REDUCED RCS UHF RFID GOSPER AND HILBERT TAG ANTENNAS

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ABSTRACT

In this paper printed flexible conventional, Gosper and Hilbert loop shape antennas with reduced structure mode radar cross section RCS are proposed for small object identification. Conventional wire loop antenna input admittance using Fourier series analysis for the equivalent half-loop antenna excited with a transverse electromagnetic (TEM) mode is rearranged to obtain the wire loop input impedance versus loop radius at 900 MHz. T-matched charts as a method of matching the antenna input impedance with the chip input impedance is also introduced. The proposed Gosper and Hilbert shapes have size reduction of 76.26% and 83.75 % compared to conventional structure. RCS reduction of 99.67 % and 99.12 % are obtained for Gosper and Hilbert loop antennas respectively, compared to conventional one at 900 MHz. Both Gosper and Hilbert loop antennas are fabricated, measured and the results are discussed.

1. INTRODUCTION

Radio-frequency identification (RFID) is one of the fastest growing wireless technologies in recent decades. Recent interest for RFID technologies increases studies and applications of these devices. Many different purposes of RFID are found such as warehouse management, access control system, electronic toll collection, etc. UHF RFID requires three components, a transponder, an antenna and a transceiver. The transponder, or tag, contains data and is attached to the item. The antenna transmits the UHF radio signal to the transponder, powering and activating it. The activated transponder then transmits the data stored on the tag back to the transceiver. There are many standards for UHF RFID systems and they differ according to the country [1]. The paper idea is to introduce a flexible RFID tag antennas with reduced radar cross section to identify object location precisely such as weapons, bullets and all military stuff. Also, it can be used commercially to identify object location in huge
warehouses. Methods aiming to decrease object RCS is of great practical interest and many solutions have been proposed. Some approaches modify the target shape or orientation to deflect the scattered energy away from the detecting radar while other converts the radio frequency energy into heat [2]. Passive and active cancellation technology could be also used [3]. The radar cross section RCS of an antenna is determined by an antenna component and by a structural term [3-4]. Our investigation will focus on the reduction of structural scattering of an antenna. Liquid crystal polymer LCP substrate with dielectric constant $e_r = 2.9$, thickness of 0.05 mm and loss tangent $\tan \delta = 0.0025$ is used as antenna substrate where flexible, reliable and low cost features are provided, so the proposed structure gains these features. In this paper conventional, Gosper and Hilbert loop shape antennas are proposed. Gosper and Hilbert shapes have size reduction of 76.26% and 83.75 % compared to conventional structure. RCS reduction of 99.67 % and 99.12 % are also obtained for Gosper and Hilbert shapes respectively, compared to conventional one at 900 MHz. The paper is organized as; section 2 introduces conventional loop analyses using Fourier series analysis, T-matched chart and conventional loop with T-matched section design. Sections 3 and 4 introduce the design of Gosper and Hilbert loop antenna. Comparison among the aforementioned proposed antennas is introduced in section 5. Experimental results are introduced and discussed in section 6. Conclusions are given in section 7.

2. CONVENTIONAL LOOP ANTENNA

In this section Fourier series analysis is used and rearranged to obtain the wire loop input impedance versus loop radius at 900 MHz and a suitable radius is chosen. T-matched chart as a method of matching the antenna input impedance with the chip input impedance is also introduced. Conventional printed T-matched loop is designed.

2.1 Conventional loop antenna analyses

Fourier series analysis for the equivalent half-loop antenna excited with a transverse electromagnetic (TEM) mode assumed in the aperture of the coaxial line was used to obtain the input admittance of the wire loop antenna [5]. The antenna has radius $R$, resonant wavelength $\lambda_o$, constructed from a perfectly conducting wire of radius $a_i$, $a_i \ll R$, $\beta_o a_i \ll 1$ and $\beta_o = 2 \pi / \lambda_o$. The wire circular loop input admittance $Y_{in}$ is found as:

$$Y_{in} = G + jB = I(0)/V_o = \left( I_o + 2 \sum_{n=1} \frac{I_n}{V_o} \right) / V_o$$  \hspace{1cm} (1)

$$I_n = -jV_o b_n \frac{\varepsilon_o \pi}{a_n} n = 0,1,2,...$$ \hspace{1cm} (2)

$$a_n = \frac{\beta_o R}{2} \left( K_{n+1} + K_{n+1} \right) - \frac{n^2}{\beta_o R} K_n$$ \hspace{1cm} (3)

$$K_n = \frac{1}{\pi R} \left[ \frac{\alpha_n}{\beta_o} \sqrt{n^2 - (\beta_o R)^2} \right] H_0 \left[ \frac{\alpha_n}{\beta_o} \sqrt{n^2 - (\beta_o R)^2} \right] + \frac{1}{\pi} \left\{ \gamma + \ln \left[ 4(n^2 - \beta_o^2 R^2)^{1/2} \right] \right\}$$ \hspace{1cm} (4)

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\[ b_n = \frac{1}{\ln(a_1/a_0)} \left( B \left[ \frac{a_n}{R} \sqrt{(n+1)^2 - (\beta R)^2} \right] - H_0 \left[ \frac{a_n}{R} \sqrt{(n-1)^2 - (\beta R)^2} \right] \right) \]

Referring to Fig. 2, a dipole of length \( a_d \) is connected to a second dipole of length \( a_d + \xi \), placed at a close distance \( b \) from the first and larger one. It can be proved that the impedance at the source point is given by [6]:

\[ Z_{in} = \frac{2Z_t(1+\alpha)^2Z_d}{2Z_t+(1+\alpha)^2Z_e} \]

Where

\[ Z_t = |Z_0| \tan\left( \frac{k a_d}{2} \right) \]

\[ Z_0 = \frac{1}{\pi} \cos^{-1}\left( \frac{b/2}{\sqrt{r_e r_f}} \right) \]

\[ \alpha = \frac{\cosh^{-1}\left( \frac{v^2 - u^2 + 1}{2v} \right)}{\cosh^{-1}\left( \frac{v^2 + u^2 - 1}{2uv} \right)} \]

\[ r_f = 0.25(2w) \]

2.2 T-matched chart

The T-matched chart is a method to match the chip input impedance with dipole input impedance. Referring to Fig. 2, a dipole of length \( a_d \) is connected to a second dipole of length \( a_d + \xi \), placed at a close distance \( b \) from the first and larger one. It can be proved that the impedance at the source point is given by [6]:

\[ Z_{in} = \frac{2Z_t(1+\alpha)^2Z_d}{2Z_t+(1+\alpha)^2Z_e} \]

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\[ \alpha = \frac{\cosh^{-1}\left( \frac{v^2 - u^2 + 1}{2v} \right)}{\cosh^{-1}\left( \frac{v^2 + u^2 - 1}{2uv} \right)} \]

\[ r_f = 0.25(2w) \]

Fig. 1 Circular loop antenna input impedance versus different radii with \( a_d = 0.5 \) mm (fabrication purpose), coaxial outer radius \( a_o = 1.15 \) mm at 900 MHz.

Fig. 2 T-matched configuration for planar dipoles and equivalent circuit.
2.3 Conventional T-matched loop antenna design

As a prototype design, wire circular loop antenna with external radius of 57 mm which has an input impedance of (63.16 + j8.14) Ω would be suitable for conjugate matching with chip input impedance of 13.9 - j143.6 Ω at 900 MHz. This is mainly referred to the fact that the loop antenna input impedance does not change very much when R is within the range from 50 mm to 64 mm, Fig. 1. It should be mentioned that the operating frequency for the chip will cover the band from 860 MHz to 960 MHz, and its input impedance varies from 15.69 - j152.6 Ohm at 860 MHz to 12.61 - j137 at 960 MHz [7]. Chip input impedance of 13.9 - j143.6 Ω at 900 MHz is chosen as the value to be matched with the designed antenna. By choosing this value the designed antenna input impedance will be remain in an acceptable level of variation relative to the variance of the chip input impedance with frequency. Transform the structure to planar one [8] and using the IE3D simulator, the input impedance of the loop antenna is calculated using an LCP substrate with 50 μm substrate thickness and εr of 2.9. It is found to be (130.5 - j44.3) Ω at 900 MHz (difference between input impedance predicted by IE3D and that obtained from Fig. 1 may be attributed to the approximate wire to planar transformation formulae and the presence of LCP material). This value is used as input impedance for the T-matched circuit. The T-matched chart is shown in Fig. 3 which indicates that the matching condition with the chip could be met with b/2w = 2 and ad/l ranges from 0.11 to 0.18. IE3D simulator was used and final optimized dimensions are shown in Fig. 4 which indicates that on average ad/w = 2 and ad/l = 0.13. The power reflection coefficient, shown in Fig. 5, indicates that a frequency band from 780 MHz to 1122.2 MHz is covered which is suitable for UHF universal tag application. As shown in Fig. 6, RCS of 0.182 m² at 900 MHz is obtained indicating that the tag antenna is detectable. CMF of 0.837 is obtained at 900 MHz, as shown in Fig. 7, indicating that conjugate matching is at a good level. Fig. 8 shows the radiation pattern which is almost figure of 8 at the E-plane and H-plane. Other antenna parameters such as conjugate match gain and radiation efficiency are given in table 1.

![Fig. 3 Conventional printed circular loop antenna T-matched chart](image-url)

\[ Z_L = 130.5 - j44.3 \ \Omega \]
Fig. 4 Conventional printed circular loop antenna T-matched circuit section.

Fig. 5 PRC versus frequency for conventional printed loop antenna with T-matched circuit (R=55mm).

Fig. 6 RCS versus frequency for conventional printed loop antenna with T-matched circuit (R=55mm).

Fig. 7 CMF versus frequency for conventional printed loop antenna with T-matched circuit (R=55mm).

Fig. 8 Conventional printed loop antenna with T-matched circuit radiation pattern at 900 MHz (R=55mm).
2. GOSPER LOOP ANTENNA

The Gosper curve is a space filling curve discovered by William Gosper, an American computer scientist, in 1973, and was introduced by Martin Gardner in 1976. The Gosper curve is a recursive curve constructed by recursively replacing a dotted arrow, called the initiator, by seven arrows, called generator, Fig. 9 [9].

Matlab code for Gosper curve generation of any order is built and Gosper curve of order 2 is shown in Fig. 10. The resonance frequency of the aforementioned conventional circular loop was found to be 1.25 GHz. Gosper loop antenna was designed at the same resonance frequency using IE3D simulator. Its radius was found to be 26.8 mm. Gosper loop antenna achieves size reduction of 76.26% compared to conventional loop antenna. It was chosen as a prototype to complete the T-matched circuit design at 900 MHz. At 900 MHz, the input impedance is \((8.15 + j103.95) \, \Omega\).

We considered the structure as asymmetric dipole loaded by Gosper loop antenna. The T-matched diagram shown in Fig. 11 was used as an indicator for the total input impedance performance. It should be noted that conjugate matching condition with the chip input impedance is difficult to obtain. As a starting point \( \frac{b}{2w} = 2 \) was chosen and varying \( \frac{a_1}{l} \) through changing the length \( a_1 \) till matching condition was reached. IE3D simulator was used to get the optimum design dimensions, Fig. 12. The power reflection coefficient is shown in Fig. 13 and clearly covers the frequency band from 884 MHz to 936 MHz which is suitable for the bands of 920.5 - 924.5 MHz in China, 920 - 925MHz in Singapore and 902 - 928 MHz in USA, Canada, Mexico,
Puerto Rico, Costa Rica, Latin America. As shown in Fig. 14, RCS of 0.0006 \( \text{m}^2 \) at 900 MHz is obtained indicating that the tag antenna is detectable. We should mention that this small RCS is useful in small targets in package identification. As shown in Fig. 15, CMF is 0.62 at 900 MHz, indicating that conjugate matching is at acceptable level. Fig. 16 shows the radiation pattern which is almost omnidirectional at the H-plane and figure of 8 at the E-plane. Other antenna parameters such as conjugate match gain and radiation efficiency are given in Table 1.

![Gosper loop antenna T-matched chart](image1)

*Fig. 11 Gosper loop antenna T-matched chart (\( Z_o = 8.15 + j103.95 \Omega \))

![Optimum dimensions of Gosper loop antenna with T-matched circuit](image2)

*Fig. 12 Optimum dimensions of Gosper loop antenna with T-matched circuit.*
4. HILBERT LOOP ANTENNA

In 1891 Hilbert defined a space filling curve [10]. The general idea is to divide, at step n, the unit square in 4^n equal subquares each of them containing an equal length part of the curve (except the first and the last ones which contain a part of length 1/2). A Matlab program is built to draw Hilbert curve of any order n. Hilbert curve of order 4, Fig. 17 is simulated using IE3D and input impedance of (10.78 + j53.17) Ω is obtained at 900 MHz. T-matched chart for that input impedance is shown in Fig. 18. Choosing \( b/2w = 1.5 \) and varying \( a_d/L \) from 0.35 to 0.55 till matched condition was obtained. The optimum structure is shown in Fig. 19. The PRC is shown in Fig. 20 which covers the frequency band from 901 MHz to 928 MHz which is suitable for the UHF RFID application at China (920.5 - 924.5 MHz), Singapore (920 - 925MHz), USA, Canada, Mexico, Puerto Rico, Costa Rica and Latin America (902 - 928 MHz). RCS, Fig. 21 of 0.0016 m^2 at 900 MHz is obtained indicating that the tag antenna is detectable and is useful at small target identification. As shown in Fig. 22, CMF of 0.49 is obtained at 900 MHz. Fig. 23 shows the radiation pattern which is almost...
omnidirectional at the H plane and figure of 8 at the E plane. Other antenna parameters such as conjugate match gain and radiation efficiency are given in table 1.

Fig. 17 Hilbert mean curve (n = 4).

Fig. 18 Hilbert loop antenna T-matched chart \( Z_\infty = 10.78 + j53.17 \Omega \).
Fig. 19 Optimum structure of Hilbert loop antenna with T-matched circuit structure.

Fig. 20 PRC of Hilbert loop antenna versus frequency.

Fig. 21 RCS of Hilbert loop antenna versus frequency.

Fig. 22 CMF versus frequency for Hilbert loop antenna.

Fig. 23 Hilbert loop antenna radiation pattern at 900 MHz.
5. COMPARISON AMONG CONVENTIONAL, GOSPER AND HILBERT LOOP TAG ANTENNAS

This section introduces a comparison among various proposed loop antenna structures namely Conventional, Gosper and Hilbert tag antennas. The comparison includes radiator and T-matched section areas, conjugate match gain, radiation efficiency, bandwidth, minimum values of PRC, structure RCS and conjugate match factor CMF. Table 1. As indicated by table 1, Gosper antenna introduces the most reduced RCS compared to the other two antennas’ RCS and area. Also Gosper antenna radiation efficiency is 99.8 % which is better than the conventional and Hilbert antennas.

| Table 1 Comparison among performance of Conventional, Gosper and Hilbert loop antennas. |
|---------------------------------|------------------|------------------|------------------|
| Loop Shape | Parameter | Conventional | Gosper | Hilbert |
| Radiator area (\text{mm}^2) | 9503.33 | 2256.4 | 1600 |
| T-matched section area (\text{mm}^2) | 48 | 709.8 | 243.375 |
| Conjugate match gain (dB) | -0.29 | -1.2 | -2.1 |
| Radiation efficiency (%) | 80.28 | 99.8 | 58 |
| Bandwidth (MHz) | 780-1122.2 | 884-936 | 901-928 |
| Minimum value of PRC (dB) | -20.5 | -13.5 | -8.1 |
| RCS (\text{m}^2) at 900 MHz | 0.182 | 0.0006 | 0.0016 |
| CMF at 900 MHz | 0.837 | 0.62 | 0.49 |

6. GOSPER AND HILBERT LOOP ANTENNA EXPERIMENTAL RESULT

Gosper printed loop antenna was fabricated using LCP substrate as shown in Fig. 24(a). The input impedance was measured by measuring half of the structure over ground plane and multiply the resultant input impedance by two then, power reflection coefficients are calculated. Since Gosper antenna is asymmetrical at the excitation, so both halves are considered and the average is used in power reflection coefficient calculation and denoted as PRCM. As shown in Fig. 24(b), there is a difference between computed and simulated PRC which may be attributed mainly to the presence of the air gap between the half Gosper structure and the ground plane which was difficult to be eliminated due to the flexible nature of the LCP substrate. So, computed PRC was considered twice once with an air gap with 1 mm inserted at the excitation symmetrical plane through all the structure, (0.5 mm between half structure and the ground plane), and the resultant power reflection coefficient is denoted as PRCs1 and PRCs is the resultant power reflection coefficient in the absence of that air gap. The obtained PRCs1 agree with the measured PRCM. We may also refer the difference between PRCM and PRCs1 to the average process in the measured results. Hilbert loop antenna was also fabricated using LCP substrate, Fig. 24(c) and the input impedance was measured as aforementioned method used in measuring Gosper antenna input impedance. Also, the difference between simulated power reflection coefficient denoted by PRCs and the measured power reflection coefficient denoted by PRCm may be attributed to the presence of the air gap between the half Hilbert structure and the ground. So, an air gap of 1 mm was inserted at the symmetrical plane of the proposed structure (0.5 mm between half structure and the
ground plane), simulated PRCs1 was obtained which agree very well with the measured one, Fig. 24(d).

![Fig. 24(a) Fabricated Gosper loop antenna.](image)

![Fig. 24(b) Computed and measured PRC of Gosper loop antenna.](image)

![Fig. 24(c) Fabricated Hilbert loop Antenna.](image)

![Fig. 24(d) Computed and measured Hilbert loop Antenna.](image)

7. CONCLUSIONS

In this paper a loop type tag antenna, Conventional, Gosper and Hilbert loop tag antennas were presented. Both Gosper and Hilbert loop tag antennas were fabricated using LCP substrate and the measured results agreed with computed ones. Comparison among Gosper, Hilbert and Conventional loop tag antenna was done and size reduction relative to conventional one was obtained. Both Gosper and Hilbert loop antennas had a reduced RCS compared to their physical areas and conventional loop one. The proposed antennas may be used in tagging a small object where identifying its location is a must.
REFERENCES