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Some Recent Advances in Space-Time-Coding Metasurfaces

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Abstract

We provide a compact summary of our recent results and ongoing research on digital metasurfaces based on spatio-temporal coding. Examples of field manipulations include harmonic beam steering and/or shaping and programmable nonreciprocal effects. Possible applications range from wireless communications to radars and imaging.

1 Introduction

Conventional metamaterials and metasurfaces are artificially engineered structures realized by arranging suitably designed sub-wavelength inclusions in a host medium. A variety of advanced field manipulations can be attained by gradually changing the inclusions' properties along one or multiple *spatial* directions. More recently, the increased availability of rapidly reconfigurable inclusions has granted access to the *temporal* dimension as well, and the field of *space-time* meta-structures [1, 2] is establishing itself as one of the most promising research areas.

In a series of ongoing studies, we have been exploring a class of space-time metastructures based on the concept of "digital coding metasurface" originally introduced by Cui *et al.* [3]. These platforms rely on a limited number of (e.g., only two) inclusion types, which not only yields significant simplifications in the design process, but also establishes an important connection between the physical and digital worlds, with fascinating information-theoretic implications and perspectives [4]. Moreover, the "coding" description of metamaterials is particularly apt to the integration of active elements (e.g., diodes or micro-electro-mechanical systems) controlled by an integrated circuit, thereby leading to "programmable" metamaterial architectures. In what follows, we briefly summarize the main outcomes from our studies, as well as possible future investigations and perspectives [5].

2 Summary of Recent Results and Ongoing Research

In [6], we put forward the idea of a space-time-coding metasurface, which is conceptually illustrated in Fig. 1. We consider a digital, programmable metasurface [3] for which the

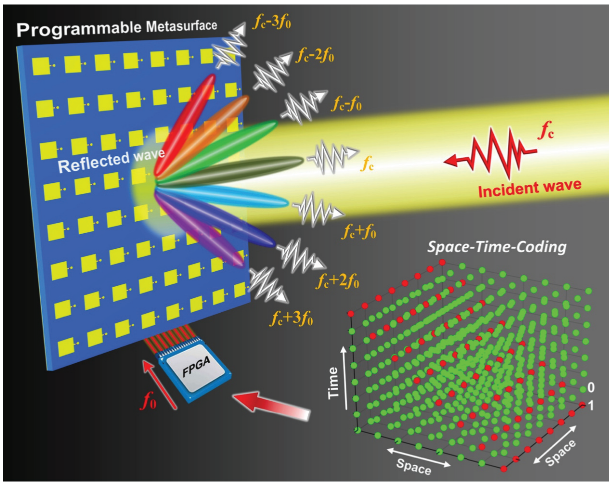

Figure 1. Conceptual illustration of a space-time-coding digital metasurface (adapted from [6]).

electromagnetic response of each element (yellow square patches) can be switched via a diode between two possible states (e.g., in-phase and out-of-phase reflection), associated with the 0/1 bits. The switching is controlled in space and time by a field-programmable gate array (FPGA), according to a given coding (represented by the 3-D matrix of red and green dots) which can be designed and optimized so as to perform simultaneous field manipulations in both space and frequency domains. For instance, as shown in Fig. 1, the metasurface can re-radiate an impinging beam into multiple beams at different frequencies and directions, in a controllable fashion, thereby realizing harmonic beam steering. This specific application example was also verified experimentally by means of a microwave (X-band) prototype, demonstrating good agreement with the theoretical predictions [6]. Other possible manipulations include beam steering and shaping at the central frequency, and radar-cross-section reduction by redistributing the scattered power in both space and frequency domains [6].

More recently, we applied the space-time-coding concept to break Lorentz reciprocity [7]. Our approach provides a technologically viable route for the time-varying schemes theoretically proposed in [8, 9] to attain nonreciprocal effects. As conceptually illustrated in Fig. 2, by inducing a suitable spatio-temporal phase gradient in a digital (four-

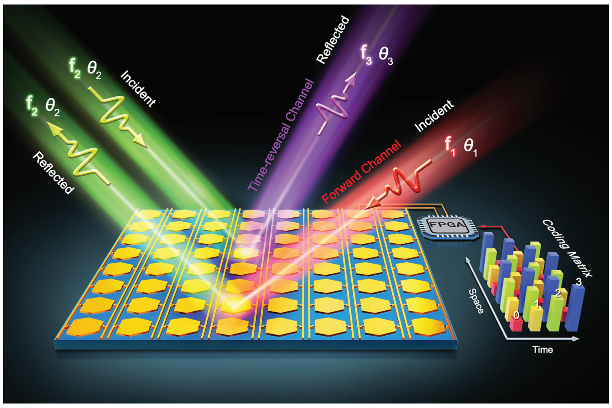

Figure 2. Conceptual illustration of a a nonreciprocal reflection realized via a space-time-coding digital metasurface (from [7]).

state) metasurface, we can realize a nonreciprocal reflection. Specifically, the reflected wave in the time-reversal scenario exhibits a different direction and a frequency shift with respect to the original obliquely incident wave. Also in this case, the theoretical predictions are backed by experimental validation at microwave frequencies [7], although, due to some experimental restrictions, we were only able to demonstrate the frequency-shift effect. It is worth stressing that, in view of the the inherently programmable nature of the platform, these nonreciprocal effects can also be realized "on-demand."

We are currently working on the implementation of more advanced harmonic beam-shaping/steering functionalities, whereby the scattering patterns at different harmonics can be controlled *simultaneously* and *independently*. Preliminary numerical and experimental results are encouraging [10]. We are also exploring hybrid (phase/amplitude) modulation schemes for better tailoring of the harmonic content.

3 Conclusions

Digital programmable metasurface provide a very powerful and versatile platform for implementing spatio-temporal modulation schemes. The temporal dimensionality represents a crucial addition within the emerging paradigm of "information metastructures" [11, 12], enabling advanced (possibly non-reciprocal) field-manipulation capabilities in both the frequency and spatial domains. Potential applications are abundant, and include for instance multi-input and multi-output wireless communications, cognitive radars, adaptive beamforming, and holographic imaging. Specifically, non-reciprocal effects can be very useful for separating the transmitting and receiving channels in communications and radar systems.

With a view toward extensions to the terahertz and optical ranges, the exploration of faster (e.g., graphene-based, femtosecond laser-driven) switching mechanisms is of great interest. Other worthwhile extensions include transmission-type scenarios as well as different physical domains (e.g., acoustics).

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