feedback control loop could maintain optimal switching performance in operational systems.

System-level tests were carried out on an optical communication test-bed operating 25 Gbps DPSK modulation formats, in particular with the objective to assess the impact of the optical switch isolation on BER performance of the entire system. Promising results were obtained at 25 Gbps for instance under DPSK modulation, with power penalty < 1 dB for crosstalk < -20 dB. Switch operation was also shown possible for system within the [-15°C;+50°C] range without significant BER performance degradation. These results confirmed the potential of such an integrated switch technology for the target space applications.

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