Planar Modulated Reactance Surfaces for Endfire Antenna Applications

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Abstract. Modulated reactance synthesis for planar impenetrable electromagnetic surfaces for endfire radiation characteristics is presented. It is based on aperture field synthesis over the entire spectral range, where the desired radiation pattern is prescribed by a traveling-wave current over the aperture. Carefully constructed auxiliary waves in the evanescent spectrum are added and the total aperture fields are optimized such that the entire aperture surface becomes pointwise reactive. The optimized aperture fields define the modulated surface reactance that realizes the desired pattern when excited by a feed surface wave. The reactance distribution may be realized as modulated metasurfaces.

1. Introduction
A modulated surface reactance on an electromagnetically impenetrable surface can couple a bound wave and a space wave. The classical work by Oliner and Hessel established a relation between the complex propagation constant of a leaky-wave mode and the parameters of a periodic sinusoidal reactance modulation [1]. Recent active development of modulated metasurface antennas has largely built on locally periodic sinusoidal modulation, including metasurface antennas capable of amplitude, phase, and polarization control [2]. Overcoming the issues associated with locally periodic modulations, a modulated reactance design method based on complete aperture field synthesis has been reported [3] for leaky-wave antenna (LWA) applications.

In this paper, the aperture field synthesis approach in [3] is extended to treat endfire radiation. Over the aperture, a desired endfire pattern is characterized by the propagating wave component with a phase velocity matching the speed of light in free space. Evanescent spectral components are introduced and optimized such that the entire aperture surface becomes locally and globally passive and lossless. The field synthesis technique enables pattern control over the entire 180° angular range above the planar aperture, greatly expanding the limited capability in endfire pattern synthesis traditionally provided by surface wave (SW) antennas [4].

2. Complete endfire aperture field synthesis
Consider 2-D endfire radiation using a modulated reactance surface in TM polarization, as illustrated in Fig. 1(a). On an infinite perfect electric conductor (PEC) ground plane, an aperture of length $\ell = x_1 - x_0$ is characterized by an inhomogeneous surface reactance $X_s(x)$. It is desired that the modulated reactance surface realize a given endfire pattern when it is excited...
Figure 1. 2-D endfire radiation from a planar modulated reactance surface in TM polarization. (a) A planar modulated reactance surface mounted on a PEC ground excited by a feed SW. (b) The tangential $E$-field component of a $20\lambda$-long uniform aperture at $f = 300$ MHz. (c) The associated tangential $H$-field component over the aperture. For a $20\lambda$-long aperture at $f = 300$ MHz, a uniform aperture with $E_{tx}(x) = E_{0x}(x) + E_1(x) e^{-jk_c x} + \sum_{n=2}^{N} E_n(x) e^{j\psi_n(x)},$ (1)

where $k_c$ is the phase constant of the feed SW. The slowly-varying functions $E_n(x)$ ($n = 1, \ldots, N$) define the envelopes of the diminishing feed SW ($n = 1$) and fast spatially-varying [defined via $\psi_n(x)$] higher-order components ($n = 2, \ldots, N$). The associated tangential aperture $H$-field, $H_{tx}(x) = H_z(x, y = 0)$, is completely specified by $E_{tx}(x)$ via Maxwell’s equations. The desired far-zone radiation pattern is specified by the field pair $(E_{0x}, H_{0z})$ over the aperture. For a $20\lambda$-long aperture at $f = 300$ MHz, a uniform aperture with $E_{0x}(x) = e^{-jk_c x}$ V/m ($k = 2\pi/\lambda$ = free-space wavenumber) is shown Fig. 1(b), which includes a $\lambda$-wide transition at each end. The associated $H$-field component, $H_{0z}(x)$, is plotted in Fig. 1(c). Unlike $E_{0x}$, a significant tangential $H$-field exists beyond the aperture on the PEC ground, associated with endfire radiation.

A local condition for no loss and no gain at an impenetrable surface point is [5]

$$S_y(x) = -\frac{1}{2} \text{Re}\{E_{tx}(x)H^*_{tx}(x)\} = 0,$$ (2)

i.e., the normal component for the time-average Poynting vector vanishes. The envelopes $E_n(x)$ ($n = 1, \ldots, N$) can be numerically optimized to enforce (2) at all $x \in [x_0, x_1]$ in an average sense. To the optimization process described in [3], two pieces of refinement are added: $E_1(x)$ is allowed to be complex-valued and the feed SW strength is updated during optimization. Once the optimized tangential fields are found, the aperture surface is characterized by the surface impedance $Z_s(x) = R_s(x) + j X_s(x) = E_{tx}(x)/H_{tx}(x)$. As satisfaction of (2) implies $R_s(x) = 0$, the surface reactance $X_s(x)$ defines the aperture as a modulated reactance surface.

3. Numerical example

Consider a target endfire radiation with a main beam in the +$x$-axis direction associated with $(E_{0x}, H_{0z})$ in Figs. 1(b)–(c). Using $k_c = 2k$ and $N = 14$, the optimized $E_{tx}(x)$ produces the power density profile $S_y(x)$ in Fig. 2(a). Also shown is the power profile associated with the $n = 0$ term only, denoted by $S_0(x)$. It shows that an increasing amount of power leaves the surface as a
Figure 2. Field and reactance synthesis results for the 20λ-long uniform aperture. (a) The normal component of the Poynting vector in mW/m². (b) The retrieved surface impedance $Z_s$ normalized by the free-space intrinsic impedance $\eta \approx 377 \Omega$.

Figure 3. Characteristics of the reactance surface for a uniform-aperture endfire pattern. (a) Snapshot of $H_z(x,y)$ when the reactance surface is excited by a feed SW. The inset shows a magnified view near $x = 0$. (b) Simulated 2-D directivity patterns for the specification $[(E_0x, H_0z)]$, the optimized fields $[(E_{tx}, H_{tz})]$, and the continuous as well as discretized reactance-specified aperture surfaces $[X_s(x)]$.

space wave (i.e., radiation) with increasing $x$. For comparison, the power density associated with the first two terms in (1) is plotted in the inset. The pattern-defining component ($n = 0$) and the diminishing SW component ($n = 1$) interfere to create a strong spatially-oscillatory interference pattern. The higher-order terms ($n = 2, \ldots, 14$) play a role of neutralizing this power interference to bring the overall profile $S_y(x)$ for the total fields, $(E_{tx}, H_{tz})$, close to zero everywhere. From the optimized tangential aperture fields, the surface impedance $Z_s(x)$ is retrieved, as shown Fig. 2(b). The surface resistance is essentially zero all over the 20λ-long aperture, as desired. The surface reactance has an oscillatory behavior with an increasing amplitude, starting from an unmodulated value of $X_{s0} = \eta \sqrt{(k_c/k)^2 - 1} = \sqrt{3}\eta$. The modulation profile is clearly distinct from locally sinusoidal variations.

Performance of the synthesized reactance surface in creating the desired endfire pattern is assessed using full-wave simulation. Using COMSOL MULTIPHYSICS, $X_s(x)$ in Fig. 2(b) is mathematically enforced in $x \in [-10, 10]$ m and a feed SW carrying a power of 106.5 mW/m that matches the radiated power is launched onto the aperture surface. Figure 3(a) shows a snapshot of the resulting $H$-field distribution. Strong endfire radiation in the $+x$-axis direction is observed. A magnified view in the inset shows a mix of an SW bound to the surface and a space wave leaving the surface. In Fig. 3(b) are plotted 2-D directivity patterns associated with the specification, the synthesized fields, and the continuous as well as discretized (20 samples per wavelength) reactance surfaces. The pattern for the synthesized fields has a broad shoulder
near $\phi = 70^\circ$. It is associated with an abrupt change in the feed SW envelope $E_1(x)$ over a short distance that resulted from the field optimization. The patterns for both reactance surfaces have a good agreement with that associated with $E_{tx}(x)$ and they accurately reproduce the main beam and a few minor lobes of the desired pattern.

4. Conclusion
Using complete aperture field synthesis over both propagating and evanescent spectral ranges, design of modulated reactance surfaces for endfire characteristics has been presented. To the propagating wave fields that define the desired endfire pattern, auxiliary evanescent waves are added and optimized to render the entire radiating aperture passive and lossless. Starting from an appropriately defined propagating-spectrum component of the aperture fields, modulated reactance profiles for a variety of different endfire patterns can be designed. The synthesized reactance profiles may be realized using modulated metasurfaces.

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