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Triple-band compact circularly polarised stacked microstrip antenna over reactive impedance meta-surface for GPS applications

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Abstract: In this study, a compact, triple-band, circularly polarised stacked microstrip antenna is proposed over the artificial meta-surface called reactive impedance surface (RIS) for enhancing antenna radiation efficiency for GPS applications. The proposed design utilises the concept of combining multi-stacked patches with RIS as imaginary-impedance metamaterial-ground-plane for selective frequency reduction of lower bands with improvement in antenna radiation properties for multi-band applications. The circularly polarised (CP) radiation with compact antenna size is achieved for triple-band GPS frequencies of L1 (1.575 GHz), L2 (1.227 GHz) and L5 (1.176 GHz) by placing three stacked patches with two different pairs of symmetric slits, four different sized symmetric cross-shaped slots and truncated corners over RIS. As RIS meta-surface reduces the wave penetration through the lossy substrate beneath it, the proposed stacked patch antenna over RIS demonstrates enhanced forward gain with suppressed back radiation. The measured results for antenna prototype are (1.168–1.185 GHz): L5 band, (1.2–1.245 GHz): L2 band and (1.51–1.59 GHz): L1 band for 10 dB return loss bandwidth with good CP radiation. Forward (boresight) right-handed CP gain of 2.88 dBic (L5 band), 3.25 dBic (L2 band) and 5.53 dBic (L1 band) is observed for compact antenna overall volume of $0.32\lambda_0 \times 0.32\lambda_0 \times 0.024\lambda_0$ at 1.2 GHz.

1 Introduction

Compact circularly polarised microstrip antennas (CPMAs) are useful for handheld, portable wireless global positioning system (GPS) devices because of their ability to receive polarised signals from transmitting antennas regardless their orientation. GPS antennas with the right-handed circular polarisation (RHCP) are required to operate in triple L1 (1.575 GHz), L2 (1.227 GHz) and L5 (1.176 GHz) bands. For handheld and portable wireless GPS devices, antenna's overall volume is an important factor for determining the size of communication system. The compact triple-band CPMA using single feed is difficult to design for GPS applications because the frequency ratio of the bands is small. Various types of antenna structures with different feeding networks have already been proposed for multi-band applications [1–8]. Recently in [9], dual-band circularly polarised (CP) radiation is achieved using cavity-backed annular slot antenna. The overall volume of the antenna is $0.4\lambda_0 \times 0.4\lambda_0 \times 0.0864\lambda_0$ at 1.2 GHz with low gain of 1.45 dBic (L1 band) and 1.10 dBic (L2 band), respectively.

Single feed CPMAs loaded with slots/slits have been used [10–12] earlier with an intention to increase the effective

current path length, thus lowering the resonance frequency of the patch antenna with the CP radiation. Although this size reduction technique of slots/slits has been frequently used for realising small CP patch antennas, it only gives good CP radiation with smaller degree of size reduction. In the recent years, reactive impedance metamaterial periodic surfaces (reactive impedance surfaces – RISs) [13–15] comprising periodic unit cell elements have been used for antenna size miniaturisation and performance enhancement. A microstrip patch antenna designed to operate in all the three L1, L2 and L5 GPS frequency bands is required to have wide CP beamwidth in all bands and a high front-to-back ratio to avoid interference from the ground. By using an inductive RIS as antenna ground plane, considerable improvement in the front-to-back ratio can be achieved with size reduction whereas maintaining its wide CP radiation beamwidth.

In this paper, a compact triple-band CP stacked microstrip antenna is proposed and studied over the RIS to solve all the above-mentioned concerns regarding the GPS antennas. The CP radiation with compact antenna size is achieved using three patch radiators based on the designs proposed in [11, 12] stacked over RIS. The RIS is used in its inductive

region for further decreasing and fine tuning the lower L2 and L5 resonance frequency bands and improving the antenna radiation performances. All the antennas are designed and simulated using the CST Microwave Studio [16]. In the following sections, the design aspects of the RIS meta-surface and its effect on integration with the multi-patch stacked antenna will be discussed in detail. Section 2 provides a brief introduction to the basic concept of RIS and different patch configurations used to achieve the CP radiation in all the three GPS bands. Section 3 focuses on the comparison and brief analysis of antenna performances of different antenna configurations using RISs and perfect electric conductor (PEC) as antenna ground plane based on CST simulation results. The measured antenna prototype results incorporating the RIS structure are discussed and compared with the simulation results in Section 4. Section 5 summarises the results obtained in this paper.

2 Proposed antenna geometry and design

Fig. 1a shows the cross-sectional geometry of the proposed single feed CP stacked patch antenna over the RIS structure. The antenna consists of three stacked square patches (Sq-patch): an upper truncated corner square patch (TCSP), the middle patch with four different sized

Fig. 1 Proposed triple-band stacked microstrip patch antenna over RIS

a Cross-sectional view

b Top view of TCSP, CSSP and SSSP stacked patches over 10×10 array of PEC ground backed RIS meta-surface

symmetric cross-shaped slots square patch (CSSP) and the lower patch with two different pairs of symmetric slits square patch (SSSP), all introduced in the patches for size reduction with the CP radiation. The feed arrangement is done using a coaxial probe at point $(x, 0)$ with respect to the Sq-patch centre, feeding the upper patch directly, whereas the lower two patches are excited by the electromagnetic coupling with the driven patch. An array of 10×10 unit RIS elements is printed periodically along the x - and y -axis on the grounded FR4 substrate to realise the purely reactive impedance metamaterial surface.

Thus, the overall antenna structure is a four-dielectric layered geometry, with upper two dielectric layers made up of Rogers RO4003 substrate ($\epsilon_r = 3.38$ and $\tan \delta = 0.0027$) of thicknesses, $h_1 = 0.8$ mm and $h_2 = 1.524$ mm, and the lower two dielectric layers made up of FR4 substrate ($\epsilon_r = 4.2$ and $\tan \delta = 0.02$) with thicknesses of $h_3 = 0.5$ mm and $h_4 = 3.2$ mm, respectively. The ground plane size is $L \times L$, $L = 80$ mm. The RIS design and the proposed TCSP, CSSP and SSSP patch radiators are discussed in Sections 2.1 and 2.2, respectively.

2.1 Reactive impedance surface

Top view of an array of 10×10 RIS units forming the metamaterial surface is shown in Fig. 1b under the stacked patch radiators. First, a single RIS unit cell is optimised under the CP wave illumination assuming an infinite periodic lattice (Floquet boundary conditions) to tune the desired operating frequency bands between the PEC (180° reflection phase) and perfect magnetic conductor (PMC) (0° reflection phase) boundary limits for achieving the optimal bandwidth and miniaturisation factor, and then the RIS is designed by periodically repeating the RIS units along the x - and y -axis to cover the ground plane size of $L \times L$. The resulting RIS substrate is slightly optimised again (RIS unit cell parameters) before incorporating it with the stacked antenna patches in the complete proposed design structure to take into account the finiteness of the realised substrate

Fig. 2 Reflection phase graph of Sq-patch and J-cross RIS unit cells with the RIS unit cell (shown in inset) enclosed by the boundary conditions as $(x_{min}, x_{max}, y_{min}$ and $y_{max} = \text{unit cell})$, $(z_{min} = \text{electric } (E_t = 0))$, and $(z_{max} = \text{open})$, illuminated by the circular polarisation (LCP, RCP instead of TE_{00} , TM_{00}) floquet port settings

Also shown are the optimised dimensions of Sq-patch and J-cross RIS units

and the finite number of RIS units within the lateral dimensions. Two RIS surfaces have been designed for comparison to be used as antenna ground plane: (a) Sq-patch and (b) Jerusalem cross (J-cross) [17–19]. Reflection phase response of both the unit cells with their final optimised dimensions is shown in Fig. 2. Best agreement between the desired frequency bandwidth in all the three L1, L2 and L5 bands and size reduction is achieved for the optimised dimensions. The RIS unit cell model used for simulation is also shown in the inset of Fig. 2.

The RIS unit can be realised using a transmission line circuit model where the RIS units provide the shunt capacitance between its periodic patches, which is in parallel with the shunt inductance provided by the dielectric material after the separation distance (dielectric thickness). Based on the values of this capacitance, inductance and the operating resonance frequency (f_c), this RIS can be tuned as an inductive or capacitive RIS. The parallel LC circuit is inductive at frequencies less than f_c , open circuited at f_c and capacitive above f_c [13, 15]. An inductive RIS when placed under the patch (capacitive below its resonance frequency),

improves the three main backdrops of conventionally used PEC and PMC ground plane surfaces: (a) for the surfaces with real impedance values (i.e. PEC and PMC), the image current is mostly concentrated at the image point and so the mutual coupling is higher. Whereas in an inductive RIS with a purely reactive impedance of $\eta = j\nu$, the image current follows a sinusoidal form and is distributed in space rather than being focused at a point, thus minimising its mutual interaction with the source and lowering the coupling, resulting in the wider bandwidth, (b) the stored magnetic energy in the image of the source compensates for the energy stored by the source itself, resulting in resonance at a frequency lower than the free space resonance frequency, thus showing antenna size miniaturisation and (c) it improves the front-to-back ratio.

2.2 Stacked TCSP, CSSP and SSSP patch radiators

The upper TCSP, middle CSSP and lower SSSP radiators are designed over RIS for the CP radiation, as shown in Fig. 3. Fig. 3a shows the TCSP patch used for the CP radiation in

Fig. 3 Top view of the proposed patch radiators

- a Upper patch: truncated corner Sq-patch
- b Middle patch: cross-shaped slotted Sq-patch
- c Bottom patch: symmetric-slit Sq-patch

Table 1 Optimised dimensions of the antenna design parameters

Symbol	Value, mm
h_1	0.8
h_2	1.524
h_3	0.5
h_4	3.2
L	80
L_{p1}	47
L_{p2}	48.25
L_{p3}	53
l_c	3.5
X	12
S	12.0625 ($L_{p2}/4$)
W	3
L_1	11
L_2	16
L_3	21.4
L_4	22
S_1	10
S_r	12
L	4.5

the L1 (1.575 GHz) band in which opposite corners of Sq-patch of length, L_{p1} are chamfered by length, l_c . Four symmetric cross-shaped slots of different arm lengths and the same width are introduced in the four quadrants of the Sq-patch of side length, L_{p2} for the CP radiation in the L2 (1.227 GHz) band as shown in Fig. 3b. Fig. 3c shows the SSSP patch in which two different pairs of symmetric slits are introduced along the patch diagonals to increase the current path length and consequently reduce the resonance frequency with the CP radiation in the L5 (1.176 GHz) band for the Sq-patch of side length, L_{p3} . The upper TCSP patch is fed directly by the SMA feed through circular via holes of 3 mm diameter in the middle CSSP, lower SSSP patches and the RIS layer, and excites the lower CSSP and SSSP patches underneath it by electromagnetic coupling between the patches. The via holes will contribute to the capacitive coupling, which will negate the inductive effect because of inner conductor of the probe. All the designed and optimised dimensions (in mm) of the proposed triple-band antenna over J-cross RIS are tabulated in Table 1.

Fig. 4 CST MWS simulation results for stacked antenna over three surfaces – Sq-patch RIS, J-cross RIS and PEC

a Return loss graph

b Axial ratio (boresight) graph

c Right-handed CP gain (boresight) graph

Fig. 5 Normalised RHCP radiation patterns of antenna configurations over Sq-patch and J-cross RIS, and PEC, for the x-z and y-z principal planes

a $f = 1.176$ GHz (L5 band)

b $f = 1.227$ GHz (L2 band)

c $f = 1.575$ GHz (L1 band)

Fig. 6 Snapshots of all three fabricated patches with RIS

- a* TCSP (upper patch)
- b* CSSP (middle patch)
- c* SSSP (lower patch)
- d* RIS

3 Comparison between RIS- and PEC-based CPMAAs

The simulations for the stacked antennas over Sq-patch and J-cross RIS, as well as PEC, are discussed in this section. As seen in Fig. 4a, resonance frequency reduction can be achieved using RIS compared to a PEC ground plane. The centre frequencies for lower two bands drop from $f = 1.29$ to $f = 1.227$ GHz and from $f = 1.26$ to $f = 1.176$ GHz, respectively. Good CP radiation in all the three L1, L2 and L5 bands can be obtained by proper optimisation of all patch parameters responsible for orthogonal resonance modes, as shown in Fig. 4b. Better impedance matching is achieved in the lowest L5 resonance band when RIS replaces PEC as antenna ground plane. The L5 band (1.176 GHz) is most sensitive to the overall antenna size as it is electrically the smallest.

Slight decrease in right-handed CP gain in the L2 band as compared to the gain at $f = 1.29$ GHz for the PEC backed antenna can be seen in Fig. 4c which can be attributed to the fact that the electrical size of the antenna reduces as the operating frequency goes down because of the RIS effect for the same effective antenna ground plane size. Also, as

the RIS-based antennas show better impedance matching for the lowest L5 band than the PEC-based antenna at $f = 1.26$ GHz, improved forward RHCP gain is observed for RIS-based antenna configurations. Antenna with J-cross RIS shows improved gain and better impedance matching as compared to Sq-patch RIS because of lower level of metallisation in J-cross RIS units accounting for the improvement in the front-to-back ratio.

The normalised RHCP radiation patterns are shown in Figs. 5a–c for L5, L2 and L1 band centre frequencies. A slight improvement in the front-to-back ratio (reduction in back lobe) is observed when Sq-patch RIS is used in place of PEC as the antenna ground plane. Further improvement of around 3 dB in the front-to-back ratio is observed for the L1 band (1.575 GHz) using J-cross RIS in place of Sq-patch RIS. Any significant improvement for the L2 and L5 bands is hard to achieve for this ground plane size as the antenna is electrically small for these frequency bands. Based on all observations, J-cross RIS was used for fabrication of triple-band stacked antenna to validate the proposed design idea of frequency reduction for multiband antennas. The snapshots of different fabricated substrate layers for the triple band stacked antenna are shown in Fig. 6.

Fig. 7 Measured results for the proposed J-cross RIS-based triple band stacked GPS antenna

- a Return loss
b Axial ratio (boresight)
c Right handed CP gain (boresight)

4 Measurement results

The simulated and measurement results of the return loss, axial ratio (boresight) and gain (boresight) are shown in Figs. 7a–c for the fabricated J-cross RIS-based stacked antenna, respectively. A slight increase in return loss and axial ratio bandwidths is observed in the measurement results compared to the simulations because of small air gaps introduced in the multilayered microstrip antenna prototype prepared in our fabrication lab. This will not be observed if the antenna fabrication is done using the standard professional multilayered PCB fabrication process. The measured 10 dB return loss bandwidths for the L5, L2 and L1 bands are (1.168–1.185 GHz), (1.2–1.245 GHz) and (1.51–1.59 GHz) and the fabricated antenna shows good impedance matching in all the three GPS bands, as shown in Fig. 7a. The CP radiation is measured using the rotating linearly polarised transmitting horn antenna. Good CP radiation ($AR < 1$ dB) with improved forward right-handed CP gain is observed in the boresight ($\theta = 0^\circ$, $\phi = 0^\circ$) in all the three resonance bands for the compact antenna design as shown in Figs. 7b and c, thus validating our proposed design of frequency reduction with improved impedance matching and the front-to-back ratio using RIS for multi-band stacked antennas. As the measured gains (boresight) for the antenna design are 2.88 dBic (L5 band), 3.25 dBic (L2 band) and 5.53 dBic (L1 band), respectively,

the proposed antenna can be used for both the transmitting as well as receiving GPS applications.

The measured and simulated (co- and cross-) normalised radiation patterns with both the principal planes (x - z and y - z) are plotted in Figs. 8a–c for the L5 band (1.176 GHz), L2 band (1.227 GHz) and L1 band (1.575 GHz), respectively. As the proposed antenna has RHCP radiation, so the RHCP is the co-polarisation and left-handed CP (LHCP) is the cross-polarisation of the antenna. The cross-polarisation level [RHCP – LHCP] over the 3 dB AR bandwidth is better than 24 dB for the L5 band, 27 dB for the L2 band and 28 dB for the L1 band in the boresight. The 3 dB AR beamwidth is more than 120° for the 3 dB AR bandwidth frequency range.

Table 2 shows the comparison of the measured performances of the proposed triple band stacked antenna over RIS and other dual band antennas, mostly for the GPS applications. Performances of the compact single band reference antennas [11, 12] have also been compared with the proposed antenna in the table.

5 Conclusions

A novel technique of selective frequency reduction for the lower frequency bands and improving the radiation performance has been demonstrated for multi-band CP

Fig. 8 Measured and simulated (co- and cross-) normalised radiation patterns of the triple band stacked antenna over J-cross RIS for both the principal planes (x-z and y-z)

a 1.176 GHz
b 1.227 GHz
c 1.575 GHz

stacked patch GPS antenna over RIS. Two RIS-based antennas with Sq-patch and J-cross elements have been designed and compared with the PEC ground-based antenna for the same effective ground plane size for antenna radiation enhancement. Better impedance matching in the lowest L5 band and significant improvement in the front-to-back ratio for the L1 band have been achieved with

size reduction when J-cross RIS replaces PEC as the antenna ground plane. Prototyped antenna demonstrates improved forward RHCP gain (boresight) with good impedance matching and CP bandwidth in all the three L1, L2 and L5 bands, thus making it useful for both transmitting as well as receiving GPS applications. The proposed technique of combining slot/slit based multiple

Table 2 Comparison of measured performances of antennas

Antenna structures	Mechanical specifications	Electrical specifications		
	Dimensions in $L \times L \times H$ (in terms of electrical length)	10 dB return-loss bandwidth, %	3 dB AR bandwidth, %	Max. gain, dBic
proposed antenna	$0.32\lambda_o \times 0.32\lambda_o \times 0.024\lambda_o$ at 1.2 GHz	L1 band: 5.16 L2 band: 3.68 L5 band: 1.45	L1 band: 3.19 L2 band: 3.04 L5 band: 2.21	L1 band: 5.53 L2 band: 3.25 L5 band: 2.88
[1]	$0.373\lambda_o \times 0.373\lambda_o \times 0.008\lambda_o$ at 1.6 GHz	1.6 GHz: 8.70 2.2 GHz: 23.0	1.6 GHz: 8.40 2.2 GHz: 19.2	1.6 GHz: 3.82 2.2 GHz: 3.95
[2]	$0.46\lambda_o \times 0.46\lambda_o \times 0.086\lambda_o$ at 1.2 GHz	L1 band: 12.5 L2 band: 16.0	L1 band: 0.60 L2 band: 6.90	L1 band: 5.00 L2 band: 5.00
[3]	exact values not specified	exact values not specified	exact values not specified	exact values not specified
[4]	exact values not specified	L1 band: 8.82 L2 band: 10.6	L1 band: 4.50 L2 band: 4.30	L1 band: 4.90 L2 band: 4.40
[9]	$0.40\lambda_o \times 0.40\lambda_o \times 0.086\lambda_o$ at 1.2 GHz	L1 band: 1.20 L2 band: 3.70	L1 band: 0.60 L2 band: 0.90	L1 band: 1.45 L2 band: 1.10
[10]	$0.375\lambda_o \times 0.375\lambda_o \times 0.008\lambda_o$ at 1.5 GHz	1.5 GHz: 3.44 3.0 GHz: 3.21	1.5 GHz: 1.17 3.0 GHz: 1.05	1.5 GHz: 3.50 3.0 GHz: 0.70
[11]	$0.273\lambda_o \times 0.273\lambda_o \times 0.013\lambda_o$ at 900 MHz	1.97	0.66	3.80
[12]	$0.288\lambda_o \times 0.288\lambda_o \times 0.012\lambda_o$ at 2.4 GHz	2.53	0.50	4.35

stacked antenna with RIS can be useful for antenna design applications where electrical size of the antenna is small, the frequency ratios are close to one, and good CP beamwidth and high forward RHCP gain is required with an ease to design and optimise all the bands distinctly. The structure of the multi-stacked patch-based antenna combined with RIS consisting of J-cross elements can be easily fabricated using printed circuit board (PCB) technology.

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