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Advances of Computational Efficiency and Characterizations of Metamaterials: Tribute to Brilliant Contributions in Wave Interaction with Complex Media

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Abstract— **Many have used equivalent representation of metamaterials with isotropic or anisotropic media. Analyses were basically based on matching measured or calculated scattering parameters of metamaterial design with those of a material slab with, in general, 18 terms permittivity and permeability tensors were developed for the equivalent material representation. The objective is to provide better understanding of the propagation and scattering characteristics of the metamaterial designs, based on fundamental wave materials interaction, and to examine avenues for achieving advanced characteristics, e.g., broader band, enhanced absorbability, improved focus efficiency, etc. With the continued advances in metamaterials designs, many unintuitively and dimensionally multiscale configurations were reported and many hours if not days of computational time were required to develop these designs. This brings additional benefits of the equivalent material representation of complex, and intuitively difficult to explain metamaterial structures, and the use of fundamentally established concepts of wave interaction with complex media, to help improve computational efficiency in optimizing the characteristics, in addition to providing critically needed fundamental understanding of the achieved results. This is where we believe Professor Ishimaru's foundational work on wave propagation in random and complex mediums will play a key role.**

We were fortunate to share some common research interest with Professor Ishimaru's group back in the 2000s [1, 2]. At that time the application of time reversal to wireless communications was an important topic to many researchers in the area. We were particularly interested in the ultra-wide band radios because they were promising in enhancing time reversal effect through random media. In [2] we examined how a single transmitter can realize time reversal effect in a realistic indoor office environment. Our approach is numerical simulation using the finite-difference time-domain method. The results showed that when small furniture help increase the focusing resolution. Professor Ishimaru and his colleagues investigated time reversal effect using a theoretical approach [1]. Many effects including superresolution provide a foundation for our numerical simulation results.

More recently our group have been working on metamaterials to achieve different goals [3-8]. The genetic programming (GP) method is adopted to obtain designs that can has strange, complicated, and unintuitive shapes or structures [5-7]. We found it is difficult to explain why these designs work and their performance is better than the designs by human experts. Some of these designs are shown in Fig.1 for a variety of applications including perfect magnetic conductors (PMC), 2D and 3D designs, graphene-based metamaterial absorbers, and microwave lenses.

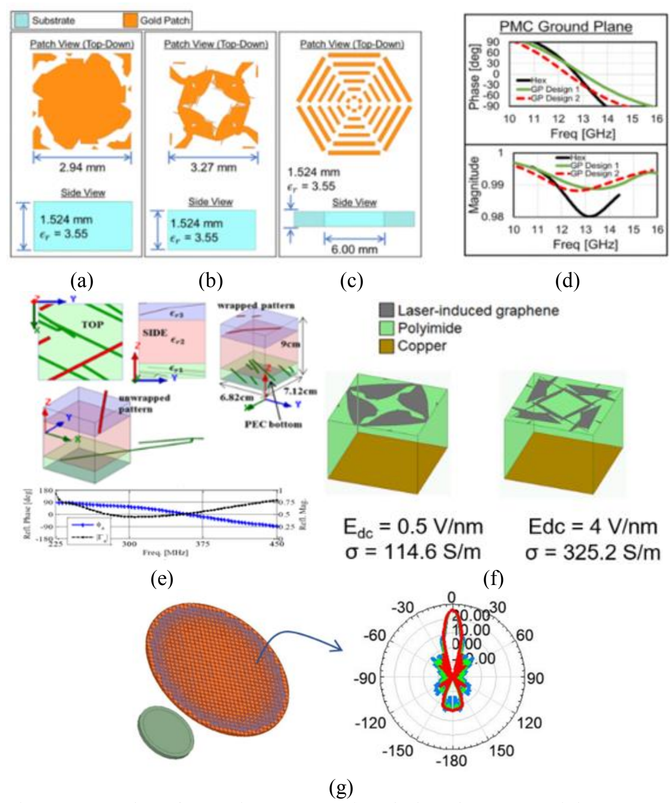
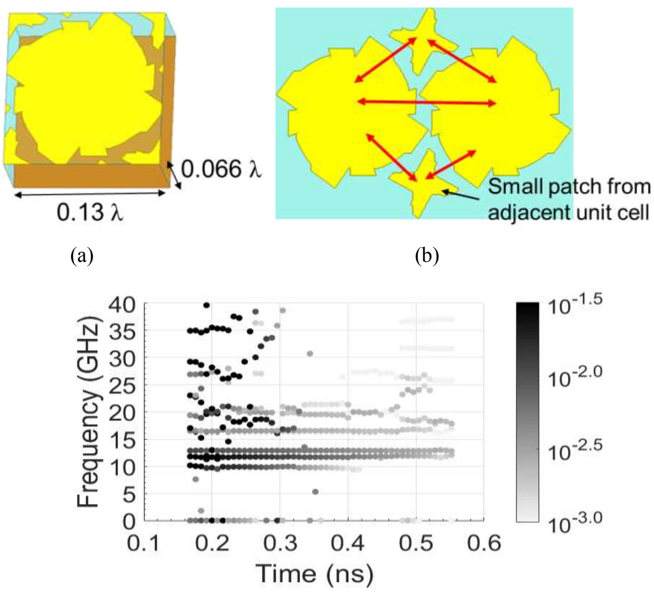


Fig. 1. Examples of Genetic Programming designed metamaterial structures. This includes, perfect magnetic conductors (PMC), (a), (b), and results in (d), 3D PMC in the 225-450 MHz band (e), metamaterial absorbers using Laser Induced Graphene patterning (f), and a 10 GHz metamaterial lens (g). The design in (c) is from literature included here for comparison.

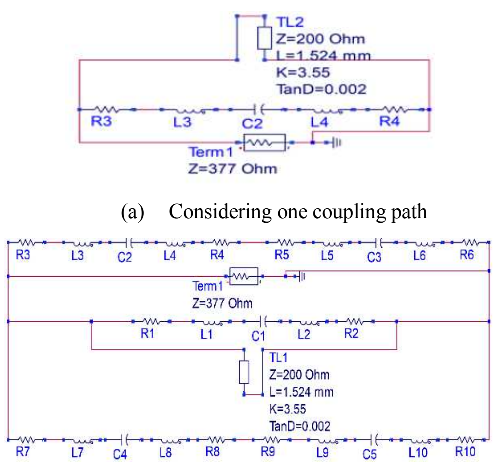
It can be seen from the figure that the shapes of the GP-designed structures are complicated and unintuitive, Fig. 1 (a), (b), (e) and (f) while the performance are exceeding human-experts' designs. Initial efforts to explain the advanced performance of these designs were based on either equivalent circuit models or using Prony's method to identify overlapping natural frequencies that resulted in the achieved broadband characteristics [8]. In Fig. 2, we show an example of GP-designed artificial magnetic conductor (AMC) composed of many unit cells. Using Prony's method, extracted three resonant frequencies at 11.9 GHz, 12.9 GHz, and 16.5 GHz.



(a) (b)

(c)

Fig. 2. Features of an AMC. (a) The unit cell. (b) Unit cells combined with neighbors. (c) Resonant frequencies identified using Prony's method.



(a) Considering one coupling path

(b) Considering all coupling paths

Fig. 3. Equivalent circuit models for the AMC in Fig. 2.

To explain the wideband feature using equivalent-circuit model, we noticed that mutual couplings between the different parts of the patches can be associated with the resonant frequencies in Fig. 2(c). For example, the mutual coupling between the larger patch with a small patch gives rise to the ~17 GHz resonant frequency and its equivalent circuit is shown in Fig. 3(a). If the mutual coupling between the all the neighboring components is considered and using the equivalent circuit in Fig. 3(b), we find that the resonant frequency shifts to the ~12 GHz band.

These methods are clearly useful in helping with some electromagnetic-based understanding of the achieved characteristics, and possibly with some guidance on avenues on how to further optimize the performance of these designs, but they are far limited in providing help with reducing the computational time and effort. Using the equivalent material representation [9,10], on the other hand, accomplishes this goal, and thanks to Professor Ishimaru's scholarly work and brilliant career in studying wave interaction with random and complex media [11,12] that lead to computationally efficient advances in metamaterials designs and characterization.

In the conference presentation we will give more details about the status and advances in metamaterial designs and highlight how Professor's Ishimaru's brilliant contributions in the field of wave propagation and scattering in random media will continue advances and speed up progress in the metamaterials design and application field.

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