Dual-Frequency Probe-Fed Rectangular Microstrip Antenna Design Using a Fuzzy Approach

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Abstract: -Dual frequency operation of antennas has become a necessity for many applications in wireless communication systems such as GPS, GSM services operating at two different frequency bands and services of PCS and IMT-2000 applications. Although there are various techniques to achieve dual-band operation from various types of microstrip antennas, there is no efficient design tool that has been incorporated with a suitable optimization algorithm. In this paper the cavity-model based simulation tool along with an intelligent fuzzy system is presented for the design of dual-band microstrip antennas, using multiple shorting strips placed between the patch and ground plane. Since this approach is based on cavity model, the multiport approach is efficiently employed to analyze the effects of the shorting strips on the input impedance. Then the optimization of the positions of shorting strips is performed via an intelligent fuzzy system, to achieve an acceptable antenna operation over the desired frequency bands. The antennas designed by this efficient design procedure were realized experimentally, and the results are compared. In addition, these results are also compared to the results obtained by the commercial electromagnetic simulation tool, FEM-based software HFSS by ANSOFT.

Key Words: - Fuzzy systems, microstrip antenna, multiple band antennas, multiport circuits, soft computing

1 Introduction

Recent advances in wireless communication systems, such as GSM and DCS in Europe, PCS in America wireless local area networks (WLAN), wireless local loops (WLL), broadband 3G systems and etc., have instigated flurry of interest in microstrip antennas. This is mainly due to the unique features of microstrip antennas; which are namely, low in profile, compact in structure, light in weight, conformable to nonplanar surfaces, easy and inexpensive for mass production, and well suited for integration with feeding networks and microwave devices, especially with the modern monolithic microwave integrated circuits technology. In addition, from the applications point of view, the microstrip antennas can be designed to perform any function that other antenna structures can perform, such as, circularly polarized radiation, multiband operations, etc. Since most wireless communications systems co-exist in the same geographic area, one handset needs to cover some of these services, which requires multimode or at least dual-mode operation. Therefore, it is of paramount importance to device a computationally efficient approach to design dual or multiband microstrip antennas that also satisfy other specifications like input voltage standing wave ratio (VSWR) over each band. In this paper, an efficient systematic approach based on cavity model and a fuzzy intelligent algorithm is developed to design multiband microstrip antennas with shorting strips.

Recent studies on microstrip antennas have primarily concentrated on the improvement of bandwidth and on the design of multifunction operations [1]-[9]. Along with this revised interest on the applications of microstrip antennas, development of efficient and accurate simulation tools to help analyze and design such antennas has gained some interest as well. For the simulation of printed antennas, there have been three major approaches, namely, the transmission line model, the cavity model and the full-wave techniques, ordered according to increasing accuracy [10]. Among these, the cavity model has a special place for providing physical intuition on the electrical characteristics and radiation mechanisms of microstrip antennas, in addition to better accuracy as compared to the transmission line model, and better computational efficiency as compared to full-wave approaches [11]-[13]. Therefore the cavity model is often used to design the first trial antenna, and then the fine tuning is performed with a full-wave approach, like HFSS by ANSOFT. Since the cavity model is numerically quite efficient and capable of handling variety of microstrip antennas with shorting pins, when it is coupled with a suitable intelligent optimization system, the combination would be a very efficient and effective design tool, at least during the initial phase of the design. During this study, a fuzzy system was chosen as the suitable intelligent tool that would be coupled with the cavity model. The idea of using a single patch in dual-frequency operation was first proposed and developed by Derneryd, where a singe disc-shaped patch was connected to a complex impedance matching network, resulting in two narrowly spaced frequency bands. Since then, a variety of single patch, dual-band microstrip antennas have been proposed and designed, some of which use patches loaded with shorting pins[16]-[18], some others use patches with slots [19]-[22], and patches with more than one port [6]-[8]. In addition, there are some other approaches to achieve the dual band operation: triangular microstrip antenna with a V-shaped slot loading [23]; circular microstrip antenna with an open-ring slot [24]; and drum shaped patches [26]; stacked quarter wavelength rectangular patch elements [25] are just a few of these examples available in the literature. Considering that microstrip antennas are resonant structures and can resonate at many discrete frequencies, they are bound to operate more than one frequency by nature. However, the dual-frequency operation with just a single patch antenna is mostly useful if the antenna over both frequency bands of interest has similar radiation patterns, polarization and input impedance characteristics. Therefore, in the design of dual-band microstrip antennas, one needs to decide on the useful modes of resonance satisfying these constraints. For example, if an antenna is to be designed for linear polarization for the same direction over both frequency bands, then the two lowest useful modes of resonance are (0,1) and (0,3) modes according to the cavity model. Furthermore, since the frequencies associated with these modes are fixed (the ratio of the frequencies of the modes is 3), they need to be turned according to the specification of the required bands of frequencies. In this respect, shorting pins (or strips) located between the patch and the ground plane and slots in the patch geometry play very important roles in turning the modal frequencies to the desired frequencies. By properly placing the shorting pins under the patch, the ratio of the frequencies corresponding to the lowest useful cavity modes, namely (0,1) and (0,3), can be adjusted to any value less than 3. Note that a shorting pin placed at the nodal lines of (0,3) mode does not affect the resonance frequency of (0,3) mode significantly, but increases the resonant frequency of (0,1) mode, by forcing the electric field to be zero at the position of the shorting pins as seen in fig. 1. Brief review of the cavity model in conjunction with the multiport analysis for microstrip antenna with shorting strips is provided in section 2. Then, the design process of microstrip antennas with strips via the fuzzy system is discussed in section 3, where some examples and discussions on the proposed method for the design of multifrequency antennas are also included. In addition, the electrical characteristics of the designed antennas, as obtained by the multiport analysis, are compared to those obtained experimentally and to those obtained by the full-wave method, HFSS by ANSOFT. This is followed by the conclusion in section 4.

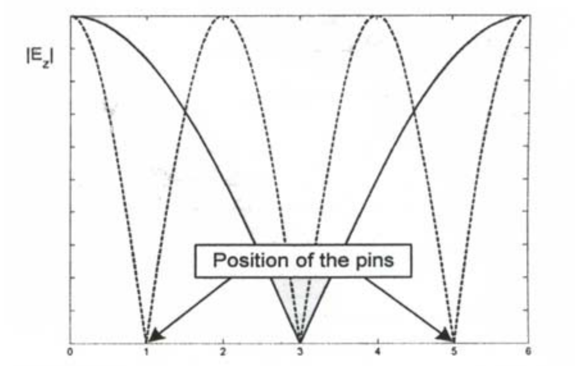

Fig. 1

2 Cavity Model with Shorting Strips

The cavity model was first proposed in 1979 for probe-fed microstrip antennas [11]. Since then the method has been improved to predict the input impedance of microstrip antennas with multiple strips or slots, and to cover microstrip antennas fed by slots in the ground plane [17], [19], [27]. The major restriction of the cavity model is on the thickness of substrate which is supposed to be not more than a few hundredths of a wavelength. This is mainly because the model assumes that neither field components nor the source can be a function of the vertical coordinate under the patch. As a result of this assumption, the electric field has only z component, while the magnetic field has only x and y components in the region bounded by the microstrip patch and the ground plane, fig. 2. in addition, using the fact that the electric current density on the microstrip patch has no normal component along the edge of the patch, the tangential magnetic field is assumed to be negligible not just at the edge of the patch but all the way down to the ground plane. Therefore, the region between the patch and the ground plane can be surrounded by perfect magnetic conductor (PMC) wall that would be not significantly alter the original field distribution under the patch, and hence forms a cavity. Consequently, once the cavity is formed as the model of the patch antenna, the fields in the cavity and subsequently other electrical characteristics can be easily obtained by the well-known solution of the cavity.

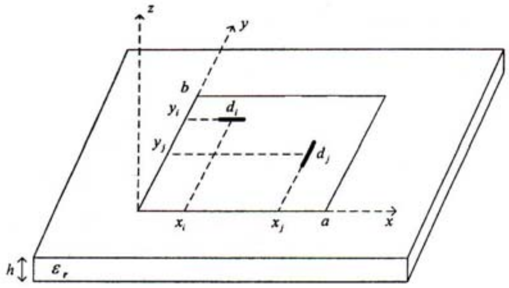

Fig. 2

2.1 Multiple Shorting Strips

With the use of above stated assumptions on the field directions and variations, and the boundary conditions of the cavity, the electric field E_{zi} anywhere under the patch can be obtained, for a 1 Amp uniform probe current located at a point (x_i, y_i), as [19]

$$E_{zi} = j\omega\mu \sum_m \sum_n \frac{\psi_{mn}(x,y)\psi_{mn}(x_i,y_i)}{k^2 - k_{mn}{}^2} \times \sin c\left(\frac{m\pi d_i}{2a}\right) \qquad (1)$$

Where

$$\psi_{mn}(x,y) = \alpha_{mn} \cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)$$

$$\alpha_{mn} = \sqrt{\frac{\varepsilon_{0m}\varepsilon_{0n}}{ab}} \qquad \varepsilon_{0m,n} = \begin{cases} 1 & m,n = 0 \\ 2 & m,n \neq 0 \end{cases}$$

k_{mn} is the eigenvalue of the (m,n) mode, $k^2 = k_0{}^2\varepsilon_r(1 - j/Q)$, Q is the quality factor of the cavity, and (a,b) and d_i are the effective dimensions of the patch and effective width of the feeding strip extended laterally in x direction, respectively. Since the electric field is constant along z direction, the voltage created by i th source at any point under the patch can simply be written as $V_i = -hE_{zi}$. Hence the self and mutual impedances, z_{ii} and z_{ij}, for the z polarized uniform current densities on any two strips, as shown in Fig. 2, can be calculated by averaging the voltage generated by the j th source over the extend of the i th shorting strip (V_{ij}). The shorting strips could be extended laterally either in the same direction or in perpendicular directions and the mutual impedances are obtained

$$z_{ij} = \frac{V_{ij}}{I_i} = V_{ij} = -\frac{h}{d_i} \int_{over\, d_i} E_{zj}\Big|_{y=y_i} dx$$

$$= -j\omega\mu h \sum_m \sum_n \frac{\psi_{mn}(x_i,y_i)\psi_{mn}(x_j,y_j)}{k^2 - k_{mn}{}^2} \times \begin{Bmatrix} \sin c(\frac{m\pi d_i}{2a}) \\ \sin c(\frac{n\pi d_i}{2b}) \end{Bmatrix} \times \begin{Bmatrix} \sin c(\frac{m\pi d_j}{2a}) \\ \sin c(\frac{n\pi d_j}{2b}) \end{Bmatrix} \qquad (2)$$

Where the upper and lower expressions in each curly bracket are for the lateral extensions of x and y directions, respectively, for the strips, i and j. Since the main goal of the multiport analysis is to get the effect of the shorting strip on the input impedance, there is no need to assign the feeding probe a *priori*, that is, any strip can be the feeding probe or shorting strip. For an N-port microstrip antenna, the input impedance seen at port-I can be calculated by assigning zero voltage (short circuit) to all ports except the ith port. In this case, the port currents are related to each other in the following form:

$$\bar{\bar{Z}}_{-i,-i}\bar{I}_{-i} = -\bar{Z}_{-i}{}^T I_i \Rightarrow \bar{I}_{-i} = -\bar{\bar{Z}}_{-i,-i}{}^{-1}\bar{Z}_{-i}{}^T I_i \qquad (3)$$

Where $\overline{\overline{Z}}_{-i,-i}$ is the impedance matrix from which ith row and ith column have been extracted, $\overline{Z}_{-i}$ is the ith row of the impedance matrix, $\overline{I}_{-i}$ and $\overline{V}_{-i}$ are the port current and voltage vectors, respectively, all with the ith entries are extracted. Superscript -1 and T denote the inverse and transpose operators, respectively. By using (3), the input impedance seen at port-i is obtained as

$$Z_{in}(port-i) = \left.\frac{V_i}{I_i}\right|_{V_j=0,\, j\neq i} = \frac{Z_{ii}I_i + \overline{Z}_{-i}\overline{I}_{-i}}{I_i}$$
$$= Z_{ii} - \overline{Z}_{-i}\overline{\overline{Z}}_{-i,i}^{\;-1}\overline{Z}_{-i}^{\;T} \tag{4}$$

3 Fuzzy Systems

In the last few years, the interest towards the automated optimization of electromagnetic design problems has increased. While several optimization algorithms have been developed and applied to single objective functions or scalar problems, the optimization of actual design problems usually requires the minimization/maximization of a set of objective functions often conflicting with each other.

The first fuzzy system model goes back to the 1970s. Around this time, zadeh [14] suggested the description of a system as a set of fuzzy logical rules with fuzzy sets. In particular, the compositional rule of inference was considered to be the backbone of the system. The first application of fuzzy system was by Mamdani [31], who used a fuzzy system in the control of a laboratory model steam engine.

From a system-theoretic view point, a fuzzy system represents merely a versatile nonlinear static map. Functional values are stored in a distributed rule-base fashion so that the rule of the function at any point in the input space is derived by aggregating the consequences of the fuzzy logical rules. Since fuzzy systems can, in principle, be constructed to approximate relations between variables regardless of their analytical dependency, they can be thought of as model free estimators [32]-[33].

3.1 Model Structures for Fuzzy Systems

In this context, by the term fuzzy system, we mean that the model gives a complete description of the system response using fuzzy logical rules. An approximately chosen model structure can greatly simplify the learning procedure and facilitate system design. A fuzzy system with M fuzzy logical rules can be designed by

$$f(x) = \frac{\sum_{j=1}^{n}\prod_{i=1}^{n}\mu_{Aij}(x_i)w_j}{\sum_{l=1}^{m}\prod_{k=1}^{n}\mu_{Aki}(x_k)} = \frac{\sum_{j=1}^{m}\xi_i(x)w_j}{\sum_{l=1}^{m}\xi_l(x)}$$

Where the n-dimensional vector $X = (x_1, x_2, x_3, ..., x_n)$ denotes the input, function μ_{Aij} denotes the membership function of the jth input fuzzy set for the ith input variable, and scalar w_j denotes the jth output fuzzy singleton.

The objective function that must be approximated is of the form

$$f_{obj} = (Z_{in_l} - 50)^2 + (Z_{in_h} - 50)^2$$

Since we want to match the input impedance of the microstrip antenna to $50\,\Omega$ at both high and low resonance frequencies, this form of f_{obj} is considered (Z_{in_l} and Z_{in_h} are input impedance of microstrip antenna at low and high resonance frequencies respectively).

In this study we have approximated the inverse of f_{obj} using a fuzzy system, by gradient descent training algorithm. It is clear that if f_{obj} is equal to zero then the desired strips specifications (x_s, y_s, d_s) are achieved. The input/output pairs applied to fuzzy system for training are generated by f_{obj} itself.

4 Results and Discussion

In this study, the fuzzy system (introduced above) was first used to find the appropriate locations and widths of the shorting strips in a microstrip patch antenna to match the input impedances to $50\,\Omega$ at both low and high frequencies. The feed location, its width and orientation, the number of shorting strips, their orientations and the desired resonance frequencies are used as known and fixed parameters, while the x and y coordinates and the width of each shorting strip are used as the optimization parameters.

For the presentation of the method discussed so far in this paper, two microstrip antennas with some shorting strips have been designed for dual band operation. The first example is an air-filled antenna and its fixed parameters are as follows: a=8cm, b=10cm, h=0.6cm, σ=10^5 mho/cm, $\tan\delta = 10^{-5}$, the position of the feed, $(x_f, y_f) = (4cm, 0cm)$, the width of the feed, $d_f = 0.5cm$ and the lateral extensions of the feed is in x direction. The antenna was designed for $f_l = 1.7GHZ$ and $\frac{f_h}{f_l} = 2.24$.

Simulation results for air-filled antenna with one and two shorting strips are given in table 1. (x_{s1}, y_{s1}) and (x_{s2}, y_{s2}) denote the coordinates of the first and second strips, respectively, d_{s1} and d_{s2} are the widths of the strips, M is the number of rules and k is the fuzzy system training step. Case 1 corresponds to the patch with one shorting strip extended laterally in x direction, case 2 and case 3 correspond to the patches with two shorting strips: the former has both strips extended in x direction, the latter has one extended in x direction and the other extended in y direction. For the first antenna, with the designed positions and widths of the shorting strips given in Table 1, the simulation results are provided in Table 2. To asses the accuracy of the simulation technique used in conjunction with the design method, the results of a full-wave approach, namely HFSS, are also provided. It is observed from Table 2 that the resonant frequencies and the reflection coefficients for both low and high bands agree very well with those predicted by HFSS.

The dielectric filled antenna was designed to demonstrate the applicability of the proposed algorithm for microstrip antennas over a dielectric material $(\varepsilon_r = 4.7)$, for which the fixed parameters are $a = 5cm$, $b = 6cm$, $h = 0.16cm$, $\sigma = 10^6\, mho/cm$, $\tan\delta = 5\times 10^{-4}$, $(x_f, y_f) = (2.5cm, 1.8cm)$, $d_f = 1cm$. The strip extended laterally in x direction, $f_l = 1.55GHZ$ and $\frac{f_h}{f_l} = 2.44$.

The location of shorting strips and the reflection coefficients at the resonance are presented and compared in Table 3.

To verify the design results, the second designed antenna was realized and tested experimentally. Then the input impedances obtained from the multiport analysis in conjunction with the cavity model, from measurements and from HFSS are compared over both low and high bands as shown in Figs. 3 and 4.

From the designs of these dual-band antennas, it is observed that the antennas designed by the fuzzy design method with the multiport analysis, agree with the specifications, as confirmed by the results of a rigorous full-wave method, HFSS, and also the results obtained from measurements. This observation suggests that the design method presented here can make an efficient and accurate CAD tool, at least for the initial design of dual-band microstrip antennas with multiple shorting strips. Another point worth noting is that, during the design iterations, the strip locations tend to converge to the nodal E field lines of the third cavity model, as expected.

case	M	k	f_{ratio}	strip	x_{s1}	y_{s1}	d_{s1}	x_{s2}	y_{s2}	d_{s2}
1	9	100	2.24	1	4.98	3.71	1.41	-	-	-
2	20	150	2.24	2	5.08	4.5	0.35	2.14	3.00	1.21
3	15	200	2.24	2	5.05	3.76	1.25	4.95	3.65	1.14

Table 1

Model	Case	$f_l\,(GHZ)$	$\lvert\Gamma_{in}\rvert_l$	$f_h\,(GHZ)$	$\lvert\Gamma_{in}\rvert_h$	$\frac{f_h}{f_l}$
Multi-port	1	1.7	0.041	3.808	0.008	2.24
	2	1.7	0.032	3.808	0.017	2.24
	3	1.7	0.041	3.808	0.002	2.24
HFSS	1	1.68	0.217	3.96	0.110	2.36
	2	1.74	0.090	4.05	0.169	2.33
	3	1.71	0.157	4.01	0.070	2.34

Table 2

Case	$f_l\,(GHZ)$	$\lvert\Gamma_{in}\rvert_l$	$f_h\,(GHZ)$	$\lvert\Gamma_{in}\rvert_h$	$\frac{f_h}{f_l}$
Multi-port	1.55	0.045	3.782	0.560	2.44
HFSS	1.568	0.030	3.76	0.441	2.40

Table 3

5 Conclusions

Dual-frequency operation of rectangular patch antennas with shorting strips has been investigated via the cavity model in conjunction with the multiport theory. By combining this approach with a robust fuzzy training algorithm, an efficient and

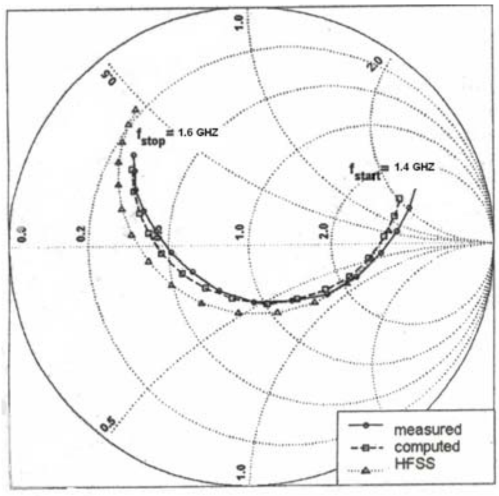

Fig. 3

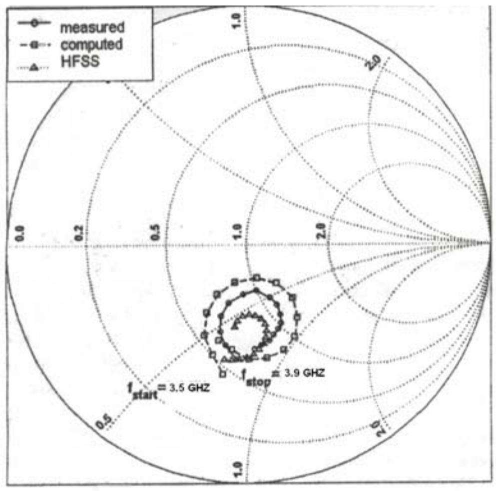

Fig. 4

Figures 3 and 4: measured and computed impedance loci of the dielectric filled antenna for low band and high band respectively

accurate design tool was proposed for dual-band microstrip antennas using multiple vertical strips. For the examples provided in this study, the frequency ratio of the high-band and low-band frequencies, and the input impedances over these bands were used as specifications, while the coordinates and dimensions of strips were the designed parameters. One of the antennas so designed was realized, and dual band operation was verified experimentally as well as by simulation rigorously via HFSS by ANSOFT. It is observed that the theoretical results agree well with the experimental results. Therefore, this approach can be safely proposed as an efficient CAD tool for dual-band microstrip antennas that would use vertical strips, at least for the initial design of the antennas.

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