Metamaterial-Based Miniaturized DGS Antenna for wireless Applications

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Abstract. In this article, metamaterial based miniaturized DGS (Defective Ground Structure) antenna is presented. Initially conventional antenna is designed for 2.4 GHz and by using DGS method, the same conventional antenna size is reduced upto 50% of initial design. But antenna gain down due to DGS in antenna structure. By using metamaterial as a reflector, the antenna gain can be enhanced. The antenna and metamaterial are designed on Rogers RT5880 and Teflon Ceramic TF-1/2 (\(\varepsilon_r = 10.2, \tan\delta = 0.001\)) respectively. All simulation results are carried out by using EM simulator CST software and for the operating frequency of 2.415 GHz a gain of 6.28dB is observed.

Keywords: DGS, Miniaturized antenna, Metamaterial, and Wireless applications

1. Introduction

Nowadays in RFID tags, communication systems and radiating systems for radar and automotive applications integrated miniaturized antennas becomes relevant need. Since last decades efforts are being made to design low power RF components and miniaturized microstrip antennas which are not available readily without changing its features and size. Integration of radiating element like microstrip antenna along with remaining circuit on printed chip becomes the main challenge for the designer. In literature many researchers have used many techniques to reduce the size of antenna. For squeezing the dimension of the antenna, lumped elements, shorting post and suitable slots are used as a reactive load with patch of antenna. However, these techniques are not sufficient to provide the drastic and required reduction in dimension of the patch antenna used for various applications. Another method used to squeeze the dimension of patch is used by applying the dielectric substrate of high permittivity. But performance parameters like gain, efficiency bandwidth and shape of radiation pattern deteriorated due to increase in surface wave excitation between patch and substrate of antenna. The standard techniques available were not sufficient to provide the required miniaturized antenna. At this stage some other artificial materials like metamaterial seems to be much effective for reduction of dimension of antenna without affecting the other performance parameters [1-3].

Metamaterials have been discovered to exhibit some unique qualities not seen in natural materials. These artificial materials can be formed by arranging the periodic structure of metallic strip and rings at regular interval. First metamaterial concept was published by Victor Veselago a Russian physicist in 1968. Later on after thirty years, Sir John Pendry also presented that the geometry of conductor arranging in regular interval can produce the negative permeability and negative permittivity, which was also a another type of metamaterial. The negative permeability and permittivity of material can
be used to design electrical small antenna by miniaturizing the antenna. Further by increasing the gain and directivity high directive antenna can be designed for various applications. Range of antenna array and beam scanning can be increased by using metamaterial to support communication link, navigation systems, surveillance sensor and command control systems [4-6].

Due to wide range of applications one of the most suitable techniques used for electromagnetic shielding and miniaturization of antenna is frequency selective surfaces (FSSs). An artificial substance called electromagnetic band gap (EBG) is utilised to provide the electromagnetic shielding required to minimise the specific absorption rate (SAR). FSS and EBG acts as bandpass or bandstop structure depending on the periodic structure at the required frequency [7-9]. EBG is also used to eliminate mutual coupling between antennas and increase microstrip patch antenna impedance matching and efficiency. A metamaterial loaded microstrip patch antenna reduces the resonance frequency by exciting the negative order resonance and reduces the actual size of antenna at the designed frequency. Reactive impedance surface (RIS) or artificial magnetic surface (AMS) is also another type of metamaterial which is also reported as effective technique used for antenna miniaturization by various researcher. There are various types of meta-surfaces available like periodic metallic patch and mushroom-like high-impedance surface etc [10]. Complementary split ring resonators (CSSRs) are also employed for miniaturisation and design of multiband antennas because of their ability to provide a quasi-static frequency that is much smaller than the guided wavelength [11].

Due to availability of unused bandwidth the interest is increasing towards the millimetre wave spectrum to meet the requirement of lower latency, high throughput and wider bandwidth for future wireless communication [12-14]. In this paper we have presented a metamaterial based antenna for wireless application. Initially a rectangular patch antenna is designed and simulated at 2.4 GHz. Then same antenna is miniaturized using DGS miniaturization technique and again simulated. By miniaturization technique the size of antenna is reduced approximately 50% of actual size of antenna at the same frequency. For the miniaturized antenna size has been reduced but gain has been decreased at the designed frequency. Further a FSS based (frequency selective surface) metamaterial has been used to improve the gain and other performance parameters.

2. Antenna Design

A microstrip patch antenna with dielectric constant \( \varepsilon_r = 2.2 \) and tangent loss 0.00009 is designed on Rogers RT5880 dielectric material. The height of substrate is 0.787 mm and length and width of the patch are calculated using the transmission line model.

Step 1: The width of the patch (W) is calculated as follows: The patch's width is determined by

\[
W = \frac{c}{f_r} \sqrt{\frac{2}{\varepsilon_{r+1}}}
\]  

(1)

Where, \( c \) denotes the speed of light in free space. For the current design, \( f_r \) stands for resonance frequency, which is 2.4 GHz. The substrate is 0.787 mm thick and has a relative permittivity of 2.2. The permittivity changes due to the presence of air between the patch and the dielectric, and this is known as effective permittivity (\( \varepsilon_{reff} \)) and is given by

\[
\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2} \left[ 1 + \frac{h}{w} \right]^{-\frac{1}{2}}
\]  

(2)

Where, \( h \) denotes the substrate's height or thickness.
Step 3: The length extension $\Delta L$, which is given by

$$\frac{\Delta L}{h} = 0.412 \left( \frac{\varepsilon_{\text{reff}} + 0.3}{\varepsilon_{\text{reff}} - 0.258} \right)^{\left( \frac{W}{h} + 0.8 \right)}$$

(3)

Step 4: The length of the patch must now be calculated.

$$L = \frac{c}{2\sqrt{\varepsilon_{\text{reff}}} - 2\Delta L}$$

(4)

The extra length on both sides of the patch due to the fringing field is $\Delta L$.

$$L_{\text{eff}} = L + 2\Delta L$$

(5)

$L_{\text{eff}}$ is the patch's overall length, including the length caused by the fringing effect.

2.1 Conventional microstrip patch antenna

The dimensions of conventional patch antenna using transmission line theory are calculated and shown in Table 1.

| Table 1. Antenna parameters | Table 2. Metamaterial parameters |
|-----------------------------|----------------------------------|
|                             | Conventional Antenna(mm) | Miniaturized Antenna(mm) | Parameters | Value (mm) |
| $W=L$                      | 80                           | 40                        | $W_s=L_s$  | 12         |
| $W_p=L_p$                  | 42                           | 20                        | $L_2$      | 3.90       |
| $L_f$                      | 14.50                        | 7.50                      | $L_3$      | 2.50       |
| $W_f$                      | 0.50                         | 0.50                      | $L_4$      | 3          |
| $L_1$                      | ------                       | 26.60                     | $W$        | 14.50      |
| $W_1$                      | ------                       | 0.80                      | $W_p$      | 42         |

A square substrate of 80 mm$^2$ and a patch of 42 mm$^2$ are taken at the designed frequency of 2.4 GHz. The Roger RT5880 of thickness 0.787 mm is used as a substrate. Figure 1 depicts the geometry of a constructed conventional antenna.

Figure 1. Conventional antenna at 2.4 GHz
2.2 DGS Miniaturized antenna

At low frequencies, it is always necessary to integrate and reduce the antenna size. At lower frequency antenna size become very high. As a result, numerous strategies are utilised to minimise the antenna at low frequencies. At the 2.4 GHz frequency, DGS (defective ground surface) is one of the most effective strategies for reducing antenna size. The concept behind DGS technique is increasing the current path, so that electrical length is increased and frequency down to shift in lower side. The slot $L_1 \times W_1$ is responsible to reduce antenna size by increasing electrical length of antenna, which is shown in fig.2. In DGS miniaturized antenna effective size of antenna has been reduced to 50% of its actual size at the same frequency.

![Figure 2. DGS Miniaturized antenna](image)

2.3 DGS Miniaturized antenna loaded with metamaterial

Metamaterial does not exists in natural form, but they are created by arranging the metal strips, rings or rods in a regular intervals as shown in figure 3. In this figure an array of 4x4 metallic rings are arranged. The array of rings behaves as metamaterial and provides a band gap of frequency at which it provides high impedance. The dimensions of metamaterial are shown in table 2.

![Figure 3. a) Metamaterial unit cell, b) Metamaterial array c) Antenna loaded with metamaterial](image)
3 Result Analyses

The designed antenna is simulated using CST software. The operating frequency of a conventional antenna is 2.4 GHz, and the return loss is -21.36 dB, as shown in figure 4, and the corresponding radiation pattern is shown in figure 5, with 5.62 dB gain at the same resonating frequency and a maximum radiation direction of 2 degrees with an angular beam-width (3 dB) of 84.4 degrees. So antenna is able to radiate and intercept the energy from the desired direction.

Figure 4. S11 Conventional antenna at 2.4 GHz

Figure 5. Gain Conventional antenna at 2.4 GHz

Figure 6 shows the return loss of DGS miniaturized antenna at 2.4 GHz, in this plot return loss is -33.988 dB, which is improved as compared to conventional antenna at same resonating frequency. But gain of the DGS antenna is reduce from 5.62 dB to 3.48 dB due to increasing the surface current at DGS slot and also increasing back side radiation shown in figure 7. To increase gain of DGS antenna, a reflector is required below the DGS antenna, which can improve gain by reflecting the back side radiation from DGS antenna and it add with main lobe of radiation pattern. So metamaterial is best option to work as reflector for this DGS antenna.

Figure 8 shows the reflection and transmission coefficient of proposed metamaterial, the forward transmission coefficient S21 and reverse isolation coefficient S12 are exactly same and traces the same curve, further input reflection coefficient S11 is out of phase with S12 and S21 at the designed frequency of 2.4 GHz. So metamaterial is acting as high impedance surface at this frequency and proves the metamaterial behaviour. DGS miniaturized antenna effectively reduced the size of antenna...
but at the same time gain has been also reduced. So another technique used to improve the gain of DGS miniaturized antenna is loaded with the metamaterial. Metamaterial loaded antenna is shown in figure 3 (c).

**Figure 6.** S11 DGS Miniaturized antenna

**Figure 7.** Gain DGS Miniaturized antenna

**Figure 8.** S11 and S21 of metamaterial at 2.4 GHz
Figures 9 and 10 depict the S11 parameter and metamaterial loaded antenna gain, respectively. The metamaterial loaded antenna's gain has been improved, because at this frequency metamaterial is providing high impedance and decreasing the spatial wave and directs all the power in desired direction of maximum radiations. So gain of antenna has been increased to 6.28 dB which is higher than conventional and DGS miniaturized antenna gain. Figure 11 shows radiation efficiency of DGS antenna with and without metamaterial, in which the radiation efficiency of DGS antenna at 2.41 GHz is 92.07 % and for DGS antenna with metamaterial at same frequency is 94.66 %. Figure 12 illustrates the VSWR for both situations and indicates that the antenna is perfectly matched. Figure 13 shows the realised gain for both situations, which is 3.44dB for the DGS antenna and 6.14dB for the DGS antenna with metamaterial at 2.41 GHz. The Surface Currents of a DGS antenna with and without metamaterial are shown in Figure 14.

Figure 9. S11 and S21 of metamaterial at 2.4 GHz

Figure 10. S11 and S21 of metamaterial at 2.4 GHz
Figure 11. Radiation Efficiency of DGS antenna with and without metamaterial

Figure 12. VSWR of DGS antenna with and without metamaterial

Figure 13. Realized Gain of DGS antenna with and without metamaterial

Figure 14. Surface Currents of DGS antenna with and without metamaterial
4 Conclusions

A miniaturized antenna loaded with metamaterial operating at 2.4 GHz is designed and presented in this paper. Initially, a conventional 2.4 GHz antenna is developed by estimating the dimensions using transmission line model theory. The length and width of square patch is 42 mm at the designed frequency. When same antenna is designed using miniaturization technique the length and width has been reduced to 20 mm, which is less than 50% of original one. So using miniaturization technique the actual size of antenna has been reduced upto much extent but at the same time gain of antenna has been decreased at the designed frequency. A metamaterial array of 4x4 has been used to improve the gain of miniaturized antenna. At the desired frequency, Metamaterial has enhanced the antenna gain without increasing the antenna size.

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