

# Ring resonator-based single-chip 1x8 optical beam forming network in LPCVD waveguide technology

L. Zhuang<sup>1</sup>, C. G. H. Roeloffzen<sup>1</sup>, R. G. Heideman<sup>2</sup>, A. Borreman<sup>2</sup>,  
A. Meijerink<sup>1</sup>, W. van Etten<sup>1</sup>

<sup>1</sup>University of Twente, Faculty of Electrical Engineering, Mathematics and Computer Science,  
Telecommunication Engineering group, P.O. Box 217, 7500 AE, Enschede, The Netherlands

<sup>2</sup>LioniX B.V., P.O. Box 456, 7500 AH, Enschede, The Netherlands

*Optical ring resonators (ORRs) are good candidates to provide continuously tunable delay in optical beam forming networks (OBFNs) for phased array antenna systems. Delay and splitting/combining elements can be integrated on a single optical chip to form an OBFN. A state-of-the-art 1×8 OBFN chip has been fabricated in LPCVD waveguide technology. It is designed with 1 input and 8 outputs, between which a binary-tree topology is used. A different number of ORRs (up to 7) are cascaded for each output. In this paper, the principle of operation is explained and demonstrated by presenting measurements on the 1×8 OBFN chip.*

## 1 Introduction

Beam forming for broadband RF signals can be achieved by means of a phased-array antenna working with an optical beam forming network (OBFN). This OBFN consists of optical splitting/combining circuitry and delay elements, which need to be continuously tunable in order to achieve continuous beam angle control. Moreover, in order to support relatively broadband RF signals, the delay elements should have a flat magnitude response and a linear phase response in the corresponding frequency range. To meet these requirements, optical ring resonators (ORRs) appear to be good candidates due to their continuous tunability, and well-known advantages of integrated optics [1]-[5]. This paper demonstrates the advantages of optical beam forming using integrated ORRs, by explaining its operating principles, and by presenting some measurement results on an actual ORR-based 1×8 OBFN chip. The chip is realized in LPCVD planar optical waveguide technology [6].

## 2 Principles of Ring resonator-based optical beam forming networks

### A. Optical ring resonator (ORR) delay elements

A single ring resonator has a periodic bell-shaped group delay response. The peak delay value and its position are determined by the coupling coefficient  $\kappa$  and the additional round-trip phase shift  $\phi$  of the ring, respectively. An ORR delay element shows an inherent trade-off between peak delay and bandwidth. The bandwidth of the delay element can be increased, however, by cascading multiple ORR sections, as illustrated in the inset of Fig. 1. Since the group delay responses of the individual sections simply add up, the total delay response can be flattened by properly tuning the ORRs, as illustrated in Fig. 1. The bandwidth of the delay element can be extended by adding more sections, and the peak-peak ripple of the group delay response in the flattened frequency band can be decreased by decreasing the difference between the resonance frequencies of the rings

[1],[3]–[5]. Measurements on a 3-ring optical delay device realized in LPCVD waveguide technology have been presented in [5], showing good agreement with theory.

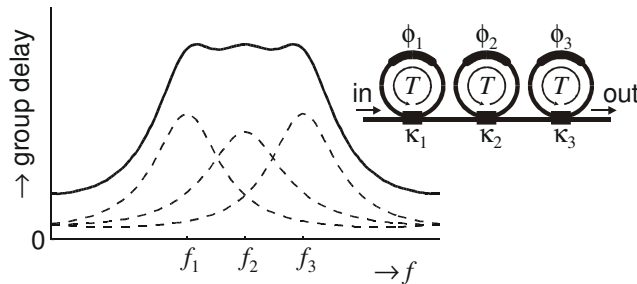


Fig. 1. Theoretical group delay response of three cascaded ORR sections. The dashed lines represent the group delay responses of the individual sections. Inset: cascade of three ORRs with round-trip delay  $T$ , additional round-trip phase-shifts  $\phi_i$  and power coupling coefficients  $\kappa_i$ .

### B. Optical beam forming network (OBFN)

When the optical delay elements are integrated together with signal processing circuitry, an 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. An ORR-based 1x8 OBFN has been proposed, consisting of 3 stages with in total 12 ORRs and 7 tunable splitters, as shown in Fig. 2.

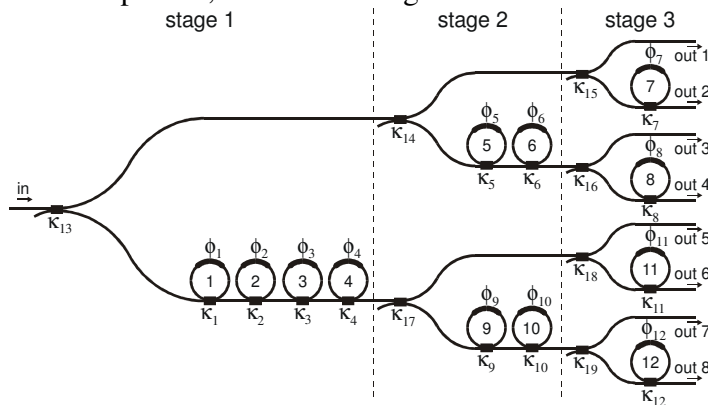


Fig. 2. Binary tree-based 1x8 optical beam forming network for a phased-array transmitter system, consisting of 12 ORRs and 7 tunable splitters.

## 3 Device design and realization

The complete beam forming operation can be integrated into one optical chip [7]. The actual design of the 1x8 OBFN has been divided in the design of elementary basic building blocks: bent waveguides, Mach-Zehnder interferometers (MZIs) for the tunable coupling and splitting function, and the tapered waveguide end-faces. Next, the most promising building blocks have been selected and fabricated using the TripleX<sup>TM</sup> technology [6]. The actuation of the couplers, splitters and phase shifters is done thermo-optically, allowing tuning of the resonance frequency of the ORR, tuning of the delay, and tuning of the splitting ratio, within 1 ms. Fig. 3 shows a photograph of a realized 1x8 OBFN chip. The chip length is 4.85 cm and the chip width is 0.95 cm.

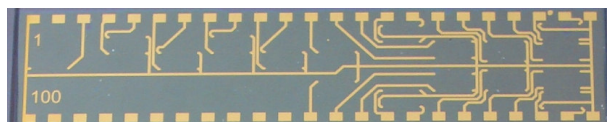


Fig. 3. Photograph of the 1x8 OBFN chip. The bondpads and electrodes are clearly visible.

A single 1x8 OBFN as depicted in Fig. 2 requires 31 heaters (two tuning elements for each ORR and one for each splitter) and therefore at least 31 electrodes and one ground electrode to drive the heater elements.

## 4 Measurements

The optical group delay responses at each output of the 1×8 OBFN chip have been measured by means of the phase-shift method, using the setup that is shown in Fig. 4.

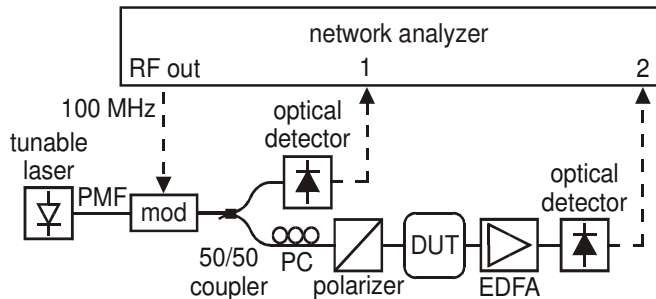


Fig. 4. Group delay measurement setup. DUT: Device under test, EDFA: erbium-doped fiber amplifier, mod: external Mach-Zehnder intensity modulator, PC: polarization controller, PMF: polarization-maintaining fiber.

The Agilent PNA network analyzer generates an electrical 100 MHz RF signal, which modulates the monochromatic light from the Santec tunable by means of an external LiNbO<sub>3</sub> Mach-Zehnder-based intensity modulator. The modulated optical signal is splitted by means of a fiber splitter. One part is detected and directly led back to the network analyzer. The other part is re-polarized and coupled into the device under test (DUT), such that the 1×8 OBFN is investigated for TE-polarized light. The eight output powers are subsequently measured by moving the fiber to the desired output ports. An erbium-doped fiber amplifier is used to boost the optical power, which is measured by means of a second detector and led to the network analyzer. The network analyzer measures the RF phases  $\varphi_1(\lambda)$  and  $\varphi_2(\lambda)$  of the output signals of the optical detectors for different laser wavelengths  $\lambda$ . The group delay response is estimated from these results by calculating

$$\tau_g(\lambda) = \frac{\varphi_1(\lambda) - \varphi_2(\lambda)}{2\pi f_{\text{RF}}}, \quad (1)$$

where  $f_{\text{RF}}$  is the frequency of the electrical signal (100 MHz in our case). Note that this is a relative group delay response: it is biased by an eventual path length difference between the two paths from the 50/50 coupler to the inputs of the network analyzer. The average powers at the outputs of the OBFN chip were measured using an HP 81532A Power Meter (not shown in Fig. 4). With this setup the group delay responses at each output of the OBFN chip have 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. Measurements have been carried out with different settings for the heating elements. The measurement results prove that the waveguide loss is  $\ll 1$  dB/cm. 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 7 cascaded rings. As a 1×8 OBFN, each output is required to give a different delay value over a common frequency band, in order to satisfy the condition of beam forming. 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 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 of approximately 1.2 ns (corresponding to 36 cm of physical distance in air) and delay ripple of approximately 0.1 ns (3 cm). Since the 1×8 OBFN chip is designed such that each of the 3 stages can be measured separately, in practice the final delay responses at the outputs are achieved by tuning every stage to a flattened delay response over a common frequency band before they add up.

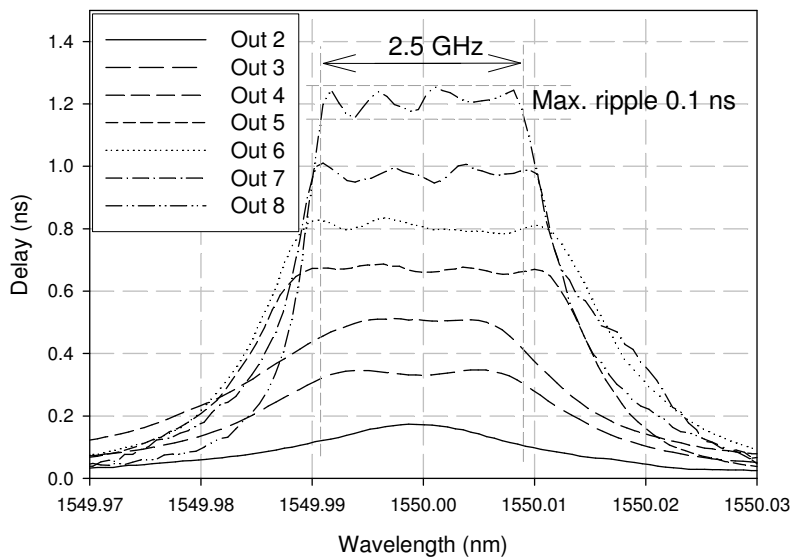


Fig. 5. Measured group delay responses at different outputs of the 1x8 OBFN chip.

## 5 Conclusion

Group delay responses at each output of the ORR-based 1×8 OBFN chip realized in LPCVD waveguide technology have been measured. The measurement results are in good agreements with theory. Delay generation of up to 7 cascaded rings for optical beam forming is demonstrated with a maximum delay of 1.2 ns, with a bandwidth of 2.5 GHz, and ripple of 0.1 ns. To our knowledge, this is the first single-chip demonstration of eight-element optical beam forming with true time delay and continuous tunability.

## Acknowledgements

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