Multi-port Network Modeling for Fractal Shape Microstrip Antenna

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Abstract

In this paper we demonstrate the use of multi-port network modeling to analyze one such antenna with fractal shaped parts. Based on simulation and experimental studies, it has been demonstrated that the model can accurately predict the input characteristics of antennas with Minkowski geometry replacing a side of a microstrip square ring.

Keywords: Microstrip, EM coupling, MNM, Green's functions

1. Introduction

Many wireless applications require the design of multi-frequency mobile terminals and components. For such low-profile and portable communication systems, the size of the antenna with multi-frequency operation is critical. Modified microstrip antennas are widely used in these systems due to its important characteristics, such as compact size, light weigh, low cost, mechanical robustness, easy manufacturability, and simplicity of integration with RF devices [1]. Several miniaturization techniques applied to microstrip antennas have been studied extensively.

Fractal designs have stimulated significant research interest lately in antenna engineering, mainly to exploit their two main features-- self-similarity (which means that some of its parts have the same shape as the whole object, but on a different scale) and space filling properties. These are expected to result in smaller antennas with dual-band and multi-band characteristics. Several fractal antennas with microstrip configurations have been proposed. For example, the antenna geometries proposed in [2-3] have a ring geometry electromagnetically coupled to the feed transmission line. The space filling properties of the fractal geometry increases the electrical length of the ring but reduces the overall antenna size. With the proper choice of orientation, these geometries can be used to realize dual frequency antennas with similar radiation patterns at both resonant frequencies. However, most of the analysis approaches used in the context of fractal dipole and monopole antennas can not be used for such geometries which have a ground plane beneath the dielectric support.

In this work, we propose the use of Coplanar Multiport Network Model (MNM) with segmentation approach for the analysis of such antennas with fractal shaped parts. This method is a generalization of cavity model, which is suitable for irregular geometries [4]. The fractal antenna is decomposed into regular elemental segments for which the Green's functions are available to develop the Multi-port network models of each segment and then synthesize each segments to reconstruct original fractal shaped antenna structure. This segmentation approach and microstrip antenna analysis was first introduced in [5] to determine the input impedance of the microstrip antenna structures of composite geometric forms.

2. Antenna Design

In this paper, a dual-band microstrip fractal antenna is designed and analyzed using multi-port network modeling (MNM) with segmentation approach. The antenna is fabricated on a two layer dielectric structure (Figure 1), in which a ring type microstrip radiator is placed on the top layer, where as the feed microstrip transmission line is placed in layer beneath the radiating patch.

We used dielectric materials with relative dielectric constant of 2.5 (Arlon), loss tangent of 0.0023, and thickness of 1.56 mm.

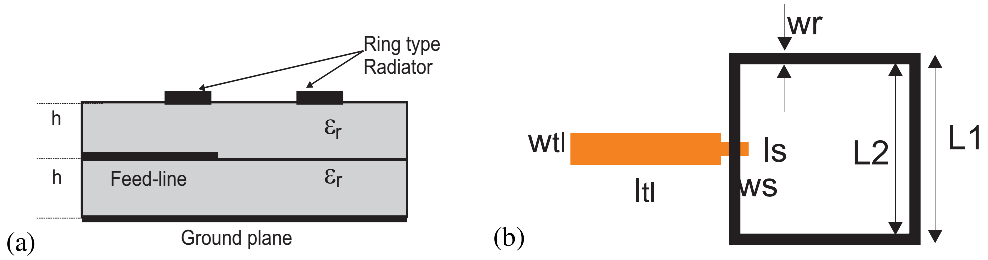

Figure 1: (a) Cross section and (b) Top view of the proposed antenna

In this design, the microstrip ring radiator has one of its arms replaced by fractal Minkowski geometries of the first and second iterations. This geometry has dual-band characteristics and the radiation patterns at both resonances are similar. With the use of fractal structure, this antenna can be designed for a desired pair of resonant frequencies with reasonable bandwidth and good gain at both the resonant frequencies.

The construction of radiating patch, which is excited by microstrip transmission line feed is explained in Figure 1. Here L1 = 23.7 mm (outer length of the ring) and L2 = 21.7 mm (inner length of the ring), only when width of the ring = 1mm [2]. From the parametric studies, it has been observed that, by changing the indentation depth, a desired pair of resonant frequencies can be chosen as per the applications.

3. Modeling Approach

The proposed multi-port network model (MNM) is the generalization of cavity model, which is suitable for irregular geometries [4]. In this approach, the fractal antenna is decomposed into regular elemental segments for which the Green's functions are available as shown in Figure 2. Multi-port Network Models of each segment is then developed and synthesized to reconstruct original fractal antenna structure [4-5]. This segmentation approach for microstrip antenna analysis was first introduced in [5] to determine the input impedance of antennas with composite geometric forms. The geometry with the first iteration Minkowski curve is segmented into eight segments of regular shape (Figure 2). This has sixteen interconnecting port sets and port 3 is input feed port of the antenna.

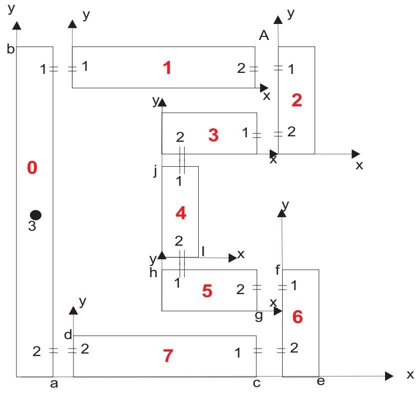

Figure 2: Segmentation of square ring microstrip antenna with one side replaced by 1^{st} iteration fractal geometry.

As there are eight segments, there will be nine equations for terminal voltages. These nine equations can be reduced to an equivalent set of one equation by using boundary conditions. The resulting matrix equations are then solved to obtain the input impedance of the microstrip fractal ring antenna. The methods of cojoining all the elemental segments to obtain the final structure and the formulas of the self-impedances and mutual impedances or coupling impedances of the individual elemental segments have been proposed in [6, 7]. The electrical size of the every segment is obtained by increasing delta (outward extension due to fringing of the segment) in the physical size of the segment and the total quality factor obtained from experimental/simulated return loss characteristic. For example, the geometry in Figure 2 has Q1 = 106.5 and Q2 = 80.65 at its first and second resonant frequencies respectively. Here each segment is assigned by two end ports (i.e. 1 = i and 2 = j). The voltage, current and impedance at port 1 of segment number 1 can be written as V_{1_1}, I_{1_1} and Z_{1_1} respectively. Thus the voltage and current equations of the above Figure 2 can be written in general form as:

$$V_{n_1} = Z_{n_{11}} I_{n_1} + Z_{n_{12}} I_{n_2}$$

$$V_{n_2} = Z_{n_{22}} I_{n_2} + Z_{n_{21}} I_{n_1}$$

Where n = 1 to 7 representing segment numbers, as shown in the above figure. Subscripts 1 and 2 in the above expressions denote interconnected port numbers of the corresponding segment.

The voltage and current equations of the segment (n = 0) containing excitation port 3 is:

$$V_{0_1} = Z_{0_{11}} I_{0_1} + Z_{0_{12}} I_{0_2} + Z_{0_{13}} I_{0_3}$$

$$V_{0_2} = Z_{0_{22}} I_{0_2} + Z_{0_{21}} I_{0_1} + Z_{0_{23}} I_{0_3}$$

$$V_{0_3} = Z_{0_{33}} I_{0_3} + Z_{0_{31}} I_{0_1} + Z_{0_{32}} I_{0_2}$$

We can define the boundary condition at point ‘A’ of 1st and 2nd segment of the Figure 2 as:

$$V_{1_2} = V_{2_1} \Rightarrow I_{1_2} = -I_{2_1}$$

Hence, for n = 1 to 6 this could be summarized as:

$$V_{n_2} = V_{(n+1)_1} \Rightarrow I_{n_2} = -I_{(n+1)_1}$$

For the 0th segment (n = 0), the boundary condition is

$$V_{n_1} = V_{(n+1)_1} \Rightarrow I_{n1} = -I_{(n+1)_1}$$

By applying the boundary conditions, the voltage and current equations are solved; we obtain the final expression for the input impedance of the microstrip fractal ring antenna with first iteration (Design-1) as

$$Z_{in\_radiator} = \frac{V_{0_3}}{I_{0_3}} = Z_{0_{33}} - A Z_{m2}^{-1} A^T$$

Where

$$A = \begin{bmatrix} Z_{0_{31}} & Z_{0_{32}} \end{bmatrix}$$

By using the symmetry of the segments we obtain the sub matrices Z_m as:

$$Z_{m2} = \begin{bmatrix} Z_{0_{11}} + Z_{1_{11}} & Z_{0_{12}} \\ Z_{0_{12}} & Z_{0_{11}} + Z_{1_{11}} \end{bmatrix} - \begin{bmatrix} Z_{1_{12}} & 0 \\ 0 & Z_{1_{12}} \end{bmatrix} [Z_{m1}]^{-1} \begin{bmatrix} Z_{1_{12}} & 0 \\ 0 & Z_{1_{12}} \end{bmatrix}$$

$$Z_{m1} = \begin{bmatrix} Z_{1_{11}} + Z_{2_{11}} & 0 \\ 0 & Z_{1_{11}} + Z_{2_{11}} \end{bmatrix} - \begin{bmatrix} Z_{2_{12}} & 0 \\ 0 & Z_{2_{12}} \end{bmatrix} [Z_{m0}]^{-1} \begin{bmatrix} Z_{2_{12}} & 0 \\ 0 & Z_{2_{12}} \end{bmatrix}$$

$$Z_{m0} = \begin{bmatrix} Z_{2_{11}} + Z_{3_{11}} & 0 \\ 0 & Z_{2_{11}} + Z_{3_{11}} \end{bmatrix} -$$

$$\begin{bmatrix} Z_{3_{12}} & 0 \\ 0 & Z_{3_{12}} \end{bmatrix} \begin{bmatrix} Z_{3_{22}} + Z_{4_{11}} & Z_{4_{12}} \\ Z_{4_{12}} & Z_{3_{22}} + Z_{4_{11}} \end{bmatrix}^{-1} \begin{bmatrix} Z_{3_{12}} & 0 \\ 0 & Z_{3_{12}} \end{bmatrix}$$

The input impedance of the microstrip fractal ring antenna appears in series with the coupling impedance generated by microstrip transmission line feed located beneath the radiating patch. The amount of coupling capacitor can be calculated from the dimensions of the coupling strip and the coupling coefficient to give critical electromagnetic coupling to the radiator. Based on this, one can obtain a coupling coefficient of $g_1 = 0.0211$ and $g_2 = 0.0290$ at the first and second resonant frequencies respectively. This approach is also applied to analyze the antenna geometry with second iteration fractal geometry (Design-2). In this case, n = 27 as there is an increased number of segments. There are twenty nine basic matrix equations for voltages. By cojoining the various pair of port voltages by using boundary conditions at the every pair of ports of the elemental segments, the twenty nine equations are solved and reduced to a single resultant matrix equation, in which each element in the resultant matrix equation is appear in the form of sub-matrices. Furthermore one can make use of the fractal self-similarity properties to avoid several duplicate calculations.

4. Validation

The photograph of the prototype antennas fabricated with the physical dimensions of 1mm ring width and the length of the initiator = 21.7 mm. and the indentation depth calculation factor (k) = 1, excited through electromagnetic coupling and the corresponding return loss characteristics are shown in Figure 3. These results indicate that multi-port network model can be used to accurately predict the input characteristics of microstrip patch antennas with irregular fractal geometry parts. One can make use of self-similarity properties to avoid several duplicate calculations.

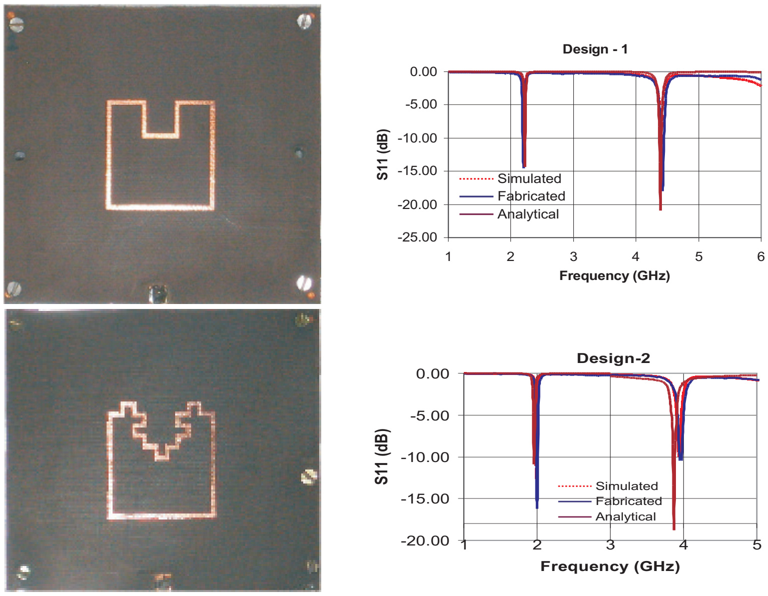

Figure 3: Photographs of fabricated antennas and Comparison of S11

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