Simulation of a Ring Resonator-Based Optical Beamformer System for Phased Array Receive Antennas

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***Abstract*—A new simulator tool is described that can be used in the field of RF photonics. It has been developed on the basis of a broadband, continuously tunable optical beamformer system for phased array receive antennas. The application that is considered in this paper is airborne satellite reception of digital television. The simulator tool has been developed in LabVIEW. The simulation model comprises a dynamical implementation of the optical beamforming network, such that beamforming can be performed for any number of antenna elements (AEs). The scalability of the model has been investigated by determining the computational complexity relations of the most critical blocks. It was found that a simulation of a full-scale beamformer can be performed within a reasonable amount of time.**

I. Introduction

Phased array antennas (PAAs) have some major benefits over traditional mechanical steering antennas. The most obvious advantage is the electronic steering instead of mechanical steering, giving a more robust and flexible antenna system. That is the reason why for instance modern radio telescopes are using PAAs instead of the traditional mechanically steerable antennas [1]. Also the reception of a satellite signal on an airplane can be done by means of a PAA [2], thereby reducing aerodynamic drag. Additionally, a PAA has the possibility for beamshaping and multi-beam tracking. These last two advantages rely on the processing capabilities of the beamforming network.

The beamformer system processes the signals from all antenna elements (AEs) in the PAA. The signal of each individual AE consists of a time-delayed version of some desired satellite signal (see Fig. 1), together with possible time-delayed versions of undesired signals. The delays of the desired signals are compensated for by the delay elements in the beamformer, so that combining them results in constructive interference. The undesired signals interfere destructively and are hence suppressed.

When considering the reception of satellite TV signals on a moving aircraft (or other mobile platforms), there are two desirable properties that can be identified:

- High angular resolution, to be able to receive the satellite signal from any direction;
- Frequency-independent operation, to be able to receive multiple TV channels (covering a wide frequency band) simultaneously.

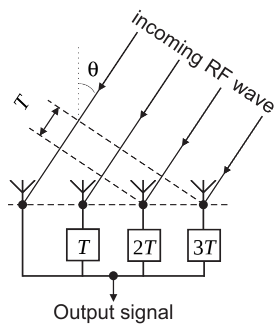

Fig. 1. Beamforming operation for a phased array antenna

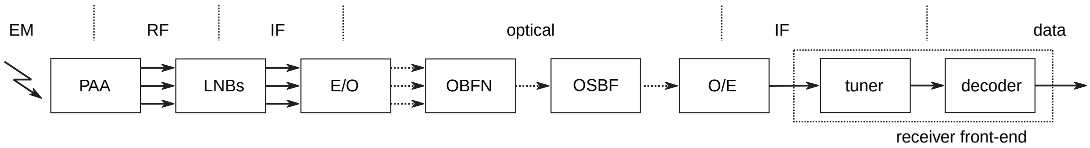

Fig. 2. System overview (PAA = phased array antenna, LNB = low-noise block, E/O = electrical/optical conversion, OBFN = optical beamforming network, OSBF = optical sideband filter, O/E = optical/electrical conversion)

To satisfy these properties, the individual antenna elements (AEs) should be broadband, but also the processing beamformer system should be able to realize true time delays for broadband signals, which can be tuned to any value in a (bounded) continuous range [3]. For narrowband systems it is possible to delay signals by means of a phase shifter. However, for broadband systems this will result in a frequency-dependent beam angle and shape. By using switchable delay matrices the appropriate amount of delay can be generated over a wide frequency range, but only for a discrete number of angles. Switchable delay matrices show a trade-off between beam angle resolution and complexity.

In the optical domain continuously tunable delays can be realized over a large bandwidth by means of optical ring resonators (ORRs), thereby satisfying the desired properties mentioned before. The system-level design of a complete beamformer based on ORRs has been described in [3], including the choice of suitable electro-optical (E/O) and opto-electrical (O/E) conversions. Also, a performance study for a full PAA satellite receiver system (containing 2,048 AEs) based on this beamformer concept has been described, to determine how well this optical beamformer performs compared to its electrical equivalent, and to locate any bottlenecks. A simplified experimental prototype of an 8-port optical beamformer based on optical integrated circuits is described in [4].

To verify the results of the analysis and anticipate any issues in the development of a full-scale experimental prototype of the optical beamformer (with 2,048 input ports), a simulation tool has been developed. In this paper we describe the design and testing of this simulation tool.

In the next section, a short overview of the satellite reception system employing ORR-based optical beamforming is given. In Section III the choice for a suitable simulation environment is motivated, followed by a brief description of the models for the components in Section IV. Some simulation results are presented in Section V. The computational complexity of the simulation tool is discussed in Section VI, followed by conclusions in Section VII.

II. System overview

In Fig. 2 a functional overview of the satellite reception system is given. A more detailed schematic of the beamformer part is given in Fig. 3. The received satellite signal is a digital video broadcasting (DVB) signal, which uses phase modulation through quadrature phase-shift keying (QPSK). As can be seen in Fig. 2, the system can be split up in an electrical and optical part. The actual beamforming operation is performed by the ORRs in the optical beamforming network (OBFN). The signals received by the AEs are first downconverted to IF (950–2150 MHz) by means of the low-noise blocks (LNBs), to relax the electrical bandwidth constraints for the beamformer. After this

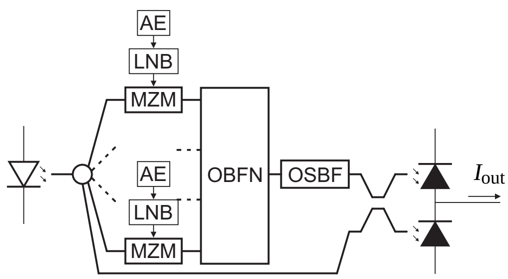

Fig. 3. Optical beamformer system, including the conversion from and to the electrical domain (MZM = Mach-Zehnder modulator)

conversion the signals are converted to the optical domain by means of single-sideband suppressed-carrier (SSB-SC) modulation, using Mach-Zehnder modulators (MZMs) with carrier suppression, and a common optical sideband filter (OSBF) after the OBFN. Therefore, the beamforming operation is performed on a relatively small optical signal bandwidth, which equals the IF bandwidth. (This is done to minimize the required complexity of the OBFN, since the required number of rings increases roughly proportional to the required optical bandwidth [3].) The signal is converted back to the electrical domain using coherent optical detection. This is performed by means of a balanced detector, to minimize the effect of the relative intensity noise of the laser. The final step is the decoding of the signal, after selection of the desired subcarrier.

III. Simulation environment

In selecting a simulation environment, there are three approaches that can be considered:

- dedicated simulation software, specifically designed for optical and/or electrical systems;
- general purpose simulation software, designed for multi-domain systems;
- self-built simulation software, specifically designed for RF photonics and the application at hand.

The easiest approach is to take a dedicated software package that can be used to implement the model. However, most commercially available dedicated software packages are not able to handle signals from both the electrical and optical domain. Furthermore, most optical simulation environments are not suitable for coherent optical systems, since they are based on power-equivalent signal representations. (This will be further discussed in Subsection IV-A.) This limits the choice for a good commercial dedicated software package. Another approach is to develop completely new simulation software from scratch, specifically designed for RF photonics and the applications mentioned in this paper. This, however, requires a deep understanding of a suitable programming language, and the model needs to be constructed from very basic blocks.

We chose to use a general purpose simulator. With this software it is possible to use the correct signal representation in both domains. Both LabVIEW [5] and Matlab Simulink [6] are examples of such simulation software. Unlike dedicated software packages, LabVIEW offers flexibility in specifying the signal representation. This enables a suitable optical signal representation, such that interference effects can be simulated, and is convenient for simulation concerning multiple domains (electrical/optical), as required in RF photonics applications such as optical beamforming. Furthermore, LabVIEW offers an excellent interface with hardware components, such that –in future work– experimental demonstrators can be used as being part of the simulation model. The simulator tool is developed in the time domain, to be able to investigate the performance on individual bits, and understand the influence of noise and distortion on the system performance.

IV. Modeling the signals and optical components

When developing a simulation tool, all components of the system must be modeled. In this section the modeling of the optical beamforming system in Fig. 3 will be discussed in more detail, with particular emphasis on the ORRs and the OBFN. (More details on modeling the other parts can be found in [7].) Before doing so, a suitable representation of the optical signals is introduced.

A. Optical signal representation

Obviously, simulating the system in the time domain requires the signals to be represented in time-discrete form. As will be illustrated in the next section, the operation of the ORR-based delay element relies on optical interference effects. Therefore, the simulator is required to represent the optical signals as optical fields (rather than optical powers or intensities). Since the optical frequency is in the order of 200 THz, representing optical signals by means of samples of the optical field would —following Nyquist's sampling criterion— require a sample rate in the order of 400 THz, resulting in a massive number of samples per simulated bit, and, as a result, excessive calculation times.

A much lower sample rate can be used when the optical signals are represented by samples of the complex envelope (or baseband equivalent) of the optical field. Assuming that its spectrum is centered around baseband, this requires a sample rate that is at least equal to the bandwidth of the optical signal. In our case, the optical signals are modulated by IF signals with a maximum frequency of 2150 MHz, so the minimum sampling rate is 4.3 GHz. We will come back to this in the next subsection.

B. Modeling the Optical Ring Resonators

The ORRs are the core components in the optical beamformer system, as they provide a broadband true time delay [3]. ORRs consist of a straight waveguide and a recirculating waveguide coupled parallel to it, of which a schematic drawing is given in the inset of Fig. 4. When modeling an ORR, three components can be distinguished:

- a ring, with a certain round-trip time T and a waveguide loss, both depending on the circumference of the ring;
- an optical phase shifter, with tunable phase shift ϕ;
- a directional coupler, with tunable power coupling coefficient κ;

An ideal ORR acts as an optical all-pass filter, which is characterized by a unity magnitude response. The effective time delay to the RF signal that is modulated on the optical carrier is given by the group delay response. This response is periodic, with a period —or free spectral range (FSR)— that equals $1/T$. Within one FSR of the group delay response a peak is centered at the resonance frequency, as shown in Fig. 4. The delay response shows an inherent trade-off between the peak delay value and the width of the peak, as a result of the constant area underneath the delay curve in a single FSR.

For a broadband RF signal a single ORR may not provide enough delay bandwidth. When multiple ORRs are cascaded —as illustrated in the inset of Fig. 5— their individual group delay responses can be superposed to form a response with sufficient bandwidth. By tuning the rings properly, a response with a flattened delay band can be achieved, as shown in Fig. 5.

All delays in the simulator are modeled as shift registers. Since the round-trip delay of the ORRs in the OBFN is the smallest delay in the system, and all other delays can be approximated as integer multiples of this delay, the sample rate of the simulator was chosen to be equal to the FSR of the ORRs in the OBFN, which is approximately 13.4 GHz in our chip [4]. Hence, the round-trip delay of the ORRs in the OBFN is modeled as a single sample shift.

In practice, the phase shift ϕ is tuned by means of a heater that relies on the thermo-optic effect to change the refractive index and subsequently change the round-trip time of the ring [4]. Since the resulting variations in the round-trip time are very small, these can be approximated by optical phase shifts, which are modeled as multiplication by a complex number in the simulator.

The coupling section of the ORR is simply modeled as a lossless directional coupler, with tunable power coupling coefficient κ.

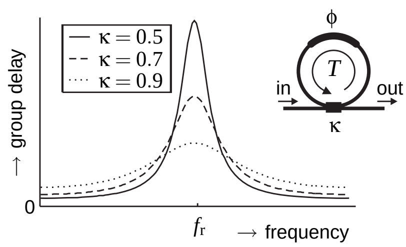

Fig. 4. Group delay response of an ORR-based delay element, showing a trade-off between peak height and width

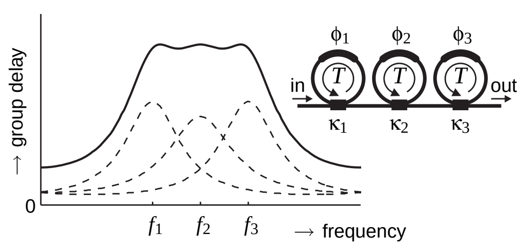

Fig. 5. Individual and combined group delay responses of three cascaded ORRs

C. Modeling the Optical Beamforming Network

The OBFN consists of combiners and ORR-based delay elements, as shown in Fig. 6. Within the OBFN three levels of abstraction can be identified:

- a ring section, consisting of one or more rings in cascade;
- a branch couple, consisting of two branches and a combiner;
- a stage, consisting of one or more branch couples.

In order to be able to simulate any size of OBFN, it is desirable to use a dynamical implementation that loops through several stages, branch couples and ring sections, until only a single output remains. The number of stages m can be found using $m = \log_2(n)$, where n is the number of inputs or AEs. The outputs of the previous stage are used as the inputs of the next stage, using shift registers. Within each stage, the model loops through the branch couples. For each branch couple the lower branch is processed by a ring section and the upper branch is aligned in optical phase with the lower branch, after which both branches are combined and added to the output. When there are multiple ORRs in a ring section this loop is executed multiple times, using shift registers as well.

So far, we have only considered OBFNs for linear arrays, limiting the focusing of the beam in only one dimension. With planar arrays we can focus in two dimensions, resulting in the ability to focus to any point in the sky. In the simulation the processing for focusing in two dimensions can be implemented using multiple OBFNs. In this setting the inputs are synchronized and combined for one dimension and subsequently synchronized and combined for the other dimension.

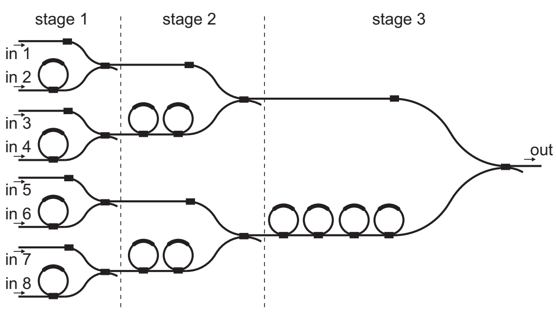

Fig. 6. An OBFN structure with eight inputs and one output, employing eight ORRs

V. Results

In order to test the simulator, several simulations were executed based on a linear antenna array with eight AEs. Therefore, an 8×1 OBFN in a binary tree configuration is used to synchronize the signals, as shown in Fig. 6. The individual delay responses for each input are shown in Fig. 7. In this figure, the delays are normalized to the ORRs' round-trip time T, and the frequency is normalized to the ORRs' FSR $1/T$. Zero normalized frequency corresponds to the optical center frequency. The delay curves are centered around one sideband of the modulated optical signal, with a bandwidth that corresponds to the IF bandwidth of the AE signals. Note that the normalized delays are not evenly spaced, which results from the fact that, for each ORR, a minimum normalized delay of one round-trip time T is introduced. (Hence, these offsets have to be compensated for by means of fixed delays elsewhere in the system.)

Because the signals are only synchronized and combined correctly for a single sideband, the faulty sideband of the resulting signal is filtered out by means of the OSBF, as shown in Fig. 8. In the figure it is shown that the left sideband is almost completely passed, whereas the right sideband is

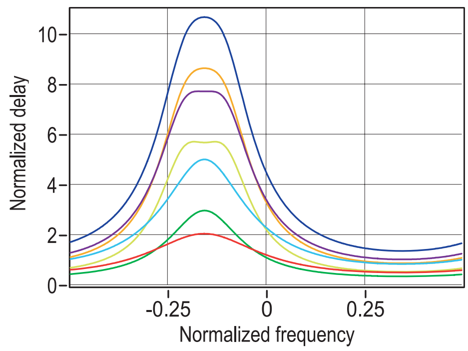

Fig. 7. Group delay responses of the OBFN, corresponding to the delay paths for each of the AE signals. Increasing peak delays correspond to increasing input port numbers in Fig. 6.

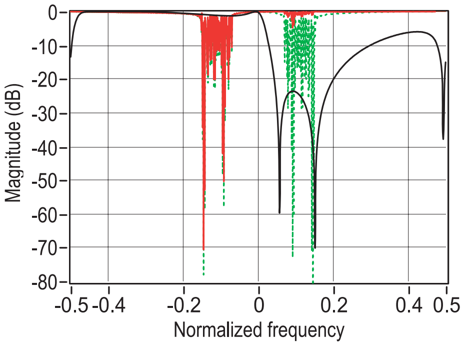

Fig. 8. Magnitude response of the OSBF (black), with the negated and scaled spectra of the signals before (light grey) and after (dark grey) filtering added to the figure.

almost completely suppressed, as expected based on the frequency response in the figure.

After the IF signals are converted to the optical domain, the signals must be synchronized and combined by the operation of the OBFN. The magnitude of the complex envelope for both a single input and the output of the OBFN is shown in Fig. 9. As a result of the coherent combining in the OBFN, the input signals are added in amplitude.

VI. Computational complexity

In the previous section we have shown a simulation test for a small optical beamformer, but in the future beamformers with roughly 2,000 inputs must be simulated to investigate the eventual performance of the full PAA system [3]. For the simulator it is important to know what the required computational time will be, and how it scales with the size of the model.

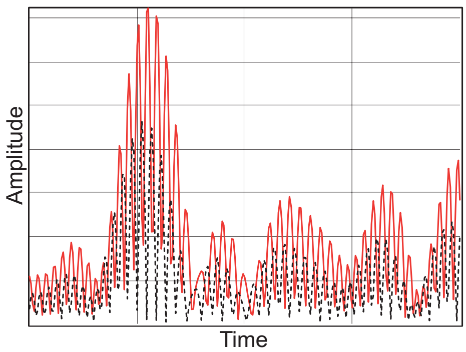

Fig. 9. Magnitude of the complex envelope of a single OBFN input (dashed), and the magnitude of the OBFN output (solid) for a random datastream.

The most critical building blocks in the simulation tool were found to be the QPSK modulation, the upconversion, the generation of sky noise, the LNBs, the MZMs, the determination of the ring settings, and the OBFN itself. It can be shown that most building blocks scale with $O(n)$, with n the number of inputs. Of course we have to keep in mind that these relations will not hold for infinite scaling. At a certain moment a maximum size of arrays and matrices will be reached, and buffers will be full. Depending on the operating system and the simulation software, additional computational time will be required to cope with large arrays and matrices, which will lead to calculation times that are larger than expected.

Suppose that we consider a PAA with 16×16 AEs, and we are using pulse shaping and omitting sky noise. The satellite signal is considered to consists of 20 channels, each containing a message of 100 bits. The simulation tool was run on a standard desktop computer. Using the profiling tools of LabVIEW, the following timing results were obtained: QPSK modulation 6.2 seconds; upconversion 10.6 seconds; LNBs 15.1 seconds; MZMs 8.4 seconds; determining the ring settings 4.0 seconds; OBFN 14.0 seconds; remainder, unaccounted LabVIEW time 9.0 seconds. This constitutes a total executing time of 67.3 seconds. With these results and the relations deduced, it is possible to extrapolate to get an indication on the required computational time for larger systems. For example, a full-scale beamformer for a 64×32 PAA (2,048 AEs) is expected to require a simulation time below ten minutes.

VII. Conclusions

In this paper we have presented a tool that has been developed to simulate optical beamformer systems for phased array receive antennas. In the design process the specific application of airborne satellite reception has been taken as a pilot application. The tool has been developed in LabVIEW, and —because of the dynamical implementation of the OBFN— can be used to simulate beamformers with any number of input ports.

The models of the individual components have been tested and were found to match their theoretical responses. Also, a simulation of a simplified beamformer has been performed, validating the functionality of the simulator as a whole. Finally, a scalability study indicated that it should be possible to simulate a full-scale beamformer system within a reasonable amount of time. As a result, it can be concluded that a profound simulator tool has been realized, specifically usable for optical beamformers. From this application we can generalize to other applications in RF photonics, such as radio-over-fibre links, making it a widely usable simulator.

In future work the simulation results will be compared with actual measurements presented in [4]. The combination of theory, measurements, and simulations will result in a comprehensive understanding of optical beamformers and allows for full-size system evaluations with more than 2,000 AEs.

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