A Novel 1.5" Quadruple Antenna for Tri-Band GPS Applications

Yijun Zhou, Stavros Koulouridis, Gullu Kiziltas, and John L.Volakis

Electroscience Lab, ECE department, The Ohio State University

Columbus, OH 43212

Email: {zhou.160, koulouridis.1, kiziltas.1, volakis.1}@osu.edu,

Abstract

A new GPS antenna is proposed to cover the three GPS bands (L1, L2 and L5 namely 1575MHz, 1227MHz and 1176MHz) with the L5 band to be added after 2006. The developed antenna size is only 1.5"x1.5" in aperture corresponding to λ/7 x λ/7 (λ = free space wavelength) and λ/13 thick. Quadrature feeding is employed to ensure RHCP radiation. The final miniature antenna exhibits a gain greater than 2dBi, and to our knowledge this is the smallest such size for CP operation covering all three bands. Detailed parametric simulations leading to the best design along with measurements for the constructed antenna are presented.

I. Introduction

Several GPS antennas designs [1]-[6] have been presented in the literature. These cover either one or both of the standard L1 (1575MHz) and L2 (1227MHz) bands. The introduction of the L5 band operating at 1176GHz calls for designs that cover all three bands (each having 25 MHz bandwidth). To achieve tri-band GPS operation, a design was presented in [7] using integrated inductors and capacitors for dual frequency operation (with the lower resonance having sufficient bandwidth to cover the L2 and L5 bands) and quadrature feeding to ensure RHCP radiation. However, this design [7] is relatively large for portable GPS devices since it has an aperture of 5''x5''or λ/2 x λ/2 at the lowest frequency (L5).

In this paper we present a new small size tri-band GPS antenna. The overall aperture size of the proposed antenna is only 1.5"x1.5" (λ/7 x λ/7) and λ/13 thick. It is based on an F-shaped conductor design (hence the name F-antenna) embedded in a two-layer dielectric substrate. Below (section II) we discuss the design concept and approach for this novel F antenna. This is followed (section III) by a parametric analysis along with simulations and measurements (section IV) of the final design.

II. Antenna Design

Noting that the L2 (1227MHz) and L5 (1176MHz) bands are very close, our design strategy is to use a dual band resonant antenna with the lower resonant frequency to cover the L2 and L5 bands. To start the design we refer to the LC loaded inverted L antenna given in [7] which demonstrates a satisfactory performance over all three GPS bands. To reduce the size of the antenna we proceeded to add a high dielectric constant as part of the substrate. However, high permittivity substrates resulted in a narrower bandwidth performance due to unavoidable impedance mismatches. Among possible solutions to regain bandwidth performance was that of optimizing the conductor shape and tuning the inductive and capacitive loads (L and C). However, such modifications did not lead to a satisfactory design. Thus, we proceeded to introduce a new antenna design.

Specifically, we removed the LC elements and added another conductor layer to the original inverted-L configuration, intended to introduce a new resonance. We also tapered the horizontal conductors (see Fig. 1) to improve impedance matching and, thus, increase bandwidth at the resonances. In the following, we discuss how the optimized geometry of this new design leads to a 38mm x 38mm size for tri-band operation. The antenna has four F-shaped conductor arms (each fed with 90^o sequential phase shift) to achieve CP operation.

III. Parametric Analysis

A. Antenna design

The proposed F antenna is depicted in Fig 1a and consists of four F shaped conductor sections each fed by a 50Ω coaxial cable as shown. Further, the patch-like conductors forming the F shape are printed on different dielectrics substrates to allow for resonance control. With reference to Fig. 1, the first (or top) layer is indicated as the No. 1 layer, whereas the second (or lower) layer is denoted as the No. 2 layer. Among the parameters shown in Fig. 1, l_1 and l_2 represent the lengths of the horizontal conductors, d_1 and d_2 denote the thickness of the layers, ε_{r1} and ε_{r2} are the relative dielectric constants of the substrates. Also, w_a and w_b refer to the inner and outer thicknesses, respectively, of the patches (the patches of the top and lower layers have the same thicknesses). The vertical conductors are also of thickness w_b (see Fig. 1).

To better understand the operation of the proposed F antenna, several plots of the fields within the substrate where examined. Assuming $\varepsilon_{r1}>\varepsilon_{r2}$, we found that the top conductors are responsible for the lower frequency resonance (L2 and L5). However, the higher frequency resonance (L1) is affected by the coupling between the top and bottom horizontal conductors and their interaction (see Fig. 1b).

B. Horizontal conductors' length effect

We begin the tuning of the configuration (Fig. 1) by first adjusting the l_1 and l_2 lengths that correspond to the top and bottom patches. Fig. 2 shows the effect of l_1 and l_2 lengths on antenna gain (with d_1=11mm, d_2=9mm, ε_{r1}=25, ε_{r2}=10.2, w_a=4mm, w_b=12mm). As seen, the gain for l_1=l_2=10mm peaks around 1.2 GHz and 1.6 GHz giving about 1dBi gain at L2 and L5 bands and almost 2dBi at the L1 band. If we keep l_1=10mm and increase l_2 by 0.75mm (l_2=10.75mm) the gain at the L2 and L5 bands remains the same whereas, around L1 band, it moves 25MHz towards the right and concurrently decreases. Finally, if we choose l_1=l_2=11mm the low and higher frequency resonances move to the right and the gain peaks at 1.5GHz (lower than before) covering the L1 band (with greater than 0dBi gain). However the L2 band is not covered and the gain at the L5 band somewhat decreases.

C. Dielectric layers' thickness effect

From the above, it is best to chose the conductors lengths so that l_1=l_2=10mm. With this choice, we next proceed to tune the dielectric layer thickness. The goal is to better center the resonances and to improve gain. Example gain curves for different substrate thicknesses d_1 and d_2 (with l_1=l_2=10mm, ε_{r1}=25, ε_{r2}=10.2, w_a=4mm, w_b=12mm) are shown in Fig. 3. We observe the trend that increasing d_1 (d_1=8mm, 11mm, 12mm) shifts both resonances towards the right and improves the gain for the L1 band. Of the three curves (with d_2 kept at 9mm) we observe that d_1=11mm provides a better compromise on gain and frequency performance. Thus, d_1 is kept at 11mm while d_2 is varied as shown in Fig. 3b. Among the three gain curves

(d_2= 7mm, 9mm, 11mm), we readily conclude that the curve corresponding to d_2=9mm provides better gain at L2 and L5 without compromising performance at the L1 band.

D. Dielectric layers' permittivity effect

Permittivity values are not normally changed due to the limited availability of substrate materials. Nevertheless, it is worth looking at the effect of permittivity on gain to assess the appropriateness of dielectric constants ε_{r1}, ε_{r2}. To do so, we chose the geometrical parameters l_1=l_2=10mm, d_1=11mm, d_2=9mm (with w_a=4mm and w_b=12mm) since they have shown the best performance so far with ε_{r1}=25 and ε_{r2}=10.2. Fig. 4 shows gain plots as they are varied around the mentioned values. As expected (Fig. 4a), increasing ε_{r1} or ε_{r2} results in lower resonance frequencies. More importantly, it is seen that the choices of ε_{r1}=25 and ε_{r2}=12 are rather good in terms of gain and resonance frequencies.

IV. Final Design: Simulation and Measurements

The parameter choices for the final design (see Fig. 1a) are a=38mm (aperture width and length), l_1=9.6mm (upper conductor length), l_2=10.5mm (lower conductor length), d_1=12mm (upper substrate thickness), d_2=8mm (lower substrate thickness), w_a=4mm (smallest width of lower and upper patches), w_b=12.5mm (largest width of lower and upper patches), ε_{r1}=25 (upper substrate permittivity), ε_{r2}=12 (lower substrate permittivity). Fig. 5 shows the gain for the fabricated antenna and it is readily observed that the measured RHCP gain is in good agreement with the calculated for the L2 and L5 bands. Also the radiation patterns in Fig. 5b show that the polarization purity is rather good as well (although only L5 pattern is shown, the corresponding patterns for the other frequencies are omitted since they are alike).

However, the measured gain around L1, although it tracks the calculations it deviates from them. Specifically, its rise from the gain dip is not as sharp and does not therefore reach the 2-3dBi gain point as quickly. Thus, for the L1 band, the measured gain is on average 0dBi (about 2dB lower than calculated). This is likely due to possible air gaps between the lower conductors and the substrate and between the substrates. Such gaps are pronounced for the higher frequencies and do not therefore affect the L2 and L5 bands. This conclusion is confirmed from the calculations shown in Fig. 5a where a 0.2mm air gap has been inserted between the upper and lower substrate in the simulated antenna. Such gaps may not be easy to eliminate completely. Therefore it may be more practical to slightly increase the length of the lower conductor (say 0.75mm). As seen in Fig. 2, the choices of l_1=10mm and l_2=10.75 mm (instead of l_1=l_2=10mm) can lead to a shift of 25 MHz at the L1 band (without significantly affecting the L2 and L5 bands) needed to ensure a gain of greater than 0dBi for the measured curve in Fig. 5 while accounting for the air gaps.

The S parameters of the measured prototype were measured using an Agilent E8362B network analyzer. Fig. 6b gives the S11 (return loss) and S13 (coupling) parameters. Considering that the opposite (1 and 3) ports have 180^o phase difference, this coupling implies that the current is traveling from one port to the other through the horizontal conductors. Hence, the proposed inverted F antenna includes traveling wave components.

V. Conclusions

We proposed a λ/7 x λ/7 and λ/13 thick (at L5) rectangular antenna which employed two homogeneous layers to achieve a gain greater than 0dBi and at least 24MHz bandwidth at all three GPS frequencies (L5: 1176MHz, L2:1227MHz, L1: 1575MHz). Quadrature feeding with 90^o phase shift was employed to ensure RHCP radiation. The design was verified using a fabricated prototype and the measurements showed a gain of 2dBi at boresight for the L2 and L5 bands and about 0dBi for the L1 band. A challenging task for further miniaturization is to decrease the coupling among the ports which will however affect gain. Use of inhomogeneous dielectrics may therefore be an alternative way to overcome coupling [8] without sacrificing the gain.

References

[1] C. Y. Huang, "Microstrip antenna with lossy patch," *Microwave Opt. Tech. Letters,* vol. 18, issue 3, pp.228-230, 1998.

[2] L. Xing, "A novel high performance GPS microstrip antenna," *IEEE Proc. Anten. Prop. Soc. Intern. Symp.,* vol. 2, pp. 988-991, 2000.

[3] L. Boccia, G. Amendola, G. Di Massa, "A shorted elliptical patch antenna for GPS applications," *Ant. Wireless. Prop. Letters*, vol. 2, issue 1, pp. 6-8 2003.

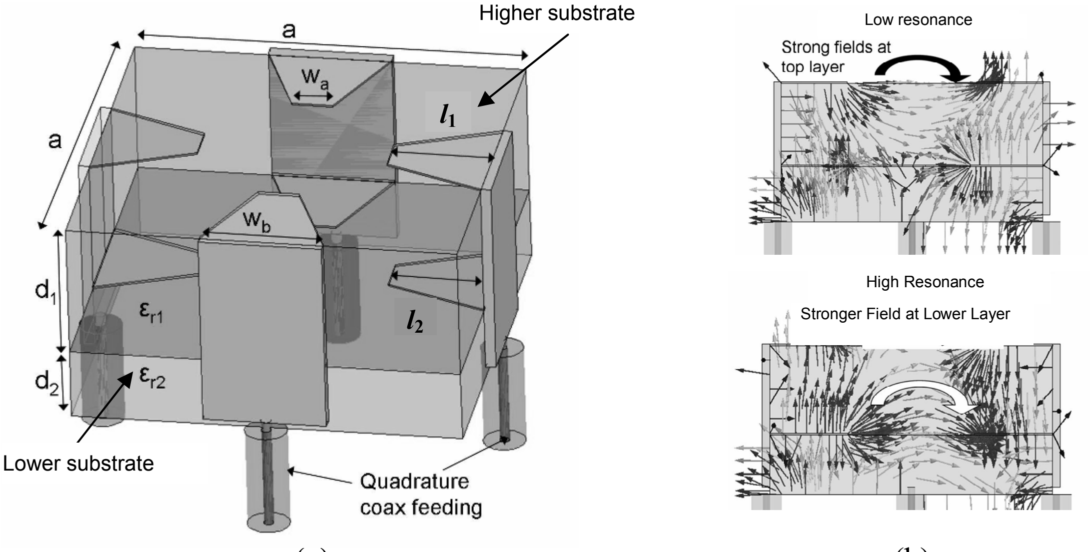
[4] Y. C. Lin, T. W. Chiu, K. L. Wong "Small-size surface-mountable circularly polarized ceramic-chip antenna for GPS application," *Microwave Opt. Tech. Letters*, vol. 40, issue 4, pp. 300-302, 2004.

[5] C. M. Su and K. L. Wong, "A dual-band GPS microstrip antenna," *Microwave Opt. Tech. Letters,* vol.33, issue 4, pp.238-240, 2002.

[6] X. F. Peng, S. S. Zhong, S. Q. Xu and Q. Wu, "Compact dual-band GPS microstrip Antenna," *Microwave and Opt. Tech. Letters,* vol. 44, issue 1, pp. 58-61, 2005.

[7] B. Rama Rao, M. A. Smolinski, C. C. Quach and E. N. Rosario, “Triple-band GPS Trap-loaded Inverted L Antenna Array,” *Microwave and Opt. Tech. Letters,* vol.38, issue 1, pp. 35-375, 2003.

[8] G. Kiziltas, D. Psychoudakis, J. L. Volakis and N. Kikuchi, “Topology design optimization of dielectric substrates for bandwidth improvement of a patch antenna,” *IEEE Trans. Anten. Prop.,* vol.51, pp. 2732-2743, Oct. 2003.



(a) (b)

Figure 1. (a) Proposed F antenna after removing the LC elements in [7] and adding another conductor and dielectric layer to generate a second resonance, (b) Resonant modes of the F antenna; darker vectors represent higher electric fields; lower frequency (L5 and L2) fields are higher on the upper horizontal conductors whereas the higher frequency (L1) fields are more concentrated around the lower conductors.

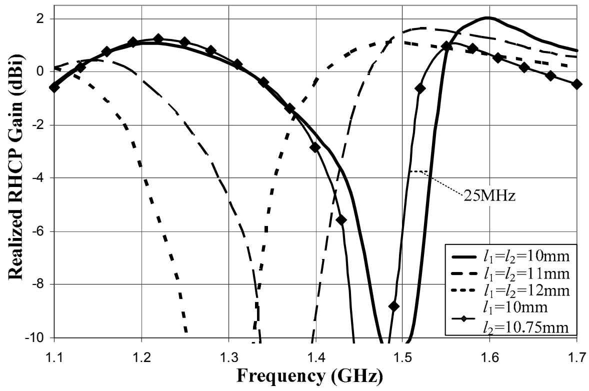
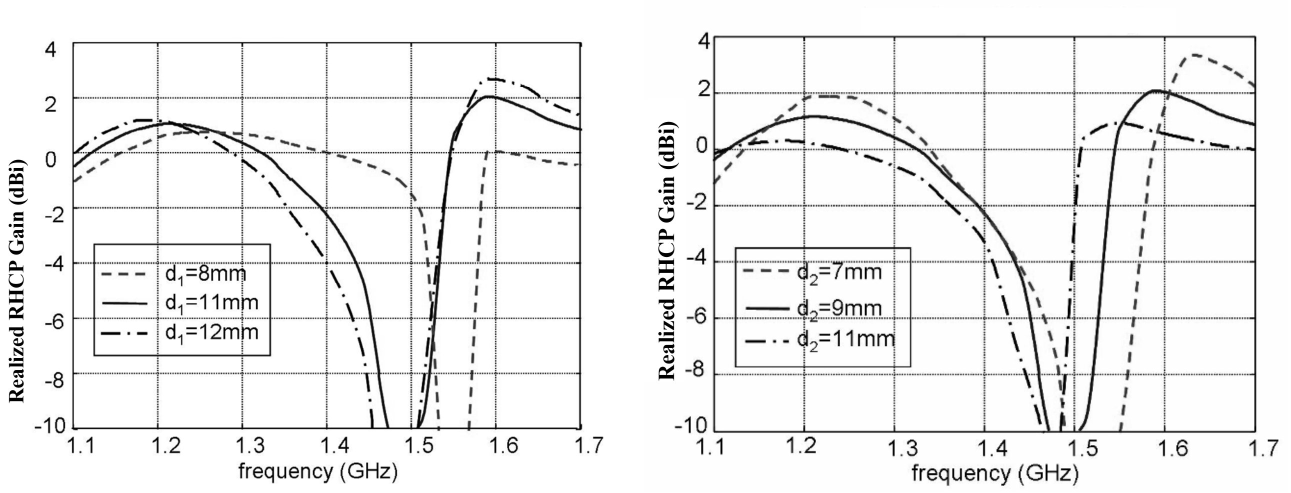


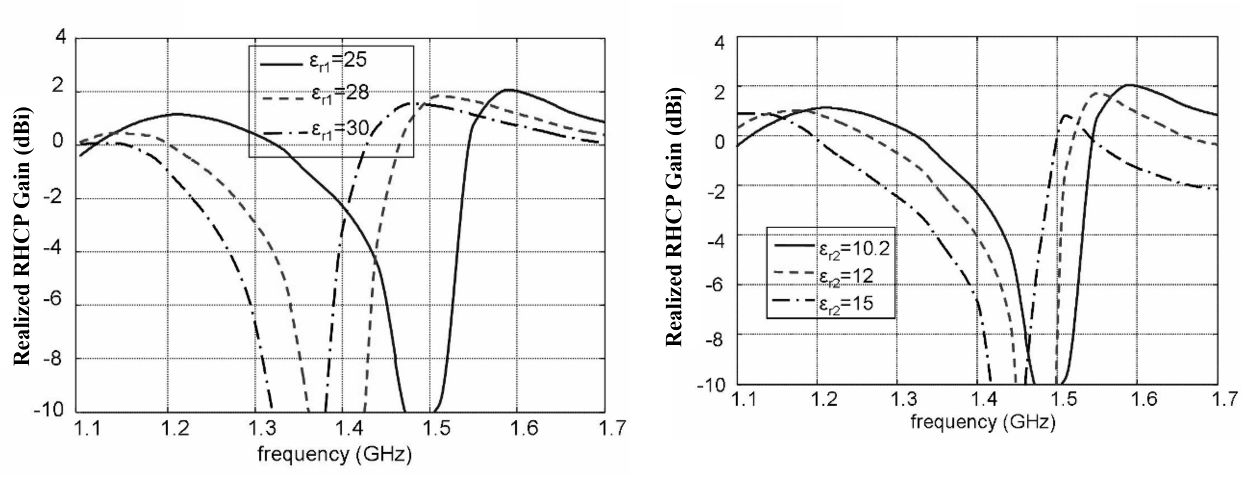
Figure 2. Effect of the horizontal conductors lengths on antenna gain (d_1=11mm, d_2=9mm, ε_{r1}=25, ε_{r2}=10.2, w_a=4mm, w_b=12mm).



(a)

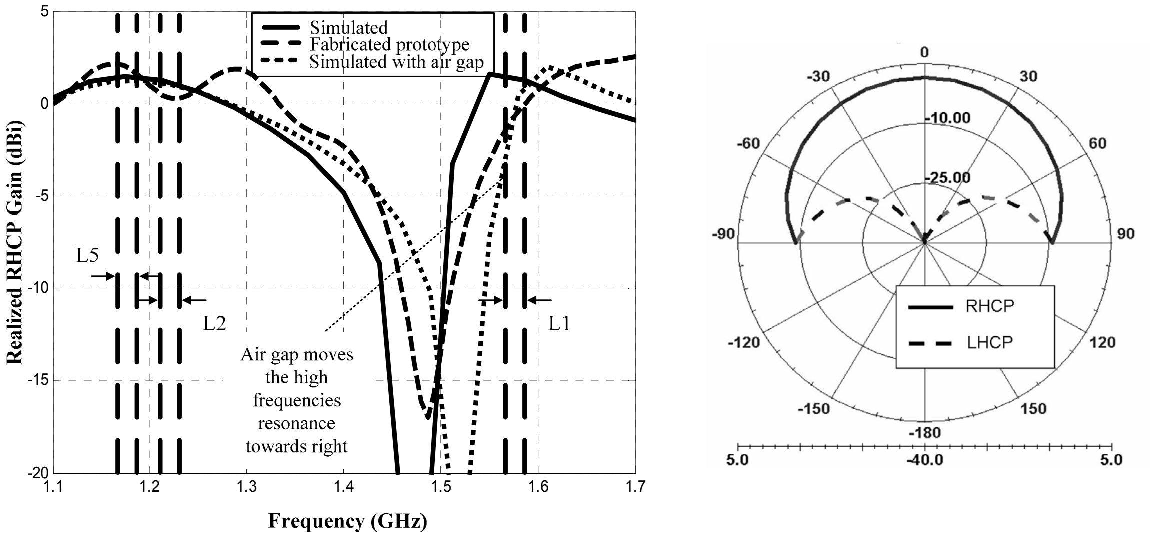
(b)

Figure 3. Dielectric thickness effect on antenna gain; (a) gain plots for d_1=8mm, 11mm, 12mm with d_2=9mm and (b) gain plots for d_2=7mm, 9mm, 11mm with d_1=11mm; with l_1=l_2=10mm, ε_{r1}=25, ε_{r2}=10.2, w_a=4mm, w_b=12mm.



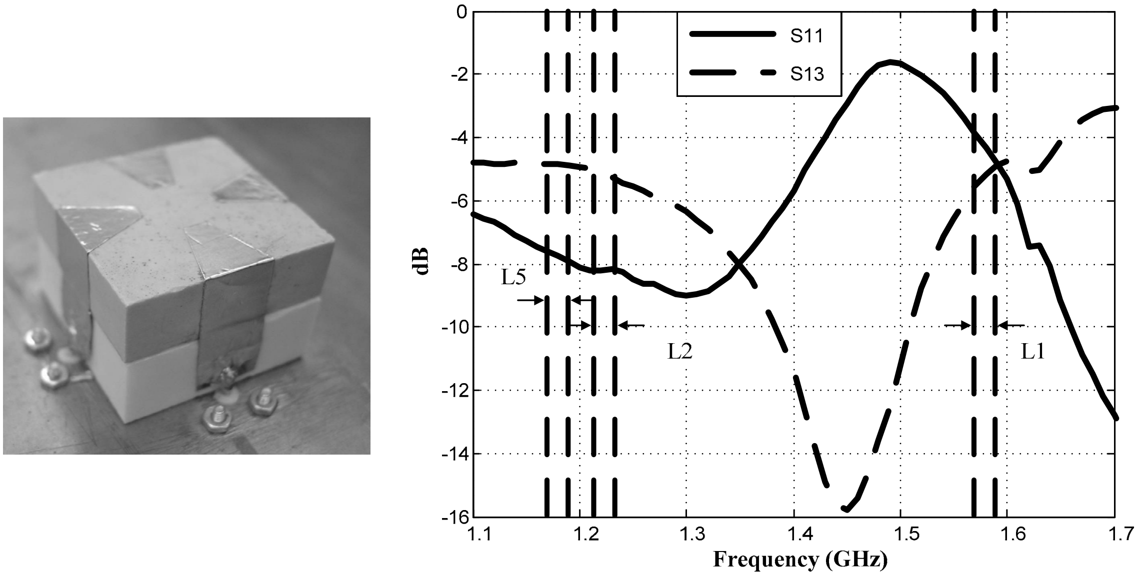
(a) (b)

Figure 4. Permittivity effects on antenna gain; (a) variation in the upper layer permittivity (ε_{r1}) with ε_{r2}=10.2 and (b) variation in the lower layer permittivity (ε_{r2}) with ε_{r1}=25; with l_1=l_2=10mm, d_1=11mm, d_2=9mm, w_a=4mm, w_b=12mm.



(a) (b)

Figure 5. (a) Measured and simulated boresight RHCP gain; also simulated gain when a 0.2mm air gap has been inserted between the upper and lower substrate and (b) radiation pattern in the center frequency of 1176MHz.



(a) (b)

Figure 6. (a) Fabricated prototype; (b) Return loss (S11) and coupling between the opposite ports (S13)