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Recent Advances and Current Trends in Metamaterial-by-Design

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Abstract. Thanks to their potential applications in several engineering areas, metamaterials gained much of attentions among different research communities, leading to the development of several analysis and synthesis tools. In this context, the metamaterial-by-design (*MbD*) paradigm has been recently introduced as a powerful tool for the design of complex metamaterials-based structures. In this work a review of the state-of-art, as well as the recent advancements of *MbD*-based methods are presented.

1. Introduction and Metamaterial-by-Design Paradigm

In the last years artificial metamaterials attract the attention of researchers from different engineering areas, thanks to the several kinds of applications that effectively exploit the promising electromagnetic (*EM*) features of this class of artificial materials [1][2]. Anyway, the design of metamaterials when integrated into complex *EM* systems is a challenging task. The main issues are related to the time consuming optimizations, as well as non-optimal integrations of subparts of the complex system during the optimization of the metamaterial, leading to sub-optimal solutions [3]. For this reasons, the *Metamaterial-by-Design (MbD)* paradigm has been introduced, affording a new synthesis strategy based on a modular representation of the design process [3]. By sub-dividing the whole synthesis/analysis procedure, into several interconnected functional blocks, an *MbD* synthesis procedure allows to drive the design of the metamaterial towards the fulfilment of the system functional requirements. More in detail this novel design approach permits to select the most suitable methodology within each functional block in order to reach optimal trade-offs depending on the design constraints/requirements, and to combine together the advantages of different existing and novel techniques within the same design tool. Four main blocks compose the *MbD* synthesis loop: i) a global optimizer for the optimization of the geometric descriptors and dielectric properties of the elementary metamaterial cell; ii) an homogenization functional block, devoted to the computation of the macro equivalent homogenized dielectric parameters; iii) the forward solver tool, for a fast computation of the *EM* behaviour of the metamaterial device; iv) a physical linkage analysis module aimed at verify if the current solution fits the design goals and constraints, giving feedback to the optimization block. According to this synthesis scheme, different *EM* synthesis problems have been effectively addressed, starting from the design of radome-coated arrays for array miniaturization [4]-[6] integrating a quasi-conformal transformation optics (*QCTO*) method and a source inversion technique [4][5], and exploiting spline basis functions in order to reduce the number of degrees-of-freedom handled by the global optimizer [6]. These flexible design tools allow to reduce the number of radiators, having radiation properties that are close to the corresponding wider array, and to obtain trade-off solutions between the complexity/feasibility of the synthesized radome material and the array miniaturization.



In [7] the design of electromagnetic surface wave devices combining transformation optics and modal analysis has been recently proposed, while in [8][9] the synthesis of modulated metasurfaces with polarization control [8] and with multi-beam functionalities [9] have been presented, as well as metamaterial-based design methodologies for broadband aperture antennas [10] and dual-circularly polarized antenna based on the field transformation [11]. In [12][13] the problem of adding new features or to enhance the performances of linear phased arrays, without increasing the complexity of the feeding network, has been addressed exploiting the *MbD* paradigm, while in [14] the radiation efficiency of planar phased arrays has been enhanced by using layers of wide-angle impedance matching (*WAIM*) printed metasurfaces, by means of a multi-scale *MbD*-based methodology. Innovative design approaches for the synthesis of sectoral/conical horn antennas with advanced polarization functionalities [15] and compact layouts [16] have been recently proposed, exploiting metamaterial properties. Recently, multi-objective optimization strategies for the synthesis of highly directive nanodevices [17] and three dimensional frequency selective surfaces [18] have been proposed within the *MbD* framework. The presented instances of the *MbD* paradigm show that it represents a powerful approach for the design of future metamaterial-based complex systems, with promising potentialities on many other possible applicative contexts.

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