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From spacetime effective media to cascaded frequency conversion

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Abstract

Wave propagation in materials modulated in space and time has become a new paradigm for a full control of wave-matter interactions. Here, we will discuss our recent efforts in the field using time interfaces (i.e., a rapid change in time of the electromagnetic parameters of the medium where a wave travels). Applications include the use of time interfaces to enable space-time effective media, as well as frequency conversion in dielectric slab waveguides (single and cascaded waveguides) where the cladding material is time varying while the core does not change with time.

1. Introduction

The arbitrary control of wave propagation allowed by artificially engineered metastructures has enabled the proposal and demonstration of improved and new applications in fields such as computing, sensors, antennas, and even artificial intelligence, among others [1]–[6]. This has been possible as metamaterials and metasurfaces provide an unparalleled manipulation of their electromagnetic (EM) responses, which are not always easily available in natural media at a given desired spectral range (such as negative or near-zero values of permittivity, ε_r , and or permeability μ_r)[7]–[9]. Research and innovation in this field has shown how wave propagation can be controlled using spatial inhomogeneities.

In recent years, we have witnessed an increased interest into exploring the physical phenomena that occur when the EM response of the media where a wave propagates is modified not only in *space* but also in *time* (i.e., space-time media)[10–23]. An example of such time-modulation is time interfaces (or time boundaries) where the EM parameters of a material are rapidly changed in time from $(\varepsilon_{r1}, \mu_{r1})$ to $(\varepsilon_{r2}, \mu_{r2})$ at a time $t = t_0$ [24], [25]. In so doing, a time reflected (backward) and a time refracted (forward) wave are produced. Different from spatial interfaces between two media, for time interfaces the wave number and wavelength are not modified while the frequency of the wave(s) (forward/backward waves) inside such material is changed due to this process.

In this work, we will discuss some of our recent efforts in exploring four-dimensional media using time interfaces. It will be considered that the permittivity of the medium where the wave travels is time-modulated while the permeability is not time-dependent. Several applications will be discussed including how a combination of spatially subwavelength multilayers (formed by two materials, A and B) can be engineered to develop effective medium concepts in space and time. This is achieved by considering that one of the filling materials (material B in this case) is time-dependent [26] while the other material (A) is not. Other applications will also be discussed in detail such as optical dielectric slab waveguides where their cladding material is modulated in time to induce a time interface at $t = t_0$. It will be shown how effective medium concepts also apply in this scenario demonstrating how frequency conversion is also possible even when only the cladding materials is time-dependent [27].

2. Space-time media

Schematic representations of some of the applications to be discussed using space and time interfaces along with effective medium concepts are shown in Fig. 1. In Fig. 1a, we consider the case of a parallel plate cavity filled with an isotropic dielectric medium having a relative permittivity value of ε_{r1} for times $t < t_0$. At $t = t_0$, a spatial subwavelength multilayer structure is generated inside the cavity by keeping some layers with the same value of $\varepsilon_{rA} = \varepsilon_{r1}$ while other layers are changed in time to $\varepsilon_{rB} = \varepsilon_{r2} \neq \varepsilon_{r1}$. Various scenarios will be discussed during the conference such as $\varepsilon_{rB}(t)$ being defined as a step function or multi-stepped periodic function, and the effect of inducing vertical or horizontal multilayers in time, among others.

As another application. the schematic representation of dielectric slab waveguides where their cladding is time-dependent is shown in Fig. 1b. Here, the core is time-independent with time interfaces induced only to the cladding. i.e., ε_{clad}(t). A full physical study of this scenario will be presented during the conference showing how the effective refractive index of the single mode that propagates within the waveguide is changed in time when applying the time interface to the cladding material. The effect of cascading, both in space and time, multiple dielectric slab waveguides will also be discussed It will be shown that cascaded frequency conversion is also possible with the proposed four-dimensional waveguides.

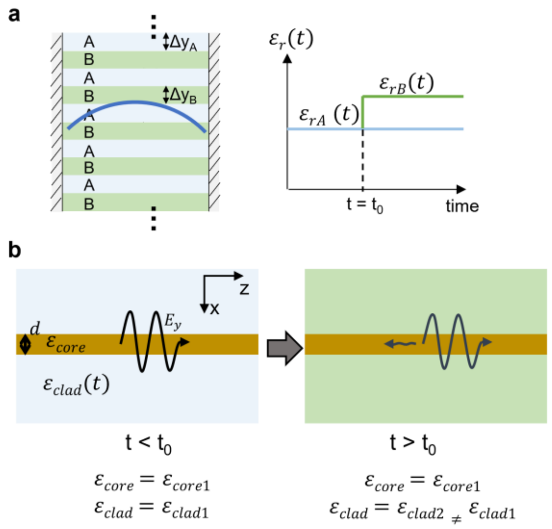

Figure 1. Effective medium concepts in space-time media (a) and dielectric slab waveguides involving time modulated cladding.

3. Conclusions

In summary, here we propose and study the effects of inducing time interfaces to create spatially subwavelength multilayer structures in time, and evaluate their response in terms of effective medium theory in four-dimensions (*x,y,z,t*). It has also been discussed how space-time effective medium theory can also be exploited in dielectric slab waveguides where time interfaces are applied to their cladding material. These results may open new avenues for a full control of wave-matter interactions in four-dimensional metastructures.

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