

# Optical beam forming for phased-array antennas

A. Meijerink<sup>1</sup> • C.G.H Roeloffzen<sup>1</sup> • L. Zhuang<sup>1</sup> • D. Marpaung<sup>1</sup> • R.G. Heideman<sup>2</sup> • A. Borreman<sup>2</sup> • Wim van Etten<sup>1</sup>

<sup>1</sup> University of Twente

Faculty of Electrical Engineering, Mathematics and Computer Science

Telecommunication Engineering group

PO Box 217

7500 AE Enschede

The Netherlands

<sup>2</sup> LioniX BV

PO Box 456

7500 AH Enschede

The Netherlands

**The activities of the Telecommunication Engineering (TE) group span the communications spectrum from copper cables, optical fibres, microwaves, radio and electromagnetic compatibility. Our research concentrates on optical signal processing and networks, mobile communications, microwave techniques and radiation from ICs and PCBs [1]. A considerable (and particularly interesting) part of it is related to optical beam forming for phased array antennas, using optical ring resonators. In this article the theoretical basics and practical challenges of this interesting research topic will be summarized.**

## 1 Phased array antennas (PAAs)

A phased array antenna (PAA) consists of an array of antenna elements (AEs) and a so-called beam forming circuit.

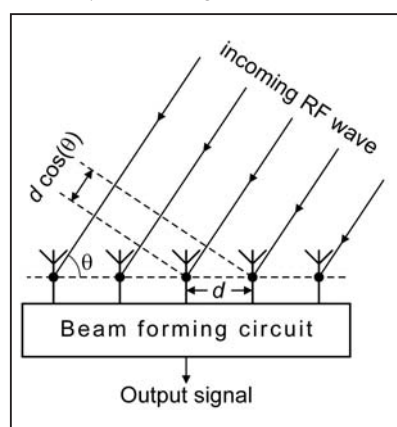
In contrast to for example a dish antenna -which has to be mechanically controlled- the radiation pattern of a PAA can be controlled by properly tuning the relative phases between the

AEs by means of the beam forming circuit, such that radiation (or reception) is reinforced in the desired direction and suppressed in the undesired direction. This is illustrated for a linear 1-dimensional PAA in Figure 1a.

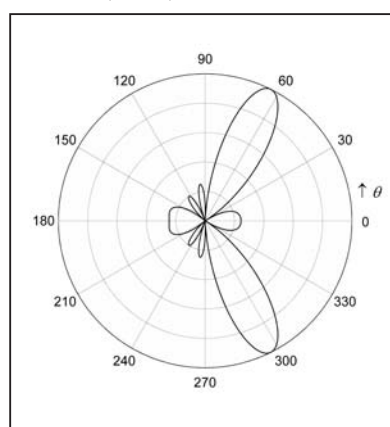
Suppose this PAA receives a (desired) plane RF wave at an angle  $\theta$  with

Figure 1: A linear 1-dimensional phased array antenna (PAA)

a) Schematic diagram of the PAA



b) Beam pattern of the PAA



The first author, Arjan Meijerink, was born in Almelo, The Netherlands, in 1976. He received the MSc and PhD degrees in Electrical Engineering (both with honours) from the University of Twente, Enschede, The Netherlands, in January 2001 and November 2005, respectively. His PhD work "on optical coherence multiplexing" was carried out in the Telecommunication Engineering group, under supervision of Prof.dr.ir. Wim van Etten.

Currently he is working as a postdoctoral researcher, in the same group, on photonic signal processing systems for RF applications. His particular research interest is in optical beam forming systems for phased array receive antennas.

E-mail: [a.meijerink@utwente.nl](mailto:a.meijerink@utwente.nl)

respect to the array. The inter-arrival time between two neighbouring AEs will be  $\tau = d \cos(\theta)/c_0$ , where  $d$  is the spacing between the AEs and  $c_0$  is the speed of light in vacuum. This results in a mutual phase difference  $\psi = 2\pi f_{RF}\tau$ , where  $f_{RF}$  is the frequency of the RF wave.

In a narrowband PAA receiver system the beam forming circuit consists of set of phase shifters (that compensate for these phase differences  $\psi$ ) and a summing circuit. Hence constructive interference occurs for waves received from the desired direction, so that the PAA has a high gain in that direction. Waves from different directions cause destructive interference and are hence suppressed. Figure 1b shows the field radiation pattern of the PAA in Figure 1a (where the spacing  $d$  between the AEs is assumed to be half the wavelength of the received signal).

Note that the phase shifts  $\psi$  depend on the frequency  $f_{RF}$ , so that the beam pattern is frequency-dependent. In a broadband PAA system this results in an undesired effect which is called beam squinting. Beam squinting can be prevented by replacing the phase shifters in the beam forming circuit by true time delay (TTD) devices. In order to achieve continuous beam angle control, these TTD devices should be continuously tunable.

In the TE group we work on a beam forming method where TDD behavior and continuous tunability is achieved by implementing the beam forming circuit in the optical domain. This offers several additional advantages such as compactness and small weight (particularly when integrated on chip), low loss, high instantaneous bandwidth, frequency independence, and inherent immunity to electromagnetic interference. In Section 2 it will be illustrated how the optical beam forming circuit can be implemented on an optical chip using ring resonator-based TTD devices. In Section 3 a typical application of this principle will be illustrated, and in Section 4 it will be explained how the electro-optical and opto-electrical conversion around the chip should be performed in this application. Section 5 will conclude the paper and shortly describe our short-term research plans.

## 2. The optical beam forming network (OBFN) chip

A narrowband continuously tunable optical TTD device can be realized as a circular waveguide (also called optical ring resonator, or ORR) coupled parallel to a straight waveguide [2]-[5]. When propagation losses are neglected, such configuration can be considered as an all-pass filter, with a periodic, bell-shaped group delay response, as illustrated by the dotted lines in Figure 2. The period or free spectral range (FSR) is equal to the inverse of the ORR's round-trip time  $T$ .

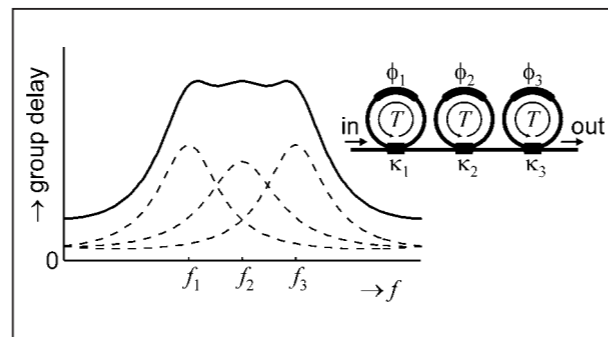


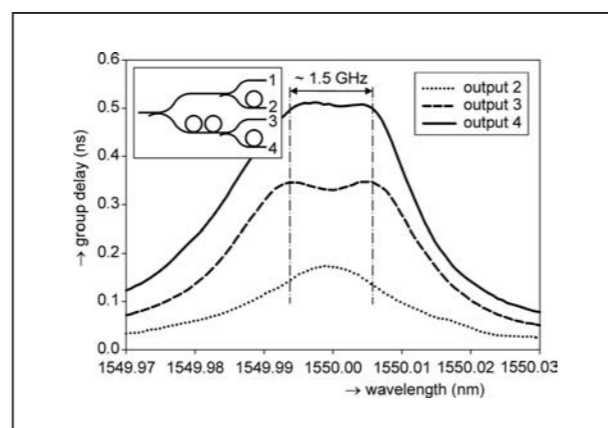
Figure 2: Theoretical group delay response of three cascaded ORR sections

The maximum group delay occurs at the resonance frequency, which can be varied by tuning the round-trip phase shift  $\phi$  of the ORR, using thermo-optical tuning elements. Similarly, the maximum delay can be varied by tuning the coupling coefficient  $\kappa$  between waveguide and ORR. The width of the bell shape is more or less inversely proportional to its height, resulting in a trade-off between peak delay and optical bandwidth.

The bandwidth can be extended by cascading multiple ORR sections, as shown in the inset of Figure 2. The resulting group delay response (the solid line in Figure 2) is equal to the sum of the individual group delay responses (dashed lines), so the group delay curve can be flattened by tuning the ORRs to different resonance frequencies. Such multi-stage delay element has a trade-off between peak delay, optical bandwidth, relative delay ripple and number of ORR sections [2],[3].

When multiple delay and combining elements are grouped in one optical circuit, an optical beam forming network (OBFN) is obtained. In [4] we presented the -to our knowledge- first single-chip realization of such an OBFN. This chip was fabricated by LioniX BV [6] in their TriPleX™ waveguide technology [7],[8]. The chip design is based on a 1x4 binary

Figure 3: Group delay measurement results on a 1x4 binary tree OBFN



tree topology, as shown in the inset of Figure 3.

Measurements of the group delay responses at the outputs of this OBFN demonstrate delay equalization with a maximum delay of 0.5 ns and bandwidth of 1.5 GHz; see Figure 3. Additional measurements on a 1x8 OBFN are presented in [5].

## 3. Application: satellite TV reception

One of the intended applications of the optical beam forming system is a conformal PAA for receiving satellite TV channels on an airplane.

This is investigated within the framework of the SMART Antennas system for Radio Transceivers (SMART) project.

RF waves from DVB-S television satellites arrive in two linear polarizations (horizontal and vertical) and span a frequency range of 10.7-12.75 GHz. In a conventional satellite dish antenna, the dish focusses this wave on the feedhorn of the low-noise block (LNB). The LNB selects one polarization, suppresses either the upper or lower half of its spectrum by means of bandpass-filtering, and down-converts the remaining band to an intermediate frequency (IF) range of 950-2050 MHz. After suitable amplification this IF signal can be transmitted through a 75  $\Omega$  coaxial cable, to the satellite TV receiver unit.

Now suppose the dish antenna were replaced by a PAA with a beam forming circuit based on the OBFN described above, and the output signals of the AEs (spanning 10.7-12.75 GHz) were modulated directly onto the optical signal by means of double sideband (DSB) modulation. First of all this would require very high-speed optical modulators and an equally fast detector. Moreover it requires the OBFN to have a very large optical bandwidth, namely  $2 \times 12.75 = 25.5$  GHz. It can be shown that such a large bandwidth can only be achieved when the OBFN contains a very large number of ORRs, in the order of a few hundreds. Moreover the FSR should be larger than 25.5 GHz. Since the FSR is inversely proportional to the ORRs' round-trip time  $T$ , this requires a very small bending radius (in the order of 1 mm), which will introduce severe optical losses.

## 4. Enhanced system architecture

The requirements can be relaxed by performing frequency down conversion (FDC) -which is normally performed in the LNB- prior to electro-optical conversion. This lowers the maximum frequency of the modulating signal from 12.75 GHz to 2050 MHz and hence reduces the costs of the required optical modulators and detector. It also reduces the bandwidth of the modulated optical signal, hence relaxing the requirements on the OBFN.

This optical bandwidth can be further reduced by applying

single sideband modulation with suppressed carrier (SSB-SC) instead of DSB modulation. Note that this reduces the total optical bandwidth from 25.5 GHz to 1.2 GHz, which implies that approximately 20 times less ORRs are required in the OBFN, and that the ORRs' bending radii can be 20 times larger.

SSB-SC modulation can be implemented in different ways, for example using quadrature carriers and Hilbert transformation, or by applying optical heterodyning. The most attractive way of performing SSB-SC modulation in this particular application, however, is by means of a DSB modulator and an optical sideband filter (OSBF), as this requires only one laser, one modulator per AE, and -since the linearity of beam forming and sideband filtering allows their order to be reversed- only one common OSBF. This OSBF can be realized using similar components as in the OBFN (directional couplers and ORRs), so that the OBFN and the OSBF can be integrated on the same chip. Mach-Zehnder modulators can be used as DSB modulators, eventually linearized by means of predistortion amplifiers.

The SSB-SC-modulated optical signal has to be detected coherently. This can be done by means of a balanced coherent detector configuration, consisting of a 2x2 directional coupler and two photodiodes. This balanced detector mixes the output signal of the OSBF with an unmodulated version of the laser signal, which is passed around the OBFN.

All these design considerations result in the system architecture that is shown in Figure 4.

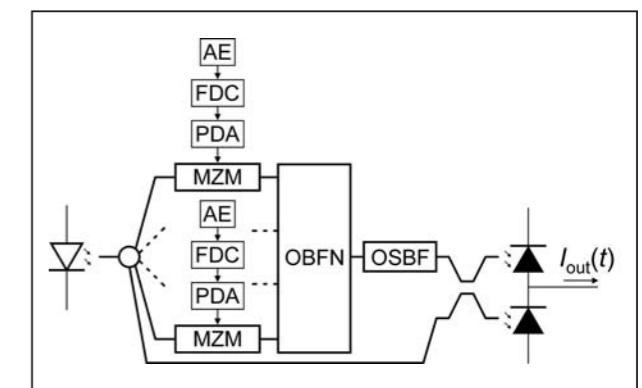


Figure 4: Architecture of the PAA control system

AE=antenna element,  
FDC=frequency down conversion,  
PDA=predistortion amplifier,  
MZM=Mach-Zehnder modulator,  
OBFN=optical beam forming network,  
OSBF=optical sideband filter

## 5. Conclusion and further work

A novel optical beam forming concept for PAA reception has been proposed, relying on FDC, OSBF-based optical SSB-SC modulation, optical beam forming using an integrated ORR-based OBFN, and balanced coherent optical detection. To our best knowledge it is the first demonstration of a squint-free, continuously tunable beam steering mechanism with fully integrated OBFN. A significant amount of work remains to be done, however.

A particular challenge is the actual control of the OBFN chip. The 8x1 binary tree OBFN that we tested, for example, has 32 heater elements that all have to be properly tuned in order to get the correct group delay responses at the output ports of the OBFN. Each value of the beam angle requires a different set of voltages for the heater elements. These voltages are provided by an array of amplifiers that amplify the low-level voltages from a DAC chip. A PCB containing 32 of such amplifiers has nearly been finalized. Currently, a PCB is being

designed containing an ARM 7 processor, which is intended to calculate the required heater voltages from the desired delay settings. Also the algorithm that is required for performing this calculation is yet to be developed, and to be programmed into the processor.

Another important aspect that deserves further attention is the implementation of the SSB-SC modulation. The OSBF is currently being designed, and will be fabricated along with the OBFN on a new version of the chip. Then a driving circuit for the optical modulators will have to be designed and realized, and tested along with the OSBF. Once the optical receiver is also implemented and tested, the functionality of the full beam forming system can be verified.

And finally, the ultimate challenge is to prove that the proposed concept has potential for full integration of the entire beam forming functionality, including optical sources, modulators and detectors, and additional electronics. ♦

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