Equivalent Circuit Models and Prony's Analysis of Electromagnetic Designs Using Genetic Programing

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***Abstract*—Prior electromagnetic designs using Genetic Programing (GP) showed that GP based designs are competitive and often exceed those based on human expertise. Resulting topologies, however, are unconventional and are less understood. In this paper we propose equivalent circuit models and use Prony's method analysis to explain the high-performance characteristics of the GP designs. Simulation and example analysis are focused on Artificial Magnetic Conductors (AMCs) designed using GP. Ansys Q3D Extractor is used to help determine the RLC component values of the complex computer designed pattern. The equivalent model and multiple resonant results from Prony's method show that complex computer designed AMCs can be explained with electromagnetic and circuit theories.**

Keywords—AMC; equivalent circuit

I. INTRODUCTION

Recently, metamaterials, such as left-handed media and AMCs, have drawn a lot of interest due to their unique electromagnetic properties are not available in natural materials. AMCs have a unique property of in-phase reflection. To take advantage of this property, AMCs are often used as ground plane of antennas to generate unidirectional radiation pattern and reduce the antennas' size. In designing AMCs, simple sub-wavelength planar geometries are commonly used to create resonant structures, such as the well-known mushroom EBG structure [1, 2]. To achieve wider bandwidth or multiple desired resonant frequencies, computational optimization algorithms such as genetic algorithm and GP [3, 4] can be used. In [4], AMCs designed by GP were compared with human designed ones. It shows that for using the same dielectric substrate and thickness, AMCs designed by PG have wider bandwidth coverage than the human designs. However, computational optimization algorithms often generate complex design patterns hard to explain with electromagnetic theory. To have a physics-based understanding of how computer-designed AMCs work in regards to their geometry and electromagnetic properties, we develop equivalent circuit models for the AMCs. These models can also save optimization time and possibly modularize sub-structures for future designs. In this paper, we use one of the computer-designed AMCs in [4] as an example to demonstrate how the equivalent circuit model is developed and more examples will be presented in the conference. Furthermore, Prony's method is employed to better understand the AMC structure.

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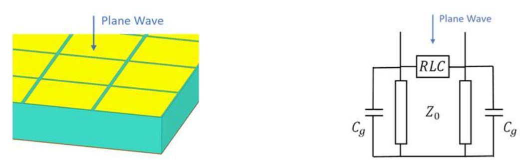
II. EQUIVALENT CIRCUIT MODEL

Fig. 1a shows a simple AMC structure which consists of square patches on top of a substrate and a ground plane on the other side of the substrate. The unit cell equivalent circuit of such structure can be expressed as a shorted transmission line with a RLC circuit connect to other end of the transmission line as shown in Fig. 1b. In the equivalent circuit model, the characteristic impedance of the transmission line represents the characteristic impedance of the dielectric medium. The RLC circuit represents the fringing capacitance between the patches and the resistance and inductance from the patches. The capacitors connecting both end of the transmission line represent the capacitance between the patches and the ground plane.



(a) (b)

Fig. 1. (a) Square patch AMC. (b) Unit cell equivalent circuit.

One of the computer-designed AMC unit cells in [4] is shown in Fig. 2a. This AMC unit cell is designed on Rogers RO4003 substrate with relative dielectric constant of 3.55 and thickness of 1.524 mm. The unit cell pattern can also be depicted as a periodic pattern as shown in Fig. 2b. Based on the equivalent circuit model in Fig. 1, the AMC pattern in Fig. 2b can be represented by an equivalent circuit model as shown in Fig. 2c, where R1, R2, L1, L2, and C1 represent the RLC circuit for the coupling path between the two large patches while R(3-6), L(3-6), and C(2-3) represent the RLC circuit for the coupling path between the large and small patches.

The capacitance between the patches and the ground plane are assumed to be zero. This is based on the full-wave HFSS simulation result of the unit cell structure which shows there is no vertical E-field between the ground plane and the patches.

The characteristic impedance of the transmission line in Fig. 2c is calculated to be 200 Ohm (using $Z_0 = \sqrt{\mu/\varepsilon}$). Unlike mushroom EBG or other simple AMC structures, the irregular patterns designed by optimization algorithms make it hard to express the RLC component values analytically. Hence, Ansys Q3D Extractor is used to simulate the fringing capacitance between the patches. It is found that the fringing capacitance between large patches is 0.045 pF and it is 0.027 pF between the large and small patches. The resistance and inductance of the patches cannot be simulated directly using Q3D Extractor, as it only gives resistance and inductance of a closed circuit. Thus, the patches are simulated as part of a closed circuit (current pass through the patch) which gives us the maximum limit of the resistance and inductance values. Then the resistance and inductance values are tuned using ADS and are determined to be 0.05 ohm, 0.08 nH, 0.06 ohm and 0.06 nH for large and small patches, respectively, as shown in Fig. 2c.

The simulated result of the proposed equivalent circuit model is compared with the full-wave simulation in HFSS as shown in Fig. 3. It can be seen that the equivalent circuit model matches very well with the full-wave simulation result.

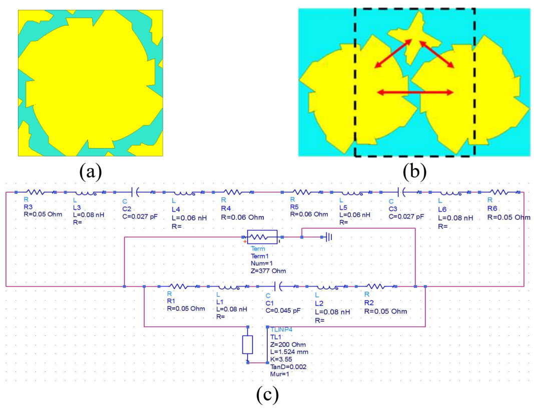


Fig. 2. (a) Computer designed unit cell. (b) Two unit cells. (c) Proposed equivalent circuit model.

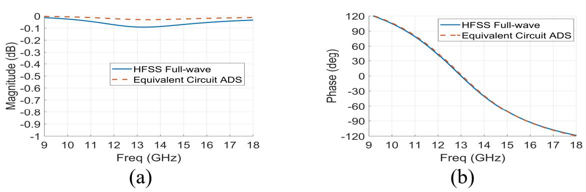


Fig. 3. Simulation results of the equivalent circuit model in ADS and the full-wave simulation in HFSS: (a) Reflection magnitude. (b) Reflection phase.

III. Prony Method

To better understand the AMC structure, further study is conducted in time domain simulation using HFSS Transient. In the simulation setup, a broadband pulse is in normal incidence to an AMC surface consist of 10×10 unit cell structures. The late time scattered signal is analyzed using Prony method to extract the resonant frequencies of the structure. Fig. 4 shows the extracted resonant frequencies over time. Three stable resonant frequencies are obtained, which are 11.9 GHz, 12.9 GHz, and 16.5 GHz. Note that the 12.9 GHz resonant frequency matches that of the unit cell structure as shown in Fig. 3b. By analyzing the AMC structure together with the proposed equivalent circuit model in Section II, the other two resonant frequencies can be found in specific part or module of the AMC structure. When only consider the coupling path between the large patch and small patch, the corresponding equivalent circuit resonance is 17 GHz (close to 16.5 GHz) as shown in Fig. 5. If the small patch from the adjacent unit cell is considered, the corresponding equivalent circuit resonance is 12 GHz as shown in Fig. 6. Thus, the resonance frequencies from Prony method further verify the proposed equivalent circuit model.

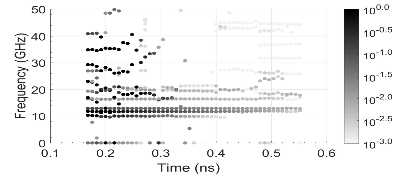


Fig. 4. Prony method result.

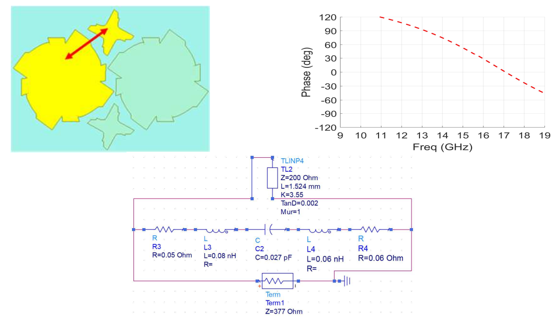


Fig. 5. Equivalent circuit model and result when only consider the coupling path between the large patch and small patch.

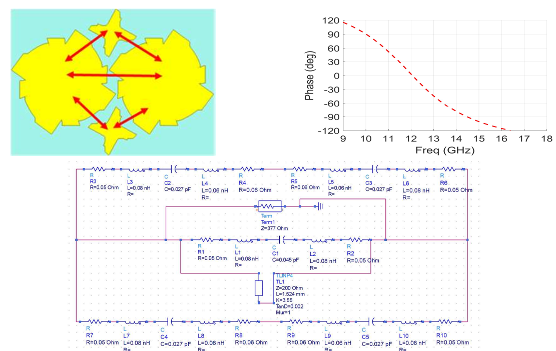


Fig. 6. Equivalent circuit model and result when consider the small patch from the adjacent unit cell.

IV. Conclusion

An equivalent circuit model for computer designed AMC is proposed. Ansys Q3D Extractor is used to help to determine the RLC component values of the equivalent model. The equivalent model result agrees very well with the full-wave simulation result. More examples for different computer designed AMCs will be presented in the conference.

References

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