A Novel Design Procedure for Minimum RF Phase Error in Optical Ring Resonator Based Integrated Optical Beamformers for Phased Array Antennas

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We present a novel design procedure for optical ring resonator (ORR)-based integrated optical beam forming networks (OBFN) for microwave phased array antenna applications. Given the system specifications of minimum RF signal bandwidth (2.05 GHz), propagation loss in the optical waveguide (0.2 dB/cm) and maximum phase error allowed in band (π/16), the method is used to determine the number of ORRs required in each delay unit for minimum complexity and, in turn, minimum footprint in the realized chip. The effects of the RF phase errors obtained with the described procedure are also analyzed. The result shows negligible degradation in the array radiation pattern when imposing a maximum phase error of π/16 or lower.

Introduction

In recent years, phased array antennas (PAAs) have drawn more and more attention as they have been gradually entering the field of commercial applications. The advantage of this type of antennas originates from the possibility to modify their radiation characteristics (namely, beam direction, shape and interference rejection) using a reconfigurable feeding network, called *beamformer*.

Photonic technology allows to realize *optical* beam forming networks (OBFN) which offer several advantages in comparison with their electronic counterpart: this makes them an attractive solution in several fields of application. When large percentage bandwidths are required, OBFNs can implement true-time delay for wideband beamsteering [1]; RF signal processing in optical domain takes advantage of the EMI immunity of the optical components; low losses of optical fibers can be exploited both for antenna remoting and reference signal distribution to large arrays [2].

When compactness and lightweight are demanded, high complexity beamformers can be integrated on an optical chip. When such approach is used, it is not easy to obtain the desired continuously tunable true time delay characteristics needed for wideband operation. For example, semiconductor optical amplifiers (SOAs) can be also used for delay generation, but their phase linearity is limited to a relatively narrow percentage band [3]. A very attractive solution is the use of optical ring resonator (ORR)-based delay units, which offer low losses, continuous tunability and compactness [4]-[7]. We recently demonstrated the capability of a complete beamformer built using this type of delay units to provide squint-free beamsteering on a high percentage bandwidth to a 4×4 antenna array [1]. Such a beamformer can be designed using the method shown here.

In this paper we describe a novel design procedure for optical beamformers based on optical ring resonators. Taking into account the bandwidth, beamsteering angle and maximum phase error requirements, the method determines the OBFN layout with minimum complexity and footprint.

Design of the Symmetric Binary Tree OBFN structure

In our study we assume the most common case of linear or planar arrays, with identical, equally spaced antenna elements (AEs). Let us assume the array on the *xy* plane of a Cartesian coordinate system. An antenna element placed in the origin is chosen as reference AE with zero delay. It can be shown that, for a desired pointing direction (θ_0, φ_0), the required delay at the p^{th} element located at (x_p, y_p) equals

$$\Delta\tau_p = \frac{\sin(\theta_0)\cos(\varphi_0)x_p + \sin(\theta_0)\sin(\varphi_0)y_p}{c_0} \quad (1)$$

indicating that the required delay tuning range increases with the space coordinate of the AE. This motivates the choice of *binary tree* architecture as the structure of lowest complexity for the OBFN, since different delay paths can share the same delay units to achieve the desired linear delay profile, as shown in Fig. 1. The *symmetry* of the structure comes from the general need to steer the beam in both directions, without need of additional delay offset compensation.

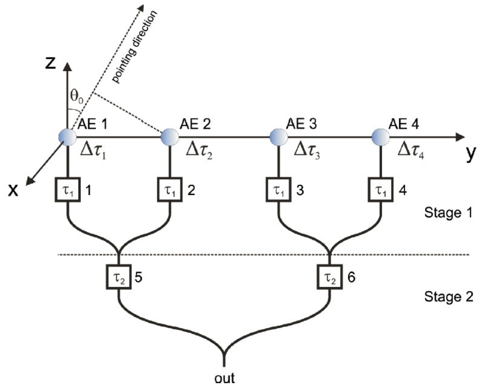

Figure 1. Architecture of a symmetric binary tree 4×1 OBFN feeding a 4-elements linear array. Note how delay units 5 and 6 are shared among multiple paths.

In this architecture, the maximum delay tuning ranges τ_1, τ_2 for the delay units in stages 1 and 2 are given by

$$\tau_1 = \frac{1}{2}\tau_2 = \left(\Delta\tau_{n+1} - \Delta\tau_n\right)_{\max} = \frac{d\sin(\theta_{0,\max})}{c_0} \ , \quad n = 1,...,3 . \quad (2)$$

In our example, we consider an antenna tile for Ku-band satellite communications, where d = 23.6 mm and $\theta_{0,\max}$ = 60 degrees, obtaining τ_1 = 68.13 ps and τ_2 = 136.26 ps.

Design of the delay units

The required delays are implemented by ORR-based delay units. Those components are optical filters with a frequency periodic response, the period being called free spectral range (FSR). Within its optical band, the ORR can be tuned to approximate the desired linear phase dispersion characteristic of an ideal delay line, where the slope is proportional to the amount of delay. The bandwidth of the delay element is defined as the range of frequencies where the phase error $\varepsilon < \varepsilon_{\max}$, which is the maximum allowed by the design specifications, obtained by the maximum acceptable beam pointing fluctuation. Simulations show that at Ku-band this effect is negligible if $\varepsilon < \pi/16$. For a single ORR, the bandwidth decreases when the required delay increases, in a quasi-inversely proportional manner [1], and it can be increased by cascading additional ORRs [7]-[8]. The design consists in determining the number of ORRs in each delay unit, based on three system-level requirements (1. optical bandwidth; 2. maximum delay tuning range required, obtained from (2) based on AE spacing and maximum scanning angle; 3. maximum phase deviation from ideal) and two technological parameters (maximum *FSR* of the ORRs and waveguide losses). The design procedure makes use of an ORR simulator based on LabView® software, which accounts for the effects of the technological parameters. The design steps are as follows.

1. The simplest structure is considered as a starting point, that is, each delay element is composed by one ORR only.
2. The phase response of each of the resulting optical paths (from the n-th antenna element, AE_n, to the output, see Fig. 1) is simulated, and tuned to approximate the desired maximum delay for that path, as obtained from (2). The tuning is performed in such a way to maximize the band in which the phase error (difference between the desired phase characteristic and the phase of the ORR delay unit) is within the maximum allowed by the design specifications (Fig. 2).

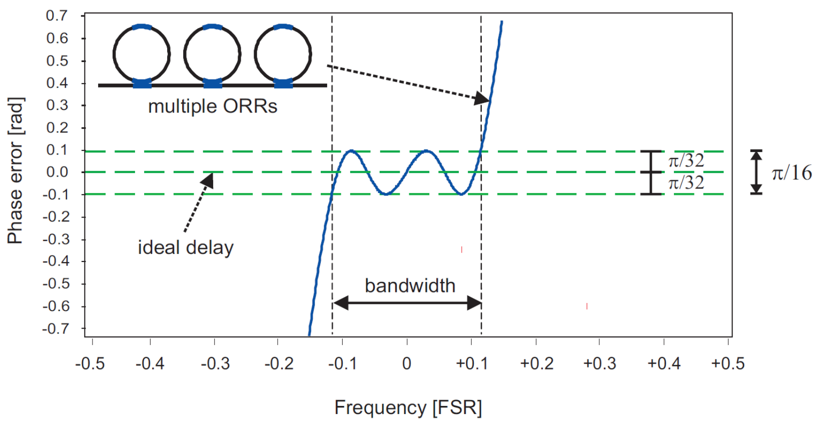

Figure 2. ORR-based delay elements: phase error response

3. The bandwidth of each path is evaluated.
4. If any of those bands is below the required RF band, the complexity of the beamformer must be increased by adding extra ORRs in the delay elements (starting from the highest stage) and the design steps 2, 3 and 4 are repeated.

This procedure can be easily extended to the case of a planar array, as is the example of a 4×4 OBFN for a Ku-band antenna. The system specifications are shown in Table 1 (*FSR* of the ORRs = 20 GHz, waveguide loss = 0.2 dB/cm), together with the bandwidth of each OBFN path. The obtained layout is displayed in Fig. 3.

Table 1. Specifications of a 4×4 OBFN for a Ku-band antenna

Frequency range	1.05 – 3.10 GHz (IF band of DVB-S)
Scan angle (elevation, azimuth)	-60 to +60 degrees
OBFN input subarray spacing (x and y dir.)	23.6 mm
Max phase error (between adjacent inputs)	π/16
Antenna configuration	Planar, separable illumination

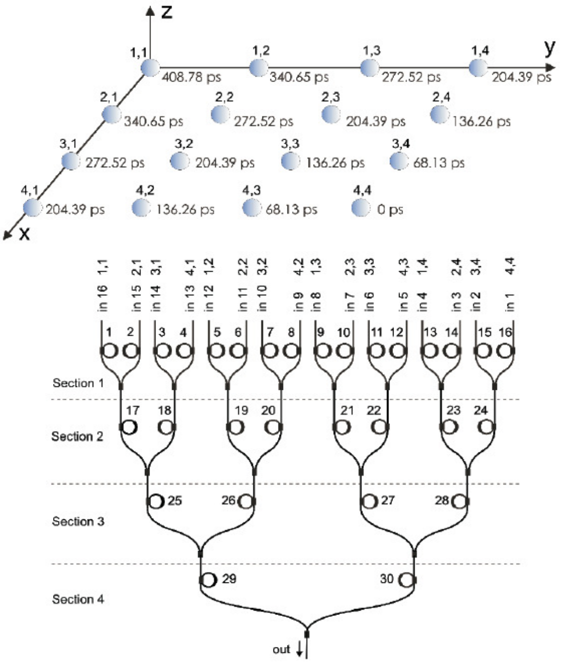

Figure 3. Ex. of OBFN for a 4×4 Ku-band planar antenna.

Table 2. Delays and bandwidths in the 4×4 OBFN for a Ku-band antenna

Optical path	Required delay	Bandwidth
4, 4	0 ps	>> FSR
4, 3	68.13 ps	0.238 FSR = 4.7660 GHz
4, 2	136.26 ps	0.146 FSR = 2.9297 GHz
4, 1	204.39 ps	0.135 FSR = 2.6953 GHz
3, 4	68.13 ps	0.238 FSR = 4.7660 GHz
3, 3	136.26 ps	0.189 FSR = 3.7890 GHz
3, 2	204.39 ps	0.141 FSR = 2.8125 GHz
3, 1	272.52 ps	0.133 FSR = 2.6535 GHz
2, 4	136.26 ps	0.146 FSR = 2.9297 GHz
2, 3	204.39 ps	0.135 FSR = 2.6953 GHz
2, 2	272.52 ps	0.115 FSR = 2.3047 GHz
2, 1	340.65 ps	0.111 FSR = 2.2266 GHz
1, 4	204.39 ps	0.135 FSR = 2.6953 GHz
1, 3	272.52 ps	0.127 FSR = 2.5391 GHz
1, 2	340.65 ps	0.111 FSR = 2.2266 GHz
1, 1	408.78 ps	0.107 FSR = 2.1484 GHz

Conclusions

A novel design procedure for symmetric binary-tree optical beamformers has been shown in this paper, using as example a design for a Ku-band phased array antenna for satellite reception. The method allows to design the beamformer with minimum complexity based on the given system specifications and technological constraints.

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