Modeling Metamaterials

Metamaterial Development using Electromagnetic Simulation

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Metamaterials are a subject of great interest for both academia and industry, offering the ability to produce electromagnetic phenomena that are not seen in natural materials. These offer potential for new technologies and for existing devices to be made smaller, faster and more efficient. When developing a new metamaterial, simulations can be used both to analyze the bulk effects of the material and to design the individual unit cell.

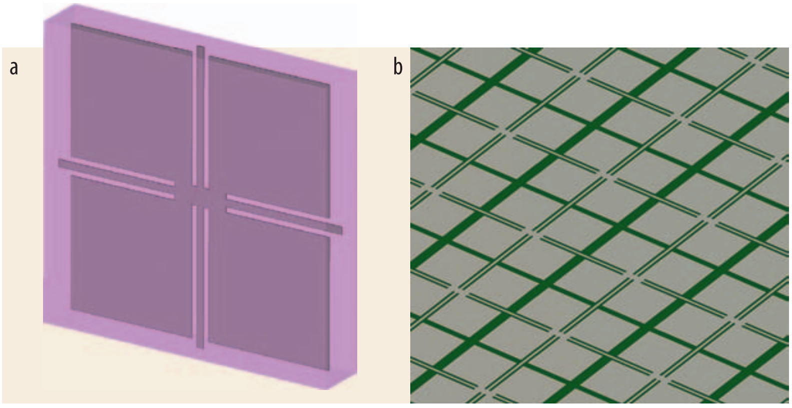

Fig. 1 A single gapped plane element (a). An EBG power plane for a low-noise PCB (b).

Metamaterials – structures designed to have exotic electromagnetic properties – promise great advances in the fields of electronics and optics. Researchers have proposed a huge range of devices using metamaterials, from miniaturized, low-noise versions of existing components such as waveguides, filters and antennas to brand new devices that previously only existed in science fiction, such as cloaks and superlenses that can overcome the diffraction limit.

The term "metamaterial" covers a range of concepts, including double negative (DNG) materials, electronic band gap (EBG) structures and artificial magnetic conductors (AMC). A typical metamaterial device consists of an array of resonators at the millimeter or microscopic scale, embedded in or around a macroscopic structure. To develop a metamaterial, both the individual unit cell and the full-scale system need to be considered. While treating the metamaterial as a bulk material with negative refractive index is useful at early stages of the development, the final design needs to take into account the properties of the metamaterial at the scale of individual cells.

Electromagnetic simulation can be used to verify theories and develop metamaterial concepts before constructing any prototypes. However, there are several special considerations that the researcher should be aware of when modeling metamaterials. By nature, metamaterials comprise sub-wavelength elements, but these elements are often arranged in electrically large arrays. This means that a variety of solver technologies are required to develop a metamaterial device efficiently. The solvers demonstrated in this article are part of CST MICROWAVE STUDIO® (CST MWS), a full-wave 3D electromagnetic simulation tool [1].

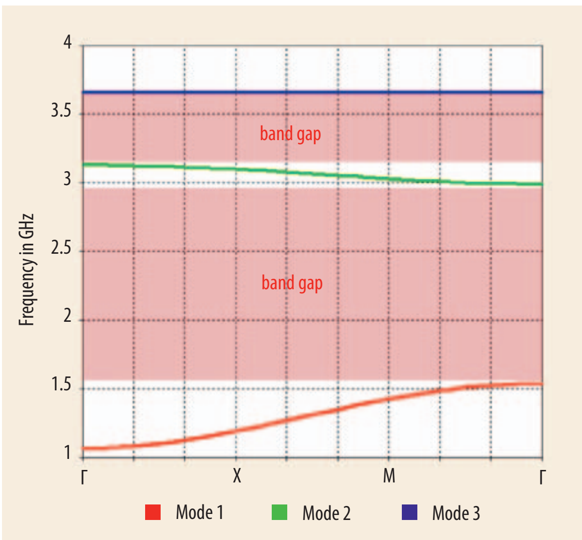

Fig. 2 Band gaps over the irreducible Brillouin zone (Γ-X-M-Γ) in the EBG structure shown in **Fig. 1**.

Unit cell design

Numerous metamaterial topologies exist, and while their designs are different, they all need to be carefully engineered so that they give the correct behavior at the frequencies of interest.

For EBG applications (e. g. **Fig. 1**), their behavior can be characterized by a single element of the periodic structure by means of the dispersion diagram. For a given geometry, this can be modeled and calculated using an eigenmode solver. Eigen-

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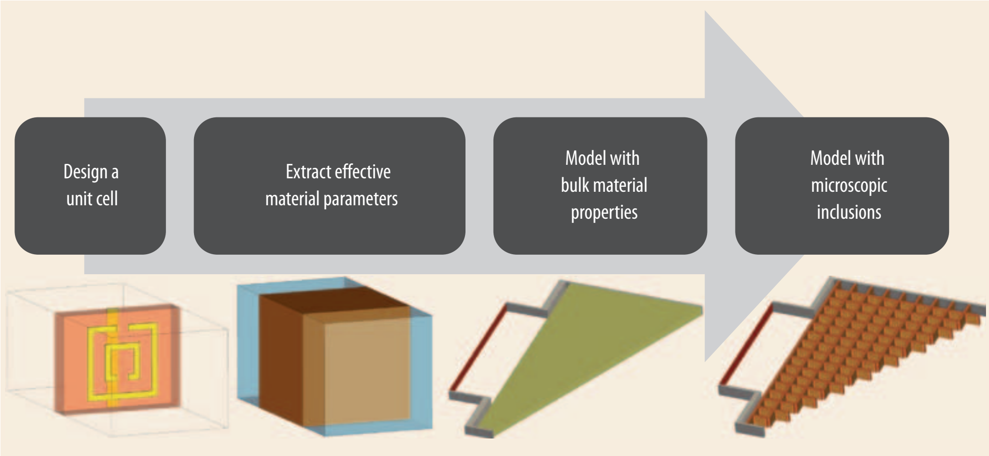

Fig. 3 Workflow for modeling the behavior of a metamaterial system, from a single unit cell to a whole device.

mode solvers can handle the lossy metal properties of the resonators and the dispersive properties of the substrate, and can use periodic boundary conditions to model an entire array based on a single element [2].

The dispersion diagram is produced by performing a parameter sweep over the phase relations in the transverse directions, as an example between the *x* and *y* periodic boundaries (**Fig. 2**). After calculating the modes across all phases, the band gaps are given by the absence of propagating modes in certain frequency bands.

For problems which are driven by an excitation source, the dispersion diagram can be obtained from the scattering parameters (S-parameters). This is common in transmission line based devices like leaky wave antennas. To generate these, a time or a frequency domain solver can be used. Just as with a classical material, the S-parameters show how much power is reflected, how much is transmitted, and how much is absorbed or re-radiated at different frequencies.

Frequency domain simulation also allows the use of Floquet ports. These can be used with the unit cell structure to calculate the phase reflection diagram for any angle of incidence. This phase relationship diagram offers an alternative approach for calculating the band gap for an artificial magnetic conductor (AMC). The band gap corresponds to those frequencies where the reflection phase is between ± 90°. In this region, the magnitude of the surface impedance exceeds the free space impedance thus enabling antenna elements to lie very close to the ground plane without being shorted out.

Bulk property extraction

Once the element has been designed, its effective electromagnetic properties can be extracted (**Fig. 3**). The bulk properties of a metamaterial can be calculated using the Drude model for permittivity and the Lorentz model for permeability:

$$\varepsilon_{eff}(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega - i\nu_c)},$$

$$\mu_{eff}(\omega) = \mu_\infty + \frac{(\mu_S - \mu_\infty)\,\omega_0^2}{\omega_0^2 + i\omega\delta - \omega^2}.$$

This gives seven variables that need to be calculated: permittivity at infinite frequency, permeability at infinite frequency, plasma

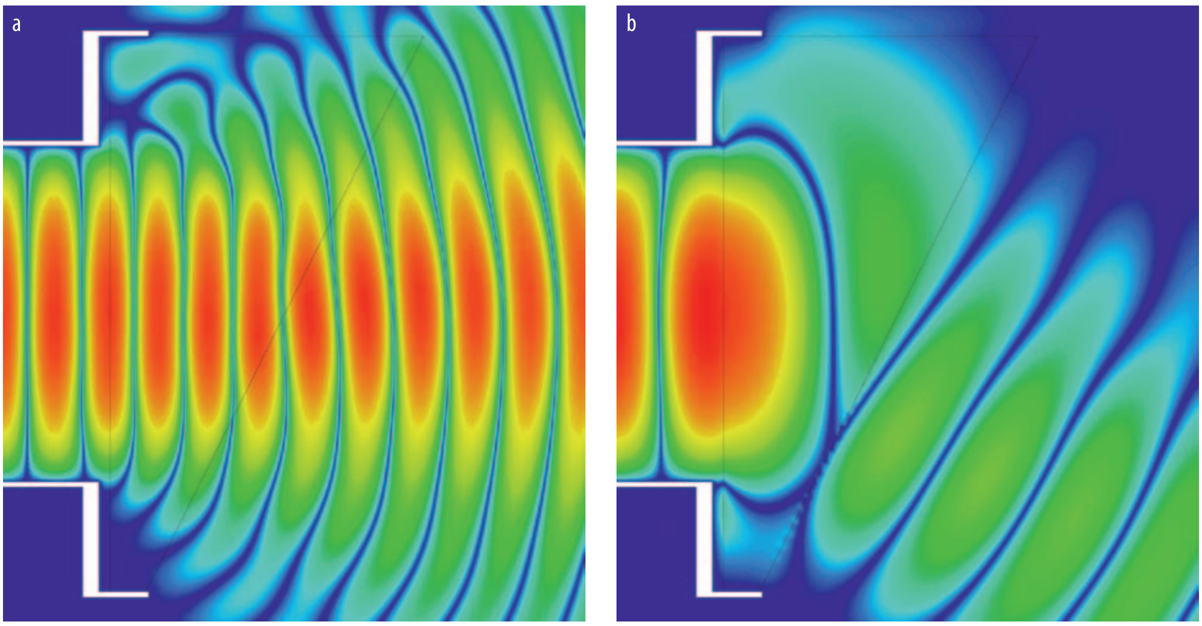

Fig. 4 Electric field values in the metamaterial wedge lens from **Fig. 3**, (left) in the double-positive region and (right) in the double-negative region.

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frequency, resonance frequency, collision frequency, damping factor and static permeability. To find the values that best fit the metamaterial, a new 3D model of the system is created with the detailed metamaterial structure replaced by a single bulk material.

The variables of the Drude-Lorentz material are parameterized in CST MWS. An optimization is then carried out, using the calculated S-parameters for the unit cell as the goal. The optimizer searches the parameter space for the combination of values in the Drude-Lorentz model that best replicates the behavior of the unit cell, by iteratively simulating the material and tweaking the variables. Using the calculated values, the engineer can identify the double-negative region of the unit cell.

The bulk material can then be substituted into the full-sized structure to ensure that the device still works when the behaviour of the individual unit cells is considered (**Fig. 4**).

For a standard metamaterial-based device, individual elements can be a fraction of a wavelength in size, while the device itself is many times larger. This means that a very fine but very large mesh is required to accurately model the system.

Time domain simulation with hexahedral meshing can deal with these large, complex structures in an efficient way [3]. With time domain simulation, a wide range of field results can be calculated. These include the near-field behavior in both the time and frequency domains, the farfield and phase center of the device and its transmission and reflection coefficients.

Conclusion

Developing a metamaterial for a particular application requires careful choice of the topology and dimensions of the individual elements. Electromagnetic simulation enables the behavior of a potential metamaterial to be investigated prior to the prototyping stage, making it easier to extract the properties of a given design and to optimize the element for better performance. Metamaterials can be simulated both in isolation and in situ, and depending on the project requirements, considered either as a bulk material or an ensemble of individual elements.

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