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Meta-Molecular Devices

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***Abstract*—We report the development of a new method to both describe and design metamaterials, meta-surfaces and meta-structures in which discrete passive structures are combined into ensembles. We call these structures, meta-atoms and the structures that result are meta-molecules. By using this concept new structures can be designed with a wide range of desirable properties.**

I. Introduction

Metamaterials are often designed using arrays of identical elements or meta-atoms [1]. Such structures are rich with novel properties and already offer a significant range of design freedoms to provide new electromagnetic properties. Metamaterials have lead to the development and use of transformation optical methods developing lenses, cloaking devices and more [2]. Applications span the fields of antennas and wireless power [3] Some examples have been developed which incorporate multiple distinct species of meta-atoms - for instance the early microwave negative index demonstrations included both magnetically and electrically resonant elements in each unit cell of their structures [4]. Other researchers have considered complex assemblies of nanoparticles to realise new optical circuits [5]. We are involved in the development of additive manufacturing methods for the production of large scale metamaterial devices. These techniques offer the potential to create highly diverse, anisotropic arrangements of meta-structures for future agile antennas, filters, waveguides, lenses and other Radio Frequency (RF) front end components [6].

II. Meta-molecular crystals and Meta-molecules from Meta-atoms

Figure 1 shows one possible meta molecular system using resonant, magnetic, split-ring type meta-atoms. Often these structures are coupled via magnetic interactions [7] denoted by the mutual inductance of proximal meta-atoms. Structures with capacitive gaps also carry electric fields that result in electric coupling [8], [9] where the coupling strength varies with the orientation of the meta-atoms. In many studies, particularly those considering microwave and mm-wave applications, circuit methods are used to analyse and optimise structures. For structures and frequencies where the meta-atoms are much smaller than a free space wavelength such non-retarding methods work well. In general most circuit calculations require the use of an impedance matrix which is used in a generalised Kirchoff equation of the usual form $\vec{V} = \mathbf{Z}\vec{I}$ with $\mathbf{Z}$ being the impedance matrix,

$$\mathbf{Z} = \begin{bmatrix} Z_{11} & X_{12} & X_{13} & \dots & X_{1n} \\ X_{21} & Z_{22} & X_{23} & \dots & X_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ X_{n1} & X_{n2} & X_{n3} & \dots & Z_{nn} \end{bmatrix} \quad (1)$$

and $\vec{V}$ is a vector which contains the exciting potential applied to each meta-atom, $\vec{I}$ is another vector containing their circulating currents and $\mathbf{Z}$ encapsulates self and mutual impedances in which Z_{nn} and X_{nm} are the meta-atom impedances and couplings respectively.

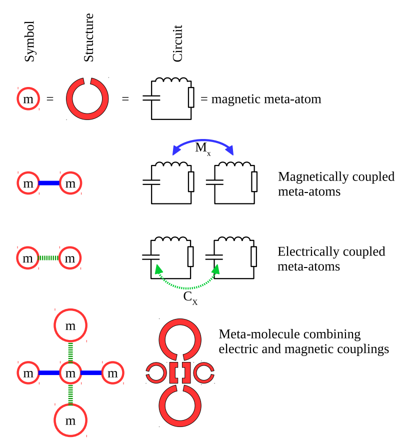

Fig. 1. (upper)Construction of meta-molecules from magnetic meta-atom such as split ring resonators or LRC resonant circuits. (middle) Two possible remote couplings exist between such structures - magnetic coupling via magnetic flux and electric coupling via electric fields. In general the former is mediated by the inductance of the circuits and the latter via the capacitors. (lower) a meta-molecule formed from 5 meta-atoms with both E and H couplings.

Meta-molecules are formed by coupling two or more meta-atoms together to form a composite object which now interacts with a greater range of frequencies than its individual atoms. In turn one can form Meta-molecular crystals by combining meta-molecules. There are a number of famous structures which already use a meta-molecular structure including some of the earliest double negative materials which were formed from molecules comprising a magnetic split ring and electric dipole combination [4].

In our analogy we consider the electromagnetic coupling between meta-atoms to form a 'bond' between them. Meta-chemistry in this case is the design of meta-molecules and their assembly into useful structures. Such structures could be selectively permeable electromagnetic shielding, frequency selective surfaces, cloaking structures and no doubt many more besides.

When one is constructing a metamaterial the coupling of meta-atoms together is not always desirable, in the earliest attempts to realise perfect lenses, coupling which adds new propagation modes to structures resulted in energy being distributed across surfaces rather than focussed to a single point [10].

Meta-atoms need not be in contact to become coupled - magnetic and electric couplings are long range in nature, however Meta-atoms may be in intimate contact resulting in direct circuit connections between their internal structures. In this case the detailed nature of those contacts and their configuration will be important. We define three types of coupling in this case, 'magnetic' where induction links meta-atoms, 'electric' where electric dipolar interactions are dominant and 'current' for the case where one has a circuit connection between meta-atoms.

Figure 2 shows what might be realised using the meta-molecule technique. A meta-surface and meta-polymer are shown each of which could be modelled using a combination of circuit theory and periodic boundary conditions. For the meta-molecule the impedance matrix would be formed by considering the relative couplings and impedances of the meta-atoms from which it is formed. This impedance matrix then becomes one subset of the overall system impedance matrix which describes the whole metamaterial.In the case of surface waves, a simple matrix inversion allows the rapid evaluation of meta-atom currents while the molecule impedance provides a route to simple evaluation of surface wave dispersion [11].

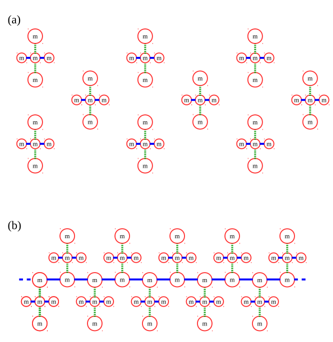

Fig. 2. Structures formed from meta-molecules. (a) A metasurface formed from isolated non-interacting meta-molecules each engineered for a set of resonances and radiation interactions to modify the propagation, absorption and reflection of TEM waves. (b) A meta-polymer formed from a chain of meta-molecules, magnetically coupled by one of their meta-atoms to create a strong waveguiding structure with a designed passband and dispersion

For many meta-structures its sufficient to have a uniform, or slowly varying arrangement of meta-atoms, but there are many possible devices where arrangements of quite different meta-atoms and this can be problematic. If one seeks to simulate and optimise a structure with on the order of 500 meta-atoms, all of which are unique, most commercial finite element codes require unrealistic memory size and inconveniently long run times. Using our meta-atom approach we can derive polarisabilities for meta-molecules which may then be combined using ensemble scattering and other techniques. This kind of scattering technique allows one to generalise the method to include free space TEM waves and their interaction with meta-atoms.

III. Device Demonstration

To illustrate the potential of meta-molecular design methods we have used the method to design a meta-polymer waveguide similar to that of figure 2 and a meta-surface reflector. We report on design of a multiband waveguide carrying signals with an optimised passband structure for several UHF bands.

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