Automatic Transmission Parameters Measurement and Radiation Pattern Simulation for an RF Photonic Integrated Beamformer

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We present the implementation and demonstration of a software tool for the performance characterization of integrated N-by-1 photonic beamformers for phased array antennas. The software operates the automatic measurement of the transmission parameters of an equivalent N+1 ports microwave network, corresponding to the complex excitations of the individual antenna elements of the array. The measured excitations are used to simulate the array factor generated by the optical beamformer and to analyze it in terms of maximum directivity, sidelobe levels and wideband behaviour. The software provides a useful tool to test the wideband performance of the network, the effects of excitation inaccuracies, and a straightforward evaluation of the effects of amplitude and phase weighting for beam shaping.

Introduction

Phased array antenna systems have gained much interest in modern wireless systems (e.g. radar, radio communications, satellite reception, radio astronomy) mainly thanks to the specific ability of this type of antenna structures to dynamically reconfigure their radiation characteristics [1]. In fact, the radiation pattern of an antenna array directly depends on the complex excitations, provided by the so-called beamforming network (BFN), to the individual antenna elements constituting the array. The ability to reconfigure those excitations allows to modify important radiation characteristics of the antenna array, as the spatial pointing direction of the main antenna beam, its shape, the levels of the sidelobes, the possibility to place nulls of radiations in desired directions, and more. This gives a large degree of flexibility when compared to individual antennas, making arrays highly desirable in many applications within the field of wireless communications. In very broadband applications, and where continuous tunability of the beam direction is required, it might become advantageous to realize the beamformer employing *optical* technology, thanks to inherent advantages of photonics such as compactness, light weight, low loss, frequency independence, large instantaneous bandwidth and inherent immunity to electromagnetic interferences [2, 3]. In this case we refer to the beamformer as *optical beamforming network* (OBFN).

To characterize the performance of any beamforming network, it is very useful to analyze the characteristics of the *radiation pattern* generated when this feeding network is connected to an actual antenna array. In general, this type of test requires the integration of the OBFN with an antenna system, in an anechoic chamber or another suitable environment, using a complex measurement setup, leading to a characterization process which might be expensive and not trivial to realize.

An attractive solution to facilitate the initial test of the performance of the OBFN before integration is to *simulate* the array factor, based on the *measured* complex excitations provided by the realized beamformer. This is a common approach used by several authors [4, 5].

In this work, we implemented and demonstrated the functionality of a computer application written to automate the testing procedure of the optical beamformer chips using the same approach. The aim of the software application is twofold. First, it creates a communication between the measurement instrument (a vector network analyzer, VNA) and the computer to automate the measurement of the OBFN transmission parameters, corresponding to the antenna excitations. After that, the acquired data are used to calculate the simulated array factor generated by the optical beamformer. This can be done for both linear (1-D) and planar (2-D) arrays. The program allows to display the array factor in various forms and to analyze different important quality parameters, included its frequency-dependent behaviour.

Modelling a beamformer as a microwave network

When the OBFN is integrated to electro-optical modulators and photodetectors, it can be used to generate the complex excitations required to feed the individual elements of the antenna array. Those excitations can be directly related to the s-parameters of an *equivalent* microwave network which has as many inputs as the number of antenna elements, and as many outputs as the number of beams generated by the OBFN.

Let us consider an optical beamformer with N antenna ports and M beam ports. When integrated with modulators and photodetectors, this OBFN can be modelled as an N-by-M microwave circuit, where the n-th input-output response (that is, the nm-th transmission parameter, s_{mn}) corresponds to the complex excitation provided to the n-th antenna element of the array (C_n) when exciting the m-th beam port:

$$\underbrace{C_n = |C_n| e^{j\varphi_n}}_{\text{beam } m} \quad \text{is equivalent to} \quad s_{mn} = [S]_{m,n} \quad (n \in [1,\ldots,N],\ m \in [1,\ldots,M]) \tag{1}$$

Fig. 1 shows the described equivalence principle for the common case of a single-beam OBFN ($M = 1$).

Fig. 1. The complex excitations that the beamformer system provides to the N antenna elements of the array coincide with the complex-valued transmission parameters of an equivalent N-by-M microwave network, evaluated between each of the n-th antenna ports and the m-th beam port.

Magnitudes ($|C_n|$) and phases (φ_n) of the s-parameters can be measured using a VNA over the frequency range of interest. The software employs the measured data to calculate the array factor of a linear array by implementing the relation [1]

$$F(\psi, f) = |C_n| \sum_{n=1}^{N} \exp(j\varphi_n) \exp\left(j \frac{2f\pi nd}{c_0} \cos(\psi) \right) \tag{2}$$

Where f is the frequency, ψ is the pointing angle, and d is the inter-element distance of the array. A similar formula is implemented for the case of a planar array [1].

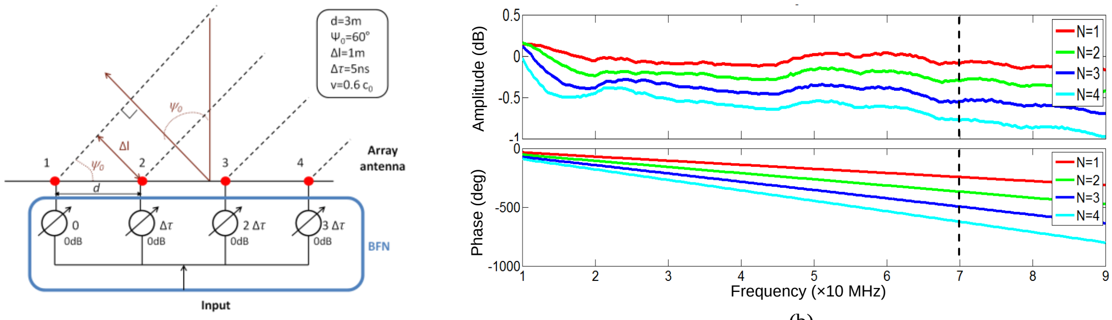
Structure of the application

The application has been developed in the LabView programming environment. An interactive graphical interface allows first to select the array configuration (linear or planar) and then to specify the array parameters: operating frequency range, inter-element spacing d and desired beam direction ψ. Through VISA communication protocol, the LabView application implements an automatic instrument control. First, it sets the network analyzer to the specific frequency range, and then it remotely measures magnitude and phase of the complex network transmission coefficient s_{mn}, specified by the user, over the frequency range of interest. The measured data are then acquired in the computer and displayed in the user interface for comparison with the desired behaviour. The user can select the desired display format as when directly operating on the VNA interface. The data can be saved in *smp* format and recalled, with the same application, for further offline processing.

A MatLab script is placed within the LabView structure to simulate the array factor, which can then be plotted (in 2-D) with respect to steering angle, for a specific frequency (to analyze the array factor characteristic in comparison with theory at a specific frequency), both in linear and polar coordinates, or (in 3-D) with respect to both angle and frequency, to analyze the frequency dependent behaviour, the presence of grating lobes or frequency squint [1].

Test

To demonstrate the functionality of the software, a simple 4×1 beamformer was built using an RF combiner and coaxial cables with a length difference $\Delta l = 1$ m. This length was chosen to generate an array factor with a maximum at -60 degrees from broadside direction, when used to feed a linear antenna array with an inter-element distance $d = 3$ m, as shown in Fig. 3a.



(a)

(b)

Fig. 3. Schematic of the BFN used in the test (a) and its measured transmission characteristics (b)

The software was then employed to measure and display the magnitude and phase of the transmission coefficients of the BFN, in the frequency range 10 MHz - 90 MHz. The measured excitations are shown in Fig. 3b. Based on those, the software can simulate the array factor. Fig. 4a shows the comparison of the simulated array factor with the theoretical one at 70 MHz, for the case of uniform amplitude excitation (fluctuation <1 dB). The software also allows to see the effects of amplitude tapering [1]. In this case, reducing by 3 dB the amplitude of the excitations of elements 1 and 4 in Fig. 3a, the sidelobe levels decrease, the main lobe widens, and the max gain reduces when compared to the case of uniform excitation (Fig. 4b).

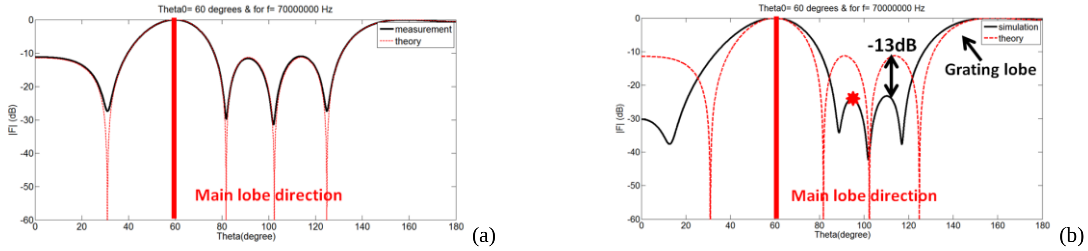


Fig. 4. Normalized array factor versus pointing angle. (a) The simulated response obtained by the software, using Eq. 2, based on the measured scattering parameters, can be directly compared to the theoretical array factor. (b) Effect of amplitude tapering: widened main lobe, reduced sidelobe levels. Gain reduction is not visible in the normalized graph.

In wideband beamformer applications, the frequency-dependent behavior of the beamformer is of primary interest. The analysis of desired characteristics as squint-free behavior and absence of grating lobes becomes straightforward by employing the capability of the software to plot the *array factor versus angle and frequency*. The 3-D plot obtained for our test structure in Fig. 3a is displayed in Fig. 5. This plot shows in a graphical, straightforward way that the employed beamformer has a squint-free behaviour (that is, the direction of the main lobe -red line- does not vary with frequency) in the selected band, and also confirms that the condition for absence of grating lobes ($d < \lambda/2$, [1]) is only satisfied at frequencies below 50 MHz, as expected for $d = 3$ m. In the top-view of Fig. 5b, the grating lobe clearly appears at frequencies above 50 MHz.

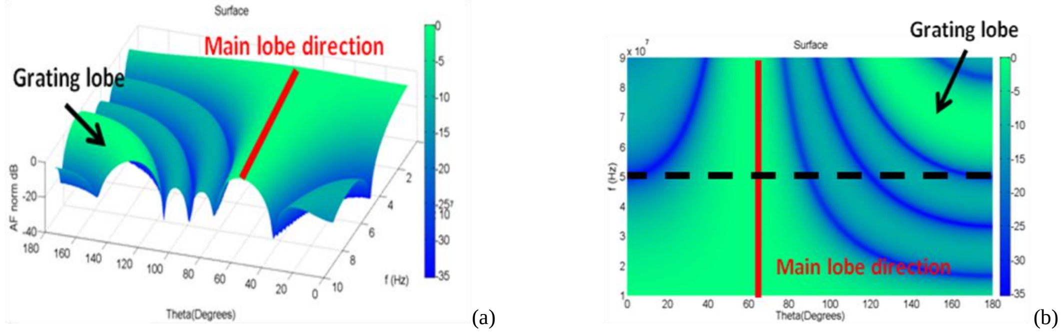


Fig. 5. 3-D view (a) and top view (b) of the array factor versus angle and frequency for the test BFN.

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