Review of recent progress on the homogenization theory and applications of wire media

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Abstract

We review recent contributions to the homogenization theory of wire media and discuss a variety of applications at microwave and THz frequencies. The analysis is based on spatially dispersive homogenization models for unloaded and loaded wire media with additional boundary conditions derived for different interface scenarios. The applications include, but are not limited to, metamaterial-based antenna and waveguide technology, subwavelength imaging, super lenses, absorbers, and have been recently extended to carbon-based nanomaterials.

The intention of this review paper is to demonstrate that the interaction of electromagnetic waves with complex wire-medium (WM) structures (in general, multilayered, periodic, and aperiodic configurations) with some typical geometries shown in Fig. 1, can be analyzed in a most elegant, physically insightful manner using the effective medium approximation, resulting in accurate analytical solutions for a wide range of frequencies. The homogenization theory is based on the quasi-static approach for uniaxial WM with a nonlocal dielectric function, which takes into account spatial dispersion effects, and generalized additional boundary conditions (GABC) at different WM interfaces [1, 2]. This has been extended to WM structures with deeply-subwavelength inclusions for the analysis of indefinite dielectric response and all-angle negative refraction [3]. With the use of thin metal conductors or graphene, an appropriate form of GABC has been obtained with applications to analytical modelling of wideband microwave absorbers. In addition, an alternative approach, which is based on the transport (drift-diffusion) model, has been proposed for analysis of 2-D and 3-D WM structures [4]. Moreover, a numerical model [5] and the effective medium model [6] have been developed for periodic arrays of metallic carbon nanotubes, which take into account quantum properties of carbon nanotubes and electromagnetic interactions between them.

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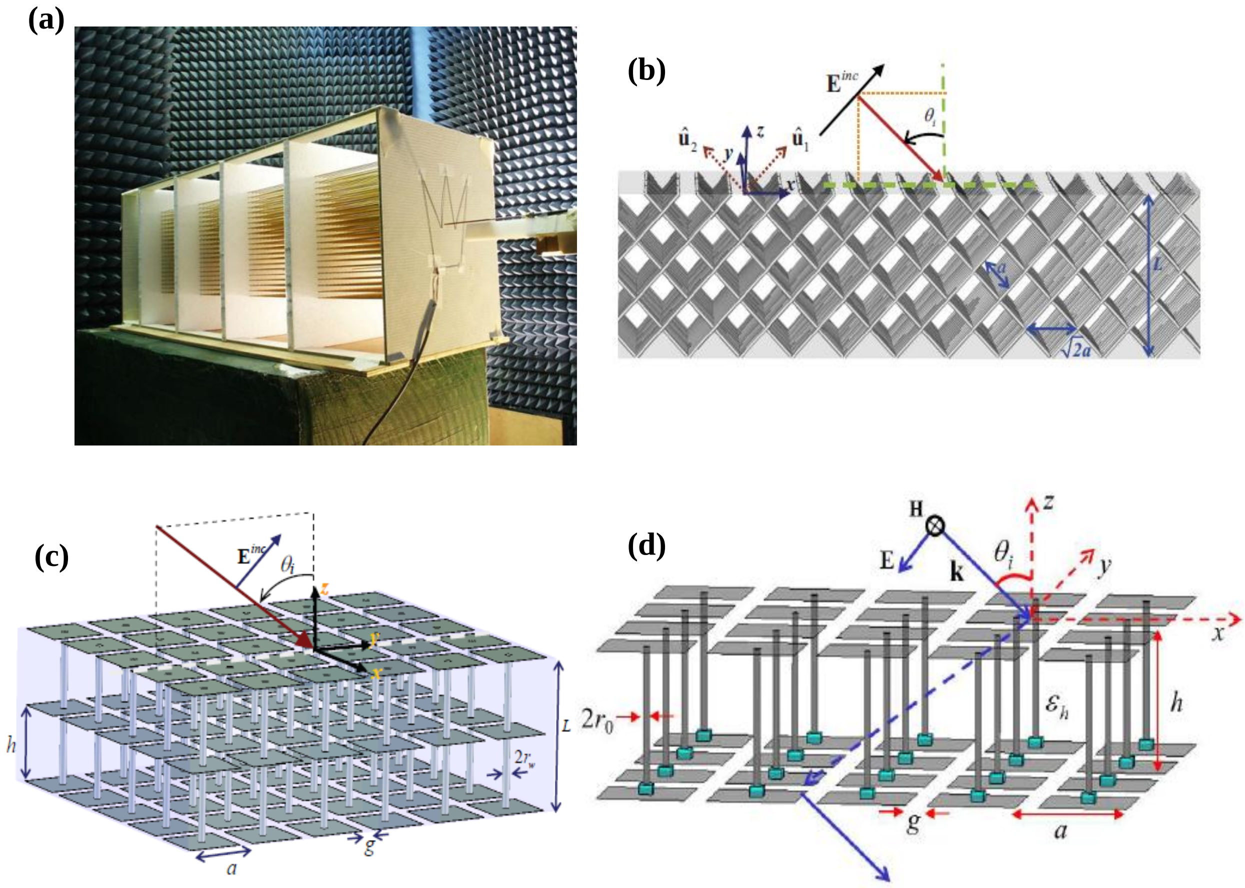

Fig. 1: Geometries of structured uniaxial wire medium that have been analyzed using the homogenization theory methods. (a) Wire medium [7], (b) crossed wire mesh [9], (c) WM loaded with patches [10], and (d) mushroom structure with loaded vias [3].

Within the framework of homogenization models developed for WM structures, a variety of electromagnetic problems have been solved for applications at microwave and THz frequencies. This includes the analysis of artificial impedance surfaces (reflection properties and natural waves of high-impedance surfaces, such as bed-of-nails and mushroom-type surfaces) [11-13], subwavelength imaging with the array of parallel wires [7, 8], negative refraction phenomena with crossed wires [9], mushroom-type structures with lumped inductive/capacitive loads, broadband microwave absorbers with stable angle characteristics, among others. In all the cases the analytical results of homogenization models have been verified with full-wave commercial programs (with some results depicted in Figs. 2(a) and 2(b)), showing excellent agreement, and in some cases the results have been confirmed with experiment (Fig. 2(c)).

In the presentation, the basic concepts of the homogenization theory of wire media will be discussed, with a variety of examples and applications demonstrating different physical phenomena and practical realization of devices.

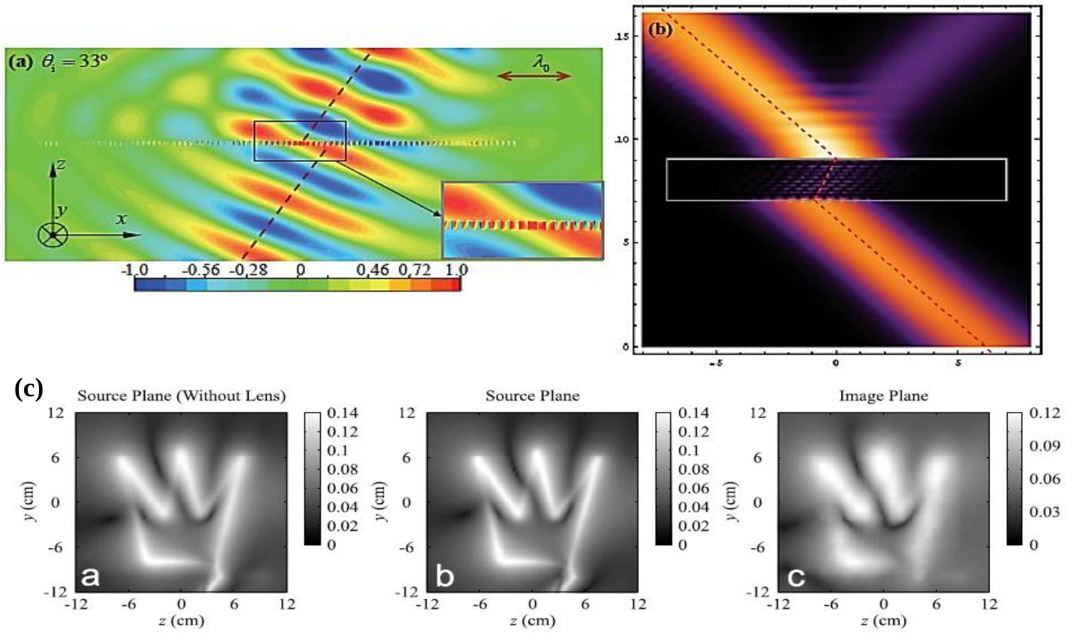

Fig. 2: Numerical results validating the predictions of the homogenization theory: (a) Negative refraction by a mushroom structure with loaded vias [3], (b) negative refraction by a crossed wire mesh [9], and (c) experimental validation of subwavelength imaging using parallel wires [7].

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