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Modular approach to understanding and synthesis of metamaterials and metasurfaces

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Abstract – **The vast majority of previously proposed metamaterials and metasurfaces are anisotropic or bianisotropic (exhibiting magnetoelectric coupling). Nevertheless, their anisotropy was not fully exploited as they were designed only for one or several specific illumination directions. In this talk, we propose a simple analytical approach to characterize properties of general bianisotropic meta-atoms for an *arbitrary* illumination. The approach is based on the qualitative decomposition of an arbitrary meta-atom into separate basic "modules" with elementary polarization properties. Such decomposition can be used for comprehensive characterization of previously designed structures as well as for synthesizing novel bianisotropic inclusions of arbitrary complexity and with desired response.**

I. Introduction

During the last two decades, metamaterials expanded from a small subject into a multidisciplinary area of research with applications for controlling waves of different spectrum and nature: From seismic waves to ultraviolet radiation. In contrast to natural substances, properties of metamaterials are defined mainly by their internal structure and geometry of constituents. In the linear regime of material response, through precise engineering of the material inclusions, it is possible to synthesize composites with both electric and magnetic polarization responses as well as with magnetoelectric coupling (the latter case refers to bianisotropic composites). Although a rich variety of bianisotropic metamaterials has been proposed and studied, a comprehensive methodology for designing material with *general* electromagnetic response remains still a serious challenge. Indeed, in the literature, mostly materials of one specific bianisotropic type were considered, e.g. chiral or omega materials [1, 2]. The complication arises due to the absence of theoretical models of inclusions with arbitrary geometries.

On the other hand, previously proposed metamaterials have been designed only for one or several specific illuminations, while their response at other angles of incidence was either unexplored or taken for granted. Nevertheless, due to anisotropic response, the same material illuminated from different directions can exhibit drastically different physical response. One well-known example is a planar metasurface consisting of non-chiral inclusions (omega inclusions [3], gammadions [4], or asymmetric split rings [5]) whose thickness can be *arbitrarily small*. Although for the normal incidence, this metasurface reveals no chirality, there exist specific illumination directions at which it exhibits strong chiral effects (such as circular dichroism or/and optical activity).

In this talk, we will present our recent advances on the concept of "materiatronics" [6]. This concept implies decomposition of an arbitrary given complex meta-atom into separate "modules", i.e. fundamental meta-atoms with pure polarization response of one type along one direction. Such decomposition allows one to understand and predict how a designed metamaterial will act for illuminations from different directions. Moreover, our modular approach can be conceptually used to provide some insight on how to design a metamaterial with arbitrary desired response: e.g., a metamaterial which will behave as chiral slab or metasurface for one illumination and exhibit strong nonreciprocal bianisotropic effects for the other.

II. Decomposition of a general reciprocal anisotropic meta-atom

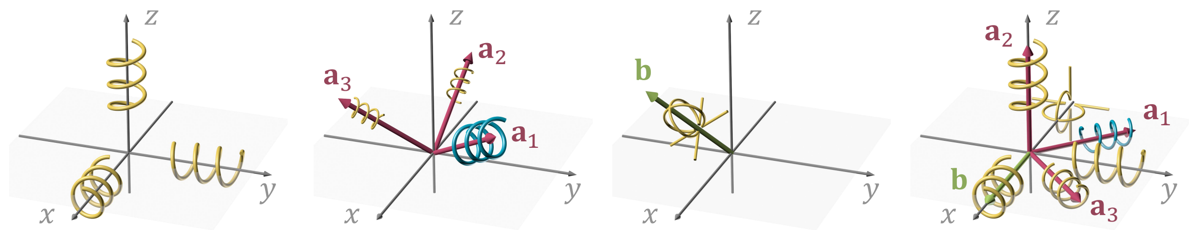
An arbitrary complex reciprocal meta-atom with electric anisotropy (the same can be applied to magnetic anisotropy) of polarization response can be always decomposed into (or represented by) *six* basic modules. Indeed, according to the Onsager-Casimir symmetry relations [7], if the linear meta-atom is reciprocal (that is, there is no external time-odd bias field nor external time modulation), then its polarizability dyadic is symmetric, i.e. $\overline{\overline{\alpha}}_{\rm ee} = \overline{\overline{\alpha}}_{\rm ee}^T$, where T denotes the transpose operation. Next, the dyadic can be decomposed to real and imaginary parts $\overline{\overline{\alpha}}_{\rm ee} = (\overline{\overline{\alpha}}_{\rm ee} + \overline{\overline{\alpha}}_{\rm ee}^*)/2 + (\overline{\overline{\alpha}}_{\rm ee} - \overline{\overline{\alpha}}_{\rm ee}^*)/2$. Each of the obtained dyadics can be always diagonalized in a new basis formed by three unit vectors $\mathbf{a}_i$ ($i = 1, 2, 3$). Thus, the real part of dyadic $\overline{\overline{\alpha}}_{\rm ee}$ can be represented by three *lossless* modules (basic meta-atoms) oriented along the basis vectors $\mathbf{a}_i$. The imaginary part is modeled by another three *purely lossy* modules oriented along, generally, different basis vectors. A typical meta-atom with strong electric polarizability along a single direction, which can play the role of the electrical module, is a straight metal wire of appropriate length. If we think about a magnetic module, probably, the best candidate could be a double split-ring resonator exhibiting large magnetic polarizability $\alpha_{\rm mm}$ along its axis. However, it should be noted that this meta-atom is not purely magnetic: It possesses also electric polarization response.

III. Decomposition of a general reciprocal bianisotropic meta-atom

General reciprocal *bianisotropic* meta-atom, in addition to electric and magnetic response, possesses magnetoelectric coupling characterized by polarizability dyadic $\overline{\overline{\alpha}}_{\rm em}$. In contrast to dyadics $\overline{\overline{\alpha}}_{\rm ee}$ and $\overline{\overline{\alpha}}_{\rm mm}$, polarizability dyadic $\overline{\overline{\alpha}}_{\rm em}$ has both symmetric and antisymmetric parts even for the reciprocal inclusions. Therefore, the decomposition of magnetoelectric dyadic has the following three terms [7]:

$$\overline{\overline{\alpha}}_{\rm em} = T\overline{\overline{I}} + \sum_{i=1}^{3} P_i \mathbf{a}_i \mathbf{a}_i + A(\mathbf{b} \times \overline{\overline{I}}), \tag{1}$$

where T, P_i, and A are complex amplitudes defining the weights of each dyadic in the linear combination, $\overline{\overline{I}}$ is the unit dyadic, $\mathbf{a}_i$ are the unit vectors in the diagonalized basis (here we assume that they are real), and $\mathbf{b}$ is a unit vector defining the asymmetry axis. The first term in (1) defines isotropic *true chiral* bianisotropic response. It is not zero only for three-dimensional meta-atoms with broken mirror symmetry. One can model this response, as is shown in Fig. 1(a), by the response of three uniaxial helices of the same helicity state arranged along the Cartesian basis unit vectors. The dimensions of the helices define amplitude T. A true chiral meta-atom (the three helices)



True (intrinsic) chiral (a) | Pseudochiral (extrinsic chiral) (b) | Uniaxial omega (c) | General reciprocal bi-anisotropic (d)

Fig. 1: Conceptual realizations of general reciprocal bianisotropic meta-atoms. (a) True chiral meta-atom. (b) Pseudochiral meta-atom. The right- and left-handed helices are shown in yellow and blue, respectively. Different size of the helices corresponds to the different amplitudes of polarizabilities. (c) Uniaxial omega meta-atom. (d) The conceptual representation of the bianisotropic meta-atom with electromagnetic coupling described by (2).

exhibits chiral effects (polarization rotation, circular dichroism, etc.) when illuminated from an *arbitrary* direction. It should be noted that true chirality can be achieved only with three-dimensional meta-atoms.

The second term in (1) refers to the so-called *pseudochiral* (or extrinsic) bianisotropic response [3, 5]. In the lossless case, it can be modelled by three metal helices oriented along the basis vectors $\mathbf{a}_i$ with the strengths of electromagnetic coupling determined by amplitudes P_i [see Fig. 1(b)]. The sum of all amplitudes P_i must be equal to the trace of the second dyadic in composition (1), i.e. equal to zero. This implies that the helices oriented along the basis vectors $\mathbf{a}_i$ must be of different handedness so that in total true chirality in the entire meta-atom is compensated. Importantly, although pseudochiral bianisotropic inclusions do not possess true chiral (isotropic) electromagnetic response, they do exhibit chiral effects for *certain* illumination directions, namely along the eigenvectors $\mathbf{a}_i$. This fact has led to far-reaching implications, enabling to achieve various chiral effects even with planar (two-dimensional) structures suitable for various nanofabrication techniques [3, 4, 5].

Finally, the last (antisymmetric) term in (1) represents *omega* bianisotropic coupling. A uniaxial omega meta-atom [2] (formed by two orthogonal omega-shaped inclusions) shown in Fig. 1(c) oriented along vector $\mathbf{b}$ is a proper module modeling such electromagnetic coupling. Illuminated along the $-\mathbf{b}$ and $+\mathbf{b}$ directions, the omega meta-atom possesses asymmetric scattering towards the direction of the source.

The universality of the described modular approach of reciprocal bianisotropic meta-atoms can be demonstrated by an example of an arbitrary inclusion with a given magnetoelectric dyadic $\overline{\overline{\alpha}}_{\rm em}$ (magnetoelectric dyadic can be determined for an arbitrary inclusion using various techniques [8, 9]):

$$\overline{\overline{\alpha}}_{\rm em} = -\frac{jV}{c}\begin{bmatrix} 2 & 1 & 0 \\ 1 & 2 & -1 \\ 0 & 1 & 2 \end{bmatrix}, \qquad (2)$$

where V is the volume of the meta-atom, c is the speed of light in vacuum, and j is the imaginary unit (time-harmonic dependency in the form $e^{j\omega t}$ is assumed). From (1) the amplitudes can be found: $T = -2jV/c$, $P_1 = jV/c$, $P_2 = 0$, $P_3 = -jV/c$, $A = -jV/c$. The eigenvectors are given in terms of the original basis vectors as $\mathbf{a}_1 = [-1;1;0]^T$, $\mathbf{a}_2 = [0;0;1]^T$, and $\mathbf{a}_3 = [1;1;0]^T$, while vector $\mathbf{b}$ is equal to $[1;0;0]^T$. Therefore, electromagnetic properties of the meta-atom with bianisotropic dyadic (2) can be described by the decomposition depicted in Fig. 1(d). As is seen from the figure, now the electromagnetic response is easily determined for different illumination directions. For example, the maximum chiral effect appears when the incident wave propagates along $\mathbf{a}_1$ because in this scenario the left-handed helix (shown in blue) is not excited, while the other three right-handed helices are polarized. Furthermore, the highest asymmetry of backscattering occurs when the virtual omega inclusion is excited, i.e. for incident waves propagating along vector $\mathbf{b}$.

IV. Conclusions

The modular approach allows us to extract all relevant information on the properties of a given bianisotropic meta-atom. Furthermore, to some extent, the approach can be also used for the inverse problem. Defining the desired electromagnetic response of the meta-atom for different illumination directions *in terms of separate modules* (similarly to Fig. 1(d)), one can find the required polarizability dyadics using (1). Next, synthesizing topology and dimensions of the meta-atom with the required polarizabilities is performed using either known theoretical models [7] or numerical and semi-analytical techniques (see e.g., [8, 9]). In the presentation, we will show more examples of the use of the modular approach for characterizing and synthesizing meta-atoms, including nonreciprocal designs.

References

[1] D.L. Jaggard, A.R. Mickelson, and C.H. Papas, “On electromagnetic waves in chiral media,” *Appl. Phys.*, vol. 18, pp. 211–216, 1979.
[2] M.M.I. Saadoun and N. Engheta, “A reciprocal phase shifter using novel pseudochiral or Ω medium,” *Microw. Optical Techn. Lett.*, vol. 5, no. 4, pp. 184–188, 1992.
[3] A.A. Sochava, C.R. Simovski, and S.A. Tretyakov, “Chiral Effects and Eigenwaves in Bi-Anisotropic Omega Structures,” in *Advances in Complex Electromagnetic Materials*, no. 28 in NATO ASI Series, pp. 85–102, Springer, Netherlands, 1997.
[4] A. Papakostas, A. Potts, D.M. Bagnall, S.L. Prosvirnin, H.J. Coles, and N.I. Zheludev, “Optical manifestations of planar chirality,” *Phys. Rev. Lett.*, vol. 90, p. 107404, 2003.
[5] E. Plum, X.-X. Liu, V.A. Fedotov, Y. Chen, D.P. Tsai, and N.I. Zheludev, “Metamaterials: Optical activity without chirality,” *Phys. Rev. Lett.*, vol. 102, p. 113902, 2009.
[6] S.A. Tretyakov, “Electromagnetic metamaterials: Past, present, and future,” Proceedings of *9th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (Metamaterials’ 2015),* pp. 19–21, Oxford, UK, September 2015.
[7] A. Serdyukov, I. Semchenko, S. Tretyakov, and A. Sihvola, *Electromagnetics of Bi-Anisotropic Materials – Theory and Application*, Amsterdam, the Netherlands: Gordon and Breach Science Publishers, 2001.
[8] V.S. Asadchy, I.A. Faniayeu, Y. Ra’di, and S.A. Tretyakov, “Determining polarizability tensors for an arbitrary small electromagnetic scatterer,” *Phot. Nanostr. – Fundam. Applic.*, vol. 12, pp. 298–304, 2014.
[9] R. Alaee, C. Rockstuhl, and I. Fernandez-Corbaton, “An electromagnetic multipole expansion beyond the long-wavelength approximation,” *Optics Communic.*, vol. 407, pp. 17–21, 2018.