Applications of AMC-based impedance surfaces

Constantine A. Balanis*, Mikal Askarian Amiri, Anuj Y. Modi, Sivaseetharaman Pandi, and Craig R. Birtcher

Arizona State University, Tempe, Arizona, USA

Received: 21 September 2017 / Accepted: 29 October 2017

Abstract. The recent and major enhancements of artificial magnetic conductor (AMC) and their applications namely RCS reduction, low-profile antennas and holographic leaky wave antennas are reviewed. Full-wave simulations are compared to measurements of fabricated models, and a good agreement is attained. All of the measurement were conducted in the Arizona State University electromagnetic anechoic chamber (EMAC).

Keywords: High impedance surface / metasurfaces / artificial magnetic conductors / RCS reduction / checkerboard surface / ultra wideband / curvilinear patches / loop antenna / spiral antenna / low-profile / superdirective / holography / leaky waves

1 Introduction

Artificial magnetic conductors (AMC) were proposed for the first time in 1999 [1], and since then have been extensively explored and widely used in antenna and electromagnetics applications. These structures consist of periodic grid of metallic patches which are mounted on top of a thin grounded dielectric substrate. The unique property of AMCs is their in-phase reflection coefficient at a certain frequency which makes them similar to magnetic conductors. To understand the in-phase reflection mechanism, the AMC under plane wave illumination can be modeled as a lumped parallel LC circuit. The capacitance is primarily due to the fringing fields between adjacent patches while the inductance is basically attributed to the thin grounded dielectric. Since the equivalent LC model is *open circuit* at the resonant frequency $\omega_r = 1/\sqrt{LC}$, the HIS has also a high impedance at ω_r similar to a PMC surface. Further analysis and modelings of AMCs are available in [2–4].

Given that perfect magnetic conductors do not exist in nature, the significance of these AMC becomes even more pivotal in some applications. *Image* theory indicates that a perfect magnetic conductor (PMC) surface would be an efficient candidate in the applications where the radiating element is very close to the ground plane, unlike a perfect electric conductor (PEC) surface whose radiation efficiency is very poor [5–7]. Thus, in the recent years, AMCs are considered a major breakthrough in antenna and electromagnetics engineering. This paper is an attempt to review

some of their latest applications, particularly:

- *RCS reduction using checkerboard artificial impedance surfaces:* Conventional methods of radar cross section (RCS) reduction are primarily based on two mechanisms: (i) Absorbing the incoming waves using bulky radar absorbent material (RAM), (ii) Redirecting the scattered waves by altering the physical geometry of the original structure. The functionality of the former mechanism is limited to a narrow bandwidth, and it requires bulky lossy materials; the latter mechanism is not aerodynamically efficient.

As mentioned earlier, AMCs exhibit a unique dispersive reflection response, which varies from 180° to -180° , in the designed frequency band. Previously, all the conventional RCS reduction techniques were developed with the assumption that such reflection phase responses can neither be easily found in nature nor tailored within the desired frequency range. Consequently, the introduction of AMCs not only eliminated some of the limitations of the conventional RCS reduction techniques but also improved their RCS reduction performance. For instance, in [8], AMC-based thin RAM was presented which eliminated its bulky nature. Later, in [9], the scattered waves were redirected using AMC-based tailored metasurfaces without altering the physical geometry of the original surface. However, such metasurfaces reduce the RCS only in a narrow frequency band. In Section 2, the recent developments in this field [10–15] which lead to ultra-broadband RCS reduction, are presented. A general guideline for synthesizing such ultra-broadband RCS reduction metasurfaces is also outlined.

- *Curvilinear AMCs for low-profile super-directive loop and spiral antennas:* As mentioned before, AMCs are judicial ground planes to be used in low-profile

* e-mail: balanis@asu.edu

applications. These structures are also utilized for miniaturization and bandwidth enhancement [16–21]. Although most of the literature focus on the rectangular AMCs, the circularly symmetric ground planes are addressed in [22–27] however, they mostly concentrate on the electromagnetic bandgap properties rather than on reflection types which take place at a different frequency band. In Section 3 the reflection properties of a circular AMC and its design guidelines are presented. Loop and spiral elements are then located above the designed AMC to illustrate the superior bandwidth and gain of such ground planes compared to their rectangular counterparts [28,29]. It should also be noted that when an AMC is used as an antenna ground plane, it is usually referred to as high impedance surface (HIS).

- *High gain leaky-wave antennas using Holography:* holographic artificial impedance surfaces (HAIS) are leaky wave antennas that are designed by applying holographic principle to AMC-based surfaces [30–34]. Along with achievement of high-gain pencil beam formation, the unidirectional beam scanning ability of the leaky waves grants HAIS the advantage over the conventionally used array antennas. The surface-wave propagation control using electrically small patches can be further extended to form two-dimensional surface waveguides [35]. In Section 4, we discuss the control mechanism to manipulate the polarization of the electric fields radiated by these surfaces. This provides a degree of freedom in mounting the antenna on the system that utilizes it.

To verify simulations all of the proposed designs are fabricated. Measurements are conducted and they are compared with simulations. This paper is mainly based on the results presented in [11,28,29,33].

2 RCS reduction using checkerboard artificial impedance surfaces

Since the RCS is a critical parameter in characterizing a target's scattering properties, with the advent of meta-surfaces within last few years, there has been an increasing interest in the development of RCS-reduction techniques utilizing such meta-surfaces [6]. Especially, one such well-known technique is reported in [10,11] where two AMC supercells are configured with each other in checkerboard type architectures as demonstrated in Figure 1. The primary appealing feature of this technique is its ability to provide RCS reduction over a broad/ultra-broadband frequency range [10,11].

2.1 Conventional checkerboard surfaces

When the plane waves impinge on a PEC surface, as demonstrated in Figure 2a, most of the scattered waves get scattered back with the single major lobe in the normal direction. However, when such checkerboard surface (Fig. 1) is illuminated by the same plane waves, the fields scattered from each of these comprising AMC supercells are 180° out of phase and result in destructive interferences along two orthogonal directions. This forces the scattered

Fig. 1. Generic design of checkerboard surface [11].

Fig. 2. Simulated 3D bistatic RCS pattern for (a) PEC, and (b) conventional checkerboard surface with the same physical dimensions.

waves to be redirected along four quadrants with four major lobes (θ_0, ϕ_0) as exhibited in Figure 2b. The direction of all the grating lobes can approximately be determined using array theory, particularly [36]:

$$\tan \phi_{m,n} = \frac{\sin \theta_i \sin \phi_i \pm (2n+1) \frac{\beta_y}{kd_y}}{\sin \theta_i \cos \phi_i \pm (2m+1) \frac{\beta_x}{kd_x}}, \quad (1a)$$

Fig. 3. Design and fabricated prototype of *conventional checkerboard surface* for wideband RCS reduction [10].

$$\sin^2 \theta_{m,n} = \left[\sin \theta_i \sin \phi_i \pm (2n+1) \frac{\beta_y}{kd_y} \right]^2 + \left[\sin \theta_i \cos \phi_i \pm (2m+1) \frac{\beta_x}{kd_x} \right]^2 \quad (1b)$$

where (θ_{mn}, ϕ_{mn}) define the direction of the grating lobes with the $n+m+1$ order, while (θ_i, ϕ_i) is the angle of incidence. β_x and β_y are the reflection phase difference between the adjacent supercells in the x and y directions, respectively, while d_x and d_y are the distances between adjacent supercells. Therefore, the direction of the four major lobes (θ_0, ϕ_0) can approximately be calculated by letting $n = m = 0$.

For such RCS-reduction checkerboard surfaces, an analytical expression that approximates the RCS reduction is given by [10,11]:

$$\text{RCS Red} = \left| \frac{A_1 e^{j\Phi_1} + A_2 e^{j\Phi_2}}{2} \right|^2, \quad (2)$$

where Φ_1 and Φ_2 are the phases of the fields reflected by AMC-1 and AMC-2, respectively, while A_1 and A_2 are the reflection coefficient amplitudes of AMC-1 and AMC-2 [10]. Therefore, to reduce the RCS by at least 10 dB, a phase difference of $(180 \pm 37)^\circ$ must be obeyed between the building AMC supercells [10].

As a result, the selection of AMCs is a critical step in realizing a broadband RCS reduction surface. In [10], two single-band AMCs were considered for designing wideband checkerboard surface (Fig. 3), where about 60% bandwidth of 10-dB RCS reduction was reported (Fig. 4). Such checkerboard architectures are classified as *conventional checkerboard surfaces* [11]. Similarly, in [12,13] two dual-band AMCs were utilized to reduce RCS in two separate wide frequency band, where about 60% and 26% 10-dB RCS reduction bandwidths were observed in the measurements.

Also, notice that once the size of AMC unit cells is fixed, the number of unit cells in individual AMC supercell defines the distances (d_x, d_y) between adjacent supercells. According to (2), since the distances between the adjacent supercells are not critical for the RCS reduction under the

Fig. 4. Simulated and measured RCS reduction using *conventional checkerboard surface* [10].

normal incidence, the number of unit cells in individual AMC supercell is not as pivotal. However, according to (1), these distances still determine the direction of maxima (θ_0, ϕ_0) of the scattered fields [11].

2.2 Blended checkerboard surfaces

More recently in [11,14] a judicious selection of AMCs has been investigated, and a guideline for the selection of AMCs has been presented to yield/synthesize ultra-broadband RCS reduction checkerboard surfaces. It is demonstrated that a combination of single- and dual-band AMCs, instead of two single-band AMCs, provides broader RCS reduction bandwidth. Such checkerboard surfaces with a combination of single-band and dual-band AMCs are considered as *blended checkerboard surfaces* [11]. For validation, the *conventional checkerboard surface* reported in [10] was transformed to *blended checkerboard surfaces*, with a combination of single- and dual-band AMCs [11,14]. Where the single-band AMC (AMC-1) was realized by the same single circular patch design used in [10], while the introduction of an outer ring to the other single-band AMC design (i.e. square patch) of *conventional checkerboard surface* converted it to dual-

Fig. 5. Selection of AMC unit-cell designs to convert *conventional checkerboard surface* into *blended checkerboard surface*: (a) AMC-1, (b) AMC-2 [11].

band AMC (AMC-2), as shown in Figure 5. As rendered in Figure 6, with single-band AMC as AMC-2 as suggested in [10], the $(180 \pm 37)^\circ$ phase difference would have been satisfied only from 3.6 GHz to 6.5 GHz which resulted in about 60% fractional bandwidth of 10-dB RCS reduction bandwidth. However, after the transformation of AMC-2 from single-band to dual-band AMC, the required phase difference of $(180 \pm 37)^\circ$, has been maintained from 3.6 GHz to 9.4 GHz, an increase of +23% in 10-dB RCS reduction bandwidth from 60% to 83%. This suggests that the *conventional checkerboard surface* should first be designed and optimized with two single-band AMCs. After the optimization, to extend the RCS reduction bandwidth, one of the single-band AMCs should be transformed to dual-band AMC.

The RCS reduction performance of *blended checkerboard surface* (Fig. 7a) is verified using a prototype displayed in Figure 7b, fabricated on a standard Rogers RT/duroid-5880 dielectric substrate backed by a PEC ground plane (with thickness of 6.35 mm and dielectric constant of 2.2) [11].

However, in both the *conventional* and *blended* designs, the checkerboard surfaces have the same design configuration/architecture. In each of them, only the selection of the building supercells is different to achieve the required destructive interference (i.e. two different single-band AMCs in *conventional*, a combination of single- and dual-band AMCs in *blended*). Therefore, in both of these checkerboard surfaces, to obtain greater than 10 dB RCS reduction, the $(180 \pm 37)^\circ$ phase difference still must be obeyed between the building supercells. This is a primary limitation of such checkerboard designs which restricts their RCS reduction bandwidth.

2.3 Modified checkerboard surfaces

To overcome this limitation, design configuration of these surfaces has to be modified [15]. As exhibited in Figure 8a, in both the *conventional* and the *blended checkerboard surfaces*, the *identical* destructive interference is not necessary in two orthogonal planes. To provide the same RCS reduction under the normal incidence, only one of these two destructive interferences is required [11]. Consequently, the surface of Figure 8b, where destructive interference is developed only along the x -direction, is equivalent to the original *conventional/blended checkerboard surface* of Figure 8a for reducing the RCS under the normal incidence [11]. As depicted in Figure 8c, this then allows the introduction of another type of destructive interference. Here, to increase the RCS reduction bandwidth, the second combination of AMCs (AMC-3 and AMC-4) should be selected such that destructive interference produced by these AMCs (AMC-3 and AMC-4) reduces the RCS more than 10 dB *outside* the 10-dB RCS reduction bandwidth of the first combination (AMC-1 and AMC-2) [15]. Further, the RCS reduction bandwidth can be enhanced by changing the respective portion of the total area covered by the individual combination of AMCs as suggested in Figure 8d.

In [11], the same technique was implemented on *blended checkerboard surface* with a combination of single- and dual-band AMCs as illustrated here in Figure 9a to convert it into the *modified checkerboard surface* (Fig. 10) of Figure 9d. For that, initially, the second combination of AMCs (AMC-3 and AMC-4) was designed and introduced (Fig. 9c). Here, when implemented as an independent *blended checkerboard surface*, the second combination of AMCs can attain RCS reduction of more than 27 dB near 9.7 GHz. Therefore, in the final design of Figure 9d, area covered by the second combination was increased. As a result, the RCS reduction bandwidth was extended above 9.3 GHz. Due to the phase difference limitation, for the original *blended checkerboard surface*, the 10-dB RCS reduction bandwidth was limited to 83%. However, after employing the proposed technique, a 91% fractional bandwidth (+8% increment) for the 10-dB RCS reduction was observed. Simulation and measured data are illustrated and compared in Figure 11 for both the polarizations.

2.4 Generalized approach to synthesize an ultra-broadband RCS reduction checkerboard surface

Therefore, a generalized approach to synthesize an ultra-broadband RCS reduction checkerboard surface, can be listed in the following steps:

- initially, design a *conventional checkerboard surface* as demonstrated in Figure 9a. Design and optimize the *conventional checkerboard surface* to achieve maximum RCS reduction bandwidth with a combination of two single band AMC structures (i.e. first combination of AMCs; AMC-1 and AMC-2);
- alter one of these single-band AMCs by a dual-band AMC to convert *conventional checkerboard surface* into *blended checkerboard surface* to improve the RCS reduction bandwidth;

Fig. 6. Typical Reflection phase for AMC-1 and AMC-2 as a function of frequency [11].

Fig. 7. Blended checkerboard surface: (a) Design, (b) Fabricated prototype, and (c) Measured RCS reduction performance [11].

– design and introduce another blended checkerboard surface with the second combination of AMCs (i.e. AMC-3 and AMC-4) as shown in Figure 9c where the selection criteria for the second combination was established in the previous subsection;

Fig. 8. Design of RCS-reduction (a) Conventional/Blended checkerboard surface, (b) Surface with only one destructive interference, (c) Modified surface with equal sized supercells, and (d) Modified surface with unequal sized supercells.

– finally, to further extend the RCS reduction bandwidth, change the respective areas covered by the individual AMC-combination of these *blended checkerboard surfaces* to develop a *modified checkerboard surface*. Again, this is explained in the previous subsection as depicted in Figure 9d.

3 Curvilinear AMCs for low-profile super-directive loop and spiral antennas

As it was mentioned in Section 1, HISs are proper ground planes to be used in low-profile applications. Most of the HIS ground planes reported in the literature, such as the mushroom surface, have rectangular geometries (rectilinear periodicity). In this paper the design procedure of a novel HIS ground plane with circular periodicity for curvilinear

Fig. 9. Evolution of modified checkerboard surfaces: Design of (a) Blended checkerboard surface, (b) Surface with only one destructive interference, (c) Modified surface with equal sized supercells, and (d) Modified surface with unequal sized supercells.

Fig. 10. Fabricated prototype of *modified checkerboard surface* [11].

elements, such as spirals and loops, is reviewed. The advantages of the circular HIS ground plane with such radiating elements are the following:

- greater operational and fractional bandwidth; due to the more effective interaction of the ϕ -polarized electric fields of the loop or spiral antenna in the near-field region with circular geometry of the patches;
- additional increase in the broadside gain compared to conventional mushroom surfaces; due to the radial reflection phase profile which results in a more constructive interference of the electromagnetic waves in the far-field. Thus the surface is referred to as *Super-directive*.

3.1 Design procedure

The design procedure of the conventional HIS with linear periodicity, where the reflection phase under plane wave illumination is examined, a cylindrical TEM^z wave is used to investigate the reflection properties of the HIS of Figure 12. Figure 13 illustrates two adjacent unit cells on

Fig. 11. RCS reduction performance of the *modified checkerboard surface* under normal incidence with TM (a) and TE (b) polarizations.

the same ring and also the appropriate boundary conditions to generate a cylindrical TEM^z wave. This type of circular ground planes are specifically designed for curvilinear elements whose radiated waves in the near-field are mainly oriented in the ϕ -direction. As it is detailed in [28], the reflection properties of each of the rings in Figure 12 are superimposed on the other ones when they are put together. Thus to design a circular HIS with an in-phase reflection coefficient at frequency f_r , the following procedure should be followed:

- illuminate each individual ring with cylindrical TEM^z wave: To generate a cylindrical TEM^z wave, the unit cells of each ring is enclosed in a sector of a cylindrical waveguide with the boundary conditions shown in Figure 13 and the patch size is adjusted such that the zero-cross of the reflection phase occurs at f_r ;
- illuminate the entire surface in a similar manner when all of the rings are together: The surface should have a reflection behaviour and resonant frequency close to those of all individuals rings.

Table 1 in [28] summarizes the design parameters of a circular HIS which resonates at 4.5 GHz, and Figure 14 illustrates the reflection phases of the individual rings and the entire circular HIS.

Fig. 12. Top view of the HIS with an angular periodicity and its design parameters [28].

Fig. 13. Two adjacent unit cells with appropriate boundary conditions to generate cylindrical TEM^z wave.

Fig. 14. Reflection phases of the individual rings and the entire surface of Figure 12 with design parameters of [28, Tab. 1].

3.2 Antenna applications

The designed circular HIS of Section 3.1 is used as antenna ground plane for curvilinear radiating elements (loops and spirals), and its performance is compared to that of rectangular HIS with the same reflection reflection phase. Figure 15 illustrates the geometry of a spiral and loop radiating element located in the vicinity of the circular HIS.

Fig. 15. Curvilinear elements located at height 0.005λ (@3 GHz) above the circular HIS; Spiral (left) [29], Loop (right) [28].

3.2.1 Operational bandwidth

As defined in [5], the operational bandwidth of an HIS is obtained by varying the size of the radiating element which is placed at a constant small height above it. Changing the size of the radiating element results in the shifting of the resonant frequency. The frequency interval within which the reflection coefficient of the antenna is below -10 dB is considered as the operational bandwidth. As Figure 16 indicates, the operational bandwidth of the designed surface for the spiral and loop element is 51% and 37% at 3 GHz, respectively.

To compare the bandwidth of these elements above the circular HIS with those located above the conventional ones, a rectangular HIS with square patches is designed such that it has the same reflection phase under normal plane wave illumination. Spiral and loop elements are located at the same height and the same procedure is followed to obtain the operational bandwidth. According to Figure 16, simulations indicate that the operational bandwidth of the circular HIS for spiral and loop elements is 18% and 11% greater than that of their rectangular counterparts.

3.2.2 Super-Directivity

The broadside gain of the spiral and loop antennas located above the circular HIS, rectangular HIS, PMC ground plane and also in free space, within the operational bandwidth, is illustrated in Figure 17. It is evident that the gain of the radiating element located above the rectangular HIS or PMC ground plane is 3 dB higher than that of the same element in free space, which is expectable due to the *image* theory. However, when a circular HIS is used as antenna ground plane, an additional gain increase is observed compared to the rectangular HIS or PMC surface. For instance, the gain of spiral element of size 0.12λ (λ is the wavelength at 3.5 GHz) is 2.5 dB in free space, 5.5 dB above the PMC ground plane and 8.5 dB above the circular HIS. Thus the gain is increased by 3 dB in case of the circular HIS compared to the rectangular HIS or PMC ground plane. This notable increase is attributed to the radial phase profile introduced along the surface of the circular geometry.

To validate this, a new ground plane is assumed whose surface is divided into four rings as illustrated in Figure 18a. The impedance of each spot on the surface is obtained based on the phase with which the waves of the localized source (spiral or loop element) is reflected. Figure 18b displays the reflection phase profile of the surface under the illumination of the spiral element along

Fig. 16. Operational bandwidth of the curvilinear elements located at height 0.005λ (@3 GHz) above the circular HIS: (a) Spiral [29], (b) Loop [28].

the dashed line of Figure 18a. To approximate, the average phase value along each portion is calculated and its surface impedance is obtained accordingly. The surface impedance of the 1st, 2nd, 3rd and 4th rings are $-j377\ \Omega$, $-j90\ \Omega$, $j120\ \Omega$ and $j377\ \Omega$, respectively. It should be noted that the surface impedance of the innermost ring is obtained under normal incidence assumption. The gain pattern of the spiral and loop elements above the circular HIS of Figure 15 and synthesized surface of Figure 18a is displayed and compared in the following section. An excellent agreement is evident and thus the circular HIS ground plane is considered to be *super-directive* compared to conventional HIS.

3.3 Measurements

To validate the simulations, the circular HIS ground planes and the antenna elements were fabricated and measurements were performed. Figure 19 displays the fabricated prototype of the circular HIS along with the spiral and loop elements. To feed the loop element, the inner conductor of

Fig. 17. Broadside gain: (a) Loop, (b) Spiral [29].

the coaxial cable was passed through the substrate of the HIS and connected to one of the terminals of the loop and the other terminal was connected to the outer conductor of the coaxial cable. However, in the case of the spiral antenna a balun also had to be designed as the radiator is a balanced element [29]. Figure 20 illustrates the simulated and measured S_{11} of the both elements located above the circular HIS of Figure 19. Figure 21 compares the simulated gain patterns of the loop and spiral elements located above the circular HIS of Figure 15, synthesized surface of Figure 18 and the measured realized gain patterns of the elements above the fabricated prototypes of Figure 19. An excellent agreement is indicated.

4 High gain leaky-wave antennas using holography

HAISs are two dimensional surfaces obtained by introducing functional modifications to the AMC Surfaces discussed above. Besides their regular usage as ground planes, these surfaces can be transformed into radiating sources by

Fig. 18. Surface synthesis: (a) Rings with average impedance (b) Radial reflection phase profile.

Fig. 19. Fabricated prototype of the circular HIS with radiating elements above; spiral (left), loop (right) [28,29].

incorporating in homogeneity to their geometric structure. This section elaborates on the radiation properties of HAIS and its design. The conventional AMC supports the propagation of surface waves at the interface between free space and the dielectric substrate, where the patches are placed periodically. The first two fundamental modes of surface wave propagation (TM and TE, respectively) are considered in the design of HAIS. The electric and magnetic field configurations of the modes are illustrated in Figure 22. Isotropic HAIS support TM modes at lower frequencies and TE mode at higher frequencies whereas they coexist in anisotropic HAIS as degenerate modes. The propagation modes of these surface waves are refined to

Fig. 20. Measured and simulated return loss of the elements above the circular HIS: (a) Loop (b) Spiral [28,29].

support a leakage mechanism which enables the electromagnetic waves to extend into the far-field region as leaky waves, where they are directed methodically to form a high gain antenna. The leakage mechanism and the methodical redirection of leaky waves are enabled by systematic modulation of the surface impedance of AMC, based on holographic principle, and hence the name HAIS.

Automotives employ radar systems for various applications like object detection, blind spot detection, adaptive cruise control and parking assistance. These radar systems require high spatial resolution and wide vision. The holographic leaky wave antennas possess high directivity, narrow beam width and beam steering capability that make them ideal candidates for automotive radar systems. The following sections elaborates the design methodology for HAIS.

4.1 Surface impedance modulation

Surface impedance is a complex parameter defined to express the electromagnetic behavior at the interface between two different media. It quantifies losses and characterizes the modal behavior of the surface and leaky

Fig. 21. Measured and simulated realized gain patterns of the elements above the circular HIS at 2.7 GHz: (a) Loop (b) Spiral [28,29].

Fig. 22. Electric and magnetic field configurations of TE and TM modes [33].

waves at the interface [1,6]. Surface impedance of the AMC can be determined using a 3D electromagnetic simulator or by the transverse resonance method (TRM). These methods are described in [30–35,38–40]. The square metallic patches on a dielectric covered ground plane are modeled as a lumped capacitor connected in parallel to a shorted transmission line whose length is equal to the dielectric substrate thickness. The previous sections

Fig. 23. Surface impedance variation with respect to gap size between patches [33].

discussed the surface impedance variation of AMC with the frequency, while this section requires a parametric study on the variation of the surface impedance of AMC with respect to the size of the square patches at a single frequency. Figure 23 shows the variation of the surface impedance with respect to size of the square patches for a period of 4 mm. The surface impedance is a scalar value for isotropic surfaces and a dyad for anisotropic surfaces. This paper encompasses only the isotropic surfaces. Hence the surface impedance values are inductive for TM modes and capacitive for TE modes of the surface waves.

In order to align the radiation from the leaky waves in one direction to form a highly directive beam, a holography based surface impedance profile is required. This surface impedance profile is synthesized by varying the patch size on the dielectric covered ground plane. The resulting surface is inhomogeneous with spatial variation of the surface impedance, which is modulated sinusoidally along the direction of propagation of surface waves to engineer the leakage of electromagnetic energy from the HAIS. A detailed study on the properties of sinusoidally modulated impedance surfaces is presented in [41–45]. Sinusoidal modulation of the surface impedance is periodic along the direction of surface wave propagation, which is expressed as

$$Z_s(x) = jX_a \left[1 + M \cos\left(\frac{2x\pi}{p}\right) \right], \quad (3)$$

where X_a is the average surface impedance, M is the modulation index, p is the period of modulation.

The periodic variation of surface impedance results in periodic electric and magnetic fields that exist as Floquet modes. Although infinite number of Floquet modes exist, only three modes are dominant for sinusoidal surface impedance modulation. These modes are identified based on their indices. While $n=0$ remain as a surface wave Floquet mode, $n=-1$ and $n=1$ exist as leaky wave modes. The $n=-1$ mode corresponds to forward leaky waves which radiates in the forward direction while $n=1$ mode radiates in the opposite direction to the direction of

Fig. 24. Forward and backward leaky wave modes.

propagation, as shown in [Figure 24](#). The forward and backward waves are excited by controlling the period of the sinusoidal modulation. The propagation constants of the three modes are

$$k_n = \kappa + \frac{2n\pi}{p} \quad n = 0, \pm 1, \quad (4)$$

where κ is the propagation constant of the surface wave mode with index zero and n is the index of the mode.

4.2 HAIS with desired polarizations

An HAIS is designed by realizing a surface impedance profile given by the holographic principle and sinusoidal modulation. This is accomplished by using the interference pattern of the holographic principle as the argument for the sinusoidal modulation function in [\(3\)](#). The interference pattern is configured by performing a dot product between the phase projections of the source and desired waves on the surface of HAIS. The source wave is the surface wave excited on the HAIS using an electrically small radiating source (in this case a monopole) and the desired wave is a pencil beam in the desired direction. A conventional HAIS is designed to radiate along $\theta = 35^\circ$ in xz plane according to

$$Z_s(x) = jX_a[1 + MRe(e^{-k_0 x \sin 35^\circ} e^{j\kappa r})], \quad (5)$$

where $X_a = 337 \Omega$ is the average surface reactance, κ is phase constant of the surface wave, $M = 0.5$ is the modulation index, k_0 is the free-space phase constant, and r is the radial distance from the monopole. The resultant structure illustrated in [Figure 25](#), and designed for an operation frequency of 10 GHz, is capable of forming a pencil beam in the desired direction that is contributed by both forward and backward leaky waves. The radiation pattern along the cross sectional plane of the pencil beam is shown in [Figure 26](#). The holographic interference pattern provides the spatial adjustment to the period of the sinusoidal modulation to align the radiations from the forward and backward leaky waves in the same direction at the design frequency. The frequency band around the design frequency, where the forward and backward leaky waves radiate in the same direction is referred to as the *phase-crossover* frequency band. The HAIS under phase-crossover frequency operation is capable of radiating a linearly polarized electric field along the peak direction of the pencil beam. TM mode leaky waves radiate a vertically

(a)

(b)

Fig. 25. Conventional HAIS: (a) Ground plane designed to radiate a pencil beam using square patches (b) Core of HAIS with a monopole to excite surface waves.

polarized electric fields that are oriented normal to the surface and TE mode leaky waves radiate horizontally polarized waves that are parallel to HAIS.

A control of the polarization of the radiated electric fields can be accomplished by modifying the holographic pattern and operating at nonphase-crossover frequency band where the forward and backward leaky waves radiate in different directions. The holographic interference pattern can be viewed as concentric ellipses sharing common center, as displayed in [Figure 27](#). This interference pattern can be modified to establish a control over the polarization of the radiated fields. The holographic pattern required to achieve different polarizations along the pencil beam, and their corresponding frequency bands of operation are discussed in the following sections.

4.2.1 Horizontal polarization

The concentric ellipses have a plane of symmetry as demonstrated in [Figure 27](#). HAIS is divided into two symmetric halves by this plane. A phase shift of 180° is introduced to one of these symmetric halves relative to the other to obtain a modified HAIS that radiates horizontally polarized waves along the peak of the pencil beam as shown in [Figure 28a](#). This is due to the reinforcement of the E_ϕ components. The surface is operated at a nonphase-crossover frequency band. The radiation pattern along the plane of symmetry is presented in [Figure 28b](#).

This structure was fabricated using the dielectric substrate ROGERS 5880 with a thickness of 0.125 in. The surface dimensions are $9.4'' \times 7.8''$. 3600 square

Fig. 26. The radiation pattern of a conventional HAIS operated at a phase matching frequency: (a) Pencil beam formed by HAIS designed for 10 GHz and (b) E_θ component along the XZ plane ($\varphi = 0^\circ$, $\varphi = 180^\circ$) [33].

Fig. 27. Concentric ellipses of holographic interference pattern.

patches were used to emulate the surface impedance holographic pattern. A quarter-wavelength monopole (7.5 mm) was placed in the center of the surface to excite surface waves. Figure 29 shows the fabricated surface that is capable of forming a beam along $\theta = 45^\circ$ in xz plane. The resulting beam has maximum peak gain of 14.8 dB as illustrated in Figure 30.

4.2.2 Vertical polarization

The non-symmetrical halves of HAIS radiate different modes of leaky waves as described in Figure 31a. A phase

Fig. 28. HAIS designed to radiate horizontally polarized electric field at 12 GHz: (a) Holographic pattern (b) E_θ and E_ϕ along the XZ plane ($\varphi = 0^\circ$, $\varphi = 180^\circ$) [33].

Fig. 29. Fabricated HAIS to obtain horizontal polarization. The monopole is shown enlarged in the inner picture [33].

shift of 180° introduced in the surface impedance function between these two halves would result in radiation of vertically polarized waves in the nonphase-crossover frequency band. The radiation pattern of the resultant HAIS is displayed in Figure 31b.

Fig. 30. Comparison between measured and simulated E_ϕ components along the XZ plane ($\varphi = 0^\circ$, $\varphi = 180^\circ$) [33].

(a)

Fig. 31. HAIS designed to radiate vertically polarized electric field at 12 GHz: (a) Holographic pattern (b) E_θ and E_ϕ along the XZ plane [33].

4.2.3 Circular polarization

Circularly polarized radiated fields can be accomplished by superimposing the surface impedance modulation functions corresponding to vertical and horizontal polarizations with a phase shift of 90° . The resulting structure is

(a)

Fig. 32. HAIS designed to radiate circularly polarized electric field at 12 GHz: (a) Holographic pattern (b) RHCP and LHCP components along the XZ plane [33].

illustrated in Figure 32. The sense of rotation of the circularly polarized fields is determined by the modulation function of the component which undergoes the 90° phase shift. The radiation pattern of the HAIS is illustrated in Figure 32b.

HAISs are two dimensional leaky wave antennas that are capable of forming a pencil beam in a desired direction. They are derived by incorporating inhomogeneity to the surface impedance of the AMC surfaces discussed in the previous sections. The inhomogeneous surface impedance is a radiation mechanism that facilitates the leakage of surface waves supported by the AMC surfaces. The radiation patterns of HAISs indicate the achievement of all the types of polarizations by varying the holographic pattern of the AMC based structure. The holographic patterns enable the reinforcement of the desired vector components of the surface waves to leak out of the surface resulting in the radiation of pencil beam with desired polarization.

5 Conclusions

In this paper, some recent applications of AMC-based surfaces for RCS reduction, low-profile antenna design and high gain leaky-wave antennas were discussed. The conclusions for each topic can be summarized as follow:

- *RCS reduction using checkerboard artificial impedance surfaces:* The advancements in metasurfaces tailored in the checkerboard type architecture, were reviewed where

the fundamental mechanism was elaborated with corresponding governing formulas and simulated RCS patterns. First, the *conventional checkerboard surface* using two single-band AMCs was presented which resulted in 10 dB RCS reduction bandwidth enhancement from 27% to 60%. Then, the judicious selection criteria for AMCs was discussed which ultimately led to *blended checkerboard surfaces* which increased the 10 dB RCS reduction bandwidth from 60% to 83%. However, RCS reduction bandwidth of such surfaces were still limited by the reflection phase difference criteria of $(180 \pm 37)^\circ$. After that, a review of a technique for modifying such *blended checkerboard surfaces* was presented which eliminated this limitation and enhanced the 10-dB RCS reduction bandwidth from 83% to 91%. A general guideline for synthesizing such ultra-broadband RCS reduction metasurfaces was outlined.

- *Curvilinear AMCs for low-profile super-directive loop and spiral antennas*: The design procedure of a novel HIS ground plane with circular periodicity was reviewed. This type of HISs are specifically designed for curvilinear elements, such as spirals and loops. Simulations indicated that the operational bandwidth of the spiral and loop located above circular HISs are 18% and 11% greater than those of the spiral and loop above conventional HISs with rectilinear periodicity. An additional 3 dB increase in the directivity (compared to the PMC and rectangular HIS) was also observed which is attributed to the radial phase profile introduced along the surface.
- *High gain leaky-wave antennas using holography*: The design methodology of HAIS, radiating a pencil beam with a desired polarization was discussed. The holographic pattern required to form a pencil beam is implemented using the surface impedance modulation technique. The surface impedance is modulated by varying the size of metallic square patches embedded on a dielectric covered ground plane. It is shown that holographic pattern modification enables a degree of freedom to control the polarization of the radiated fields along the pencil beam.

To validate the simulations, all of the prototypes were fabricated and measurements were performed. An excellent agreement was observed throughout.

References

1. D. Sievenpiper, High-Impedance Electromagnetic Surfaces, Ph.D. dissertation, (Dept. Elect. Eng., Univ. California, Los Angeles, Los Angeles, CA, USA, 1999).
2. S. Tretyakov, Analytical modeling in applied electromagnetics, (Artech House, Boston, 2003).
3. O. Luukkainen, C. Simovski, G. Granet, G. Goussetis, D. Lioubtchenko, A.V. Risen, S.A. Tretyakov, Simple and accurate analytical model of planar grids and high-impedance surfaces comprising metal strips or patches, IEEE Trans. Antennas Propag. **56**, 1624 (2008).
4. R. Rodrigues-Berral, F. Medina, F. Mesa, M.G. Vigueras, Quasi-analytical modeling of transmission/reflection in strips/slit gratings loaded with dielectric slabs, IEEE Trans. Microw Theory Tech. **60**, 405 (2012).
5. Y. Fan, Y. Rahmat-Samii, Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications, IEEE Trans. Antennas Propag. **51**, 2691 (2003).
6. C.A. Balanis, Advanced engineering electromagnetics, 2nd ed, (Wiley, New York, 2012).
7. A. Vallecchi, J.R. De Luis, F. Capolino, F. De Flaviis, Low profile fully planar folded dipole antenna on a high impedance surface, IEEE Trans. Antennas Propag. **60**, 51 (2012).
8. N. Engheta, Thin absorbing screens using metamaterial surfaces, Proc. IEEE Antennas Propag. Soc. Int. Symp. **2**, 392 (2002).
9. M. Paquay, J.C. Iriarte, I. Ederra, R. Gonzalo, P. de Maagt, Thin AMC structure for radar cross-section reduction, IEEE Trans. Antennas Propag. **55**, 3630 (2007).
10. W. Chen, C.A. Balanis, C.R. Birtcher, Checkerboard EBG surfaces for wideband radar cross section reduction, IEEE Trans. Antennas Propag. **63**, 2636 (2015).
11. A.Y. Modi, C.A. Balanis, C.R. Birtcher, H. Shaman, Novel design of ultrabroadband radar cross section reduction surfaces using artificial magnetic conductors, IEEE Trans. Antennas Propag. **65**, 5406 (2017).
12. W. Chen, C.A. Balanis, C.R. Birtcher, Dual wide-band checkerboard surfaces for radar cross section reduction, IEEE Trans. Antennas Propag. **64**, 4133 (2016).
13. W. Chen, C. A. Balanis, C.R. Birtcher, Dual frequency band RCS reduction using checkerboard surfaces, Proc. of IEEE Int. Symp. Antennas Propag., San Diego, CA, 2017, pp. 1913–1914.
14. A.Y. Modi, C.A. Balanis, C. Birtcher, AMC cells for broadband RCS reduction checkerboard surfaces, Proc. of IEEE Int. Symp. Antennas Propag., San Diego, CA, 2017, pp. 1911–1912.
15. A.Y. Modi, C.A. Balanis, C. Birtcher, Novel technique for enhancing RCS reduction bandwidth of checkerboard surfaces, Proc. of IEEE Int. Symp. Antennas Propag., San Diego, CA, 2017, pp. 1915–1916.
16. M.Z. Azad, M. Ali, Novel wideband directional dipole antenna on a mushroom like EBG structure, IEEE Trans. Antennas Propag. **56**, 1242 (2008).
17. L. Akhoondzadeh-Asl, D.J. Kern, P.S. Hall, D.H. Werner, Wideband dipoles on electromagnetic bandgap ground planes, IEEE Trans. Antennas Propag. **55**, 2426 (2007).
18. H. Mosallaei, K. Sarabandi, Antenna miniaturization and bandwidth enhancement using a reactive impedance substrate, IEEE Trans. Antennas Propag. **52**, 2403 (2004).
19. D.J. Kern, D.H. Werner, A. Monorchio, L. Lanuzza, M.J. Wilhelm, The design synthesis of multiband artificial magnetic conductors using high impedance frequency selective surfaces, IEEE Trans. Antennas Propag. **53**, 8 (2005).
20. D.J. Kern, D.H. Werner, A. Monorchio, L. Lanuzza, M.J. Wilhelm, Reconfigurable ultra-thin EBG absorbers using conducting polymers, Antennas and Propagation Society International Symposium (APSURSI), 2005 IEEE, 2B, 2005, pp. 204–217.
21. A.C. Durgun, C.A. Balanis C.R. Birtcher, Reflection phase characterization of curved high impedance surfaces, IEEE Trans. Antennas Propag. **61**, 6030 (2013).
22. J. Sarrazin, A.C. Lepage, X. Begaud, Circular high-impedance surfaces characterization, IEEE Lett. Antennas Wirel. Propag. **11**, 260 (2012).
23. N. Llombart, A. Neto, G. Gerini, Planar circularly symmetric EBG structures for reducing surface waves in printed antennas, IEEE Trans. Antennas Propag. **53**, 3210 (2005).

24. A. Neto, N. Llombart, G. Gerini, P. de Maagt, On the optimal radiation bandwidth of printed slot antennas surrounded by EBGs, *IEEE Trans. Antennas Propag.* **54**, 1074 (2006).
25. M. Ettore, S. Bruni, G. Gerini, A. Neto, N. Llombart, S. Maci, Sector PCS-EG antenna for low-cost high-directivity applications, *IEEE Lett. Antennas Wirel. Propag.* **6**, 537 (2007).
26. M. SalarRahimi, J. Rashed-Mohassel, M. Edalatipour, Radiation properties enhancement of a GSM/WLAN micro-strip antenna using a dual band circularly symmetric EBG substrate, *IEEE Trans. Antennas Propag.* **60**, 5491 (2012).
27. T.A. Dendini, Y. Coulibaly, H. Boutayeb, Hybrid dielectric resonator antenna with circular mushroom-like structure for gain improvement, *IEEE Trans. Antennas Propag.* **57**, 1043 (2009).
28. M.A. Amiri, C.A. Balanis, C.R. Birtcher, Analysis, design and measurements of circularly symmetric high impedance surfaces for loop antenna applications, *IEEE Trans. Antennas Propag.* **64**, 618 (2015).
29. M.A. Amiri, C.A. Balanis, C.R. Birtcher, Gain and bandwidth enhancement of spiral antenna using circularly symmetric HIS, *IEEE Lett. Antennas Wirel. Propag.* **16**, 1080 (2017).
30. B.H. Fong, J.S. Colburn, J.J. Ottusch, J.L. Visser, D.F. Sievenpiper, Scalar and tensor holographic artificial impedance surfaces, *IEEE Trans. Antennas Propag.* **58**, 3212 (2010).
31. A.M. Patel, A. Grbic, A printed leaky-wave antenna based on a sinusoidally-modulated reactance surface, *IEEE Trans. Antennas Propag.* **59**, 2087 (2011).
32. S. Maci, G. Minatti, M. Casaletti, M. Bosiljevac, Metasurfing: addressing waves on impenetrable metasurfaces, *IEEE Antennas Wireless Propag. Lett.* **10**, 1499 (2011).
33. S. Pandi, C.A. Balanis, C.R. Birtcher, Design of scalar impedance holographic metasurfaces for antenna beam formation with desired polarization, *IEEE Trans. Antennas Propag.* **63**, 3016 (2015).
34. G. Minatti, S. Maci, P. De Vita, A. Freni, M. Sabbadini, A circularly-polarized isoflux antenna based on anisotropic metasurface, *IEEE Trans. Antennas Propag.* **60**, 4998 (2012).
35. R. Quarfoth, D. Sievenpiper, Artificial tensor impedance wave-guides, *IEEE Trans. Antennas Propag.* **61**, 3597 (2013).
36. C.A. Balanis, *Antenna theory: analysis design*, 4th ed., (Wiley, Hoboken, NJ, USA, 2016).
37. M.A. Amiri, C. Balanis, C. Birtcher, Notable gain enhancement of curvilinear elements using a circular HIS ground plane, *Proc. of IEEE Int. Symp. Antennas Propag.* San Diego, CA, 2017, pp. 1671–1672.
38. S. Pandi, C.A. Balanis, Antenna beam forming using holographic artificial impedance surface, *Antenna Technol. Appl. Electromagn. (ANTEM)*, Victoria, BC, 2014, pp. 1–2.
39. O. Luukkonen, C. Simovski, G. Granet, G. Goussetis, D. Lioubtchenko, A.V. Risen, S.A. Tretyakov, Simple accurate analytical model of planar grids high-impedance surfaces comprising metal strips patches, *IEEE Trans. Antennas Propag.* **56**, 1624 (2008).
40. A.M. Patel, Controlling electromagnetic surface waves with scalar tensor impedance surfaces, Ph.D. dissertation, (Department of Electrical Engineering, The University of Michigan, Ann Arbor, MI, 2013).
41. A.A. Oliner, A. Hessel, Guided waves on sinusoidally-modulated reactance surfaces, *IRE Trans. Antennas Propag.* **7**, 201 (1959).
42. S. Pandi, C.A. Balanis, C.R. Birtcher, Analysis of wideband multilayered sinusoidally modulated metasurface, *IEEE Antennas Wirel. Propag. Lett.* **15**, 1491 (2016).
43. S. Pandi, C.A. Balanis, C.R. Birtcher, Curvature modeling in design of circumferentially modulated cylindrical metasurface LWA, *IEEE Antennas Wirel. Propag. Lett.* **16**, 1024 (2016).
44. S. Pandi, S. Ramalingam, C.A. Balanis, C.R. Birtcher, Bandwidth analysis of phase crossover non-phase crossover frequency operations of H AIS, *IEEE Antennas and Propagation International Symposium*, San Diego, CA, 2017, pp. 287–288.
45. S. Ramalingam, S. Pandi, C.A. Balanis, C.R. Birtcher, Axial and circumferential modulation of cylindrical metasurfaces, *2017 IEEE Antennas and Propagation International Symposium*, San Diego, CA, 2017, pp. 279–280.

Cite this article as: Constantine A. Balanis, Mikal Askarian Amiri, Anuj Y. Modi, Sivaseetharaman Pandi, Craig R. Birtcher, Applications of AMC-based impedance surfaces, *EPJ Appl. Metamat.* 2018, **5**, 3