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Evaluation of Optical Switches for Space Applications

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ABSTRACT

We have evaluated the performance for space applications of commercial off-the-shelf fiber coupled optical switches with no-moving parts, based on different technologies. The technical requirements of several space applications of optical switches were defined. After the technology selection, a tradeoff was performed to select the final optical switches to be tested, which are based on three technologies (Magneto-Optic MO, Bulk Electro-Optic B-EO, and Waveguide Electro-Optic W-EO) and fabricated by four different manufacturers. Other potential technologies (acousto-optic, liquid crystal, thermo-optic, micro/nano photonic waveguides) were not selected due to the lack of commercial products. A test campaign was carried out, consisting of thermal vacuum cycles, mechanical tests (vibration and shocks) and radiation tests (gamma radiation). The main performance parameters were the insertion loss, crosstalk, and switching speed. After the final electro-optical characterization, a destructive physical analysis was made to some optical switches. The results of the tests indicated that B-EO and MO technologies are excellent candidates for the analyzed space applications. They respond very well under typical space conditions as radiation, vibration, shocks and thermal vacuum; B-EO technology presents lower switching time but its crosstalk is worse. WG-EO technology is very fast, but a mechanical failure in one device was observed, the insertion losses are very high and the crosstalk is very low.

Keywords: Optical switches, Space photonics, Magneto-optic switches, Electro-optic switches

1. INTRODUCTION

Optical switches are important components for many optical systems and they are widely used for a large variety of space applications, such as optical communication terminals, LIDAR, altimeters, optical on-board communication and fiber optic sensing. These applications require highly reliable optical switches to provide redundancy, multiplexing capacity, and new functionalities in systems based in optical fibers. Many different approaches are available in terrestrial applications to provide this switching function, including those with and without moving parts. Optical switch technologies without moving parts, sometimes called solid-state switching, are clearly appropriate for the space requirements. Commercial off-the-shelf (COTS) 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.

This paper summarizes the work done by the authors in the frame of the European Space Agency (ESA) contract "Optical Switches with No Moving Parts for Space Applications" aimed at examining the suitability of solid state fiber optic switches to meet the requirements of future space missions, and at defining a complete technology development and space qualification roadmap for the most suitable solid state optical switch technology for future satellite payloads.

The paper is organized as follows: Section 2 is devoted to the identification of the technical requirements of some selected space applications which require the use of reliable optical switches; the fundamentals of the different switching technologies, as well as the reasons to select some of them~~,~~ are summarized in Section 3; the central part of the work is described in Section 4, including the selection of the COTS devices to be tested, the test conditions and the test results. Finally, the conclusions are summarized in section 5.

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2. REQUIREMENTS OF OPTICAL SWITCHES FOR SPACE APPLICATIONS

ESA proposed the following space applications for the optical switches:

#1: *CO_2 Monitoring Lidar* [1,2]: Carbon dioxide (CO_2) is the major anthropogenic greenhouse gas contributing to global warming and climate change. A better knowledge of the spatial and temporal distribution of the sources and sinks of CO_2 at the Earth surface is required. This is and has been the objective of NASA mission proposal ASCENDS and ESA mission proposal A-SCOPE based in space-borne Integrated Path Differential Absorption (IPDA) pulsed lidar systems. These systems are based in sending pulses at different wavelengths and detecting the received echoes with the aim of measuring the differential absorption and determining the so-called column averaged dry air CO_2 mixing ratio (X_{CO2}).
#2: *Atomic sensors*[3,4]: Atomic sensors, or atomic interferometers, have a number of potential applications in space including precise measurements of the earth gravitational field, in navigation and ranging, and in fundamental physics such as tests of the weak equivalence principle and gravitational wave detection.
#3: *Optical Sensing*[5-9]: fiber optic sensors are ubiquitous in satellites. Temperature monitoring is massively performed on the lateral walls of the satellite communication modules, where the payload is attached. The use of fiber-optic sensors significantly reduces the MAIT time (Manufacturing, Assembly, Integration and Test) and the structural weight without compromising reliability.
#4: *Digital Communications*[10]: Digital communications based on Vertical Cavity Surface Emitting Lasers and PIN photodiodes are expected to be widely used for high data rate intra-satellite communication.
#5: *Local Oscillator-Distribution*[11-12]: There are multiple applications of photonics in next generation of telecommunication satellite payloads. A very important one is the distribution of photonic Local Oscillator signals to facilitate the Photonic/RF conversion process.
#6: *Optical Communication Terminal:* The use of free-space optical communication systems in satellites has been continuously increasing over the last 15 years, starting with short range inter-satellite link terminals (Gbit/s rates over distances of around 2000 km), later up to distances of 80,000 km, and recently with the development of deep space optical link terminals.
#7: *Optopyrotechnics*[13-14]: The role of optical switches in optopyro systems is to control the access of the light pulse into the so-called Optical Safety Barrier (OSB). The OSB acts as the ultimate safety barrier downstream of the Laser Firing Unit.
#8:*Laser Interferometry*: Laser interferometry is the basic technology for fundamental physics missions such as LISA (Laser Interferometer Space Antenna).

In order to define the requirements of the optical switches to be used in the different applications, the Consortium contacted with experts in each application. The operating wavelength, type of fiber, typical number of inputs/outputs, switching speed, maximum input power, number of switch cycles or lifetime, Insertion losses (IL) and Crosstalk (CT) required by each application were estimated. Application #2 (Atom sensor) was divided in two sets of requirements: #2A (750nm) and #2B (1580nm). Application #6 (Optical Communication Terminals) was divided in three sets of requirements: #6A (5 kWpeak, 1s); #6B (10 W, 100 ms); #6C (100 mW, 500 ns). In consequence, eleven sets of requirements were defined, which are summarized in Table 1, where the applications are identified by the code number.

Table 1: Requirements of the optical switches for the different space applications. SMF: Single Mode Fiber; PMF: Polarization Maintaining Fiber; MMF: Multi-Mode Fiber; NLF: Non-Limiting Factor

APP. CODE	#1	#2A	#2B	#3	#4	#5
Wavelength (nm)	~2000 and 1550-1650	767/780	1534-1560	1520-1570	850	1525-1565
No. of Inputs	2 (typical); 8 maximum	1	2(4)	1	8	1 (better 4)
No. of Outputs	1	1	1	4	8	4
Max. Input Power (mW)	≥ 50	≥ 300	≥ 1000	≥10	≥ 1	≥ 40
Fibre Type	PMF	PMF	PMF	SMF	MMF (50/125)	PMF
Response time (µs)	< 10	< 0.3	NLF.	< 50	< 5	Irrelevant
Number of Switch Cycles	> 5·109	very high	NLF	5 billion	> 100	>1000
Lifetime (years)	>3	15	15	15	15	15
CT (dB)	> 30	NLF	NLF	> 40	> 30	> 30
IL (dB)	< 3	< 1	< 1	< 2	< 2	< 1

APP. CODE	#6A	#6B	#6C	#7	#8
Wavelength (nm)	1550 1064	1550 1064	1550 1064	980+/-15	1064
No. of Inputs	1 (better more)	1(better more)	1(better more)	2	2
No. of Outputs	2 (better more)	2(better more)	2(better more)	8 (better 40)	1
Max. Input Power (mW)	≥ 10000 average ≥ 5 kW peak	≥ 10000 average	≥ 100	≥ 7500 peak	≥ 3000
Fibre Type	PMF SMF	PMF SMF	PMF SMF	MMF (105/125)	PMF
Response time (µs)	Irrelevant	Irrelevant	< 0.5	Irrelevant	NLF
Number of Switch Cycles	>1000	> 1E8	no wear out	1000	NLF
Lifetime (years)	15	15	15	15	5
CT (dB)	> 20	> 20	> 20	> 50	NLF
IL (dB))	< 1.5	< 1.5	< 3	< 1	<1

3. OPTICAL SWITCH TECHNOLOGIES

The potential of different switching technologies without moving parts 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), Thermo-optic (TO), and other micro/nano photonics waveguides. A good description of the technologies for optical switching with and without moving parts can be found in Refs.[15-17].

3.1 Description of technologies

Bulk Electro-Optic switches

B-EO switches are classical devices that have been used for many years in optics setups, especially associated with lasers. More recently, B-EO switches have been miniaturized to match the dimensions required in fiber optics. The structure of B-EO switches is similar to that of polarization-independent optical circulators, with an additional voltage-controlled EO element that switches the polarization of the beam and therefore selects the output port. The materials used as electro-optic phase retarders in commercial B-EO switches are non-centrosymmetric materials which have been proposed in some patents. They include ferroelectric complex oxides having a Curie temperature lower than 600 °C and high electro-optic coefficient, for instance lead niobate zirconate (PNZ), lead manganese niobate (PMN), lanthanum modified lead zirconate titanate (PLZT), and a solid solution of lead manganese niobate and lead tantalate (PMN-PT).

Waveguide Electro-Optic switches

These devices are similar to optical modulators, based on an interference effect, which selects the output with constructive interference depending on the applied electrical field. There are different geometrical approaches, such as the Mach-Zehnder interferometer (MZI), the directional coupler, and the Y-brand switch. The main advantage of WG-EO optical switches is the low switching time due to the development of high-speed optical modulators, which can reach up to 40 Gb/s. The maturity of the optical modulator technology is also an important advantage. The main inconveniences are the relatively high losses due to the coupling of the waveguide to the optical fiber, and the relatively reduced optical power handling capacity. The materials employed are those used in optical modulator technology (lithium niobate, GaAs, polymers, etc.), and also epitaxial PLZT.

Acousto-optic switches

Optical switches can be made by exploiting the acousto-optic effect where the refractive index of an optical medium is modulated by acoustic waves. An acoustic or elastic wave travelling in a medium induces periodical deformation in the form of alternating compressions and rarefactions. This results in a periodical strain in the medium. The vibrations of the molecules due to this strain alter the optical polarizability of the material and, consequently, its refractive index. Beam deflection by the acousto-optic effect can be exploited to make several optical devices such as deflectors, tunable filters, switches, modulators, spectrum analyzers, and frequency shifters. The main materials used for AO devices include Lithium niobate (LN), tellurium dioxide and tellurite glasses, GaAs/ZnO, InGaAsP/ZnO. A review on AO switches can be found in Ref. [18].

Magneto-Optic switches

MO switches are based on Faraday materials attached to non-permanent magnets, with a basic structure similar to that of the B-EO switches. Applying the appropriate signal to an electromagnet, the required magnetic field can be induced, changing the polarization of the beam crossing the Faraday material and therefore selecting the output port.

Liquid Crystal switches

LCs are rod-like molecules in a state of the matter intermediate between liquid and solid. The optical properties of LCs depend on molecular orientation and can be controlled by applying relative modest electric fields across LC cells. This effect is exploited in very mature technologies such as the LC Displays (LCD) and Wavelength Selective Switches (WSS).

Thermo-optic switches

TO switches are based on the dependence of the refractive index on the temperature. The physical configuration of TO switches is similar to that explained in the case of WG-EO switches, they are devices based on the interference between optical waveguides. The temperature variation is achieved by means of micro heaters positioned above one of the waveguides. The main materials employed for TO switches are silica based waveguides on Si, polymer based waveguides, hybrid polymer/silica and silicon-on-insulator. III-V compounds, amorphous Si, LN, Tantalum and Aluminum oxides have been also investigated for this application. TO switches have been reviewed in Refs. [19-20].

Other micro/nano photonics waveguides

The strong interest in efficient, fast and large density optical switches for communications has led to an intensive research activity in many different materials and physical phenomena which could be applied to this purpose. We mention some of them, but we do not consider them later as they have not yet reached commercial status. The most interesting approach is silicon photonics, which is continuously increasing the quality and speed of optical modulators, and therefore optical switches. Plasmonics is also producing very promising results, and other approaches include Quantum Confined Stark Effect in Quantum Wells, photonic crystals, graphene, etc.[21].

3.2 Selection of Optical Switch Technologies

After a survey of commercial products, the nominal specifications of the COTS devices were compared with the requirements in table 1. The main conclusions were the following:

- There are no commercial products using either TO technologies or micro/nano photonics waveguides. In consequence these technologies were not further analyzed.
- LC technology can only be tested through custom components, as simple NxM switches are not directly available in COTS components. No manufacturer showed interest in cooperating with the project. In consequence this technology was not further analyzed.
- All applications require as low 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.
- Three technologies, WG-EO, B-EO and MO, are used by different manufacturers supplying optical switches with different characteristics (wavelength, maximum power, type of fiber, etc) and using different materials. These technologies were selected for evaluation.

4. TESTING OF OPTICAL SWITCHES

4.1 Selection of Devices

The nominal characteristics of the components offered by more than ten manufacturers were analyzed. The manufacturers were contacted and additional information (reliability, options for custom components, previous use in space applications, etc.) was requested. After a trade-off process at component level, 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 2 summarizes the nominal main characteristics of the selected components and the number of samples acquired for the testing. The operating wavelength of all switches was 1550 nm, even when many applications require other wavelengths (see Table 1), as it was considered that the wavelength was not important for reliability issues. All selected devices were 1 X 2 considering that a N X M switch is a combination of several 1 X 2 switches. Although some applications require MMF, the selected components were SMF or PMF because we could not find COTS MMF switches, although custom devices were available. Some applications require high power and therefore some high power switches were also selected.

Table 2: Nominal specifications, according to the datasheets, of the selected types of optical switches, and number of acquired samples of each type.

Manufacturer	Technol.	Ref.	Max. Power (W)	Fiber Type	Resp. time (µs)	CT (dB)	IL (dB)	No. of samples
Primanex[22] (China)	MO	#A	0.5	SMF	200-400	> 40	< 1.3	1
		#B	5	PMF	200-400	> 40	1.8	7
Agiltron[23] (US)	MO	#C	0.3	SMF	5-200	50	0.8	7
		#D	0.3	PMF	5-200	50	0.8	7
		#E	5	SMF	5-200	50	1	1
	B-EO	#F	0.3	SMF	< 0.3	25	0.8	7
BATi[24] (US)	B-EO	#G	0.5	SMF	0.06	> 20	< 1.5	10
Epiphotonics[25] (US)	WG-EO	#H	0.001	SMF	< 0.01	30	5	7

4.2 Test plan

After procuring the selected components, a test plan following the usual test procedures for space applications was defined. The test plan, for those part types with several samples, is shown schematically in Fig. 1. In the cases of the part types with only one sample a different test plan was applied and all types of test were performed.

4.3 Electro-optical characterization

All the samples were characterized at the beginning of the testing and after each step of the test plan, as it is indicated in Fig. 1. The characterization included the following measurements:

- Insertion Loss (IL): it was determined using as reference the power measured using a patchcord instead of the switch. Due to the repeatability of the FC/APC fiber connectors the estimated uncertainity of the IL was ± 0.3 dB
- Crosstalk (CT): defined as the ratio, in dB, between the power at the input and the power at the non-selected output. It was measured simultaneously with the IL considering the switch with one input and two outputs and measuring the power in the two outputs.
- Response Time: it was measured by using a control signal (nominally squared) from a signal generator to switch the output power and monitoring the power at both outputs with fast photodiodes and an oscilloscope. The response time was defined as the delay difference between the control signal and the output power during the switching.
- Return Loss (RL): measured with the help of a 1x2 splitter/combiner and of a fiber optic light trap to determine the reference level.
- Polarization Dependent Losses (PDL): measured by placing a polarization controller at the input of the optical switch and rotating the polarization in all states while the optical power at the output was monitored.
- Polarization Extinction Ratio (PER): measured for those samples with PMF. It was measured with the help of PER tester and a PMF coupled laser diode.

All the measurements were performed at room temperature using a 1550 nm low power laser. The results of the initial electro-optical characterization were used as reference for each sample

GROUP	SUBGROUP	Description	Group of Samples			
Procurement		Procurement of each Part type and review of manufacturer documentation	1	2	3	R
Initial EO		Electro-optical Measurement and Inspection - Insertion Loss - Crosstalk - Response Time - PDL / PER	T	T	T	R
Validation	Mechanical Test	Vibration	T			R
Validation	Mechanical Test	Electro-optical Measurement and Inspec.	T			R
Validation	Mechanical Test	Shock Test	T			R
Validation	Mechanical Test	Electro-optical Measurement and Inspection	T			R
Validation	Vacuum Thermal	Electro-optical Measurement and Inspection		T		R
Validation	Vacuum Thermal	Monitored Vacuum Cycles		T		R
Validation	Vacuum Thermal	Electro-optical Measurement and Inspection		T		R
Validation	Radiation	Gamma Radiation Monitoring			T	R
Validation	Radiation	Electro-optical Measurement and Inspection			T	R
Validation	Final DPA	Final DPA and comparison with initial	O	O	O	O

T	Test
R	Reference
O	Optional

Figure 1: Schematics of the test plan. DPA: Destructive Physical Analysis.

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4.4 Test conditions

A. Vibration Test

A 10 cm edge length 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 3.

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 type #H switches which need 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.

Table 3: Vibration Levels

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

B. Shock Response Spectrum (SRS) Test

The SRS was performed by using a 500 g mass producing the vibration (1ms duration half sine pulse) which was converted to a SRS test. Three impacts were made in each axis.

C. Thermal Vacuum Test

The thermal cycling tests were done under the conditions detailed in Table 4. The optical power was monitored during the cycles. A previous validation test was performed to ensure the proper functioning of the photodiodes with the temperature variations.

Table 4: Vacuum Thermal Cycling Conditions

Vacuum Thermal Cycling Test Proposed		
T_{min}	-10 ºC	-5 ºC
T_{max}	75 ºC	+70 ºC
Dwell time at T_{min} & T_{max}	2 hours	2 hours
Pressure	<10-5 mbar	<10-5 mbar
Temp. rate	<5ºC/min	<5ºC/min
Number of cycles	1	7

D. Radiation Test

The Gamma Radiation campaign was performed at the facilities of the Centro Nacional de Aceleradores (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 output optical power was monitored along the whole radiation test.

E. Destructive Physical Analysis

After the final electro-optical characterization, a Destructive Physical Analysis (DPA) 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).

4.5 Test results

The most relevant result of this work is that all tested samples passed satisfactory the test without relevant changes in the measured parameters, with the exception of one of the WG-EO switches (type #H) which had a catastrophic failure, as it will be commented later. The pass/non-pass criteria were defined comparing the results of the electro-optical characterization after each test with the corresponding results for each parameter prior to the tests, taking into account the measurement uncertainty. The total numbers of samples passing the mechanical, thermal vacuum and radiation tests was 14, 15 and 15, respectively.

During the SRS test one of the WG-EO samples was damaged, there was no power continuity between the input and the outputs. During the DPA it was observed that the input lens was unglued from the packing.

Figure 2 shows, as an example, the measured optical power at each output of three switches during the thermal vacuum cycles, together with the temperature profile. Small variations of the power in the ON and in the OFF outputs during the temperature transitions can be observed in the type #G switch, while #A and #E are quite stable. Fig. 3 shows, as an example, the evolution of the measured power during the radiation test for several samples. The power instabilities of the OFF outputs correspond to interruptions of the radiation, which lasted less than 2 hours. The output optical power is sensitive to the radiation interruption, but no sample showed degradation during the radiation period.

Table 5 shows the summary of the electro-optical characterization results for all part types. The values of the parameters are the average for all measurements and for all samples of each part type. They should be compared with the requirements of the space applications in table 1. It can be observed that MO and B-EO devices present IL lower than 1 dB, but that the WG-EO switches have high losses, higher than 10 dB. The CT of the MO devices is very high, around 60 dB, while it has lower values for the B-EO and WG-EO devices. The RL is high for all part types, except for the WG-EO devices which present a very low value. As expected, the response time of the MO switches is high (100 – 400 µs, depending on the particular part type), it is much lower in the case of B-EO switches (70 – 150 ns) and very low for WG-EO devices (~ 30 ns).

Table 5: Average values of the parameters for the part types.

Ref.	**Technology**	**Fiber type**	**High power?**	**IL (dB)**	**CT (dB)**	**RL (dB)**	**Response time (µs)**	**PDL (dB)**	**PER (dB)**
#A	MO	SM	NO	0.60	62.7	43.5	434	0.20	--
#B	MO	PM	YES	0.97	63.3	43.5	410	0.19	19.6
#C	MO	SM	NO	0.79	57.1	52.8	121	0.15	--
#D	MO	PM	NO	0.80	57.6	51.5	125	0.26	19.0
#E	MO	SM	YES	0.49	60.7	58.1	97	0.08	--
#F	B-EO	SM	NO	0.93	23.1	52.91	0.140	0.15	--
#G	B-EO	SM	NO	0.86	27.2	53.8	0.074	0.15	--
#H	WG-EO	SM	NO	10.5	19.4	16.6	0.027	1.18	--

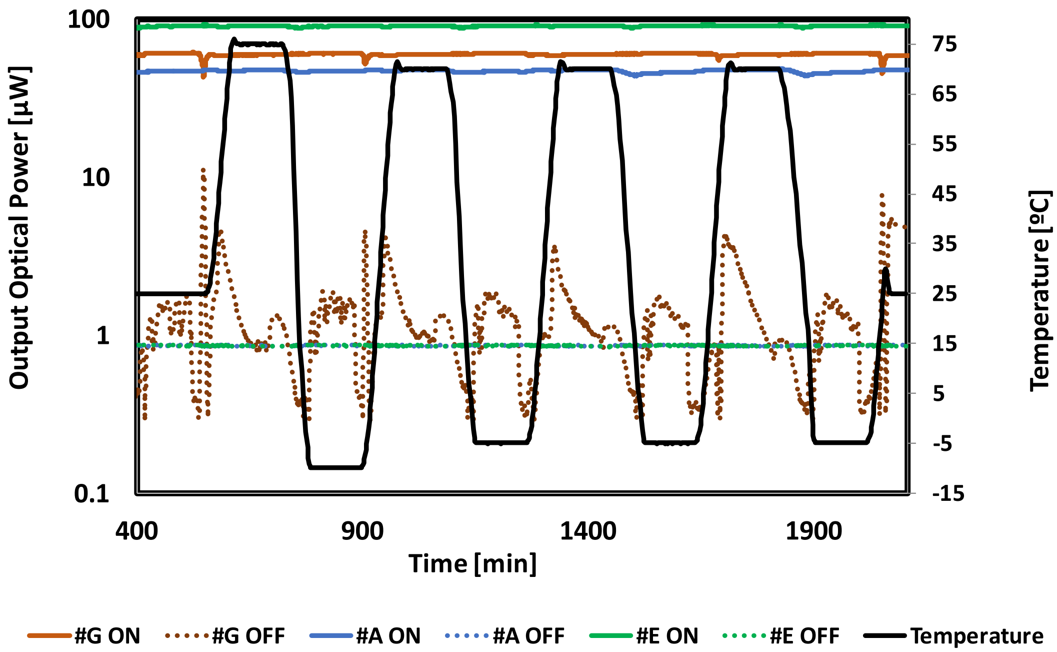

Fig. 2: Measured optical power of several samples during vacuum thermal cycles, and temperature profile.

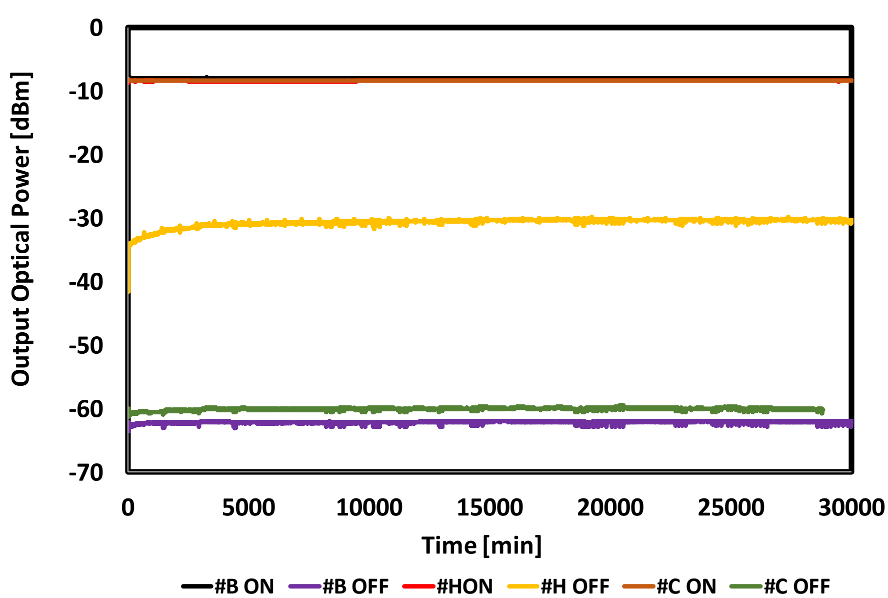

Fig. 3: Measured optical power of several samples during radiation test.

5. CONCLUSIONS

The conclusions of our study are summarized as follows:

- Optical switches based on B-EO and MO technologies are excellent candidates for the analyzed space applications. 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 has very fast response. The observed mechanical problems could be solved by a better gluing procedure. However, these switches are very complex to handle and control, their insertion losses are very high and the crosstalk very low.
- No difference has been found between the behavior of polarization maintaining fibers and single mode fibers.
- The low power MO devices and the high power devices from the same manufacturer behave similarly when tested at low power.

In summary, the results of this work pave the way for the future use of optical switches without moving parts in space applications. Further work is still necessary to assess the practical use: each future application should select the appropriate switch in terms of wavelength, type of fiber, maximum power, switching speed, and the technology should be tested to demonstrate the achievement of the required lifetime or number switching cycles.

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