Optical Switches with No Moving Parts for Space Applications

Components, Short Paper

David Poudereux, Juan Barbero
Alter Technology TÜV Nord
Tres Cantos, Madrid, Spain
David.poudereux@altertechnology.com

José Manuel G. Tijero, Ignacio Esquivias
Universidad Politécnica de Madrid
Madrid, Spain

Iain Mackencie
ESTEC
European Space Agency
Noordwijk, The Netherlands

Abstract: **We present the work done under the ESA Invitation-To-Tender (ITT) "Optical Switches with No Moving Parts for Space Applications". In this study the consortium reviewed the technical requirements of the space applications envisioned for solid state optical switches. After the technology selection a tradeoff was performed to select the final optical switches, based on three technologies (Magneto-Optic, Bulk Electro-Optic and Waveguide Electro-Optic) and fabricated by four different manufacturers. A test plan was developed, consisting of Thermal Vacuum Cycles, Mechanical Tests (vibration and shocks) and Radiation Test (gamma radiation). The results of the tests indicated that the three technologies are able to be used in space environment, that some technologies are more appropriate for some applications, and that some failure problems should be fixed in specific devices.**

Index Terms— **Relevant indexing terms: SpaceWire, Solid State Optical Switches, Spacecraft Electronics.**

I. Introduction

Optical switching is a generic building block for many optical systems and it has been proposed for a wide variety of future space applications, i.e., simple redundancy, providing fast isolation, or low speed modulation of the optical intensity.

The use of solid state switching greatly improves the reliability of optical switch technology when compared with the use of bulky mechanical switching systems [1]. In addition to this benefit solid state switching can provide faster switching speeds [2] which is required in SpaceFiber and in some optical switching applications.

Commercial off-the-shelf solid state optical switching technology exists in many forms developed for terrestrial markets such as Telecom or optical sensing; however, a comprehensive analysis of these technologies has not been previously performed with the aim of examining the challenges and benefits of adapting them to space applications.

It is an objective of the ESA to examine the suitability of solid state fiber optic switches to meet future space applications and define a complete technology development and space qualification roadmap for the most suitable solid state optical switch technology to be used in satellite payloads.

This paper summarizes the work done by the authors in response to the ESA ITT "Optical Switches with No Moving Parts for Space Applications" aimed at making a preliminary study of the maturity of the technology and defining a start point for the space qualification roadmap of these devices. The paper is organized as follows: Section II is devoted to the identification of promising space applications and the requirements imposed to the optical switches by these applications. The conclusions of an analysis of the state-of-the-art at market level of several optical switch technologies as well as the trade-off analysis for selecting the technologies and the devices to be tested are reported in section III. The central part of the work is the analysis of the results of the mechanical, thermal vacuum and radiation tests which is made in section IV. Finally, the conclusions and recommendations are summarized in section V

II. Requirements of the Space Applications

Several space related applications of the optical switches were identified. The envisaged applications are the following:

1- CO_2 Monitoring Lidar
2A- Atom Sensor-A (750nm)
2B- Atom Sensor-B (1580nm)
3- Optical Sensing
4- Digital Communications
5- Local Oscillator-Distribution
6A- Optical Communic. T. (5 KWpeak, 1s)
6B- Optical Communic. T. (10 W, 100 ms)
6C- Optical Communic. T. (100 mW, 500 ns)
7- Optopyrotechnics
8- Laser Interferometry

To review the requirements of the applications, the consortium contacted with experts in the applications, each application was analyzed, and eleven sets of requirements were defined. These requirements are summarized in Table I.

TABLE I. SUMMARY OF REQUIREMENTS (NLF: NON-LIMITING FACTOR)

APP. CODE	#1	#2A	#2B	#3	#4	#5	#6A	#6B	#6C	#7	#8
Wavelength (nm)	~2000 and 1550-1650	767/780	1534-1560	1520-1570 nm	850 nm	1525-1565	1550 1064	1550 1064	1550 1064	980+/-15	1064
Number of Inputs	2 (typical); 8 maximum	1	2(4)	1	8	1 (better 4)	1 (better more)	1(better more)	1(better more)	2	2
Number of Outputs	1	1	1	4	8	4	2 (better more)	2(better more)	2(better more)	8 (better 40)	1
Max. Input Power (mW)	≥ 50	≥ 300	≥ 1000	≥10 mW	≥ 1	≥ 40	≥ 10000 average ≥ 5 KW peak	≥ 10000 average	≥ 100	≥ 7500 peak	≥ 3000
Fibre Type	PMF	PMF	PMF	SMF	MMF (50/125)	PMF	PMF SMF	PMF SMF	PMF SMF	MMF (105/125)	PMF
Switch Speed (µs)	< 10	< 0.3	NLF.	< 50 µs	< 5	Irrelevant	Irrelevant	Irrelevant	< 0.5	Irrelevant	NLF
Number of Switch Cycles	$> 5 \cdot 10^9$	very high	NLF	5 billion	> 100	>1000	>1000	> 1E8	no wear out	1000	NLF
Lifetime (years)	>3 years LEO	15 years GEO	15 years GEO	15 years GEO	15 years GEO	15 years GEO	15 years GEO	15 years GEO	15 years GEO	15 years GEO	5 years 1 AU
Crosstalk (dB)	> 30	NLF	NLF	> 40 dB	> 30	> 30	> 20	> 20	> 20	> 50	NLF
Insertion Losses (dB)	< 3	< 1	< 1	< 2 dB	< 2	< 1	< 1.5	< 1.5	< 3	< 1	<1

III. ANALYSIS OF TECHNOLOGIES AND DEVICE SELECTION

The potential of different switch technologies for accomplishing the selected requirements was examined. The operating principles, advantages and inconveniences of seven different technologies were analyzed: Bulk Electro-optic (B-EO), Waveguide Electro-optic (WG-EO), Magneto-optic (MO), Acousto-optic (AO), Liquid Crystal (LC) and Thermo-optic (TO).

After the comparison between the requirements in table I and the specifications of commercial products the main conclusions were the following:

- There are no commercial products using TO technologies. In consequence this technology was not further analyzed.
- LC technology can be only tested through custom components, as it is not directly available. No manufacturer showed interest in cooperating in the project. In consequence this technology was not further analyzed.
- All applications require as minimum as possible insertion losses, in any case < 3 dB and in some cases < 1 dB. The products based on AO present IL > 3 dB. This technology is complex regarding the electronic driving, and its advantage is a high switching speed which is not required by any application. In consequence it was not further considered.
- In conclusion three technologies were considered: WG-EO, B-EO and MO. Within these technologies there are different manufacturers supplying optical switches with different characteristics (wavelength, maximum power, type of fiber, etc) and using different materials. Some of them were selected after a tradeoff process.

Two types of tradeoffs were considered:

- Tradeoff at Technology Level: The applicability of each technology was analyzed considering the space related possible applications without considering a particular device.
- Tradeoff at Component Level: In this case each part type was analyzed considering also the manufacturer. The output of this analysis was the final selection of components for the testing activities summarized in Table II, where the nominal characteristics of each device and the number of components are included.

In summary, eight different commercial models of optical switches fabricated by four manufactures using the three technologies (MO, B-EO and WG-EO) were selected for the testing.

TABLE II. SELECTED OPTICAL SWITCHES

Manufac.	Type	Max. Power (W)	Fiber Type	Sw. Speed (µs)	CT (dB)	IL (dB)	No
Agiltron (US)	MO	0.3	SMF	5-200	50	0.8	7
		0.3	PMF	5-200	50	0.8	7
		5	SMF	5-200	50	1	1
	B-EO	0.3	SMF	<0.3	25	0.8	7
Epiphotonics (US)	WG-EO	0.001	SMF	< 0.01	30	5	7
BATi (US)	B-EO	0.5	SMF	0.06	>20	<1.5	10
Primanex (CH)	MO	0.5	SMF	200-400	>40	< 1.3	1
		5	PMF	200-400		1.8	7

IV. Test Results

After procuring the selected components, a test plan following the usual test procedures for space applications was carried out.

The test plan consisted in the following steps and items:

- Initial Electro-Optical characterization
  - Insertion Loss (IL)
  - Crosstalk (CT)
  - Response Time
  - Polarization Dependent Losses/Polarization Extinction Ratio (PDL/PER)
- Mechanical Test
  - Vibration
  - Shock test
- Thermal Vacuum Test
- Radiation Test
- Destructive Physical Analysis

All the samples were electro-optically characterized and the results were compared with the nominal specifications in the manufacturer datasheets. The measured values were in some cases better and in other worse than the nominal values. They were taken as a reference

A. Vibration Test

A 10 cm side vibration cube was used for fixing the samples. This cube is free of resonances up to more than 2000 Hz and it can be rotated to allow changing the axis easily. The levels of the vibration are summarized in Table III.

The duration on each of the 3 orthogonal axes test was 3 minutes. One sample of each part type was monitored during test, and the output of the switches was changed alternatively with a periodicity of approximately 10 seconds. Each switch had three optical fibers (one input and two outputs) and two electric wires (except EpiPhotonics switch which needs 24 electric wires to control the applied voltages). Before the random vibration a pre-vibration test was performed in each axis looking for possible undesirable resonances. Two accelerometers collected the data, one uniaxial, fixed to the shaker and a second triaxial, fixed to the cube. Each one provides different information, but both data are correlated. The data taken for the accelerometers attached to the shaker and cube of the first run in the X axis are shown in Figure 1.

Figure 2 shows the stability of the measured optical power at each output of the switches during the vibration test. There are in fact two sets of data for each output, one for the values in the maximum (ON state) and other for minimum (OFF state). The IL and the CT of each output are calculated by simultaneously measuring the power at both outputs. The flatness of these plots reveals that the optical power, i.e. the insertion loss, kept constant during the vibration test.

TABLE III. VIBRATION LEVELS

Frequency (Hz)	Protoflight Level
20	0.52 g^2/Hz
20-50	+6 dB/Octave
80-800	0.32 g^2/Hz
800-2000	-6 dB/Octave
2000	0.052 g^2/Hz
Overall	20 grms

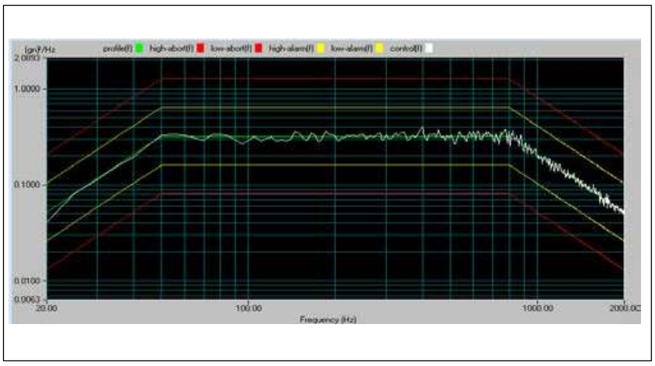

Fig. 1. Random vibration in X axis.

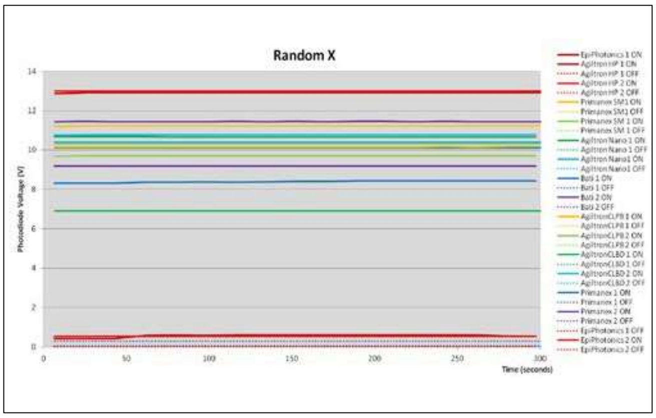

Fig. 2. Random vibration optical power monitoring in X axis

B. SRS Shock Test

The 500g half Sine Pulse 1ms duration shock profile was converted to a SRS shock test. Three impacts were made in each axis. All the electro-optic parameters of all the switches were measured after the test showing no variation. Only one of the switches (EpiPhotonics) was damaged during this test. One of its arms (the input one) was unglued.

C. Thermal Vacuum Test

The thermal cycling tests were done under the conditions detailed in Table IV.

Five thermocouples were fixed to the hot/cold plate to control and measure the temperature. Two runs were performed at the beginning in order to test the same part types of all the switches that underwent the vibration test. The monitoring set-up was very similar, the only difference being that the drivers and the splitter were placed inside the vacuum chamber, isolated from the cold/hot plate. A previous validation test was performed to ensure the proper functioning of the photodiodes.

TABLE IV. VACUUM THERMAL CYCLING CONDITIONS

Vacuum Thermal Cycling Test Proposed		
Tmin	-10º C	-5ºC
Tmax	75ºC	+70ºC
Dwell time at Tmin & Tmax	2 hours	2 hours
Pressure	$<10^{-5}$ mbar	$<10^{-5}$ mbar
Temp rate	<5ºC/min	<5ºC/min
Number of cycles	1	7

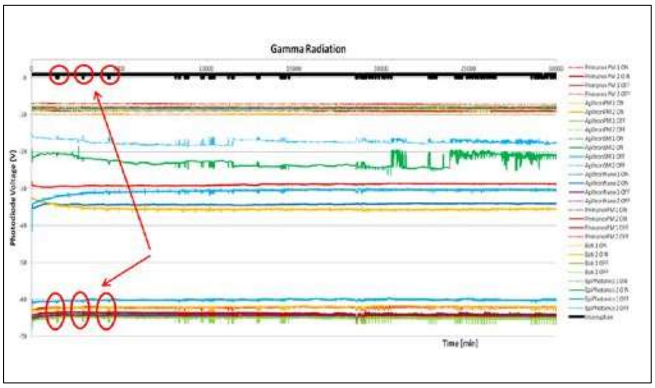

Figure 3. Evolution of the optical power along the radiation test

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D. Radiation Test

The Gamma Radiation campaign was performed at the facilities of the National Center of Accelerators (CAN) in Seville (Spain). The dose rate was ~210 rad/(Si)h with an accumulated dose of ~100 krad(Si) and a duration of ~480 hours. The switches were placed in an aluminum box covered with PMMA to achieve the condition of electronic balance. The optical output power was monitored along the whole radiation test.

The evolution of the optical power through all the outputs (two per switch) in both states ON/OFF (output 1/ output 2) is plotted in Figure 3. The interruptions of the radiation, inherent to the regular operation of the facility, are also highlighted with black marks. These interruptions lasted less than 2 hours. Note that the output optical power is sensitive to the radiation interruption, mainly in the OFF states.

E. Destructive Physical Analysis

After the final electro-optical characterization, a destructive physical analysis was made to some optical switches. Only six part-types were analyzed since two part-types differ only in the fiber type (SM or PM) (see table II).

Only one switch (EpiPhotonic) showed damage. It was the switch which input fiber was broken in the shock test. It seems that the crystal spliced to the fiber was unglued in the test. Likely, this failure is not inherent to the WG-EO technology since the aligning of the crystal in the photonic circuit is not more complex than for other technologies.

F. Evaluation of the test results

The results of the electro-optical characterization after each test were compared with the corresponding results for each parameter prior to the tests. The averaged standard deviation of all the measurements of each reference part type has been taken as a value of the uncertainty and the deviation of the values of each parameter after each test has been compared with this uncertainty. The Student's t-distribution was used for this statistic. Judicious criteria were defined to decide whether a part type passed the test. According with these criteria all the tested samples, except the mentioned EpiPhotonic switch, passed all the tests.

V. Conclusions And Recommendations

The conclusions of our study are the following:

- B-EO and MO technologies are excellent candidates for the space applications analyzed. They respond very well under typical space conditions as radiation, vibration, shocks and thermal vacuum.
- B-EO technology behaves slightly better than MO technology and it is the choice for those applications requiring high switching speed. However, its crosstalk is worse
- MO technology exhibits very good properties, except for the switching time. Moreover, there are many manufacturers and commercial products fabricated with this technology.
- WG-EO technology is very fast. Its mechanical problems could be solved if the gluing of the crystals to the socket is improved to resist the shock tests. However, the switches are very complex to handle and control, their insertion losses are very high and the cross talk very low. The high-speed requirement of some applications is covered by B-EO technology and therefore WG-EO is not recommended for space applications.
- Switches are more sensitive to temperature than to radiation and vibration.
- No difference has been found between the behavior of polarization maintaining fibers and single mode fibers.
- The low power (single mode fiber) MO devices and the high power (multimode fiber) devices from the same manufacturer (Agiltron) behave alike under the tests when operated at low power.

Based on these conclusions the recommendations were:

- To use B-EO and MO technologies for the space applications analyzed. B-EO should be used for applications requiring high switching speed while MO technology should be used for those applications requiring a minimum crosstalk.
- To keep constant the device temperature if constant output power is required.

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