Interwoven Spiral Array (ISPA) With a 10:1 Bandwidth on a Ground Plane

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***Abstract*—We describe a novel, planar, circularly polarized (CP), interwoven spiral array (ISPA) having a 10:1 bandwidth while operating conformally on a perfect electric conducting (PEC) ground plane. The array is comprised of rectangular, self-complementary spirals. However, unlike typical array designs, the elements have their arms "interwoven" to enhance coupling. This coupling serves to mitigate the inductive effects contributed by the PEC ground plane. Consequently, the unit cell of the array encompasses several adjacent array elements. This feature leads to unique array properties, and in this letter, we pursue a numerical analysis and design of an array version that delivers a 10:1 bandwidth, for a broadside scan, in a conformal setting.**

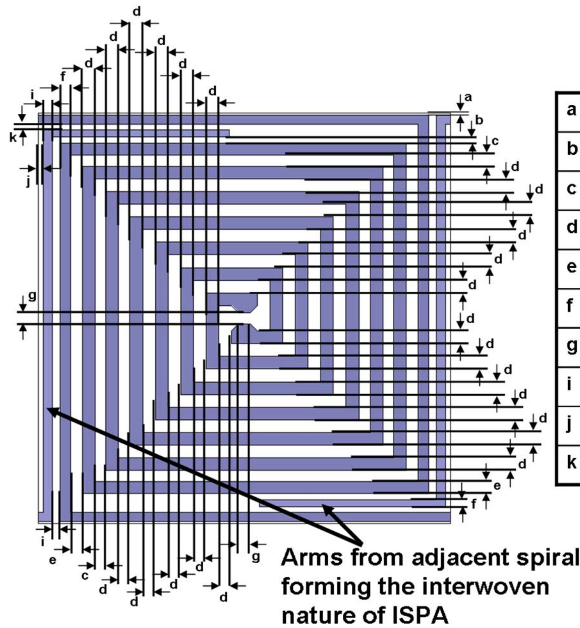
***Index Terms*—Conformal arrays, spiral antenna, ultrawideband (UWB) antenna arrays.**

I. Introduction

As NOTED by Hansen [1], it was Baum [2] who first worked to show that interconnected dipole arrays exhibit adequate low-frequency performance in free space. However, when placed above a ground plane, the impedance bandwidth deteriorates significantly, due to: 1) the inductance introduced by the ground plane; and 2) the small value of the radiation resistance.

Recently, Munk [3] demonstrated a technique to compensate for the ground plane inductance by adding interdigital capacitors between the tips of a densely packed dipole array. This dipole configuration, referred to as the current sheet antenna (CSA), provided for a 4.5:1 bandwidth (without use of dielectric superstrates). Similar broadband performance was achieved by the subsequent work in [4]–[7]. However, to achieve greater bandwidth using these conformal arrays, it is important to improve the radiation resistance at lower frequencies. Particularly, the work in [7] has noted that when it comes to off-broadside scanning, very narrow "resonances" occur in the spiral antenna impedance, at frequencies where the spiral length is multiples of $\lambda/2$. In this letter, we are considering broadside operation, i.e., all elements are fed in phase, but we confirm the occurrence of the aforementioned resonances when scanning the array beam.

In this letter, we propose a new, ultrawideband (UWB) array concept, based on an interwoven spiral array (ISPA) placed conformally on a ground plane. A key feature of the ISPA performance is that its radiation resistance remains at a relatively constant level (about 188 Ω) above the lowest operation frequency, as compared to the CSA array in [3]. More specifically, the ISPA design does not exhibit the typical impedance peak, associated with the ground plane reflection, often seen in conformal dipole- and bowtie-type arrays. In our design, a novel mechanism was introduced to control both the real and imaginary components of the array impedance and therefore extend the VSWR bandwidth to 10:1. This ultra-wide bandwidth is achieved without use of dielectric superstrates or lossy materials.



a	λ/375
b	λ/107
c	λ/71
d	λ/60
e	λ/63
f	λ/75
g	λ/65
i	λ/83
j	λ/166
k	λ/188

Fig. 1. ISPA array unit cell and its dimensions in wavelengths. The element is fed at the center.

II. ISPA Unit Cell

The array unit cell is shown in Fig. 1. It is comprised of a rectangular, self-complementary, two-arm Archimedean spiral antenna covering the entire unit cell, except for the small region close to the unit cell edges, where it also incorporates arm sections from adjacent cells on the right and left. These interwoven arms continue for about 3/8 of a turn. The unit cell is repeated in two dimensions to form a 2-D infinite array.

The dimensions of the spiral are given in detail in Fig. 1 (all in wavelengths). Also, the overall unit cell size is $\lambda/1.83 \times \lambda/1.83$ with the array placed $\lambda/1.83$ from the perfect electric conducting (PEC) ground plane. We note that the spiral arm width varies within the unit cell. In particular, it is chosen

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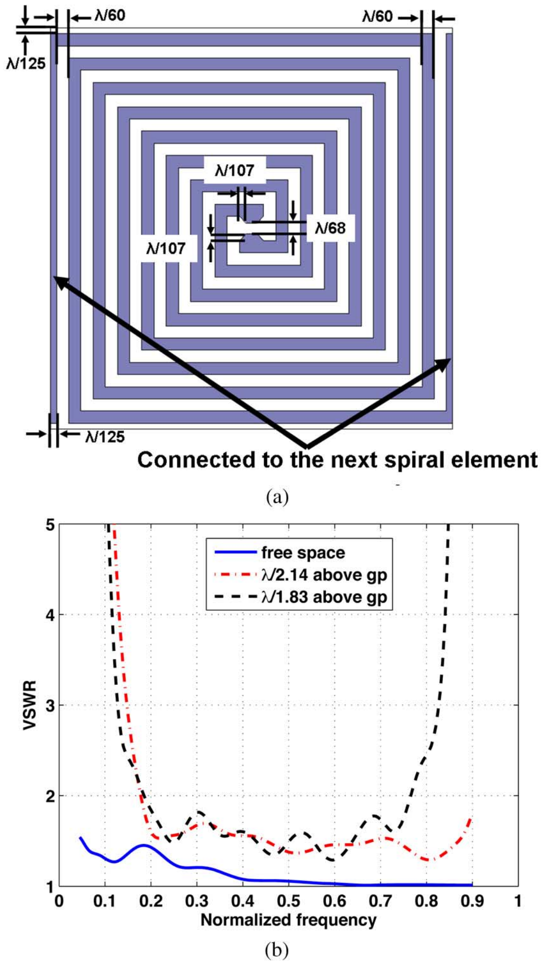


Fig. 2. (a) Interconnected (i.e., continuous) spiral array unit cell without interwoven arms. (b) Simulated VSWR in free space and above a PEC ground plane ($\lambda/2.14$ and $\lambda/1.83$ height). Reference impedance was chosen as 188 Ω.

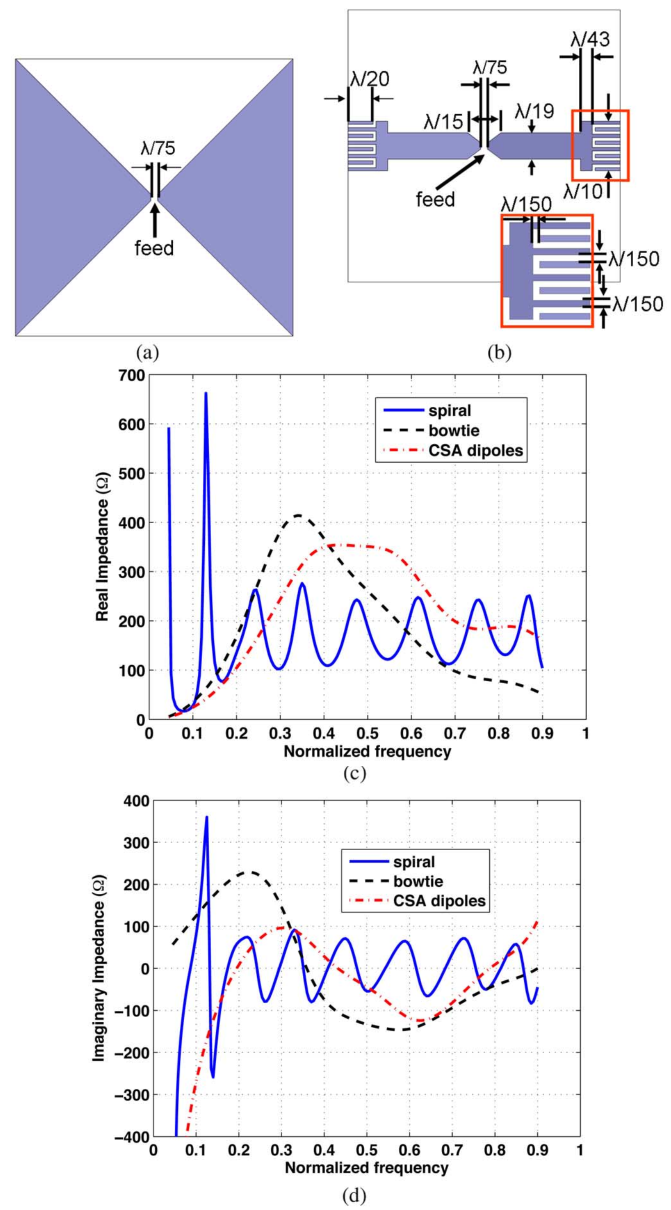


Fig. 3. (a) Unit cell of interconnected bowtie array. (b) Unit cell of the CSA dipole array. (c) Comparison of real and (d) imaginary impedance of the conformal bowtie, CSA dipole, and interconnected spiral (not interwoven) arrays [see Fig. 2(a) for unit cell of latter].

to be $\lambda/60$ at the central region of the spiral, but becomes thinner ($\lambda/100$) toward the spiral arm ends. This particular design layout (and associated dimensions) was generated via a trial-and-error process with the objective of maximizing the VSWR bandwidth. At this point, no formal optimization was adopted, therefore the presented design is one of many possibilities within the ISPA concept. In the following section, we present some intermediate steps in the development of the configuration of Fig. 1 and provide its performance.

III. Development of ISPA Unit Cell

As mentioned earlier, interconnected, planar dipole arrays (where adjacent elements are connected) exhibit adequate low-frequency performance in free space [2]. The same also holds for self-complementary structures such as interconnected bowtie and spiral arrays. To observe their performance and therefore assess the improvement achieved by the proposed ISPA, we refer to Figs. 2 and 3. Fig. 2(a) shows the unit cell ($\lambda/1.83 \times \lambda/1.83$) and calculated VSWR of a self-complementary, interconnected (i.e. continuous) spiral array in free space. The arm width and gap dimensions are indicated. The calculated VSWR of 2-D infinite arrays in free space and over a PEC ground plane ($\lambda/2.14$ and $\lambda/1.83$ height) is shown in Fig. 2(b). The array's impressive low-frequency performance in free space can be attributed to Wheeler's Current Sheet [8] concept and the self-complementary nature of the geometry.

However, when placed above a ground plane, the low-frequency performance is lost due to the highly inductive impedance caused by the ground plane [3]. Specifically, the spiral array of Fig. 2(a), while exhibiting an over 20:1 bandwidth ($\mathrm{VSWR} < 2$) in free space, only achieves a 4:1 or 4.5:1 bandwidth when placed $\lambda/1.83$ and $\lambda/2.14$, respectively, above a PEC ground plane (note that first grating lobe occurs at normalized frequency 0.915, at which unit cell size is half a wavelength).

Of interest is also the performance of the interconnected bowtie and the CSA [10] dipole arrays shown in Fig. 3(a) and (b).

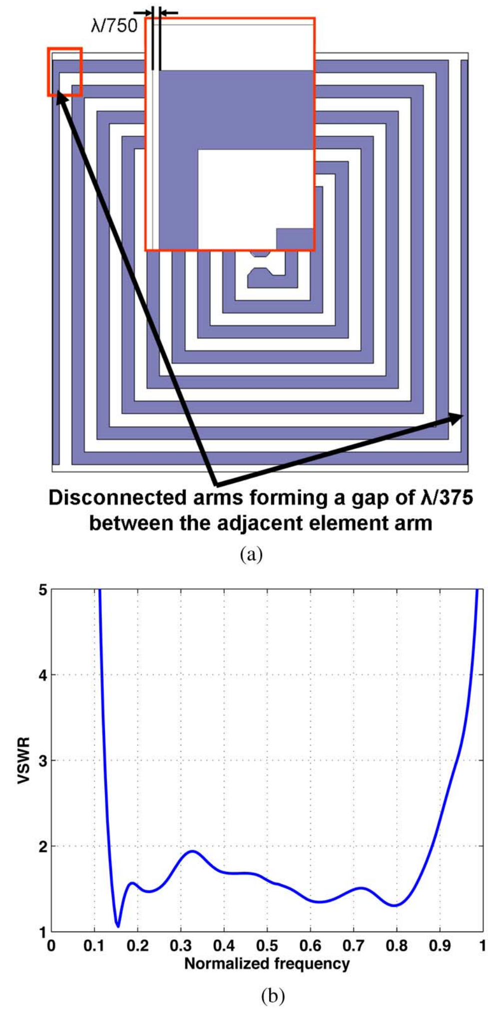


Fig. 4. (a) Unit cell of disconnected spiral array. (b) Simulated VSWR.

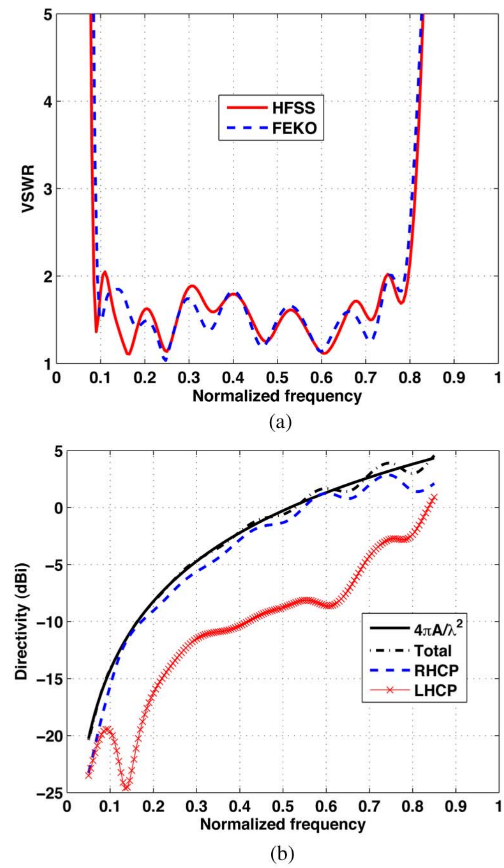
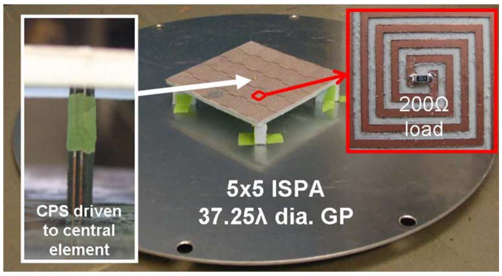


Fig. 5. (a) VSWR of ISPA array using HFSS ver. 10 and FEKO Suite ver. 5.5. Reference impedance was chosen as 200 and 250 Ω, respectively. (b) Total, RHCP, and LHCP directivity calculated with HFSS ver. 10 as compared to the directivity of a uniformly excited aperture of area $A = \lambda/1.83 \times \lambda/1.83$.

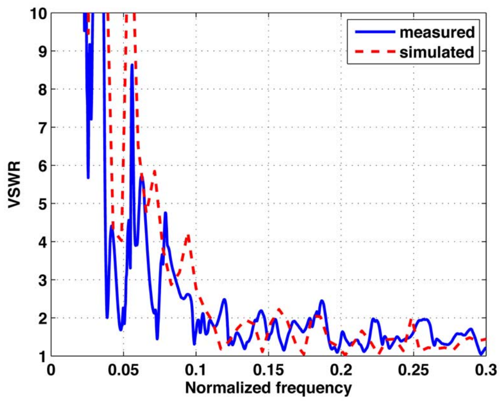
Again, for these arrays, the unit cell was $\lambda/1.83 \times \lambda/1.83$ in aperture and placed $\lambda/2.14$ above the ground plane. As seen, the interconnected spiral array exhibits much less variation in the real and imaginary impedance across the bandwidth where $\mathrm{VSWR} < 2$. The spiral array is also associated with a more highly oscillatory behavior even though the maximum value of the oscillations is much lower and within 25% of the average real impedance value. We also found that the ripples in the spiral's impedance performance are associated with the spiral arm tightness (in other words, with the number of turns within a given unit cell size). From Fig. 3, the interconnected spiral array has more attractive impedance behavior.

Concurrently, it was found that substantial improvement in the VSWR performance, at lower frequencies, could be achieved by increasing the coupling capacitance between the spiral elements to counter the increased inductance from the ground plane. A way to increase capacitance is to disconnect the arms of adjacent elements but maintain a small gap. This was done in Fig. 4, where the performance is shown for the same spiral array ($\lambda/2.14$ above the ground plane), but with a gap of $\lambda/375$. This separation was produced by shrinking the unit cell of Fig. 2(a) to 99% of its size. As seen (see Fig. 4), the $(\mathrm{VSWR} < 2)$ bandwidth is dramatically increased to 7:1 (0.125–0.88) from 5:1 (0.18–0.9) shown in Fig. 2(b). We remark that the largest bandwidth was found when the gap was $\lambda/375$ $(2 \times \lambda/750)$.

To further increase the bandwidth, we increased interelement coupling by extending the arm lengths. We initially did so by planar-meandering the arms into the next spiral to form a configuration similar to interdigital capacitors. However, this approach did not appreciably increase the bandwidth. After attempting several interweaving approaches to increase the coupling, we found that the design in Fig. 1 was best in increasing interelement coupling as well as improving the spiral array's low-frequency performance. Because of its geometry, we named this design the ISPA. The corresponding VSWR and directivity are shown respectively in Fig. 5(a) and (b). As seen, both FEKO ver. 5.5 and HFSS ver. 10 provide close results giving confidence on the performance. We note that the array gives a 10:1 bandwidth (normalized frequency 0.08–0.8) with $\mathrm{VSWR} < 2$ when $\lambda/1.83$ above a PEC ground plane. In that range, the array achieves a ~7-dB isolation between co- and cross-pol gains [see Fig. 5(b)]. The right-hand circularly polarized (RHCP) and left-hand circularly polarized (LHCP) directivity of the ISPA array were calculated based on one unit cell as part of an infinite array. The two gains are compared to the directivity of a uniformly excited aperture A, with A being equal to the unit cell size [9].



(a)



(b)

Fig. 6. (a) Fabricated 5 × 5 ISPA array. The central element is fed while the rest are terminated in 200-Ω resistors. (b) Measured and simulated VSWR.

IV. Validation of a 5 × 5 Array With Measurements

In order to obtain a 10:1 bandwidth, the ISPA array should be made, in theory, infinitely large. However, in practice and for the CSA array, the infinite extent was emulated [10] by printing a couple of thousands of dipole elements, of which only a small portion (8 × 8 elements in the center of the array) were fed, while the rest were terminated with resistors. Considering our design being still in early stages of development, at this point, we will not pursue the full 10:1 bandwidth. Instead, we set to test the concept of the ISPA in terms of fabrication and also validate the performance of a 5 × 5 array [see Fig. 6(a)].

The unit cell of Fig. 1 was scaled by 3.6 times (i.e., $1.97\lambda \times 1.97\lambda$) to allow for in-house fabrication with a standard printed circuit board (PCB) milling machine. The latter is capable of milling 6-mil traces (slots) with a precision of ± 1 mil. The array was printed on a $\lambda/30$ RO5880LZ board ($\epsilon_r' = 1.96$, $\tan_\delta = 0.002$). Only the central element was fed, while the other 24 elements were terminated in 200-Ω resistors [this was the value of the system impedance in the infinite array analysis in Fig. 5(a)], as seen in the detail in Fig. 6(a). The array was placed above a circular, 37.25λ-diameter aluminum ground plane, with foam separators providing the appropriate height $(= 1.97\lambda)$.

To cover the intended 10:1 BW, the active element was fed with a broadband microstrip-to-coplanar strip (CPS) balun [11], which provides a 4:1 impedance transformation (i.e., 50 Ω coax.–200 Ω CPS). The balun was placed vertically under the ground plane, and the CPS was driven through a small hole to the antenna terminals [see Fig. 6(a)]. The measured VSWR is shown in Fig. 6(b) in comparison to the simulated performance. The numerical analysis was carried out using FEKO Suite ver. 5.5. An infinite ground plane and dielectric layer were used to make the analysis feasible. As seen, the measured and numerical data are in excellent agreement with $\mathrm{VSWR} < 2.5$ above 0.1 normalized frequency. This initial prototype gives us confidence that the proposed ISPA can achieve a 10:1 BW via excitation of multiple elements and the use of a larger (for example, 10 × 10 elements) aperture.

V. Conclusion and Future Work

A novel, conformal, interwoven spiral array was presented. The array can theoretically achieve a 10:1 bandwidth $(\mathrm{VSWR} < 2)$ on a ground plane, i.e. a performance nearly a factor of 2 better than other published arrays, such as the CSA dipoles. The unit cell size was $\lambda/1.83 \times \lambda/1.83 \times \lambda/1.83$ at the highest frequency (normalized frequency 1). The reported performance is based on an infinitely periodic planar array, and all elements were fed with 0° phase (broadside radiation). In this operating mode, grating lobes will not occur until the frequency reaches ~normalized frequency 1.8 ($\lambda = d$, where d is the element spacing). For scanning at low grazing angles, the frequency should be kept to less than ~normalized frequency 0.9 ($d = \lambda/2$, for end-fire radiation). Nevertheless, Fig. 5(a) indicates that the performance will degrade before 0.9 due to poor VSWR above 0.8. Assessing the array scanning behavior is a future task. We remark that our design is based on simulations, where feeding was done by simple ports. In practice, a broadband transformer/balun will be required to suppress the common mode resonances [12].

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