Analysis of Common-Mode Resonances in Arrays of Connected Dipoles and Possible Solutions

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***Abstract*— A prototype array of dual polarized connected dipoles has been manufactured. The feed structure is composed by two orthogonal 8×8 elements for each polarization (128). The operational frequency ranges from 6 to 9 GHz (40% relative bandwidth). Preliminary measurements highlighted the presence of unpredicted common-mode resonances excited in the vertical feeding lines. An analysis of the common-mode excitation is carried out and exit strategies for a design of a resonance-free connected array are presented.**

I. INTRODUCTION

The realization of wide band, wide scanning angle, phased arrays with good cross-polarization performance has been the object of many recent investigations. Although tapered slot antennas have very broad bandwidth, they are known to produce high cross polarization components, especially in the diagonal cuts (45°), [1]. On the other hand, conventional phased array based on printed radiating elements can achieve only moderate bandwidths (~25%), [2]-[4]. A novel trend in this field is the use of planar long dipole or slot antennas periodically fed at Nyquist intervals to effectively achieve an amplitude and phase aperture distribution without necessarily using separate antenna elements. This concept was originally proposed by Hansen, [5], and further theoretically developed in [6], showing the wideband characteristic of such array. The first practical demonstration of a planar connected array antenna was given in [7]. Thanks to the planarity of the radiators, the low cross-polarization level is among the most important features of such antenna solutions.

This paper reports the development of a phased array of connected dipoles, designed for applications requiring dual polarization, in the operational frequency band 6-9 GHz. The impedance transformation from the wave impedance of the free space, 377 Ohms, at the aperture level, to 50 Ohms at the connector, is performed with two wavelengths long transmission lines, printed on vertical printed circuit boards arranged in egg-crate configuration (Fig. 1). A transition from coplanar strip-lines (CPS) to coplanar waveguide (CPW) and then to micro-strip (MS) performs the balanced to unbalanced conversion, together with a wideband impedance transformation (Fig. 2). The measurements highlighted an unpredicted problem with the performance of the array. The CPS transmission lines used to feed connected arrays of dipole or slots are balanced and they can support two types of modes: differential (desired) and common (undesired). The transmission line lengths are long enough for common mode currents undergo strong resonances.

II. DESCRIPTION OF THE ARRAY

The prototype array is shown in Fig. 1. The dipoles are printed on one side of a low permittivity (ε_r=2.2) thin Duroid substrate, and electrically connected to form a unique long dipole periodically fed. The element spacing is 15.52 mm, which is about half wavelength at 9 GHz. The single element is depicted in Fig. 2, with the relative impedance values at different cross sections of the feeding lines. A double feed configuration in each periodic cell has been adopted in order to decrease the reactive capacitance associated with the feeding gaps. This arrangement of the feeding lines, implemented with a CPS power divider (Fig. 3), improves the bandwidth of the array, [8]. A ground plane is included at a

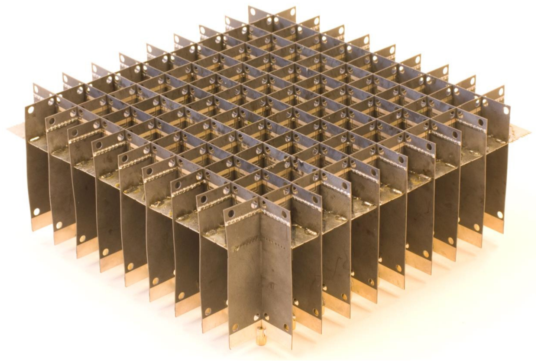

Fig. 1 Prototype 128-elements dual-polarized array for 6-9 GHz experiments.

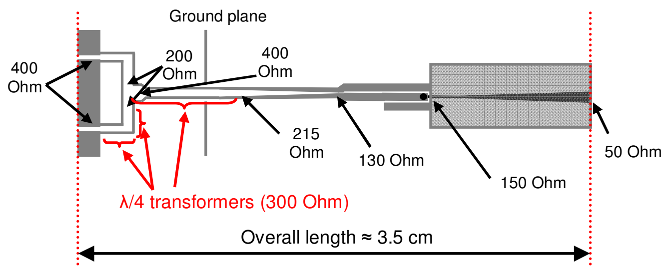

Fig. 2 Feeding lines of the unit element of the array. Impedance transformation from 400 to 50 Ohms is performed.

height of approximately 0.3 λ_0 (with λ_0 being the wavelength at 9 GHz) from the centre of the dipole, acting as a backing reflector.

III. Comparison of Measurement and Simulations

Measurements of the array performance have been performed only partially because, for budget reasons, it was not possible to include a complete feeding network that would allow the simultaneous excitation of all the elements in phase. However, the scattering parameters of some of the central elements were measured and their comparison with the results of full wave simulations allowed us to qualitatively interpret the behaviour of the array. Fig. 3 shows the active reflection coefficient of a central port of the finite array prototype when scanning toward broadside. From the measured curves, two unexpected resonance were observed at about 7 GHz and 8.5 GHz. Triggered by such observation, full-wave simulations of the entire structure including the feeding network have been performed, for the first time. Note that the measurements include the summation of all significant co-polarized S parameters for the investigated port, while the equivalent simulations are performed using the full wave simulator tool CST and account for the entire finite array (8×8 elements). The comparison between simulations and measurements is relatively good, indicating that the numerical tools are able to efficiently describe the wave phenomena in place.

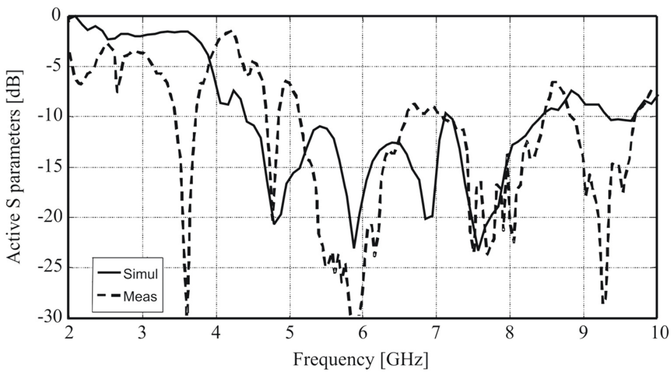

Fig. 3 Active reflection coefficient of a central element of the finite array; comparison between simulations and measurements.

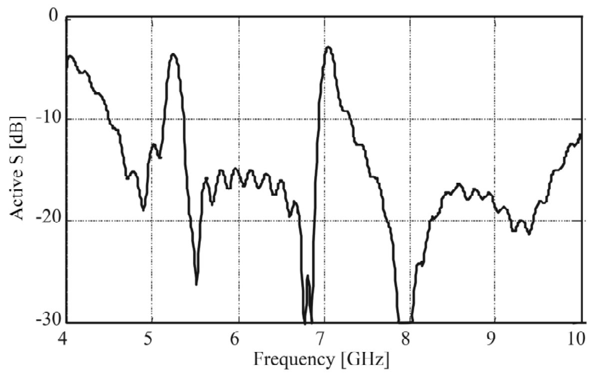

Fig. 4 Active reflection coefficient for an infinite array when radiating toward θ=0° and ϕ=0°.

In order to analyse the nature of such resonances, further simulations were carried out assuming an infinite periodic array analysis. The reflection coefficient in the presence of the feeding lines was significantly different from those that were simulated in the design phase without the inclusion of the long matching network. In Fig. 4, the simulated active reflection coefficient when the array is radiating toward θ=0° and ϕ=0° is reported. It is apparent that the array is completely mismatched at 5.25 and 7 GHz. At those frequencies, the simulations explicitly show the coexistence of common and differential modes in the long transmission lines. In Fig. 5, a schematic view of the electric current distribution along the feeding lines shows common mode propagation at 7 GHz, in correspondence of the resonance, while at 8 GHz, the designed differential mode is dominant. It should be noted that these resonances are sharp and the radiation patterns, not reported here for brevity, do not indicate polarization degradation. However, the same simulations realized for the array radiating toward θ = 45° and ϕ = 45° also show significant increases of the cross-polarized field levels. In practice, the scanning performance of the prototype array is limited by common modes excited in the vertical feeding lines. Needless to say that the infinite array configurations, while of great help in understanding the physics, overestimate the coherence of these standing waves, which are much less strong in a finite array (Fig. 3).

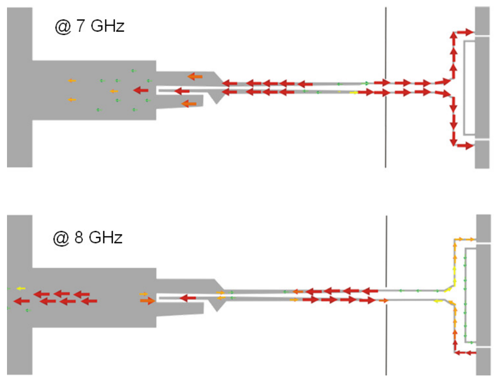

Fig. 5 Vector surface current distribution at 7 GHz and 8 Ghz. Common modes are excited in the first case, while differential mode is dominant at the second frequency.

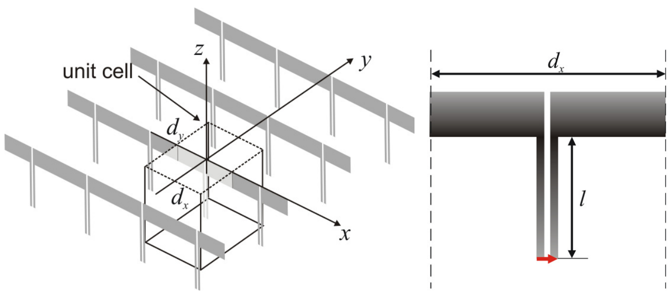

Fig. 6 Geometry of a single-polarized array of connected dipoles and of a single element. The element spacing is d_x along x and d_y along y, and l is the length of the feeding lines.

IV. RESONANCES IN CONNECTED ARRAYS

An analysis of the effects of common-mode resonances on the efficiency of a connected array was presented in [9]. The main reason for this problem is that typically connected arrays of dipoles involve the presence of a backing reflector. Accordingly, the transmission line lengths are in the order of a quarter of the free space wavelength, in order to reach the ground-plane level, where load or source circuit is located. Depending on the substrate on which the lines are printed, this distance can be sufficient for common mode currents to undergo strong resonances. Even in cases in which the lines are printed on low dielectric constant Printed Circuit Boards (PCB), the fact that the feeds are electrically connected one to the other may generate hybrid resonances, where the electrical length that generates unwanted resonances is part in the vertical transmission lines and part in the radiating dipoles.

In order to analyse the effects of common-mode propagation in a connected array of dipoles, let us consider the simplified case of an infinite two-dimensional array of dipoles with periodicity d_x and d_y, as shown in Fig. 6. For sake of generality, no backing reflector is introduced. The array elements are fed by CPS lines, whose length is l.

One reason why the arising of common modes is cause of particular concern in connected arrays is that these undesired resonances can be easily confused with other resonances, also unwanted. Three types of resonant effects may occur in connected array:

1) Standard grating lobes, occurring when the $k_{zm}=\sqrt{k_0^2-k_{xm}^2-k_{ym}^2}=0$, with $k_{xm}=k_0\sin\theta\cos\varphi+\dfrac{2\pi m_x}{d_x}$ and $k_{ym}=k_0\sin\theta\sin\varphi+\dfrac{2\pi m_y}{d_y}$.
   Thus, for certain periodicities in terms of the wavelength, the array can undergo drastic impedance variations.
2) Coincidence of a Floquet wave pole with the propagation constant of the wave that travels un-attenuated along the radiating dipole, i.e. $k_{xm}=-k_0$ for array scanning at a certain elevation angle θ.

These resonances will occur at some frequencies independently from the length of the transmission lines thus in principle can be identified also in design phase that does not include the feeding lines.

3) Resonances of the common modes. As an example, in the most standard design situation in which the periodicity of the array is about half wavelength, and the vertical lines are a quarter wavelength, two neighboring feeding lines and the electrical connection via the dipole constitute a one wavelength electric path (d_x+2l=λ) and create a strong cross polarizing standing wave.

Even if only this third resonance is directly associated with the transmission lines, the second type of resonance is also characteristic only of connected arrays. Moreover, when all three resonances are closely spaced one from the other, it takes significant simulation time to highlight and separate the nature of each phenomenon that is observed.

As a significant example, we will consider a design situation in which the periodicity of the array is half wavelength at 10 GHz, and the vertical lines length is parametrically varied. The scanning angle is considered to be $\theta = 45^o$ and $\phi = 45^o$ as the most critical design case. For the sake of simplicity we only investigate a frequency range where resonances of first and second type are not present.

Fig. 9 shows that the reflection coefficient is significantly degraded when the mentioned overall length d_x+2l is equal to λ. However, this is not as worrying as the polarization purity, expressed in Fig. 10 as the ratio between co-polarized and cross-polarized gain, according to the third Ludwig definition. It is apparent that, close to the common mode resonance, the cross-polarization level becomes dramatically high.

V. RESONANCE-FREE CONNECTED ARRAY DESIGN

A CPStoCPS transformer, based on aperture coupling, has been designed to shorten the length of continuous current paths and to reject common-mode propagation. A schematic view of the component is shown in Fig. 11, where the ground plane on which the slot is etched is assumed to be infinite along x. The component is divided in two parts separated by the ground plane. The part at $z=h$, here in after the primary circuit, comprises a transition from CPS lines to Grounded CPS (GCPS) lines, then a power divider that splits the circuit in two equal halves, which are eventually re-connected in correspondence of a coupling slot. The secondary circuit at $z=-h$ is the same as the primary, but mirrored with respect to

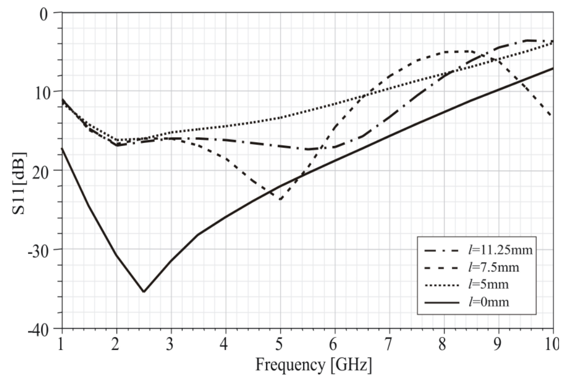

Fig. 9 Active reflection coefficient for d_x=15mm and different values of l.

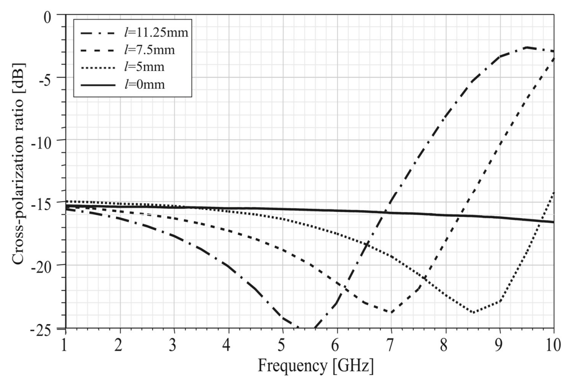

Fig. 10 X-pol ratio for d_x=15mm and different values of l ($\theta = 45^o$, $\phi = 45^o$).

the slot. The initial input from the CPS lines can be associated with a differential-mode or a common-mode type of current. The common mode in input corresponds to a zero of electric current in correspondence of the slot. In turn, this translates in no electric current being excited in the secondary circuit of the transformer.

The condition for high transmission levels of the differential mode is $Z_{cell} \ll Z_{slot}$, where Z_{slot} is the impedance of the slot and Z_{cell} is the connected array element loading. Therefore, the bandwidth of the transformer is wider for low values of Z_{cell}. Normally, the input impedance of an evenly sampled array (d_x=d_y) in the presence of a backing reflector is about $\zeta_0 \approx 400\ \Omega$. However, since Z_{cell} is proportional to d_x/d_y, lower impedances can be obtained by considering a denser sampling of the array in the longitudinal direction. For example, with 4 feeds per cell (d_x=λ_0/8), the input impedance at each feed point becomes $Z_{cell} = \zeta_0/4 \approx 100\ \Omega$. The CPStoCPS or CPStoMS (balun) transitions can be made compact on high permittivity dielectric (ε_r=10), and the same number on T/R modules can be kept by means of power dividers (Fig. 12).

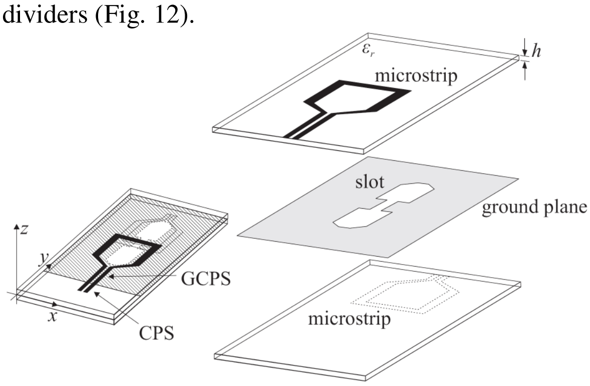

Fig. 11 Geometry of the transformer.

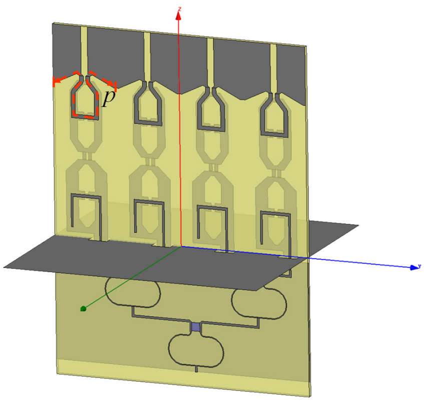

Fig. 12 Geometry of a unit cell of a connected array with periods d_x=d_y=λ_0/2.

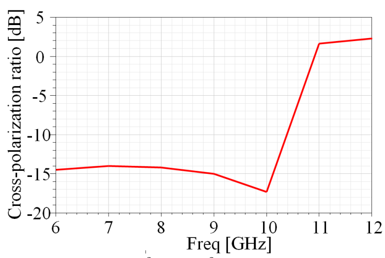

Fig. 13 X-pol level (θ=45°, φ=45°), for the geometry in Fig. 12.

Fig. 13 shows the X-pol ratio as a function of the frequency for the geometry depicted in Fig. 12. For an array designed to work until 10 GHz, the X-pol level remains lower than -14 dBs within the band of the array, while the common-mode resonance appears at a higher frequency (11 GHz). This is because the path p, shown in Fig. 12, has an electric length shorter than one wavelength at the frequencies within the operational band of the array, avoiding the occurrence of resonances.

VI. Conclusions

The preliminary S-parameter measurements of a demonstrator have been presented. The comparison with full wave simulations that include the entire array indicates that the prototype has been well manufactured, just as designed. Unfortunately, the elevation angles until which it can be used maintaining good polarization purity is limited to about 20°. For larger angles, the common mode currents excited on the vertical feeding lines portion becomes dominant and can have a disruptive effect not only on the reflection coefficients but also on the purity of the polarization of radiated fields. Due to the electrical connection of the elements, standard wideband baluns are not effective in a connected array. Therefore, a novel type of Printed Circuit Board (PCB) transformers is proposed as a valid solution for the design a resonance-free connected dipole array.

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