Measurement and Analysis of Horn Antennas with Integrated High Impedance Surfaces

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Abstract — Rectangular horn antennas with integrated Sievenpiper high-impedance surfaces are presented. This high-impedance surface approximates a magnetic conductor, allowing TEM propagation within its stopband. This enables the horn antennas to operate at frequencies that would otherwise be below the TE_{1,0} cutoff frequency. Because the unit cell of a Sievenpiper high-impedance can be arbitrarily small, such an antenna can be reduced in volume arbitrarily. Four antennas in two geometries with metal and high-impedance sidewalls are designed, measured, and compared.

1 Introduction

A high-impedance surface (HIS) is an electrically thin, in-phase reflector that provides surface-wave suppression. Within a given frequency band the currents from an adjacent antenna and its image are in phase, as opposed to being 180° out of phase as typical with conductors. A Sievenpiper high-impedance surface is realized as an array of capacitive patches connected to a ground plane with vias [1]. The geometry and thus the lumped-circuit equivalents are tuned to exhibit high impedance over a predetermined frequency band. The structure is a composite right/left-handed (CRLH) metamaterial whose subwavelength unit cells act as a homogeneous effective dielectric.

Surface impedance is modeled as a parallel resonant circuit that is tuned to exhibit high impedance over a predetermined frequency band. Fringing electric fields between adjacent top patches are represented as a capacitance and magnetic fields in the dielectric generated by current through the vias and ground are represented as an inductance. A sheet impedance is defined to be equal to the impedance of this equivalent parallel resonant circuit, with a resonant frequency that marks the center of the HIS frequency bandgap.

The bandwidth of the HIS region is defined as the frequencies, where the radiation drops to half of its maximum value and occurs where the surface impedance is equal to the impedance of free space. The total bandwidth is approximately equal to the characteristic impedance of the surface divided by the impedance of free space. This is the bandwidth over which the reflection coefficient falls between ±90° and represents the maximum usable bandwidth for a parallel antenna over a resonant surface. A unit cell of the fabricated high-impedance surface with design parameters are shown in Figure 1. It is 20.2 mm (\lambda/6) square with a center frequency of 2.45 GHz and a 12% bandwidth [2, 3].

2 TEM Waveguides

From electromagnetics it is known that the transverse dimension of a waveguide must be at least one half wavelength to satisfy the boundary conditions needed for the propagation of an electromagnetic wave. To miniaturize a rectangular waveguide, traditionally one would fill it with a dielectric, where the transverse dimension would decrease by the square root of the relative permittivity. Due to dielectric loss, difficulty in manufacturing, and maximum permittivities, this approach has limits.

It has been shown that a TEM parallel-plate mode can be realized in a rectangular waveguide by replacing the

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Figure 1: Unit cell of the fabricated Sievenpiper high-impedance surface with design parameters. The unit cell is a 20.2 mm square.

Figure 2: Dimensions of simulated TEM waveguides and fabricated rectangular horn antennas. Metal-walled H31 and H13 structures have TE_{1,0} cutoff frequencies of 2.47 GHz and 7.42 GHz respectively.
Four antennas in two geometries with metal and HIS sidewalls are designed. Metal-walled H31 (a) and H13 (b) antennas have cutoff frequencies of 2.47 GHz and 7.42 GHz respectively. Antennas are modular (c) and tuned by moving a feed antenna in a channel.

metallic sidewalls with photonic bandgap structures [4, 5] and more recently with metamaterials [6-11]. Unlike a photonic-bandgap material, a high-impedance surface does not suppress surfaces waves through Bragg scattering from a periodic unit cell. Thus a unit cell can be a fraction of the free-space wavelength, providing a greater potential for volumetric reduction.

Because the high-impedance surface approximates a magnetic conductor, the waveguide supports TEM propagation within its stopband. This enables operation at frequencies that would otherwise be below the TE₁₀ cutoff frequency. This work seeks to build upon this related work by implementing reduced-volume rectangular horn antennas using a subwavelength high-impedance surface. Two rectangular-horn-antenna geometries are defined, analyzed as waveguides, and then implemented as rectangular horn antennas.

3 TEM Horn Antennas

Four antennas in two geometries with metal and HIS sidewalls are compared. Antenna dimensions are integer multiples of a HIS unit cell (20.2 mm) with a depth of five unit cells (101.0 mm). The first geometry, H31, shown in Figure 3(a) is three unit cells wide and one unit cell high. The metal- and HIS-walled H31 waveg-
Figure 5: Measured insertion loss (a), E-plane (b), and H-plane (c) far-field pattern measurements for the H31 antenna configurations.

The second geometry, H13, shown in Figure 3(b) is one unit cell wide and three unit cells high. The metal-walled H13 waveguide is cutoff below 7.42 GHz. The HIS-walled H13 waveguide has a simulated characteristic impedance of 1130 Ω at 2.45 GHz.

Figure 6: Measured insertion loss (a), E-plane (b), and H-plane (c) far-field pattern measurements for the H13 antenna configurations. The H13 metal-walled antenna is in cutoff.
angular waveguides are shown in Figure 4. TEM propagation is evident, with operation below the TE_{1,0} cutoff frequencies of the metal-walled counterparts. It is believed that the variation in the expected center frequency and bandwidth of the high-impedance surface and that of the guiding structures is due to intersurface coupling.

The four horn antennas are assembled from modular pieces of machined aluminum and high-impedance surfaces, as seen in Figure 3(c). The top, bottom, and back of the antennas are aluminum and the sides are either aluminum or a high-impedance surface. The bottom aluminum plate has a channel to allow for the tuning of an inserted feed antenna. Because the characteristic impedance of each waveguide is different, the position of the feed antenna in the channel varies. An optimal match near 2.45 GHz, guided by waveguide simulations, is found through tuning, the frequency sweep is performed, and the far-field pattern is measured.

The insertion loss and far-field radiation pattern of the H31 horns are shown in Figure 5. Pattern measurements are performed at the frequency indicated by the circle. The metal-walled H31 antenna is operating above its TE_{1,0} cutoff frequency of 2.47 GHz. As can be seen in the insertion-loss and far-field-pattern measurements, the metal- and HIS-walled antennas perform similarly. The insertion loss and far-field pattern of the H13 horns are shown in Figure 6. It can be seen in the far-field pattern measurements, that the metal-walled antenna is operating below its TE_{1,0} cutoff frequency of 7.42 GHz, whereas the HIS-walled antenna is functioning in a TEM parallel-plate mode. Agreement between measurement (Figure 5(a) and 6(a)) and simulation (Figure 4) indicate that waveguide analysis is an accurate method of predicting antenna performance.

4 Conclusions

Rectangular horn antennas with integrated Sievenpiper high-impedance surfaces have been shown to function at frequencies below the cutoff of a metallic horn antenna of the same dimensions. This high-impedance surface approximates a magnetic conductor in its stopband, allowing TEM propagation. Because the unit cell of a Sievenpiper high-impedance can be arbitrarily small, this antenna shows promise for further reductions in volume. In addition to reducing the size of the unit cell, future work will include improving bandwidth with an alternate feed.

References