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Reconfigurable Metasurfaces for Radar and Communications Systems

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Abstract

Recent research on holographic and diffractive metasurfaces shows enormous promise for developing cheaper and more compact systems. A metasurface aperture exploits the phase shift inherent in the guided reference wave and avoids using active elements such as phase-shifters associated with conventional phased arrays and electronically scanned antennas. The radiation pattern can thus be controlled by altering properties of each metasurface element coupled to the reference wave. In this paper, we discuss parameters to control the metasurface for a radar or communications payload. In both cases, the reconstruction of the received aperture field relies on using computational imaging techniques on arbitrary and spatially diverse field patterns.

1 Introduction

Metamaterials are artificial composite materials specifically engineered to exhibit properties not typically found in nature, for instance, the ability to manipulate electromagnetic radiation in new ways [1]. Metasurfaces provide unique capability to control electromagnetic (EM) waves using a low-profile low-cost hardware by controlling phase across the surface using periodic arrays of sub-wavelength elements. Traditionally, metasurfaces have been passive and fabricated for a specific functionality over a narrow bandwidth, such as beam reflection, polarization conversion, scattering reduction, or beam focusing. However, recent advances in metamaterial research have shown that these radio-frequency (RF) metasurfaces can be made reconfigurable by embedding tunable voltage-controlled elements, such as diodes, in each of the sub-wavelength unit cells.

A major distinction between metasurface antennas and traditional phased arrays are the sub-wavelength spacing and thickness of the scattering particles in the metasurface. Given the operating wavelength λ, the traditional phased arrays comprise of conventional radiating elements, such as dipoles, patches, or notches, spaced $\sim \lambda/2$ at the highest frequency of operation and a phase shifter at each radiating element. Beamforming is performed by varying the phase at each element to steer the beam in a desired direction through constructive interference. Typically, RF power amplifiers are combined with phase shifters to compensate for loss in active phase shifting, which results in greater power consumption and significant cost.

In contrast, metasurface antennas are electrically thin composite structures able to transform arbitrary incident waves into desired transmitted/reflected waves through the use of sub-wavelength scatterers (meta-atoms) to control the transmitted/reflected amplitude and phase distribution across the antenna aperture. Using the surface equivalence principle (SEP) and effective boundary conditions, meta-atoms are carefully designed to transform the incident wave (source) into a transmitted/reflected wave with a desired amplitude and phase response. Typically, each meta-atom is characterized by its electric and magnetic surface impedance, susceptibility, or polarizibility. A common technique to synthesize the effective surface suscepbilities of a metasurface is to use the generalized sheet transition conditions (GSTCs) [2, 3]. Through similar principles, Huygens' metasurfaces (HMS) are realized with two-dimensional arrays of polarizable particles that provide both electric and magnetic polarization currents to generate prescribed wave fronts [4, 5]. The following relations between the effective electric and magnetic surface currents ($\vec{J}_s$ and $\vec{M}_s$), respectively, of a meta-atom with the electric sheet admittance ($\bar{\bar{Y}}_{es}$) and magnetic sheet impedance ($\bar{\bar{Z}}_{ms}$) can be used to transform fields across the metasurface interface [4],

$$\vec{J}_s = \hat{n} \times (\vec{H}_2 - \vec{H}_1) = \bar{\bar{Y}}_{es} \cdot \vec{E}_{t,av}|_S \tag{1}$$

$$\vec{M}_s = -\hat{n} \times (\vec{E}_2 - \vec{E}_1) = \bar{\bar{Z}}_{ms} \cdot \vec{H}_{t,av}|_S, \tag{2}$$

where $\vec{E}_{t,av}|_S$ and $\vec{H}_{t,av}|_S$ are the average tangential electric and magnetic fields to the meta-atom surface. Additionally, transmission (T) and reflection (R) of a periodic metasurface can be related to isotropic sheet impedances for a normally incident plane wave using,

$$Y_{es} = \frac{2(1-T-R)}{\eta(1+T+R)} \tag{3}$$

$$Z_{ms} = \frac{2\eta(1-T-R)}{(1+T+R)}, \tag{4}$$

where $\eta = \sqrt{\frac{\mu}{\varepsilon}}$ is the free-space impedance [4]. The far-field radiation pattern of the reconfigurable metasurface under point source excitation can be calculated using [6],

$$f(\theta,\phi) = \sum_{m=1}^{M}\sum_{n=1}^{N} e^{j\left(\phi'(m,n)+kD\sin\theta\left[\left(m-\frac{1}{2}\right)\cos\phi+\left(n-\frac{1}{2}\right)\sin\phi\right]\right)}, \tag{5}$$

where $\phi'(m,n) = \phi(m,n) - kr'_{m,n}$, M and N denote the number of unit cells along the x and y dimensions of the planar metasurface, respectively. The index of each individual unit cell is denoted by m and n and $\phi(m,n)$ is the reflection phase of each unit cell, D is the unit cell grid spacing, the wavenumber is $k = \frac{2\pi}{\lambda}$, and $r'_{m,n}$ is the distance between the feed and each unit cell. While [6] assumes $\phi(m,n)$ to be binary, either 0^o or 180^o, this work extends the definition of unit cell reflection phase to $\phi(m,n,t) = \phi_{beamforming}(m,n) + \phi_{modulation}(m,n,t)$ incorporate both reconfigurable beamforming and time-varying signal modulation functionalities directly in the metasurface. $\phi_{beamforming}(m,n)$ is typically performed by applying a periodic progressive phase shift along the electric field direction [7, 8] or using other holographic beamforming techniques [9, 10].

In our previous work [11], we demonstrated innovative techniques to transform a conventional dipole antenna into a directive high-gain mechanically scanned antenna for radar, communication, and direction finding applications by parasitically loading the dipole antenna with arrays of electrically close metamaterial elements. Later, in [12], we incorporated electronic switching and tuning using embedded active circuit elements for dynamic frequency tuning and electronic beam scanning. We then extended this *reconfigurable* metamaterial antenna concept to metasurfaces in [13] by simulating passive and active variants of a holographic metasurface antenna as a proof of concept of an addressable and reconfigurable metasurface.

In this paper, we provide an overview of controllable metasurface parameters for both radar and communications payloads. In nearly every antenna application, the far-field radiation pattern has a Fourier transform relationship with the aperture field distribution and it suffices to have the ability to create arbitrary field distributions within the aperture. Reconfigurable metasurface antennas are generalized programmable RF devices that provide multifunction control of electromagnetic waves through amplitude and/or phase control of transmitted and reflected fields. In the next section, we discuss some specific radar applications of reconfigurable metasurfaces.

2 Metasurfaces for Radar Systems

A radar system sends out radio waves and uses the reflected echoes to create an image of a distant target. Metasurfaces are attractive for array-based radars and can enable mass production of compact radar systems. For example, in platforms such as small unmanned aircraft systems (UASs), the relatively high cost and SWaP (size, weight, and power) of phased array antennas is prohibitive. Traditional phased arrays typically require many costly active RF components, which also create significant power, cooling, weight requirements. Low-cost low-SWaP defense systems, including the next generation of swarm UASs, could benefit from metasurfaces - a low-cost alternative to a traditional phased array. The applications of metasurfaces in radar include both far (e.g. automotive collision avoidance, drone surveillance) and near-field (e.g. through-wall imaging) systems.

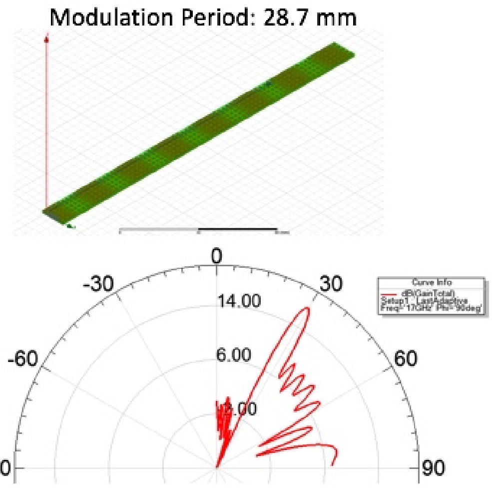

Figure 1. HFSS simulation demonstrating the beam scanning capability of a metasurface antenna by periodically modulating the surface impedance [18, 13].

In the context of far-field applications, reconfigurable apertures of dynamic metasurfaces for radar imaging and sensing have been explored with specific focus on synthetic aperture radar (SAR) [14]SAR systems scan a large area using a single transceiver and simulate an extremely large antenna aperture through the movement of space or airborne platforms. A common near-field (Fresnel-zone) application is multiple-input, multiple-out (MIMO) radar imaging which has captured significant interest recently [15]. However, use of several orthogonal signals in a large MIMO array could be a disadvantage in a spectrally constrained environment if frequency-division-multiplexing is employed. Here, metasurfaces have proved advantageous because they can be operated with use of single-frequency for near-field imaging [16].

In addition to transmitting and receiving radar signals as an antenna, a reconfigurable metasurface can also be used to provide dynamic scattering reduction [17] by applying pseudo-random phase codings spatially across the metasurface to scatter an incoming wave in many directions. This dynamic scattering functionality can be used to reduce the radar cross-section (RCS) of the metasurface antenna. Additionally, a time-varying metasurface with a-priori knowledge of an incoming radar signal could be pulsed to frequency-shift or spoof the reflected return signal (Fig. 1).

3 Metasurfaces for RF Communications

While a number of recent studies have investigated the use of dynamic metasurface antennas for radar systems, their applications for wireless RF communication systems remain relatively unexamined. Reconfigurable antennas, with the ability to radiate more than one pattern at different frequencies and polarizations, are necessary in modern telecommunication systems [22]. Time-varying reconfigurable metasurface antennas have the potential to

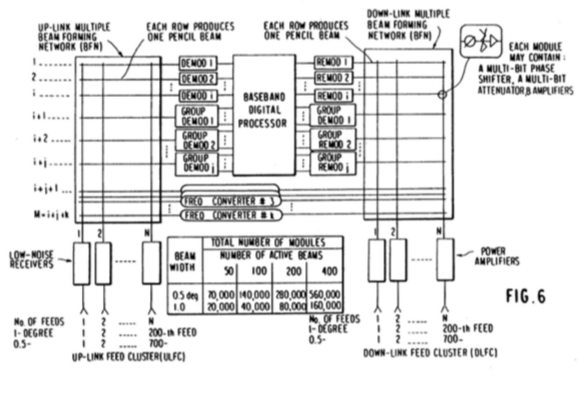

Figure 2. Complex RF switch matrix architecture for satellite communication, which could be simplified using a reconfigurable metasurface [19].

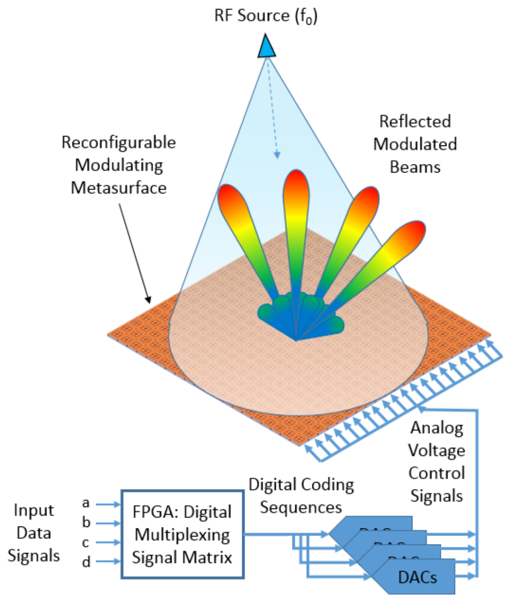

Figure 3. Digital control of metasurface multiplexing and modulation in a communications transmitter.

simplify the system architecture of modern communication systems (Fig. 2) and enhance their performance.

In [7], we proposed the concept of using an active reconfigurable metasurface for spatially multiplexing and modulating RF wireless communication signals due to its sub-wavelength thickness, planar nature, and reduced cost & complexity compared to traditional phased arrays. Most studies on reconfigurable metasurface antennas focus on beam scanning or beam shaping [1, 17, 8, 6]. However, they assume that the signal would modulate the carrier signal using RF circuitry before the antenna feed.

In our proposed concept (Fig. 3), the communications signal is modulated onto the carrier wave directly by the metasurface using electronic phase tuning of individual metasurface unit-elements (meta-atoms) to perform phase shift keying (PSK) [7]. In addition to PSK, a reconfigurable metasurface antenna can also perform frequency-shift

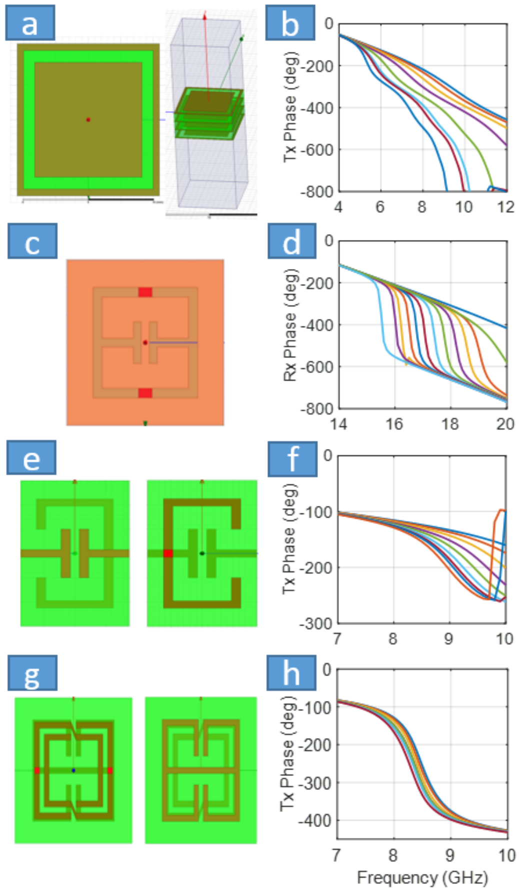

Figure 4. (a) Four-layer passive metasurface unit-cell with metal patch inside wire grid similar to [20] (b) Realization of full range of transmission phases by varying physical patch size (c) Tunable complementary electric-LC (cELC) resonator above PEC groundplane in reflectarray configuration (d) Realization of broad reflection phase tuning range (∼350 degrees) through capacitive tuning of active embedded element (e) Tunable variant of unit cell shown in [4] using active embedded elements to achieve (f) 90 degree tunable transmission phase range (g) Tunable variant of unit cell shown in [21] using active embedded elements to achieve (h) 90 degree tunable transmission phase range.

keying (FSK), spatial code modulation (SCM), and spatial shift keying (SSK) signal modulation techniques (see e.g. Fig. 2). If designed to provide dynamic polarization control, a reconfigurable metasurface could also modulate a communication signal using polarization-shift keying [23] or provide transmit diversity over multiple polarizations to boost link reliability. Communication data rates can be enhanced by simultaneously incorporating and combining multiple spatial and time-varying modulation techniques. Additionally, a reconfigurable metasurface can perform spatial multiplexing by generating multiple beams or dividing the aperture into multiple phase centers (sub-apertures) to simultaneously transmit multiple signals.

Further, multiple data signals are fed into a multiplexing signal matrix which is used to control the phase distribution across the metasurface using addressable embedded elements, such as varactor or PIN diodes, within each metasurface unit-cell (referred to as a meta-atom). This multiplexing metasurface device provides the opportunity for both spatial and time modulation. The modulation of the metasurface can be engineered to support carrier waves at multiple frequencies. Additionally, the reconfigurable metasurface antenna can function as a modulator, multiplexer, and a beamformer.

Grayscale tuning provides finer control of the magnitude and phase of each unit cell element at the cost of added complexity relative to binary tuning elements. Some multifunctional metasurfaces have used both varactor and PIN diodes in the unit cell for both binary and grayscale tuning [8]. Based on the application, the unit cell of the metasurface can have different types of switches and embedded tuning mechanisms with different switching speeds to control multiple functions and reduce power consumption. For example, beam scanning may be performed using varactor diodes and communication signal modulation, with faster switching requirements, could be performed using PIN diodes.

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References

[1] D. R. Smith, O. Yurduseven, L. P. Mancera, P. Bowen, and N. B. Kundtz, "Analysis of a waveguide-fed metasurface antenna," *Physical Review Applied*, vol. 8, no. 5, p. 054048, 2017.

[2] C. L. Holloway, E. F. Kuester, J. A. Gordon, J. O'Hara, J. Booth, and D. R. Smith, "An overview of the theory and applications of metasurfaces: The two-dimensional equivalents of metamaterials," *IEEE Antennas and Propagation Magazine*, vol. 54, no. 2, pp. 10–35, 2012.

[3] K. Achouri, G. Lavigne, M. A. Salem, and C. Caloz, "Metasurface spatial processor for electromagnetic remote control," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 5, pp. 1759–1767, 2016.

[4] C. Pfeiffer and A. Grbic, "Metamaterial huygens' surfaces: Tailoring wave fronts with reflectionless sheets," *Physical Review Letters*, vol. 110, no. 19, p. 197401, 2013.

[5] A. Epstein and G. V. Eleftheriades, "Huygens' metasurfaces via the equivalence principle: Design and applications," *JOSA B*, vol. 33, no. 2, pp. A31–A50, 2016.

[6] S. Liu and T. J. Cui, "Concepts, working principles, and applications of coding and programmable metamaterials," *Advanced Optical Materials*, vol. 5, no. 22, p. 1700624, 2017.

[7] J. A. Hodge and A. I. Zaghloul, "Utilizing a reconfigurable metasurface antenna as a device for spatial multiplexing and modulation," in *URSI Radio Science Meeting*, 2018.

[8] C. Huang, C. Zhang, J. Yang, B. Sun, B. Zhao, and X. Luo, "Reconfigurable metasurface for multifunctional control of electromagnetic waves," *Advanced Optical Materials*, vol. 5, no. 22, p. 1700485, 2017.

[9] B. H. Fong, J. S. Colburn, J. J. Ottusch, J. L. Visher, and D. F. Sievenpiper, "Scalar and tensor holographic artificial impedance surfaces," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 10, pp. 3212–3221, 2010.

[10] O. Yurduseven, D. L. Marks, J. N. Gollub, and D. R. Smith, "Design and analysis of a reconfigurable holographic metasurface aperture for dynamic focusing in the Fresnel zone," *IEEE Access*, vol. 5, pp. 15 055–15 065, 2017.

[11] J. A. Hodge, T. Anthony, and A. I. Zaghloul, "Enhancement of the dipole antenna using a capcitively loaded loop (CLL) structure," in *IEEE Antennas and Propagation Society International Symposium*, 2014, pp. 1544–1545.

[12] J. A. Hodge, T. K. Anthony, and A. I. Zaghloul, "Utilizing active circuit elements for dynamic tuning and electronic scanning of CLL-loaded dipole antenna structure," in *URSI Radio Science Meeting*, 2015, p. 16.

[13] J. A. Hodge and A. I. Zaghloul, "Towards addressable and reconfigurable metasurfaces: Utilizing active and passive variants of the capacitive-loaded loop (CLL) element for the design of modulated metasurface antennas," in *URSI Radio Science Meeting*, 2017.

[14] T. Sleasman, M. Boyarsky, L. Pulido-Mancera, T. Fromenteze, M. F. Imani, M. S. Reynolds, and D. R. Smith, "Experimental synthetic aperture radar with dynamic metasurfaces," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6864–6877, 2017.

[15] K. V. Mishra, Y. C. Eldar, E. Shoshan, M. Namer, and M. Meltsin, "A cognitive sub-nyquist MIMO radar prototype," *arXiv preprint arXiv:1807.09126*, 2018.

[16] T. Fromenteze, M. Boyarsky, J. Gollub, T. Sleasman, M. Imani, and D. R. Smith, "Single-frequency near-field MIMO imaging," in *European Conference on Antennas and Propagation*, 2017, pp. 1415–1418.

[17] H. Yang, X. Cao, F. Yang, J. Gao, S. Xu, M. Li, X. Chen, Y. Zhao, Y. Zheng, and S. Li, "A programmable metasurface with dynamic polarization, scattering and focusing control," *Scientific Reports*, vol. 6, p. 35692, 2016.

[18] K. V. Mishra, I. Kahane, A. Kaufmann, and Y. C. Eldar, "High spatial resolution radar using thinned arrays," in *IEEE Radar Conference*, 2017, pp. 1119–1124.

[19] F. T. Assal, J. V. Evans, C. E. Mahle, A. I. Zaghloul, and R. K. Gupta, "Switch matrix including both b switching elements and crossbar switch matrices," *US Patent 5220320*, 1993.

[20] C. Pfeiffer and A. Grbic, "Cascaded metasurfaces for complete phase and polarization control," *Applied Physics Letters*, vol. 102, no. 23, p. 231116, 2013.

[21] Q. Nguyen and A. I. Zaghloul, "Impedance matching metamaterials composed of elc and nb-srr," in *IEEE Antennas and Propagation Society International Symposium*, 2018.

[22] C. G. Christodoulou, Y. Tawk, S. A. Lane, and S. R. Erwin, "Reconfigurable antennas for wireless and space applications," *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2250–2261, 2012.

[23] S. Benedetto and P. Poggiolini, "Theory of polarization shift keying modulation," *IEEE Transactions on Communications*, vol. 40, no. 4, pp. 708–721, 1992.