Abstract: Artificial magnetic conductor (AMC) surfaces allow flush-mounted wire or strip antennas to radiate efficiently by exhibiting both a high surface impedance and a surface wave bandgap over some limited frequency range. In this paper, an electronically reconfigurable AMC is presented which dramatically increases the range of operating frequencies for an AMC device of specified thickness. Broadband planar antennas placed in close proximity to the reconfigurable AMC surface have been shown to radiate efficiently only in the surface wave bandgap of the AMC, and therefore are themselves tuned by the AMC structure. A planar spiral antenna has been demonstrated to tune over more than 3:1 bandwidth in a thickness of one-twentieth of a wavelength ($\lambda/20$) at band-center with instantaneous bandwidths ranging from 5 to 20%.

1. Introduction

An artificial magnetic conductor (AMC) - sometimes referred to as a high impedance surface - is a lossless reactive surface, usually realized as a printed circuit board that inhibits the flow of tangential electric surface current. This approximates a zero tangential magnetic field and results in a high equivalent surface impedance over some finite frequency range. This property allows wire
antennas (electric currents) to be placed flush in close proximity to the surface (<λ/100 away) without adversely affecting the antenna’s input impedance.

AMCs have the second property that both transverse magnetic (TM) and transverse electric (TE) surface waves are cutoff over some frequency range. This property is critical for maintaining good radiation efficiency. When properly designed, the AMC surface wave bandgap will correspond to same frequency band where the AMC exhibits a high surface impedance - thus enabling realization of an efficient, electrically thin antenna structure.

Figure 1-1 shows one AMC embodiment, invented at UCLA in the late 1990’s by Dan Sievenpiper et. al [1-4]. It consists of an electrically thin, planar, periodic structure with vertical and horizontal conductors, which can be fabricated using low cost printed circuit technologies.

The impedance properties of an AMC surface can be derived using the simple circuit model shown below in Figure 1-2.
The fractional bandwidth of a non-magnetically loaded Sievenpiper type AMC structure, defined by the ± 90° reflection phase points, is described by equation 1

\[
\frac{\omega_2 - \omega_1}{\omega_0} = 2\pi \frac{d}{\lambda_0}
\]  

where \(d\) is the thickness of the spacer layer, and \(\lambda_0\) is the free space wavelength at resonance where a zero degree reflection phase is observed. Thus, to support a wide instantaneous bandwidth, the AMC must be relatively thick. For example, to accommodate an octave frequency range (fractional BW = 0.667), the AMC thickness must be over a tenth of a free space wavelength thick (\(d = 0.106 \lambda_0\)). This thickness is too large for many practical applications. The limiting case of a passive Sievenpiper AMC is one whose thickness is a full \(\lambda_0/4\), and whose FSS capacitance has gone to zero. The phase bandwidth for this case (maximum instantaneous bandwidth for an AMC) is 3:1 or 100% fractional bandwidth.

Because antenna applications often do not require a broad instantaneous bandwidth but rather a narrow instantaneous bandwidth that is tunable over a broad frequency range, a viable alternative is to realize an electrically thin AMC structure that is electronically reconfigured. This reconfiguration can be achieved by adjusting the electrical properties of either the spacer layer (using ferrites or ferro-electrics) or by adjusting the capacitance of the FSS region. The FSS capacitance can be adjusted using PIN diodes, MEMs switches or MEMS actuators to adjust overlap area in two-layer FSSs, or via varactor diodes in a single layer FSS configuration [5]. The latter approach is the subject of this paper.

2. Varactor-Tuned AMC Implementation

A reconfigurable AMC (RAMC) realized by integrating varactor diodes into a single layer FSS is illustrated conceptually in Figure 2-1. This figure shows the general layout and the biasing scheme. The basic idea is that the varactor diodes add a voltage-variable capacitance in parallel to the intrinsic capacitance of the FSS layer. In this embodiment, the bias voltage is applied through the RF backplane. The vias, indigenous to the high-impedance surface, are used to route DC bias currents and voltages from stripline control lines buried inside the RF
backplane. RF bypass capacitors are used to decouple RF current at the base of the biasing vias. A ballast resistor of large value is placed in parallel with each diode to ensure an equal voltage drop across each series diode in the strings that are found between the biasing vias and the grounded vias. In practice, varactor diodes can be installed in a "thinned" pattern as shown in Figure 2-1 so as to reduce the number of varactors per unit area, and hence the cost, weight, and complexity. In the example shown, every other row and column is “thinned” for the integration of diodes. However, we could also skip two, three, or N rows of patches between diode strings (so long as the spacing of diodes remains smaller than approximately one quarter of a free space wavelength).

A physical realization of this approach, where every third unit cell contains a varactor is shown in Figure 2-2. This model was fabricated by sandwiching a 250 mil thick foam core ($\varepsilon_r=1.07$) between two printed circuit boards. The upper board is single-sided 60 mil Rogers R04003 board and forms the FSS. Plated through holes are located in the center of one out of every nine square patches, 300 mils on a side with a period of 360 mils. Tuning diodes are M/A-COM GaAs MA46H202 diodes, and the ballast resistors are each 2.2 M$\Omega$ chips. The RAMC is assembled by installing 22 AWG wire vias between the FSS board and the RF backplane on 1080 mil centers. The RF backplane is a 3 layer FR4 board, 62 mils thick, which contains an internal stripline bias network. Ceramic decoupling capacitors are used on the bottom side of the RF backplane, one at every biasing via (providing an RF short while maintaining DC isolation from ground). The size of the RAMC substrate is 10”x16”.
Figure 2-2. Physical realization of varactor-tuned RAMC. Total thickness is 375 mils, excluding surface mount components.

The design was accomplished initially using a simple equivalent circuit model analysis followed by rigorous analysis using a commercial TLM tool (Flomerics’ Microstripes) and rigorous surface wave analysis after Diaz, et. al. [6-7]. The equivalent circuit model for the FSS shown in figure 2-3 below included the extended unit cell (with diodes on every third patch) as well as practical implementation effects including diode packaging capacitance and necking inductance at the leads of each diode).

Figure 2-3. Equivalent circuit model for FSS portion of RAMC.
The measured reflection coefficient phase angle versus frequency is shown in Figure 2-4 with the varactor bias voltage as a parameter. At each bias level, the instantaneous +/- 90-degree bandwidth of the device is relatively narrow. However, as the bias level changes, the instantaneous +/- 90-degree bandwidth continuously moves across a much wider frequency band from 590 to 2110 MHz (0° reflection phase tunes from approximately 590 to 1920 MHz).

![Reflection Phase Measurements: Varactor-Tuned AMC](image)

Figure 2-4. Measured reflection phase of the varactor-tuned AMC with varactor bias voltage as a parameter. Note that \( d/\lambda_0 \) is 1/52 at 600 MHz & 1/16 at 1920 MHz.

Figure 2-5 shows the test set-up that is used to experimentally verify the existence of a TE surface wave bandgap. In this case, the transmission response \( (S_{21}) \) is measured between two Vivaldi-notch radiators that are mounted so as to excite the dominant electric field polarization for TE modes on the AMC surface. For the TE set-up, both antennas are oriented horizontally. For the TM set-up (not shown), the antennas are oriented vertically. Absorber is placed around the surface-under-test to minimize the space wave coupling between the antennas. The optimal configuration – defined empirically as “that which gives us the smoothest, least-noisy response and cleanest surface wave cutoff” – is obtained by trial and error. This optimal configuration is obtained by varying the location of the antennas, the placement of the absorber, the height of absorber above the surface-under-test, the thickness of absorber, and by placing a conducting foil “wall” between layers of absorber.
Figures 2-6 through 2-8 show the measured $S_{21}$ for the TE and TM surface wave measurements as described above for 50, 20 and 0 volt bias levels, respectively. The surface wave bandgaps observed are correlated closely to the +/- 90-degree reflection phase bandwidths at each bias level.

![Test setup for measuring TE surface wave frequency response](Image)

**Figure 2-5.** Test setup for measuring TE surface wave frequency response

![Surface wave measurements for RAMC w/bias voltage of 50V. The +/- 90 degree reflection phase bandwidth is indicated by the green bar.](Image)

**Figure 2-6.** Surface wave measurements for RAMC w/bias voltage of 50V. The +/- 90 degree reflection phase bandwidth is indicated by the green bar.
Figure 2-7. Surface wave measurements for RAMC w/bias voltage of 20V. The +/- 90 degree reflection phase bandwidth is indicated by the green bar.

Figure 2-8. Surface wave measurements for RAMC w/bias voltage of 0V. The +/- 90 degree reflection phase bandwidth is indicated by the green bar.
For expediency, the results above show only a few discrete bias conditions. However, it should be noted, that as bias voltage was changed in analog fashion, both the high-impedance band and the surface wave bandgap tuned continuously over more than 3:1 bandwidth. We next consider antennas in proximity to the tunable AMC surface.

3. Broadband Spiral Antenna Over Varactor-Tuned AMC

Demonstration of the properties in the previous section is necessary in order to characterize the AMC surface. However, in order for the AMC to be of practical use, we now consider integrated wire antenna/AMC radiating structures consisting of flush-mounted wire elements in close proximity to the AMC. Similar to the choice for the AMC itself, we can choose an antenna element with broad instantaneous bandwidth or a narrowband element which is tuned. In this case, the tradeoff in complexity associated with tuning is not favorable because broadband elements can be realized without severe penalties in size/weight.

Figure 3-1 below shows an 8 inch diameter, non-complementary, equiangular spiral flush mounted above the reconfigurable AMC. Note that the spiral arms contain less metal than a complementary spiral structure. This was done to minimize the capacitive perturbation to the AMC FSS layer. The spiral

![Figure 3-1. Printed spiral antenna located above the varactor-tuned RAMC.](image)
was etched on a 60 mil substrate of Rogers R04003. On the lower side of the substrate was attached a 100 mil thick foam spacer layer. This foam rested against the surface mounted diodes and chip resistors installed on the RAMC, such that the printed spiral was about 0.150” above the printed FSS surface. This spiral was fed with a Chebyshev-Duncan coaxial balun, which exhibited approximately a 3:1 impedance transformation ration (50:150Ω). When the spiral is in a free space environment, the return loss looking into the balun-fed spiral with a 50 ohm system is less than –8 dB over 400 MHz to 1000 MHz, less than -10 dB over 1000 MHz to 1200 MHz, and less than –15 dB over 1200 MHz to 2 GHz.

Figures 3-2 and 3-3 illustrate the fact that the broadband printed spiral antenna has a high gain bandwidth and a good impedance match over a range of frequencies defined explicitly by the surface wave bandgap of the RAMC upon which it rests. For the case of a 20 volt bias, the return loss has a plateau at approximately –15 dB over the frequency range of 1100 to 1400 MHz, which is effectively the surface wave bandgap as illustrated in Figure 2-7. Also, the swept gain plot of Figure 3-3 reveals that the broadside gain of the RAMC backed spiral is at least 3 dB higher than the case of the same spiral located above an absorber (i.e. in free space), for a frequency range from about 1150 to 1350 MHz, which is within the frequency range of the surface wave bandgap.

![Figure 3-2 Return loss measurement for the RAMC backed spiral antenna with bias set to 20 volts.](image-url)
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When the RAMC is biased to 50 volts, the surface wave bandgap, observed in Figure 2-6, extends from approximately 1600 to 2100 MHz. Figure 3-4 reveals that the return loss of the spiral element on this RAMC drops below –15 dB over this same frequency range. The swept gain shown in Figure 3-5 reveals that the boresight gain is at least 3 dB higher than the case of the same spiral located above an absorber, for the same frequency range of 1600 MHz to 2100 MHz.

Figure 3-3. Swept boresight gain for the RAMC backed spiral with 20 volt bias.

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Figure 3-4 Return loss measurement for the RAMC backed spiral antenna with the RAMC bias set to 50 volts.
Thus, by electronically adjusting the surface wave bandgap of the RAMC, we can obtain the desirable properties of an integrated planar broadband element over a wide tuning range. Just as the AMC reflection phase and surface wave bandgap are tuned smoothly by analog changes to the bias voltage, the antenna match and gain characteristics tuned smoothly across more than 3:1 bandwidth. We suspect that this behavior is possible in other classic broadband elements such as a bowtie antenna, a log-periodic bowtie, other planar log-periodic structures, etc.

For comparison, consider the commercially available Spiral Antenna Model 2090 from Microwave Engineering Corporation. This antenna is a spiral over an absorber-filled cavity with 9” diameter and 3.5” depth. The published gain characteristic (available on their web site) is very similar to the spiral presented here when placed over an absorber (cyan curve in Figure 3-5). In essence the RAMC approach allows us to achieve at least 3 dB more gain in a much thinner structure at a cost of decreased instantaneous bandwidth and added complexity.
4. Conclusions

We have demonstrated that a broadband spiral antenna can be mounted over a reconfigurable artificial magnetic conductor (AMC) and exhibit good impedance and gain performance over the range of frequencies defined by the high impedance band and surface wave bandgap of the AMC. As the RAMC is tuned over a wide range of frequencies, the spiral antenna can operate efficiently in the surface wave bandgap, even though the entire structure is only \( \lambda_0/30 \) thick at the lowest frequency.

This experiment demonstrates several key concepts. (1) A very physically and electrically thin antenna can be fabricated by installing a broadband printed element very close to a RAMC surface. In this case, the RAMC plus spiral has a total height of \( \lambda/20 \) at 1 GHz. (2) Over the frequency range defined by the tunable surface wave bandgap, the gain of this spiral at boresight, or broadside, is at least 3 dB greater than for the case of the same spiral element backed by an absorber. (3) The impedance match for the antenna is good (-15 dB or better) only over the high-impedance band for the AMC.
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References


