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Research paper

Designing Multiband, Reconfigurable Printed Antenna for Modern Communication Systems

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Abstract

Background and Objectives: Printed monopole antenna has an omnidirectional radiation pattern but a narrow impedance bandwidth. To achieve multiband behavior, modification of the antenna shape is necessary. There is no systematic approach for the shape modification and commonly it is done by parametric studies, adjusting, tuning or optimization of an initial shape.
Methods: The method for designing a multiband antenna is based on transmission line theory and lumped element model. It applies to all desired multiband operations without needing tuning or optimizing a complex configuration. Every length and dimension are computed from the mathematical formula or Smith chart as a graphical tool. The proposed matching method in the design of a multiband and reconfigurable CPW-fed monopole antenna employed. Both series and parallel impedance matching stubs are investigated and compared with each other.
Results: To explain the challenges, the proposed method was applied to a desired antenna. It showed that using matching stubs in the CPW line can design a multiband and reconfigurable antenna. Also, the measurements have been done and compared with the simulations and show a good agreement.
Conclusion: Compared to the microstrip line, the CPW feeding of the monopole antenna has the advantage that both parallel and series stubs can be implemented for the matching of the antenna. In this case, the required space for these stubs placed inside the antenna and no extra space needed. So, the printed size of the proposed antenna does not change. The impedance matching method for the integrated stubs with the antenna has been proposed. The high-pass and low-pass properties of each matching network were considered. The authors showed that this method can successfully design multiband, reconfigurable CPW-fed monopole antennas.

Introduction

Today, the use of different frequency bands in a single device for access to various telecommunication services is very common. An Antenna as a part of the wireless systems, play an important role in achieving this goal. The appropriate antenna should have a multiband operation and an omnidirectional pattern, where full spatial coverage is required. One of prevalent and simple way to get an omnidirectional pattern is the monopole antenna. But the monopole antenna due to the resonance characteristic is very sensitive to frequency and does not have multiband properties. So, a lot of changes have been made to the monopole antenna shape by researchers to overcome this problem [1]-[16]. In order to attain multiband properties, in reference [1] two connected strip monopoles with different lengths are tuned, in [2] two stacked T-shaped monopoles with different sizes are adjusted, in [3] the dimensions of G-shaped monopole are optimized, in [4] the geometry of shorted parasitic inverted-L wire closely placed to the inverted L-shaped monopole is founded by tuning, in [5] appropriate slits into the CPW feeding line are optimized by particle swarm optimization, in [6] dimensions of modified T-shaped monopole are obtained by parametric studies, in [7] the lengths of the monopole antenna and an n-shaped slot on the radiating element properly adjusted, in [8] the parameters of two inverted-L slots etched on the radiator element optimized and tuned. In [9]-[24] by using a more complicated structure and shape for the monopole antenna, the multiband operation has been achieved.

Coplanar waveguide (CPW) implementation of microwave and antenna devices is widely considered in research. This is due to its attractive features such as a single metallic layer, low dispersion and loss, more design parameters for impedance matching, low radiation losses, and easy connection of series and shunt components. Some of the antenna mentioned in the past are fed by the CPW line. Furthermore, the CPW line also used in microwave devices such as filter [25], phase shifters [26], power splitters [27], amplifier [28], coupler [29] and etc. The matching stubs described here can be used for a better design of them.

The multiband antenna design method described here is very simple and completely applicable to all of the desired multiband operations without the need to tuning or optimizing a complex configuration. Every length and dimension are computed from the mathematical formula or Smith chart as a graphical tool. Because the shape of the monopole antenna does not change and the matching network integrated with the antenna structure, no need to increase in the monopole size.

In this paper, first in Section II the theory of impedance matching for CPW line based on the single-stub tuning developed and customized for CPW-fed monopole antenna. In this way, the effects of both series and parallel impedance matching stubs modeled with transmission line theory. Because the monopole antenna can be matched in the first operational band through the antenna length and proper feeding line, the matching network used for the second operational band and should not have any adverse effect on the first one. This can be explained through the concept of high-pass and low-pass properties of each matching network. To have a better view, each stub before the first resonance frequency modeled with the lumped elements.

In Section III, the proposed matching method in the design of a multiband and reconfigurable CPW-fed monopole antenna employed. Both series and parallel impedance matching stubs are investigated and compared with each other. Also, the effect of the difference between the upper and lower frequency bands on the success of the proposed method investigated. The tuning of the second band with the length of the stubs has been done and the independence of the two frequency bands is studied. For all case, the measurement results are compared with the Feko software simulations and show good agreement.

Matching Stubs in CPW Line

Single stub matching network is based on a short or open- ended transmission line (stub) with a specified length which connected to the feeder line at a certain position in the form of serial or parallel. Due to fabrication constraints, the parallel stub can be implemented in the microstrip line but the serial one not. For the CPW transmission line, both serial and parallel connections can be considered, due to presence of ground and center conductor in the same plane. The theory of single stub matching is well known [30]. But for using this theory in the design of the CPW-fed monopole antenna, we need to clarify some of the points. One of them is about the rotation direction in the Smith chart (toward the generator or load) that will be different here with usual impedance matching methods.

The other one is about stub termination (short or open) which must be selected in serial and parallel connection of stubs. The termination choosing for serial or parallel connection is related to the high-pass and low-pass properties of matching network. To design a multiband monopole antenna, the first operational band was matched (with a length of about quarter-wavelength) and for the second band, the matching stub must be designed so that the first one not disturbed by the matching network.

A. Modeling of Serial and Parallel Stubs

Let's consider the Fig. 1 (a) which part of center strip conductor expanded into surrounding ground and ended without connecting to it. Hence, this part can be modeled as an open-end CPW parallel stub (see Fig. 1 (b)). For circuit analysis based on the Smith chart, moving from the open circuit gives rise to a capacitive reactance that must be connected in parallel with the main CPW line (see Fig. 1 (c)).

The input impedance of this stub can be calculated from transmission line theory as:

$$Z_{in} = -jZ_0 \cot(\beta l_p) \tag{1}$$

where Z_0 is the open-end CPW parallel stub characteristic impedance (here we assumed that it is equal to the main line), l_p is the physical length of it and β is the phase constant. The values of Z_0 and β dependent on the physical dimensions can be found in [31].

If the stub, before the quarter-wavelength, modeled as a capacitance, then from (1) we have:

$$C = \frac{tan(\beta l_P)}{\omega Z_0} \qquad (2)$$

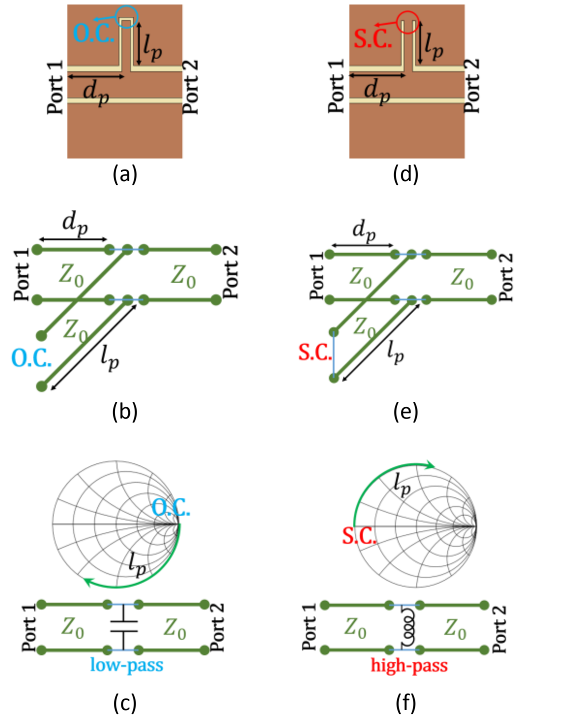


Fig. 1: Parallel stubs in CPW transmission line. Open-end CPW parallel stub (a) board layout, (b) equivalent transmission line and (c) equivalent circuit element with Smith chart. Short-end CPW parallel stub (d) board layout, (e) equivalent transmission line and (f) equivalent circuit element with Smith chart.

For Fig. 1 (d) the center strip conductor expanded into surrounding ground and connected to it to form a short circuit. Similarly, this part can be modeled as a short-end CPW parallel stub (see Fig. 1 (e)). In this case, moving from the short circuit gives rise to an inductive reactance that must be connected in parallel with the main CPW line (see Fig. 1 (f)). To explain the inductive properties of this stub, we must consider the current following around the end of termination like a loop. The input impedance of this short parallel stub can be calculated from transmission line theory as:

$$Z_{in} = jZ_0\, tan(\beta l_p) \qquad (3)$$

where the parameters are defined similar to (1). The equivalent inductance value, before the quarter-wavelength, determined by:

$$L = \frac{Z_0\, tan(\beta l_p)}{\omega} \qquad (4)$$

The values of C and L in (2) and (4) are a function of l_p (stub length), Z_0 and β.

In Fig. 2 (a), the center strip changed so that to form an interdigital structure. In circuit analysis, this structure can be modeled obviously as a series capacitance (see Fig. 2 (c)) and also based on transmission line theory it can be considered as a series open circuit CPW stub (see Fig. 2 (b)). So, the input impedance of the stub and the equivalent capacitance value, before the quarter-wavelength, can be computed with (1) and (2) respectively. The difference is that this open circuit stub, connected in series with the main CPW line (compare Fig. 1 (a) and Fig. 2 (a)).

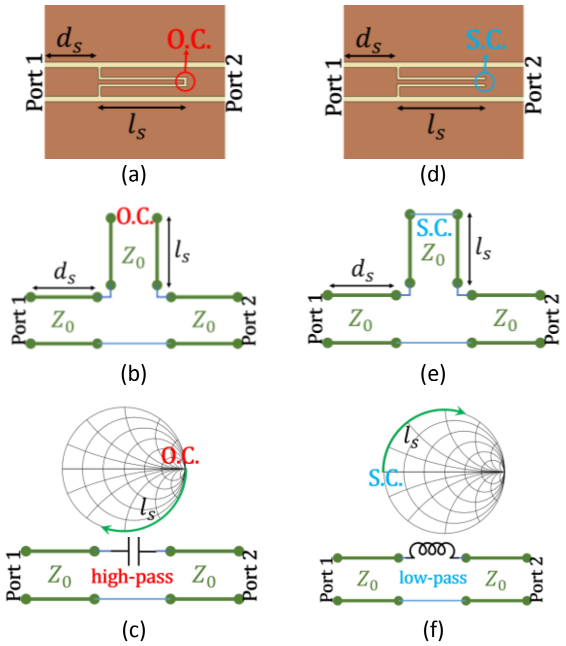


Fig. 2: Series stubs in CPW transmission line. Open-end CPW series stub (a) board layout, (b) equivalent transmission line and (c) equivalent circuit element with Smith chart. Short-end CPW series stub (d) board layout, (e) equivalent transmission line and (f) equivalent circuit element with Smith chart.

In Fig. 2 (d), the interdigital structure shorted in the end and form a short-end CPW series stub (see Fig. 2 (e)). Based on the Smith chart, moving from the short circuit gives rise to an inductive reactance that must be connected in series with the main CPW line (see Fig. 2 (f)). So, the input impedance of the stub and the equivalent inductance value, before the quarter-wavelength, can be computed with (3) and (4) respectively.

To achieve a multiband antenna, the matching network used for the second operational band, should not have any adverse effect on the first one. This simple lumped element model is useful when we must consider the effect of different stubs on the first operational bandwidth based on the high-pass and the low-pass properties of each matching network. Thus, we can conclude that the stubs shown in Fig. 1 (a) and Fig. 2 (d) are low-pass and suitable for matching of the second operational band, but the others are not useful for our purpose.

The simple lumped element equivalent circuit model is accurate before the first resonance frequency (the quarter-wavelength) and does not predict the resonance. But the transmission line model does it (see Fig. 3). In Fig. 3 (a) and (b) the S_{21} of low-pass CPW stubs simulated in full wave (FW) and compared with the transmission line (TL) model. The values of capacitance for open-end CPW parallel stub computed with (2) and illustrated in Fig.3 (a). The FW simulation for parallel stub agrees with TL model properly.

But for CPW series stub, the resonance frequency is shifted (see Fig. 3 (b)). It is because of the low width of surrounding ground for CPW series stub in comparison with the common CPW line. The values of inductance for short-end CPW series stub computed with (4) and illustrated in Fig. 3 (b). In Fig. 3 (c) the structure of low-pass CPW stubs for multi-band monopole antenna illustrated.

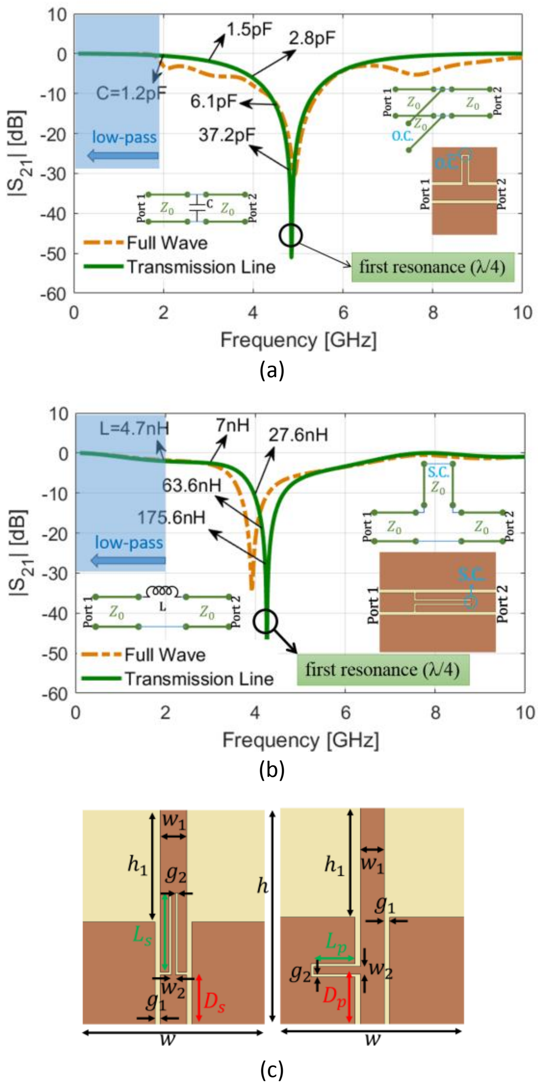


Fig. 3: The low-pass CPW stubs. The S_{21} magnitude of (a) open-end CPW parallel stub and (b) short-end CPW series stub. The FW and TL simulations compared and equivalent circuit element values before first resonance computed. (c) The low-pass CPW stubs solution for multi-band monopole antenna.

The D_S (D_P) and L_S (L_P) dimensions as the series (parallel) stub position and length must be designed to achieve multiband antenna. The following is an explanation of the design process with help of some examples.

B. CPW Stubs Design for Multi-Band Monopole Antenna

At the first, a CPW fed monopole antenna designed for the first frequency band based of the common method (with a length of about quarter-wavelength). Then the input impedance of the antenna gets through simulation at all frequencies. In this step, for more accurate results, the subminiature version A (SMA) connector is also considered in simulations. Now the input impedance of the antenna in the second desired band has been achieved and the matching problem is specified. To match this load to a 50Ω line the Smith chart can be used as a graphical tool. Since the goal of this work is the integration of matching circuit with the antenna, rotation direction in the Smith chart chosen toward the load (inside the antenna).

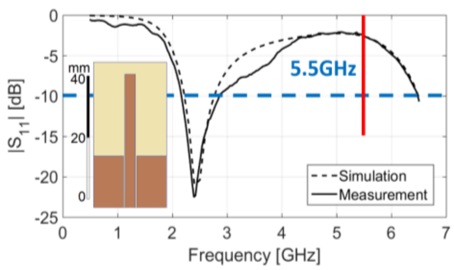
For parallel stubs case, the admittance Smith chart could be used and the normalized load must be plotted. The D_P calculated from the SWR circle intersection with the $1 + jb$ circle. The length of the open-end parallel stub (L_P) that gives a susceptance of $-jb$ can be found on the Smith chart. The design process for the CPW series stubs is similar to the above.

Let's assume the first frequency band of the required antenna is 2.4 GHz and it is desirable to be matched in 5.5 GHz. The monopole antenna with such properties is illustrated in Fig. 4 (a). As can be seen, the antenna in 5.5 GHz poorly matched and it is required to a matching network. Now the input impedance of the antenna in the 5.5 GHz can be normalized and plotted on the Smith chart.

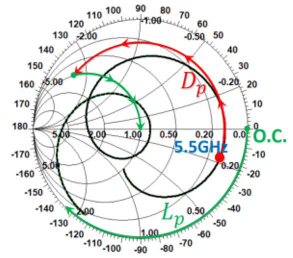
Because the SMA connector modeled when simulating the antenna, the input impedance computed in the place of the SMA input as a wave port. Thus, the de-embedding result (removing the influence of the SMA connector) leads to 5.5 GHz point on the Smith chart rotate counterclockwise (CCW). The rotated 5.5 GHz point plotted on the Smith chart as illustrated in Fig. 4 (b).

First parallel CPW stubs case is explained. The rotation along a constant radius SWR circle chosen CCW to embed the matching network into the antenna board. This brings the solution to a point on the $1 + jb$ circle. Here, due to limited space available in antenna board, just the first intersection point which leads to the shortest distance (D_P) considered. The D_P calculated from the wavelengths toward load (WTL) scale. In this desired antenna, the normalized admittance at the intersection point is $1 + jb$ ($b < 0$) as illustrated in Fig. 4 (b). Thus, the solution requires a parallel stub with a susceptance of $-jb$. The length of the open-end parallel CPW stub (L_P) that lead to a susceptance of $-jb$ can be found through starting at

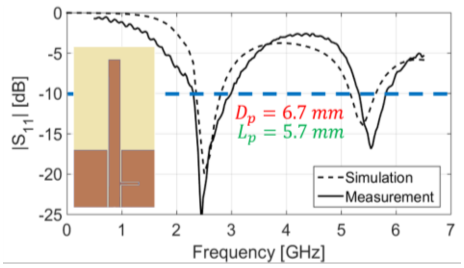
$y = 0$ (open circuit), and moving along the outer edge of the Smith chart ($|\Gamma| = 1$) toward the generator to the $-jb$ point. So, the both of D_P and L_P have been achieved and the design of matching network completed. The printed circuit board and the radiation patterns of parallel stub solution illustrated in Fig. 5.



(a)



(b)



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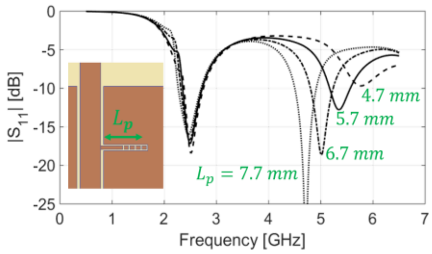
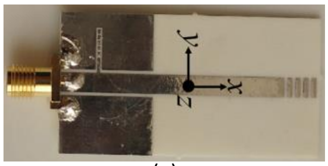
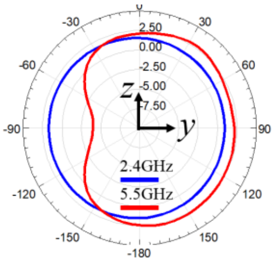


(d)

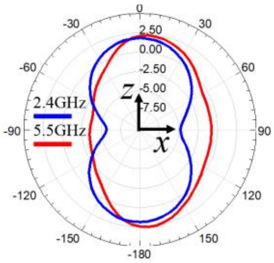
Fig. 4: The open-end CPW parallel stub design process and results for 5.5 GHz. (a) Simulation and measurement of primary 2.4 GHz CPW-fed monopole antenna. (b) The Smith chart graphical solution to find D_p and L_p for the open-end CPW parallel stub. (c) Simulation and measurement of parallel stub solution in CPW transmission line for impedance matching in 5.5 GHz. (d). The effect of different values of stub length (L_p) on the second band to have reconfigurable antenna.

For the series CPW stub case, a same matching problem assumed (both Fig. 4 (a) and Fig. 6 (a) are the same). In this case the impedance Smith chart could be used (see Fig. 6 (b)).


(a)

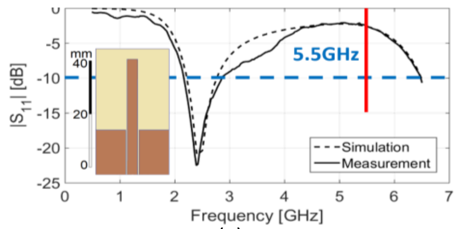


(b)

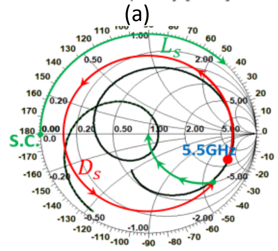


(c)

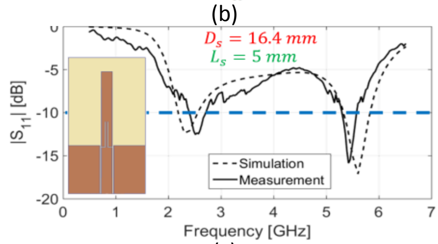
Fig. 5: Printed circuit board (Ro4003 ε_r=3.55, thickness=0.8mm), (a) and simulated radiation patterns of parallel stub solution for impedance matching in 2.4 GHz and 5.5 GHz, (b) *yz* (c) *xz* plane. ($h_1 = 30mm, w_1 = 3.5mm, g_1 = 0.5mm$)



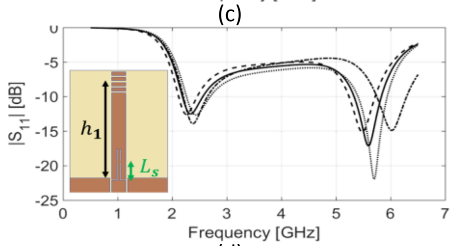
(a)



(b)



(c)



(d)

Fig. 6: The short-end CPW series stub design process and results for 5.5 GHz. (a) Simulation and measurement of primary 2.4 GHz CPW-fed monopole antenna. (b) The Smith chart graphical solution to find D_p and L_p for the short-end CPW series stub. (c) Simulation and measurement of series stub solution in CPW transmission line for impedance matching in 5.5 GHz. (d) The effect of different values of stub length (L_s) and monopole antenna length (h_1) on the second band to have reconfigurable antenna.

Again, the rotation along a constant radius SWR circle chosen CCW and this leads to intersection with a point on the $1 + jx$ circle. In our example, the first intersection point leads to a small length for D_S (see Fig. 3 (c)) and the assembly of the SMA connector is difficult. Thus, the rotation continues along a constant radius SWR circle to intersect with second point on the $1 + jx$ circle (see Fig. 6 (b)). In this desired antenna, the normalized impedance at the intersection point is $1 + jx$ $(x < 0)$ as illustrated in Fig. 6 (b). Thus, the solution requires a series stub with a reactance of $-jx$. The length of the short-end series CPW stub (L_S) that lead to a reactance of $-jx$ can be found through starting at $z = 0$ (short circuit), and moving along the outer edge of the Smith chart ($|\Gamma| = 1$) toward the generator to the $-jx$ point. So, the both of D_S and L_S have been achieved and the design of matching network with series CPW stub completed.

In the next section, this method implemented and the simulation and measurement result presented.

Result and Discussions of Reconfigurable Multiband Monopole Antenna

This section illustrates that the implementation of matching stubs in the CPW line with the proposed method can be used for design of a multiband and reconfigurable antenna. Here are a few examples to explain the challenges and to compare the both series and parallel methods.

In the first case, assume the frequency band of the required antenna is 2.4 GHz and it is desirable to be matched in 5.5 GHz (see Fig. 4 (a)). The usage of the Smith chart as a graphical tool for matching the antenna illustrated in Fig. 4 (b). The designed D_P and L_P dimensions as the parallel stub position and length are 6.7 mm and 5.7 mm respectively. The results of the simulation and measurement of the designed antenna have been shown in Fig. 4 (c) and as can be seen, there is a good agreement between them. Thus, the validation of the method described in the previous section approved. Due to manufacturing constraints, the parallel stub position cannot be changed, so the D_P has a fixed value. But the parallel stub length (L_P) can be changed. The effect of L_P variation on the input impedance matching of the antenna illustrated in Fig. 4 (d). The variable L_P implemented here by connecting of the pads through the copper ribbon. As can be seen in Fig. 4 (d), by adjusting the L_P value the second band of the antenna tuned as a reconfigurable antenna. The advantage of this implementation is that the first frequency band remains unchanged and the two frequency bands are independent (see Fig. 4 (d)). It is evident that the first frequency band is dependent on monopole length. The printed circuit board and the radiation patterns of parallel stub solution illustrated in Fig. 5.

For the series CPW stub case, again assume the frequency band of the required antenna is 2.4 GHz and it is desirable to be matched in 5.5 GHz (see Fig. 6 (a)). By using the Smith chart (see Fig. 6 (b)), the D_S and L_S dimensions as the series stub position and length, attain 16.4 mm and 5 mm respectively. Since the D_S has a fixed value, only the series stub length (L_S) can be changed by shortening the stub in appropriate length. Unlike the parallel stub, the first and second frequency band for series stub are not independent. Thus, to freeze the first frequency band, both of L_S and h_1 need to be tuned and it is a difficult task (see Fig. 6 (c)). The printed circuit board of series stub solution and the radiation patterns illustrated in Fig. 7.

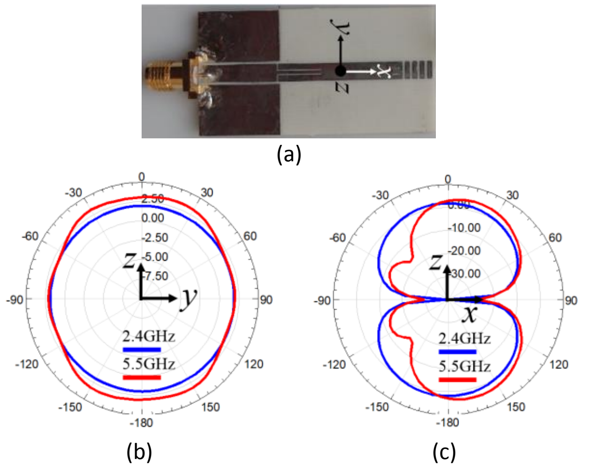


Fig. 7: Printed circuit board (a) and simulated radiation patterns of series stub solution for impedance matching in 2.4 GHz and 5.5 GHz, (b) *yz* (c) *xz* plane. $(h_1 = 18mm, w_1 = 3.5mm, g_1 = 0.5mm)$

To investigate the effect of the difference between the upper and lower frequency bands on the success of the proposed method, let's consider another problem and assume the frequency band of the required antenna is 3.5 GHz and it is desirable to be matched in 5.5 GHz. In this case, the low pass properties of the matching network are more important to have no adverse effect on the first band of the antenna (see Fig. 8). The matching stubs for both series and parallel cases designed with the help of the Smith chart (see Fig. 8. (b) and (c)). The designed $D_P(D_S)$ and $L_P(L_S)$ dimensions as the parallel (series) stub position and length are 3 (12) mm and 5.5 (3.7) mm respectively.

For parallel stub, in addition to the 5.5 GHz, another frequency band around 2.4 GHz has been matched by chance (see Fig. 9 (a)). But the authors check and found that the additional matched band is not due to the parasitic effect and the parallel stub length and position are also suitable for matching in 2.4 GHz. In the series stub case, the 3.5 GHz and 5.5 GHz bands are near to each other and merged. On the other hand, a wideband antenna instead of multiband antenna has been achieved (see Fig. 9 (b)). The printed circuit board of parallel and series stub solution in CPW-fed monopole antenna for impedance matching in 5.5 GHz illustrated in Fig. 9.

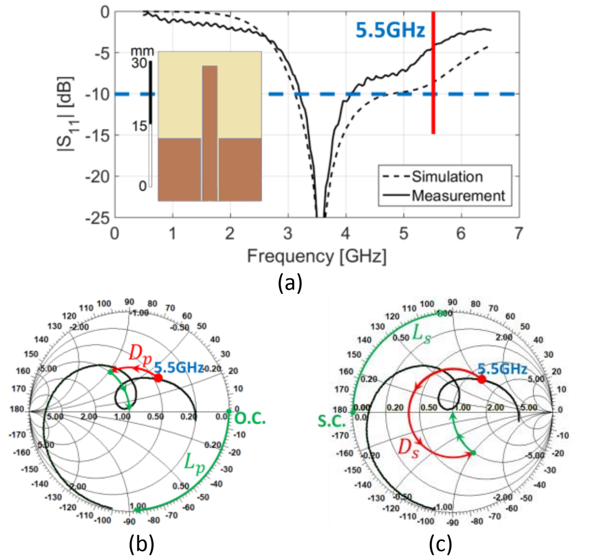


Fig. 8: (a) Simulation and measurement of antenna for 3.5 GHz and it is desirable to be matched in 5.5 GHz, (b), (c) The matching stubs for both series and parallel cases designed with the help of the Smith chart.

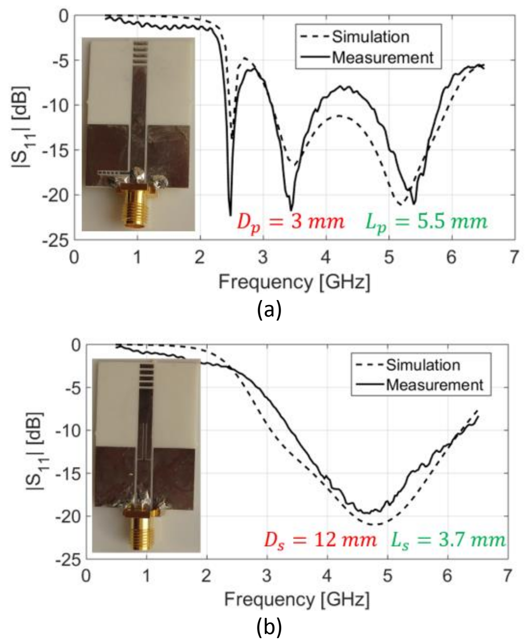


Fig. 9: Simulation and measurement of (a) parallel stub solution, (b) series stub solution.

Since, this work is about the antenna design method, a comparison has been made with previous works in this field, which illustrated in Table 1.

Table 1: Comparison with other works

Ref	Antenna Shape	Design Approach	Bandwidth	Reconfigurable
[1]	Two monopoles with different lengths	Tuning the antenna parameters	Dual-Band	NA
[2]	Two stacked T-shaped monopoles of different sizes	Adjusting the antenna parameters	Dual-Band	NA
[3]	G-shaped profile	The antenna dimensions are optimized	Dual-Band	NA
[4]	Shorted parasitic inverted-L	Parametric studies	Triple-Band	NA
[5]	Embedding appropriate slits into the 50 Ω CPW feeding line	Particle swarm optimization approach	Multiband	NA
[6]	Modified T-shaped antenna	Parametric studies	Dual-Band	NA
[7]	n-shaped slot	Adjusting the lengths of the element and slot	Dual-Band	NA
[8]	Two inverted-L slots	Adjusting the lengths of the element and slot	Triple-Band	NA
This work	Parallel and series stubs	Serial and parallel stubs Using Smith chart	Dual-Band Triple-Band Wide-Band	Yes

The design methods in previous works are based on changing the antenna parameters to reach the desired solution, and the ability to change the frequency by changing the dimensions is limited. Therefore, the design method is more complicated and the reconfigurable capability of the antenna is reduced.

Also, in some previous works, the size of the antenna increases due to the change in the shape of the antenna which in some cases leads to a decrease in the omnidirectionality of the antennas. The method presented in this work allows the implementation of dual-band, triple-band and wide-band antennas without changing the shape of the antenna and with a simple design method.

Conclusion

Compared to the microstrip line, the CPW feeding of the monopole antenna has the advantage that both parallel and series stubs can be implemented for the matching of the antenna. In this case, the required space for these stubs placed inside the antenna and no extra space needed. So, the printed size of the proposed antenna does not change. The impedance matching method for the integrated stubs with the antenna has been proposed. The concept of high-pass and low-pass properties of each matching network considered and the authors showed that this method can be successfully used for designing of multiband, reconfigurable CPW-fed monopole antenna.

Author Contributions

M. Zahiry carried out the simulation, S. M. Hashemi has presented the idea of the research and J. Ghalibafan contributed to the analysis of results and implementation. All authors contributed to the writing of the article.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Acknowledgment

We appreciate the editorial team and reviewers for their time and constructive feedback.

Abbreviations

CPW	Coplanar Waveguide
SMA	Subminiature Version A
SWR	Spectral Angle Mapper
CCW	Counterclockwise
TL	Transmission Line
FW	Full Wave
WTL	Wavelengths Toward Load

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