Antenna's Profile Miniaturization and Performance Booster Using Metamaterial

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Abstract. Antennas are an integral part of any wireless communication systems and also demanded to be compact in size as it is easy in its fabrication while having a good performance. Some of the antenna have its capability in maintaining the performance but still bulky in size which is not fulfil the current requirements in wireless communication system. Hence, in this project, low profile miniaturization and the performance booster of an antenna using metamaterial is proposed that operates at 2.4 GHz for Wi-Fi application. The proposed antenna is designed with a modified microstrip patch antenna with FR-4 substrate of 1.6 mm thickness having size of 37.02 mm × 26.00 mm from the rectangular microstrip patch antenna. After that, the antenna is integrated with the metamaterial of artificial magnetic conductor (AMC) which having the size of 49.89 mm×49.89 mm. Then, the performance of the antenna is analysed and evaluated in terms of area of patch antenna, reflection coefficient, frequency bandwidth and directivity in comparison with and without integration of metamaterial. The antenna is designed and simulated by using Electromagnetic (EM) wave simulator software and further improved to ensure the antenna can operate at 2.4 GHz with implementation of metamaterial. Throughout the simulation, it is found that the area of patch antenna has decreased by 62.12% from 1085.26 mm^2 to 411.25 mm^2. Also, the proposed antenna offers high reflection coefficient by 46.38% from -17.29 dB to -25.31 dB whereas frequency bandwidth increased from 28 MHz to 69 MHz by 146.43% of increment. The directivity is improved by 19.48% whereas other performance such as impedance matching, gain and efficiency is reduced by 5.91%, 35.24% and 45.89% respectively. Therefore, the proposed antenna is suitable for Wi-Fi applications at 2.4 GHz.

1. Introduction

In the modern wireless communication system, the requirements of miniaturized electronic devices become necessary in which it has been developed rapidly. Thus, the demand for compact, small size and low-profile antennas is increasing with the rapid development of modern wireless communication systems (Fatima et al., 2021). Even though the antenna can operate in a certain range of frequency, the size of the antenna is bulky especially for the lower operating frequency hence, it shows the low performance (Moinuddin & Sudhir, 2017). The performance of an antenna is involved in its frequency bandwidth, reflection coefficient and so on. Some of the designed antennas that are bulky in size may have capability in maintaining its performance. But still it could not satisfy those requirements in terms of its size especially if it is used in wireless communication systems. Moreover, as electronic devices are getting smaller in size, the demand for a reduction in antenna size is high (Varindra, 2017) but the side effect arising out of the miniaturization brings in some reduction in its performance especially in frequency bandwidth (Wojciech & Thanh, 2018).

Therefore, metamaterial plays an important role in designing highly integrated miniaturized antennas as they have sub-wavelength constituent elements that make the structure behave as a medium with its negative permittivity and permeability that have negative values which do not exist in nature (Singh et al., 2018). An application of metamaterial to antenna lead to the design of compact and low-profile antenna systems in which it can be used as the antenna environment and as part of antenna structure that can improve antenna performance (Wojciech & Thanh, 2018).

In this project, a microstrip patch antenna takes parts to construct an antenna for radiation elements due to its small size and weight, low cost, positive performance and it is simple to design and fabricate (Norhana et al., 2018). The aim of this project is to miniaturize the size and boost the performance of the antenna. Thus, such objective can be achieved by designing the antenna that can operate for Wi-Fi application, develop a metamaterial at 2.4 GHz and evaluate the performance of the antenna integrated with and without metamaterial.

2. Literature Review

2.1. Antenna Design Integrated with Metamaterial

Various techniques or methods are proposed in designing an antenna with implementation of metamaterial as a high quality of antenna required in the rapid development of communication industry. There are five types of metamaterial which are artificial dielectric, Frequency Selective Surface (FSS), Electromagnetic Band-Gap (EBG), Artificial Magnetic Conductor (AMC) and Negative Refractive Index (NRI) (Albert, 2020). Most of the techniques focus on some particular aspect, for instance in reduction of size antennas while maintaining higher radiation efficiency. Rectangular microstrip patch antenna with rectangular slot and slotted meanderline structure in the ground plane has been studied in the improvement of antenna performance and its miniaturization. The designed antenna in the project is operated as an ultra-wide band (UWB) within the range of 5.24 GHz to 6.18 GHz in which both of the WLAN and UWB signals are operating. Metamaterial properties have been implemented on the ground plane as the slot and slotted meanderline structure are introduced to ensure there is no interference of WLAN with UWB signal occur. Also, it offers 90% of efficiency at 4.9 GHz while 67% at 5.6 GHz compared to the efficiency of antenna without metamaterial which is 27.9% at 5.6 GHz. Figure 1 and Figure 2 shows the structure of the designed antenna without and with meanderline respectively (Moinuddin & Sudhir, 2017).

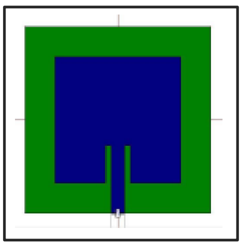

Figure 1. Top View of Proposed Antenna without Meanderline

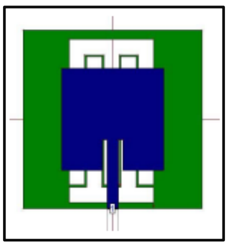

Figure 2. Top View of Proposed Antenna with Meanderline

Another related work of a technique of single band microstrip patch antenna at operating frequency of 2.4 GHz that is implemented left-handed double negative (DNG) metamaterial has been proposed as in Figure 3 (Samir & Mohd, 2018). The unit cell of left-handed metamaterial plane is the combination of split-ring resonator, square electric ring resonator and rectangular electrical coupled resonator that enables metamaterial exhibits both of negative permeability and permittivity which leads to the antenna miniaturization, increment in its gain and efficiency (Mohamed, 2021). A gap of 15 mm is applied on the top of antenna with the selected metamaterial of unit cells in observing its effect on reflection coefficient that leads to the enhancement of antenna performances.

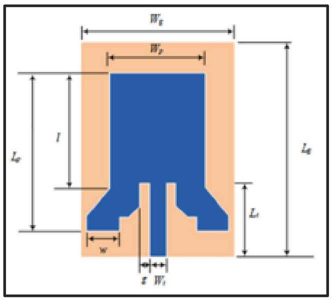

Figure 3. Geometry of Patch Antenna Design**.**

3. Methodology

3.1 Antenna Modelling with Integration of Metamaterial

In designing the antenna, its dimension is calculated by using microstrip patch antenna formula based on its specification that operates at 2.4 GHz having dielectric constant (ε_r) of 4.7 and height substrate of 1.6 mm. All the parameters of the antenna are used in the EM wave software and an improvement process is needed so that the designed antenna satisfies the targeted objectives. For the metamaterial, an artificial magnetic conductor (AMC) is selected before integration with the designed antenna which having the size of a unit cell is λ/8 of operating wavelength having size of 49.89 mm×49.89 mm. This is due to the minimum size of metamaterial which is (3×3) of unit cells (Wojciech & Thanh, 2018). Also, the bandwidth of the AMC is generally defined as +90° to -90° at the central frequency that can function as a new type of plane for low-profile antennas.

The design of the antenna with metamaterial is illustrated as in Figure 4 and Figure 5 in which it is based on the layering technique. The AMC plane is placed at the center of the design which separates both of the substrates whereas the radiating patch is placed at the top of the design as in Figure 5. The top view of antenna is shown in Figure 4 in which the area of patch antenna is reduced from $1085.26\,\text{mm}^2$ to $411.24\,\text{mm}^2$. This is due to the improvement process in which the dimension of the patch antenna has been adjusted so that it can be operated at 2.4 GHz. Moreover, the improvement process only involved the radiating patch because the dimension of AMC is already compatible with the dimension of substrates' antenna which is 49.89 mm×49.89 mm.

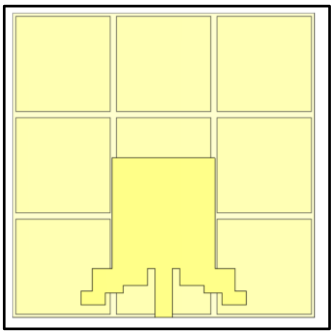

Figure 4. Top View of Modified Antenna with AMC

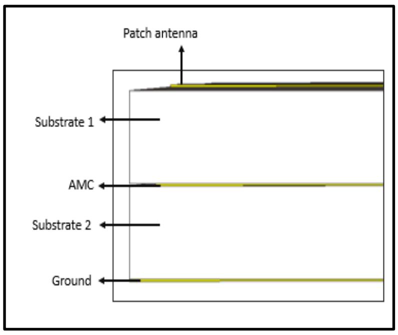

Figure 5. Side View of Modified Antenna with AMC

4. Result and Discussion

4.1 Comparative Analysis of Antenna Design

The comparative analysis of rectangular microstrip patch antenna and modification of antenna design is evaluated in terms of its area of patch antenna and its performance as tabulated in Table 1. The Figure 6 and Figure 7 shows the S-parameter of rectangular microstrip patch antenna and S-parameters of microstrip patch antenna with additional area of radiating patch.

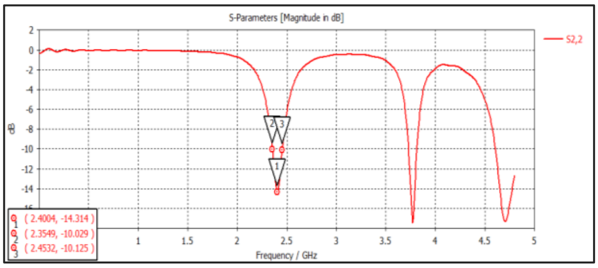

Figure 6. S-parameter of Rectangular Microstrip Patch Antenna

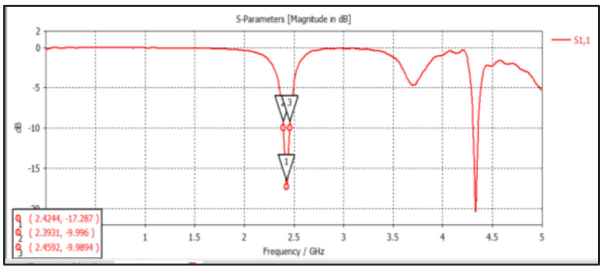

Figure 7. S-parameter of Modified Microstrip Patch Antenna

Table 1. Simulated Results of Rectangular Microstrip Patch Antenna and Modified Microstrip Patch Antenna.

Performance of Antenna	Rectangular Microstrip Patch Antenna	Modified Microstrip Patch Antenna
Area of the patch antenna (mm^2)	1098.62	1085.26
Frequency bandwidth (GHz)	0.041	0.028
Reflection coefficient (dB)	-14.314	-17.287
Impedance matching (Ω)	54.819	50.731
Gain (dB)	2.546	4.373
Efficiency (%)	54.04	80.94
Directivity (dB)	5.219	5.292

From the Table 1, the reflection coefficient in the modified antenna shows higher value than the rectangular antenna. This indicates that the modified antenna is much better as result in the negative return loss which has lesser reflection in the antenna. The loss is minimized as the impedance is properly matched that is almost to 50 Ω and placed in a correct position to increase the antenna performance. Thus, there is less mismatch impedance occurred in the modified antenna compared with the rectangular microstrip patch antenna.

Furthermore, as the area of patch antenna is reduced with the difference of 13.36 mm^2, it gives an impact towards the directivity, gain and efficiency of the antenna. The efficiency 80.94% is obtained in a modified antenna much higher than the other one which is 54.04%. Comparing the gain achieved in these two antennas, the rectangular microstrip patch antenna has demonstrated 2.546 dB of lower gain difference from modified antennas which demonstrate 4.373 dB. The increment of gain in the antenna will have an increment in its directivity and efficiency in which the gain is the product of the antenna efficiency and its directivity (Olav et al., 2017).

In other words, the gain of the antenna is directly proportional to its efficiency and directivity of the antenna. It can be seen as the directivity modified antenna is higher compared to the rectangular microstrip patch antenna. A higher directivity implies that the channel of the antenna will travel further indicate high performance of antenna. Having higher gain antenna have benefits of longer range and better quality of signal to ensure better transmission of electromagnetic waves. However, the frequency bandwidth of the modified antenna showed 0.028 GHz which is lower than others patch antenna. In order to enhance bandwidth, again the improvement of the antenna should be done. Therefore, future improvement in this design is needed so that the antenna can have better performance but still it is workable at 2.4 GHz. Implementation of metamaterial in this project will be used to miniaturise and improve performance of the antenna.

4.2 Simulation and Improvement of Metamaterial at 2.4 GHz

The design of metamaterial gives 49.89 mm × 49.89 mm dimensions in which the AMC is selected to be implemented with the antenna design. As AMC mimics the PMC, it has the ability to provide zero-degree reflection phases at its resonant frequency which is 2.4 GHz as in Figure 8. The reflection phase here means the phase of the reflected electric field which is normalised to the phase of the incident electric field at the reflecting surface. Zero-degree reflection phase can be called in-phase that is due to the very high impedance within a specific limit of frequency range. The properties of AMC can be observed by its bandwidth and in most cases of AMC, the useful bandwidth is defined as +90° to -90° degree as illustrated in the Figure 8. Because of this unusual boundary condition, an AMC surface can function as a new type of plane for low-profile antennas, in contrast to the conventional metal plane. Thus, the bandwidth of the AMC gives 0.712 dB as both upper and lower frequency shows 2.981 dB and 1.268 dB respectively. The 0.712 dB can be considered as low frequency bandwidth which leads to the narrow in-phase reflection bandwidth.

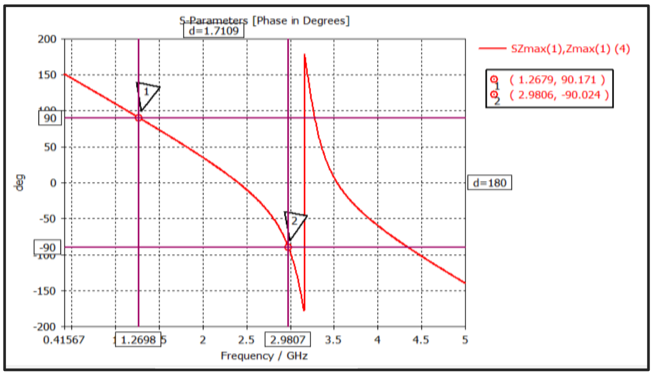

Figure 8. Bandwitdth of Metamaterial

4.3 Comparative Analysis With and Without Metamaterial

The comparative analysis with and without metamaterial is done after the size of modified antenna is compatible with the size of AMC design which resulting the S-parameter in the Figure 9.

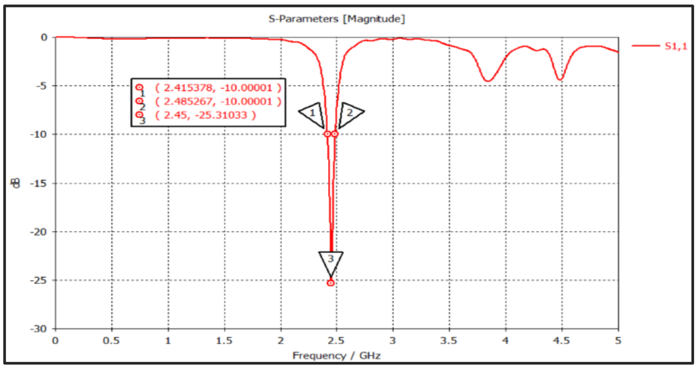

Figure 9. S-parameter of Antenna Design with AMC

Table 2. Comparative Analysis of Antenna Design with and without Metamaterial.

Performance of Antenna	Antenna before Implementation of Metamaterial	Antenna after Implementation of Metamaterial
Area of the patch antenna (mm^2)	1085.26	411.25
Frequency bandwidth (GHz)	0.028	0.069
Reflection coefficient (dB)	-17.29	-25.310
Impedance matching (Ω)	50.731	53.773
Gain (dB)	4.373	2.827
Efficiency (%)	82.63	44.71
Directivity (dB)	5.292	6.323

From Table 2, it can be seen that the area of patch antenna is reduced about 62.12% from 1085.26 mm^2 to 411.25 mm^2 after implementation of AMC. The miniaturisation of the designed antenna in terms of area of the patch is important and most likely influenced by the operating frequency. Technically said, low frequency will have larger patches area compared to the higher frequency. But, since the improvement process has been done with the integration of AMC, the minimum area of patch has been obtained which is shown as the reduction area of the patch antenna.

As the patch of antenna is improved, it does affect the frequency bandwidth and reflection coefficient of the antenna. The frequency bandwidth increased from 28 MHz to 69 MHz which is about 146.43% increment. It means that the radiation of the antenna to properly radiate or receive energy is much better with the implementation of AMC as the range of frequency is higher compared without the AMC. The antenna also offers high reflection coefficient by 46.38% from -17.29 dB to -25.31 dB which is good for an antenna to be operated at 2.4 GHz as long as it below -10 dB.

For the impedance matching, the integration of AMC leads the antenna to have more mismatched impedance compared without the integration of AMC with decrement of 5.91%. This may be caused by the physical path of the feedline as the transmission line which will reduce the quality of the signal affected by the improvement of area patch antenna. The directivity after implementation of AMC has increased from 5.292 dB to 6.323 dB by 19.48%. Other performances such as gain and efficiency, do not show a great significance before and after implementation of AMC as this project does not focus much on these performances. Both of the gain and efficiency shows decrement of 35.24% and 45.89% respectively. Therefore, an improvement process will be needed to enhance the performance of the antenna in terms of gain, efficiency and impedance matching.

The implementation of AMC also has suppressed the harmonic signal as shown in Figure 9. The harmonic is suppressed above -10 dB compared to Figure 7 in which the harmonic is below -10 dB. It can be seen that, the AMC is not cover within the suppression at the bandwidth of 4 GHz above, but still it acts as a filter. Therefore, all energy can be focused only to one frequency which is at 2.4 GHz and the bandwidth does not cover at 4 GHz above with integration of AMC, hence the antenna can have better radiation whether transmitting or receiving the antenna signal.

5. Conclusion

5.1 Conclusion

From this project, it concludes that the techniques in miniaturising and improving the antenna is important to ensure the antenna can be operated at a certain frequency and implemented in any application. Throughout the design and improvement process, it is found that some of the parameter antenna performance shows improvement like the reflection coefficient increased by 46.38% whereas frequency bandwidth and directivity increased by 146.43% and 19.48% respectively with the reduction area of patch antenna about 62.12% with the implementation of AMC. Other performance such as impedance matching, gain and efficiency has reduced by 5.91%, 35.24% and 45.89% respectively as the size of patch is reduced affecting those performance.

Besides that, it is realised the first objective of this project which is to design the antenna that can operate for Wi-Fi application is achieved. The antenna is designed based on rectangular microstrip patch antenna and further improved with some additional area of radiating patch which gives modified antenna design. After that, the second design involved with metamaterial as AMC has been selected as a part configuration of antenna which is the most relevant and easy to be implement with microstrip patch antenna. It gives high surface impedance to be operate at 2.4 GHz. To fulfil the third objective, the design of AMC is integrated with the modified antenna and further improved its performance to be operate at 2.4 GHz. The size of patch antenna is reduced to the small area of radiating patch in which the reflection coefficient, frequency bandwidth and directivity has increased whereas the impedance matching, gain and efficiency does not show great improvement. Therefore, the proposed antenna designed in this project has a small dimension affecting reflection coefficient, frequency bandwidth and directivity that having harmonic suppression which operates at 2.4 GHz.

5.2 Recommendations

For future work based on this project, the improvement of the antenna design can be made by using different shapes of patch, techniques used for feedline and different types of patch. Thus, the performance of an antenna can be improved inclusive of its gain, directivity, frequency bandwidth and so on. Furthermore, as a lot of researchers used microstrip patch antenna in designing antenna, other types such as aperture antenna and array antenna can be used due to their ease of construction and versatility considering its advantages and disadvantages. In implementation metamaterial towards the antenna, it can be applied in any form depends on the type of metamaterial. This is due to the properties each of the metamaterial whether focuses on the miniaturization or boost its performance. Application of metamaterial with antenna can be applied as a superstrate or layering with more types of metamaterial. As other performance of the antenna does not show great significance in its improvement before and after integration of AMC, future work will be needed by having improvement process or alteration towards the design, hence the antenna can work efficiently at the desired frequency.

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