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Analysis and Experimental Verification of Multi Band Thin Monopole Antennas Loaded with Half Mode CRLH Inspired Resonators

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Reply to Reviewer 1's Comments:

Reviewer(s)' Comments to Author:

It seems the paper has too many self citations, which the authors are strongly suggested to eliminate.

Reply:

Some references were added to demonstrate the authors experience in the paper topic. However, to meet the reviewer comment, in the revised manuscript, self references from [33]-[39] were deleted and replaced by only [7] in citing in page 3. Hence, the self references have been reduced from 14 to 7 only.

Analysis and Experimental Verification of Multi Band Thin Monopole Antennas Loaded with Half Mode CRLH Inspired Resonators

Keywords: Metamaterial, Dual / Triple Multi-band antenna, Half mode-CRLH.

This paper presents analysis and experimental measurements of CPW and microstrip compact monopole antennas loaded with resonator circuits inspired from simplified half mode composite right / left handed unit cell. The antennas were designed to have a typical omnidirectional radiation pattern. The CPW fed dual band antenna resonates at 2.4 GHz and 5.8 GHz, respectively. The antenna size is $20 \times 30 \text{ mm}^2$ and the radiator patch is only 25% at 2.4 GHz and 60% at 5.8 GHz in comparison with a conventional patch antenna. The microstrip triple band antenna covers the frequency bands from 2 GHz-2.4 GHz, 5.4 GHz-6 GHz, and 6.8 GHz-8 GHz. The antenna size is $28 \times 25 \text{ mm}^2$ which is less than 25% at lower frequency band compared to the size of the conventional patch antenna. Detailed theoretical and full wave analysis are presented and experimental results demonstrate a good agreement between the measured and the simulated. The suggested antennas can be employed for compact size and multiband functionalities in wireless applications. The loading technique can be adapted for more frequency bands.

Introduction

In wireless communication, the need for low profile antennas is a continuous demand for antenna engineer's community. Since different wireless applications are assigned differing frequencies, therefore, antennas are desirable to have multi band functionality. Moreover, these antennas are required to have an omnidirectional radiation pattern and simple design procedures. Many attempts for multiband antennas

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3 have been discussed in the literature. These attempts include using different radiating
4 resonators which can be either separated on one/two sides of the printed antenna [1]-[4],
5 or incorporated in one configuration [5],[6]. However, the first approach increases the
6 antenna size; especially when the number of bands increases. Also, the second approach
7 is difficult in design; especially when the number of desired operating bands increases.
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13 The planar left handed metamaterials transmission line has been presented with
14 promising electromagnetic wave properties for new trend in designing microwave
15 components and antennas. It has been realized by loading a transmission line (TL) with
16 series capacitors and shunt inductors known as a composite right / left handed (CRLH)
17 [7] or negative refractive index [8]. CRLH TL has been employed in miniaturization of
18 single/multiband functionalities for planar antennas [9]-[17].
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26 To introduce even more compact size and multi-bands, different modifications
27 based on increasing the order of the CRLH TL have been suggested. These approaches
28 are dual CRLH TLs [18], inductor loaded CRLH TL [19], extended CRLH TL [20]-
29 [22], generalized LHM TL [23]-[25], expanded CRLH TL [26] and doubled CRLH TL
30 [27]. However, one of the drawbacks of these attempts is the increase of the complexity
31 of the unit cell structure and hence the microwave element design procedures.
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39 To simplify antenna design, antennas have made use of the idea of reducing
40 CRLH unit cell by using only two elements in [28],[29]. However, detailed analyses of
41 antenna designs were not provided. In this paper, we present detailed design procedures
42 and analysis based on the concept of simplified half mode CRLH (H-CRLH) antennas
43 [30]-[32]. Also, extensive full wave simulation and experimental measurements are
44 presented to confirm the analysis.
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Half Mode CRLH Inspired Antenna Principles

Conventional CRLH unit cell is formed by loading a planar transmission line with series capacitor (C_L) and shunt inductor (L_L). The equivalent circuit of a lossless CRLH unit cell is shown in Fig. 1, where C_R and L_R are corresponding to the intrinsic elements of loaded transmission line. The basic concept of CRLH resonating antenna is to terminate the CRLH cell with either short or open circuit as shown in Fig. 1 (a). In the case of open circuit termination, the operating frequencies of CRLH TL based antennas is [9]

$$\phi_{oc} = \left(\frac{1}{\omega \sqrt{C_L L_L}} - \omega \sqrt{C_R L_R} \right) = \pm n\pi, \quad n = 0, 1, \dots, (N-1) \quad (1)$$

Fig. 1. The equivalent circuit model of the CRLH TL antenna (a) The full mode case (b) The practical half mode case.

Compact zeroth order antenna has been suggested in [7], however, it has been suggested in [31] that simpler and ultra compact metamaterial antenna is possible by using open-

circuited terminated H-CRLH cell. The H-CRLH based antenna is shown in Fig. 1 (b), where it is realized by loading a TL with only shunt inductive load with no series capacitive load. The resonance frequency for the shunt branch (f_{0sh}) can be written as

$$f_{0sh} = \frac{1}{2 \pi \sqrt{L_L C_R}} \tag{2}$$

Dual Band H-CRLH Resonator Inspired Antenna

Dual Band Antenna Structure

The dual band CPW antenna is fed by a 50 Ω line (length = 12 mm) on low loss Duroid substrate with $\epsilon_r=2.2$, and 1.59 mm thickness. The antenna is designed by loading a thin monopole antenna (T shape) with narrow meander line to fulfil the equivalent circuit in Fig. 1 (b). The unloaded antenna layout is shown in Fig. 2 (a), where the antenna dimensions were specified to adjust the monopole resonance at 2.4 GHz with as small size as possible. The simulated reflection coefficient of the unloaded monopole antenna is shown in Fig. 4. As it can be seen, the antenna has a resonance with -14 dB reflection coefficient at 2.4 GHz.

The dual band H-CRLH inspired antenna geometry is shown in Fig. 2 (b). The antenna is constructed by loading the previously designed T shaped monopole with multi turns meander line. The narrow gaps in the meander line should be equivalent to a capacitor (C_R) connected in parallel with the line inductance (L_L). Comparing this configuration to H-CRLH antenna in Fig. 1 (b), we can notice that this configuration makes use only of the shunt parallel tank circuit with no complete transmission line realization. The dimensions for the T-Shape strip monopole and the overall antenna size are the same as those in Fig. 2 (a). The dimensions of the employed meander line were adjusted for introducing a second band at 5.8 GHz using (2). The fabricated dual band half mode antenna prototype is shown in Fig. 3.

Fig. 2. The dual band H-CRLH inspired antenna (a) The unloaded antenna ($W_1 = 1.5$ mm and $W_2 = W_t = 0.3$ mm, $L_1 = 8.5$, $L_2 = 5$ mm and $L_t = 18$ mm) (b) the loaded antenna ($L_0 = 0.4$ mm, $L_f = 2.25$ mm, $W_f = S_f = 0.25$ mm)

Fig. 3. The fabricated dual band H-CRLH inspired antenna prototype.

Both full wave simulation and experimental measurement results are shown in Fig. 4, a good agreement between the two can be observed. As shown, the antenna can demonstrate almost identical and better than -15 dB in the reflection coefficient at the two designed frequencies. Comparing the results of the unloaded and loaded antennas,

we can observe that the first band at 2.4 GHz is the same with or without using loading cell. Also, it is observed that the antenna has better than 10 dB bandwidth from 2 GHz - 2.8 GHz in the first 2.4 GHz band and 5.74 GHz -5.95 GHz in the second band.

Fig. 4. The comparison between the simulated reflection coefficient for the loaded / unloaded antennas and the measured one for the loaded dual band antenna.

Dual Band Antenna Radiation Mechanism

To confirm the radiation mechanism of the dual band antenna, the simulated current distribution at 2.4 GHz and 5.8 GHz were extracted and plotted in Fig. 5. It can be seen that at 2.4 GHz, peak current is concentrated along the thin strip monopole with weak current passing through the loading meander line. This can be explained that the resonance is caused by the unloaded monopole. However, at 5.8 GHz, the peak current is passing through the loading meander line. The current distribution results confirm that the radiation mechanism of the second band is due to the resonance introduced by the meander line resonator.

The role of the loading meander line can be further confirmed by simulating the antenna for different values of the finger length (L_f) , as shown in Fig. 6. It is obvious

that the change of the finger length does not affect the first band at 2.4 GHz. However, by increasing the finger length, i.e., increasing both L_L and C_R the resonant frequency is shifted down to 5.2 GHz, 5.6 GHz 6.1 GHz and 6.9 GHz for $L_f = 2.5$ mm, 2 mm, 1.5 mm and 1 mm, respectively. This result can also confirm the resonance behaviour in (2) that supports our loading principles.

Fig. 5. The current distribution of the dual band inspired H-CRLH antenna at (a) 2.4 GHz, (b) 5.8 GHz.

Fig. 6. The simulated reflection coefficient of the dual band H-CRLH inspired antenna for different L_f values.

The Antenna Radiation Properties

The antenna radiation performance at the two operating band has been checked by investigating the radiation pattern at each band centre frequency. The 3D normalized power pattern at 2.4 GHz and 5.8 GHz of the dual band antenna is shown in Fig. 7. It is obvious that the dual band antenna has an omni-directional radiation pattern with maximum radiation in Z direction, perpendicular to the antenna. Such radiation pattern is appreciated in the WiMAX applications for which the antenna was designed.

The antenna gain, directivity and radiation efficiency were computed at the two operating frequencies as summarized as in Table 1. It can be high-lighted that excellent efficiency was achieved which makes the antenna very good for wireless services.

Table I: The dual band antenna radiation parameters summary

Antenna Parameter	Frequency (2.4 GHz)	Frequency (5.8 GHz)
Antenna Directivity	2.39 dB	3.41 dB
Antenna Efficiency	-0.04 dB (99%)	-0.06 dB (98 %)
Antenna Gain	2.35 dB	3.35 dB

Fig. 7. The 3D normalized radiation pattern at 2.4 GHz and 5.8 GHz of the dual band H-CRLH inspired antenna.

A comparison between the measured and simulated radiation pattern in the H plane (YZ plane) and E plane (XZ plane) at 2.4 GHz and 5.8 GHz are shown in Fig. 8

and Fig. 9, respectively. It is clear that there is a very good between the two data in both planes at 2.4 GHz whereas within the H plane, the plane is isotropic pattern and it is typical figure of eight. On the other hand, at 5.8 GHz, in Fig. 9, the comparison illustrates the same phenomenon with slight variation in the E plane at $\theta=120^\circ$. Both of the results given in Fig. 8 and Fig. 9 confirm the simulated 3D pattern. The data in Fig. 8, agrees with the data in Fig. 7.

Fig. 8. A comparison between the simulated and measured radiation pattern of the the dual band H-CRLH inspired antenna at 2.4 GHz in (a) H (YZ) plane, (b) E (XZ) plane

Fig. 9. A comparison between the simulated and measured radiation pattern of the dual band H-CRLH inspired antenna at 5.8 GHz in (a) H (YZ) plane, (b) E (XZ) plane

Triple Band Asymmetric H-CRLH Resonator Inspired Antenna

Triple Band Antenna Structure

The triple band antenna configuration is shown in Fig. 10 (a) and the fabricated antenna prototype is shown in Fig. 10 (b). As shown, the antenna geometry is based on loading a thin monopole with two different tank circuits (tank circuit # 1 corresponding to L_{L1} and C_{R1} in one side and tank circuit # 2 corresponding to L_{L2} and C_{R2} on the second side).

The antenna is fed by a $50\ \Omega$ microstrip line. The antenna is fabricated on low cost FR4 substrate with dielectric constant = 4.3, thickness = 1.6 mm, and $\tan\delta=0.02$. The two different resonator circuits are formed using two different meander lines in length and number of lines. All the meander line space and width were 0.25 mm.

The triple bands are the result of the resonance of each shunt resonator circuit. The tank circuit # 1 is constructed using longer meander line (9 pairs of $L_{f1} = 2.6$ mm) whereas tank circuit # 2 is constructed using only pair of $L_{f2}=2$ mm). Therefore, L_{L1} and C_{R1} will be larger than L_{L2} and C_{R2} . As a consequence, the antenna has two resonance frequencies, f_1 and f_2 . In addition a third resonance, f_3 , can be obtained due to the overall resonance of the two tank circuits.

Fig. 10. The H-CRLH inspired triple band antenna layout ($L_g=10$ mm, $L_1=3.75$ mm, $W_1=1.5$ mm, $L_{f1}=2.6$ mm and $L_{f2}=2$ mm,) (b) The fabricated prototype antenna

The antenna design was examined using the electromagnetic full wave simulation and experimental measurement as shown in Fig. 11. As shown it can be seen, the antenna can demonstrate triple band. The first band is centred at 2.2 GHz with lower than -10 dB reflection coefficient bandwidth from 2 GHz –2.4 GHz. The second band is centred at 5.7 GHz with bandwidth from 5.4 GHz –6 GHz. The third band is centred at 7.3 GHz with bandwidth from 6.8 GHz–8 GHz. The reflection coefficients at the centre frequency of the three bands are all better than -10 dB. Good agreement between the simulated and measured results are also achieved.

Fig. 11. The simulated and measured results of the triple band H-CRLH triple band antenna.

Triple Band Antenna Radiation Mechanism

A confirmation of the radiation mechanism can be done by plotting the current distribution at the three resonance frequencies 2.2 GHz, 5.7 GHz and 7.3 GHz in Fig. 12 (a), (b) and (c), respectively. As shown in Fig. 12 (a), the current is concentrated at resonator # 1 which agrees with the theoretical prediction. In Fig. 12 (c), the current is concentrated at the resonator # 2 which also confirms the theoretical prediction. In Fig. 12 (b), at 5.7 GHz, the current is concentrated at the two resonators which can be claimed that the resonance is due the contribution of overall resonances.

Fig. 12 The simulated current distribution along the triple band H-CRLH inspired antenna at (a) 2.2 GHz, (b) 5.7 GHz and (c) 7.3 GHz.

Triple Bands Antenna Radiation Properties

The 3D radiation patterns at the three centre frequencies are shown in Fig. 13. As shown, the three patterns are almost omnidirectional. The pattern at 2.2 GHz is the most typical omnidirectional one whereas that at 7.3 GHz is less typical one. This point can be emphasized by (1) effect of difference between measured and simulated reflection coefficient at 7.3 GHz in Fig. 11. (2) Also, this can be conducted as some difference in measured and simulated antenna gain at 5.7 GHz and 7.3 GHz.

Similar to dual band antenna, the triple band antenna gain, directivity and radiation efficiency were computed at the two operating frequencies as summarized as in Table II.

Table II: The triple band antenna radiation parameters summary

Antenna Parameter	Freq. (2.2 GHz)	Freq. (5.7 GHz)	Freq. (7.3 GHz)
Antenna Directivity	2.2 dB	3.39 dB	4.36 dB
Antenna Efficiency	-2.6 dB (55%)	-0.49 dB (89 %)	-0.41 dB (88 %)
Antenna Gain	-0.04 dB	2.9 dB	3.95 dB

Similar to the dual band antenna, the presented data confirm that the antenna is a good candidate for wireless applications. It is wort to comment that the triple band has

relatively lower values, compared to dual band antenna, as the triple one was implemented on low cost lossy FR4 substrate.

Similar to verification has been done for the dual band antenna, a comparison between measured and simulated radiation patterns of the triple band H-CRLH inspired antenna in the H plane and E plane at 2.2 GHz, 5.7 GHz and 7.3 GHz are shown in Fig. 14, Fig. 15 and Fig. 16, respectively. Relatively good agreement between the measured and simulated can be observed.

Fig. 13. The simulated 3D radiation pattern at 2.2 GHz, 5.7 GHz, and 7.3 GHz of the triple band H-CRLH inspired antenna.

Fig. 14. A comparison between the simulated and measured radiation pattern of the H-CRLH inspired triple band antenna at 2.2 GHz in (a) H (YZ) plane, (b) E (XZ) plane

Fig. 15. A comparison between the simulated and measured radiation pattern of the H-CRLH inspired triple band antenna at 5.7 GHz in (a) H (YZ) plane, (b) E (XZ) plane

Fig. 16. A comparison between the simulated and measured radiation pattern of the H-CRLH inspired triple band antenna at 7.3 GHz in (a) H (YZ) plane, (b) E (XZ) plane

Conclusion

A detailed study of new configurations for dual/triple bands H-CRLH inspired antennas are presented. The study has been emphasized using the full wave simulation and experimental results. The first antenna is a compact dual band antenna for lower 2.4 GHz and upper 5.8 GHz WiMAX frequency bands with almost typical omni-directional radiation pattern at the two operating frequencies. The antenna size is only $30 \times 20 \text{ mm}^2$ where the antenna has been miniaturized up to 75% compared to conventional patch antenna. The second antenna is a triple band antenna at 2.2 GHz, 5.7 GHz and 7.3 GHz

of an omnidirectional pattern with minimum 15 dB return loss at the band center frequency. The antenna is compact whose size is only $28 \times 25 \text{ mm}^2$.

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