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

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***Abstract*—A new global positioning system (GPS) antenna is proposed to cover the three GPS bands (L1, L2, and L5, namely 1575, 1227, and 1176 MHz) with the L5 band to be added after 2006. The developed antenna size is only $1.5'' \times 1.5''$ in aperture corresponding to $\lambda/7 \times \lambda/7$ ($\lambda =$ free space wavelength) and $\lambda/13$ thick. Quadrature feeding is employed to ensure right-hand circular polarized (RHCP) radiation. The final miniature antenna exhibits a gain greater than 2 dBi, and to our knowledge this is the smallest such size for circular polarized (CP) operation covering all three bands. Detailed parametric simulations leading to the best design along with measurements for the constructed antenna are presented.**

***Index Terms*—Antenna minimization, circular polarization, dielectric loading, F shape conductors.**

I. Introduction

Several GPS antenna designs [1]–[6] have been presented in the literature. These cover either one or both of the standard L1 (1575 MHz) and L2 (1227 MHz) bands. The introduction of the L5 band operating at 1176 GHz calls for antennas that cover all three bands (each having 24-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 $5'' \times 5''$ or $\lambda/2 \times \lambda/2$ at the lowest frequency (L5).

In this letter, we present a new small size tri-band GPS antenna. The overall aperture size of the proposed antenna is only $1.5'' \times 1.5''$ $(\lambda/7 \times \lambda/7)$ and $\lambda/13$ thick. It is based on an F-shaped conductor design (hence the name F-antenna) embedded in a two-layer dielectric substrate with $\varepsilon_{r1} = 25$ (upper substrate permittivity), $\varepsilon_{r2} = 12$ (lower substrate permittivity) (see Fig. 1). 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.

Manuscript received December 22, 2005; revised March 24, 2006.

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Digital Object Identifier 10.1109/LAWP.2006.875282

II. Antenna Design

Noting that the L2 (1227 MHz) and L5 (1176 MHz) bands are very close, our design strategy is to use a dual band resonant antenna with the lower resonant frequency covering 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 use a high dielectric constant material as part of the substrate. However, high permittivity substrates increased the quality factor Q which caused a narrower bandwidth performance. 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.

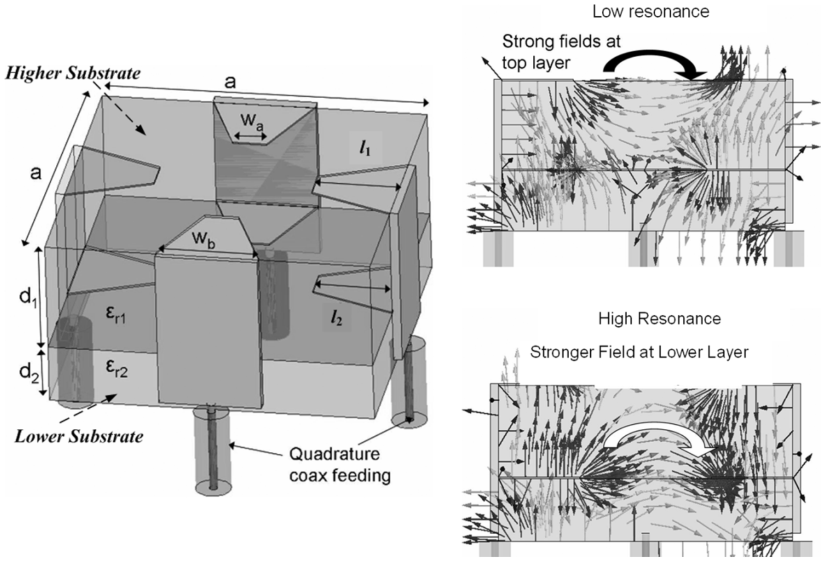
Specifically, we removed the LC elements and added another conductor layer to the original inverted-L configuration to introduce a new resonance. We also tapered the horizontal conductors (see Fig. 1) to improve impedance matching and, thus, increase bandwidth at the resonances. In the following, we discuss how the optimized geometry of this new design leads to a 38×38-mm^2 aperture size antenna for tri-band operation. The antenna has four F-shaped conductor arms (each fed with 90° sequential phase shift) to achieve CP operation.

III. Parametric Analysis

A. Antenna Geometry

The proposed F antenna is depicted in Fig. 1(a) and consists of four F shaped conductor sections each fed by a 50 Ω 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 #1 layer, whereas the second (or lower) layer is denoted as the #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 widths, respectively, of the patches (the patches of the top and lower layers have the same width). The vertical conductors are also of width 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.



(a) (b)

Fig. 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.

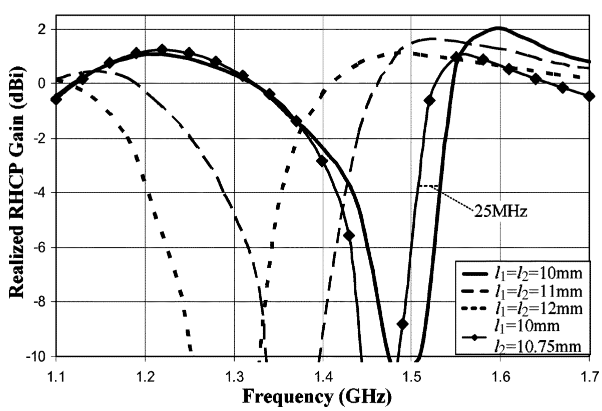


Fig. 2. Effect of the horizontal conductors lengths on antenna gain ($d_1 = 11$ mm, $d_2 = 9$ mm, $\varepsilon_{r1} = 25$, $\varepsilon_{r2} = 10.2$, $w_a = 4$ mm, $w_b = 12$ mm).

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 [see Fig. 1(b)].

B. Horizontal Conductors' Length Effect

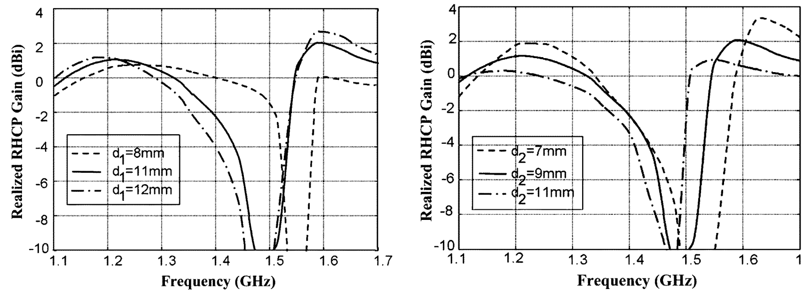
We begin the tuning of the proposed design (Fig. 1) by first adjusting the l_1 and l_2 lengths that correspond to the top and bottom patches. Fig. 2 shows the effect of l_1 and l_2 lengths on antenna gain (with $d_1 = 11$ mm, $d_2 = 9$ mm, $\varepsilon_{r1} = 25$, $\varepsilon_{r2} = 10.2$, $w_a = 4$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

C. Dielectric Layers' Thickness Effect

From the previous information, it is best to choose the conductors lengths so that $l_1 = l_2 = 10$ mm. 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 $l_1 = l_2 = 10$ mm, $\varepsilon_{r1} = 25$, $\varepsilon_{r2} = 10.2$, $w_a = 4$ mm, $w_b = 12$ mm) are shown in Fig. 3. We observe that by increasing d_1 ($d_1 = 8, 11, 12$ mm) both resonances shift toward the left and the gain for the L1 band improves. Of the three curves (with d_2 kept at 9 mm), we notice that $d_1 = 11$ mm provides a better compromise on gain and frequency performance. Thus, d_1 is kept at 11 mm while d_2 is varied as shown in Fig. 3(b). Among the three gain curves ($d_2 = 7, 9, 11$mm), we readily conclude that the curve corresponding to $d_2 = 9$ mm provides better gain at L2 and L5 bands without compromising performance at the L1 band.

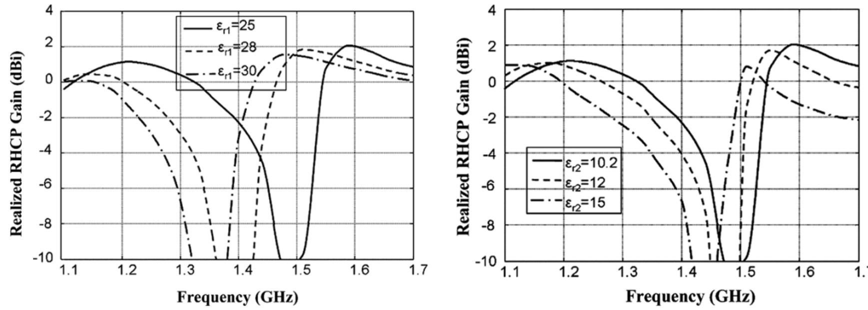
D. Dielectric Layers' Permittivity Effect

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 choose the geometrical parameters $l_1 = l_2 = 10$ mm, $d_1 = 11$ mm, $d_2 = 9$ mm (with $w_a = 4$ mm and $w_b = 12$ mm) since they have shown the best performance so far with $\varepsilon_{r1} = 25$ and $\varepsilon_{r2} = 10.2$. Fig. 4 shows gain plots as the dielectric constants are varied around the mentioned values. As expected (Fig. 4(a)), increasing ε_{r1} or ε_{r2} results in lower resonance frequencies. More importantly, it is seen that the choices of $\varepsilon_{r1} = 25$ and



(a) (b)

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



(a) (b)

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

$\varepsilon_{r2} = 12$ are rather good in terms of gain and resonance frequencies.

IV. Final Design: Simulation and Measurements

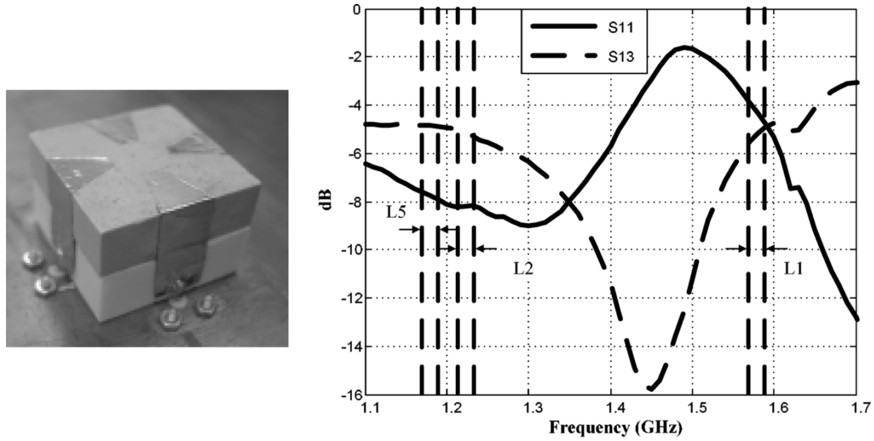
The parameter choices for the final design (see Fig. 1(a)) are $a = 38$ mm (aperture width and length), $l_1 = 9.6$ mm (upper conductor length), $l_2 = 10.5$ mm (lower conductor length), $d_1 = 12$ mm (upper substrate thickness), $d_2 = 8$ mm (lower substrate thickness), $w_a = 4$ mm (smallest width of lower and upper patches), $w_b = 12.5$ mm (largest width of lower and upper patches), $\varepsilon_{r1} = 25$ (upper substrate permittivity), $\varepsilon_{r2} = 12$ (lower substrate permittivity).

The S parameters of the fabricated prototype [see Fig. 5(a)] were measured using an Agilent E8362B network analyzer. Fig. 5(b) gives the S11 (return loss) and S13 (coupling) parameters. As seen, the return loss depicts an acceptable performance of less than -7.7 dB (i.e., corresponding to $\mathrm{VSWR} = 2.4 : 1$) for L2 and L5 bands. However, there is deviation for the L1 band indicating that the resonance moved to the right. As it will be elaborated later, this behavior is due to fabrication issues and fully reversible. Furthermore, the coupling parameter presents us with a possible interpretation of the antenna operation. Bearing in mind that the opposite (1 and 3) ports have 180° phase difference, this coupling implies that current is traveling from one port to the other through the horizontal conductors. That is, the proposed inverted F antenna includes traveling wave components.

Fig. 6 shows the gain for the fabricated antenna. It is readily observed that the measured RHCP gain is in good agreement with the calculated for the L2 and L5 bands. Also, the simulated radiation patterns in Fig. 6(b) show that the polarization purity is rather good as well (although only the L5 band pattern is shown, the corresponding patterns for the other bands are alike and therefore omitted). However, the measured gain around the L1 band, although it tracks calculations, it deviates somewhat. Specifically, its rise from the gain dip is not as sharp and does not therefore reach the 2–3 dBi gain point as quickly. Thus, for the L1 band, the measured gain is on average 0 dBi (about 2-dB lower than calculated). This is likely due to the possible air gaps between the lower conductors and their substrate. Such gaps are pronounced at higher frequencies and do not therefore affect the L2 and L5 bands. This conclusion is confirmed from the calculations shown in Fig. 6(a) where a 0.2-mm 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 is more practical to slightly increase the length of the lower conductor (say, 0.75 mm). As seen in Fig. 2, the choices of $l_1 = 10$ mm and $l_2 = 10.75$ mm (instead of $l_1 = l_2 = 10$ mm) 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 0 dBi for the measured curve in Fig. 6 while accounting for the air gaps.

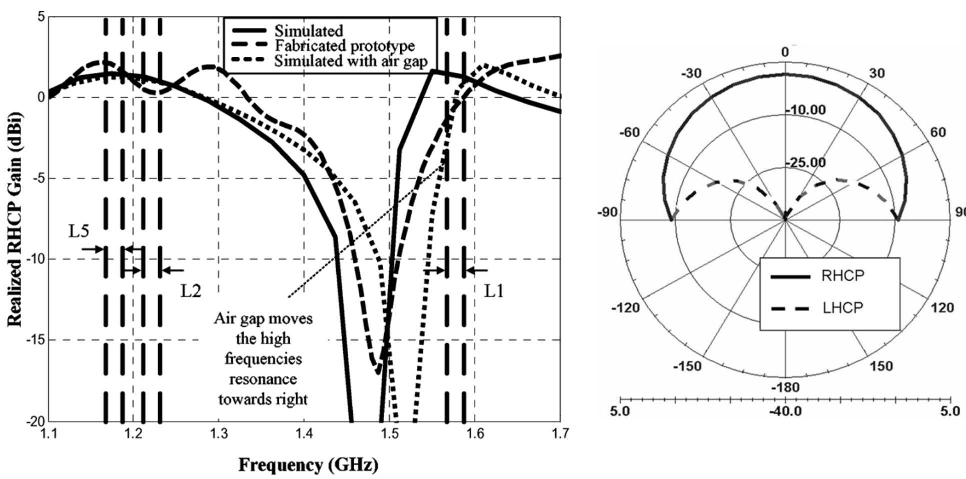
V. Conclusion

We proposed a $\lambda/7 \times \lambda/7$ and $\lambda/13$ thick (at L5 band) rectangular antenna which employed two homogeneous layers to achieve a gain greater than 0 dBi and at least 24 MHz bandwidth at all three GPS frequencies (L5: 1176 MHz, L2:1227



(a) (b)

Fig. 5. (a) Fabricated prototype. (b) Return loss (S11) and coupling between the opposite ports (S13).



(a) (b)

Fig. 6. (a) Measured and simulated boresight RHCP gain; also, simulated gain when a 0.2-mm air gap has been inserted between the upper and lower substrate. (b) Radiation pattern in the center frequency of 1176 MHz.

MHz, L1: 1575 MHz). Quadrature feeding with 90° progressive phase shift was employed to ensure RHCP radiation. The design was verified using a fabricated prototype and the measurements showed a gain of 2 dBi at boresight for the L2 and L5 bands and about 0 dBi 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 approach to overcoming coupling [8] without sacrificing the gain.

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