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Design of a Wire Grid Inverted-F Antenna with Ultra Wideband Characteristics

Mehdi Hosseini*

Abstract—In this paper, a new wire inverted-F antenna (IFA) is proposed, which is structured by grids of thin wires. This novel wire grid IFA is $\sim 0.3\lambda$ long and $\sim 0.14\lambda$ high and renders 41% fractional bandwidth which is nearly 5 times higher than the bandwidth of a classic IFA. In addition to the novel structure and high bandwidth, the distinguishing feature of the design process employed is its computational efficiency. While the constituent wires of the wire grid (WG) model are one-dimensional (1D) *thin wires*, they can indirectly form *very thick* arms leading to bandwidth enhancement. The thin-wire structure of the WG-IFA provides the opportunity to carry out the analysis and design accurately and fast in a 1D MoM-based software like NEC.

1. INTRODUCTION

With rapid development of wireless communications technology, wideband and low-profile antennas have become a necessity for mobile communication devices. One of the candidates able to meet most requirements is the inverted-F antenna (IFA). This antenna is particularly known for its ability to allow a simple impedance matching in a low-profile design which can produce both vertically and horizontally polarized electric fields [1], bringing about a desirable signal diversity which can mitigate fading in a multi-path environment. Other attractive features of IFA are its low profile and light weight structure and the ease of integration [2] into small form factors of space-limited wireless terminals. As a consequence, IFA has been widely applied to a variety of communication systems [3–7], most commonly, handheld mobile phone terminals. In the wake of standard and frequency proliferation, current and future mobile terminals should be able to accommodate more co-existing RF and antenna front-ends. This fact highlights the importance of multiband [2], reconfigurable [8] and wideband [9–11] antennas like IFA, and PIFA (Planar IFA), which can potentially cover more of the demanded frequency bands including WLAN, WiMAX [2], ISM, GSM (legacy and new), GPS, and even Digital TV, and UWB [12]. A sufficiently wideband IFA design can cover many of such bands and obviate the need for multiple antennas.

It is well known that if the IFA height over ground plane is approximately one-tenth of free-space wavelength, the frequency bandwidth (BW) is approximately 8%, considering VSWR $< 2:1$ [13]. To broaden this BW, a few techniques have been proposed such as decreasing the size of the ground plane [14], adding parasitic elements [10, 13], and introducing dual resonance concept [15]. Another successful method has been replacing the IFA horizontal element by a planar conducting patch forming a PIFA [5–7]. However, the regular PIFA on PEC ground plane exhibits a maximum BW of 25% subject to having a very large ground plane. To improve this BW, another design employs an electromagnetic bandgap (EBG) ground plane for PIFA and achieves BW = 27.5% [5]. Some recent efforts focus on the shoring and feeding pins (plates) of the PIFA and show that deliberately widening these pins can further enhance the BW [9, 10].

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* Corresponding author: Mehdi Hosseini (m.hosseini@usask.ac.ir).
The author is with the Department of Electrical and Computer Engineering, University of Saskatchewan, Saskatoon, SK, Canada.

Following these efforts, the present work proposes a simple yet effective approach to further improve BW. The approach is based on applying wire grid modeling [16–19] to the structure of an IFA. The sample wire grid IFA designed and prototyped renders BW = 41% and has the potential for reaching further improvement. This high bandwidth qualifies the antenna to fit within the definition of the ultra wideband (UWB) antennas as any antenna with the BW exceeding the lesser of 500 MHz or 20% (fractional BW) is classified as UWB antenna [20]. To carry out the required analyses, the NEC software is utilized which is a MoM-based software for efficiently simulating wire antennas.

2. PARAMETRIC STUDY ON THE BANDWIDTH OF IFA

In this section, a parametric study is conducted to gain some insights on the relationship between the BW of IFA and its physical dimensions. To this purpose, a typical IFA (similar to the one in [13]) is considered with the following dimensions: $R = 1\,\text{mm}$, $H = 3.3\,\text{cm}$, $S = 0.9\,\text{cm}$, and $L = 5.37\,\text{cm}$. Here S is known as matching pin distance, H is the antenna height over ground plane, $L + H$ is the antenna electric length, and R is wire radius, as depicted in Figure 1. The antenna resonance frequency (f_r) is 925 MHz and exhibits BW = 7.5% at f_r. The first step of the study is to change S between 0.9 cm and 3 cm while keeping other dimensions fixed. In the next step, S is kept fixed at 3 cm, and R is varied between 1 mm and 4 mm. As seen in Figure 2, increasing S generally increases both BW and f_r while increasing R increases BW and decreases f_r. Figure 2 also shows that although changing R or S shifts the matching frequency range, it does not deteriorate the matching quality.

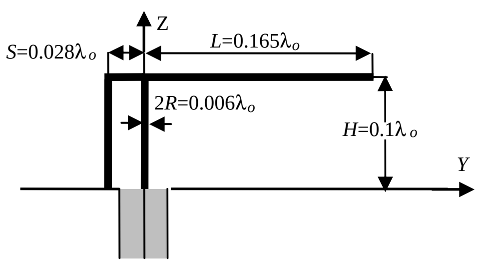


Figure 1. Dimensions of a typical IFA; $R = 0.1\,\text{cm}$, $H = 3.2\,\text{cm}$, $S = 0.9\,\text{cm}$ and $L = 5.37\,\text{cm}$; λ_o is the wavelength at 925 MHz.

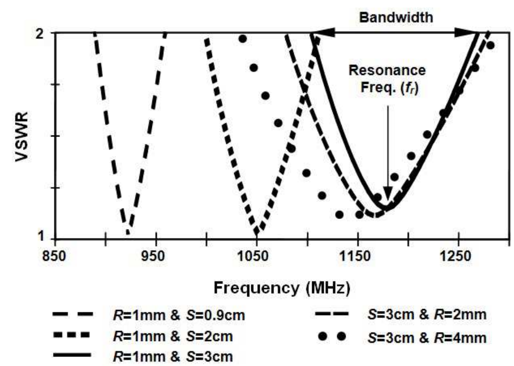


Figure 2. Parametric study on the effect of S and R on the BW of a typical IFA; for all cases, $L + S = 6.27\,\text{cm}$ and $H = 3.3\,\text{cm}$.

3. THIN AND THICK WIRE MODELING ISSUES

In Section 2, it was shown that to enhance the BW, the radius of IFA wires should increase as much as possible. However, there is a restriction on the radius. NEC is primarily designed to only model thin wire segments. A wire segment is considered thin provided that its length (l) over its radius (r) is greater than 8 ($l/r > 8$). When thickening the wire segments of an IFA, some of the segments become quite small relative to r, and hence, the accuracy deteriorates. In fact, on the one hand, to increase the accuracy of numerical analysis, the number of segments should increase, while on the other hand, this reduces the length of each segment and then violate the $l/r > 8$ condition. To surmount this issue, some NEC versions (e.g., see [21]) benefit from supplementary kernels which enable the designer to accurately model slightly thicker wires with $l/r > 2$. Another factor that affects the modeling accuracy of an IFA is the way its gap source is modeled in NEC. As shown in Figure 3(a), to model the source accurately, the ground plane should be replaced by the antenna image. The advantage of this approach is that it provides a segment, the center of which is placed right on the surface of the ground plane. This segment can then accommodate a gap source exactly at its center. On the contrary, in case not

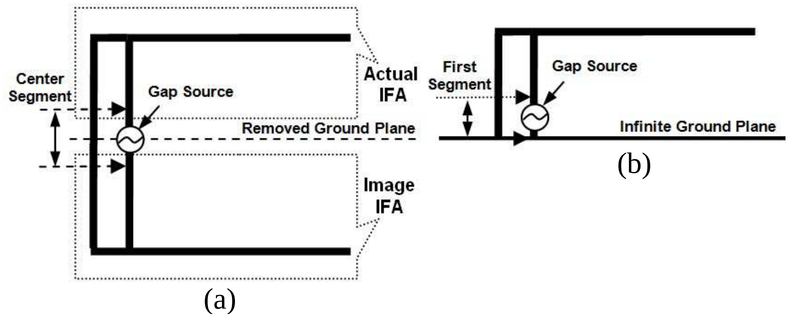


Figure 3. Modeling an IFA in NEC; (a) accurate method, applying the image theory, (b) roughly accurate method, considering infinite ground plane and a source slightly positioned above the ground.

using the image theory, as in Figure 3(b), the gap source has to be placed a little above the surface (off-center) which causes a slight shift (inaccuracy) in resonance frequency. In the case of a conventional thin wire IFA, because r is typically very small, this condition could be ameliorated by reducing the size of the source segment while not having much problem with retaining the l/r. However, in case of a thick wire IFA with a significantly higher r, there will be a tighter restriction, comparatively. It is noted that all simulations presented in this work are based on the image theory, as described in Figure 3(a).

4. A THICK-WIRE IFA DESIGN

Considering the limitations described in Section 3, in this section, a sample IFA is optimized to show wideband characteristics. Only for demonstration of the ability to achieve a wideband design, the design operating frequency is set to be around GSM 900 band. The optimization process has the following features:

Objectives:

- BW $> 25\%$ at 925 MHz.
- $L + S < \lambda/3$ in order to limit the antenna size along Y-axis (Figure 1).
- $H < \lambda/7$ in order to limit the antenna height over ground plane.
- $G_{\max} - G_{\min} < 3$ dBi, where $G_{\max}$ and $G_{\min}$ are maximum and minimum gains in $\theta = 90°$ plane.

To clarify the last objective, it is noted that during the parametric study in Section 2, it is observed that increasing S decreases the total gain over a small angular area around $\varphi = 270°$ (in $\theta = 90°$ plane). This effect, shown in Figure 4, is considered as deterioration of pattern circularity and can be attributed

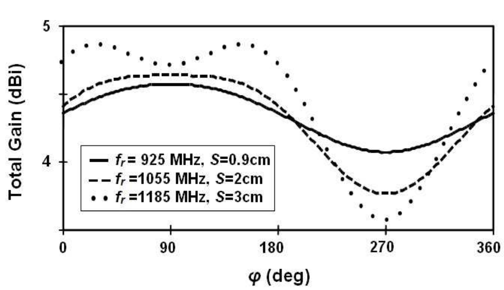


Figure 4. The effect of increasing S on the circularity of the IFA radiation pattern in $\theta = 90°$ plane ($L+S = 6.27$ cm, $H = 3.3$ cm, and $R = 1$ mm); physical parameters are defined in Figure 1.

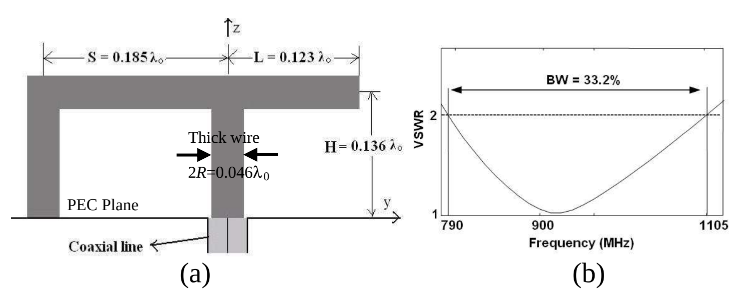


Figure 5. (a) Dimensions of the thick-wire IFA after optimization where $2R = 1.48$ cm, $H = 4.4$ cm, $S = 6$ cm, and $L = 4$ cm, (b) the related VSWR; λ_o is the wavelength at 925 MHz.

to the growing phase difference between the currents along the two parallel vertical wires in Figure 1. The last objective is set to restrict this undesirable effect.

Variables: S, H, and L, where $0.9\,\text{cm} < S < 6\,\text{cm}$, $3\,\text{cm} < H < 5\,\text{cm}$, and $3\,\text{cm} < L < 5\,\text{cm}$.

Constants: R is kept fixed at 7.4 mm, as a moderate value chosen deliberately. In fact, R should increase as much as possible to maximize BW while an excessively increased R can yield inaccuracy in modeling of small segments, as indicated previously.

Algorithm: Because the available NEC version does not offer any built-in optimization algorithm, the two-way software interface between NEC and MATLAB used in [22] is employed. As described in [22], an m-file exports a set of dimensions from MATLAB to NEC, runs NEC to analyze the antenna with the defined dimensions, imports the results back to MATLAB, and analyzes the results for competence (according to objectives). This procedure is repeated until the optimization objectives are fulfilled. The optimization is based on a globally optimal algorithm introduced for template matching in image processing [23].

Results: The dimensions and VSWR of the ensuing IFA design is shown in Figure 5. As seen, the antenna shows VSWR < 2 over 790–1105 MHz (BW $= 33.2\%$). Because this IFA is considerably thicker than a typical IFA [13], it is referred to as thick-wire IFA.

5. APPLYING WIRE GRID MODELING

In Section 4, a wideband thick-wire IFA was designed while there was a limit on its wire thickness, R, due to inherent inaccuracy in analysis of very thick wires. To surmount this problem, a technique called wire grid modeling [16–18, 24] is applied to the structure of the IFA designed in Section 4. This technique transforms the IFA in Figure 5 into a new version composed of wire grids (see Figure 7), referred to as wire grid IFA (WG-IFA). Wire grid modeling is an attractive approach offering the opportunity to model and study EM structures with computationally fast 1D MoM-based numerical codes [19, 22]. Among the previous works, [16] focuses on wire grid modeling for very thick wires with diameter of about $\lambda/4$. Therefore, the results in [16] are applied to the thick-wire IFA in Figure 5. Generally, when modeling a structure with wire grids, it is essential to know which wire radius and also which grid size (spacing between the wires) should be chosen [18]. For the present work, choosing a suitable grid size is equivalent to choosing an appropriate number of parallel wires deployed on the surface area of the thick wire, as described in Figure 6. Studies on wire grid modeling in [16] implies that a thin cylinder, which is in fact a very thick wire ($2R \approx \lambda/10$), can be modeled by 4 to 6 parallel thin wires, and increasing the number of parallel wires has no significant effect on the current characteristic modes. In this study, each thick wire is realized by only four parallel thin wires ($n = 4$) as in Figure 7. Note that to better realize an artificial thick wire, as shown in Figure 6, some cross wires are also added at the bends and the junctions of the WG-IFA. As a result, the structure in Figure 5 will turn into the one shown in Figure 7.

To help choose a proper radius for the thin wires, Ludwig [17] suggests a rule of thumb called the "same surface area". This rule, states that for nearly accurate modeling of a solid surface with wire grids, the surface area of all wires, which are parallel to one linear polarization, should be equal to the surface area of the solid surface. In other words, if the surface area of a thick wire with radius R is to be modeled with n thin wires, the radius of thin wires should be R/n [17, 18]. Accordingly, to find the best

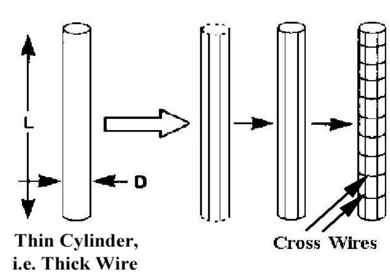


Figure 6. Wire grid modeling of thick wires studied in [16].

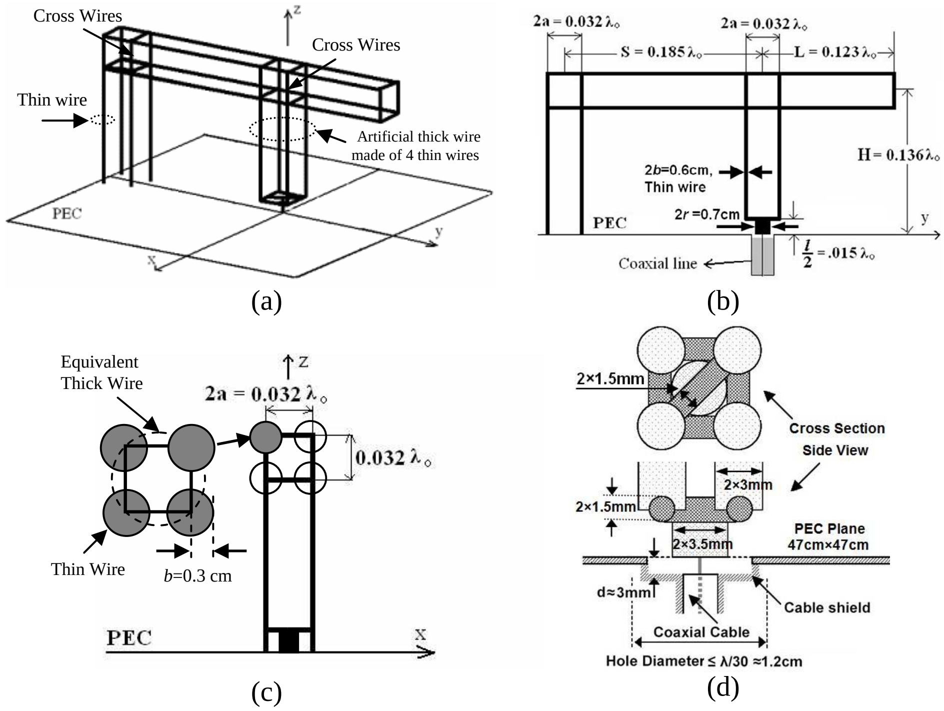


Figure 7. Configuration and dimensions of the WG-IFA; all thin wires have a radius of 3 mm except those located near the source as highlighted in (d); ($2a = 1.04$ cm, $H = 4.4$ cm, $l/2$=0.5 cm, $S = 6$ cm, $L = 4$ cm, and λ_0 is the wavelength at 925 MHz). (a) 3D view. (b) Side view. (c) Cross view. (d) Close-up of the feed section.

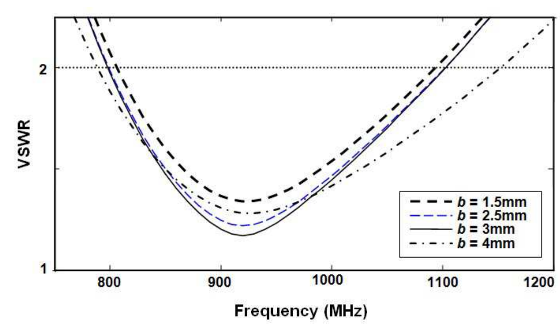
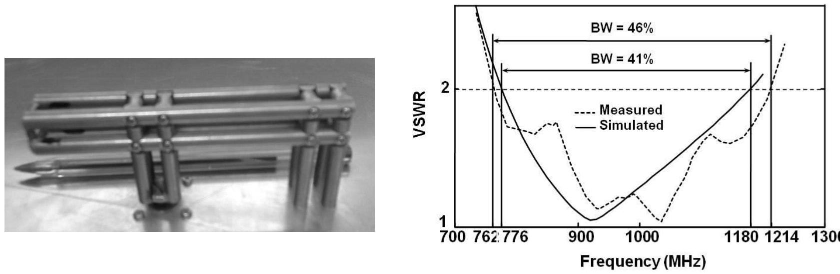


Figure 8. Parametric study on the effect b (see Figure 7) on the impedance bandwidth of the WG-IFA.

radius for the proposed IFA structure, a simple parametric study is arranged which includes Ludwig's suggestion as well. Since n is 4 for the Wire Grid IFA, and also, because the radius of thick wires in Figure 5 is $R = 7.4$ mm, Ludwig's criterion gives $b = 7.4/4 = 1.85$ mm for the radius of thin wires. This radius is regarded as baseline and then b is changed around it from 1.5 to 4 mm while observing the ensuing effects on antenna VSWR. During this parametric study, all the thin wires are considered to have identical radius except the parts shown in Figure 7(d) with the fixed radii of 1.5 mm and 3.5 mm. The 1.5 mm wires are chosen to simplify antenna fabrication, and the 3.5 mm one is chosen to achieve the best accuracy for modeling of the feed.

The outcomes of the parametric study are shown in Figure 8, based on which the radius of thin wires, b, is set to be 3 mm which is 1.6 times more than Ludwig's value. As in Figure 8, this radius yields a BW of 41% over 776–1180 MHz. It is noted that although a larger radius (e.g., $b = 4$ mm) can provide a slightly more BW, it can adversely yield rather thick wires which are more difficult to fabricate in practice. The dimensions of the final WG-IFA are rendered in Figure 7(b) and Figure 7(c). Also, an



(a) (b)

Figure 9. (a) The fabricated WG-IFA as well as (b) its simulated and measured VSWRs.

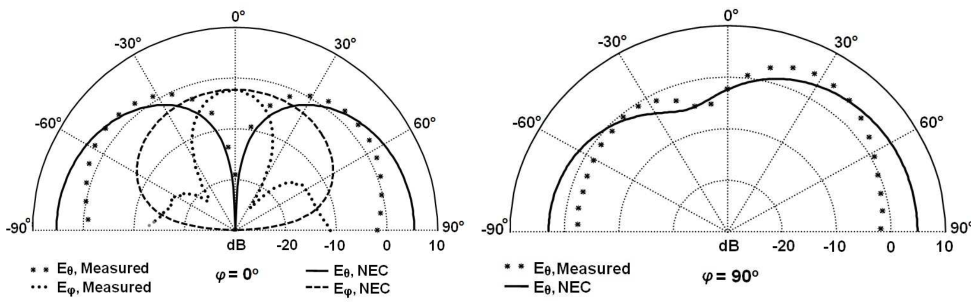


Figure 10. Measured and simulated radiation patterns of the WG-IFA at 925 MHz; simulations are based on infinite ground while the prototype has a finite ground plane ($1.4\lambda \times 1.4\lambda$); patterns are plotted only in the hemisphere above the ground.

enlarged view of the parts around the feed point is shown in Figure 7(d). A prototype corresponding to Figure 7 is fabricated and measured. Figure 9 shows the prototype and its simulated and measured VSWRs and demonstrates a satisfactory agreement between the results. The measured and simulated radiation patterns are also shown in Figure 10. As seen, there are slight differences between the measured and simulated patterns (see E_φ) which stems from the fact that the simulation is based on an infinite ground plane while the fabricated antenna has a finite plane of 47 cm × 47 cm ($1.4\lambda \times 1.4\lambda$). Also, the measured front-to-back ratio is better than 13 dB.

6. CONCLUSION

The paper presents a new inverted-F antenna (IFA) with ultra wideband characteristics developed based on wire grid modeling. The antenna is desirably composed of a number of thin wires while these wires indirectly realize thick arms and result in improving the bandwidth. Taking this strategy, while the structure acts as a thick/broadband wire antenna, the basic antenna constituents are still thin wires, and hence, the antenna can be designed by 1D MoM-based analyzers much faster than rival 3D analyzers. A sample design of this wire grid IFA (WG-IFA) is presented which demonstrates VSWR $< 2:1$ from 776 to 1180 MHz (BW $=$ 41%). The design serves only as an example and, using the described approach, comparable or higher bandwidths in different frequency bands could be achieved. To examine the soundness of modeling and numerical analyses, the WG-IFA was prototyped and successfully experimented. The computationally efficient design methodology proposed for this WG-IFA promises for bandwidth enhancement of similar conventional wire antennas.

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