

International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas



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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 105633Q · © 2014 ESA and CNES
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2304244

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: $N \cdot (\log_2 N) / 2$, 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 the figure below, 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 $< 2m$.

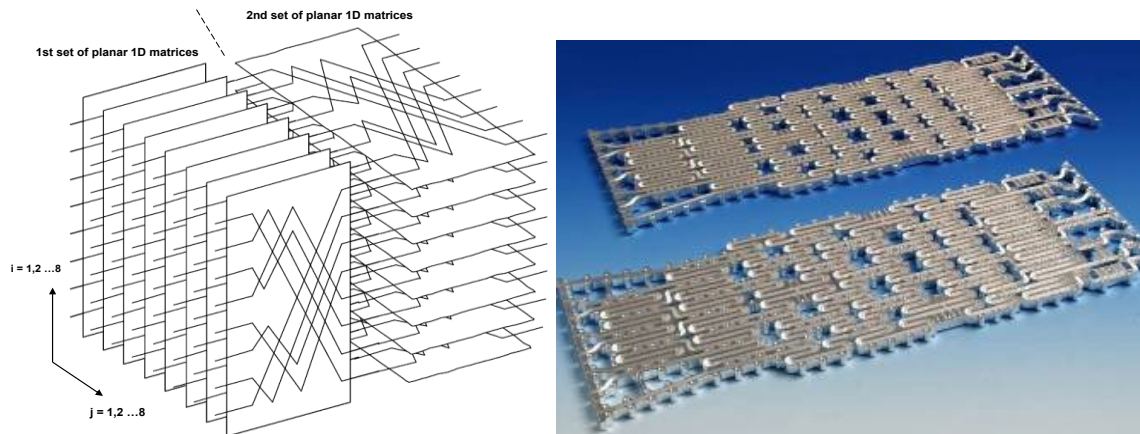


Fig 1. Microwave Butler matrices (left) 3D orthogonal double set of 8x8 Butler matrices (right) example of a 8x8 RF matrix ($\approx 15 \times 8 \text{ cm}^2$ at 30 GHz)

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 90° hybrids or sigma-delta dividers (180° hybrids). In fact, a RF hybrid can be seen as a 2×2 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 2×2 ports that performs the signals splitting and the phase shift simultaneously, which could be 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 Figure 2. This device has a unitary transfer matrix and performs the functionality of a 90° RF hybrid for the RF signal modulating the optical carrier.

In figure 2 the construction of a 8×8 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.

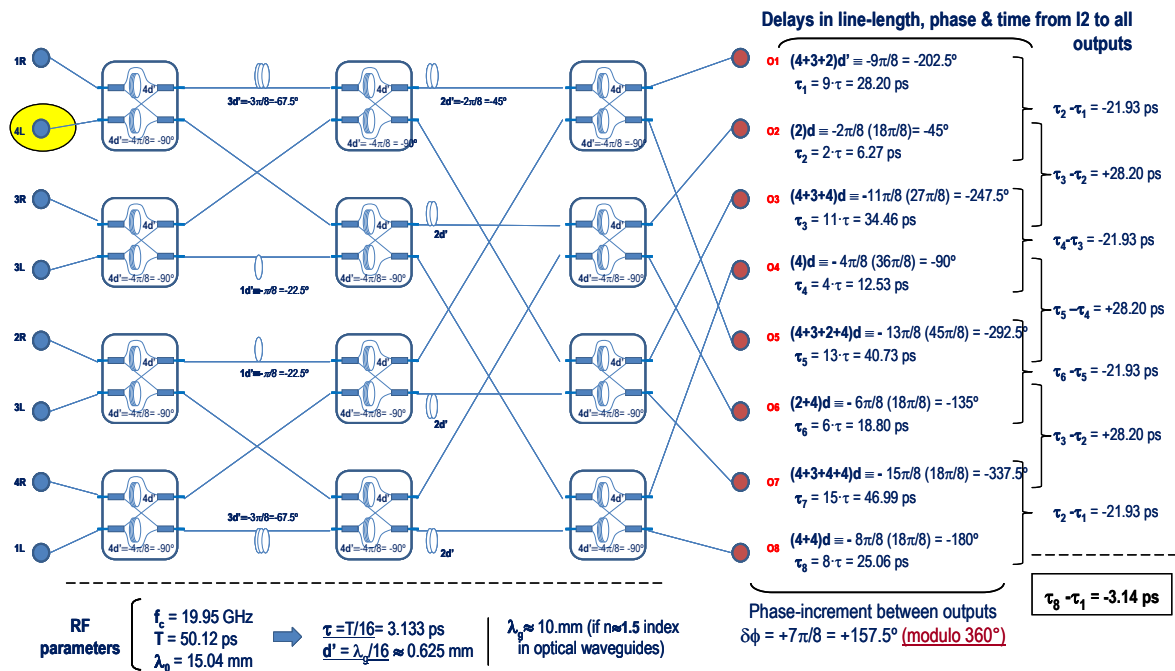


Fig 2. Scheme of an optical Butler matrix of 8x8 ports implemented by optical splitters/combiners and optical delays. The squares indicate the structures working as 90° RF Hybrid. In the bottom of the figure some calculations for the matrix parameters are included. The right side includes the calculated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

The Optical Butler Matrix is well suited for modular and scalable implementations of 3D multi-beam beamformers, 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 Figure 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 beamforming for horizontal linear arrays of sources;
- 2nd stage of so-called vertical stacked optical Butler matrices, OBM V1 –OBM V8; for achieving beamforming 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 Rf_i modulates an optical carrier λ_i . 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 λ_i .

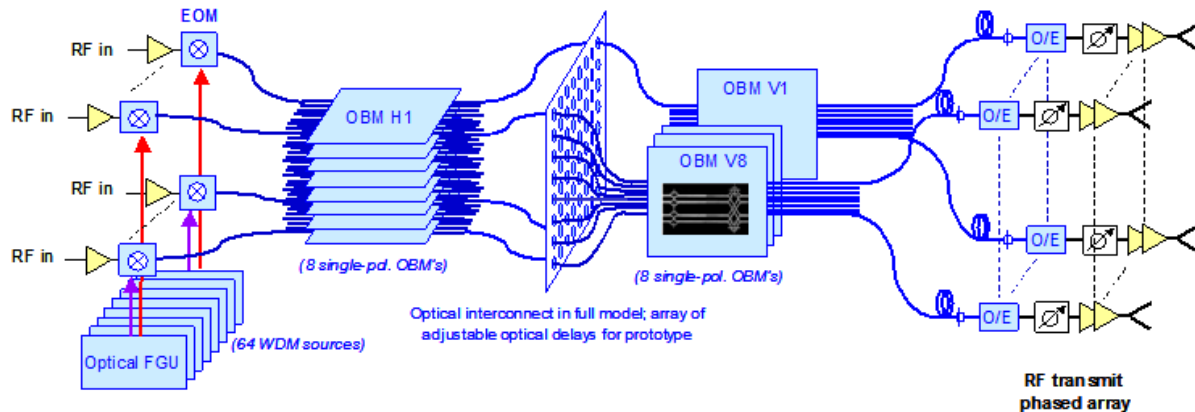


Fig 3. Schematic of the baseline architecture of a transmit Optical Beamformer Network (OBN), that features the full-scale optical beam-former, the E/O and O/E conversion interfaces and all the associated optical links

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 the following figure 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 a antenna beamformer network.

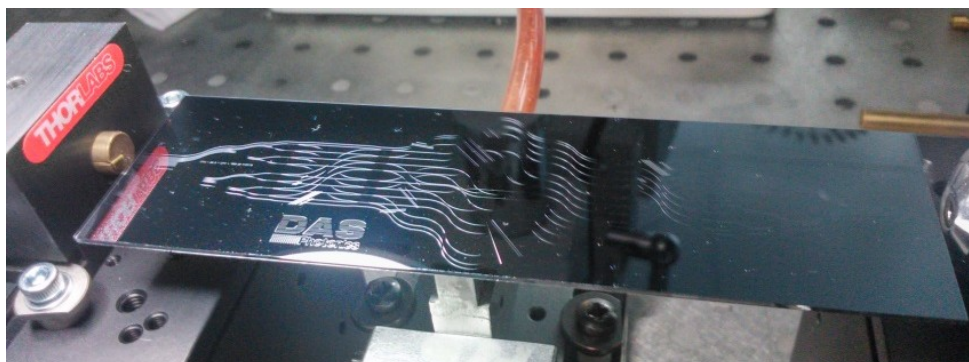


Fig 4. Picture of the optical Butler matrix chip in the characterization set-up before packaging

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.