A 3- to 5-GHz Wideband Array of Connected Dipoles With Low Cross Polarization and Wide-Scan Capability

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***Abstract*—A wideband, wide-scan phased array of connected dipoles has been designed and fabricated. Measured results from a 7 × 7 prototype demonstrator are presented for experimental validation. In order to avoid common-mode resonances that typically affect this type of array, loop-shaped transformers are included in the feed network. The common-mode rejection implemented by these transformers allow maintaining the cross-polarization levels to values lower than −10 dB over a 30% relative bandwidth, for an elevation angle up to 45° in all azimuth planes. The array exhibits a measured voltage standing-wave ratio (VSWR) lower than 2.5 from 3 to 5 GHz for broadside radiation. The VSWR maintains levels lower than 3 within a scan volume of 45° from broadside in all planes.**

***Index Terms*—Common-mode rejection, connected arrays, cross polarization, ultra-wideband arrays, wide-scanning arrays.**

I. Introduction

WIDE-BAND, wide-scanning phased arrays with low cross polarization across the entire bandwidth are increasingly desired for many applications. A novel trend in this field is the use of connected arrays, which are arrays of long dipoles or slots periodically fed in order to approximate the Wheeler current sheet [1]. A successful implementation of this concept was given in [2], and it was based on an array of capacitively coupled dipoles. Besides the broad bandwidth [3], this type of antenna is characterized by low cross polarization (X-pol) over a wide-scan volume. The scanning performance of connected arrays was investigated in [4], showing that connected arrays of dipoles are better suited for wide-scan applications as compared with slot arrays.

A theoretical design of a connected dipole array was also presented, with 40% relative bandwidth and a wide-scan capability up to 45° for all azimuth angles. However, this design assumed an idealized delta-gap source as excitation of the dipoles. In practical designs, the implementation of the feed network is a problematic matter. In connected arrays of dipoles, the balanced transmission lines used to feed the elements can support both differential and common-mode propagation. This latter is undesired, since it can give rise to strong resonances that deteriorate the array performance [5]. These types of resonances have been observed also in other wideband phased arrays that are differentially fed, like checkerboard arrays [6] and tapered slot antenna arrays [7].

Due to the electrical connection between the array elements, and the consequent high mutual coupling, standard baluns typically used for resonant dipoles are not effective in connected arrays [8]. On the other hand, common-mode rejection circuits based on ferrite are available only at low frequencies (< 3 GHz). Furthermore, other solutions based on active components or differential low noise amplifiers are not always possible, since they are mainly used for receiving antennas [9].

A printed circuit board (PCB) solution to avoid common-mode resonances was proposed in [10]. It consists of a loop-shaped component that constitutes a choke for the common mode, while representing a small impedance change for the differential mode. The use of such a common-mode rejection loop and a sleeve balun allowed the design of linearly and doubly polarized arrays of connected dipoles with low X-pol levels over about a 30% relative bandwidth.

This paper presents a design of a S-band connected array of dipoles for wideband applications. A 7 × 7 prototype array has been manufactured and tested over a 3–5-GHz operational band. Within a scan volume of 45° from broadside in all planes, X-pol levels lower than −10 dB are observed over a 30% relative bandwidth, while the voltage standing wave ratio (VSWR) is lower than 3 from 3 to 5 GHz. The measured performance is in good agreement with what is predicted by the simulations.

II. Common-Mode Currents in Connected Arrays

A detailed analysis of common-mode resonances in connected dipole arrays and possible solutions to the common-mode problem suitable for PCB manufacturing were reported by some of the present authors in [5] and [10].

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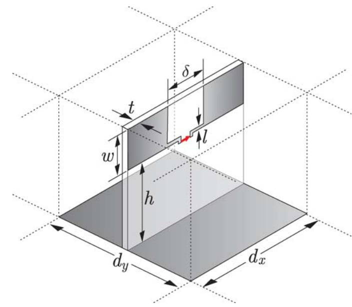

Fig. 1. Connected array unit cell with characteristic parameters.

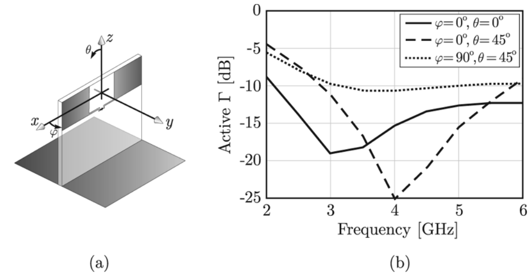

Fig. 2. Connected array of dipoles without vertical feed lines: (a) array unit cell; (b) active reflection coefficient, assuming a 350 Ω feed line, for broadside and $\theta = 45°$ on the E- and the H-planes.

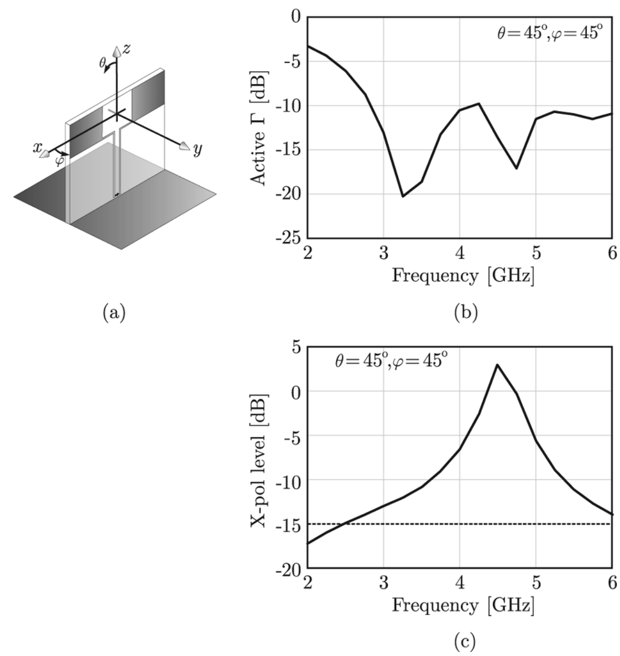

Fig. 3. Connected array of dipoles with vertical feed lines: (a) array unit cell; (b) active reflection coefficient, assuming a 100-Ω feed line, for $\theta = 45°$ on the D-plane; (c) X-pol level for the same observation angle (the horizontal dashed lines indicates the -15 dB reference value).

In this section, we only give an explicative example to quantify the impact of the common-mode propagation on the array performance.

Fig. 1 shows the unit cell of an array of connected dipoles in the presence of a backing reflector. The dipoles are printed on thin vertical PCBs of a Rogers 4003 dielectric substrate, with relative permittivity $\varepsilon_r = 3.55$ and thickness $t = 1.216$ mm. The array periods d_x and d_y along the longitudinal and transverse direction of the dipole have been selected to be 0.42λ at the highest frequency of operation. Tighter spacing typically implies broader bandwidths within a wide-scan volume, at the expense of increased costs due to the higher number of transmit–receive modules.

The following parameters can be adjusted in order to optimize the performance in the band from 3 to 5 GHz: the interelement periods (d_x and d_y), the dipole width (w), the size of the feed gap (δ), the distance from the ground plane (h), and the width of the inductive lines that connect the dipole arms to the feed (l).

The set of parameters that has been found to yield good matching in the frequency range 3 to 5 GHz within a 45° scan volume is the following: $w = 7.56$ mm, $\delta = 7.875$ mm, $h = 15.12$ mm, and $l = 0.15$ mm, and $d_x = d_y = 25.2$ mm, which corresponds to 0.42λ at 5 GHz. At this stage, the elements are assumed to be fed at the dipole level, without the inclusion of vertical transmission lines. Referring to the coordinate system in Fig. 2(a), the active reflection coefficient of the periodic array unit cell is shown in Fig. 2(b), assuming a 350-Ω feed line. Curves are shown for scanning at broadside and to $\theta = 45°$ on the main planes (E- and H-planes) and have been calculated via Ansoft HFSS [11]. It can be noted that, when observing only at broadside (continuous line), the considered connected dipole element can achieve bandwidths in the order of 1:4 in the presence of a backing reflector. However, the input resistance is lowered by a factor of $\cos(\theta)$ when scanning on the E-plane and increased by a factor of $\sec(\theta)$ when scanning on the H-plane. Consequently, even in this case of ideally fed dipoles, the usable bandwidth within a 45° scan volume is reduced to about an octave (3 to 6 GHz).

Even if not reported for the sake of brevity, the X-pol level of this element for observation at $\theta = 45°$ on the diagonal plane (D-plane, $\varphi = 45°$) is of about -15 dB. This value of X-pol is typical of perfectly linear radiating currents oriented along the x- or y-axis, according to the third definition of cross polarization by Ludwig [12].

To highlight the effect of common-mode propagation in the feed lines, Fig. 3 shows the performance of a similar array geometry, in which the same dipole elements are fed by vertical co-planar strip (CPS) lines, in order to reach the ground plane level, where the feed is located [Fig. 3(a)]. The lines perform an impedance transformation from 350 Ω to 100 Ω. The active reflection coefficient and the X-pol level are shown in Fig. 3(b) and (c), respectively, for observation at $\theta = 45°$ on the D-plane. It is apparent that the inclusion of long vertical feed lines has only a marginal impact on the matching. However, a highly deleterious resonance appears in the X-pol level. Such degradation is attributable to the common-mode current propagation in the CPS lines. The values of X-pol are much higher than the ones typically expected from printed linearly polarized dipoles (≈ -15 dB). The X-pol radiation can even equal or exceed the co-polar component for some frequency within the operational band.

Thus, it is important to note that the effect of common-mode resonances on the array efficiency should not be analyzed in

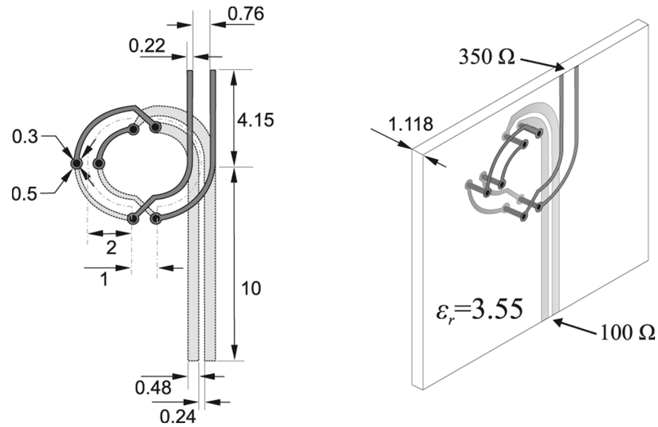

Fig. 4. Dimensions (in mm) of the loop-shaped transformer.

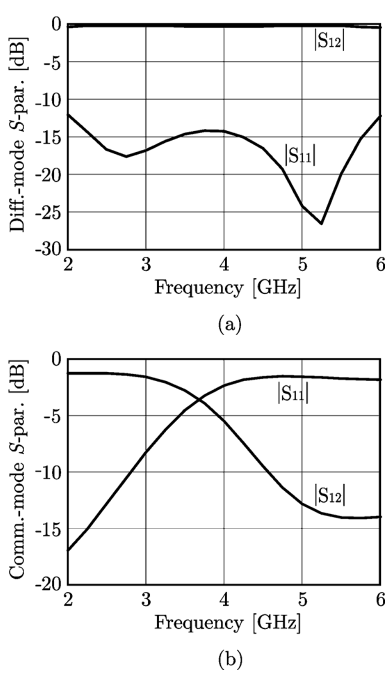

Fig. 5. S-parameters of the loop transformer pertaining to (a) differential mode and (b) common mode.

terms of matching properties only. The usable bandwidth defined by the X-pol levels can be radically different from the bandwidth defined by the matching characteristics.

III. Common-Mode Rejection Loop Design

In order to reject common-mode propagation on the vertical feed lines, we consider a loop-shaped component as in Fig. 4. The loop radius is 2 mm, and the loop is printed part on the bottom layer and part on the top layer of a Rogers 4003 dielectric substrate with relative permittivity 3.55.

As explained in [10], when a common-mode input is applied, at low frequencies, the currents flowing in the loop are equal in phase, and therefore the loop only behaves as a small series inductance for the common mode. As the frequency increases, different portions of the loops have currents with different phases generating canceling magnetic fields, which in turn produce a magnetic field with close to zero contributions in the center of a loop's cross section. Consequently, at frequencies higher than a

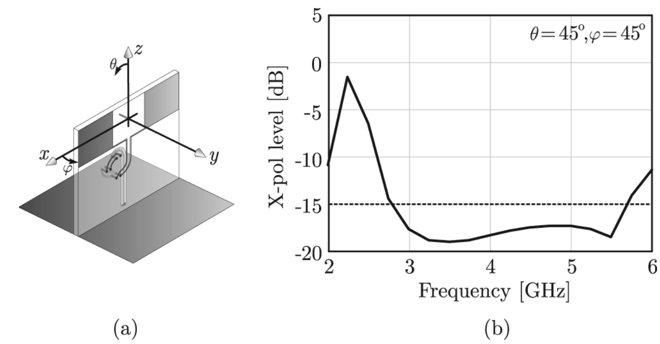

Fig. 6. (a) Array element with the inclusion of the loop-shaped transformer in the feed lines and (b) X-pol performance.

certain threshold, the average distributed inductance of the loop becomes lower, creating a strong impedance discontinuity. This effect is quantified in Fig. 5 by the S-parameters pertaining to differential and common modes. A 10-dB common-mode rejection is observed for frequencies higher than 4.5 GHz, while good match is experienced by the differential mode from 2 to 6 GHz.

Since the active input impedance of a connected dipole element typically exhibits high values (350 Ω), the loop can be used to implement an impedance transformation for the differential mode. To this aim, a two-section transformer from 350 to 100 Ω has been implemented. The total length of the loop corresponds to a quarter wavelength in the dielectric at 3.5 GHz. Two inverters have been added to compensate for the slightly different radius of the inner and outer conductors within the loop, thereby reducing the spurious radiation of the loop when a differential input is applied.

IV. Simulated Performance of Connected Dipole Arrays With Loop-Shaped Feed Structure

Fig. 6 shows the X-pol levels of an array of connected dipoles including the loop-shaped feed structure of Fig. 4. By comparing Fig. 6(b) with Fig. 3(c), it is evident that, when the common-mode rejection loop is used, the degradation of polarization performance introduced by the vertical lines is strongly mitigated over the bandwidth of interest. In fact, the X-pol ratio becomes lower than -17 dB over the band of operation.

Although the cross polarization maintains low levels for this particular observation angle, the element in Fig. 6(a) is not symmetric with respect to the zy plane, due to the presence of the loop. For this reason, the X-pol can be different on the two diagonal planes ($\varphi = 45^\circ$ and $\varphi = 135^\circ$). To highlight this effect, Fig. 7 shows the X-pol level for maximum elevation angle $\theta = 45^\circ$ as a function of the azimuth φ. The maximum value of X-pol is in the proximity of the diagonal plane $\varphi = 135^\circ$, and it is approximately -15 dB for all frequencies in the range 3 to 5 GHz.

The previous results pertain to a differential excitation located at the ground plane level. A more realistic coaxial feed requires the inclusion of a transition from CPS to microstrip (MS). To this purpose, a sleeve balun has been designed, and a tapered line to reach 50-Ω impedance has been included. The geometry of the array unit cell and dimensions of the balun are shown in Fig. 8(a). The resulting performance of the overall structure are

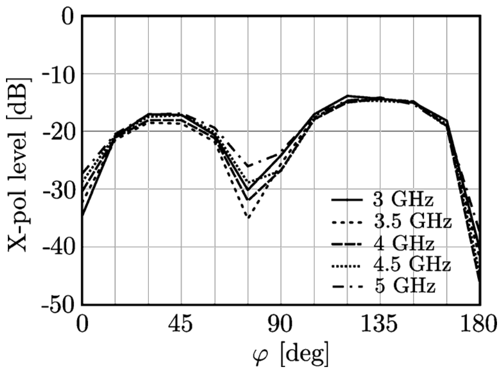

Fig. 7. X-pol level of the element in Fig. 6(a) for $\theta = 45°$, as a function of the azimuthal angle φ and for different frequencies.

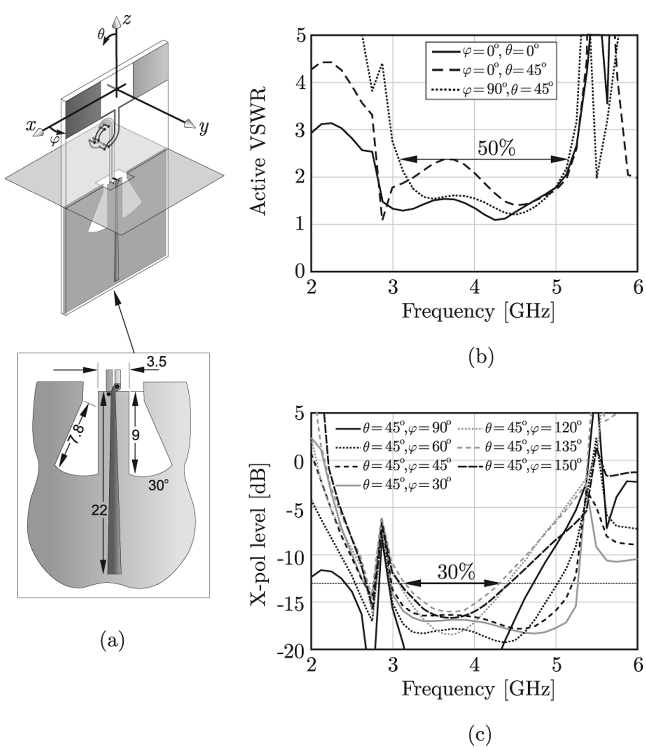

Fig. 8. Performance of the loop when included in the unit cell of a linearly polarized connected dipole array: (a) array unit cell with dimensions of the balun; (b) active VSWR for broadside and for $\theta = 45°$ in the main planes (50-Ω impedance); and (c) X-pol level for observation at $\theta = 45°$ and several azimuths.

presented in Fig. 8(a) and (b), which show the active VSWR for broadside and for $\theta = 45°$ in the main planes (normalized to a 50-Ω impedance line), and the X-pol ratio for observation at $\theta = 45°$, and several azimuthal planes. A VSWR lower than 2.4 is achieved over 50% relative bandwidth. The polarization bandwidth is limited by the band of the balun. The cross-pol level achieved by this configuration is at least 13 dB lower than the co-polar component over a 30% BW.

V. Prototype Demonstrator

Based on the design described in the previous section, a 7×7 prototype array has been manufactured. The array is singly polarized and consists of seven vertically arranged PCBs like the one shown in Fig. 9. The external arms of the two dipoles at the edges include eight series resistors with increasing values of resistance (from 10 to 400 Ω). This ensures that the surface current gradually decreases to zero close to the edges in order to limit truncation effects. Edge effects in arrays of connected dipoles can be remarkably strong, due to the electrical connection between the elements that support guided waves along the array. However, these effects have been studied in details in [13] and can be controlled by means of *ad hoc* designs based on high-impedance elements.

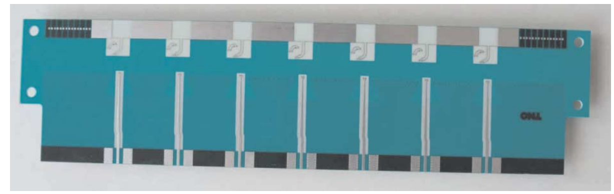

Fig. 9. Printed boards of the prototype array.

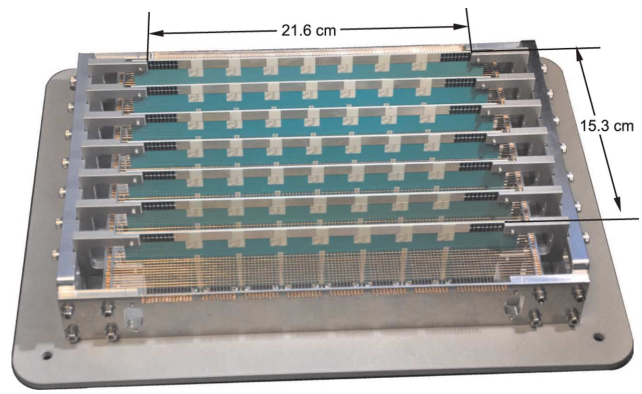

Fig. 10. 7×7 prototype array with dimensions.

The entire array is shown in Fig. 10, assembled with a mechanical support structure.

A. Practical Implementation of the Backing Reflector

A particularly complicated manufacturing aspect is associated with the practical implementation of the backing reflector. In fact, a continuous metallic plane has to be placed horizontally and intersect the entire set of PCBs. The problem was solved by replacing the continuous plane with a discrete grid composed by wires. Simulation results showed only minor changes to the behavior of the array, as long as the distance between wires does not exceed $\lambda/10$ at the highest frequency of operation. The set of wires along x and the one along y have no electrical contact, simplifying the assembling of the antenna by avoiding the need for soldering. A close-up of the grid is shown in Fig. 11.

B. Measured Results

The measured active VSWR is shown in Fig. 12 for the central element of the array. The active parameters are evaluated via a postprocessing summation of the passive measured S-parameters with proper weights for the elements to account for scanning. Curves are shown for broadside radiation and for scanning to 45° in the E- and H-plane. Although some oscillations around the expected values can be observed, good matching performance are achieved for broadside radiation, for which a

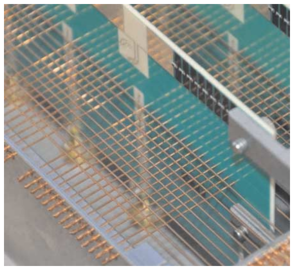

Fig. 11. Discrete ground plane made by a wire grid.

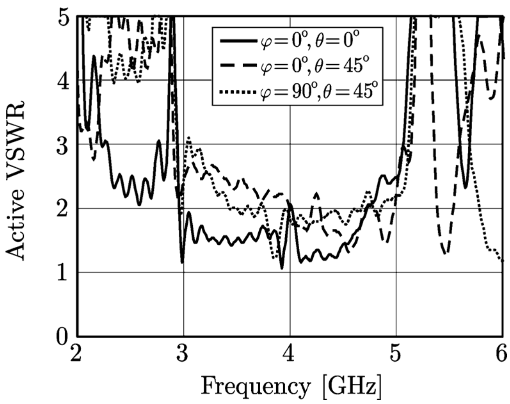

Fig. 12. Measured active VSWR of the central element of the array: curves are shown for broadside radiation and scanning to 45° in the E- and H-plane.

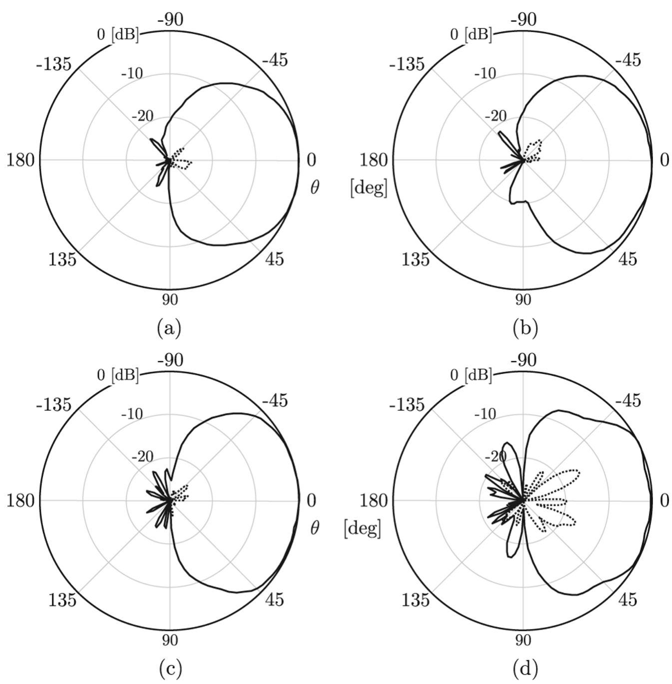

Fig. 13. Normalized active element patterns in the E-plane at different frequencies: co-polar components in continuous lines and cross-polar components in dashed lines: (a) 3.2 GHz; (b) 3.5 GHz; (c) 3.8 GHz; and (d) 4.2 GHz.

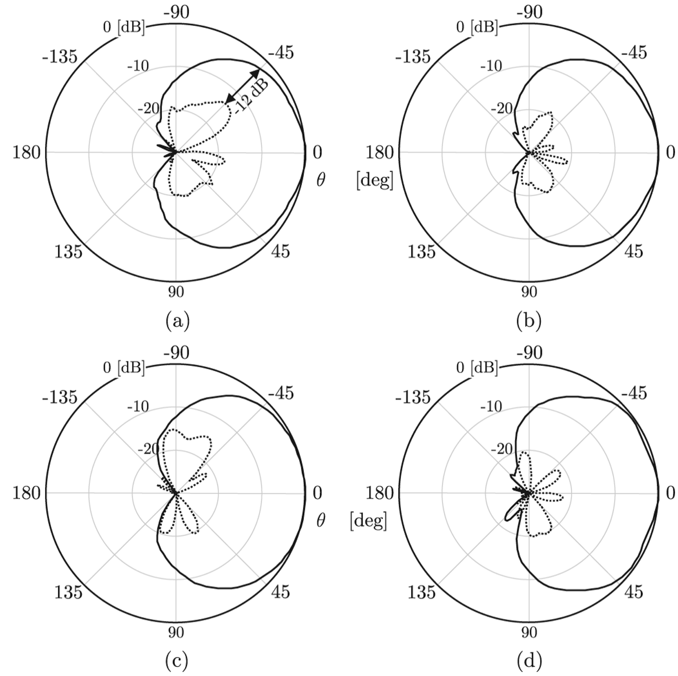

Fig. 14. Normalized active element patterns in the H-plane at different frequencies: co-polar components in continuous lines and cross-polar components in dashed lines: (a) 3.2 GHz; (b) 3.5 GHz; (c) 3.8 GHz; and (d) 4.2 GHz.

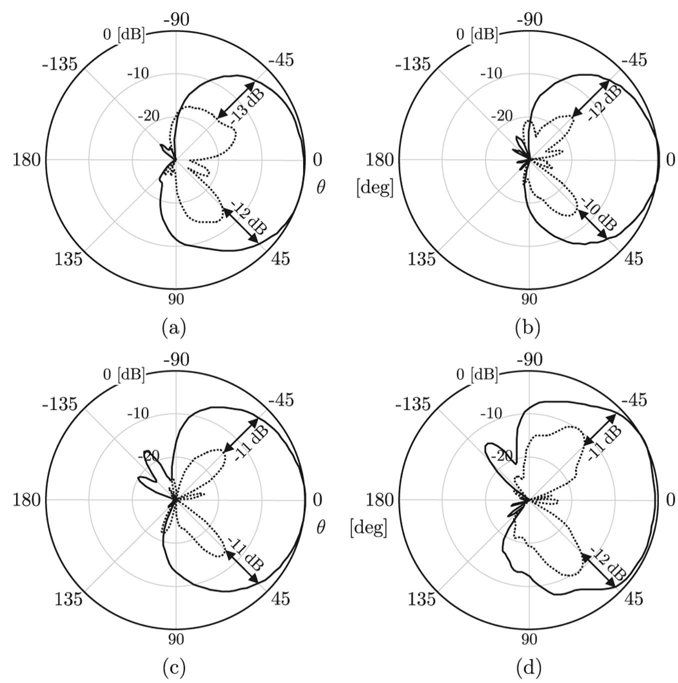

Fig. 15. Normalized active element patterns in the D-plane at different frequencies: co-polar components in continuous lines and cross-polar components in dashed lines: (a) 3.2 GHz; (b) 3.5 GHz; (c) 3.8 GHz; and (d) 4.2 GHz.

VSWR lower than 2.5 is observed over the entire bandwidth of operation (3 to 5 GHz). The matching deteriorates for scanning, for which edge effects are more important. However, values of VSWR lower than 3 are observed in the design frequency band.

Normalized active element patterns measured in the E-, H-, and D-planes are shown in Figs. 13–15. Both co-polar and cross-polar component are presented for four frequencies in the design bandwidth. Fig. 16 shows the X-pol levels as a function of theta and for all the frequency in the band from 3 to 5 GHz. The scan volume $\pm 45^\circ$ and the frequency range of about 30% (from 3.2 to 4.25 GHz) are highlighted by a white

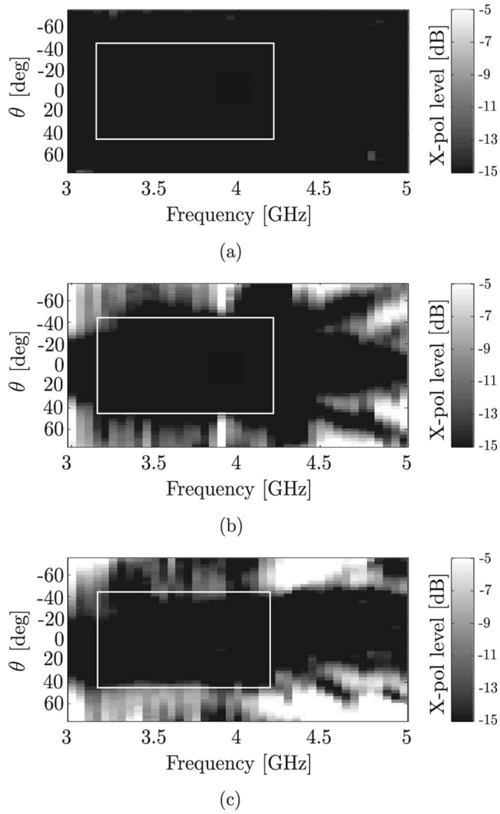

Fig. 16. X-pol level as a function of the elevation angle θ and the frequency for (a) E-plane, (b) H-plane, and (c) D-plane.

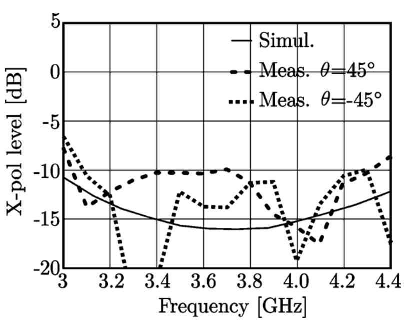

Fig. 17. Comparison between simulated and measured X-pol level for scanning to 45° in the diagonal plane.

frame. Within these values, the normalized X-pol patterns are lower than -10 dB, which is the level observed in the worst case, at the edge of the band or for maximum scanning angle.

A comparison between simulated and measured X-pol level for observation at $\theta = -45^\circ$ and $\theta = 45^\circ$ in the diagonal plane is presented in Fig. 17. The measured values oscillate around the expected ones and are lower than -10 dB over about a 30% bandwidth. The differences between measured and calculated results are most likely attributable to the finiteness of the array.

The measured results confirm that the loop-shaped transformer is a valid solution to the common-mode resonances. In fact, no resonance like the one shown in Fig. 3(c) is observed.

VI. Conclusion

A wideband, wide-scan angle array of connected dipoles has been designed and fabricated. Measured results from a 7×7 prototype demonstrator have been presented for experimental validation. In order to avoid common-mode resonances that typically affect this type of array, loop-shaped transformers are included in the feed network. The common-mode rejection implemented by these transformers allows to maintain the cross-polarization levels to low values over about 30% relative bandwidth, for elevation angle up to 45° in all azimuth planes. The measured results are in good agreement with expectation based on infinite array analysis.

The proposed feed structure is believed to be an efficient practical way to implement the matching network of a connected array, as a valid solution to common-mode resonances. The loop-shaped feed structure is based on PCB technology, to limit the costs and the complexity, without resorting to active component or to monolithic microwave integrated circuit (MMIC) technology.

The realization of the ground plane was shown to be a critical aspect of the manufacturing for previous similar designs. The problem was solved by replacing the continuous plane with a discrete grid composed by wires. The goodness of the results validates this method for ground plane implementation.

The array can keep low polarization levels in a volume of 45 degrees and a band of 30%. These results are believed to be among the best reported for wideband wide-scanning applications without severe penalty in polarization efficiency and with spacing kept at about 0.45λ at the higher frequency of operation.

Larger prototypes operating in dual polarization are currently being fabricated. In those cases, the X-pol level is expected to be at least 5 dB lower.

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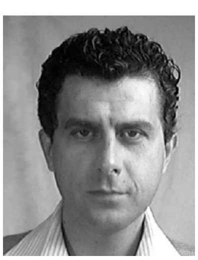
Prof. Neto was corecipient of the H. A. Wheeler Award for the best applications paper of 2008 in the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION. He was corecipient of the Best Innovative Paper Prize at the Thirtieth ESA Antenna Workshop in 2008. He was corecipient of the Best Antenna Theory Paper Prize at the European Conference on Antennas and Propagation (EuCAP) in 2010. He presently serves as Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION and for the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS (AWPL).



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From 1992 to 1994, he was Assistant Professor of electromagnetic fields at the same university. From 1994 to 1997, he was Research Fellow at the European Space Research and Technology Centre (ESA-ESTEC), Noordwijk, The Netherlands, where he joined the Radio Frequency System Division. Since 1997, he has been with the Netherlands Organization for Applied Scientific Research (TNO), The Hague, The Netherlands. At TNO Defence Security and Safety, he is currently Chief Senior Scientist of the Antenna Unit in the Transceiver Department. In 2007, he was appointed as part-time Professor in the Faculty of Electrical Engineering of the Eindhoven University of Technology, Eindhoven, The Netherlands, with a Chair on Novel Structures and Concepts for Advanced Antennas. His main research interests are phased arrays antennas, electromagnetic bandgap structures, frequency-selective surfaces and integrated antennas at microwave, and millimeter and sub-millimeter wave frequencies. The main application fields of interest are radar, imaging, and telecommunication systems.

Prof. Gerini was corecipient of the 2008 H. A. Wheeler Applications Prize Paper Award of the IEEE Antennas and Propagation Society. He was corecipient also of the Best Innovative Paper Prize of the Thirtieth ESA Antenna Workshop in 2008 and of the Best Antenna Theory Paper Prize of the European Conference on Antennas and Propagation (EuCAP) in 2010.

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Dr. Galdi is the recipient of a 2001 International Union of Radio Science (URSI) Young Scientist Award, a member of Sigma Xi, of the LIGO Scientific Collaboration (LSC), and of the Italian Electromagnetic Society (SIEM). He is a regular reviewer for several journals, conferences and funding agencies.