International Conference on Space Optics—ICSO 2008

Toulouse, France

14–17 October 2008

Edited by Josiane Costeraste, Errico Armandillo, and Nikos Karafolas

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International Conference on Space Optics — ICSO 2008, edited by Josiane Costeraste, Errico Armandillo, Nikos Karafolas, Proc. of SPIE Vol. 10566, 105661A · © 2008 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308219

PHOTONIC BEAMFORMING NETWORK FOR MULTIBEAM SATELLITE-ON-BOARD PHASED-ARRAY ANTENNAS

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Topic 5: Generic Technologies and Simulations for Space optical instruments

ABSTRACT

The implementation of a beamforming unit based on integrated photonic technologies is addressed in this work. This integrated photonic solution for multibeam coverage will be compared with the digital and the RF solution. Photonic devices show unique characteristics that match the critical requirements of space oriented devices such as low mass/size, low power consumption and easily scalable to big systems.

An experimental proof-of-concept of the photonic beamforming structure based on 4x4 and 8x8 Butler matrices is presented. The proof-of-concept is based in the heterodyne generation of multiple phase engineered RF signals for the conformation of 8-4 different beams in an antenna array. Results show the feasibility of this technology for the implementation of optical beamforming with phase distribution errors below $\sigma=10^o$ with big savings in the required mass and size of the beamforming unit.

INTRODUCTION

Beam-forming and beam-switching capabilities of next generation broadband communication satellites will consider efficient multiple access schemes, broadband operation and with low cost. As it is studied in this work, photonic devices show unique characteristics that match the critical requirements of space oriented devices such as low mass/size, low power consumption and easily scalable to big systems with large antenna arrays with low added complexity and cost. The submicron dimensions of the silicon based photonic structures employed yields to big reductions in the overall size of the beamforming unit and, at the same time, great mass saving can be achieved.

Multibeam coverage can also be implemented by digital beamforming or RF technology. On one hand, digital processors hold the potential for fine channel granularity and flexible crossconnectivity, but the processed bandwidth is limited due to power consumption and complexity constraints. On the other hand, Photonic and RF technologies rise as clear competitors with big power and mass/volume savings. The photonic approach opens a new alternative to traditional RF systems that introduces additional functionalities such as simultaneous multibeam, and high quality frequency conversion with low added complexity. These features point out the photonic approach as a promising alternative for future beamforming solutions. Estimations of the mass, volume and power requirements for the three main technological approaches for actual beamforming structures are shown in table I. These calculations have been made considering a beamforming system with 48 beams and 16x16 antennas in the frequency band of 20.2 – 29.7 GHz and with a bandwidth of 500 MHz.

	Mass (Kg)	Volume (dm^3)	Power (W)
Digital	897	1400	3500
RF	10.7	9	51
Photonic	7.2	0.6	136

Table I. Estimations for different implementations of a beamforming system with 48 beams and 256 antennas.

EXPERIMENTAL VALIDATION OF THE PHOTONIC BEAMFORMING UNIT

A basic beamforming unit has been implemented by using integrated SOI (Silicon on insulator) technology, fully compatible with already developed CMOS manufacturing processes. Highly integrated photonic waveguides with a cross section of 500x205 nm, also known as photonic wires, are employed as the basic building block of the structure.

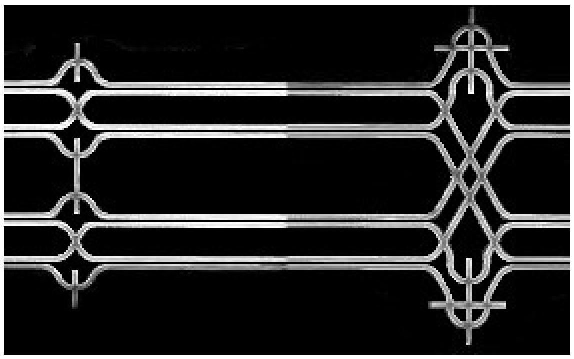

Fig. 1.- Images of the 8x8 Photonic Butler Matrix.

In the Fig 1 the fabricated 8x8 optical Butler matrix in SOI is depicted. It consists of three sets of optical couplers interconnected with optical waveguides designed to induce a differential phase shift among the different paths, following an interconnection scheme analogue to the one employed in the Fast-Fourier-Transformation algorithm. Different chips with this structure have been tested in a laboratory platform specially designed for the optical evaluation of its performance in terms of the amplitude distribution. Experimental results show a standard deviation around σ=2.5dB in optical amplitude mainly due to the difficulties in the coupling of light to the integrated structure and non-ideal distribution of the input to the output ports.

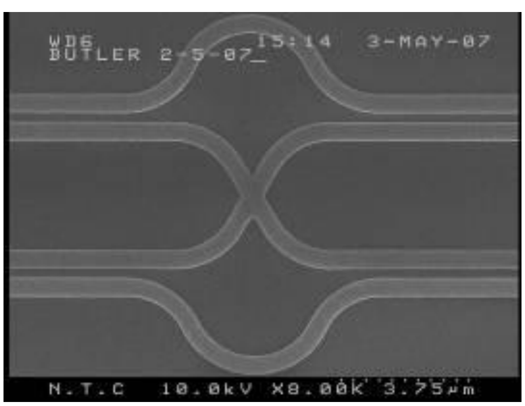

Fig. 2.- SEM Image of the 4x4 Photonic Butler Matrix

Additionally, it has been performed an RF/optical experimental proof-of-concept of the photonic beamforming structure using 4x4 Butler matrices. Fig. 2 shows a SEM image of the 4x4 Butler Matrix implemented for the measurements.

The RF distributions of this basic bemforming unit structure leads to the radiation diagrams shown in Fig. 3 in an array of 4 antennas.

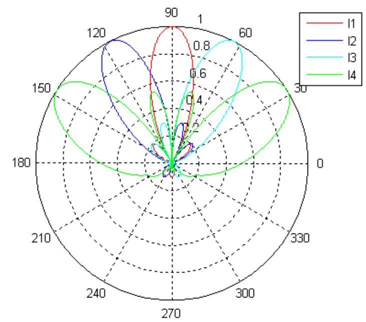

Fig. 3.-Theoretical radiation diagrams of an array of 4 antennas placed behind the beamforming unit.

A hybrid RF/optical system has been implemented for the direct measurement of the different RF phase distributions for each of the outputs of the photonic beamforming units.

The system is based in the heterodyne generation of multiple phase engineered RF signals for the conformation of 4 different beams in an antenna array with 4 elements. In the experimental verification two CW optical components with a frequency shift of nearly 40 GHz have been generated from a single laser source. With a filtering structure previous to the Butler Matrix, each of the components is redirected to a given port of the optical BM in order to achieve a given phase difference between the components and thus the desired RF phase distribution at the output of the system.

The filtering structure is implemented with Match Zehnder Interferometers (MZI). By engineering the difference in the length of the two branches of the Mach-Zehnder the Free Spectrum Range (FSR), has been fixed in 0.7nm, in order to separate the two CW optical components. In Fig. 4 it is depicted the spectral response of the MZI at each of the two output ports.

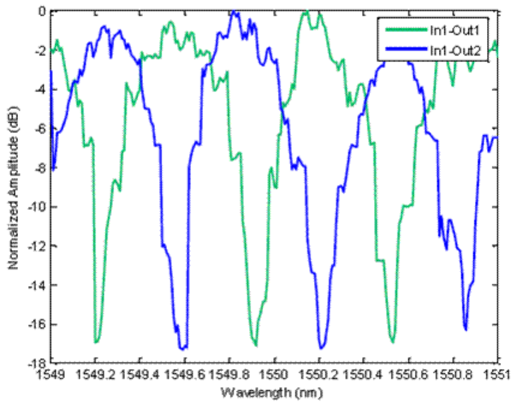

Fig. 4.-Normalized transmission of the MZI structures used to separate the CW components of the heterodyne signal.

It should be highlighted that the periodic spectral response of the Mach-Zehnder filter and the wide bandwidth of the BM gives the possibility of using Multibeam in future works. That is, to introduce different pairs of CW in different wavelengths at different ports simultaneously. Thus, the beamforming may use all the different radiation diagrams at the same time.

The RF signals for each of the output ports of the 4x4 Butler Matrix have been measured one by one. Before considering the measurements it has to be taken into account the possible error sources in the system. Two main error sources have been detected in the measurements related to the issue of coupling light inside the integrated structure and the interferences generated inside the structure.

The issue of coupling light to the integrated photonic circuit leads to inner reflections and a loss of power that takes place at each of the facets of the sample and hence, degrading the performance. The optimization of coupling structures such as grating couplers and inverted tapers that are under development at our labs will lead to an improvement of the performance of the photonic structure.

On the other hand, the non ideal filtering structures and the crosses between the photonic wires are responsible of the generation of interference noise in the system. A deep theoretical study has been carried out to identify each error component due to this source and analyze the influence of each one of them into the final phase error. As result of this study, the specifications of the filtering to assure a proper performance have been obtained resulting in a crosstalk level better than 19 dB for a phase error deviation of $\sigma=10^{o}$ as it is shown in Fig.4. An extinction ratio of 17 dB has been achieved and an improvement to 20 dB is expected to be feasible.

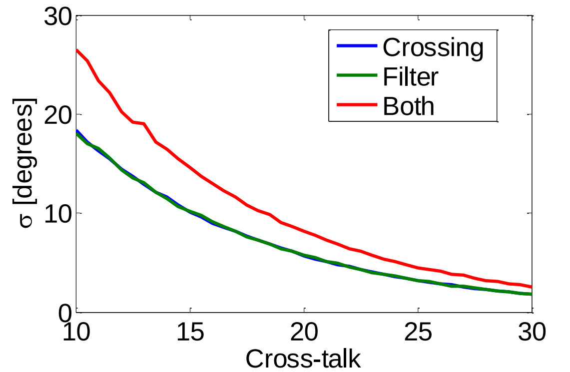

Fig.5 Standard deviation from the ideal phase distribution due to the interference generated at the crossing and filters of the structure.

Results show small deviations from the expected theoretical phase distributions. Extracting the influence of some error source in the final measurements, a sigma deviation below 10° is estimated in the photonic beamforming unit. From theoretical calculations conducted under the project it was yielded that this amount of deviation can be tolerated by the beamforming unit without a significant degradation of the system. From these results it can be concluded the feasibility of the heterodyne generation or RF phase distributions employing the photonic beamforming structure.

CONCLUSIONS

In this work it is outlined the evaluation of a photonic beamforming unit based on integrated photonic components. This technology is envisaged as a promising alternative; yet to be explored; to traditional RF and digital systems. Its high integration capabilities may lead to great savings in mass and size, especially when a large antennas array is considered. Although some constraints related to this technology need still to be overcome, results show the capabilities of this approach and, the estimations of the performance of the whole photonic system can be obtained. In conclusion integrated photonic technologies can be envisioned as a promising alternative to actual beamforming technologies offering added functionalities to future satellite systems.

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