Study of a Flexible Low Profile Tunable Dipole Antenna Using Barium Strontium Titanate Varactors

David Cure¹, Thomas Weller², Félix A. Miranda³

¹ (IEEE Member): Research Department, Kymeta Corp., Redmond, WA 98052 USA, dcure@kymetacorp.com
² (IEEE Senior Member): E.E Department, University of South Florida, Tampa, FL 33620 USA, weller@usf.edu
³ (IEEE Fellow): Antenna and Optical Systems Branch, NASA John H. Glenn Research Center, Cleveland, OH 44135 USA, felix.a.miranda@nasa.gov

Abstract—In this paper a flexible low profile dipole antenna using a frequency selective surface (FSS) with interdigital barium strontium titanate (BST) varactor-tuned unit cells is presented. The varactor chips were placed only along one dimension of the FSS to avoid the use of vias and simplify the DC bias network. The antenna uses overlapping metallic plates that resemble fish scales as a ground plane to improve the flexibility of the multi-material stack structure. The measured data of the antenna demonstrate tunability from 2.42 GHz to 2.66 GHz and 1.3 dB gain drop when using overlapping metallic plates instead of continuous ground plane. The total antenna thickness is approximately ¼λ.

Index Terms—Flexible antennas, varactor-tuned high impedance surfaces, chip capacitors, BST, Young’s module.

I. INTRODUCTION

In recent years interest in the development of flexible antennas for portable applications has increased. Their characteristics such as the ability to conform to a surface and low weight make these types of antenna desirable. In this paper a study of a flexible low profile bowtie dipole antenna backed with a barium strontium titanate (BST) varactor-loaded frequency selective surface (FSS) is presented (Fig. 1). The antenna is fed with a microstrip-to-coplanar strip balun and uses two 2.4 mm-thick substrate layers, resulting in a total antenna thickness of ¼λ at the operational central frequency of 2.4 GHz. The antenna uses overlapping metallic plates to improve the flexibility of the structure.

Typically microwave antennas are made by assembling multiple layers of different materials. Some of these layers are made of metal; generally the backside of the antenna is a metal ground plane and the top side is a metal radiating element. Sandwiched between the metal layers is some kind of non-conducting, insulating material (the substrate). Previous researchers have developed flexible antennas by reducing the thickness of a single substrate layer or by using only one metal layer [1]-[4]. However, these antennas are narrowband and do not meet the requirements of the intended application. In most cases, the antenna performs better as the thickness of the insulating material increases [5]. This is especially true for low profile antennas where the electrical performance (i.e., matching, gain, efficiency, bandwidth, etc.) improves as the antenna thickness increases. On the other hand from a mechanical standpoint, flexibility improves with thickness reduction. Stiffness increases with the cube of substrate thickness and stress increases linearly with thickness limiting the amount of deflection before the antenna permanently deforms or breaks [6]. Thus, there is a conflict between improving the antenna performance by increasing the substrate thickness and improving its flexibility by decreasing the thickness.

This paper proposes increasing the flexibility of a multilayer antenna structure by using overlapping metal plates (fish-scale) which dramatically reduce the rigidity. The antenna design builds upon prior related work on rigid substrates that used a square patch FSS loaded with varactors [7], [8]. To the best of the authors’ knowledge this is the first study of a flexible BST varactor-based FSS for low profile antenna applications. All simulation results shown herein were obtained using Ansoft’s High Frequency Structure Simulator (HFSS) software.

II. MECHANICAL AND ELECTRICAL CONSIDERATIONS

One of the biggest mechanical challenges to address in a multi-material stack structure is how to achieve flexibility. The stiffness of a composite beam is directly proportional to the cube of the thickness and the maximum deformation is experienced by those materials that are farthest from the neutral axis (O). For an antenna, the need to achieve efficient and uni-directional radiation compels the use of a ground plane far from the bending neutral axis (O) which increases the rigidity of the stack. Three different scenarios are
depicted in Fig. 2; a polymer using only one copper layer (Case I), two copper layers (Case II), and a multi-material stack (Case III). The normalized rigidity was calculated for each case and is shown in Table I. For Case I, the normalized rigidity of a board with polymer height \((t_{PDMS})\) of 1.25 mm and one copper layer of thickness \((t_{Cu})\) 0.25 \(\mu\)m is 1. If the polymer thickness doubles, then rigidity increases by a factor of 4.3. In this case, the neutral axis does not pass through the centroid of the composite material and it lies closer to the copper layer, reducing the deformation of the latter. However, when a flexible material is sandwiched between two metal layers (Case II), the rigidity is increased by over three orders of magnitude in the examples in Table I. The metal layers will experience more plastic deformation than the polymer as they have a higher modulus of elasticity and are farther from the neutral axis (Fig 2f). For a multi-material stack structure (Case III), the rigidity of the board is increased by factor of 8,300 and 30,000 with respect to case I when \(t_{PDMS}\) is 1.27 mm and 2.5 mm, respectively.

![Fig. 2. (a) Rectangular cross section of PDMS based substrate with one metal layer; (b) rectangular cross section of PDMS based substrate sandwiched between two metal layers; (c) rectangular cross section multi-material stack structure, (d) Case I bent forming a negative curvature; (e) Case II bent forming a negative curvature; (f) case II showing plastic deformation of the metal layer.](image)

**TABLE I. NORMALIZED FLEXURAL RIGIDITY FOR DIFFERENT SCENARIOS**

<table>
<thead>
<tr>
<th>Polymer height</th>
<th>Case I One layer of copper</th>
<th>Case II Two layers of copper</th>
<th>Case III Multi-material stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigidity (1.25 mm)</td>
<td>1*</td>
<td>1200</td>
<td>8300</td>
</tr>
<tr>
<td>Rigidity (2.5 mm)</td>
<td>4.3</td>
<td>8100</td>
<td>30000</td>
</tr>
</tbody>
</table>

* Less rigid case (normalized values)

Another challenge of this design is reducing the losses caused by the series resistance of the BST varactors while using a relatively thin substrate. Full wave analysis of the unit cells using Ansoft HFSS predicts that the series resistance of a varactor has less impact on the antenna performance as the substrate thickness is increased. However, increasing the substrate thickness also increases the rigidity as explained before.

III. ANTENNA DESIGN, FABRICATION AND RESULTS

The flexible material selected for the antenna fabrication was polydimethylsiloxane (PDMS) mixed with ceramic loading to achieve miniaturization. The PDMS type selected was Sylgard 184 from Dow Corning which has been widely used for microwave applications [3], [9]-[10]. The ceramic powder used for loading the PDMS was the ultra-low fire UFL990 from Ferro Corp, which is a high dielectric constant (~90), small particle size (0.4 \(\mu\)m) and low loss material. Prior to implementing the multi-layer antenna design the high frequency electrical properties of the materials were determined using Agilent’s 85070D dielectric probe kit. Fig. 3a shows the dielectric constant and electric loss tangent for different volume ratios in a frequency range from 500 MHz to 3 GHz. The frequency of operation of the dipole antenna was chosen to be around ~2.4 GHz to be consistent with previous works and to facilitate in-house fabrication (Fig. 3b). The dipole was printed on liquid crystal polymer (LCP). The LCP type used in this work was ULTRALAM 3850 which has a low dielectric constant and low dielectric loss \((\epsilon_r=2.9\text{ and }\tan \delta = 0.0025)\). The LCP layer thickness is 25 \(\mu\)m with double-side copper cladding of 9 \(\mu\)m on which the radiator and the ground plane were patterned using photolithography [11]. The PDMS has an average thickness of 2.5 mm. The LCP and (blended) PDMS were bonded together using SU8-5 photoresist as an intermediate layer [5], [12]-[13]. The SU8-5 was spun onto the LCP at 2000 rpm (~7 \(\mu\)m thickness), then exposed and developed following manufacturer specifications. The SU8 layers were patterned into a square grid (segmented) to increase their flexibility Fig. 3c. The SU8-5 was then treated with (3-Aminopropyl)triethoxysilane (APTES) as explained in [14]. Separately, the PDMS substrate was exposed to oxygen plasma at 10 W, 50 standard cubic centimeters per minute (sccm) for 30 seconds. The LCP and PDMS were aligned with respect to each other and pressed together in a vacuum oven at 70°C for 3 minutes to create a permanent bond between the two materials.

![Fig. 3. 3a) Dielectric constant and loss tangent for the PDMS-ceramic samples at different volume ratios, b) Flexible bowtie antenna and c) SU8 Patterned on the LCP.](image)

The FSS and antenna substrates were cured at ambient temperature over a leveled optical table to maintain a uniform...
Simulations of the magnitude of the reflection coefficient ($\Gamma$) of a unit cell using different substrate losses and two different substrate heights are depicted in Fig. 4. The results show that the magnitude of reflection coefficient ($\Gamma$) decreases with increasing substrate loss tangent and ($\Gamma$) is particularly degraded when the FSS substrate is thinner. Also, as it was previously discussed in section II, increasing the substrate thickness increases the rigidity. Fig. 5 shows the effect of the equivalent series resistance of the varactor on the magnitude of the reflection coefficient for different substrate thicknesses.

To validate the impact on the antenna gain due to variations on the FSS height, three FSS’s with different substrate heights were fabricated with SMD chip capacitors (equivalent series resistance, ESR=0.5 Ω). All three FSS’s consisted of 30 unit cells and 25 chip capacitors and they were designed to operate at ~2.4 GHz, but built with substrates thicknesses of 2.0 mm, 2.3 mm and 2.5 mm and capacitance values of 1.2 pF, 0.7 pF and 0.5 pF, respectively. $S_{11}$ of the antenna backed with the three capacitive loaded FSS’s are shown in Fig. 6. The antenna backed with the 2.5 mm height FSS had the highest gain (0.8 dB) and better impedance matching than the others. The gain of the 2.3mm and 2.0 mm designs was 0.6 dB and 3.5 dB lower, respectively, with respect to the 2.5 mm height. These results are in agreement with the unit cell simulations in Fig. 5.
**TABLE II. FSS BIAS CONFIGURATIONS**

<table>
<thead>
<tr>
<th>Config.</th>
<th>$V_1$</th>
<th>$V_2$</th>
<th>$V_3$</th>
<th>$V_4$</th>
<th>$V_5$</th>
<th>$V_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0 V</td>
<td>0 V</td>
<td>0 V</td>
<td>0 V</td>
<td>0 V</td>
<td>0 V</td>
</tr>
<tr>
<td>B</td>
<td>30 V</td>
<td>-30 V</td>
<td>30 V</td>
<td>-30 V</td>
<td>30 V</td>
<td>-30 V</td>
</tr>
<tr>
<td>C</td>
<td>50 V</td>
<td>-50 V</td>
<td>50 V</td>
<td>-50 V</td>
<td>50 V</td>
<td>-50 V</td>
</tr>
</tbody>
</table>

Measured $S_{11}$ data for the antenna when applying a common bias voltage of 0 and ±50 V to the DC bias ports are shown in Fig. 9. Using the 10 dB return loss criterion, there is a 280 MHz span between the low end of the response with 0 V and the high end of the response using 50 V (shaded region in Fig. 9). Two additional resonances appear at ~2.1 GHz and 3 GHz when the input bias is 0 V and then these are shifted up ~200 MHz when the voltage is 50 V as consequence of TE surface wave propagation. The resonant frequencies of these modes can be calculated using the cavity model analysis explained in detail in [15]; this analysis predicts a TE resonance at ~2.07 GHz and 3.1 GHz for a FSS structure composed of five unit cells with periodicity of 9.9 mm.

The E-plane radiation patterns of the antenna for different bias voltages are shown in Fig. 10. The radiation patterns of the antenna with bias voltage of 0 V and ±50 V demonstrate cancellation of back radiation at 2.42 GHz and 2.66 GHz, which is within to the operational frequency of the tunable antenna shown in Fig. 9. The patterns are rotated ~25° due to the presence of surface waves. The effects of surface waves are observed in the radiation pattern due to the absence of vias in the high impedance surface. Fig. 10 also depicts the patterns at 3.0 GHz and 3.21 GHz which suggest the presence of leaky waves. The dispersion diagram of the 6 cascaded unit cells for different capacitance values was simulated using one dimensional (1D) simulation in HFSS. The Bloch dispersion diagram was calculated using the scattering parameters taking into account the number of cells along the direction of the electric field of the dipole (linearly polarized) which is where major excitation of surface waves is produced. The dispersion diagram shows backward/forward leaky waves at ~3 GHz for a capacitance value of 1.5 pF and at ~3.2 GHz for 1 pF. The leaky waves are supported in the fast wave region indicated to the left side of the light line shown in Fig. 11a. The magnitude of the tangential electric fields of 6 cascaded unit cells for $C=1.0$ pF at 3.2 GHz (leakage) and at 2.3 GHz (no leakage) are depicted in Fig. 11b.

The gains of the antenna backed with an FSS using a continuous and a fish scale ground plane were compared to each other. The continuous ground plane case was obtained by covering the fish scales with adhesive copper tape. The measured gain for the fish scale case was -0.86 dBi at 2.4 GHz for a 0V input bias and for the continuous case the gain was 0.4 dBi. This represents a ~1.3 dB gain reduction when using the fish-scale metal layer instead of a continuous ground. The low gain in both cases may be attributed to the
material losses and variations on the FSS height. The simulated antenna gain at broadside obtained with Ansoft HFSS using a continuous ground plane is approximately 1.6 dBi at 2.4 GHz; however the 0.04 loss tangent of the SU8-5 bond layer and possible variations of the substrate height were not included in the model to reduce the computational requirements.

A styrofoam cylinder of 50 mm radius \( r \) was used to perform the bending tests. The angle of curvature \( \theta \) was determined using the formula which defines the central angle whose vertex is the center of a circle \( (L=64\,\text{mm}) \). Fig. 12 and Fig. 13 show the radiation pattern and \( S_{11} \) data when the antenna is unbent and bent (positive and negative). The results show that when the antenna is bent in positive curvature the frequency shifts up 40 MHz (1.6\%) and the gain at 2.36 GHz increases by 3.1 dB for an angle of 77° for \( V=0 \) V with respect to the unbent case. This gain increase is realized because there is less back radiation as the angle increases and the ground plane curves toward the dipole direction. For the negative bending case the frequency shifts up 20 MHz (0.86\%) and the gain maintains similar values as the unbent antenna (~0.7 dB), but there is less back radiation as consequence of the curvature of the ground plane.

IV. CONCLUSION

The fish-scale ground plane was demonstrated specifically for flexible microwave antennas. The approach represents a significant advance in the combined thickness and flexibility that can be achieved, especially when using relatively thick substrates which are important for optimum antenna performance. An increase in gain and further reduction of back radiation were observed when the antenna was bent in a positive radius of curvature. The demonstrations that have been done in this paper using a hybrid manufacturing approach could be transitioned to thin-film microelectronics.

ACKNOWLEDGMENT

The authors thank Rogers Corporation for donating the LCP substrates used in this work. The authors also thank Maria F. Córdoba from USF for her support during antenna measurements and fabrication.

REFERENCES