Broadband phased array antenna steering by means of coherent signal combining in an integrated ring resonator-based optical beamformer

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A squint-free, continuously tunable optical beamformer for broadband phased array receive antennas is proposed. The complete system is demonstrated, including E/O and O/E conversions, and optical signal processing. The latter involves delay synchronization and coherent optical combining, which is performed in an integrated ring resonator-based optical beam forming network, realized in low-loss, CMOS-compatible TriPleX technology. Successful combination of four beamformer input channels has been demonstrated by means of RF-to-RF measurements.

I. Introduction

Integrated optical circuits for RF signal processing have advantages over the electrical counterpart in compactness, small weight, low loss, frequency independence, large instantaneous bandwidth, and EMI immunity. One application of this technique is optical beamforming for broadband phased array antennas. By processing the antenna signals through an optical beamformer circuit, beam steering and shaping can be realized for the directional transmission and reception of the antenna. Many conventional optical beamformers are either using optical phase shifters or switchable true time delay (TTD) arrays [1], [2], which have the disadvantages of beam squint for broadband signals and limited tuning resolution, respectively. Chirped fiber gratings (CFGs) can be used as an alternative, to offer both continuous tunability and TTD [3]. However, this requires bulky optical components and a tunable laser. In our previous paper the idea of a CW-laser-compatible, squint-free, continuously tunable beam- forming mechanism for a phased array receiver system has been proposed [4] and partly demonstrated [5]─[7]. The core of the system is an integrated optical ring resonator (ORR)-based optical beam forming network (OBFN). The E/O and O/E conversions around the OBFN are performed by means of filter-based optical single-sideband suppressed-carrier (SSB-SC) modulation and balanced coherent optical detection, which provides advantages in optical chip complexity and system dynamic range [4]. In this paper a complete optical beamformer system is presented and demonstrated by RF-to-RF measurements. The principles of this optical beamformer are briefly reviewed in Section II. In Section III the realization and measurements of optical beamformer chips in TriPleX technology are presented. In Section IV conclusions are formulated.

II. Optical beamformer principles

The complete optical beamformer system configuration is shown in Fig. 1. The core of the system is an ORR-based OBFN, which consists of single and cascaded ORRs for broadband continuous tunable TTDs and a signal combining network [5]─[9]. Since the number of ORRs in the OBFN increases with the required optical bandwidth [5], optical
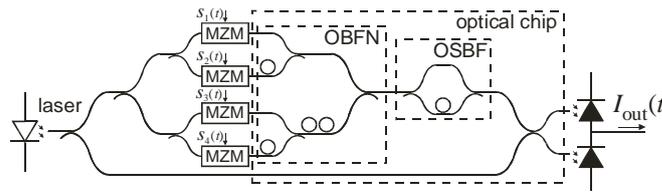
Fig. 1: Schematic of the beamformer system

SSB-SC modulation is used to minimize the optical bandwidth, and therefore to reduce the OBFN complexity, namely the number of ORRs [4]. In this case the optical signal bandwidth equals merely the RF bandwidth. The setup of MZMs and OSBFs is used to implement optical SSB-SC modulation [4], as shown in Fig. 1. Because of the linearity of the optical devices, one common OSBF is placed after the OBFN instead of one for each beamformer channel. Both the OBFN and OSBF can be integrated on one chip because of the same building blocks, namely Mach-Zehnder interferometers and ORRs. Besides, optical SSB-SC modulation requires coherent optical detection. Therefore, the unmodulated optical carrier must be re-inserted before optical detection. Balanced detection is used instead of direct single-ended detection, because it enhances the dynamic range of the system [4].

III. Realization and measurements

Integrated optical chips, each containing an ORR-based OBFN, an OSBF, and an optical carrier reinsertion circuit, have been realized in the TriPleX waveguide technology of LioniX [10]. The waveguide layout of a chip with a

Fig. 2: Waveguide layout of an integrated beamformer chip

4×1 OBFN is shown in Fig. 2, where the four signal channels differ in the number of cascaded racetrack-shaped ORRs for different required TTDs.
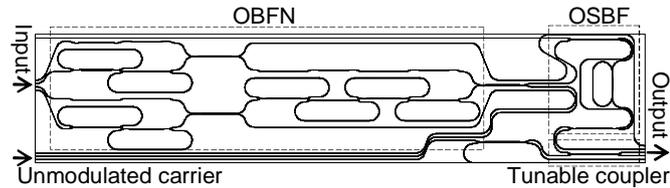
The measurements on a separate OBFN chip and an OSBF chip in TripleX technology have been presented previously in [7]─[9]. Measurements on the novel optical beamformer system have been performed lately from RF to RF, to demonstrate the functionality of the full system. Sideband filtering and carrier suppression for RF frequencies from 1 to 2 GHz are shown in Fig. 3. For this measurement the optical heterodyning technique is used before optical detection, to shift the spectrum of the modulated optical signal down into the frequency range of the RF spectrum analyzer, by
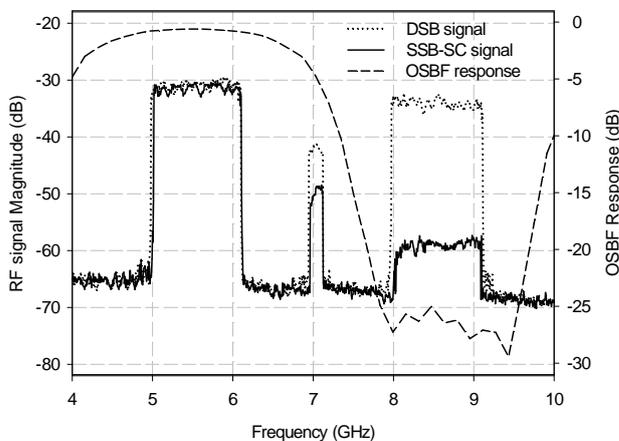

Fig. 3: Filter-based optical SSB-SC modulation

mixing the modulated light with CW light. The peak between two sidebands in Fig. 3 indicates the frequency difference between the two heterodyning optical carriers. It is shown that the magnitude of one sideband of the signal is 25 dB suppressed by the OSBF. When the OSBF is working properly, the ORRs of each signal channel of the OBFN can be tuned such that a flat group delay response covers the frequency range of the remaining sideband of the optical signals.
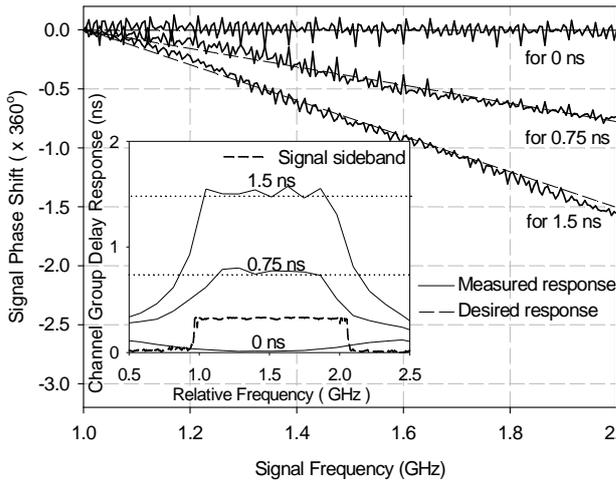
Fig. 4: Signal phase shift for different channel delays

Three group delay responses of a signal channel on the optical beamformer chip are shown in the inset of Fig. 4, with the maximum value of 1.5 ns (45 cm delay distance in air). As simple demonstration of signal recovery by means of coherent optical detection, single-ended detection is performed after the combination of the delayed sideband and the unmodulated optical carrier. The recovered RF signals over the frequency range from 1 to 2 GHz are shown in Fig. 4, in terms of RF-to-RF phase responses, after the processing of optical SSB-SC modulation, channel group delay, and coherent optical detection. The phase response for 0 ns group delay is regarded as zero phase response, and the other two phase responses show good match to the corresponding delay values. Though not shown in the figure, the corresponding magnitude responses of the RF signal are flat over the signal band, but with larger loss for higher delay, because the optical loss increases with delay value [5], [6]. Besides, the ripples in the results are mainly due to the optical phase fluctuation at the optical carrier reinsertion, which comes from the slight fluctuation in the position and temperature of the optical fibers before the chip. In the future implementation this will not be a problem because the entire beamformer will be integrated to a single chip, including laser splitter and modulators.
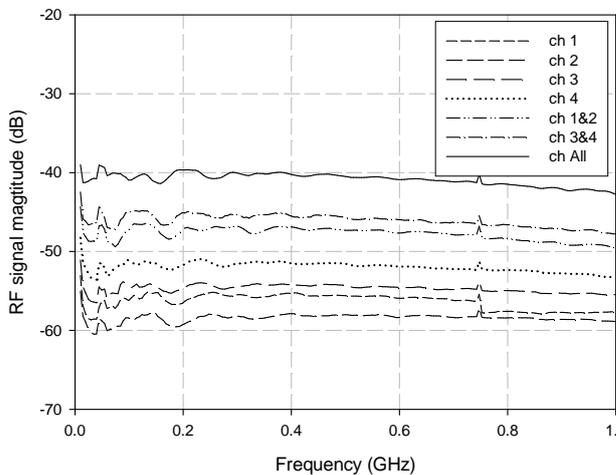

Fig. 5: RF magnitude responses for individual channels and signal combination.

For the receive antennas the delay-synchronized antenna signals on the OBFN channels are coherently combined before the output of OBFN, as illustrated in Fig. 1. Fig. 5 demonstrates the signal combination in the OBFN through RF-to-RF measurement over 1 GHz signal bandwidth. A setup consists of MZM-based intensity modulation, the OBFN, and direct detection is used for this measurement. One RF source is equally split into four RF channels for the OBFN. A delay setting of ORRs is made to compensate the signal path length differences between the four channels. The RF magnitude differences between individual channel outputs are due to the optical path loss differences, which can be removed by means of an equalized setting of the optical couplers in the OBFN. The magnitude levels illustrate that the four channels are coherently combined in the OBFN. The fluctuation in the signal band comes from the imperfection of the applied RF connections.

IV. Conclusions

A novel squint-free, continuously tunable beamformer mechanism for phased array receiver systems has been presented. It is based on filter-based optical SSB-SC modulation, an ORR-based OBFN, and optical balanced coherent detection. The system has been experimentally demonstrated by the measurements on optical sideband filtering, channel group delay responses, and RF-to-RF signal phase responses and combination. The measurement results agree with the theory and successfully demonstrate the feasibility of the proposed system.

Acknowledgement

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