RF-to-RF Characterization of a Phased Array Receive Antenna Steering System Using a Novel Ring Resonator-Based Integrated Photonic Beamformer

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***Abstract*—A novel ring resonator-based photonic beamformer has been developed for continuous and squint-free control of the reception angle of broadband phased array antenna systems. The core of the system is a ring resonator-based optical beamforming network (OBFN) used for delay synchronization and coherent signal combining. The OBFN is integrated in a single chip realized in CMOS-compatible optical waveguide technology together with an optical sideband filter for single-sideband suppressed-carrier modulation, and an optical carrier reinsertion circuit for balanced coherent detection. This paper demonstrates the system functionality by RF-to-RF measurements of the phase and power responses of the integrated OBFN.**

I. Introduction

Beam angle and shape control for a broadband phased array antenna can be realized by processing the signals of the single antenna elements using a photonic beamformer system. Optical technology offers several advantages compared to its electrical counterpart, such as compactness, small weight, low loss, frequency independence, high bandwidth, and EMI immunity. Conventionally, optical phase shifters [1] or switchable time delay arrays [2] are used in optical beamformers for signal phase synchronization, with the disadvantages of beam squinting for broadband signals and limited tuning angle resolution, respectively. Chirped fiber gratings can alternatively be used to overcome these limitations [3], but then bulky optical components and a tunable laser are required.

In our previous paper [4] a novel CW laser-compatible, squint-free, continuously tunable beamformer system for a phased array receiver system was presented, followed by the measurement results on the individual components of the system. The most important part of this novel beamformer is an optical ring resonator (ORR)-based optical beam forming network (OBFN), which generates continuous tunable broadband delays to the antenna signals [5-10], allowing continuous tunability and no beam squinting in the whole band. The E/O and O/E conversion before and after the OBFN are performed by means of optical single-sideband suppressed-carrier (SSB-SC) modulation and balanced coherent optical detection. Such a choice significantly reduces the system complexity, prevents intermodulation distortion and enhances the dynamic range [11]. The SSB-SC modulation is implemented by means of Mach-Zehnder modulators (MZMs) in push-pull configuration and an optical sideband filter (OSBF). Recently a single chip containing the ORR-based OBFN, OSBF, and optical carrier reinsertion circuit has been realized in low-cost, CMOS-compatible TriPleX^{TM} planar waveguide technology [12]. RF-to-RF measurements of phase and power response of the chip have been performed to test the functionality of the beamformer system: the results are presented here.

Section II gives a review of the novel beamformer system. Device realization is described in Section III. Section IV presents the measurement setup and results for the complete RF-to-RF characterization of the system. This demonstrates the functionality of the OBFN in terms of wideband delay generation and coherent signal combining which, in turn, allow squint-free antenna beam steering and improved output signal to noise ratio, respectively. Section V contains the conclusions and the current research topics.

II. Review of Novel Photonic Beam Forming System

A. Ring Resonator-Based Optical Beam Forming Networks

In broadband reconfigurable antenna arrays it is desirable to have a squint-free radiation pattern and a continuous angle steering of the main lobe. These two characteristics reflect, in turn, to the properties of the delay units used in the beamformer. Optical ring resonators (ORRs) appear to be good candidates for delay elements in optical beamforming networks thanks to their wideband true-time-delay behaviour, responsible for squint-free pattern characteristic, and their continuous delay tunability, which in turn allows a continuous beamsteering capability.

An ORR consists of a ring-shaped waveguide section with a round-trip time T and additional phase shift φ, coupled in parallel to a straight optical waveguide. The coupling is

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achieved using a MZI with power coupling coefficient κ. An ideal lossless ORR is equivalent to an optical all-pass filter with unit magnitude response and a periodic, continuously tunable phase response and, in turn, group delay response, which represents the actual delay to the RF signal modulated on the optical carrier:

$$\tau_g(f) = \frac{\kappa T}{2 - \kappa - 2\sqrt{1-\kappa}\cos(2\pi f T + \varphi)} \quad (1)$$

This function shows peaks at the resonance frequencies of the ring, which occur when an integer number of wavelengths is comprised into the length of the ring waveguide section. The period of the group delay response is called free spectral range (FSR) and is the reciprocal of the round-trip time T:

$$FSR = \frac{1}{T} \quad (2)$$

The ring parameters are tunable: the power coupling coefficient κ determines the peak delay, while the phase shift φ shifts the resonant frequency of the ring without varying the FSR, that depends only on T which is constant being the physical length of the ring waveguide section. Like in every resonator, the width of the bell-shape (optical bandwidth of the delay) is inversely proportional to its height (maximum delay of the ring). The result is that a single delay element shows an inherent trade-off between peak delay and bandwidth. The last statement means that, given a required delay range, the minimum bandwidth may not be sufficient for allocating the whole RF band of interest.

A possible way to solve this problem is to cascade several elementary delay elements obtaining a multi-ring delay unit, as explained in detail in [7, 8]. This combined unit can approximate a flat delay over a certain optical band, the delay ripple being smaller when the number of rings is increased, or the total bandwidth is reduced. Thus, in turn, this solution shows a tradeoff between the delay range, delay ripple and the number of rings required once the required delay range is fixed. Measurements of a three rings optical delay unit are presented in [8].

The devices described so far in this section can be used together with optical splitters/combiners as building blocks to realize an optical beam forming network. Among the several possible topologies, in [8] we discussed that the binary-three based architecture is the one which needs the minimum number of rings for a fixed maximum delay. The schematic layout of the realized OBFN is shown in Fig. 1.

B. *Optical SSB-SC Modulation and Balanced Detection*

In the previous subsection we have explained how the optical bandwidth is one of the factors which influence the complexity of the beamformer, in terms of total number of optical rings used in each delay unit. The use of a SSB-SC optical modulation can significantly reduce the required optical band and, as a consequence, allow a dramatic simplification of the OBFN structure.

Optical SSB-SC modulation can be implemented in practice by using several methods, among whom the filter based techniques, optical heterodyning and the phase-shift method. The first approach was addressed here by using a MZM properly biased in push-pull mode to first generate a DSB-SC modulation, and then by filtering out one of the sidebands with an optical side band filter (OSBF). The coherent detection required by this modulation scheme is achieved by re-injecting the non-modulated carrier in the OBFN output signal before detection. For a more detailed description of the SSB-SC implementation see [11].

III. Device Realization

The OBFN described in this work and in the previous papers is integrated in a single-chip realized in a low-loss, CMOS-compatible waveguide technology [8, 10, 12]. The dye dimensions are 4.85 cm in length by 0.95 cm in width. For the particular technological choice of a silicon-based substrate, thermo-optical tuning is used by placing heaters on top of the waveguides sections to be tuned. The heater temperature can be set with high accuracy by applying to the corresponding bond pad on the top of the chip a specific DC voltage set by a microcontroller and a D/A converter with 14 bits accuracy. For an efficient stabilization of the temperature a controller was used, employing a temperature dependent resistor as sensor and Peltier elements as actuators, placed in the bottom side of a copper bulk on which the chip is mounted. The heat dissipation is achieved by placing the bottom side of the Peltier elements in contact with a bulky copper substrate connected to a heat dissipator. A silicon heat conductive paste has been used to reduce the thermal resistance.

The 8x1 beamformer chip layout is shown in Fig. 2: there are visible the waveguide layout with the integrated optical ring resonators, the heaters used for thermo-optical tuning, and the electrical leads and bond pads employed for OBFN control.

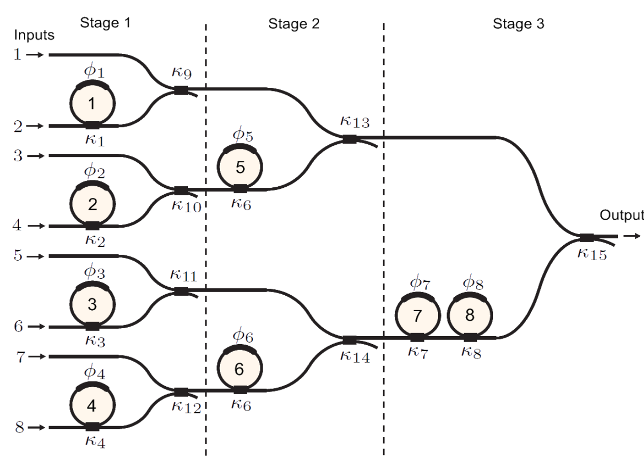

Figure 1. Schematic layout of the 8x1 OBFN

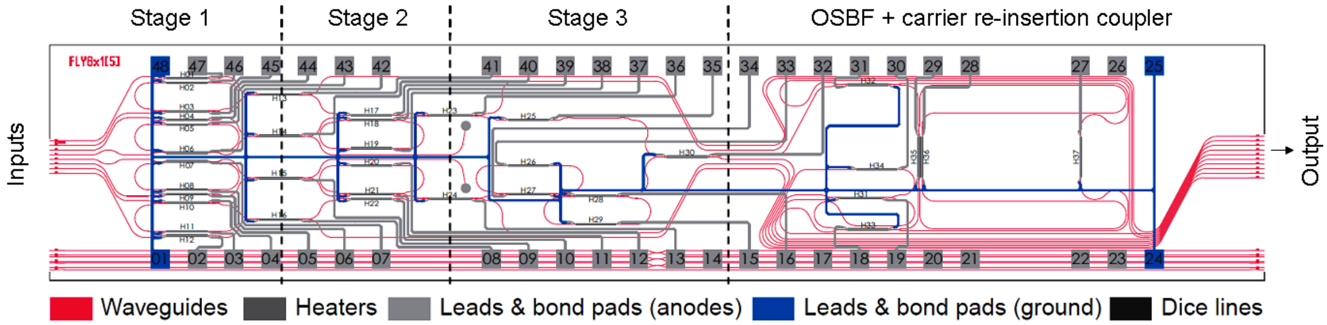

Figure 2. Mask layout of FLY 8x1 OBFN chip

IV. RF-TO-RF MEASUREMENTS

A. *Phase response (delay generation)*

The characterization of the RF-to-RF phase response of the beamformer is presented in this subsection. For this task, a network analyzer has been used to measure the phase relation between the RF signal injected into one input of the OBFN and the RF output signal, on a band of 1 GHz. Port 1 of the analyzer was used to generate an RF signal sweeping between 1 and 2 GHz, which was then fed to a MZM to modulate the optical carrier generated by a high power EM 4 laser (100 mW). The obtained modulated optical signal was then injected into Input 8 of the OBFN (Fig. 1). Part of the laser output power was extracted by means of a directional coupler and connected to the carrier re-insertion input of the beamformer, for the coherent detection of the RF signal after the SSB-SC modulation and the optical processing. The output of the OBFN was amplified by an EDFA, detected and then routed to the Port 2 of the network analyzer.

The eighth OBFN branch (Fig. 1) was first set to minimum delay and the corresponding measured phase response was used as a reference (0 ns delay). After that, more delay settings were made and the corresponding phase responses were measured with respect to the reference: the results are shown in Fig. 3 for 0.4 and 0.63 ns branch delays. The measured results show good agreement with the theoretical results expected, apart from a ripple that is mainly attributed to Fabry-Perot resonances due to the slight reflections generated by the various fiber connectors present in the optical signal path. The future fully-integrated implementation is expected to completely solve this problem.

Though not shown in the figure, the magnitude responses corresponding to the delay settings were also measured. In all cases, they showed a flat trend over the signal band but with larger losses for higher delay, due to the total optical loss increase with increased delay.

B. *Power response (coherent combining)*

For a complete RF-to-RF characterization of the optical chip, the coherent combining capability of the beamformer has also been measured. A similar setup has been used, while for this test three RF splitters and three directional fiber couplers have been added to split the 1-2 GHz signal and the laser output, respectively. Each couple of the four resulting outputs was then routed to four MZMs, whose outputs were in turn connected to the Inputs number 1, 2, 4 and 8 of the OBFN (Fig. 1). Four signal paths resulted then between the two ports of the network analyzer. The delays in each line have been synchronized by properly tuning the ORR-based delay elements and, to assure coherent combining, the optical phases were also aligned by manually tuning the dedicated phase shifters before the combiners in such a way to achieve the maximum output power. A promising research has also been carried out to implement a system for automatic phase synchronization [18]. The resulting RF-to-RF power transfer was then measured in the injected RF band and plot in Fig. 4 (top line).

A coherent combining in the OBFN would produce a decrease of 6 dB of the RF power level each time the number of combined signals is halved. This was proved by alternatively disconnecting two couples of RF inputs to the MZMs and by connecting them to matched loads, while keeping the same total RF input power. The same test was repeated by leaving only a single RF input at a time and terminating the remaining ones. Fig. 4 shows that, at each of these steps, the RF power is actually decreasing of 6 dB as expected and this demonstrates the coherent combining capability of the OBFN system.

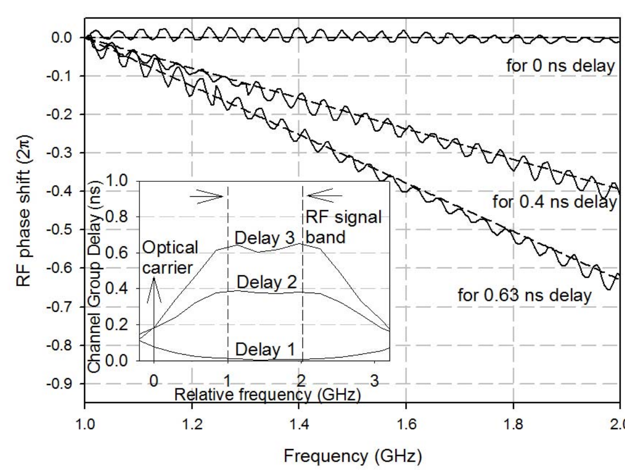

Figure 3. Measurement results of the RF-to-RF phase response of one OBFN channel, for three different delay settings. The minimum delay setting is used as reference 0 ns delay. The dashed lines indicate the ideal linear phase responses.

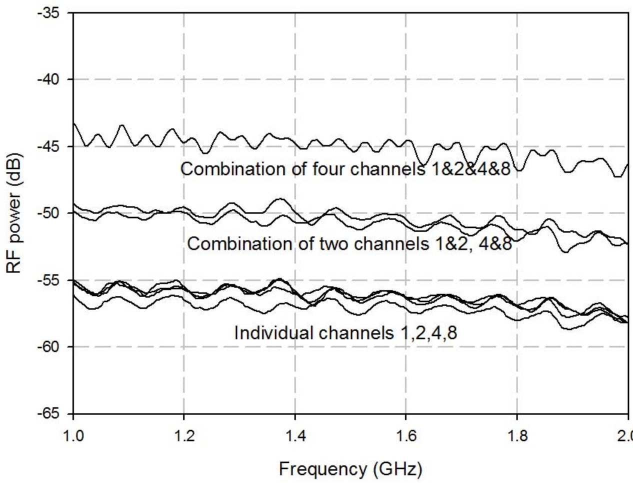

Figure 4. Measurement results of the RF-to-RF power response when of one (*bottom*), two (*middle*) and four RF inputs (*top*) are connected to the OBFN. The 6 dB increase at each doubling of the number of inputs demonstrates the OBFN coherent combining capability.

V. CONCLUSIONS

A novel broadband optical beamformer system has been presented. The core of the system is an integrated ORR-based OBFN. The system functionality has been demonstrated by a set of RF-to-RF measurements of phase and power responses, which verify the expected functionality respectively in terms of delay generation and coherent combining capability. The use of optical SSB-SC modulation and coherent balanced detection increases optical bandwidth efficiency and signal dynamic range. Currently more work is being carried out on stabilization improvement, control automation and system upscale. Also, the possibility to reduce the complexity by using WDM and multiple wavelengths is being investigated [19]. The system described in this paper and an extended 16x1 version are currently being integrated in experimental phased array antenna demonstrators, respectively for airborne satellite reception and for radioastronomy applications.

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