ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

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esa icso proceedings cnes

International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 1056259 · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296138

OPTO-MICROWAVE, BUTLER MATRIXES BASED FRONT-END FOR A MULTI-BEAM LARGE DIRECT RADIATING ARRAY ANTENNA

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I. INTRODUCTION

The evolution of broadband communication satellites shows a clear trend towards beam forming and beam-switching systems with efficient multiple access schemes with wide bandwidths, for which to be economically viable, the communication price shall be as low as possible. In such applications, the most demanding antenna concept is the Direct Radiating Array (DRA) since its use allows a flexible power allocation between beams and may afford failures in their active chains with low impact on the antenna radiating pattern.

Forming multiple antenna beams, as for 'multimedia via satellite' missions, can be done mainly in three ways: in microwave domain, by digital or optical processors:

- Microwave beam-formers are strongly constrained by the mass and volume of microwave devices and waveguides
- the bandwidth of digital processors is limited due to power consumption and complexity constraints.
- The microwave photonics is an enabling technology that can improve the antenna feeding network performances, overcoming the limitations of the traditional technology in the more demanding scenarios, and may overcome the conventional RF beam-former issues, to generate accurately the very numerous time delays or phase shifts required in a DRA with a large number of beams and of radiating elements.

Integrated optics technology can play a crucial role as an alternative technology for implementing beam-forming structures for satellite applications thanks to the well known advantages of this technology such as low volume and weight, huge electrical bandwidth, electro-magnetic interference immunity, low consumption, remote delivery capability with low-attenuation (by carrying all microwave signals over optical fibres) and the robustness and precision that exhibits integrated optics.

Under the ESA contract 4000105095/12/NL/RA the consortium formed by DAS Photonics, Thales Alenia Space and the Nanophotonic Technology Center of Valencia is developing a three-dimensional Optical Beamforming Network (OBFN) based on integrated photonics, with fibre-optics remote antenna feeding capabilities, that addresses the requirements of SoA DRA antennas in space communications, able to feed potentially hundreds of antenna elements with hundred of simultaneous, orthogonal beams.

The core of this OBFN is a Photonic Integrated Circuit (PIC) implementing a passive Butler matrix similar to the structure well known by the RF community, but overcoming the issues of scalability, size, compactness and manufacturability associated to the fact of addressing hundred of elements. This fully-integrated beam-former solution also overcomes the opto-mechanical issues and environmental sensitivity of other free-space based OBFNs.

II. CONVENTIONAL MICROWAVE BUTLER MATRICES

Since the 50's, the Butler Matrix has been known by antenna specialists as a device based on cascading couplers so that any RF signal from a given input is distributed in equal amplitude parts to each output, with a progressive phase-shift from an output to the next. So, when connecting the output ports to the elements of an antenna linear array, the signal injected in each input port is radiated in a pre-determined direction, within an 'antenna directive beam'. All beams formed by a Butler matrix are equally spaced (provided that $\sin\theta$ is taken as angular unit) and 'orthogonal', which is a fundamental property that allows no cross-talk between them.
Besides, the Butler matrix is the waveguide network able to provide N beams from N ports (at input and outputs) with the minimum number of couplers: $N\cdot(\log2N)/2$, instead of $2N\cdot(N-1)$ for a traditional beam-former

with independent ways for phase-shifting towards outputs the signal dedicated to each beam, either in microwave circuits or possibly connecting by optical fibers each input to each output.

Despite this great advantage, a Butler matrix (BM) network is very bulky if built with RF waveguide technology. When it has to connect numerous inputs to the same number of N outputs, especially as for planar arrays, this needs 2 successive sets of stacked Butler matrices, as presented in Fig.1, for the case of $N=8^2=64$.
As well-known, the optimal implementation of a BM is for M=2m; so we will take as examples matrices with 2, 4, 8 order. But higher orders are possible; and a matrix can be truncated to use a number of inputs and/or outputs < 2m.

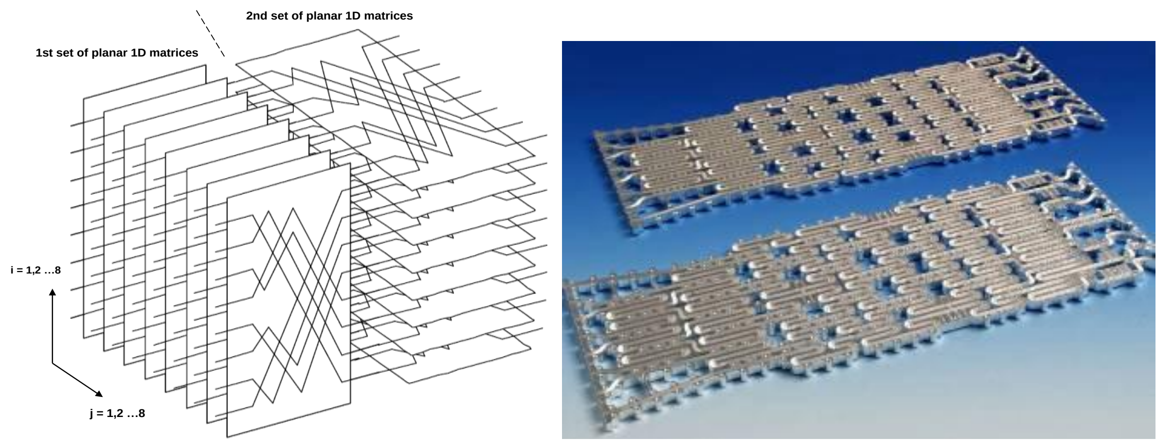

Fig. 1. Microwave Butler matrices (left) 3D orthogonal double set of 8x8 Butler matrices (right) example of a 8x8 RF matrix ($\approx$15x8 cm^2 at 30 GHz)

III. OPTICAL IMPLEMENTATION OF BUTLER MATRIXES

The fundamental structure of a Butler matrix consists in an interconnection of two fundamental building blocks: RF hybrids and phase shifters. Phase shifter can be implemented easily by generating a controlled delay that at the RF central frequency corresponds with the desired phase, which is useful in a certain range of frequencies mainly limited by the phase dispersion. Nevertheless, this technique could be valid for bandwidth up to 1 GHz in Ka band for example, enough for a practical use.

Butler matrixes could be implemented by using either 90º hybrids or sigma-delta dividers (180ª hybrids). In fact, a RF hybrid can be seen as a 2x2 Butler matrix so the fundamental component that should be photonically implemented is a “photonic RF hybrid”. It should include electro-optical and optoelectronic-conversions to have the RF interfaces and any kind of optical structure with 2x2 ports that performs the signals splitting and the phase shift simultaneously, which could implemented by a delay as seen before.

In this work we propose to build the basic coupler by 2 stages of optical splitters/combiners while adding a $\lambda/4$ added length for the diagonal arms, as presented on Fig.2. This device has a unitary transfer matrix and performs the functionality of a 90º RF hybrid for the RF signal modulating the optical carrier.

In Fig.2, the construction of a 8x8 Butler matrix by using the previous described building blocks is shown as well as an example of the differential phase/delay among the output for a single input. It is clearly seen how the functionality of generating a controlled phase difference between adjacent ports is achieved.

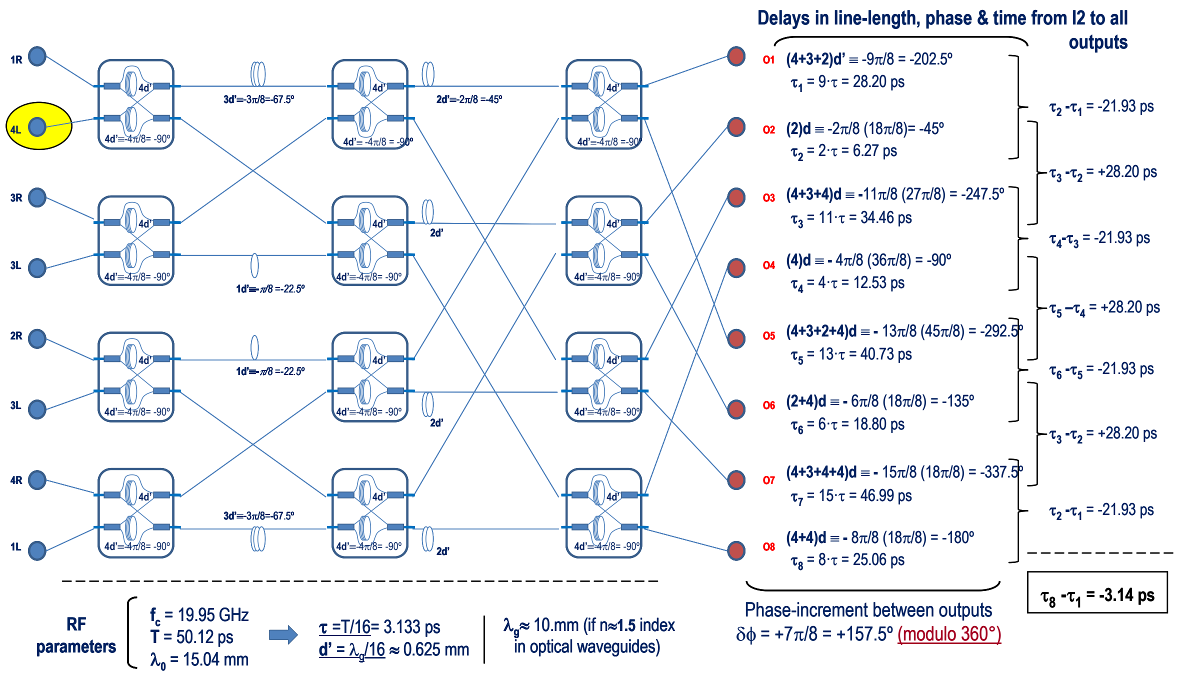

Fig. 2. Scheme of an optical Butler matrix of 8x8 ports implemented by optical splitters/combiners and optical delays. The squares indicate the structures working as 90º RF Hybrid. In the bottom of the figure some calculations for the matrix parameters are included. The right side includes the calculated delay and corresponding phase of the output signal when entering in the port 4L (in yellow), which corresponds with a differential phase of 157.5º between adjacent ports.

The Optical Butler Matrix is well suited for modular and scalable implementations of 3D multi-beam beam-formers, based on extensive use of WDM (wavelength-division-multiplexing) dimension. It supports (not only, but also) fast beam-hopping, based on wavelength-switching without any need for fast optical switch.

IV. BEAMFORMER NETWORK BASED ON 8x8 OPTICAL BUTLER MATRIXES

The Fig.3, hereafter presents a schematic of the baseline architecture of a transmit Optical Beamformer Network (OBN), that features the full-scale optical beam-former, the E/O and O/E conversion interfaces and all the associated optical links.

More specifically, it is composed of:
- an optical Frequency Generation Unit (FGU), that generates the required number of optical carriers with well determined optical wavelength and state of polarisation. These optical carriers could be either CW carriers or LO modulated carriers in order to also support frequency up/down-conversion;
- a set of E/O (or RF/O) interfaces, based on electro-optical modulators (or mixers) that are used to transfer the RF signals onto the optical carriers (or alternatively to mix the RF signals with optical LO’s so as to support frequency up-conversion). These E/O interfaces most likely include single-channel optical amplifiers not represented on the schematic;
- 1st stage of so-called horizontal stacked optical Butler matrices, OBM H1 –OBM H8, for achieving beam-forming for horizontal linear arrays of sources;
- 2st stage of so-called vertical stacked optical Butler matrices, OBM V1 –OBM V8; for achieving beam-forming for vertical linear arrays of sources;
- an intermediate optical interconnection stage, in the form of a 3-D array of miniature adjustable optical delay lines;
- an optical distribution and O/E conversion assembly, that delivers all the output composite optical signals to the 3D array of antenna radiating elements with the appropriate phase relationships, and converts these signals into RF ones through O/E detectors.

Each microwave input signal RFi modulates an optical carrier λi. A planar optical Butler matrix has 8 inputs 1 to 8; on each of which is present the optical carrier and its RF modulation but for the sake of simplification, we will write λi.

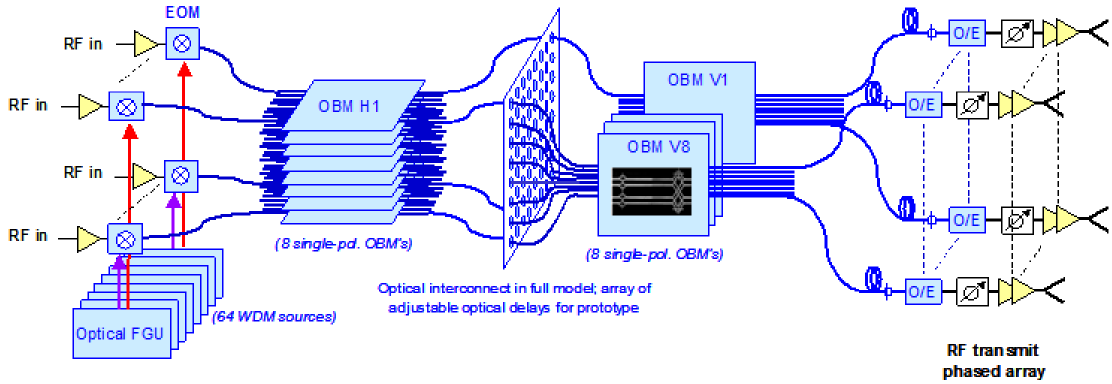

Fig. 3. Schematic of the baseline architecture of a transmit Optical Beamformer Network (OBN), that features the full-scale optical beam-former, the E/O and O/E conversion interfaces and all the associated optical links

V. PHOTONIC INTEGRATED CIRCUIT IMPLEMENTING A 8X8 BUTLER MATRIX

Although using photonics, this new concept implements the phase shifting for the RF signals by using optical delays, being a hybrid solution between the coherent optical beam-formers and the true-time delay networks. This makes the design very stable in phase-shifting and very accurate since the RF phase shifters are performed by delays implemented with PIC manufacturing technology, which allows to master photonic structures in the nanometre scale.

We keep the principle to implement phase-shifts computed at RF frequency, in a PIC; but we implement actually unitary devices, based on well-fitted assembling in-phase 'couplers' [this term includes dividers, combiners] together with phase-delays.

The PIC implementation have been done by using low propagation losses planar technology due to the delays to be implemented requires long optical waveguides. We have used Germanium-doped silica technology implementing square waveguides which are polarization insensitive and simplify the fibre coupling. The optical splitters/combiners were made by 2x2 multi-mode interferometers that exhibit a wideband optical operation and a high robustness against manufacturing tolerances. Finally, a special design of optical waveguides crosses based on genetic algorithms was done minimizing the insertion losses and crosstalk of the crosses even at very sharp angles.

In Fig.4, an image of the optical Butler matrix chip in the characterization set-up before packaging is shown. The component has been preliminary evaluated showing performance in terms of phase-shifting, power unbalance, wideband operation and polarization insensitive in line with the design. This component will be integrated in a proof-of-concept demonstrator and tested as an antenna beamformer network.

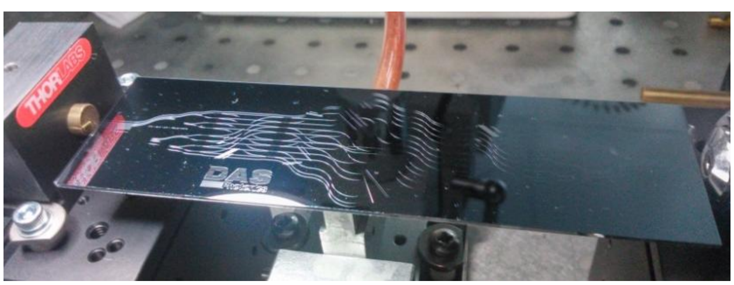

Fig. 4. Picture of the optical Butler matrix chip in the characterization set-up before packaging

VI. TEST RESULTS OF MANUFACTURED PHOTONIC INTEGRATED 8X8 BUTLER MATRIX

To carry out the test of the Butler matrix chip showed in Fig.4, it was previously packaged in order to be used as a standard passive optical component, that is, with input and output optical fibres and commercial optical connectors. As can be observed in Fig.5, the chip will be assembled in a mechanical package and the 8 input and 8 output ports were pigtailed thanks to the use of 8 ports fibre arrays.

Fig. 5. Picture of the optical Butler matrix chip after packaging

After these process, the unit was assembled in the whole laboratory set-up in order to characterize the signals in the electrical domain in terms of Phase and Amplitude Standard Deviation, Gain, Noise Figure, Polarization and wavelength dependence among others. In the following lines, only the main results measured at chip level are presented.

In this way, Table 1 shows the Phase Standard Deviation of the matrix, with the phases referenced to the output 1 of the chip, and comparing the results with the theoretical ones. As can be observed the mean of the Phase Standard Deviation is lower than 1.5º.

Table 1. Error of the RF phase with respect to the theoretical results

		Relative phases to the OUT 1 of the PIC								Stand Dev (º)
Input Port		Output Port								
		OUT 1	OUT2	OUT3	OUT4	OUT5	OUT6	OUT7	OUT8	
IN1	Theoretical	0	-157,5	-45	-112,5	-90	-67,5	-135	-22,5	1,15
	Measured	0	-155,57	-42,24	-110,23	-87,311	-65,15	-134,36	-19,01	
IN2	Theoretical	0	157,5	45	112,5	90	67,5	135	22,5	1,24
	Measured	0	160,42	46,76	114,59	93,51	70,8	138,86	24,62	
IN3	Theoretical	0	67,5	-135	202,5	90	-22,5	-45	112,5	1,72
	Measured	0	67,71	-138,43	204,55	90,83	-24,58	-45,11	112,88	
IN4	Theoretical	0	-67,5	135	-202,5	-90	22,5	45	-112,5	1,43
	Measured	0	-66,01	132,78	-205,26	-90,26	23,38	44,6	-113,04	
IN5	Theoretical	0	22,5	-45	67,5	-90	112,5	-135	157,5	1,28
	Measured	0	23,84	-45,58	69,63	-89,88	115,43	-133,28	159,98	
IN6	Theoretical	0	-22,5	45	-67,5	90	-112,5	135	-157,5	1,92
	Measured	0	-23,69	41,33	-69,37	91,68	-111,19	136,81	-157,28	
IN7	Theoretical	0	-112,5	-135	22,5	90	-202,5	-45	-67,5	1,48
	Measured	0	-111,05	-133,97	22,87	92,73	-204,42	-44,17	-68,76	
IN8	Theoretical	0	112,5	135	-22,5	-90	202,5	45	67,5	1,70
	Measured	0	115,97	133,74	-22,52	-91,75	202,98	46	65,94	
									Mean σ (º):	1,49

Regarding the Amplitude Standard Deviation, Table 2 shows the 64 normalized optical power values of the pigtailed 8x8 Optical Butler Matrix and the resulting Amplitude Standard Deviation which in this case is 0.65.

Note that due to a problem in the manufacturing process, some bubbles appeared in one of the splitter structures of the PIC affecting the insertion losses of 4 measurements (shaded cells of Table 2). These values have not been considered to calculate the standard deviation.

Table 2. Optical Insertion loss of the OBM chip with fibre array

	Normalized optical insertion losses								Stand Dev (dB)
	Output Port								
Input Port	1	2	3	4	5	6	7	8	
1	1,1	1,8	1,4	2	1,5	2,1	2,4	2,1	0,43
2	0,8	0,4	2	1,6	2	0,9	2,6	1,6	0,74
3	2,1	1,6	2,6	2	2,6	1,5	2,6	1,1	0,57
4	1	2,3	-10,3	2,3	0,8	2,3	-10,8	1,7	0,69
5	1	2,3	0,8	1,8	1,6	3	1,9	2,2	0,71
6	0,7	0,8	1,49	1,4	2,1	1,3	1,8	1,2	0,47
7	2,1	1,3	1,8	0,9	2,6	1,2	1,7	0	0,79
8	0,7	2,4	-10,94	1,4	0,5	2	-9,9	0,7	0,78
								Mean σ (dB):	0,65

Finally, to test the polarization and wavelength dependence of the chip, a set-up with a tunable CW laser and a polarization controller were used to feed the matrix. As can be observed in Fig.6 and Fig.7, the power variation in a range of 55nm (between 1520 and 1574nm) is lower than 2.5dB and the response is similar in both polarizations, so the Optical Butler Matrix can be considered independent from the polarization.

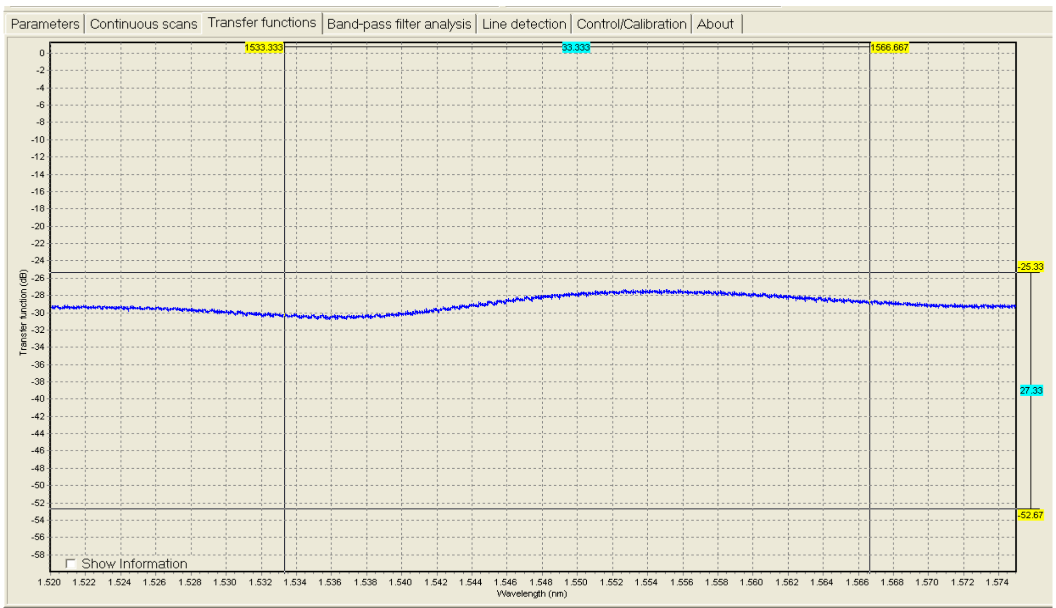

Fig. 6. Optical Power vs wavelength for TE polarization

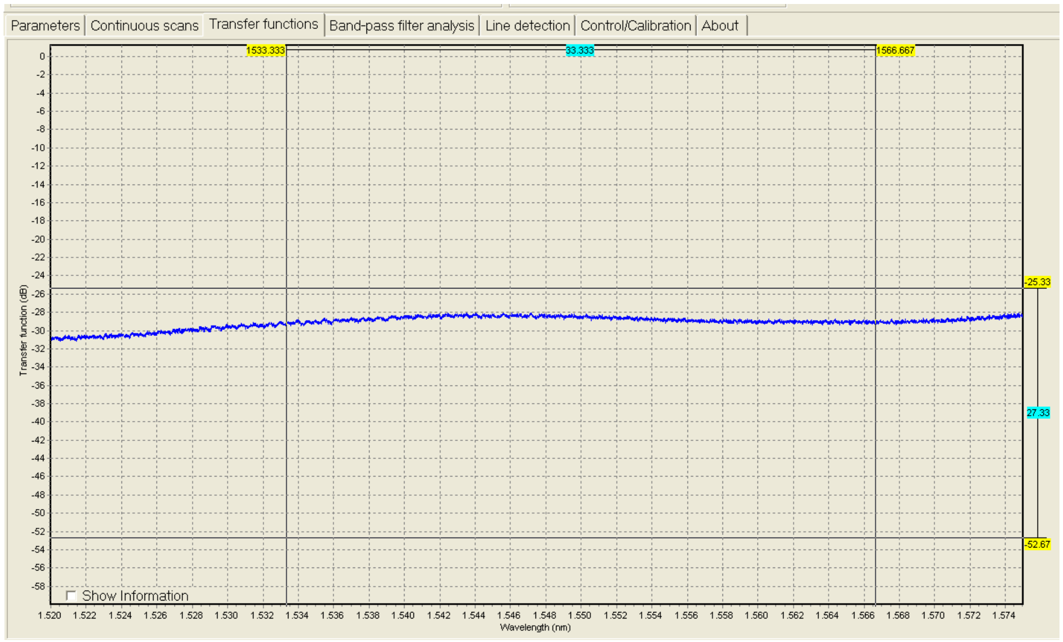

Fig. 7. Optical Power vs wavelength for TM polarization

VII. CONCLUSIONS

Photonic technology can play a crucial role as an alternative technology for implementing beam-forming structures for satellite applications thanks to the wellknown advantages of this technology such as low volume and weight, huge electrical bandwidth, electro-magnetic interference immunity, low consumption, remote delivery capability with low-attenuation (by carrying all microwave signals over optical fibres), and the robustness and precision that exhibits integrated optics. In this way, a Photonic Integrated Circuit implementing an 8x8 Butler Matrix has been designed, manufactured and tested using Germanium-doped silica technology implementing square waveguides. The assembly of the integrated Butler matrix was based on the combination of building blocks of optical splitters/combiners (2x2 multi-mode interferometers), square waveguides and waveguides crosses based on genetic algorithms in order to minimize the insertion losses of the whole and provide a robust phase accuracy against manufacturing tolerances and signal polarization variations.
The laboratory tests confirm the expected results exhibiting a Phase Standard Deviation lower than 1.5º, and an Amplitude Standard Deviation around 0.65dB for the manufactured PIC of the 8x8 Butler Matrix.

ACKNOWLEDGEMENTS

This work has been supported by the European Space Agency (ESA) under the ITI contract No 19785/06/NL/PA '*Optical beamforming network for multibeam satellite-on-board phased-array antennas*' and the TRP contract No. 4000105095/12/NL/RA '*Opto-microwave based front-end for a multi-beam large direct radiating array antenna*'.

The authors thank J. Perdigués and N. Karafolas as ESA Technical officers at ESTEC, for having initiated and stimulated these activities.