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From Tunable and Reconfigurable to Space-Time Modulated Multifunctional Metasurfaces

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***Abstract*—This abstract introduces a reconfigurable and multifunctional metasurface platform, that can adapt to various functional demands. It is shown that, by locally controlling parameters of each meta-atom, the metasurface can perform multiple reciprocal functions. In addition, by modulating the meta-atoms in both space and time, the same metasurface can provide nonreciprocal functionalities such as wave circulation and isolation. Switching between different electromagnetic functionalities is realized by setting different parameter values or different time modulation laws for tunable components embedded in each meta-atom, without the necessity of changing the metasurface body. We think that this technique is very promising for applications, especially in future adaptive and intelligent communication networks.**

I. INTRODUCTION

To adapt to the future more complex and uncertain communication environments, dynamic and instant control of electromagnetic wave propagation has become the most attractive method. Metasurfaces are ultra-thin material sheets that can realize desired wave conversions by engineering the induced surface currents. By integrating tunable components or materials, such as varactors, varistors, and graphene into a metasurface, the induced surface currents can be modified and therefore the scattering properties can be reconfigured as desired, without the need of changing the metasurface body [1].

In this talk, we will show that a universal metasurface platform with locally tunable components embedded in meta-atoms can provide not only a possibility to reconfigure its response (like changing the reflection direction), but offers a wealth of different electromagnetic functionalities. The proposed platform can dynamically control the scattering directions and amplitudes in a general manner, realizing reciprocal, nonreciprocal, and other exotic wave effects demanded by future communications.

II. RESULTS

Let us consider an impenetrable metasurface formed by periodic capacitive patches supported by a grounded substrate. The unit cell of the metasurface is shown in Fig. 1. It consists of N sub-cells, and the length of each sub-cell is d. The neighboring patches are connected by a varactor whose capacitance can be dynamically controlled by an external biasing network. The effective capacitance of each meta-atom in one unit cell is denoted as C_i, where $i \in [1, N]$. For a specific incidence angle $\theta = +\theta_\mathrm{i}$, depending on the unit-cell size $D = Nd$ and the incidence frequency ω_0, the tangential wavevectors of the scattered modes can be determined by the grating equation, $k_0 \sin\theta_\mathrm{i} + \frac{2\pi n}{D} = k_{zn}$, where n is the index of scattered modes. For modes satisfying $k_{zn} < k_0$, the wave is reflected into free space.

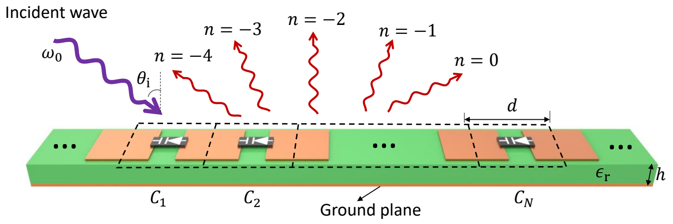

Fig. 1. Schematics of a reconfigurable metasurface composed of periodically arranged patches with embedded varactors.

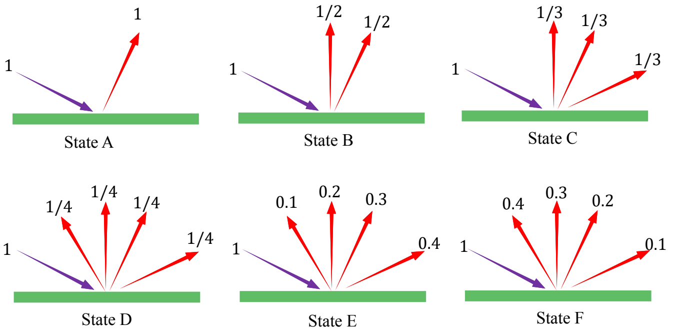

Fig. 2. Target states of the reconfigurable metasurface. The power shares of scattered modes are shown in the figure as fractions of the incident power. The indices of scattering modes are the same as shown in Fig. 1. In this example, the incidence angle is $\theta_\mathrm{i} = +70°$. The reflection angles of modes $n = 0, -1, -2, -3, -4$ are $\theta_\mathrm{r} = +70°, +28°, 0°, -28°, -70°$, respectively.

The effective impedance of the i-th meta-atom is denoted as $Z_i = \frac{1}{j\omega_0 C_i}$. Assuming that the impedance is homogeneous within each sub-cell, the effective sheet impedance of the metasurface in one unit is expressed as a function of position $Z_\mathrm{s}(x)$, where $Z_\mathrm{s}(x) = Z_i$ for $x \in (\frac{i-1}{N}d, \frac{i}{N}d)$. For an arbitrary $Z_\mathrm{s}(x)$, knowing the incident wave (θ_i, ω_0) and the substrate parameters (ϵ_r, h), the amplitudes and phases of all reflected modes can be analytically solved by the mode-matching method developed in [2]. In other words, the complex amplitude of the n-th scattered mode A_n can be expressed as a function of the physical parameters of the metasurface and the incidence parameters, $A_n = f_n(\epsilon_\mathrm{r}, h, \theta_\mathrm{i}, \omega_0, Z_1, \cdots, Z_N)$.

TABLE I
OPTIMIZED SURFACE IMPEDANCES FOR THE SIX STATES LISTED IN FIG. 2.

State \ Z_i	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	E_a
A	-j382	-j900	-j123	-j152	-j179	-j241	3.25%
B	-j281	-j112	-j167	-j338	-j499	-j191	1.05%
C	-j106	-j152	-j255	-j400	-j157	-j179	0.00%
D	-j197	-j413	-j152	-j245	-j147	-j184	2.76%
E	-j355	-j196	-j296	-j30	-j165	-j189	0.00%
F	-j124	-j336	-j119	-j193	-j181	-j332	0.00%

Unfortunately, the function f_n can not be explicitly expressed, due to the matrix operations entailed in the mode-matching method. To find the optimal impedances which can produce a desired set of scattered modes, we optimize Z_i in MATLAB until the scattered modes satisfy our targets. For different targets, we can always use the same method to find the optimal set of Z_i. In this way, only by reconfiguring Z_i (equivalently, C_i) of each meta-atom, one can achieve multiple scattering states for different practical applications.

As an example, next, we show that the proposed platform can switch among an anomalous reflector, 2-channel, 3-channel, and 4-channel beam splitters only by setting proper Z_i. To do this, we assume that there are $N = 6$ sub-cells in one spatial period. The incident angle is $\theta_{\rm i} = 70^\circ$, the incident wavelength is $\lambda_0 = \frac{\sin\theta_{\rm i} N d}{2}$, such that five Floquet modes ($n = 0, -1, -2, -3, -4$) are allowed to propagate in free space (see Fig. 1) according to the grating equation. The substrate parameters are $\epsilon_{\rm r} = 3.55$ and $h = \lambda_0/15$. Figure 2 defines six target states of the metasurface. For states E and F, we arbitrarily define the powers scattered to the 4 splitting channels, to show the generality of the design approach. The optimized impedance values for each state are listed in Table I. The last column of Table I shows the average error of optimization E_a, which is negligibly small. E_a measures the performance difference of the optimized structure with respect to the defined targets in Fig. 2. It is calculated as $E_a = \frac{1}{M}\sum_n \frac{|P_n - O_n|}{O_n}$, where P_n is the power of the n-th scattering mode for the optimized surface impedance (n refers to the target scattering modes in the optimization), O_n is the power of the n-th mode as defined in Fig. 2, and M is the total number of n.

In recent years, time-varying systems have attracted attentions, since they can break time-reversal symmetry of conventional systems and realize magnetless nonreciprocal effects. Here, we show that if the effective capacitance of each meta-atom is periodically dependent on time [see Fig. 3(a)], $C_i(t) = C_i(t - T_{\rm m})$, it is possible to realize nonreciprocal functionalities by assigning proper modulation functions on each meta-atom. Our recent work [3] has demonstrated that, by applying different traveling-wave modulations on the metasurface, the device can perform as a spatial circulator, quasi-isolator, and gyrator, without changing the physical configuration of the metasurface, as shown in Fig. 3(b). Traveling-wave modulation means that all the meta-atoms are modulated in the same way but there is a fixed phase difference of modulation of adjacent meta-atoms, i.e., $C_i(t) = C_{i+1}(t + T_m/N)$, exhibiting a progressive modulation wave along the array plane. Although Reference [3] has verified the idea using a time-varying inductive sheet, the concept can also be applied to time-varying capacitive surface, as shown in Fig. 3(a). In addition to nonreciprocal effects, such space-time modulated metasurfaces can exhibit other exotic wave phenomena that cannot be realized in passive devices. One example is a wave concentrator, where incident waves from different spatial directions are reflected to a single direction with full efficiency, as shown in Fig. 3(a).

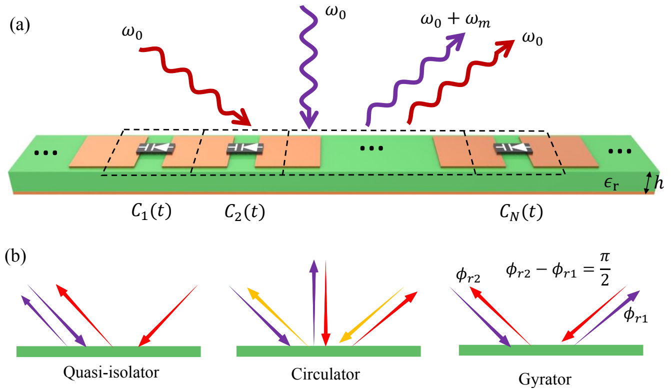

Fig. 3. (a) Space-time metasurface platform. (b) Nonreciprocal states achieved by the universal space-time platform, as demonstrated in [3].

III. CONCLUSIONS

We have proposed the concept of a multi-functional reconfigurable metasurface, where various functionalities can be instantly switched by locally changing the material parameters (capacitance of varactors). Controlling the material parameters in both space and time allows the most general wave conversions, realizing both reciprocal and nonreciprocal advanced wave effects.

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