Polarizability Extraction of Meta-Atoms Embedded in Waveguides

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Metamaterials are engineered structures composed of numerous sub-wavelength inclusions, designed to tailor electromagnetic fields in ways not feasible with readily available natural materials. The most general approach to design metamaterials, is to arrange polarizable resonant elements or "meta-atoms" in a periodic fashion. The periodic configuration can be viewed as a material with effective electromagnetic properties, such as an effective relative electric permittivity ε_{eff} and relative magnetic permeability μ_{eff}, which can be extracted from the scattering parameters. A similar method is also applied to metasurface designs, with effective material properties replaced by effective impedances.

This approach only holds true if the array of elements is infinitely-large and periodic. To circumvent this limitation, Gradient-index metasurfaces are envisioned as a collection of periodic meta-atoms with a smoothly varying geometry, such that effective medium properties can still be applied. Over the decade, given the properties properties of metasurface structures, there has been growing interest in employing their tailoring capabilities to design antennas with sculpted radiation properties. However, in many metasurface antenna designs, the periodic assumption for meta-atoms (as enforced by conventional metamaterial designs) limits the capabilities of the metasurface antennas. If the meta-atoms become tunable, this limitations become more pronounced. In addition, these methods assume infinite metasurface and cannot account for finite size of antennas.

An alternative approach to designing metasurface antennas is discrete dipole approximation. In this framework, each meta-atom is viewed as a polarizable point scatterer, whose complex amplitude is determined by the interaction of the meta-atoms as well as with the guided-mode. This method does not make any assumption on periodic configuration of meta atoms or infinite size, making it suitable for metasurface antenna designs. Vital to this methodology is the polarizability representing each meta-atom. The polarizability of the meta-atom corresponds to its relative tendency of a charge distribution in a given direction. Therefore, this property is a tensor whose components depend on the geometry of the meta-atom, its composing materials, and the structure in which it is embedded.

We introduce a technique to extract the polarizability of a single metamaterial element embedded in a waveguide as it is common in most metasurface antenna designs. First we examine a rectangular waveguide, where there are two scattering (S) parameters, which can be characterized with a full-wave solver, and directly determine the electric and magnetic polarizabilities, α_e and α_m. This relationship between polarizability and S parameters can be found considering that the total dipole moment is linearly related to the local electric and magnetic field and this dipole will generate scattered fields that will propagate in both directions through the waveguide.

In order to validate our proposed technique, full-wave simulations in *CST Microwave Studio* were performed. Different meta-atoms etched on the top wall of a rectangular waveguide were simulated and their effective polarizability was computed by means of the S-parameters. Then, the results were compared with the polarizabilities that would be obtained from the total dipole moment of an aperture, which depends on the tangential components of the field at the surface. Excellent agreement is found in these simulations.Next, we discuss how this method can be extended to 2D waveguides, such as parallel plate waveguides.

Considering that both the near-field and far-field response of a dipole-moment is known, the presented approach can be used for the design of finite metasurfaces and antennas for a wide variety of applications from telecommunications and radar, to microwave imaging. This technique opens the door for numerous antenna and metamaterial designs, considering that it is not limited by the constraints imposed by the conventional ways in which effective medium theory has been applied to metamaterials.These exciting opportunities will be also discussed in this presentation.