Radiation Pattern Analysis of Inverted-F Antenna Mounted on the Side Wall of a Long Cylinder

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Abstract- **An analytical technique is proposed for estimation of the radiation pattern of inverted-F antenna (IFA) which is mounted on the side wall of a long cylinder. The method can be applied to describe the IFA radiation in a lot of practical cases. It is indicated that this radiation pattern is a combination of radiation patterns of a horizontal and a vertical small radiator, near the cylinder with a certain proportion. Some discussion is presented about this proportion and analytical results are compared with the simulations. Also the proportion is formulated in terms of antenna dimensions using a GA optimization. Finally a typical applicable IFA with smooth radiation pattern is fabricated and its radiation pattern is measured to verify the proposed method. The proposed method can help the designer to estimate the radiation pattern of IFA antenna that mounted on a big cylinder quickly before the simulation.**

Index Terms- Inverted-F Antenna; Long Cylinder; Scattering; Radiation Pattern

I. INTRODUCTION

The inverted-F antenna is a desired and commonly used structure in aerial applications, due to its reduced size (especially low height), robust structure and being DC-grounded inherently and the strength in structure. This antenna has a lot of current applications in compact devices [1]-[4] and mobile communications [5]-[6] and the investigation on the antenna mounting on cylinders can be an important and applicable concept. According to Fig.1, this antenna includes three sections and is mainly vertical polarized.

King analysed the inverted-F antenna as a transmission line and calculated its current distribution, radiation pattern and radiation resistance [7]. Prasad performed an experimental parametric study on the inverted-F impedance [8]. In addition, Loizou described a transmission line model to analyse the capacitive loaded IFA [9]. Huynh discussed the planar inverted-F antenna with a finite ground plane. He indicated that the radiation pattern has a null in boresight with different depth for various ground plane dimensions without focusing on this matter [10].

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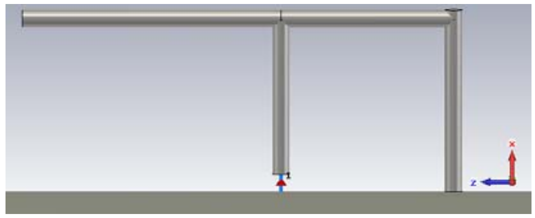


Fig.1. Inverted-F antenna structure

Niamien expressed the PIFA characteristics as the sum of two contributions: one from the vertical part (short-circuit) and the other from the horizontal part (slot) [11]. Kim simulated an array of inverted-F antennas on a PEC cylinder body and analysed the omni-directionality of the radiation pattern statistically [12]. Also some parametric studies on the planar inverted-F antenna are available in [13]-[16] and more comprehensively in [17].

Carter calculated scattering effects of an infinite conducting cylinder on the pattern of a small radiator using wave equations and the principle of reciprocity [17]. He presented multiple closed form formulas for various conditions of the antenna and cylinder standing. The results of his works are frequently applied as the basis for the analytical works. Complicated numerical calculations in [17] have been simplified by introducing a table in [18]. Lucke used the Green's function to calculate the antenna radiation pattern near circular and elliptical cylinder for some configurations [19]. Sinclair extended the Carter method for the antennas located near cylinders of elliptical cross section [20]. Moullin has related the results in his book [21]. Also, similar problems have been considered in [22-24].

A radial dipole mounted on a cylindrical wedge region is studied by Wait. He compared theoretical and experimental radiation patterns in the principal plane [25]. Kuehl derived the radiation pattern of a radial dipole near the cylinder in an asymmetrical configuration using the currents on the cylinder surface excited by dipole [26]. Goldhrish determined the antenna radiation pattern in the immediate vicinity of cylinder by a theoretical-numerical technique [27]. Also a moment method analysis on the antenna pattern on the bodies with an arbitrary cross section has been performed in [28]. In addition, in [29], a theoretical-numerical technique based on integral equation, has been applied for the determination of radiation pattern of vertical quarter-wavelength monopoles on various geometries of airborne bodies using the induced surface current on the body.

When the inverted-F antenna lies on the side wall of the conducting cylinder, the major radiated field polarization will be linear in the cylinder direction. The radiation pattern has a null in boresight. The null depth is dependent on vertical and horizontal dimensions of antenna. However, it is actually dependent on the proportion of contributions of vertical part and horizontal part of the antenna structure in the radiation.

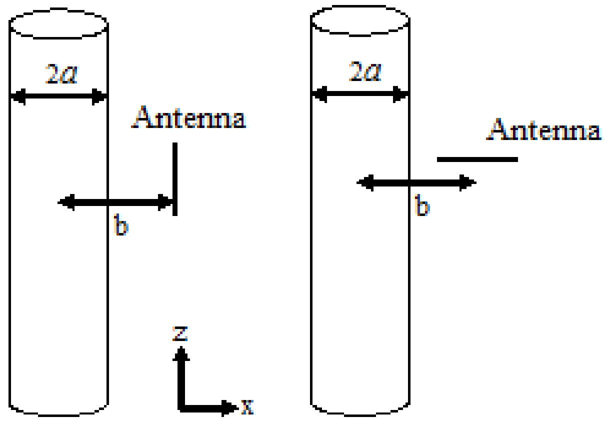


Fig. 2. Small radiator. (a) parallel with the cylinder, (b) perpendicular to the cylinder axis

In this paper, after division of the antenna structure to vertical and horizontal parts and analysed separately, the radiation pattern of the antenna on the side wall of the long cylinder is calculated. Subsequently, the proportion of pattern combination is discussed. Finally, to verify the analysis method, a sample has been realized. The calculated radiation pattern shows good agreement with the measurement.

It needs to be stated that most of the works reported in the literature has divided the antenna pattern into two parts and have estimated the radiation pattern of the inverted-F antenna mounted on a big cylinder based on scattering equations and formulized the antenna radiation pattern with respect to antenna dimensions.

II. The Inverted-F Antenna MOUNTED on the Side Wall of a Conducting Cylinder

The antenna structure consists of two sections that would be analyzed separately. Radiation equations of each section is calculated using scattering analysis and the principle of reciprocity [18] and the Green's function [20].

A. A small radiator near a long conducting cylinder

1. Antenna mounted parallel with the cylinder

Based on the conditions shown in *Fig. 2(a)*, that the antenna is mounted along the *z* direction parallel to the cylinder axis, distanced *b* from cylinder axis along the *x* direction and with the cylinder radius being *a*, Carter calculated the radiated field, solving the wave equation with the relevant boundary conditions and assumed that the antenna is small [18]:

$$E_{\theta} = \sin\theta \sum_{n=0}^{\infty} \varepsilon_n (j)^n \left\{ J_n(kb\sin\theta) - \frac{J_n(ka\sin\theta)}{H_n(ka\sin\theta)} H_n(kb\sin\theta) \right\} \cos n\varphi \tag{1}$$

Also, Lucke calculated the radiated field, using the Green's function of the structure [20]:

$$E_\theta = \sin\theta \sum_{n=-\infty}^{\infty} \exp\left\{ jn(\varphi - \frac{\pi}{2})[J_n(kb\sin\theta) - \frac{J_n(ka\sin\theta)}{H_n(ka\sin\theta)} H_n(kb\sin\theta)] \right\} \tag{2}$$

2. *Antenna mounted perpendicular to the cylinder axis*

For the condition shown in *Fig. 2(b)*, Carter presented the formula [18]:

$$E_\theta = j\cos\theta \sum_{n=0}^{\infty} \varepsilon_n (j)^n \left\{ J'_n(kb\sin\theta) - \frac{J_n(ka\sin\theta)}{H_n(ka\sin\theta)} H'_n(kb\sin\theta) \right\} \cos n\varphi \tag{3}$$

B. Inverted-F antenna

To calculate the inverted-F antenna pattern on the cylindrical ground plane, we assume the antenna as a composition of a small vertical and a small horizontal radiator. So, the radiated field can be written as:

$$E_{total} = E_{ver} + K\, E_{hor} \tag{4}$$

In which E_{ver} is the field radiated by the vertical element with length L (Eq.(3)), and E_{hor} is the field radiated by the horizontal element with length S (Eq. (1) and (2)). The K factor is an appropriate proportion of the composition.

The K factor is a function of antenna dimensions. For small L and S (typically between λ/20 and λ/4), and large cylinder radius (typically greater than λ to several wavelengths), the analytical method has a good precision and the K factor is dependent on L/S and L mainly. This parameter is extracted by matching calculated and exactly simulated radiation patterns. In the last section of this paper, we will derive a formula for it. *Table I* presents the appropriate K, null depth, maximum of gain and efficiencies, for various antenna dimensions, when the radius of cylinder is λ. The appropriate K has been determined by matching the results of analytical technique with accurate full wave simulation. Also Fig. 3 shows some samples of inverted-F radiation patterns that have been calculated analytically and simulated using CST Microwave Studio package.

Fig. 4 shows a simple comparison to describe the effect of S2/S1 value. As the S2/S1, L, L/S or S1/L is reduced the K factor and null depth will be reduced. The cylinder radius in all simulations is λ. Fig. 5 illustrates the influence of cylinder radius on the pattern. It is shown that for radius greater than λ, to several λs, the radiation pattern would not be changed prominently and we can ignore this parameter in the K factor calculations.

Table I. Appropriate *K*, null depth, maximum of gain and efficiencies, for various antenna dimensions (the radius of cylinder is λ).

S1(λ)	S2(λ)	S(λ)	L(λ)	Appropriate *K* factor	Null depth (dB)	Max. Gain (dBi)	Radiation Efficiency (%)
0.05	0.05	0.1	0.15	6.25	18	5.6	99.7
0.1	0.1	0.2	0.15	4.3	14.5	5.6	99.75
0.15	0.15	0.3	0.15	2.56	10.6	5.77	99.9
0.05	0.1	0.15	0.15	4.4	15	6.03	99.6
0.1	0.05	0.15	0.15	6.2	17.5	6.69	99.7
0.05	0.15	0.2	0.15	2.8	10.8	7.74	100
0.1	0.15	0.25	0.15	2.8	10.7	5.96	99.9
0.1	0.2	0.3	0.15	1.68	6.5	5.71	99.9
0.15	0.1	0.25	0.15	4.5	14.7	4.79	99.8
0.15	0.2	0.35	0.15	1.6	6.2	5.53	99.9
0.2	0.05	0.25	0.15	8.2	20	5.3	99.6
0.2	0.1	0.3	0.15	4.9	15.4	5.26	99.8
0.2	0.15	0.35	0.15	2.75	10.6	5.24	99.9
0.05	0.05	0.1	0.1	1.85	10	5.96	99.8
0.05	0.1	0.15	0.1	1.73	9.5	5.56	100
0.05	0.15	0.2	0.1	1.37	7.5	5.31	99.5
0.05	0.3	0.35	0.1	0.5	4	5.04	98.2
0.1	0.05	0.15	0.1	1.8	9.9	5.62	99.9
0.1	0.1	0.2	0.1	1.65	9	5.47	99.9
0.1	0.15	0.25	0.1	1.33	7.2	5.25	99.6
0.1	0.2	0.3	0.1	1.02	5	5.21	100
0.1	0.25	0.35	0.1	0.73	3.8	4.79	100
0.15	0.05	0.2	0.1	1.85	10	5.35	99.9
0.15	0.1	0.25	0.1	1.63	8.9	5.2	99.8
0.15	0.15	0.3	0.1	1.3	7	5.03	99.7
0.2	0.05	0.25	0.1	0.94	4.4	4.76	100
0.2	0.15	0.35	0.1	1.28	6.8	4.66	99.7
0.05	0.05	0.1	0.05	0.49	4.3	5.04	99.2
0.1	0.1	0.2	0.05	0.5	4.5	4.7	99.7
0.15	0.15	0.3	0.05	0.47	3.9	4.25	99.8
0.05	0.25	0.3	0.05	0.38	2.5	4.52	100
0.02	0.28	0.3	0.05	0.32	2	4.29	100
0	0.3	0.3	0.05	0.23	3	5.22	99.4

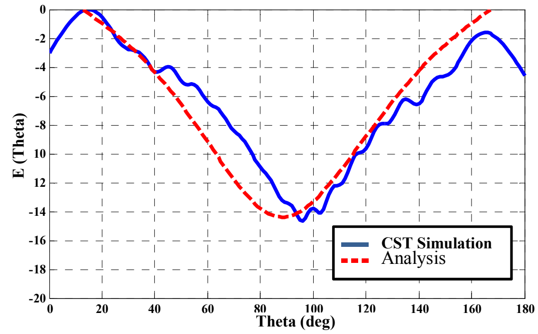
III. Estimation of the Proportion of Combination

We can estimate the proportion of the combination with this equation:

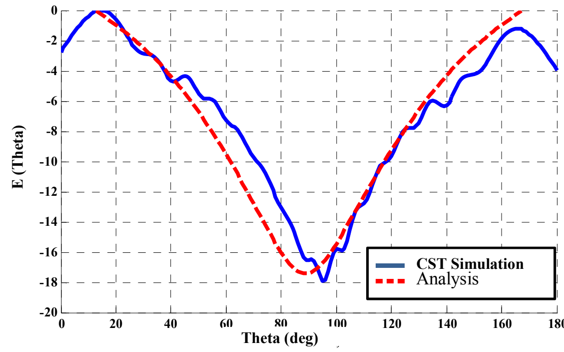
$$K = X(1)\left(\frac{S_1}{L}\right)^{X(2)} \times \left(\frac{L}{S}\right)^{X(3)} \times \left(X(4)\left(\frac{S_2}{S_1}\right)^{X(5)} + X(6)(L)^{X(7)}\right) \tag{5}$$

For X= [144.64 1.633 2.235 0.0188 1.344 20.125 2.877]

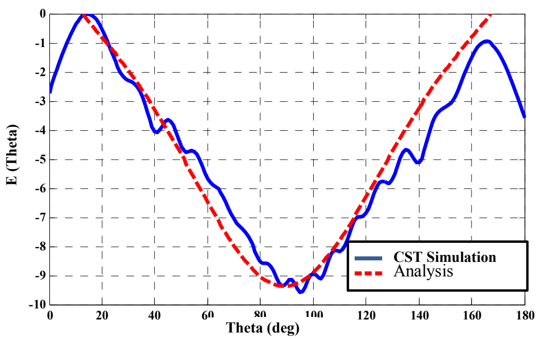
To obtain the formula, several phrases with unknown parameters are assumed as the formula draft, and this structure selected finally. The X parameters are unknown and we have several samples that construct the S1, S2, S, L and K matrixes.



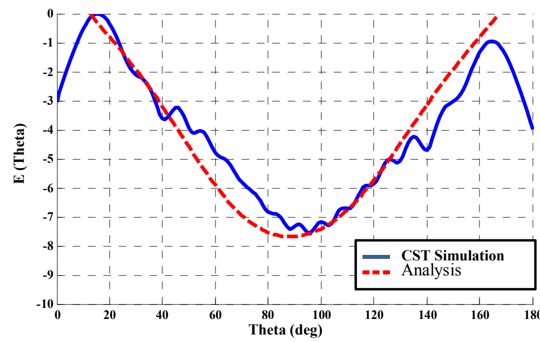
L=0.15λ, S1=S2=0.1λ (K=4.3)



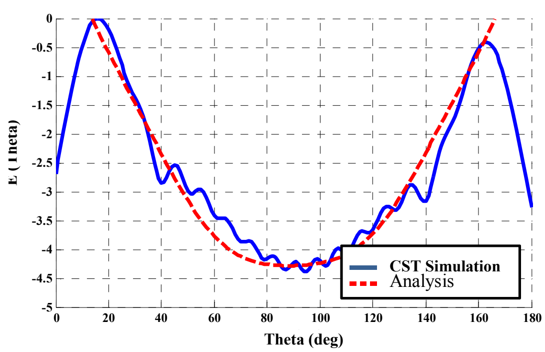
L=0.15λ, S1=S2=0.05λ (K=6.25)



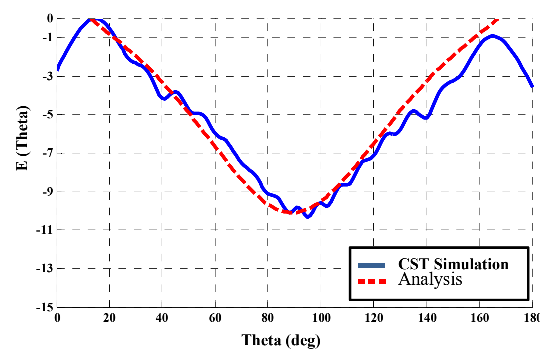
L=0.1λ, S1=0.05λ, S2=0.1λ (K=1.73)



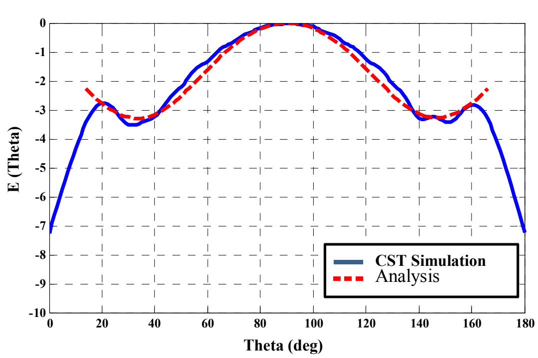
L=0.1λ, S1=0.05λ, S2=0.15λ (K=1.37)



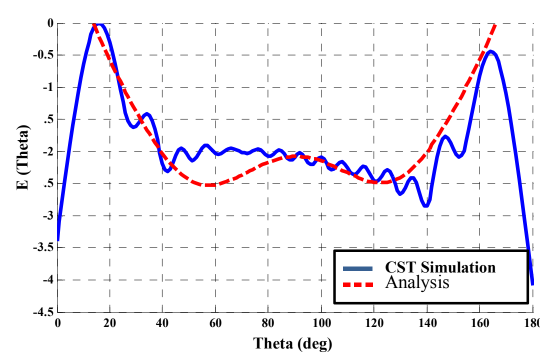
L=0.05λ, S1=S2=0.05λ (K=0.49)



L=0.1, S1=S2=0.05λ (K=1.85)



L=0.05λ, S1=0.0, S2=0.3λ (K=0.23)



L=0.05λ, S1=0.05λ, S2=0.25λ (K=0.38)

Fig. 3. Some samples of inverted-F radiation patterns on cylindrical ground plane

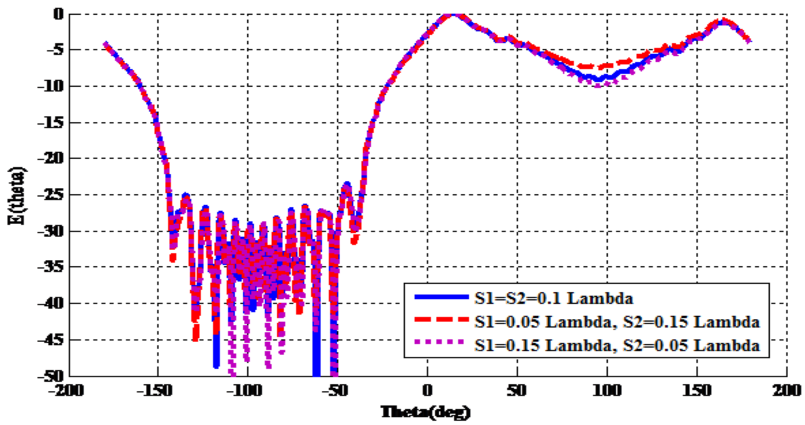


Fig. 4. Inverted-F Antenna Pattern on the Side Wall of Cylinder (a = 1, L = 0.1).

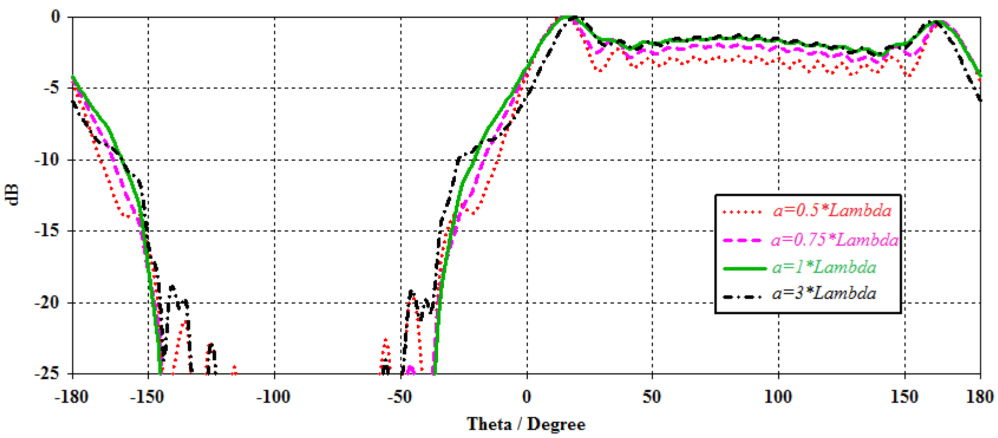


Fig. 5. Inverted-F Antenna Pattern on the side wall of cylinder for various radius a.

We should optimize the X parameters so that the formulated K has a minimized error with the actual K extracted from the accommodation of simulation and calculation in all samples. This optimization is performed using genetic algorithm with Matlab GA tools. The error of the formulated K was minimized as the fitness function and the best X parameters were obtained. The equation draft was changed frequently to obtain the optimum formula.

When the assumed concept is correct, the K expression precision will be good. The formula precision for 42 samples is shown in Fig. 6. The solid graph is the K calculated for the best adaptation in radiation pattern between simulation and analytical technique for any sample. The dashed graph shows the K calculated via the formula. For these 42 samples, the mean square of error of the equation (5) is 0.2346.

IV. Realization and Confirmation

We can synthesis any radiation pattern, using the presented technique. To confirm the simulation and analytical results, an antenna has been realized and measured. We choose a sample with smooth

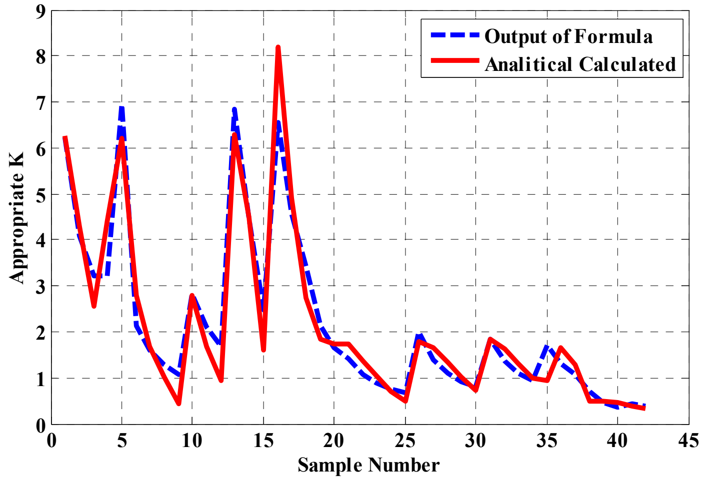
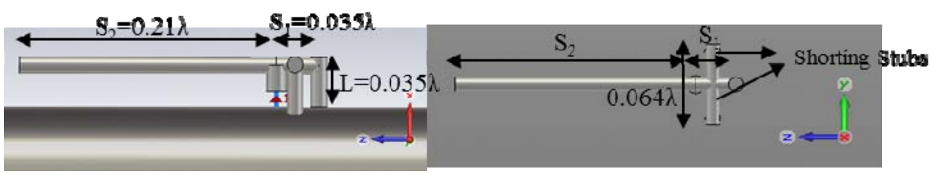


Fig. 6. Several samples of proportion values.

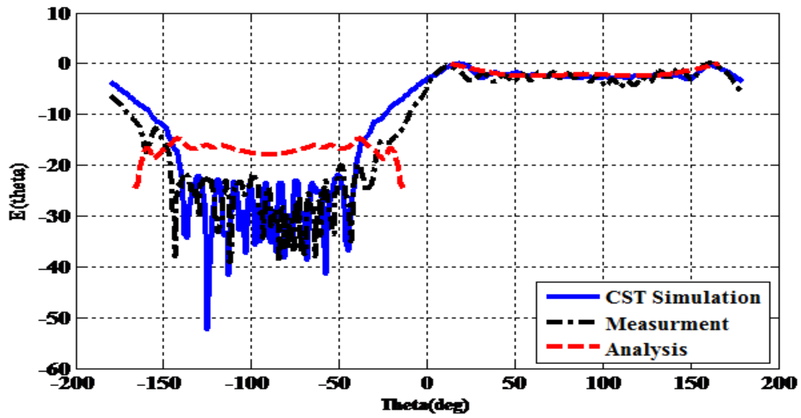


(a)

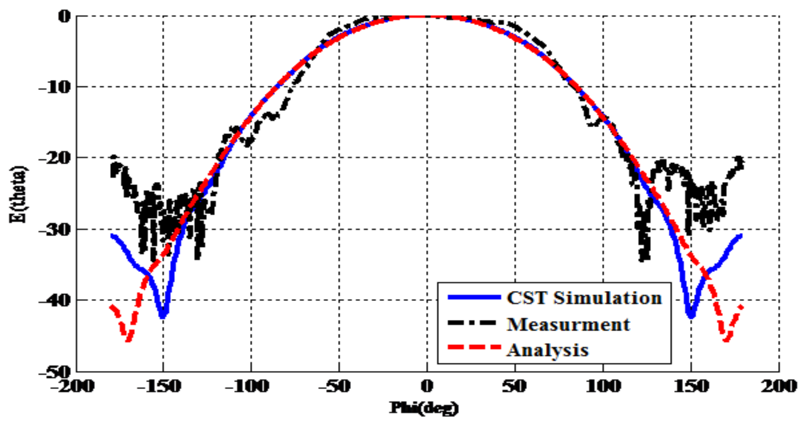
(b)

Fig.7. (a) The Schematic of Realized Antenna, (b) Realized Structure.

radiation pattern, which has many applications. The antenna, setup structure and dimensions are shown in Fig. 7. The resonance occurred at 4 GHz. As illustrated in figure, to match the antenna impedance, two simple shorting stubs are used. These stubs have no influence on the radiation pattern



a



b

Fig. 8 .The Radiation Pattern of the Realized Antenna. (a) φ=0° plane, (b) φ=90° plane

in φ=0° and 90° planes. This matching technique has been used previously in [31]-[32]. The antenna radiation pattern is showed in Fig. 8. It can be seen that, the analysed, simulated and measured radiation patterns have a good adaption. It is clear that, the calculated patterns have no precision in shadow zone (behind of the cylinder), since the analytical method was based on the scattering equations.

It should be noted that the simulation has been performed on a cylinder with radius λ and height 10λ, while the structure is big, the antenna is very small and it leads to a coarse meshing. The elapsed time of full wave simulation in CST package is 1 hour approximately. But the radiation pattern estimation based on the present method takes only a few seconds.

V. Conclusion

The radiation pattern of inverted-F antenna (IFA) mounted on the side wall of a long cylinder has been analysed using a simple method. The antenna was divided to two sections: vertical and horizontal. It is explained that the antenna radiation pattern is a combination of a horizontal and a vertical small radiator patterns with a certain proportion. An equation for this proportion was presented and its accuracy was evaluated. The equation mean square error does not exceed 0.25 for typical antenna and cylinder dimensions. The proposed method can estimate the radiation pattern of IFA antenna that is mounted on a big cylinder without the need for simulation. The structure has very small and very big segments simultanousely. Consequently, the simulation with commercial software is involved with a lot of heavy calculations, and in such a case, the required simulation time will be large. Using this analysis and formula, we can design any desired radiation pattern. To verify the method, a sample with smooth radiation pattern with 4dB ripple is realized and tested successfully. The analysis has a good reliability for small L and S (typically between λ/20 and λ/4), and large cylinder radius (typically greater than λ to several wavelengths).

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