MUTUAL COUPLING BETWEEN PLANAR INVERTED-F ANTENNAS

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ABSTRACT: Mutual coupling between two planar inverted-F antennas (PIFA) based on a ground plane has been studied numerically and experimentally. Several arrangements of collinear, orthogonal and parallel PIFA elements with interelement spacing ranging from 0.1λ to 0.9λ have been examined at the design frequency of 2.45 GHz, and in the frequency band 2.0–3.0 GHz.

Key words: inverted-F antenna, antenna arrays, mutual coupling

1. INTRODUCTION

Along with the monopole, patch and slot antennas, the inverted-F antenna (IFA) has become of primary importance for portable and handheld wireless communication units. It is known as a high efficiency quasi-omnidirectional antenna with a height of about 0.05–0.1λ, i.e. 2.5–5 times shorter than the quarter-wave monopole [1]-[3]. The inverted-F antenna, wire or planar (PIFA), is a low-profile modification of the quarter-wave monopole, and thus belongs to the group of unbalanced antennas. There is a huge amount of research and development work on classical and novel single IFA configurations [2]-[7], and on their diversity arrangements with monopole or patch antennas [8]-[10]. Surprisingly, few results are known on the theory and practice of IFA arraying. Very little has been published, in particular, for the mutual coupling between IFA array elements [11]-[12], which depends not only on the interelement spacing, but also on their mutual orientation [13]. The same observation is valid for the statistical receive characteristics of two-element or multi-element IFA arrays.

Normally, the mutual electromagnetic coupling adversely affects the antenna array input and radiation characteristics. This is typical for the single-port arrays and adaptive antennas, for example. In the multi-port antenna arrays however, exploited in MIMO communication systems, the mutual coupling may produce a positive effect: an improvement of system correlation and data capacity [14]. In this paper, the results of numerical and experimental study of single PIFA and mutual coupling in a double PIFA array are presented and discussed. Several basic array arrangements with different PIFA joint orientations (collinear, orthogonal and parallel) have been examined numerically and experimentally for a spacing ranging from about 0.1λ to 0.9λ, at the design frequency of 2.45 GHz and for a frequency band 2.0–3.0 GHz. For comparison, arrays consisting of PIFA and monopole, and of two quarter-wave monopoles have also been studied.

2. PIFA AND MONOPOLE DESIGNS

The PIFA element, drawn in Fig. 1, is located on an infinite ground plane x-y (not shown in the figure). It is fed by a coaxial cable C and consists of two sections. The first is a low-profile inverted-L planar section, made of a thin metal sheet of width w and thickness t. It has a horizontal branch c′′ −d′′ of length s′′ + s′′, and a vertical branch d′′ −e′′ of height h, with the edge e′′ grounded. The second section is a short cylindrical monopole of height h and diameter d′′′ fed at point a, and connected to the L-section at point b. Functionally the PIFA can be viewed as an inverted-L antenna c′′′−b′′′−a with a match circuit b′′′−d′′−e′′ added.

The single PIFA and PIFA arrays were simulated and optimized numerically by means of Ansoft HFSS and Optimetrics software package [15]. The measurements were made by use of a Rohde & Schwarz Vector Network Analyzer, model ZVRE [16]. At the design frequency of 2.45 GHz the final PIFA element used for the mutual coupling study, had the following optimized dimensions: h = 11.1 mm, w = 7.4 mm, s′ = 9.2 mm, s′′ = 16.7 mm, t = 0.2 mm and d′′′ = 1.5 mm.

It was found that at 2.45 GHz the single PIFA has a value of the S-parameter S11, or the reflection coefficient, equal to −38 dB, computed, and −40 dB,
measured. Its numerical input bandwidth at $S_{11} = -10$ dB is 12.7% and the corresponding measured value is 12.2%. The simulations have shown that the PIFA antenna, in contrast with the monopole can be tuned for a very good match not only to the standard 50-ohm cable as is the case here, but also for a range of other impedance values. 

The PIFA was compared to a 2.45-GHz quarter-wave monopole with a wire diameter of 1.5 mm and a resonant height of 29.5 mm. The monopole is 2.54 times higher than the PIFA and its match at the design frequency is inferior: $S_{11} = -17.3$ dB, computed, and $-18.5$ dB, measured. On the other hand the monopole has better input bandwidth: 16.5%, computed, and 19.6%, measured.

It has to be noted here that the computer simulation of PIFA and monopole antennas was made under the assumption of lossless metal structures in air and based on a lossless infinite ground plane. The measured antenna models were actually fabricated in copper, and were positioned in the middle of a square bronze plate of size 55 cm, which being much larger than the antenna arrays provides a good approximation of the infinite ground plane.

As was shown, the PIFA differs significantly from the monopole in height and input characteristics. There is also some difference in their radiation patterns. The grounded vertical monopole is an ideal omnidirectional antenna in the azimuth plane, while the PIFA’s horizontal pattern slightly deviates from the circular shape. The studied PIFA design has a gain pattern $G(\phi)$, which for four values of the azimuth angle $\phi$ is described by: $G(0^\circ) = 4.1$ dBi, $G(90^\circ) = 4.4$ dBi, $G(180^\circ) = G(0^\circ)$ and $G(270^\circ) = 3.7$ dBi. Thus, there is a 0.7 dB front to back gain difference due to the non-symmetrical and more complex current and near-field distribution in the PIFA.

3. PIFA ARRAY ARRANGEMENTS

Fig. 2 is a view from above of a two-element PIFA array defined by the interelement spacing $d$ and rotating angles $\alpha_1$ and $\alpha_2$.

The array axis passes through the PIFA element’s feed points. The rotation of each PIFA is made around its feed-monopole line $\text{a-b}$. The array axis passes through the PIFA element’s feed points. The rotation of each PIFA is made around its feed-monopole line $\text{a-b}$.

Because the array characteristics are related also to the ground plate or container size and shape, in order to isolate the dependency of mutual coupling on the element position and orientation, the PIFA arrays were situated on an infinite ground plane.

Figure 2 Geometry of two-element PIFA array

In addition, arrangements involving monopoles were examined: (i) mixed-antenna arrangement PM, where the PIFA #2 is replaced by a monopole and PIFA #1 is turned at $\alpha_1 = 90^\circ$, and (ii) two-monopole arrangement MM.

The arrangements C-1, C-3, P-1, P-2 and MM are electromagnetically symmetric in reference to the line $\text{AA'}$, while the rest are nonsymmetrical, because of specific PIFA orientation (C-2, O-1 and O-2) or different antenna elements (PM).

4. MUTUAL COUPLING OF PLANAR INVERTED-F ANTENNAS

The studied two-element PIFA arrays were computer-simulated on an ideal infinite ground plane. The fabricated array elements were fixed in the middle of a large finite ground plate. The single PIFA and the ground plate dimensions were specified in the previous section.

Figs. 3, 4 and 5 illustrate the simulated (solid line) and measured (circles on a dotted line) $S$-parameter $S_{12}$, or the mutual coupling, in decibels, between collinear (C), orthogonal (O) and parallel (P) PIFA elements, respectively, as a function of spacing $d$ in wavelengths. Similarly, Fig. 6 shows the coupling vs. spacing of a PIFA positioned next to a monopole (PM), and the coupling of two quarter-wave monopoles (MM). The spacing is defined by the distance between feed points of the two antennas. According to Fig. 3, among all collinear arrangements the smallest coupling is produced by C-1, while C-3 has the biggest coupling for all spacing values. A simplified explanation of this behavior follows from

Changing the angles $\alpha_1$ and $\alpha_2$ by a step of $90^\circ$ seven arrangements of the two-element PIFA array were defined and studied, with:

(a) collinear elements: C-1 ($\alpha_1 = 180^\circ$, $\alpha_2 = 0^\circ$), C-2 ($\alpha_1 = \alpha_2 = 0^\circ$) and C-3 ($\alpha_1 = 0^\circ$, $\alpha_2 = 180^\circ$);
(b) orthogonal elements: O-1 ($\alpha_1 = 90^\circ$, $\alpha_2 = 0^\circ$) and O-2 ($\alpha_1 = 0^\circ$, $\alpha_2 = 90^\circ$);
(c) parallel elements: P-1 ($\alpha_1 = \alpha_2 = 90^\circ$) and P-2 ($\alpha_1 = 90^\circ$, $\alpha_2 = 270^\circ$).
the current/charge distribution on a PIFA. On its open edge, the current is zero and the voltage and charge are maximum. If the charged edges of the two PIFA elements are very close, as in the case C-3, there will be a strong electromagnetic tie or coupling between them, and vice versa (case C-1). By a similar argument the coupling difference between the parallel arrangements P-1 and P-2 can be justified. This explanation would suggest that the arrangement C-2 should have coupling values intermediate to those exhibited by C-1 and C-3, as was actually found both through simulation and measurements. From the coupling graphs for O-1 and O-2 (Fig. 4) it is seen that for an orthogonal arrangement, besides spacing an important role is again played by the direction (orientation) of the open end of the PIFA.

Coupling is much larger when the open end of one antenna faces the feed point of the other (O-2).

Figure 3 Coupling between collinear PIFA elements vs. spacing in wavelengths for arrangements C-1, C-2 and C-3

Figure 4 Coupling between orthogonal PIFA elements vs. spacing in wavelengths for arrangements O-1 and O-2

Figure 5 Coupling between parallel PIFA elements vs. spacing in wavelengths for arrangements P-1 and P-2

At a spacing $0.3\lambda$ (Figs. 3-5) the mutual coupling has small variations, $\pm 0.75\, \text{dB}$ around a central value of $-11\, \text{dB}$ for all array arrangements, except for C-3 and O-2, where it has much bigger values: $-5.5\, \text{dB}$ and $-8.5\, \text{dB}$, respectively. For spacing greater than about $0.4\lambda$ the comparison between all PIFA combinations, studied in this paper, reveals that C-1 and O-1 act as minimum-coupling arrangements, with almost equal measured coupling values, which average $-9.8\, \text{dB}$, $-16.5\, \text{dB}$ and $-18.5\, \text{dB}$, for $d/\lambda = 0.25, 0.5$ and 0.75, respectively.

The mixed array (PM) comprising PIFA and monopole, and the two-monopole array (MM) have very similar coupling behavior for the whole range of $d/\lambda$ (Fig. 6). More exactly, at $d/\lambda = 0.25, 0.5$ and 0.75, the arrangements PM (and MM, respectively) have the following measured coupling values: $-9.6\, \text{dB}$ ($-9.2\, \text{dB}$), $-13.9\, \text{dB}$ ($-13.1\, \text{dB}$) and $-16.4\, \text{dB}$ ($-15.7\, \text{dB}$). Hence, in contrast to PIFA arrangements C-1 and O-1, for spacing greater than $0.5\lambda$ the arrays PM and MM have stronger coupling, about $3-4\, \text{dB}$ larger.

In most cases, C-3, O-2, P-1, PM and MM, there is a very good agreement between the graphs of simulated and measured coupling values for the complete range of spacing values. Exceptions occur for arrangements C-1, C-2, O-1 and P-2, where for spacing larger than $0.5\lambda$ the difference between simulations and measurements becomes significant. At this point we have to consider that the simulations were carried out for an infinite ground plane, while practical
considerations limited the ground plate for the measured antenna models to a square of size $4.5\lambda$.

Figure 6 Coupling between PIFA and monopole (PM), and between two monopoles (MM) vs. spacing in wavelengths

Fig. 7 is a color contour presentation of the measured two-element PIFA array $S$-parameters, $S_{11}$, $S_{22}$ and $S_{12} = S_{21}$, as functions of spacing $d$, in wavelengths, and frequency, in gigahertz, for five array arrangements: (a) collinear PIFA arrangement C-1, (b) orthogonal PIFA arrangement O-1, (c) parallel PIFA arrangement P-1, (d) array PM of PIFA and monopole, and (e) two-monopole array MM. While the graphs in Figs. 3-6 are limited only to the coupling dependency on spacing, at the design frequency of 2.45 GHz, the pictures in Fig. 7 contain abundant information about the array coupling and match performance in the spacing domain $0.1 - 0.9\lambda$ and frequency domain 2-3GHz. Several observations follow from this figure:

(i) As is expected $S_{11}$ is equal to $S_{22}$ for the symmetrical arrays C-1, P-1, and MM, while for the nonsymmetrical arrays O-1 and PM $S_{11}$ differs from $S_{22}$;
(ii) All antenna array elements have practically preserved their design resonant frequency, bandwidth and match performance for spacing greater than $0.4 - 0.5\lambda$;
(iii) For smaller spacing (say less than $0.4\lambda$) the resonant (match) frequency of both PIFAs becomes somewhat shifted from the design frequency;
(iv) The two-monopole array has better frequency bandwidth but worse match performance than the two-two-PIFA array, a behavior similar to what was described in the comparison between the single monopole and PIFA (Section 2).

5. CONCLUSIONS
The numerical and experimental study of mutual coupling and match performance in several two-PIFA arrays as function of spacing and joint orientation has resulted in a large amount of numerical and experimental data.

In the spacing domain it was observed that the coupling depends mainly on the distance between the PIFA open-ended sides. For a constant spacing between the feed points the coupling experiences considerable changes with the relative angular orientation of the PIFA elements. Also, the studied mixed-antenna array (PM) and two-monopole array (MM) have stronger coupling, about $3 - 4\text{ dB}$ greater than the majority of two-PIFA arrangements. These differences are especially pronounced for larger array spacing.
In the frequency domain has been found that for spacing greater than 0.4–0.5λ, all PIFA array elements have practically preserved their single-element design resonant frequency, bandwidth and match performance. The two-monopole array has better frequency bandwidth but worse input match than the two-PIFA array.

The findings for mutual coupling in two-PIFA arrays will be of practical value for multi-PIFA array design and optimization. In contrast with the monopole array, where the coupling depends only on the interelement spacing, the relative element orientation in the PIFA array provides an option for controlling the degree of mutual coupling and the shape of the element radiation pattern. This option can be useful, for example, in multi-port MIMO communication systems for further reduction of space correlation by adding the effects of mutual coupling and pattern (angle) diversity.

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