Multiwavelength Optical Beam Forming Network with Ring Resonator-based Binary-Tree Architecture for Broadband Phased Array Antenna Systems

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Integrated optical beam forming networks (OBFNs) offer many advantages for phased array applications. ORR-based true-time-delay units can be cascaded in a binary tree topology and tuned for continuously-adjustable broadband time delay. Nonetheless, with large number of antenna elements, the OBFN may become very complex. A novel idea is proposed to exploit the frequency periodicity of the ORRs and the WDM technique to achieve multiple-signal-paths on a single beamformer, thus reducing complexity and costs. The use of high index contrast waveguides in Si-compatible technology further reduces chip footprint and allows the use of integrated OBFNs for large arrays and multi-beam applications.

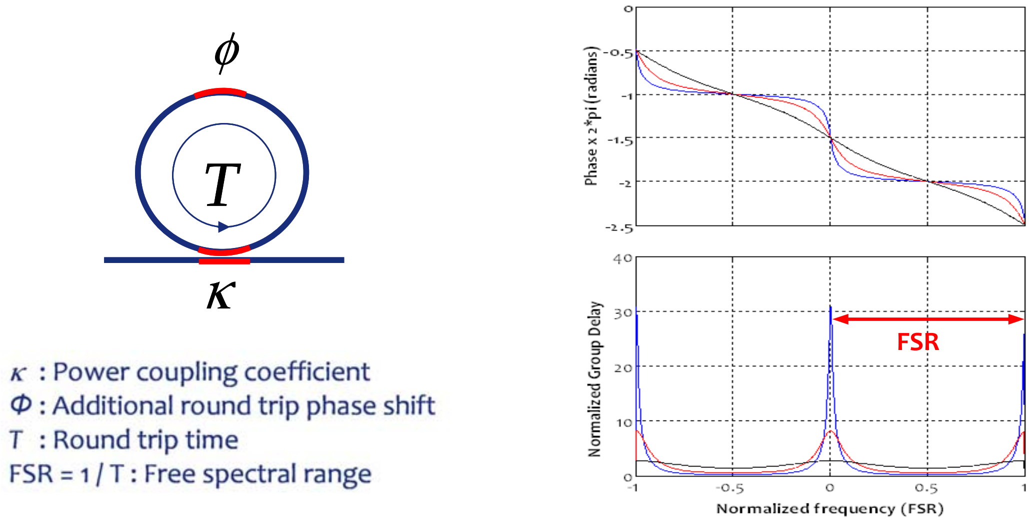
I. Introduction

Phased arrays antennas offer a number of advantages: electronic beamforming (beam shaping and beam steering), multibeaming and interference nulling capability. In practice, their performances are limited by the characteristics of the *beam forming network* (BFN) used. A possible improvement to the limitations of all-electronic BFNs can be achieved integrating electronics and photonics by realizing an *optical beam forming network* (OBFN). This, in principle, provides large bandwidths, RF frequency transparency, True Time Delay (squint-free) characteristic over the band of interest, EMI immunity, compactness and light weight, thus allowing critical size and weight applications (e.g. aerospace).

Section II of this paper describes the advantages of the OBFN architecture reported in [1, 2] and its limitations in the case of application to large receiving arrays or multi-beam systems. Then, in section III, a solution employing WDM technique to achieve multiple signal paths is proposed and the related issues analyzed.

II. ORR-based OBFN using a *single* wavelength

True time delays (TTD) realized with optical ring resonators. For an OBFN it is desirable to have two basic features: a squint-free behaviour, achievable by using true-time delays, and a continuously tunable delay operation. For this reason, *optical ring resonators* (ORR) appear to be good candidates to realize the delay elements. 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 radiofrequency (RF) signal that is modulated on the optical carrier. The basic parameters and the frequency characteristics of such devices are shown in Figure 1.



(a) (b)

Figure 1. Optical ring resonator (ORR) used as true time delay (TTD) unit. Tuning parameters (a) and spectral characteristics (b).

The peak delay value is determined by the coupling coefficient κ, while its position can be tuned by varying the additional round-trip phase shift ϕ of the ring. The delay element has a *periodic* group delay response, with the delay peaks centred at the resonance frequencies. The third parameter, the round-trip time T, determines the free spectral range (FSR), that is, the frequency separation between two adjacent resonances, whose value is

$$FSR = \frac{1}{T} \quad [\text{Hz}]. \tag{1}$$

This delay element, being a resonator, shows an inherent trade-off between peak delay and bandwidth. However, as proved in [2], the bandwidth of the delay element can be increased by cascading multiple ORR sections (Figure 2): the group delay responses of the individual sections will simply add up and the total delay response can be flattened by properly tuning the ring parameters. The drawback is the increase in complexity and required chip area.

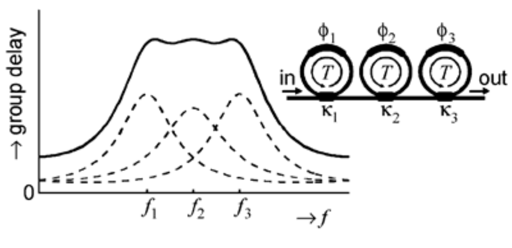


Figure 2. Cascaded optical ring resonators (ORR) are used to increase the band of the TTD unit.

ORR-based OBFN. These devices can be integrated in a single chip with the control electronics to obtain the OBFN. This is a N-by-1 network where each input is properly delayed and then combined with the others. To reduce the number of tuning elements, a binary-tree topology (Figure 3) was considered in [1], instead of a straightforward parallel OBFN.

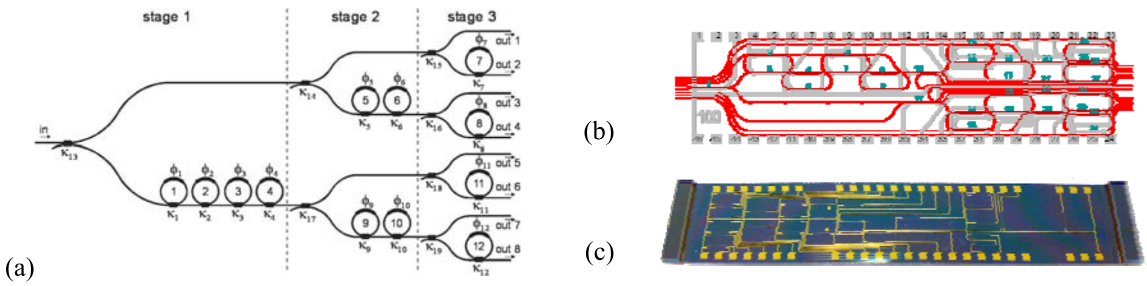


Figure 3. OBFN binary-tree topology (a), layout (b) and picture (c).

The OBFN has been fabricated using the CMOS-compatible Si-based TriPleX^{TM} waveguide technology [3]. The parameters are thermo-optically tuned by using two heaters for each ring, one heater for each splitter and one for each phase shifter for a total of 31 heaters for an 1x8 OBFN. Each heater has an average power consumption of 0.25 W.

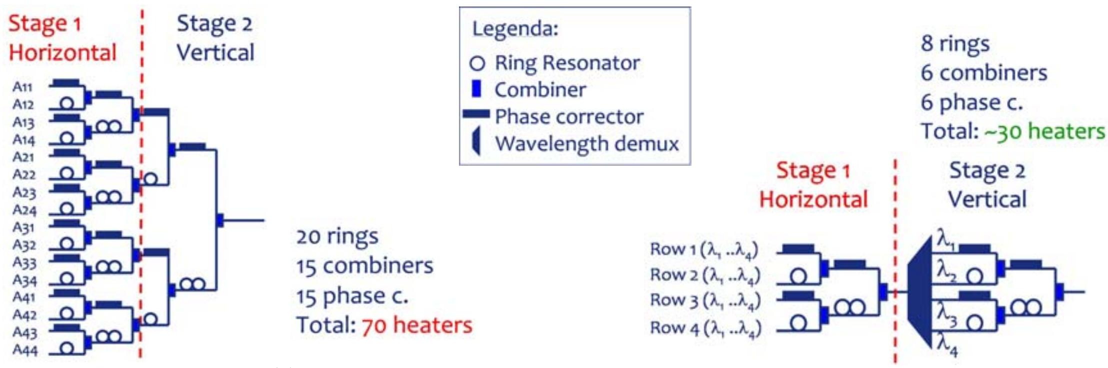
Limitations for large arrays and for multi-beaming. In many typical applications of phased-array antennas, like space communications and radioastronomy, the signal powers are typically very low, and also a narrow antenna beam is required. This requires large receiving surface, that is, large arrays with many elements, since grating lobes may appear for certain scanning angles (in conventional arrays) if the distance between the elements goes beyond half-wavelength. In this case, even using a binary-tree topology, the OBFN may become very complex, especially considering the total number of heaters required. The same problem appears when a system capable of multiple, independent beams is desired.

III. ORR-based OBFN using *multiple* wavelengths

To overcome the limitations described above, the challenge is to modify the binary-tree topology in such a way to realize an OBFN capable to be scaled to hundreds or thousands of antenna radiators, while keeping a low system complexity and cost.
The basic idea is to create multiple signal paths on the same beamformer. In this way, a single delay line carries the signal of different antenna elements, thus significantly reducing the network complexity and, in turn, the number of rings and heaters required. This idea is made possible by the exploitation of the frequency-periodic behaviour of the ORRs used as TTD units. As seen before, a ring is characterized by its *FSR*, that is fixed by the round trip time *T*. In this sense, the ring is frequency "transparent": it delays the signals in each of these frequency bands, spaced by the *FSR*, of the same amount, independently from the RF signals. Then, by using multi-wavelength lasers and fast integrated modulators, it is possible to multiplex signals from different antenna elements on a single path, delaying them of the same amount. This multiplexing technique is an optical wavelength division multiplexing (WDM). This solution appears particularly interesting in the particular but very common situation of N-by-N planar arrays with *separable illumination* [4]. In this case, the array factor $F(\theta, \varphi)$ can be written as

$$F(\theta,\varphi) = F_x(\theta,\varphi) \cdot F_y(\theta,\varphi) \qquad (2)$$

This means that the array factor can be defined by separately defining the delays between the horizontal subarrays, and then between the vertical subarrays.
In this case, the architecture of the beamformer can be greatly simplified applying the WDM technique, as shown in the Figure 4.



(a) (b)

Figure 4. Comparison between the traditional binary-tree (a) and the multi-wavelenght, mutiple signal path OBFN (b), for a 4x4 planar array. Note the dramatic reduction in the number of heaters required.

As can be seen in the schematic, this technique allows a dramatic reduction in the number of rings required, especially in the case of large number of elements *N*. As a direct consequence, we achieve a reduction in complexity, in area occupation (the ring dimensions are the limiting factor), in power and heat dissipation (drop in the number of heaters). The only additional hardware required consists in the multiplexers needed to combine the wavelengths in the single waveguides, in the first stage, and the de-multiplexer used to split them before the second stage. Important aspects to be further investigated will be the design of the combiner in the second stage, that will need to be capable of combining the RF signals carried by the different optical carriers λ_1, λ_2, λ_3, λ_4, and the design of multiplexers and de-multiplexers.

IV. Conclusions

A novel idea towards the simplification of an existing OBFN has been proposed. Exploiting the frequency-periodic behaviour of the ORR-based delay units and filters, it is possible to realize a WDM-based multi-signal-path OBFN, thus reducing system complexity and cost and making possible an integrated realization of a single-chip OBFN for large arrays or multiple-beam applications. Issues like design of the optical de-multiplexers and multi-wavelength combiners are still to be investigated.

Acknowledgments

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