DIPOLE SHAPED ARRAY ANTENNA WITH DEFECTED SUBSTRATE STRUCTURE

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ABSTRACT

In recent years, microstrip antenna has been widely used thanks to its some advantages. However, it has some disadvantages such as narrow bandwidth, low gain and low efficiency. In this paper, we propose a novel dipole shaped array antenna model using defected substrate structure (DSS) in order to improve antenna parameters. The array antenna consists of 16 dipole shaped elements in the first substrate and a DSS in the second one. DSS is an etched periodic or non-periodic cascaded configuration defected in substrate. The electrical length of microstrip line can be changed without changing its physical length by adding inductance or capacitance thanks to the use of DSS that creates parasitic capacitors. With the characteristics of DSS, it can improve some planar antenna parameters at the same time. By using DSS in the second substrate for antenna design, not only the bandwidth and efficiency of antenna are improved, but also the gain and directivity of antenna are enhanced. The array antenna is designed for X band application at a central frequency of 10 GHz. The proposed array antenna with DSS is designed, simulated and fabricated on Roger 4350B substrate with thickness of 1.524 mm, $\varepsilon r = 3.48$, $\tan\delta = 0.0037$. The bandwidth percentage of array antenna is over 22% while the gain of the proposed one reaches 12.2 dBi. In addition, the efficiency of the proposed antenna gets around 92%. The simulation results are obtained using CST Microwave Studio software and they are compared to measurement ones to verify the performance of the proposed array antenna.

KEYWORDS: *Array antenna, dipole shaped array antenna, defected substrate structure,*

I. INTRODUCTION

Recently, social demand on wireless communication has been rapidly increasing with many kinds of services. Along with these applications, modern antennas are required with compact size, low profile and light weight while the parameters such as gain, bandwidth, directivity and efficiency must still be enhanced. Microstrip antennas are the best selection for the aforementioned requirements. However, they still have some limitations, among which low gain, narrow bandwidth and low efficiency are of these drawbacks. Therefore, the improvement of antenna parameters is very necessary. Currently, there are several techniques to improve the antenna parameters such as bandwidth [1 - 3], gain [4 - 6], directivity [7 - 9] and efficiency [10 - 12]. However, there is an inverse ratio relationship between the bandwidth and quality factor of antenna [13]. Therefore, it is not easy to improve simultaneously some antenna parameters.

Besides, highly directional antennas are needed to compensate the signal attenuation which is due to high propagation loss caused by atmospheric absorption. This becomes more important in some applications such as satellite communication, radar and so on. Therefore, array antenna is getting more attention from scientists. With advantages such as high directivity, broad bandwidth, and high gain, array antenna is widely applied in both commercial and military applications [14 - 16]. In addition, using array antenna is also one of ways to improve parameters of antenna. Currently, there are many published papers about array antenna [17 - 19]. In [17], although the antenna including 16 x 16 elements is designed at E-band, the percentage of bandwidth and efficiency are only 10.5% and 72.4%, respectively. Similarly, although the antenna is designed at the central frequency of 60 GHz (including 256 elements), the bandwidth percentage is only 15.3% [18]. In another study [19], the antenna is designed at 60 GHz, the gain of antenna is only 9 dBi. It is clear that the parameters of antenna need to be improved.

This paper proposes a novel dipole shaped array antenna using defected substrate structure (DSS) model to improve antenna parameters. Using DSS in the second substrate, not only the gain and efficiency of antenna are improved, but also the bandwidth is also enhanced. In addition, by using multiple substrate, the thickness of substrate is increased and this leads to the fact that the antenna bandwidth is enhanced [20]. The proposed array antenna has high gain (over 12.2 dBi) and efficiency (92%), and large bandwidth (over 22%). The array antenna is designed on Roger 4350B with h = 1.524 mm, $\varepsilon r = 3.48$ and $\tan\delta = 0.0037$. The simulation results are obtained using CST Microwave Studio software and are compared to measurement ones.

The remained part of this paper is organized as follows. The array antenna parameters and its structure are presented in Section II. The simulated and measurement results are shown in Section III. A brief conclusion is given in Section IV.

II. DIPOLE SHAPED ARRAY ANTENNA USING DSS

2.1. Defected Substrate Structure

Currently, there are many methods to improve parameters for antenna such as metamaterial, defected ground structure (DGS) and so on. These methods are implemented based on principle of current re-distribution by changing structure or shape of radiation layer or ground layer. In fact, the structure of microstrip antenna includes three layers: radiation, substrate and ground layer and changing of any layer also significantly affects the parameters of antenna. Therefore, the parameters of substrate is also very important. For the above reason, this paper proposes a new Defected Substrate Structure (DSS) method to improve parameters of antenna. This method is also based on current re-distribution.

As DGS, DSS is an etched periodic or non-periodic cascaded configuration defected in substrate. Using DSS contributes to enhance slow-wave factor for antenna and this leads to antenna miniaturization. To verify this, let consider a normal microstrip line and a microstrip line with DSS as in Fig.1. In here, L is physical length while φ and φ′ are electrical length for normal microstrip and microstrip line with DSS, resectively. Using DSS creates parasitic capacitors while the electrical length of microstrip line can be changed without changing its physical length by adding inductance or capacitance [21]. Therefore, when DSS is used, the electrical length of microstrip line is changed while there is no changing in physical length. Then, we have:

$$\Delta\varphi = phase' - phase \quad (1)$$

in which, *phase′* and *phase* are the phase (degree) of S21 of microstrip line with and without DSS, respectively.

a) b)

Figure 1: The model of normal microstrip line (a) and microstrip line with DSS

Then, the relationship between the electrical (φ - radians) and physical length (L) of microstrip line is given by:

$$\varphi = \frac{2\pi L}{\lambda_g} \quad (2)$$

And the electrical length of a microstrip line with DSS is given by:

$$\varphi' = \frac{2\pi L}{\lambda_g{}'} \quad (3)$$

From (1) – (3), we have:

$$\frac{\Delta\varphi \cdot \pi}{180} = \frac{2\pi L}{\lambda_g{}'} - \frac{2\pi L}{\lambda_g} \quad (4)$$

or:

$$\lambda_g{}' = \frac{2\pi L}{\frac{\Delta\varphi \cdot \pi}{180} + \frac{2\pi L}{\lambda_g}} \quad (5)$$

Besides, the effective permitivity of microstrip line is determined as:

$$\varepsilon_{eff} = \left(\frac{\lambda_0}{\lambda_g}\right)^2 \quad (6)$$

And the effective permitivity of microstrip line with DSS is:

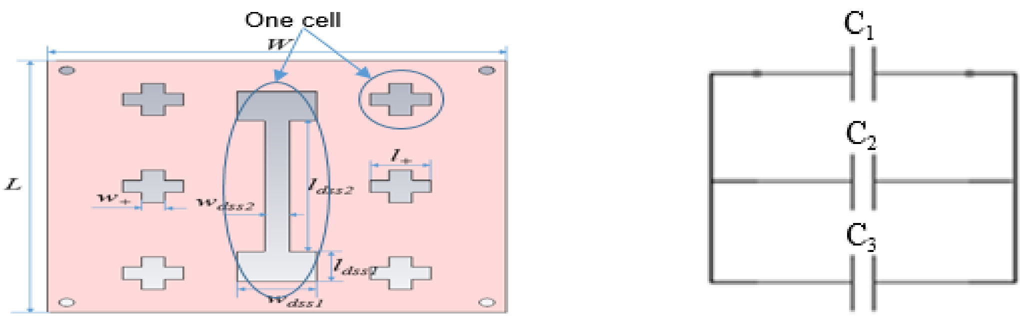
$$\varepsilon_{eff}{}' = \left(\frac{\lambda_0}{\lambda_g{}'}\right)^2 \quad (7)$$

From equations of (5) - (7), we obtain the slow-wave factor of microstrip line with DSS as [22]:

$$SWF = \frac{\lambda_0}{2\pi L} \cdot \left(\frac{\Delta\varphi \cdot \pi}{180} + \frac{2\pi L}{\lambda_g}\right) = \frac{\lambda_0 \Delta\varphi}{360L} + \sqrt{\varepsilon_{eff}} \quad (8)$$

From equation of (8), we can see that the SWF of microstrip line with DSS depends on the phase of microstrip line and the effective permittivity of substrate material. In addition, we also know that one of methods for antenna miniaturization that is slow-wave factor enhancement [23]. Therefore, using DSS also contributes antenna miniaturization. Besides, using DSS helps to creat consecutive cavity resonators and this leads to the fact that the bandwidth is enhanced. We know that the bandwidth of antenna is very narrow if antenna only has one resonant mode [24]. To enhance bandwidth, we can create two or more consecutive resonant modes and this can be implemented by creating consecutive cavity resonators. Moreover, the surface current is also re-distributed when using DSS. Therefore, the gain and directivity can be improved.

Fig. 2 illustrates the proposed model of DSS and its equivalent circuit. In here, the size of substrate is 120 x 125 mm and the DSS is used for a second substrate layer of antenna. The DSS includes six of plus and one cell of "I". The distance between cells "+" is approximately 32.5 mm while the distance from cell centre of plus and cell centre of "I" is roughly 43 mm.



a) b)

Figure 2: The model of DSS (a) and the equivalent circuit for one cell of DSS (b)

The parasitic capacitors are created when DSS is used. Then, the value of the capacitor can be calculated by:

$$C_i = \frac{\varepsilon_r S}{9 \times 10^9 4\pi d} \tag{9}$$

In which, d is the distance between two conducting plates; S is the area of conducting plate; εr is the dielectric constant between two conducting plates. Due the dielectric between two conducting plates of capacitor being a vacuum, so the dielectric constant is 1. In this case, the capacitors are shunt, so the total capacitor is determined as:

$$C_{total} = \sum_{i=1}^{n} C_i \tag{10}$$

Hence, the resonant frequency of antenna is given by:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{11}$$

It is clear that creating parasitic capacitors leads to the fact that the resonant frequency reduces. This means that the size of antenna is reduced.

2.2. Application of DSS to Antenna

With the above principle, DSS can be widely applied to many kinds of antennas. To verify the proposed DSS method, we will apply it to dipole shaped array antenna based on Roger 4350B.

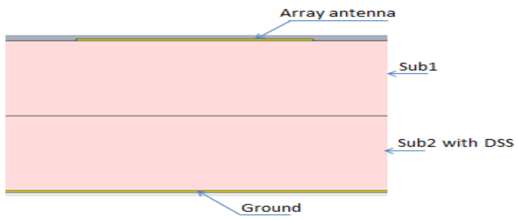
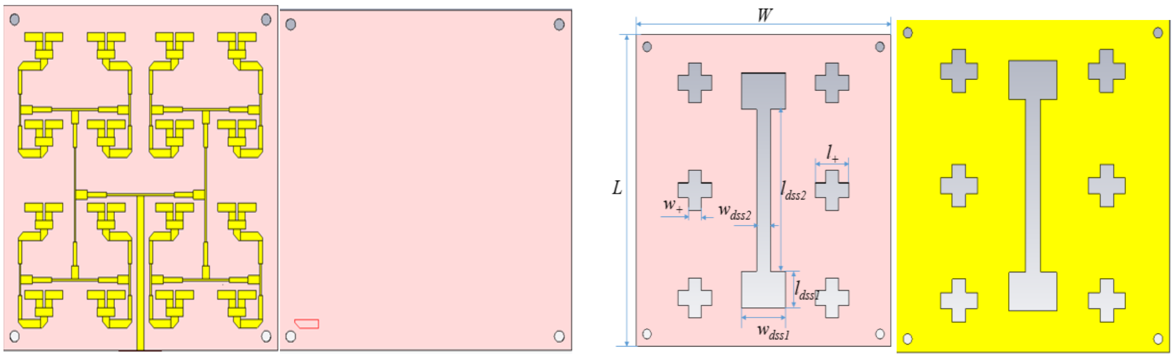


Figure 3: The model of the proposed array antenna with DSS

The model of the proposed array antenna is shown in Fig. 3 while the detailed model of array antenna is illustrated in Fig. 4. The proposed model consists of an array antenna on top in the first substrate, second substrate with DSS and ground on bottom. In this case, both the first and the second substrate are Roger 4350B with thickness of 1.524 mm, εr = 3.48 and tanδ = 0.0037.

In the first substrate, the array antenna includes 16 dipole elements and 15 T-junction power dividers. The distance between two elements is approximately 20 mm (from centre of antenna). The antenna is designed at a central frequency of 10 GHz. The size of array antenna is 120 x 125 mm and Table 1 shows the parameters of DSS.



a) b)

Figure 4: The model of the proposed antenna: (a) array antenna in the first substrate, DSS second substrate and ground (b)

Table 1 shows the parameters of DSS.

Parameter	w_+	l_+	w_{dss2}	l_{dss2}	w_{dss1}	l_{dss1}
Value	6	1	6.5	65	21	14.5

The length of dipole shaped antenna is approximately λ/2 with λ is the wavelength in free space, while the width of microstrip line is defined by [25]:

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \cdot \ln\left(\frac{8h}{w_f} + \frac{w_f}{4h}\right) if\ w/h < 1 \quad (12)$$

While w/h > 1, the width of microstrip line is given by:

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_r}} \cdot \frac{1}{\left(\frac{w_f}{h}+1.393+0.677\ln\left(\frac{w_f}{h}+1.444\right)\right)} \quad (13)$$

in which: w_f is the width of microstrip line, h is the thickness of substrate, ε_r is dielectric constant of substrate, and Z_0 is the characteristic impedance of transmission line. With the characteristic impedance of 50 Ohm, the width of microstrip line is approximately 3.4 mm.

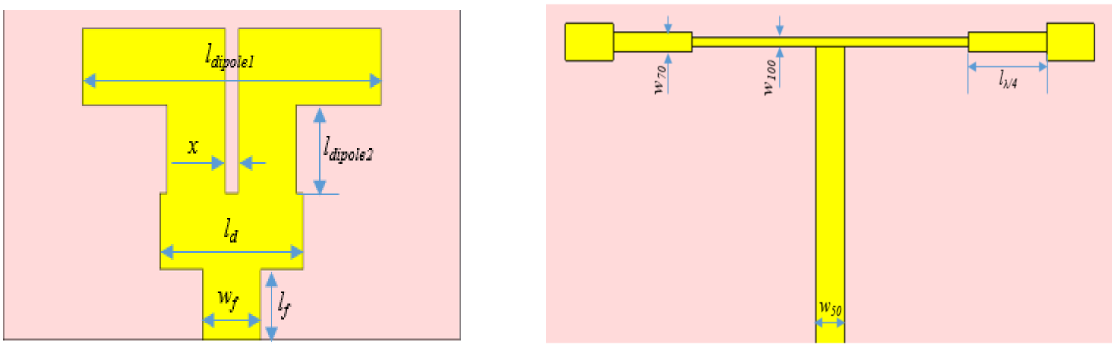
The size of an element in the array is shown in Table 2.

Table 2: The parameters of an element in array (unit: mm)

Parameter	w_f	l_f	l_d	$l_{dipole1}$	$l_{dipole2}$	X
Value	3.45	4	9.5	18	3	1

The detailed model of a dipole shaped element in the array and feeding line are shown in Fig. 5. The power dividers are three-port network with one input and two outputs. The quarter-wave transformers are used for the purpose of impedance matching and its impedance is calculated as:

$$Z_T = \sqrt{Z_{in} Z_{out}} \quad (14)$$



a) b)

Figure 5: The model of an element (a), the model of a power divider (b)

Z_{in} is the input impedance of transmission line and Z_{out} is the output impedance of transmission line. From expressions (12)-(14), we calculate the width and the length of the quarter-wave transformer. The parameters of the power divider are shown in Table 3.

Table 3: Some parameters of power divider (unit: mm)

Paramete	W_{50}	W_{70}	W_{100}	$l_{\lambda/4}$
Value	3.45	1.9	0.88	8.5

III. SIMULATION AND MEASUREMENT RESULTS

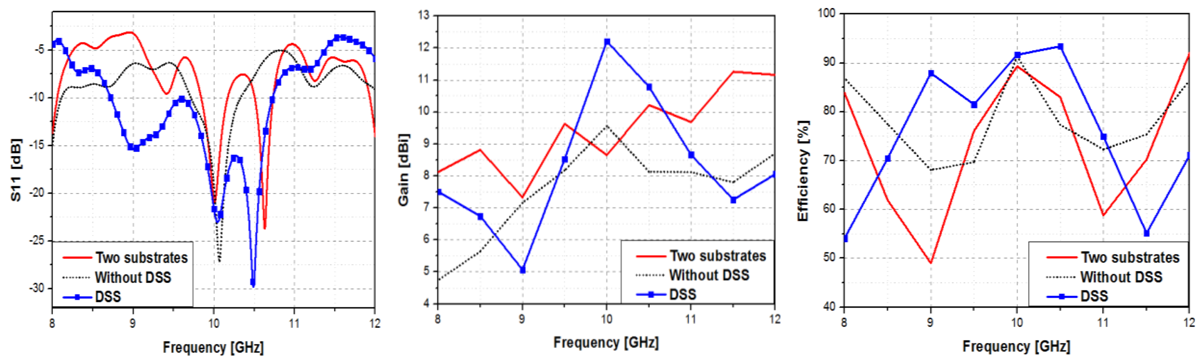
III.1. Simulation Results

To verify the proposed DSS method, the parameters of antenna are simulated in three cases: multi substrate layer, DGS and DSS. The results are compared to each other. In the simulation, the substrate material is Roger 4350B.

Fig. 6 compares the reflection coefficients, gains and efficiencies of antenna in three cases: two substrate layers, two substrate layers with DGS, and two substrate layers with DSS. From Fig. 6(a), we can see that the bandwidth of the antenna with DSS is the most large, over 2GHz while the bandwidths of antenna in cases of without DSS and two substrates are only 630 MHz and 330 MHz, respectively. It is clear that the bandwidth of antenna is improved significantly when using DSS. In case of two substrates, bandwidth improvement for antenna is only based on the increase of substrate thickness. So the bandwidth is not wide (only 330 MHz). For case of without DSS, the bandwdith of antenna is improved better than case of two substrates (630 MHz) because the antenna uses both two substrates and DGS. However, this result is much smaller than case of DSS. By using DSS at second substrate layer, it creates many consecutive cavity resonators. Therefore, the bandwidth of antenna is much enhanced. In addition, using multiple substrate layers also contributes bandwidth improvement for antenna. As a result, the bandwidth of antenna with DSS is significantly improved.

We know that the DGS method causes the current distribution disturbance in the ground plane. This leads to the fact that there is a change of tranmission line characteristics due to the increase of capacitors and inductors. In addition, DGS has two characteristics that are stopband and slow-wave effect. While the stopband is useful to suppress the unwanted surface waves, spurious and leakage transmission, the slow-wave effect is necessary for antenna miniaturization [23]. Moreover, using multiple substrate layer is also one of ways to improve antenna bandwidth [20]. DSS shows that it is a better method because the bandwidth of antenna with DSS is the largest one.

Fig. 6(b) illustrates the gain of antenna in three cases: two substrates, two substrates with DGS, and two substrates with DSS. In Fig. 6(b), we can see that the gains of antenna in cases of two substrates and two substrates with DGS are only 8.652 dBi and 9.556 dBi at the central frequency of 10 GHz, respectively. While the gain of antenna with two substrates with DSS reaches 12.12 dBi at 10 GHz. It is clear that the gain of antenna reaches the highest peak when DSS is used. Here, using DSS causes the current re-distribution for antenna. This leads to the fact that there are more in-phase currents which are concentrated in the main lobe, while the currents are limmited or there exist currents with phase opposite in other places. Therefore, the gain and directivity of antenna are improved.

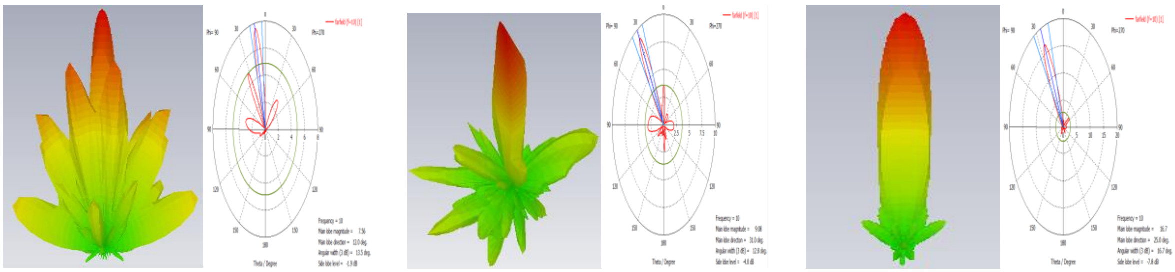


a) b) c)

Figure 6: The comparison of the antenna parameters: reflection coefficients (a), gain (b), efficiency (c) without DSS, and two substrates with DSS

Fig.6(c) illustrates the comparison about the efficiency of antenna in three cases. Although the efficiencies of antenna in cases of two substrates and two substrates with DGS are very high with over 89% and 91%, the efficiency of antenna with DSS is still the highest one with 91.67%. In here, the sizes of antenna are 123 x 126 mm for case of two substrates, 125 x 125.5 mm for case of two substrates with DGS, and 120 x 125 mm for case of two substrates with DSS. Thus, there is an optimization for both efficiency and size of antenna when DSS is used.

Fig. 7 shows the radiation patterns of antena (polar and 3D) in three cases: two substrate, two substrates with DGS, and two substrate swith DSS. From Fig. 7, we can see that in the case of two substrates, the antenna directivity is very low. Besides, the side lobe level is very high (-1.9 dB). As a result, the main lobe magnitude is only 7.56. For case of two substrates with DGS (without DSS), although the side lobe level is better than case of two substrates, it is still high (-4 dB). In addition, the directivity is very low and the main lobe magnitude is very small (9.08). When antenna uses DSS, the antenna radiation pattern is significantly improved. The main lobe magnitude is very high (16.7) while the side lobe level is only -7.8 dB. It is clear that the current re-distribution helps the current is concentrated the main lobe. Therefore, not only the side lobe level is reduced, but the directivity is also enhanced. As a result, the gain of antenna is improved.

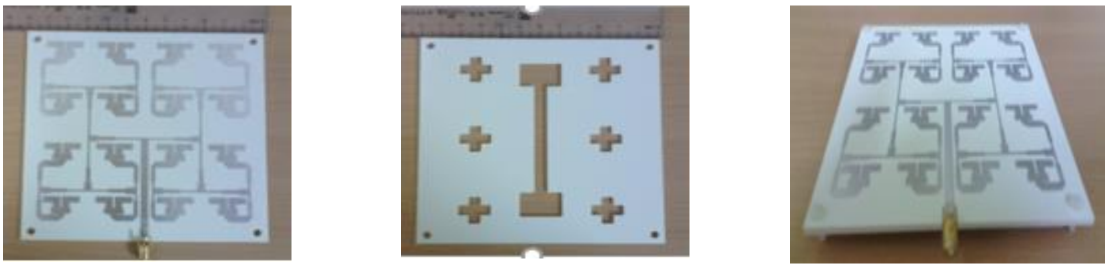


a) b) c)

Figure 7: The difference about patterns of antenna: two substrates (a), without DSS (b) and with DSS (c)

III.2. Measurement Results

Fig. 8 shows the fabricated antenna based Roger 4350B with parameters: thickness of 1.524 mm, ε_r = 3.48 and tanδ = 0.0037.



a) b) c)

Figure 8: The fabricated antenna based on Roger4350B: (a) the top and first substrate, (b) the second substrate with DSS, (c) the model of antenna

The total size of dipole shaped array antenna is 120 x 125 mm. The simulation and measurement results of reflection coefficient are presented in Fig. 9.

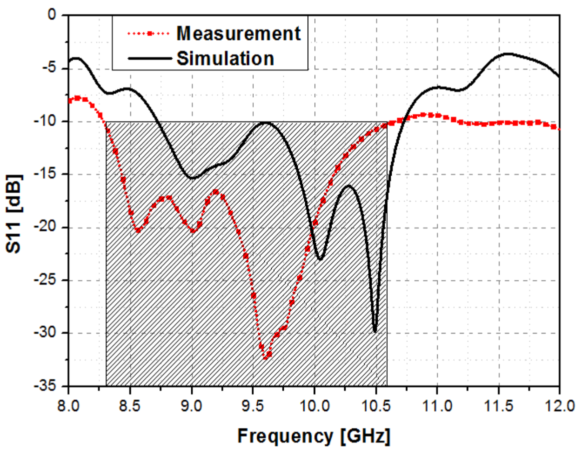


Figure 9: The simulation and measurement results of reflection coefficient

From Fig. 9, we can see that although there is a difference between simulation and measurement results, but the measurement result still covers fullly the operating band of antenna. Therefore, this result is acceptable. The measurement result shows that the bandwidth of antenna is over 2 GHz and its bandwidth percentage makes up more than 22%. Normally, the bandwidth percentage of microstrip antenna is only 7-8 % [26]. Compared to some published papers, we can see as follows. In [27], although a 4 x 4 antenna is designed at the central frequency of 60 GHz, the bandwidth of antenna is only 14.4% (at -6 dB). In addition, the efficiency of antenna is very low with 45.3%. With the above parameters, the antenna is not enough to satisfy applications at 60 GHz. In another study [28], the antenna includes 32 elements and it is designed for 60 GHz applications, but the bandwidth percentage and efficiency are only 9.8% and under 25%, respectively. Similarly, a phased array antenna including 16 elements is designed at 12 GHz, but the bandwidth of antenna is only 1.2 GHz (10%) [29]. Moreover, the gain of antenna is very low, only 8.1 dBi and the side lobe level is also quite high (-3 dB).

It is clear that using DSS, not only the bandwidth and the directivity of antenna but also the gain and efficiency for antenna are improved. This is not easy because we know that there is always a trade-off between the parameters of antenna (bandwidth and gain, efficiency). This shows that DSS is a good solution for antenna parameter improvement.

IV. CONCLUSIONS AND FUTURE WORK

This paper proposes a novel 4 x 4 dipole shaped array antenna model using DSS to improve some antenna parameters. The proposed array antenna consists of 16 dipole shaped elements in the first substrate and a DSS in the second substrate. The DSS and its equivalent circuit are also proposed and analyzed. The proposed dipole shaped array antenna is designed, simulated using CST software at the central frequency of 10 GHz and it is fabricated based on Roger 4350B with thickness of 1.524 mm, $\varepsilon r = 3.48$ and $\tan\delta = 0.0037$. By using DSS, the bandwidth, gain, directivity and efficiency of array antenna are improved. The peak gain and efficiency value of 12.21 dBi and 92% at 10 GHz have been achieved while the bandwidth percentage is over 22% for both simulation and measurement results. The size of array antenna is 120 x 125 mm. It is clear that some drawbacks of microstrip antenna such as narrow bandwidth are improved using DSS. DSS can be considered as a good solution to improve not only dipole shaped array antenna parameters but also other kinds of microstrip antennas.

In future study it is planned to use the proposed DSS method to improve parameters of multi-band antennas as well as multiple input multiple output antennas in advanced wireless communication systems.

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