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A Compact ACS-fed CRLH MIMO Antenna for Wireless Applications

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Abstract: This paper introduces a compact asymmetric coplanar strip (ACS)-fed composite right left handed (CRLH) MIMO antenna for multiband operation. The ACS-fed MIMO antenna is composed of two elements, each is operating at 5 GHz, 5.8 GHz and 6.3 GHz; for different wireless applications. The overall MIMO antenna size is compact ($46 \times 26 \text{ mm}^2$). A unit cell of the CRLH connected to 50Ω ACS-fed is considered the main block of the antenna. The edge to edge separation between antenna elements equals $0.4\lambda_0$ at 5 GHz. The insertion loss, correlation coefficient, diversity gain and channel capacity are used to evaluate the performance of the ACS-fed MIMO antenna. The isolation higher than 25 dB and envelope correlation lower than 0.05 have been achieved without using any extra decoupling structures. The experimental results are reasonably well agreed with simulated ones.

1. Introduction

Recently, MIMO technology has been utilized to increase the data transmission rate, reliability and channel capacity [1],[2]. MIMO systems can use many antennas in their transmitters and receivers. The antenna elements in MIMO systems should have low mutual coupling between them to increase the channel capacity and diversity [3],[4]. Therefore, compact size and high isolation between antenna elements are considered the main requirements as well as challenge in high performance MIMO systems. Many works have been conducted to decrease the mutual coupling between antenna elements in MIMO systems such as using electromagnetic band gap (EBG) structures [1], [5],[6]. But the EBG structures make the system complex. Also, defected ground structures (DGSs) can be utilized to increase the isolation between antenna elements [7]-[10]. However edging in the ground is not preferable for housing and increasing fabrication complexity.

From other aspects, the coplanar waveguide (CPW)-fed antenna is simple to be integrated with other microwave circuits. For reducing the size of the CPW ground, asymmetric coplanar strip (ACS) fed antenna has been suggested to reduce the microwave devices and antennas [11],[12]

To reduce the size as well as coupling effects, composite right/left handed (CRLH) transmission line (TL) structures have been used for small size antennas [13]-[19] and also in MIMO TL antennas with small mutual coupling [20]-[24]. This has been gained thanks to the CRLH unique electromagnetic properties such as anti-parallel group velocities, zero order resonance and nonlinear phase.

In this paper, we introduce a compact size CRLH two elements MIMO antenna with high isolation and simple structure. In addition to the structure simplicity, the proposed MIMO antenna can achieve multi band of operation at lower frequencies compared to symmetric configuration. This configuration enhances the performance of MIMO antenna without the need of using extra

decoupling structure. The MIMO antenna performance has been evaluated by analysing its correlation coefficient, diversity gain and channel capacity.

2. Asymmetric CRLH CPW Antenna Theory and Design

2.1. Theory and Structure

In this section, we explain the concept of the proposed compact asymmetric CRLH CPW-antenna. The geometry of a symmetric CRLH antenna and suggested asymmetric one are shown in Fig. 1 (a) and (b), respectively. It can be seen that the symmetric antenna is realized using one CRLH cell of one series interdigital capacitor and two shunt inductors in symmetric configuration with CPW feeding line, whereas the asymmetric one is composed of one CRLH cell of one series interdigital capacitor and one shunt inductor in asymmetric configuration with asymmetric coplanar strip (ACS) feeding line to decrease the overall antenna size. Both antennas are fed by 50Ω transmission line and printed on RO4003 substrate ($\epsilon_r = 3.38$, thickness = 1.6 mm and dielectric tang loss = 0.009). The equivalent circuits for the two configurations are illustrated in Fig. 2 (a) and (b), respectively. It can be seen there are two symmetric shunt branches for the symmetric antenna whereas only one branch for the asymmetric one. It is worth to point out that the physical realization of the asymmetric configuration will have smaller foot print (for the same lumped values). Referring to the symmetric configuration in Fig. 2 (a), the antenna resonating condition is [13].

$$\phi_{CLRH} = -\beta l = -\left(\omega \sqrt{L_R C_R} - \frac{1}{\omega \sqrt{L_L C_L}} \right) = n\pi \quad (1)$$

where l represent the length of the total cells, and n is an integer = 0, ± 1 , ± 2 ,etc. (L_R is the right handed inductance, C_R is the right handed capacitance, L_L is the left handed inductance and C_L is the left handed capacitance).

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Fig. 1. (a) 2D layout of single element CRLH antenna (a) CPW-fed with $W_{c1}=2.8$ mm, $L_{s1}=4.95$ mm, $L_{c1}=7.6$ mm, $W_{f1}=2.8$ mm, $W_{g1}=6.6$ mm, $L_{s1}=26$ mm, $W_{s1}=16.5$ mm, (b) ACS-Fed with $W_{c2}=2.8$ mm, $L_{s2}=4.95$ mm, $L_{c2}=11.2$ mm, $W_{f2}=2.8$ mm, $W_{g2}=6.6$ mm, $L_{s2}=26$ mm, $W_{s2}=13.5$ mm, $t_c=0.2$ mm, $S_c=0.3$ mm.

Fig. 2. (a) The equivalent circuit model of unit cell CRLH antenna (a) symmetric configuration, (b) asymmetric configuration.

According to (1), resonating antenna based on CRLH transmission line (TL) is designed to achieve integer multiple of half wave.

On the other hand, for asymmetric configuration in Fig. 2 (b), the resonant condition is modified to be

$$\phi_{CLRH} = -\beta l = -\left(\omega \sqrt{L_R \frac{C_R}{2}} - \frac{1}{\omega \sqrt{2L_L C_L}} \right) = n\pi \quad (2)$$

Comparing (1) and (2), for the same lumped values and physical lengths, the resonant frequencies will be lower in the asymmetric structure compared to symmetric one. This will be further explained in the next section.

2.2. Results and Discussions

The initial design of the proposed antenna starts with designing a symmetric CPW CRLH based antenna. To confirm the small size of the asymmetric configuration, a single band and then triple band antennas are discussed in this section for both symmetric and asymmetric configurations. For each antenna, the commercial electromagnetic full wave simulation software CST was used to check the antenna resonance.

The single band CRLH antenna was designed as a zeroth order antenna to work at frequency band of 6 GHz (at which $n=0$ in (1)). Hence, ($L_R=6.16$ nH, $C_R=2.69$ pF, $C_L=1$ pF and $L_L=0.625$ nH). Based on these values, the elements (C_L and L_L) were synthesized as interdigital capacitor, strip meander line inductor [10]. The parasitic effects of the CPW transmission line are used to achieve the values for C_R and L_R . These designed values will be synthesized in two configurations (symmetric and asymmetric) for comparison purposes.

The single band antenna with the symmetric configuration realization is shown in Fig. 1 (a) with detailed dimensions in Fig. 1 (a). A comparison between the simulated reflection coefficients of the symmetric CRLH antenna with CPW-fed using full wave simulation and circuit simulations is shown in Fig. 3 (a). It is seen that the antenna is operating at centre frequency of 6 GHz with return loss lower than 17 dB and 10 dB bandwidth ranging from 5.8 GHz to 6.2 GHz.

Consequently, to confirm our proposed asymmetric advantage, a half section of the symmetric CPW antenna was removed to convert the symmetric configuration to asymmetric one. The asymmetric CPW antenna layout is shown in Fig. 1 (b). For this configuration, the antenna length was kept the same as that in Fig. 1 (a) while removing the right hand side of the antenna reduces its width. From circuit point of view, the antenna shunt branch in Fig. 1 (a) has $C_R/2$ and $2L_L$, for the same dimensions in Fig. 3 (a). The asymmetric antenna was simulated using CST and the simulated reflection coefficient is shown in Fig. 3 (b). The simulated reflection coefficient demonstrates that the asymmetric antenna has a resonance at 5.5 GHz. This means that the ACS fed antenna has resonance frequency lower than the symmetric one by 8.5 %. In other word, the asymmetric configuration has larger electric length advantage.

Following to the previously explained asymmetric zeroth order antenna, the design of the proposed triple band antenna was developed. In other word, the triple band antenna was designed using (2), making use of the phase non linearity, to achieve three possible resonances at for $n = -1$ at 5 GHz, $n=0$ at 6 GHz and $n=1$ at 6.3 GHz. It is worth to confirm that along these specifications, a basic design condition was to achieve a compact antenna size.

Fig. 3. Simulated reflection coefficient of the unit cell CRLH antenna (a) CPW-fed, (b) CPW-fed and ACS-fed at different electric length.

Fig. 4. Simulated surface current distribution of the ACS-Fed meta-material antenna at (a) 5 GHz, (b) 5.8 GHz and 6.3 GHz

Finally, the antenna layout is the same as in Fig. 1 (b) and the dimensions are as listed in Fig. 1. This antenna is referred as ACS fed with large electric length. As shown in Fig. 3 (b), the simulated reflection coefficient has three resonances centered at 5 GHz, 5.8 GHz, 6.3 GHz with 10 dB bandwidth criterion of 8 %, 0.6%, 0.6%, respectively.

For the sake of further comparison step, another symmetric configuration CPW fed with large electric length antenna is developed (the dimensions are the same with the ACS – fed large electric length in Fig. 3 (b)). The simulated reflection coefficient is shown in Fig. 3 (b). As shown in the figure, the symmetric has only two possible resonances centred at 5.5 GHz and 6 GHz. In a summary, we can confirm that the suggested asymmetric configuration can lead to smaller antenna size for single / multi band operating frequencies.

Moreover for understating the resonance mechanism of the antenna, Fig. 4 illustrates the simulated surface current distribution of the antenna at 5 GHz, 5.8 GHz and 6.3 GHz. In the three cases, it is seen that the current is concentrated around the interdigital capacitor (the series resonance branch which means that the interdigital capacitor is responsible for the radiation than stub.

3. MIMO Antenna Design

In this section, we study the performance of the CRLH ACS-fed antenna in MIMO system. The 2D layout of proposed CRLH MIMO antenna with ACS-fed configuration is shown in Fig.5 (a). The fabricated photo of proposed CRLH MIMO antenna is illustrated in Fig.5 (b).

Fig. 5. The ACS-fed CRLH MIMO Antenna (a) 2D layout (b) fabricated antenna

The two antenna elements are based on the previous single antenna design. The distance between the edge to edge between two antenna elements equals 25 mm ($0.3\lambda_0$ at 4.5 GHz). The distance between the two antennas is chosen by using parametric analysis and this distance is given the best performance as illustrated in table 1.

Table 1 parametric study of the ACS-fed CRLH MIMO antenna

Space distance (mm)	Isolation (dB)		
	5GHz	5.8GHz	6.3 GHz
6.5	10	19	11
13	13	20	17
19	16	22	21
25	18	26	28

The CRLH MIMO antenna design is verified by comparing the simulated scattering parameters magnitudes to the measured results as shown in Fig. 6. It is worth to comment that the results were obtained by exciting port (1) and matching port (2) to 50 Ω load. From simulated results it is clear that the antenna is worked at triple bands. The centre frequencies of the three bands are 5 GHz, 5.8 GHz and 6.3 GHz with return loss of 18 dB, 20 dB and 12 dB respectively, the bandwidth of 400 MHz, 40 MHz and 40 MHz respectively and the insertion loss of 18 dB, 26 dB and 28 dB respectively. The measured results demonstrate that the antenna worked at triple bands with small shift between the measured and simulated. This frequency shift is because of the fabrication and soldering process which cannot be avoided.

The normalized simulated and measured radiation patterns in x-z plane and y-z plane of the proposed CRLH MIMO antenna at port 1 when port 2 is matched with 50 Ω load at frequency band of 5 GHz, 5.8 GHz and 6.3 GHz is illustrated in Fig.7. Antenna radiation patterns were measured inside anechoic chamber using the NSI 800F-30 system.

It is clear that the radiation pattern demonstrates nearly omnidirectional in the x-z and y-z planes. The maximum radiation of the antenna has maximum radiation along the y direction. In evaluating the obtained results, we can claim that there is matching between simulated and

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Fig. 6. The simulated and measured scattering parameter magnitudes of the ACS-fed CRLH MIMO antenna

Fig. 7. The normalized simulated and measured radiation patterns at port 1 when port 2 is matched with 50Ω load (a) x-z plane at 5 GHz, (b) y-z plane at 5 GHz, (c) x-z plane at 5.8 GHz, (d) y-z plane at 5.8 GHz, (e) x-z plane at 6.3 GHz, (f) y-z plane at 6.3 GHz

measured results. The simulated gain of the antenna at port 1 equals 1 dB. This is considered reasonable small gain because of the small size of the antenna.

4. MIMO Antenna Performance Evaluation

In this section, we study the main parameters which affect the antenna performance in MIMO system. The main three parameters which used to define the diversity of MIMO system diversity are envelope correlation coefficient (ECC), diversity gain and by channel capacity loss (CCL).

4.1. Envelope correlation coefficient and diversity gain

ECC defines the correlation between antenna elements. Therefore, for high performance in the MIMO system the ECC between the antenna elements is to be at lower value. The ECC can be calculated from S-parameters [25]. The researchers took in to account uniform multipath environment as

$$ECC = \rho_e = |\rho_{ij}| = \frac{|S_{ii}^* S_{ij} + S_{ji}^* S_{jj}|^2}{(1 - (|S_{ii}|^2 + |S_{ji}|^2)) (1 - (|S_{jj}|^2 + |S_{ij}|^2))} \quad (3)$$

and the ECC also can be calculated using the radiation pattern [25] as

$$ECC = \rho_e = \frac{|\iint_{4\pi} [F_1(\theta, \phi) \bullet F_2(\theta, \phi) d\Omega]^2}{\iint_{4\pi} |F_1(\theta, \phi)|^2 d\Omega \iint_{4\pi} |F_2(\theta, \phi)|^2 d\Omega} \quad (4)$$

where $F_i(\theta, \phi)$ is the field radiation pattern when port i is excited.

It is worth to comment that most of the published work in MIMO antennas use scattering parameters formulation which always provides very under estimating low values (less than 0.01) and suitable only for isotropic MIMO medium and lossless MIMO elements. On the other hand, it has been pointed out that ECC less than 0.5 is a fair condition for radiation pattern formulas [26].

The simulated ECC of the CRLH MIMO antenna for both S- parameters and radiation pattern is plotted in Fig. 8. From the figure, it is clear that the ECC of the proposed antenna at frequency band 5 GHz, 5.8 GHz and 6.3 GHz equals 0.002, 0.02 and 0.05 respectively from S-parameters and 0.21, 0.15 and 0.2 respectively from radiation pattern calculations.

Fig. 8. The simulated envelope correlation coefficient of ACS-fed CRLH MIMO Antenna

From the previous results it is clear that the ECC has typical very low values scattering parameters formulas and very fair results (quite lower than the reference value (0.5)).

Fig. 9. The simulated diversity gain of the ACS-fed CRLH MIMO Antenna

The diversity gain (DG), which is another important MIMO parameter, has been calculated in the analysis of the proposed MIMO antenna as

$$DG = 10 * \sqrt{1 - |ECC|} \tag{5}$$

The simulated diversity gain of the proposed MIMO antenna is shown in Fig. 9. The ECC in the equation (5) is based on scattering parameters calculations. According to (5), the highest value of the diversity gain equals 10 dB. The diversity gain of the proposed CRLH MIMO antenna at frequency 5 GHz, 5.8 GHz and 6.3 GHz equals 9.99 dB, 9.95 dB and 9.8 dB respectively.

4.2. Channel capacity loss (CCL)

CCL is used to evaluate the performance of MIMO system. The CCL increases with linear relationship with increasing the number of antenna elements in any system without changing in the bandwidth or transmitted power [28]. The relation between antenna elements in MIMO channel can produce capacity loss which calculated as (6) [29]

$$CCL = - \log_2 \det(\psi^R) \tag{6}$$

$$\psi^R = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix} \tag{7}$$

Fig. 10. The simulated channel capacity loss of the ACS-fed CRLH MIMO Antenna

where $\rho_{ii} = 1 - \left(|S_{ii}|^2 + |S_{ij}|^2 \right)$

$$\rho_{ij} = - \left(S_{ii}^* S_{ij} + S_{ji}^* S_{ij} \right) \text{ for } i, j = 1 \text{ or } 2 \tag{8}$$

The simulated CCL is illustrated in Fig.10. From Fig.10 it is observed that the CCL at frequency band 5 GHz ,5.8 GHz and 6.3 GHz equals 0.05 bits/s/Hz, 0.3 bits/s/Hz and 0.25 bits/s/Hz. These values are lower than the reference value of 0.4 bits/s/Hz within the operating frequency band [30]. The results of the ACS-fed CRLH MIMO antenna are tabulated in Table 2. It is claimed that our proposed antenna is good choice for MIMO applications.

Table 2 CRLH MIMO antenna parameters of the proposed design

	5GHz	5.8GHz	6.3GHz
Return loss (dB)	18	20	12
Mutual Coupling (dB)	-18	-26	-28
Gain (dB)	1	0.8	0.6
ECC from S-parameters	0.002	0.02	0.05
ECC from radiation patterns	0.21	0.15	0.2
Gain Diversity(dB)	9.99	9.95	9.8
CCL (bits/s/Hz)	0.05	0.3	0.25

Table 3 Performance of the proposed ACS-fed CRLH MIMO antenna and recent work

Ref No	[5]	[6]	[7]	[21]	[24]	This work
Frequency (f ₀) in GHz	4.8	3	5.8	5	0.3/5 1.7	5/5.8/6.3
Approach	Slotted meander line	EBG structure and a multilayer dielectric substrate	Defected ground structure	loaded spiral resonators	mushroom structure	Without using decoupling structure
Edge to edge spacing	0.110λ ₀ (7mm)	0.40λ ₀ (40mm)	0.058λ ₀ (3mm)	0.05λ ₀ (3.2mm)	Not reported	0.4λ ₀ / 0.46λ ₀ / 0.52λ ₀ (25 mm)
S ₂₁ (dB)	-16	-35	-28	-28	-25	-18/-26/-28
Size mm ²	54×45	Not reported	54×30	43×36	51×51	46×26

In order to validate the proposed design, Table 3 illustrates the comparison between the proposed antenna and other designs in the literature. It is observed that our proposed ACS-fed MIMO antenna has small size, low cost and good isolation.

5. Conclusion

A design of ACS CRLH MIMO antenna has been presented. The antenna element is comprised on one unit cell of CRLH TL. The MIMO antenna is operated at triple bands for different wireless applications (5 GHz, 5.8 GHz and 6.3 GHz). The MIMO antenna has size of has $46 \times 26 \text{ mm}^2$ with two elements edge to edge distance equals $0.4\lambda_0$ at 5 GHz. The presented MIMO antenna has more than 25 dB isolation between its two inputs without using any decoupling structure. The envelope correlation of the MIMO antenna does not exceed 0.2. Thanks to the achieved size and MIMO performance, the proposed antenna is a good candidate for MIMO applications.

6. References

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