Phased Array Receive Antenna Steering System Using a Ring Resonator-Based Optical Beam Forming Network and Filter-Based Optical SSB-SC Modulation

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***Abstract*—A novel phased array receive antenna steering system is introduced. The core of this system is an optical ring resonator-based broadband, continuously tunable optical beam forming network (OBFN). In the proposed system architecture, filter-based optical single-sideband suppressed-carrier modulation and balanced coherent optical detection are used. Such architecture has significant advantages over a straightforward architecture using optical double-sideband modulation and direct optical detection, namely relaxed bandwidth requirements on the optical modulators and detectors, reduced complexity of the OBFN chip, and enhanced dynamic range. Initial measurements on an actual 1×8 OBFN chip and an optical sideband filter chip are presented. Both are realized in CMOS-compatible planar optical waveguide technology.**

***Index Terms*—CMOS-compatible technology, coherent optical detection, optical beam forming, optical ring resonator, optical SSB-SC modulation, thermo-optical tuning.**

I. Introduction

Optical technology is gaining its preference in wireless transmission systems. One application is optical beam forming in phased array antennas (PAAs) [1]–[3]. A PAA consists of multiple antenna elements (AEs) and enables direction-sensitive transmission and/or reception of electromagnetic waves by working together with appropriate signal processing. Optical technology is preferred for the signal processing due to its well-known advantages such as large instantaneous bandwidth, frequency independence, low loss, compact size, reduced weight, and low EMI. The core of the optical signal processing system for a PAA is an optical beam forming network (OBFN), which consists of optical delay elements and optical signal splitting/combining circuitry. Ideally, the optical delay elements in the OBFN should provide flattened delay and magnitude responses over the desired signal band to avoid signal distortion, and should have continuous tunablility to realize continuous beam direction control. To meet these requirements, cascades of optical ring resonators (ORRs) appear to be good candidates [4]–[10]. An actual ORR-based 8×1 OBFN chip has been realized in CMOS-compatible planar waveguide technology. Outside the OBFN filter-based optical SSB-SC modulation and balanced coherent optical detection are used to reduce the bandwidth requirement and complexity of the OBFN. Additionally the dynamic range of the system is enhanced by means of this scheme.

The optical beam forming system principles and architecture are explained in Section II. Section III demonstrates the principle of the ORR-based OBFN by presenting measurement results on a realized 1×8 OBFN chip. The filter for optical SSB-SC modulation is presented in Section IV. The conclusions are formulated in Section V.

II. Optical Beam Forming System Principles

A. System Architecture

A complete optical beam forming system consists of optical modulation, optical signal processing, and optical detection. The core section is the optical signal processing which is preformed by an OBFN. Here we propose a complete system using an ORR-based OBFN, filter-based optical SSB-SC modulation, and balanced coherent detection [8]. The system architecture is shown in Fig. 1.

B. Principles of Ring Resonator-Based Optical Beam Forming Networks

Ideal lossless ORRs are optical all-pass filters, characterized by a unity magnitude response and continuously tunable group delay response, which represents the effective delay to the RF signal that is modulated on the optical carrier signal [4]. In the waveguide realization a single ORR section consists of a straight waveguide and a ring waveguide coupled parallel to it, as shown in the inset of Fig. 2. A single ORR has two tuning elements: the tunable coupler to the ring and the additional round-trip phase shifter, which together facilitate the continuous tunability. The delay element has a periodic group delay response, with the delay peaks centered at the resonance frequencies. The mathematical expression is given

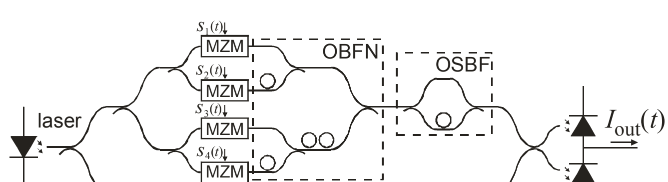

Figure 1. Schematic of the ring resonator-based optical beam forming system (MZM: Mach-Zehnder modulator, OBFN: optical beam forming network, OSBF: optical sideband filter).

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by the equation [4]

$$\tau_{\mathrm{g}}(f) = \frac{\kappa T}{2 - \kappa - 2\sqrt{1-\kappa}\cos(2\pi\, f\, T + \phi)}, \tag{1}$$

where T is the round-trip time, determining the free spectral range (FSR) of the ORR section, and κ and ϕ are the power coupling coefficient and additional round-trip phase shift of the ring, determining the peak delay value and the resonance frequencies, respectively. An ORR delay element shows an inherent trade-off between peak delay and delay bandwidth.

The bandwidth of the delay element can be increased by cascading multiple ORR sections, as illustrated in the inset of Fig. 2. The total group delay response can be obtained by simply adding up the responses of the individual ORRs, and can be flattened by properly tuning the ORRs, as illustrated in Fig. 2. Such a multi-ORR delay element shows an inherent trade-off between peak delay, delay bandwidth, delay ripple, and required number of ORRs [4]–[6]. Measurements on a three-ring optical delay device realized in CMOS-compatible waveguide technology were presented in [6], showing good agreement with theory.

When optical delay elements and signal processing circuitry are combined, a complete OBFN is obtained. In order to reduce the number of tuning elements, a binary tree OBFN topology is considered, instead of the straightforward parallel OBFN in which every output is connected to independent delay elements. A 1×8 ORR-based OBFN is proposed, consisting of 3 stages with a total of 12 ORRs and 7 tunable splitters, as shown in Fig. 3. Because of the reciprocal nature of this structure, the proposed OBFN can be used for both a 1×8 transmitter and an 8×1 receiver. The number of cascaded ORRs is different in each stage, so that an increasing number of cascaded ORRs are connected from output 1 to output 8, to meet the delay requirements for beam forming. The number of outputs of the OBFN can be extended by simply adding more stages. The tunability of the splitters provides the opportunity to specify different amplitudes for different outputs, which enables antenna side lobe suppression. Moreover, the tunable splitters compensate for the loss difference between different delay paths, which mainly results from the fact that the loss of an ORR increases with the delay [5], [6]. Measurements on an actual 1×8 OBFN chip will be described in Section III.

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

The main reason for using optical SSB-SC modulation instead of the straightforward optical DSB modulation in our system is to reduce the bandwidth of the modulated optical signal. The resulting optical bandwidth equals the RF bandwidth, which is the smallest that can be achieved without splitting the RF signals in sub-bands prior to electro-optical conversion. Since the optical bandwidth directly relates to the complexity of the ORR-based OBFN, namely the number of ORRs (see the previous subsection), applying SSB-SC modulation can significantly reduce the OBFN complexity.

Several techniques are known for implementing optical SSB modulation [8]. In our system optical SSB-SC modulation is implemented by means of Mach-Zehnder modulators (MZMs) and optical sideband filters (OSBFs).

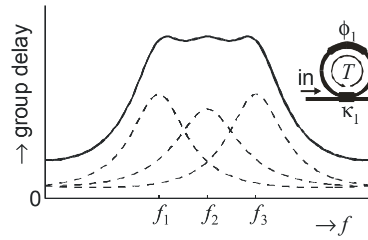

Figure 2. Theoretical group delay response of three cascaded ORR sections. The dashed lines represent the group delay responses of the individual sections. (Inset: cascade of three ORRs with round-trip delay T, additional round-trip phase-shifts ϕ_i and power coupling coefficients κ_i.)

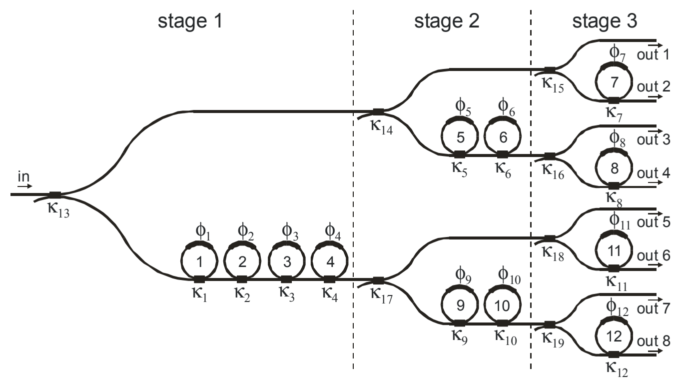

Figure 3. Binary tree-based 1×8 optical beam forming network for a transmitter system, consisting of 12 ORRs and 7 tunable splitters.

When the MZM is working in push-pull mode and properly biased, the optical carrier can be inherently suppressed [11], so that the OSBF only needs to suppress one sideband. Sideband filtering could be performed directly after the MZMs, but then every AE would require its own OSBF. However, since the OSBFs and the OBFN are both linear devices, their order can be reversed, so that actually only one common OSBF is required. Measurements on an actual OSBF chip will be described in Section IV.

Optical SSB-SC modulation requires coherent detection, which implies that the (unmodulated) optical carrier has to be re-inserted prior to optical detection. This can be done by routing one output signal of the splitter after the laser around the OBFN, and combining it with the OBFN's output signal by means of a 2×2 directional coupler, as shown in Fig. 1. Optical detection is performed by a balanced detector configuration, which has significant advantages over single-ended detection by means of just one photodiode. The output current has no DC, baseband, and double frequency terms as in the DSB direct detection case, but only the desired RF term [8]. As a result, the square-law behavior of the photodiodes will not introduce second order intermodulation distortion, even when the relative bandwidth of the RF signal is more than one octave. An additional advantage of balanced detection is that the effect of relative intensity noise in the optical signal is significantly reduced [12], which enhances the dynamic range of the PAA receiver.

Frequency down conversion could be performed prior to optical modulation, by mixing the element signals with a common local oscillator signal and low-pass-filtering. Lower-speed optical modulators and detectors could then be used [8].

III. RING RESONATOR-BASED 1×8 OPTICAL BEAM FORMING NETWORK CHIP

A. Chip Properties

The chip of the OBFN depicted in Fig. 3 is realized in CMOS-compatible optical waveguide technology [10], with a chip length of 4.85 cm and a chip width of 0.95 cm. The waveguide layout of the chip is shown in Fig. 4. The actuation of the couplers, splitters and phase shifters is done thermo-optically, allowing tuning of the resonance frequencies of the ORRs, tuning of the delays, and tuning of the splitting ratios, within 1 ms. The couplers and splitters are based on MZIs, so that the corresponding coupling coefficient and splitting ratio are determined by the phase difference of the MZI. Both the phase difference of an MZI and the phase shift of a ring resonator have a linear relation with the powers, namely squared voltages, supplied on the corresponding heaters. The 1×8 OBFN requires 31 heaters (two tuning elements for each ORR and one for each splitter), and hence 31 electrodes and one ground electrode to drive the heaters.

B. Thermal Tuning System

As expressed in (1), the group delay response of the ORRs is determined by the value of the κs and ϕs. Hence, to obtain a desired group delay response, a set of corresponding values of the κs and ϕs needs to be found. With the thermal tuning mechanism, the κs and ϕs of the ORRs in the OBFN chip are adjusted by the voltages supplied on the corresponding heaters. For a certain set of κs and ϕs, the correct voltage values for different heaters will be calculated by a high-speed microprocessor based on a dedicated algorithm. The algorithm is supposed to be able to compensate for the imperfection of the chip such as thermal crosstalk between one heater and another. The compensation is performed by inverting a matrix, the elements of which are thermal crosstalk coefficients measured between all heaters. Furthermore, one set of desired κs and ϕs may map to some negative values of the phases of the tuning elements, which would correspond to negative values of the tuning powers. Negative powers cannot be achieved practically. To avoid the negative powers, the algorithm is supposed to make use of the periodicity of the phases and shift the negative values to positive by adding 2π, and then redo the calculation until all tuning elements contribute positive phase shifts from 0 to 2π [13]. The voltage supply to the heaters is performed by using dedicated D/A converters and amplifiers which have been combined and realized on a PCB [14]. This PCB has a total of 32 channels (working with an accuracy of 14 bits), so that one PCB can control the complete OBFN chip.

C. Measurements

At the time of writing this paper, the algorithm for calculating the voltages is still under development, and the control system is still under test. Nevertheless, the measurements on the complete OBFN chip have been performed by means of manual tuning. The same measurement setup and the phase-shift approach are used, as described in [7], where the measurements on part of the 1×8 OBFN chip (1×4 OBFN) were presented. The group delay response at each output of the OBFN chip has been measured over one FSR of 14 GHz, which corresponds to a ring circumference of 1.2 cm and a group index of 1.8. Fig. 5 shows the measured group delay responses at the outputs 2 to 8 of the OBFN, which demonstrate the delay generation of one single ring up to seven cascaded rings. To realize beam forming, each output of the OBFN should give a certain delay value over a common frequency band. Fig. 5 demonstrates linearly increasing delays from outputs 2 to 8 of the 1×8 OBFN chip, considering output 1 as the zero delay reference. The resulting delays correspond to an 8-element linear array antenna. The coupling coefficients and round-trip phase-shifts of the rings are tuned such that the delays cover a bandwidth of 2.5 GHz, with the largest delay value being approximately 1.2 ns (corresponding to 36 cm distance in air) and the maximum delay ripple of approximately 0.1 ns (3 cm).

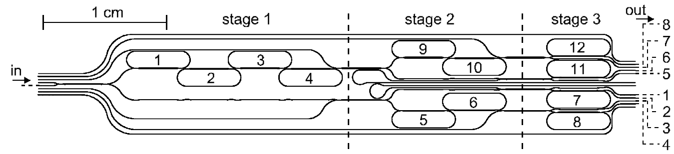

Figure 4. Waveguide structure of the 1×8 OBFN chip. The numbering of the rings and the outputs corresponds to the numbering in Fig. 3.

IV. OPTICAL SIDEBAND FILTER CHIP

An OSBF has been realized in the same technology as the OBFN chip, intended to estimate the capability of an optical band-pass filter to perform the sideband suppression. The filter consists of an ORR and an MZI, as shown in Fig. 1 (OSBF). The filter has a total of five tuning elements, namely two couplers of the MZI, one coupler of the ORR, and two phase shifters of the MZI and the ORR respectively. The FSRs of the ORR and the MZI are 20 GHz and 40 GHz, respectively. Ideally, such a filter has flat and wide passbands and stopbands, and sharp cutoff regions [15].

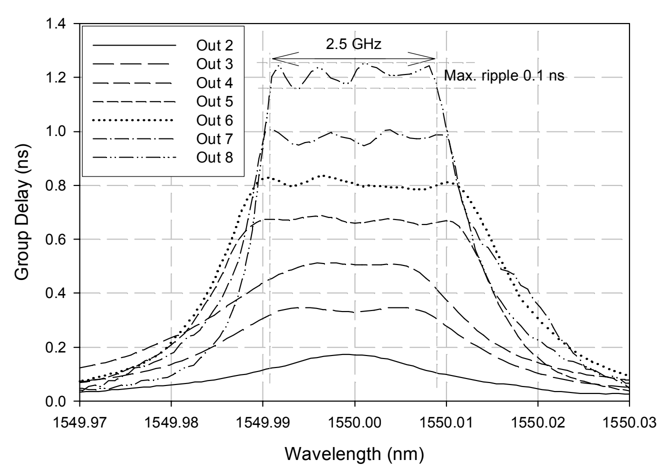

Figure 5. Measured group delay responses at different outputs of the 1×8 OBFN chip.

Fig. 6 shows the measured cross port power transmission over one FSR in comparison with the theoretical curves. By performing curve fitting, it is revealed that the current OSBF has significant waveguide loss. The chip insertion loss is also large (roughly 25 dB), but this should mainly be attributed to the large fiber-chip coupling losses, due to the fact that this OSBF chip has no tapered end faces. When the chip insertion loss is ignored by normalization, the measured cross-port power transmission curve (solid line) fits into the simulated curve (dashed line) which corresponds to an ORR roundtrip loss of 3 dB, an ORR power coupling coefficient of 0.8, and a power coupling coefficient of 0.6 for both of the two MZI couplers. The undesired waveguide loss of the current filter resulted from an incidental defect during the fabrication process. However, measurements on similar devices prove that the waveguide loss can be significantly reduced when this defect is corrected: the 1×8 OBFN chip had a waveguide loss of 0.55 dB/cm [9], and even newer devices with similar functionalities had waveguide losses below 0.1 dB/cm [10]. A simulated curve for the same parameters as the current OSBF chip but an ORR roundtrip loss of 0.082 dB (corresponding to a waveguide loss of 0.1 dB/cm) is also plotted in Fig. 6 (dotted line). Based on these results, we expect to fabricate a new OSBF chip soon with a filter isolation of approximately 25 dB. The insertion loss will be reduced by means of tapers.

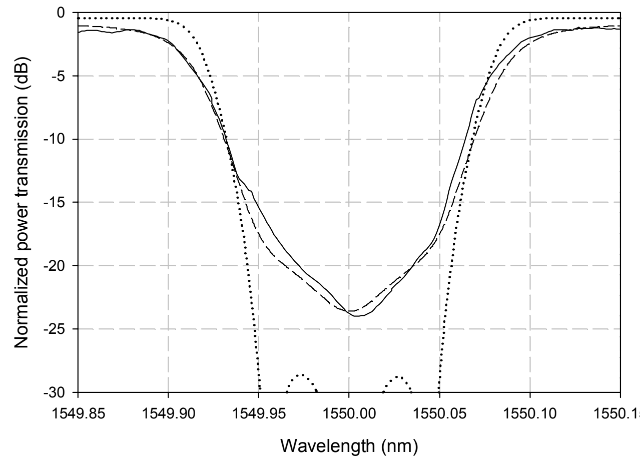

Figure 6. Measured normalized cross port power transmission of the OSBF chip. (The solid line shows the measured result. The dashed line is the simulated result for an ORR power coupling coefficient of 0.8, an MZI power coupling coefficient of 0.6, and an ORR roundtrip loss of 3 dB. The dotted line is the simulation for the same filter parameters but an ORR roundtrip loss of 0.082 dB.)

V. CONCLUSIONS

A novel continuously tunable PAA receiver system using an ORR-based OBFN, filter-based SSB-SC modulation, and balanced coherent optical detection has been described. This new scheme minimizes the bandwidth requirements on the optical modulators, optical beam forming network and optical detector, prevents intermodulation distortion, and enhances the dynamic range. Measurement results on a 1×8 OBFN chip and an OSBF chip have been presented, showing good agreement with theory. However the waveguide loss of the OSBF chip was too large for successful SSB-SC modulation, due to an incidental fabrication issue. We expect this to be improved in the near future, so that a full optical beam forming system demonstrator can be built.

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