Electromagnetic wave control by metasurfaces: from design to manufacturing

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Abstract

Recently, there have been a new interest in controlling and manipulating electromagnetic waves in different frequency ranges. The development of new two-dimensional materials, called meta-surfaces, have been used to control and tailor the electromagnetic waves propagation properties. Several studies focused their attention on phase modulation, very few on amplitude. However, there have been no general design procedure able to control both of them at the same time.
Therefore, the aim of this paper is to develop a robust design tool to manipulate the electromagnetic wave behavior over flat and 3D objects. The proposed approach will be used to design, manufacture and experimentally measure metasurface-based devices for lenses, cloaking, manipulation and bending applications. Good agreement between analytical, numerical, and experimental results has been achieved, proving that the realized devices are wideband, polarization independent, easy to fabricate and can be scaled in different frequency ranges from microwave to optics.

1. Introduction

The possibility to manipulate electromagnetic waves (in terms of amplitude and phase) is of great importance from microwave to optical frequencies. During the years, several techniques have been used: dielectric, magnetic and/or magneto-electric materials [1]; photonic crystals [2], resonators [3] and metamaterials [4]. Their peculiar interest relies on the realization of negative electric and/or magnetic responses and, thereby, negative refractive index [5], which can be used to accomplish new interesting properties not easily founding in nature [6]. Unfortunately, such promising and potential applications are limited in practice due to the high losses, strong dispersion behavior, narrow-bandwidth and the difficulty in their fabrication [7]. Recently, the concept of meta-surface emerged as new solutions to manipulate the propagation of electromagnetic waves [8]: the reason behind their success is due to the possibility to engineer phase (by controlling their permittivity/permeability) with the use of "electrically" small (metallic/dielectric) inclusions [9]. Meta-surfaces (in terms of single-layer or few-layer stacks) not only reduce problems such as losses and occupied space, but also can be rapidly fabricated using existing technologies such as lithography and nano-printing methods [10]. Despite all such advantages, a general design approach (for amplitude and phase) is still required. The aim of this work is to present a general comprehensive tool to design devices with electromagnetic properties able to control both the amplitude and phase of the electromagnetic wave.
In the first part of the paper, we will present the theory behind such general design tool. Then, to validate and test the proposed approach, some examples for space and guided waves are shown. Numerical and experimental results in the microwave frequency range are presented, showing good performance in terms of polarization/source independence and broadband behavior.

2. Generalized Meta-Surface Design Tool

Here we consider two main scenarios: planar and curvilinear 3D structure as shown in Fig.1. The dielectric slab has thickness d and relative permittivity $\varepsilon(\mathbf{r})$. Let's assume (for simplicity) that the propagation is in the generic $\mathbf{r}(x, y, z)$ direction, with $e^{-j\mathbf{k}\cdot\mathbf{r}}$ the propagation factor. To describe the generalized metasurface structure, let's start from the resolution of Non-Homogenous linear second order Wave Differential Equation (NHWD) for the source free scenario [11]. Typically, the electric field $E(\mathbf{r},\omega)$ is function of the generic position $\mathbf{r}$ and the frequency ω, but here, for simplicity we consider the electric field a scalar quantity and monochromatic. In this case we can write $E(\mathbf{r},\omega)= E(\mathbf{r})e^{-j\omega t}$, being $E(\mathbf{r})=A(\mathbf{r})e^{-\Phi(\mathbf{r})}$ the complex amplitude, where $A(\mathbf{r})$ and $\Phi(\mathbf{r})$ are the amplitude and phase (real quantities) of the wave, respectively. In literature, it is known that for arbitrary $\varepsilon(\mathbf{r})$, closed general solutions of NHWD are not available [12]. Consequently, only solutions in closed-forms and in terms of known functions for certain "special cases" have been given in the literature [13].

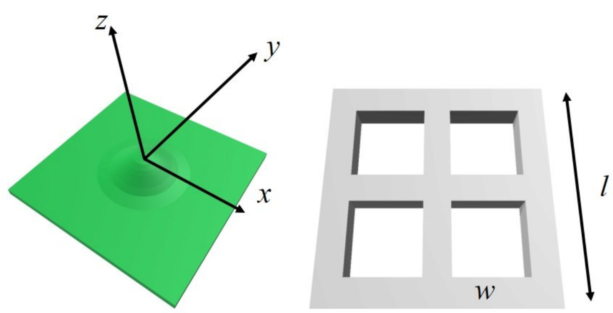


Figure 1. (a) Generic 3D object under study; (b) metasurface structure unit-cell: with w the width and l the length.

Here we developed a simple generalized method to solve the NHWD, by using the Wentzel–Kramers–Brillouin (WKB) method [14]. We have for the phase and the amplitude respectively:

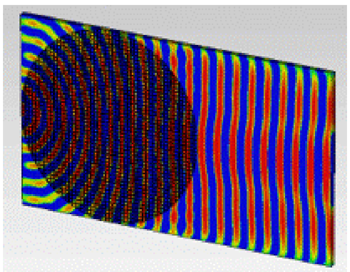
$$A(\mathbf{r}) = \frac{\varepsilon_{s2}(\mathbf{r})}{\varepsilon_{s1}(\mathbf{r})} \cdot e^{-\int_{s1}^{s2} \frac{\nabla^2 \Phi(\mathbf{r})}{\varepsilon(\mathbf{r})} ds}$$
$$\Phi(\mathbf{r}) = \Phi_0 + \int_{s1}^{s2} \varepsilon(\mathbf{r}) d\mathbf{r} \tag{1}$$

The solution of such equations permits to design the meta-surface structure properly, in accordance with specific requirements. It relates the meta-device geometrical characteristics (such as shapes, dimensions) with its electromagnetic properties. Such procedure provides an efficient tool for manipulating both space and surface waves control.

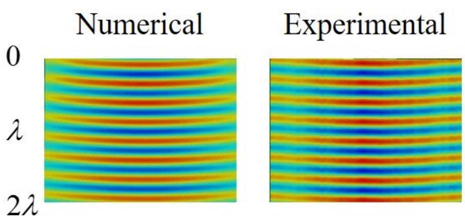
3. Metasurface-Devices Applications: modeling, design, and manufacturing

We are going to demonstrate the reliability and the usefulness of the design tool by showing some interesting applications: such as ultrathin invisibility cloaks for surface waves, modulators, flat lenses and bending of electromagnetic waves. The metasurfaces in this paper have been realized by tailoring metallic inclusion properties and integrating traditional materials.

All the structures are illuminated by an electromagnetic source (plane wave/cylindrical/spherical), placed at the left, operating in the frequency range of our interest (8-12 GHz), at a central frequency of 10 GHz. Independently from the type of the source used, the aim is to transform the original electromagnetic field configuration in a new one, by using meta-surfaces. Following the guidelines reported in the previous paragraph, we design the meta-surface, accordingly. Numerical and experimental results are shown in Figure 2, where the meta-surface acts as: flat Luneburg lens (a), electromagnetic invisibility cloak (b), beam splitter (c) and guiding structure for guided/surface waves(d).



(a)



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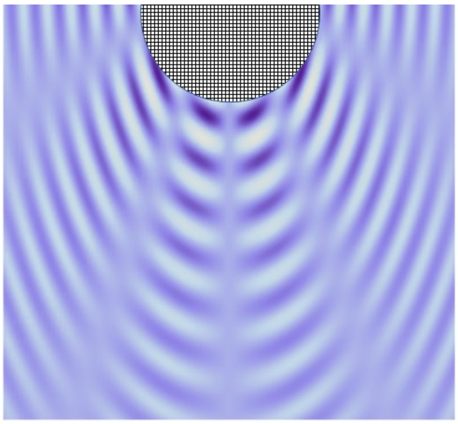
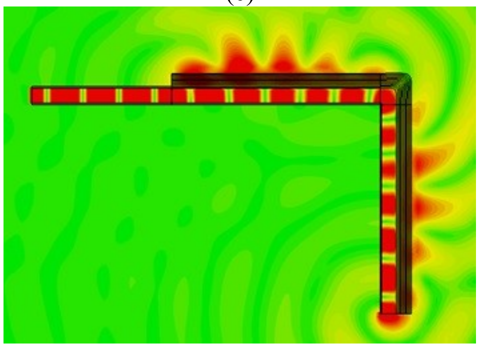


(c)



(d)

Figure 2. (a) Flat Luneburg lens; (b) electromagnetic invisibility cloak (numerical and measurements results comparison); (c) beam splitter and (d) guiding structure.

4. Conclusions

In this paper, a new metasurface-based design tool for electromagnetic wave manipulation on flat and 3D curved objects was presented. A new analytical model was developed to design specific required devices and link their electromagnetic properties with the physical and geometrical characteristics of the materials. The approach has been applied to both flat and 3D conformal surfaces. The examples have been designed, simulated, manufacture and measured in the microwave region, showing good performances in terms of insensitivity to the type of field configuration of the source used and good broadband behavior. The proposed approach can be applied for different applications such as antennas, sensing devices, and absorbers for both free space and guided waves.

5. Acknowledgements

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