Modeling and Optimization of Circularly-Polarized Patch Antennas Using the Lumped Element Equivalent Circuit Approach

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Abstract: This paper describes the application of lumped element equivalent circuit approach to the modeling of a capacitive-loaded circularly-polarized microstrip patch antenna. This is achieved by using vector fitting to properly fit frequency domain scattering parameter data to a rational function approximation. Then, the parameter coefficients from the approximate function are used to calculate the passive elements of the lumped equivalent circuit. The circular polarization is achieved by a combination of lumped capacitor loading at the ends of the antenna and feeding along either diagonal of the patch to produce left-hand or right-hand circular polarization. This technique is intended to give a designer an idea on the value of capacitance needed to achieve circular polarization and to facilitate the optimization process. The method is benchmarked for antennas for Bluetooth applications.

INTRODUCTION

Over the last thirty years, many planar microstrip antenna structures and feeding configurations have been reported to achieve circular polarization. One of these structures is the corner truncated microstrip antenna, where the two corners along one diagonal are trimmed [1]. Another method is the insertion of a cross-shaped slit in the patch to detune the two orthogonal modes introducing a 90° phase difference between them [2]. Although these methods and many other configurations have shown that circular polarization can be achieved, a major drawback is that there are few design rules that have been established for designing circularly-polarized microstrip antennas. In some lower frequency applications and designs built on low permittivity substrates, a slight modification of a parameter may not be critical in altering the performance of the antenna, but in numerous high frequency applications and designs built on high permittivity substrates, the same parameter change can have detrimental effects on performance, limiting the applicability of the existing design rules.

In this paper, an attempt to model and optimize the quality of matching (S11) and of the circular polarization through applying a lumped element equivalent circuit model to the scattering parameter data of a capacitively loaded microstrip patch antenna is presented. First, the technique of vector fitting will be used to fit the scattering parameter data to a rational function approximation [3]. Then, the parameters from this approximation can be drawn and used to produce the passive elements of the lumped equivalent circuit [4]. This presents an alternative generic approach to analyzing circular polarization of microstrip patch antennas and can be utilized in the faster and accurate design of integrated antennas on 3D multilayer architectures using organic or ceramic (e.g. low temperature co-fired ceramic (LTCC)) materials [5]. LTCC multilayer technology is maybe the most commonly used multilayer RF technology, due to its maturity and to its flexibility in realizing an arbitrary number of layers with easy-to-integrate circuit components. Although the presented method was evaluated for Bluetooth applications, higher frequency applications are not beyond the scope of this technique.

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LUMPED ELEMENT EQUIVALENT CIRCUIT APPROACH

A lumped element equivalent circuit can be generated from fitting frequency domain scattering parameter data to a rational function approximation $f_{fit}(s)$ by means of vector fitting [3]. This function is shown below,

$$f_{fit}(s)=\sum_{n=1}^{N}\frac{c_n}{s-a_n}+d+sh \tag{1}$$

where s is the frequency point, c_n and a_n are the residues and pole values, respectively from $n=1,2,\ldots,N$ where N is the number of poles, and d and h are higher order coefficients. This function multiplied to an unknown function $\sigma(s)$ gives the equation,

$$(\sigma f)_{fit}(s)=\sum_{n=1}^{N}\frac{c_n}{s-\bar{a}_n}+d+sh, \tag{2}$$

where $\bar{a}_n$ are the starting poles in the data fitting process. To effectively use the vector fitting process, one must select a set of starting poles. A rational approximation for $\sigma(s)$, denoted $\bar{\sigma}(s)$, is shown below,

$$\bar{\sigma}(s)=\sum_{n=1}^{N}\frac{\bar{c}_n}{s-\bar{a}_n}+d+sh \tag{3}$$

where $\bar{c}_n$ are the residues different from c_n. Multiplying (1) with $f(s)$ ($f(s)$ is the data values at the frequency point acquired during the simulation or measurement) and equating it with (2), gives $(\sigma f)_{fit}(s)=\bar{\sigma}(s)*f(s)$. Solving for $f(s)$ for many frequency points leads to a matrix equation, Ax=b, where A is a m-by-n matrix of known terms relating s, a_n, $\bar{a}_n$, and $f(s)$, x is an n-dimensional column vector of unknown terms, c_n, $\bar{c}_n$, a_n, $\bar{a}_n$, d and h, and b is an m-dimensional column vector of known $f(s)$ values. After the elements in the column vector x are solved in the matrix equation, $(\sigma f)_{fit}(s)$ and $\bar{\sigma}(s)$ can be written as

$$(\sigma f)_{fit}(s)=\frac{\prod_{n=1}^{N+1}(s-z_n)}{\prod_{n=1}^{N}(s-\bar{a}_n)} \quad (4) \qquad \text{and} \qquad \bar{\sigma}(s)=\frac{\prod_{n=1}^{N}(s-\bar{z}_n)}{\prod_{n=1}^{N}(s-\bar{a}_n)} \quad (5),$$

where solving for $f(s)$ gives $f(s)=(\sigma f)_{fit}(s)/\bar{\sigma}(s)$. Now it can be seen that the new poles for $f(s)$ are the zeros of $\bar{\sigma}(s)$. This is continued in an iterative fashion until the parameters in $f_{fit}(s)$ are properly fit to the chosen data. In the vector fitting approach, the poles are chosen to be complex for the purpose of fitting the non-smooth resonant peak in the data over the frequency range of interest. The number of poles that are used is determined by the number of peaks that are present in the data. Gustavsen and Semlyen suggests a least two poles should be used per peak. To maintain stability, the complex poles should have a real part that is negative. The parameters in $f(s)$ are then used to generate the lumped element equivalent circuit [4]. The circuit is shown in Fig. 1. The parameters d and h are used to determine the conductance G_0 and capacitance C_1, respectively, while the residues, c_n, are used to determine R_m, L_m, R_n, L_n, G_n, and C_n. The parameters R_n, L_n, G_n, and C_n could perhaps be used to find the input admittance of the patch modeled as a transmission line, while G_0 and C_1 could perhaps be used as edge effect parameters. This equivalent circuit can be utilized to approximate a value of capacitance necessary for optimized matching and circular polarization achievement. For example, two antenna structures, one with small load capacitor values and the other with large load capacitor values, can be simulated. After analyzing the results, the magnitude and phase of S11 versus frequency can be used to create lumped element equivalent circuits for both structures. Upon evaluating the results of these circuits, critical parameters can be identified and used to optimize the design in terms of matching. A similar procedure has to be applied for axial ratio values over a specific frequency range for both small and large capacitive loads in order to estimate the quality of the circular polarization. This method of circuit analysis can save valuable simulation time and give a designer an estimate of optimal capacitance needed to achieve both satisfactory matching and circular polarization.

CP ANTENNA STRUCTURES IN 3D MULTILAYER MODULES

The antenna structure consisted of a square-shaped, planar antenna on top of grounded LTCC substrate layers shown in Fig. 2. The dielectric constant of the substrate was 5.6 and the loss tangent was 0.0012. The feed point was selected to match a 50 Ω coaxial line. There was a lumped capacitor from the patch to the ground plane positioned along the center of each radiating edge. The capacitors introduce reactance in one of the two linearly-polarized electric far-field components. By proper selection of the capacitance as well as feeding along the diagonal, the two field components, which have the same magnitude, will then have a 90° time-phase difference. If the capacitor value is too small, the region between the patch and ground plane can be treated as an open circuit, thus the capacitor will have no effect. A capacitor value that is too large (on the order of pF's) could interfere with the feed probe, and thus, affect the radiation pattern. Through equivalent circuit modeling, an attempt was made to approximate a capacitance value that could produce circular polarization of optimum quality.

For Bluetooth applications at around 2.4 GHz, simulations of a simple square patch antenna on top of a 19-layer LTCC substrate were performed using MicroStripes 6.0. The layer thickness was 4 mils with a load capacitor present on each radiating edge. The first simulation had a capacitor value of 20fF for each capacitor. The second simulation had a value of 1pF for each capacitor. Fig. 3 shows the axial ratios of both simulations. After analyzing and evaluating the circuit parameters, an optimization of the design was performed. The value of each capacitance used to achieve circular polarization was 280 fF. Fig. 4 shows the axial ratio as a function of angle at 2.4 GHz. An axial ratio of better than -3 dB can be observed. A similar approach can be applied for the optimization of matching performance by utilizing frequency-domain S11 parameters and choosing an intermediate value between the two optimized capacitances.

CONCLUSION

A method of analysis was applied to the design of circularly-polarized microstrip patch antennas. A rational function approximation was used to fit frequency domain scattering parameter data by a vector fitting approach. The parameters in the approximation were used to generate a lumped element equivalent circuit. This circuit can be used to approximate and optimize the capacitance value needed to achieve circular polarization and satisfactory matching. Further discussion and results will be presented at conference.

ACKNOWLEDGMENTS

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REFERENCES

[1] P. Sharma, K. Gupta, "Optimized design of single feed circularly polarized microstrip patch antennas," *IEEE Trans. Antennas and Propagat.*, vol. 20, 1982, pp. 156-159.

[2] H. Iwasaki, "A circularly polarized small size microstrip antenna with a cross slot," *IEEE Trans. Antennas and Propagat.*, vol. 44, 1996, pp. 1399-1401.

[3] B. Gustavsen, A. Semlyen, "Rational approximation of frequency domain responses by vector fitting," *IEEE Trans .on Power Delivery*, 2000, vol. 14, pp. 1052 –1061

[4] P. Russer, M. Righi, C. Eswarappa, W. Hoefer, "Lumped element equivalent circuit parameter extraction of distributed microwave circuits via TLM simulation," *IEEE Microwave Theory and Techniques Digest*, 1994, pp. 887 –890.

[5] S. Chakraborty, K. Lim, A. Sutono, E. Chen, S. Yoo, A. Obatoyinbo, J. Laskar, "Development of an integrated Bluetooth RF transceiver module using multi-layer system on package technology," Radio and Wireless Conference, 2001, pp. 117-120.

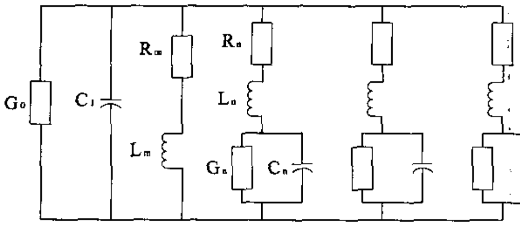

Fig. 1. Lumped element equivalent circuit.

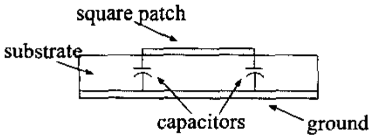

Fig. 2. Square patch antenna on LTCC substrate with tuning capacitors.

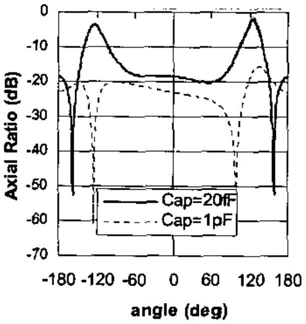

Fig. 3. Axial Ratio versus elevation angle for antenna structures at 2.4 GHz with 20fF and 1pF capacitors.

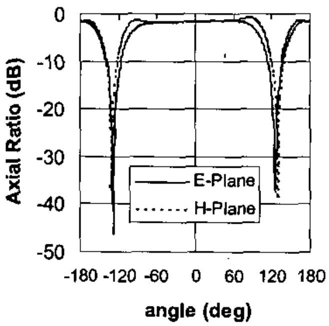

Fig. 4. Axial Ratio versus elevation angle for antenna structure at 2.4 GHz with 280fF capacitors.