Coupling Reduction of Coupled Double Loop GPS Antennas Using Split Ring Resonators

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Abstract—We utilize broadside coupled split ring resonators (BC-SRRs) for reducing the mutual coupling between two closely spaced miniature coupled double loop (CDL) antennas to improve their performance when employed in miniature anti-jam GPS arrays. The CDL GPS antenna elements have a physical size of 1.1" x 1.1" and operate in the L2 and L1 bands with measured 5.8dB and 2.8dB gains, respectively. The BC-SRRs were designed to suppress their L2 band mutual coupling by effectively realizing a homogenous medium that could be characterized with negative permeability. Stacks of BC-SRRs were strategically placed between the 1.1" (i.e. ~λg/9) separated CDL antennas to maximize their interaction with the L1 band magnetic field distribution. Preliminary computational studies demonstrate that the approach can provide >5dB reduction in L2 band coupling.

Keywords- Miniature antenna, GPS, Mutual coupling, Coupled double loop antenna, CDL, split ring resonator, SRR

I. INTRODUCTION

Mutual coupling degrades the performance of tightly packed antenna arrays in terms of input impedance mismatch, side lobe level, scan blindness, pattern degradation, and radiation efficiency [1, 2]. Several techniques were proposed in the past for mitigating the undesired effects of mutual coupling [3]-[5]. Recently, electromagnetic band gap (EBG) structures [6] and metamaterial insulators based on split ring resonators (SRRs) [7, 8] have been introduced as alternative and effective methods for suppressing the coupling in antenna arrays. Due to their compact size, SRRs have been particularly found attractive when the antenna elements of the array were placed in close proximity (<<λg). Specifically, stacked SRRs were shown to prevent wave propagation and suppress mutual coupling by emulating a medium that can be characterized via an effective negative permeability and positive permittivity (i.e. single negative medium).

In this paper, we investigate coupling reduction in a two-element miniature GPS array constructed from the recently introduced coupled double loop (CDL) antennas. The CDL antenna elements operate at the L2/L1 GPS bands with an overall size of 1.1" x 1.1" x 0.5" and placed 1.1" apart from each other. To suppress the L2 band mutual coupling, broadside coupled split ring resonators (BC-SRRs) are employed around the CDL antennas. Although SRR based coupling reduction has been already investigated in the recent literature, these studies are limited to linearly polarized patch [7] and high profile monopole [8] antennas. This effort extends the approach to circularly polarized antennas and printed loop radiators. In the following section, we briefly describe the operation principle and performance of the compact dual-band GPS CDL antenna. In Section III, we demonstrate the coupling related performance degradation in a two-element CDL GPS array. Subsequently, we carry out a computational study to investigate the L2 band magnetic field (H) distribution in order to identify the suitable locations and orientations in which the BC-SRRs could be positioned. Section IV discusses the operation principle and performance of the L2 band BC-SRRs through their extracted equivalent constitutive parameters. Section V presents preliminary computational studies demonstrating the performance of the BC-SRR based coupling reduction. Specifically, the approach is shown to provide >5dB coupling reduction in the L2 band without destroying the input impedance matching of the CDL antennas.

II. L2/L1 BAND COMPACT CDL GPS ANTENNA

Fig. 1(a) presents geometrical configuration of a fabricated dual band CDL antenna [8] operating at the L2 (1.227 GHz) and L1 (1.575 GHz) bands of the GPS. The antenna consists of two capacitively coupled loops printed on a readily available Rogers TMM10i (εr = 9.8 and tanδ = 0.002) substrate. By adjusting the line widths, lengths, and the amount of coupling capacitors, two resonances are generated at the desired GPS frequencies. The capacitive couplings and the substrate permittivity are primarily used to reduce the size of the antenna footprint. The CDL antenna shown in Fig. 1(a) differs from the earlier designs [9], since the substrate size (which is typically twice of the antenna footprint) is also significantly limited to linearly polarized patch [7] and high profile monopole [8] antennas. This effort extends the approach to circularly polarized antennas and printed loop radiators. In the following section, we briefly describe the operation principle and performance of the compact dual-band GPS CDL antenna. In Section III, we demonstrate the coupling related performance degradation in a two-element CDL GPS array. Subsequently, we carry out a computational study to investigate the L2 band magnetic field (H) distribution in order to identify the suitable locations and orientations in which the BC-SRRs could be positioned. Section IV discusses the operation principle and performance of the L2 band BC-SRRs through their extracted equivalent constitutive parameters. Section V presents preliminary computational studies demonstrating the performance of the BC-SRR based coupling reduction. Specifically, the approach is shown to provide >5dB coupling reduction in the L2 band without destroying the input impedance matching of the CDL antennas.

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reduced to barely fit the antenna footprint. To compensate the drop in the radiation efficiency associated with the small substrate size, the outer loop of the antenna is loaded with 310mil long 1mm diameter conductive pins. Circularly polarized radiation is excited by two 50Ω coaxial probe feeds with 90° out of phase. The compact CDL antenna has dimensions of 1.1" x 1.1" x 0.5" (i.e. ~λ₀/9 x λ₀/9 x λ₀/20) and placed on top of a large metal plane that was modeled as an infinite ground in numerical simulations (throughout the paper, Ansoft’s high frequency structure simulator (HFSS®) was used as the design tool). Fig. 1(b) compares the simulated and measured (over a 24" x 24" brass plate) return loss performances of the CDL antenna. Specifically, the antenna operates with 10 MHz and 14 MHz |S₁₁| < -10 dB bandwidths at the 1.239 GHz and 1.612 GHz, respectively. The resonance frequency deviations (1% at L₂, 2.3% at L₁) observed in the measurements can be very well attributed to the fabrication tolerances/errors. These deviations can be removed by modifying the value of the coupling capacitors and length of the conductive pins. The measured antenna gains are 5.8dB at 1.239GHz and 2.8 dB at 1.612 GHz. The antenna performs with > 0 dB measured gain bandwidths of 40 MHz in L₂ and 30 MHz in the L₁ bands, respectively. Further reduction in antenna size is possible by resorting to higher contrast ceramic substrates. Design and performance details of the GPS CDL antennas will be discussed elsewhere [10].

III. L₂ BAND MUTUAL COUPLING IN TWO-ELEMENT CDL GPS ARRAY

Compact size of the dual band CDL antennas makes them promising to be employed in miniature anti-jam GPS arrays. However, the undesired mutual coupling between the antenna elements could prevent them to be placed in close proximity; thus, limiting the amount of array miniaturization that could be achieved. Therefore, it is important to investigate the coupling mechanism between the CDL antennas and develop methods to reduce it as much as possible.

To understand the coupling mechanism between the CDL antennas, we considered the two-element array geometry depicted in Fig. 2. For decreasing the time necessary for the computations, we chose to investigate the coupling performance in the L₂ band. This choice is also well justified when the electrical size of the array is considered. Since the antennas are electrically much smaller and closer in the L₂ band, their coupling as well as (if possible) their isolation is expected to be much more challenging than the L₁ band. To simplify the computational model further, the inner loop and lumped capacitors are removed from the antenna layout, as they are primarily responsible in generating the L₁ band radiation. It is also important to note that the inductively loaded outer loop carries majority of the current induced in the L₂ band; thus, removal of inner loop does not significantly affect the L₂ band coupling study. As shown in Fig. 2, the antennas are mirror images of each other about the x-z plane and located 1.1" away (~λ₀/9 at L₂). This average distance was selected such that a total of five antennas could be fit within a ~4.5" diameter aperture.

Fig. 3 presents the simulated scattering (i.e. S) parameters of the two-element array. Due to mutual coupling, antenna resonances seen by the feed ports experience different amounts of frequency shift (see Fig. 2 for the port numbering). Specifically, the input impedance seen from ports #1 and #3 is well matched at 1.227 GHz, whereas the impedance seen by ports #2 and #4 are matched at 1.245GHz (see Fig. 3(a)). This discrepancy is due to the higher coupling between the modes excited by ports #2 and #4 (i.e. S₂₄) relative to that between ports #1 and #3 (i.e. S₁₃). As depicted in Fig. 3(b), the coupling between the ports #1 and #4 (i.e. S₁₄) and ports #2 and #3 (i.e. S₂₃) are ~20dB lower with respect to other couplings. Therefore, in the following, we focus only on the S₁₃ and S₂₄ responses.

To demonstrate the effect of coupling on the gain performance, Fig. 4 compares the broadside co-pol. and cross-polarized gains of the stand-alone antenna and the two-element array. We observe that the mutual coupling increases the cross-polar gain level by ~7dB.

As mentioned earlier, BC-SRRs could be employed to reduce mutual coupling within tightly packed antenna arrays. Since, they suppress coupling by interacting with the H field, it is important to investigate the field distribution when the two antennas are placed in close proximity of each other. Fig. 5(a) shows the H field distribution when port #1 is exited and the remaining ports are terminated with matched loads. As can be seen, the H field flowing from the excited towards the inactive antenna is primarily concentrated within the indicated volumes. On the contrary, Fig. 5(b) demonstrates the H field distribution.
Figure 4. A comparison of the simulated gains belonging to the stand-alone antenna and the two-element array.

Figure 5. Magnetic field distribution when: (a) port #1 is excited and the others are terminated with matched loads; (b) port #2 is excited and the others are terminated with matched loads. The indicated volumes represent potential regions in which BC-SRRs can be utilized to reduce mutual coupling.

when port #2 is excited and the other remaining ports are matched. In this case, the $H$ field is concentrated within the volume right between the antennas. This study clearly shows that the coupling mechanism is different for the modes excited on the CDL GPS antenna. The $H$ field concentrations within the indicated volumes are almost uniform and oriented in the $y$ direction. Therefore, filling these areas completely or partially with BC-SRRs having their axis oriented in the $y$-direction is expected to block the magnetic field and the associated coupling observed among the excitation ports.

IV. BC-SRR DESIGN FOR $L_2$ BAND COUPLING REDUCTION

Fig. 6 shows the computational model that was employed to design the BC-SRR unit cells. The side walls parallel to the $x$-$z$ plane are perfect magnetic conductors (PMCs), whereas the top and bottom walls are perfect electric conductors (PECs) to model propagation through an infinitely large 2D slab consisting of the BC-SRRs. By calculating the reflection and transmission coefficients of the slab, the equivalent material properties were extracted as depicted in Fig. 6(b) and (c) [11]. The design goal is to obtain an effective permeability ($\mu_r$) response to suppress the wave propagation over the desired frequency band.

The unit cell layout is a modified version of the conventional edge coupled SRR configuration [12]. Since BC-SRR provides a smaller size (due to the increased capacitance between the adjacent loops) and avoids the bi-anisotropic effects observed in the conventional edge coupled SRRs, it was selected for the coupling reduction study. The BC-SRR shown in Fig. 6 consisted of two 180° rotated open loop resonators that are printed on each side of a 0.032" thick, 15 x 12.7 mm² Rogers RO4003C ($\varepsilon_r = 3.55$, tan$\delta = 0.0027$) substrate. The loops are made of 0.5 mm wide copper lines and designed to be rectangular in order to exhibit larger inductance and higher isolation bandwidth [13]. Each loop has a footprint size of 12.5 x 11 mm² and the gap is 7 mm wide. To achieve a homogenous medium, the periodicity in the $y$ direction is assumed 4 mm, which is $<< \lambda_0$ at 1.227 GHz. As depicted in Fig. 6(b) and (c), the designed BC-SRR resonates at 1.227 GHz and exhibits an effective negative $\mu_r$ in the $L_2$ band.

V. TWO-ELEMENT GPS ARRAY LOADED WITH BC-SRRS

To decrease mutual coupling between the antenna elements, we proceeded to place the BC-SRRs in to the two-element GPS array as shown in Fig. 7. This configuration is expected to simultaneously reduce the coupling indicated by the $S_{13}$ and $S_{24}$, since the BC-SRRs are positioned to interact with the magnetic fields excited with both port #1 and port #2 as was suggested by the coupling study carried out in Section III. Fig. 8(a) shows the return loss response of the BC-SRR loaded array. As seen, all the ports exhibit a good impedance match at the $L_2$ band, although ports #1 and #3 experience another resonance at 1.16 GHz. Most importantly, the mutual couplings associated with the $S_{13}$ and $S_{24}$ responses are both reduced by >5dB as shown in Fig. 8(b) and (c). The cross-pol. gain level in
VI. CONCLUSION

The mutual coupling within a two-element GPS array consisting of miniature coupled double loop antennas were reduced by utilizing the broadside coupled split ring resonators. The BC-SRRs were placed within the antenna layout to maximize their interaction with the magnetic field distribution. Computational studies demonstrated that the approach can reduce coupling >5dB in the \( L_2 \) band and consequently, decrease cross-pol. gain by 15dB when the antennas are placed in close proximity (i.e. \( \lambda_0/9 \)). It is important to further investigate the performance for various antenna separations and BC-SRR positions. In addition, the approach must be extended to \( L_1 \) band to enable coupling reduction within a tightly packed miniature GPS array. Several designs and measurements are underway and will be presented in the conference.

REFERENCES