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Accuracy Improvement of Cavity Model Effective Patch Dimensions using a Single Full-Wave Iteration

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***Abstract*— An accuracy improvement procedure for microstrip patch antenna design is presented. The classical cavity model of a patch antenna is discussed with emphasis on the fringe fields and the compensation for these fringe fields in the form of effective patch dimensions. The effective patch dimensions are improved using a single full-wave simulation, drastically increasing accuracy at the cost of only a small increase in computation time. Using the input impedance of the patch antenna determined via a full-wave simulator, effective patch dimensions are adjusted for each single mode, matching the cavity model results to the full-wave results. It is found that adjustment of non-resonant modes cause a shift in amplitude of the input impedance and a adjustment of a resonant mode results in a shift in frequency. The error in predicted impedance decreases from 75% to 5%. An example is given where an exotic input impedance is required, to match the antenna directly to a nonlinear system. This shows that this method results in fast, efficient, reliable and optimal microstrip patch antenna design.**

I. INTRODUCTION

Microstrip patch antennas are widely used in all types of applications. It is a PCB-based antenna, making it very cheap and accessible for designers. This type of antenna can be easily integrated in a PCB design. The fact that this type of antenna can be conformal and has gain in the forward direction makes it suitable for e.g. WLAN applications. Further, the input impedance of this type of antenna can be adjusted over a wide range of impedances by adjusting the patch dimensions and by shifting the feed-point location. By adjusting the input impedance the antenna can be matched directly to the frontend, thereby eliminating a matching network. This saves space and can reduce losses. Microstrip patch antennas can be easily manufactured using e.g. an etching process, resulting in low manufacturing costs.

The need for more accurate microstrip patch models arose from the fact that we aimed to design a more efficient and compact rectenna (rectifier and antenna combined), or, a wireless battery. The increase in efficiency and the decrease of size compared to existing rectennas should emerge from eliminating the matching circuit between the antenna and the rectifier. This requires matching the antenna directly to the complex impedance of the rectifier. We have observed that the standard cavity model becomes less reliable when a complex input impedance is required. The results and the performance of this rectenna are shown in [6].

When designing an antenna, one can use different approaches. An experimental approach, employing analytical models or employing numerical models can be used, or a combination of them. Using analytical models can be very fast, compared to other approaches, further it gives us physical insight in the behavior of the antenna. However, in general, the accuracy is limited, mainly because of oversimplification in the model.

Using a full-wave simulator is fairly accurate and one has full control over the environment and all parameters. However, full-wave simulations require, in general, long computation time.

Experimental antenna design result in very reliable measurements, but does not lead to an optimal design. A disadvantage is the time involved to manufacture and measure an antenna.

The paper is organized as follows. The microstrip patch antenna model, with emphasis on effective dimensions is discussed in Section II. The accuracy improvement routine is treated in Section III, in Section IV an example design procedure is given. Next, in Section V the results are discussed and finally, conclusions and recommendations are presented in Section VI.

II. CAVITY MODEL

Microstrip patch antennas have been used for a long time. In the 1980's reliable models were created, first by Richards et al. [2] and improved by Carver and Mink [3]. A patch antenna, in its basic form, consists of a conducting ground plane, an intermediate substrate and a conducting top layer. This top layer is called the patch and is usually photo etched from a copper clad PCB. Here, we only consider probe, inset, or edge feeding, as sown in Fig. 1. Other methods of feeding a microstrip patch antenna are possible, such as slot-coupled feeding, but these are beyond the scope of this paper. The patch itself has dimensions *a* and *b*, the substrate a certain height *h*, and permittivity ε_r, see Fig. 2. The location of the feed point is denoted by (x_0,y_0). The dimensions of the feed point are d_xxd_y. When an edge or inset feed is used, one of the feed dimensions is zero.

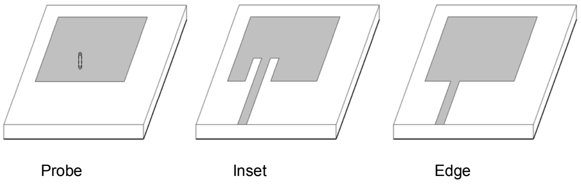

Fig. 1 Different feeding types of microstrip patch antennas.

These models treat the patch antenna as a radiating, or leaking, cavity. The cavity is formed by two perfectly electrically conducting walls (formed by the patch and the ground plane) and four perfectly magnetically conducting side walls.

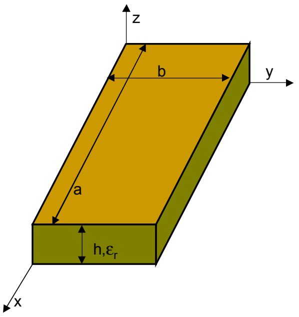

Fig. 2 Cavity modelling of a microstrip patch antenna.

The top and bottom sheet consist of the conductor, usually copper, so it is obvious that these walls can be approximated by perfect conductors. For substrates much thinner that the wavelength, i.e.

$$h << c/(f\epsilon_r) \qquad (1)$$

the electric field vector can be modeled as constant between the top and the bottom plate. The constant E-field allows us to model the side walls as perfectly magnetic conductors. In this way, a cavity is formed which is excited at a certain location, (x_0,y_0). Since this is a cavity, only signals with certain discrete field distributions, so called modes, can exist in the cavity. Other distributions will be attenuated severely. The modes can be seen as to "fit" in the cavity. The electric field distribution in the cavity can be determined for each individual mode in the cavity model. Only a limited number of modes are used, and the other modes are compensated for in a combined higher-order mode. From the electric field distribution for each mode, an equivalent electric circuit is defined and impedance of this circuit is determined. The impedances of all the modes (including the higher-order mode) are placed in series to determine the total input impedance. From the electric field distribution, an equivalent magnetic current density can be defined at the edges of the cavity. As a result of these current densities the cavity will radiate. When we treat the side walls as elements in an array, we can determine the radiation pattern of the microstrip patch antenna.

Due to edge effects, the electric field vector is in practice not constant between the top and bottom layer, at the side walls of the cavity. There, the electric field bends and so-called fringe fields are formed. To compensate for this effect, a little extra length in the horizontal and vertical direction (of the patch) is introduced, so all the field vectors are modeled constant again in the vertical direction, see Fig. 3. The feed point shifts with half the length extensions in the horizontal and vertical direction.

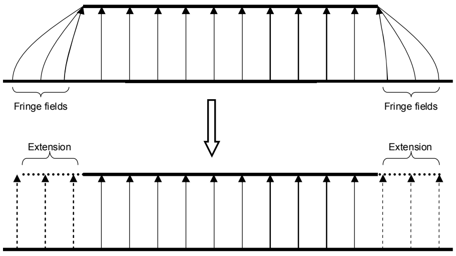

Fig. 3 Side view of the cavity with electric fields and compensation of fringe fields by a length extension.

The dimensions of the patch including extensions are called the effective dimensions. These effective dimensions increase the accuracy of the model. However, it is not clear how large the extension should be. It is suggested in [3] that the extension compensating for an open-ended microstrip line should be used [4]. These extensions have been determined empirically. The microstrip patch antenna has a certain similarity with an open-ended microstrip line, however, this kind of *a/h* or *b/h* values are usually not used for microstrip lines, since one of the dimensions is typically half a wavelength. The effective dimensions form the only fudge-factor in the model. Here, a model is presented that accounts for different error sources by adjusting the effective dimensions. We have focused on optimizing the accuracy of the input impedance.

III. ACCURACY IMPROVEMENT OF THE MODEL

To explain the procedure for improving the accuracy of the cavity model, we start from an antenna design that has been obtained via the cavity model with length extensions as described in [4].

When a (unmodified) model based antenna design has been performed, the input impedance is determined using the model for a frequency range, around the working frequency. Then, this same design is incorporated in a full-wave simulator, we have used CST Microwave Studio© [5]. Using the simulator the input impedance is determined. The full-wave simulator input impedance is compared to the model's input impedance. Typically, they will differ, the shape of the curves will be the same. However, there will be a frequency and amplitude shift. Now, for each mode that is included in the model, the length extensions (both horizontal and vertical) are optimized to result in a minimum difference between the model and the full-wave input impedance. We have observed that using the same extension for all the modes leads to lower accuracy, since we have fewer degrees of freedom. We have observed that a frequency shift is mainly caused by an inaccurate extension of a resonant mode and that the amplitude difference is mainly caused by an inaccurate non-resonant mode extension. Presently, the adjustment of the extensions is done by hand. This procedure can also be done automatically, by solving two least square problems, one for frequency shift and one for amplitude shift. This would increase design speed further.

With the improved effective dimensions, a new design cycle is entered with the newly obtained length extensions. Now we have a much more reliable predicted input impedance. A final full-wave simulation can be performed as a safety check, but in our experience they match very well.

IV. EXAMPLE: WIRELESS BATTERY ANTENNA DESIGN

The described procedure is used to design a rectenna (rectifier and antenna combined) with a patch antenna. Here, the patch antenna design is discussed. The input impedances of the antenna and the rectifier are important to avoid reflections of the received signals. We have no control over the input impedance of the rectifier, given a certain Schottky diode, or diode pair. The input impedance of the rectifier was determined with a Runge-Kutta method as described in [7]. This input impedance is 40-j45 Ω (for an input signal at 2.45GHz, 0 dBm input power, an Agilent 2852 voltage doubler and defined DC load impedance).

To eliminate the matching circuit, the antenna has to directly conjugate match to the rectifier. We have used the standard cavity model to design a microstrip patch antenna with an input impedance of 40+j45Ω using an edge feed. The substrate was standard FR4 1.6mm PCB, with a dielectric constant of 4.3. This resulted in a patch of 28x32.8mm, with a 3mm wide feed with location (5.3,0)mm. The extensions used in this model are based on the extension of an open-ended microstrip line, as described in [4], the length extension turned out to be 0.7 mm in both directions.

Next, this antenna design has been simulated in CST Microwave Studio, using the time-domain solver. Comparing the model results with the full wave simulation shows that the model is not able to predict the input impedance very well, see Fig. 4 and Fig. 5. In these figures the full wave and original model input impedances are shown. Further, the input impedance of an improved model is shown.

The input impedance determined via the full-wave simulator is used to improve the extensions. The different extensions for the individual modes are given in Table I. In this table, we can see that only modes up to the (1,1) mode are adjusted. The two peaks in the input impedance are caused by the (1,0) and the (0,1) mode, so these modes have the most impact on the input impedance. Once the difference between simulation and model had been minimized, a new design cycle, using the improved model, was entered. This new design resulted in a patch with dimensions 27.7x30.8 mm with a feed point located at (0.4,0)mm.

Fig. 6 and Fig. 7 show that an optimized cavity model can be used to design a microstrip patch antenna with a complex input impedance. When we look at the results of Fig. 6 and Fig. 7 we can see that the input impedance determined by the model has an error of 75% compared to full-wave simulations. This error is determined using

$$Error = \frac{1}{f_{up}-f_{low}}\int_{f_{low}}^{f_{up}}\left|\frac{R_{cav}-R_{fw}}{R_{fw}}+j\frac{X_{cav}-X_{fw}}{X_{fw}}\right|df \qquad (2)$$

where f_{up} and f_{low} are the upper and lower frequencies, the impedance that is determined using the cavity model is $R_{cav}+jX_{cav}$ and the impedance that is determined using the full-wave simulator is $R_{fw}+jX_{fw}$.

The improved model results in an error of only 5%. Although these numbers are encouraging the difference between the input impedance of the original model and the full wave simulations is mainly caused by a frequency shift, which results in a larger input impedance error of the original model.

Eliminating the matching network resulted in rectenna efficiency (incident RF-power versus available DC-power) of 52% at an input power of 0dBm compared to an efficiency of 42% for existing rectenna designs.

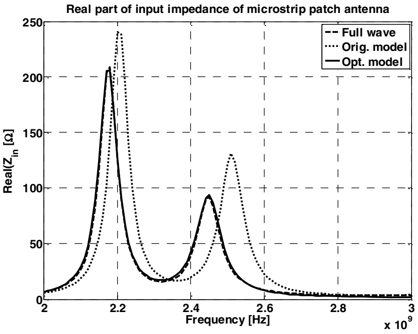

Fig. 4 Real part of input impedance of patch antenna designed using original model.

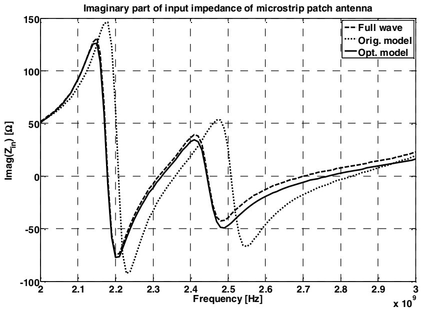

Fig. 5 Imaginary part of input impedance of patch antenna designed using original model.

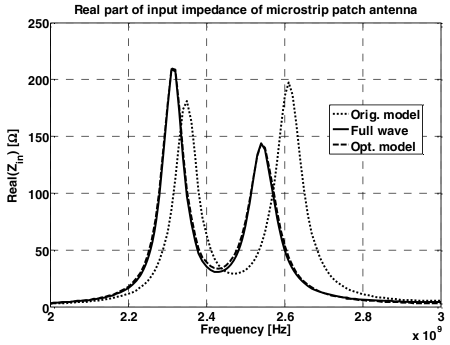

Fig. 6 Real part of input impedance of patch antenna designed using optimised model.

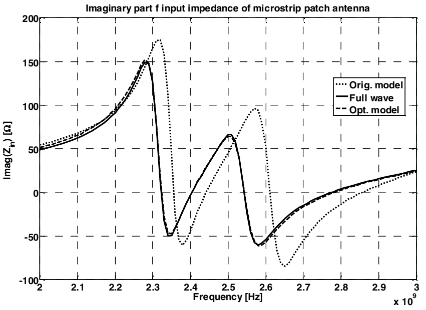

Fig. 7 Imaginary part of input impedance of patch antenna designed using optimised model.

TABLE I
OPTIMIZED LENGTH EXTENSIONS

Mode Extension	(1,0)	(0,1)	(1,1)	(2,1)	(1,2)	(2,2)
Δa(mm)	3.7	0.7	-3	0.7	0.7	0.7
Δb(mm)	0.4	8.5	-1.5	0.7	0.7	0.7

V. DISCUSSION

The example shown above shows the capabilities of the improved cavity model. The main advantage of the improved cavity model is an increased design speed without losing accuracy. A single full-wave simulation takes about 30 minutes in CST Microwave Studio, using our current simulation setup. To reach the same desired input impedance as achieved with the optimized cavity model about 8 runs are needed. When the procedure described in the paper is followed, about 8 runs of the model for the initial design are needed. These runs only take about one minute each. Next, a full-wave simulation is needed, and the model has to be optimized. The optimization only takes a few minutes. After that, a new design is generated based on the improved model, requiring about 8 runs. This way a total design time of about 45 minutes is required, compared to about 4 hours with only full-wave simulations.

The entire procedure works well because our first design, based on the original model, is a good initial estimate. The optimization maps the initial design onto the full-wave simulation. Next, an improved design is made, changing the dimensions not too drastically. This results in hardly any change in improved extensions, keeping the optimized model very accurate.

VI. CONCLUSIONS AND RECOMMENDATIONS

A method has been presented to improve the accuracy of the cavity model for a microstrip patch antenna. The existing model is discussed. It is shown how a single full-wave simulation can be used to improve the model. The input impedance results generated by a single full-wave simulation are used to adjust the length extensions needed for the fringe fields for each individual mode. In this way, the full-wave and analytical model results coincide very well. Now, with the improved model, one is able to design a microstrip patch antenna efficiently and reliably.

Future work will concern the atomization of the model improvement. Further, an empirical expression for the optimized extension will be generated.

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