Performance Analysis of Metamaterial Substrate Based MIMO Antenna Arrays

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Abstract—A rectangular patch antenna array for MIMO communications was simulated on a magnetic permeability enhanced metamaterial. The performance of this antenna array was studied relative to a similar array constructed on a regular substrate. The analysis was performed with respect to performance metrics such as degree of mutual coupling for different element spacing, achievable channel capacity, bandwidth and efficiency. The array built on the metamaterial substrate showed significant size reduction, less mutual coupling and significant channel capacity improvement compared to similar arrays on conventional substrates.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) wireless communication systems increase the spectral efficiency in multipath propagation environments by exploiting the spatial characteristics of the channel. However the theoretical gains achievable by a MIMO system is restricted due to a number of factors. A major design factor is the architecture of the transceiver antenna array. An ideal system would have independent array elements which are devoid of any mutual coupling between them while maintaining a small form factor. Although mutual coupling between the array elements have been shown to improve performance by creating pattern diversity when the angle spread of the received signal is small, in general it deteriorates system performance by increasing the correlation between the received signals [1]. Typical wireless devices also have stringent space constraints. This space constraint necessitates close placement of the array elements, which in turn results in higher levels of mutual coupling. From a power efficiency perspective, tight power constraints translate into the need for more efficient antennas. From a bandwidth perspective, the emerging popularity of ultra wide band (UWB) MIMO systems demand antennas with high bandwidths [3]. In order to meet such demanding and often conflicting design criteria, antenna designers have been constantly driven to seek better materials on which to build antenna systems.

Metamaterials are a broad class of synthetic materials that could be engineered to yield permittivity and permeability characteristics to system requirements [2]. By embedding specific structures (usually periodic structures) in some host media (usually a dielectric substrate), the resulting material can be tailored to exhibit the required characteristics. These materials have drawn a lot of interest in the antenna community [4] recently due to their promise as a candidate to overcome some of the antenna design issues discussed above. They have been shown to be able to miniaturize antennas by a significant factor for a given carrier frequency while operating at acceptable efficiencies [4].

Traditionally to keep the spatial requirements within acceptable limits, electromagnetic scaling is achieved by printing antenna structures on dielectric substrates with high $\varepsilon_r$. This scaling is due to the fact that the wavelength of a signal inside a material with dielectric constant $\varepsilon_r$ and magnetic permeability of $\mu_r$ is scaled down by a factor of $\sqrt{\varepsilon_r\mu_r}$ of its value in free space leading to antenna miniaturization. Traditionally the reason for confining antenna substrates only to high $\varepsilon_r$ materials is due to the lack of materials in nature that exhibit high $\mu_r$ in the radio frequency (RF) bands. However this technique suffers from lower bandwidths, difficulties in matching and poor efficiencies. One class of substrate, magnetic permeability enhanced metamaterials, have begun to fill this void [5]. Engineered metamaterials with high $\mu_r$ can miniaturize the antenna size without compromising other performance and design factors.

In this paper, we investigate the performance and suitability of a magnetic permeability enhanced metamaterial substrate (MS) for a MIMO communications system. The antenna element used in this analysis is a rectangular patch antenna. The system is designed to operate at 2.45 GHz. We compare the levels of mutual coupling and channel capacities to those achieved by a similar antenna array built on a regular FR4 substrate for different inter-element spacings. The analysis also compares the individual antenna element bandwidth and efficiencies.

II. METAMATERIAL SUBSTRATE

The metamaterial used to build the antennas for this work is based on the embedded circuit (EC) metamaterial described in [5]. This basic building block of this material is a unit cell structure which has a inductive spiral loop embedded in a dielectric substrate. A magnetic field normal to the plane of the spiral induces a current in the loop, a phenomenon that effectively creates an inductance within the substrate and creates magnetic energy storage in the unit cell. This storage enhances the magnetic permeability of the otherwise non-magnetic substrate material. This "induced" inductance along with the capacitance in the structure forms a resonance...
Fig. 1. Unit cell structure for the metamaterial containing a spiral loop embedded in a dielectric substrate (all units are in mm)  

Fig. 2. Variation of magnetic permeability with frequency for metamaterial unit cell. 

Fig. 3. Rectangular patch antenna array built on the magnetic permeability enhanced metamaterial substrate  

TABLE I  
RECTANGULAR PATCH ANTENNA DIMENSIONS AND PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FR4</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (mm)</td>
<td>35</td>
<td>12</td>
</tr>
<tr>
<td>W (mm)</td>
<td>20</td>
<td>10.12</td>
</tr>
<tr>
<td>l (mm)</td>
<td>30</td>
<td>7</td>
</tr>
<tr>
<td>w (mm)</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>y₀ (mm)</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>W₀ (mm)</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>t (mm)</td>
<td>1.27</td>
<td>6</td>
</tr>
<tr>
<td>Volume (mm³)</td>
<td>889</td>
<td>729</td>
</tr>
</tbody>
</table>

The resonance frequency of this structure can be controlled by tuning the spiral and substrate dimensions. The unit cell was modeled and simulated in the finite difference time domain using HFSS so as to resonate at 2.45 GHz. These unit cells are then stacked together to form a 3D structure. The resulting structure would thus have the embedded circuits distributed uniformly throughout the entire substrate. The unit cell and the corresponding dimensions are shown in Fig. 1.

The unit cell was designed on a FR4 substrate with \( \varepsilon_r \) of 4.4. The theoretically derived variation of relative permeability with frequency as in [5] for this unit cell structure is shown in Fig. 2. This model predicts a \( \mu_r \) as approximately 3.7 for this substrate in the direction perpendicular to the plane of the unit cell.

III. ANTENNA DESIGN

A rectangular patch antenna (RPA) with a recessed microstrip feed line, backed by a ground plane and operating in the \( TM_{010} \) mode was simulated on the metamaterial substrate as shown in Fig. 3, as well as on a FR4 substrate. The antenna was designed to resonate at 2.45 GHz. The antenna dimensions and parameters for both the designs are shown in Table 1.

Since current is induced in the spiral loop only by magnetic fields oriented in a direction perpendicular to the plane of the spiral, magnetic permeability enhancement is unidirectional in the substrate. The RPA can be designed to fully utilize the permeability available in this direction [5]. The length of the radiation edge can be approximately predicted by the following formula [6]:

\[
L = \frac{v_0}{2f_r\sqrt{\mu_r\varepsilon_r}}
\]  

where \( v_0 \) and \( f_r \) are the speed of light in free space and the frequency of operation respectively. The \( L \) predicted by (1) is 29.2 mm for the FR4 antenna. After simulations the final value for \( L \) was found to be approximately 30 mm. For the antenna on the metamaterial substrate, using 3.7 as a starting value for \( \mu_r \) in (1) yields a value of 15.2 mm for \( L \). However \( L \) for this design was found to be 5 mm from simulations which is significantly below the value predicted by equation (1). Plugging back these values in equation (1) yields a value of 20 for \( \mu_r \). This estimate of \( \mu_r \) is evidently an overestimate. The failure of equation (1) to predict closer values for \( L \) could be attributed to the inhomogeneous permittivity and permeability characteristics of the metamaterial substrate and further analysis and measurement is clearly needed.

A miniaturization factor of approximately 4.5 was achieved in the radiation edge length. In terms of area of the antenna plane, the metamaterial substrate design achieves a reduction of about 83%. However due to the higher thickness of the
metamaterial substrate, a reduction of only 18% was achieved in the overall volume occupied by the antenna array excluding the inter-element spacing.

IV. MUTUAL COUPLING ANALYSIS

The mutual coupling between the two antenna elements was analyzed in terms of the isolation (S21) between the two ports for the two antenna substrates. The port isolation was measured through simulation for antenna separation varying from 0.05λ to 0.5λ where λ is the signal wavelength. The results of this analysis is shown in Fig. 4. It can be clearly observed that the metamaterial array experiences around 10dB less mutual coupling at very close antenna spacing. There is even more of a gap in mutual coupling at higher spacing. Though the higher differences at larger antenna spacings could be predicted due to the reduced dimensions of the metamaterial antenna, the significant differences at smaller antenna spacings that were revealed by the simulations is encouraging if the system design does not intend to utilize pattern diversity [1]. For all other scenarios, this mutual coupling reduction is indeed an encouraging result since it means that not only these antennas could be made smaller, but could be placed very close to each other without inducing a large amount of mutual coupling.

V. CAPACITY ANALYSIS

The following analysis assumes a flat fading MIMO communication channel. The system is described by the following equation:

\[ y = Hx + n \]  

where \( x \) is the \( N_T \times 1 \) transmitted signal vector, \( y \) is the \( N_R \times 1 \) received signal vector and \( H \) is the \( N_R \times N_T \) channel transfer matrix. \( N_R \) and \( N_T \) are the number of receivers and transmitters respectively. \( n \) denotes the additive white Gaussian noise. The capacity of this system is given by:

\[ C = \log_2 \left[ \det \left( I_{N_R} + \frac{SNR}{N_T} HH^\dagger \right) \right] \]  

where \( I_{N_R} \) is the \( N_R \times N_R \) identity matrix and \( SNR \) the signal to noise ratio, \( \dagger \) denotes the complex conjugate transpose.

The effect of reduced mutual coupling was further analyzed through its impact on channel capacity. A 2 x 2 MIMO system was simulated using the electromagnetic ray tracer FASANT [7]. The metamaterial substrate antenna array was employed at each end of the communication link. The simulations were performed for two different spacings between the two elements: 0.1λ and 0.5λ. The same simulations were repeated with the FR4 antenna at both ends of the link. The atrium on the 3rd floor of the Bossone research building on Drexel University campus was chosen as the test environment. A line-of-sight link was set up and the channel matrices \( H \) were computed for all these antenna array configurations for a 2.45 GHz tone. All the channel matrices were normalized with respect to the channel matrix of the 0.5λ spaced FR4 antenna to allow for a meaningful comparison between results. The normalization factor is defined as follows:

\[ N = \sqrt{\frac{||H(0.5\lambda,FR4)||^2_F}{N_T N_R}} \]  

where \( ||\cdot||_F \) denotes the Frobenius norm.

The results of the channel capacity analysis are shown in Fig. 5. Based on the obtained results, the following observations could be made. As anticipated, the arrays with larger element spacings outperform their counterparts with smaller spacing. Among the 0.5λ spaced arrays, at lower SNRs, the performance does not show any significant differences. But as SNR increases, the metamaterial substrate antenna has gains of up to 1 bps/Hz. A promising result can be seen from the performance gap between the 0.1λ spaced arrays with and without the metamaterial substrate. The closely placed metamaterial substrate array can achieve nearly twice the capacity of its FR4 counterpart at lower SNRs and capacity increases up to nearly 400% at higher SNRs. This performance gap can be explained by looking at the difference in mutual coupling at 0.1λ separation in Fig. 4 where there is a difference.
of nearly 20dB when using a metamaterial substrate. Although the mutual coupling gap is higher at 0.5λ spacing, the absolute mutual coupling for the FR4 antenna is too low to have much of a deteriorating effect.

VI. BANDWIDTH AND EFFICIENCY

The bandwidth and efficiency for these antennas was computed as the final performance metric. The results are tabulated in Table 2. Efficiency of the metamaterial substrate antenna is significantly lower than that of the FR4 antenna. This result is anticipated since losses are incurred due to the current looping around in the unit cell spirals and due to the capacitive losses in the effectively thicker base substrate. Fig. 6 shows the return loss characteristics for an antenna element from each array. The -10 dB return loss bandwidth of the metamaterial substrate antenna is 35MHz which is half that of the FR4 antenna. This bandwidth degradation is due to the fact that the effective dielectric constant in the two directions parallel to the plane of the spiral in the unit cell experience an enhancement in permittivity [5]. This increase in permittivity negates the increase in permeability in terms of achieving a balance between capacitive and magnetic energy storage, resulting in a deterioration of antenna bandwidth. To improve bandwidth in this metamaterial substrate, the design of the inductive structure within the unit cell should be improved such that more magnetic field coupling occurs with the unit cell. In this improved design more magnetic energy can be stored resulting in a better balance with the capacitive energy storage.

![Figure 6](image_url)

Fig. 6. Return loss characteristics for the FR4 and metamaterial substrate antennas

TABLE II
ANTENNA BANDWIDTHS AND EFFICIENCIES

<table>
<thead>
<tr>
<th>Substrate Type</th>
<th>Bandwidth</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS</td>
<td>35 MHz (2.9%)</td>
<td>30%</td>
</tr>
<tr>
<td>FR4</td>
<td>70 MHz (1.45%)</td>
<td>55%</td>
</tr>
</tbody>
</table>

VII. CONCLUSION

The performance of a metamaterial substrate in a MIMO antenna array was studied. The metamaterial substrate yields a significant reduction in the antenna size while providing reasonable savings in total occupied volume. The mutual coupling between closely spaced array elements are significantly lower which translates into better channel capacity, especially for closely spaced elements. However efficiency is lower in the metamaterial substrate due to the copper losses in the unit cells. In addition there is a bandwidth deterioration in the metamaterial substrate due to increased permittivity in the substrate. Even given this efficiency and bandwidth loss, mutual coupling and capacity results with the metamaterial substrate remain encouraging. Since the metamaterial substrate discussed in this paper is not a homogeneous magnetic metamaterial, there is reason to hope that these shortcomings can be addressed by designs that are more uniform and homogeneous in its magnetic permeability characteristics.

REFERENCES