Characterization of Acrylonitrile Butadiene Styrene for 3D Printed Patch Antenna

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Abstract
3D printing is one of the additive manufacturing technologies that has gain popularity for time saving and complex design. This technology increases a degree of flexibility for potential 3D RF applications such as wearable and conformal antennas. This paper demonstrates a circular patch antenna fabricated on 3D printed Acrylonitrile Butadiene Styrene (ABS) filament. The main reason of using a 3D printer is that it is accurate, easy to fabricate of a complex geometry and the ability to create new antennas that cannot be made using conventional fabrication techniques. The ABS material has a tangent loss of 0.0051 and the relative permittivity is 2.74. The thickness of the substrate is 1.25 mm. The simulation has been performed using Computer Simulation Technology (CST). The return loss from simulation software is in good match with measurement which is 12.5dB at 2.44GHz. Hence, from the results obtained, the ABS could be used as a substrate for an antenna.

Keywords: *circular patch antenna, 3D printing, 3D printer, Acrylonitrile Butadiene Styrene (ABS).*

1. Introduction

The technology of the world has tremendously increased across the years. There are rapid changes of new technology of the devices to cater the users worldwide. Recently, 3-dimensions (3D) printing has received an enormous attention due to the time saving and design complexity. 3D printing has a potential ability in which it can print various type of materials into three dimensional that comes with high precision and accuracy. It constructs a physical object by printing up layer by layer from a digital blueprint. The consensus view seems to be that 3D printing might be as common as 2D printer in the future. It also has their own goals by developing the new structures into more complex structures such as machines, phones, cars or artificial hands, ears, eyes and etc.

However, the introduction of 3D printer into the world globally has come with their own pros and cons. The main reasons might be correlated to the geometry evolution, build speed, and the overall cost [1-2]. This type of printing allows an accurate replication of a complex components and it offers numerous advantages such as immediate printing of some complex designs [3-4]. Laser sintering, fused deposition modelling and stereolithography are the technologies that are available in 3D printing industry. The 3D printing technologies, especially the fused deposition modelling has been introduced to make the first 3D printed components to the outer space [5]. Although the old-style micro-machining could also be used to build complex structure, however it requires higher cost compare to 3D printing technology [6]. The other limitation of 3D printing is that it might produce a rough surface after finalizing the outcomes.

In correlation to the 3D printing, Acrylonitrile Butadiene Styrene (ABS) is the material that going to be used in this research. For the time being, there are only a few material that can be printed using 3D printer which includes ABS. It is a type of plastics that made from a monomer acrylonitrile, 1,3 Butadiene and a styrene. Knowing for its robust and strong structure, ABS also able to stand at high temperature. As it is easily to be printed by using 3D printer, it is not impossible to print any sizes and shapes by using this material. Known to be an additive, ABS has reduce the wastages of the materials by controlling and monitoring the process digitally [7]. The RF characterization of the ABS (such as permittivity and loss tangent) has been calculated and the values have been used in simulation and measurement.

In order to demonstrate the suitability of 3D printing technology in antenna design, a patch antenna at 2.4 GHz has been simulated and the design has been fabricated on a 3D

printed ABS. Rectangular and circular patch antenna are said to be most preferable to be an antenna design because it has multiple frequency operation, circular and linear polarization and feed line design flexibility [8]. A circular patch antenna has been chosen for simulation using CST software.

For fabrication, the ABS is printed according to the dimensions stated in antenna parameters section. The results are resonated at a frequency of 2.4 GHz. Thus, section 2 will discuss on the antenna design and RF characteristics of ABS. Whereas the results and analysis will be discussed in section 3. Lastly, section 4 is the overall conclusion on the circular patch antenna on a printed ABS using 3D printing technology.

2. Research Method
2.1. Design of a Patch Antenna
For calculating the patch, there are a few formulae that will be conducted. Some parameters are to be resolved from [9]. The parameters included in these calculations such as dielectric constant of the substrate, ε_r, resonant frequency, fr and as well as the height of the substrate, h and shown in equation (1-3).

$$a = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r}\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{1/2}} \qquad (1)$$

Kindly note that a is the radius of the patch in centimeter and the value of F can be obtained by using (2) as shown below.

$$F = \frac{8.79x10^9}{f_r\sqrt{\varepsilon_r}} \qquad (2)$$

The resonant frequency can be determined from (3):

$$(f_r)_{110} = \frac{1.8412v_0}{2\pi a_e\sqrt{\varepsilon_r}} \qquad (3)$$

where, v_0 is the speed of light. The effective radius of circular patch antenna, a_e:

$$a_e = a\sqrt{\frac{2h}{\pi\varepsilon_r a}\left[\ln\left(\frac{\pi a}{2h}\right)+1.776\right]} \qquad (4)$$

2.2. Dielectric constant (ε$_r$) and tangent loss (tan δ) of ABS
The design of a patch antenna requires knowledge of the dielectric constant (ε_r) and loss tangent (tan δ) of a substrate. Those parameters are varied and a wide variation of dielectric constant has been encountered from different manufacturers requires antenna designer looking for other approaches. Therefore, the dielectric constant (ε_r) and loss tangent (δ) of the ABS material can be determined from measurement. The dielectric constant (ε_r) is calculated by reversing equation (1-3) from the S_{11} measurement of patch antenna. On the other hand, loss tangent (tan δ) can be obtained according to the method by [10]. The procedure begins by forming a rectangular resonant cavity according to [11]. A small hole is drilled through material to insert probe feed. After the measurement is done, we can calculate the value of the loss tangent using equation (4-8). Loss tangent (tan δ) can be determined from the quality factor of dielectric losses, Q_d as [10]:

$$\frac{1}{Q_u} = \frac{1}{Q_d} + \frac{1}{Q_c} \qquad (5)$$

where Q_u is the unloaded quality factor and Q_c is due to the conducting wall loss. Q_u may be obtained from:

$$Q_u = Q_L(x)F(x) \qquad (6)$$

where $Q_L(x)$ is a generalized loaded Q from equation (7),

$$Q_L(x) = \frac{\omega_0}{(\Delta\omega)_x} \tag{7}$$

where ω_0 is the resonant angle frequency and $\Delta(\omega)_x$ is the bandwidth measured between points where $|S_{11}|=x$. $F(x)$ can be obtained from equation (8),

$$F(x) = \frac{2}{1\pm|S_{11}|_0}\sqrt{\frac{|S_{11}|_x^2 - |S_{11}|_0^2}{1-|S_{11}|_x^2}} \tag{8}$$

where $|S_{11}|$ is the magnitude of S_{11} at resonance frequency. The '-' and '+' sign in equation (8) refers to the over-coupling and under-coupling respectively. For TE_{101} mode, Q_c of the rectangular cavity with lossy wall and a lossless dielectric is as follows:

$$Q_c = \frac{(kad)^3 b\eta}{2\pi^2 R_s(2a^3b+2bd^3+a^3d+ad^3)} \tag{9}$$

where $k = \omega\sqrt{\mu\varepsilon}$ is the wavenumber in the substrate and $\eta = \sqrt{\frac{\mu}{\varepsilon}}$ is the wave impedance, and $R_s = \sqrt{\frac{\omega\mu}{2\sigma}}$ is the surface resistivity of the metallic walls. Loss tangent (tan δ) can be determined from the quality factor of dielectric losses, Q_d as:

$$\tan\delta = \frac{1}{Q_d} \tag{10}$$

Equation 1-4 is used to design a circular patch antenna (using CST software) and Equation 5-10 has been used to determine the RF properties (ε_r and tan δ) of ABS material.

3. Results and Analysis
3.1. Dielectric Constant (εr) and Loss Tangent (tan δ) of ABS

Figures 1(a) and 1(b) show the fabricated design of a circular patch antenna and rectangular resonant cavity using ABS substrate and S_{11} measurement respectively. The dielectric constant (ε_r) of the ABS substrate is calculated using S_{11} and equation (1-3) which is equal to 2.74. The result obtained in Figure 2 is being measured by using an Agilent Technologies Vector Network Analyzer (VNA) E5062A. This machine is able to measure ranging from 300 kHz to 3 GHz
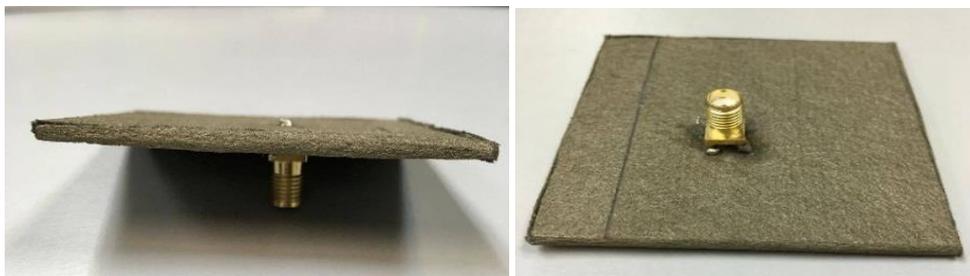
Figure 1. (a) shows a circular patch antenna using ABS as substrate to obtain dielectric constsant and Figure 1, (b) rectangular resonant cavity used to calculate loss tangent of the ABS substrate
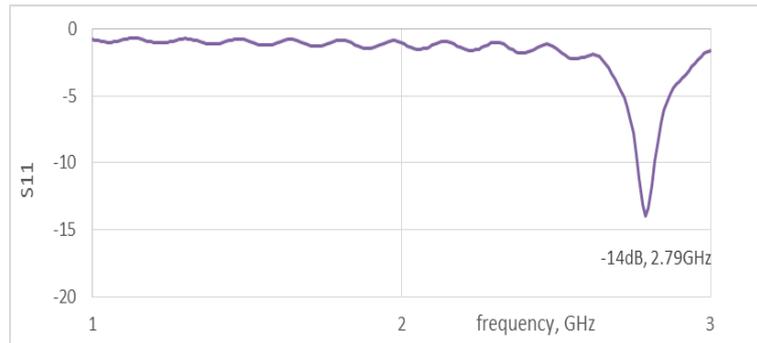
Figure 2. S11 measurement of circular patch antenna resonated at 2.79 GHz.

Then, a rectangular resonant cavity (Figure 1(b)) has been formed according to [10] and [11] to calculate loss tangent (tan δ) of the ABS substrate. The loss tangent calculated using S11 measurement (Figure 3) and equation (4-9) is equal to 0.0051. Table 1 summarizes the calculated results of dielectric constant (ε_r) and loss tangent (tan δ) of the ABS substrate.
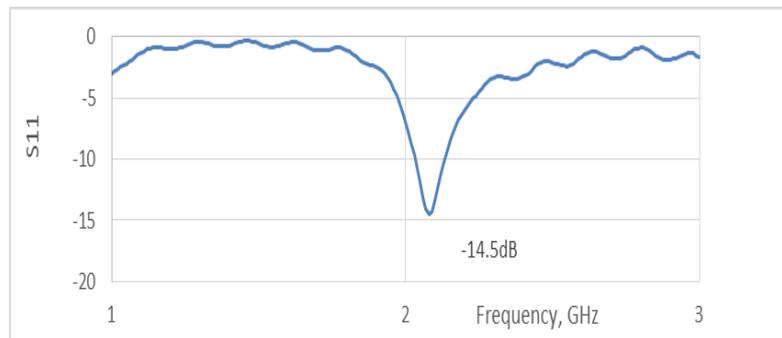
Figure 3 S11 measurement of a rectangular resonant cavity to calculate loss tangent of the ABS substrate.

Table 1. ε_r and tan δ of the ABS substrate

Parameter	Dielectric constant (ε_r)	Loss tangent (tan δ)
Value	2.74	0.0051

3.2. Design and Fabrication of Circular Patch Antenna at 2.4 GHz

A good design of an antenna must consider a few parameters. Figure 4(a) shows the design of circular patch antenna resonated at 2.4 GHz using CST software. The ABS with the parameters shown in Table 1 is used as the substrate. For the patch, a copper material is used as well as for the ground part. In addition to that, a coaxial probe feed is being used in this design. The matching impedance of the coaxial probe feed is said to be 50 ohm. As for the port, a SMA port is being used in this research. By referring to the Table 2, it shows the overall dimension of the ABS that is being simulated in CST software. After simulation has been performed using CST full wave simulation software, the antenna has been fabricated using ABS as the substrate. The ABS has been printed using Stratasys uprint SE plus 3D printer as shown in Figure 4(b).

A parameter sweep is done from simulation in order to get the best S11 results by varying the location of probe feed. In order to get a desirable results or lowest S11 results, the probe location must meet certain requirements. In Table 3, it shows the number of samples during parameterization for patch radius (r1), probe feed positioning (s1). The parameter sweeps are started from the center of the patch to the upper side of the patch. For each parameterization,

three (3) samples are tested in these procedures. Therefore, the results in S11(4) in Figure 5 gives the optimum results as compared to the rest of the samples.

Table 2. Design specification of two circular patch antennas

Parameters	Acrylonitrile Butadiene Styrene (ABS)
Patch Radius (mm)	21.50
Patch Height (mm)	0.45
Feed Height (mm)	3.25
Feed Radius (mm)	1.69
Ground Length (mm)	60
Ground Width (mm)	60
Ground Height (mm)	1.25
Substrate Length (mm)	60
Substrate Height (mm)	1.25
Substrate Width (mm)	60
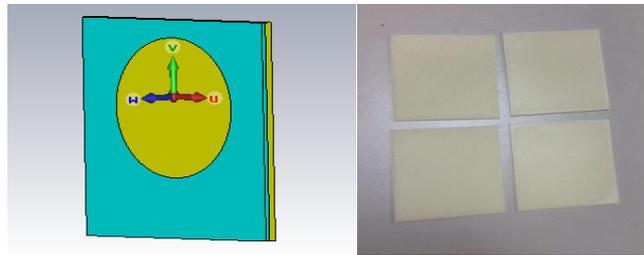
Figure 4a. Design of a circular patch antenna at 2.4 GHz and Figure 4b. is the ABS substrates printed by using 3D printer
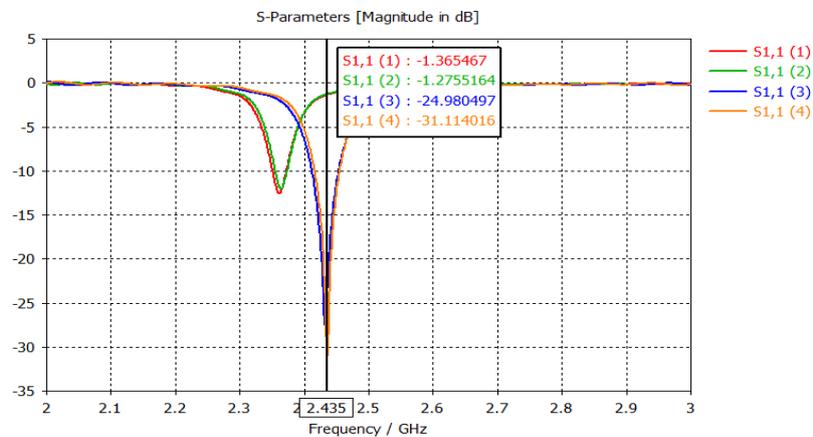
Figure 5. Parameter sweep of the S11 of a circular patch antenna

Other results such as impedance, directivity, IEEE gain and etc will be presented in Table 4 below. Meanwhile Figure 6 displays a simulated far field plot of the circular patch antenna at 2.44 GHz.

Table 3. shows the parameter sweep of circular patch antenna

No of run	r1	s1
1	21.5	0
2	21.25	1
3	21.00	2

Next, a circular patch antenna resonated at 2.4 GHz is fabricated using ABS as a substrate (Figure 7). The metallic patch for radiating and ground place has been attached with copper tape which has cut into a circle and square shape respectively. Then, a hole is drilled and inserted with SMA port with 50 Ω impedance.
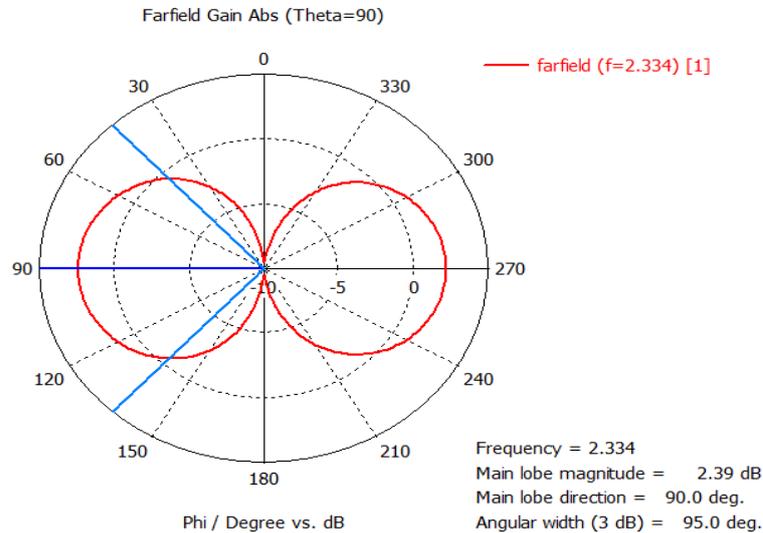
Figure 6. Polar plot for circular patch antenna as the substrate
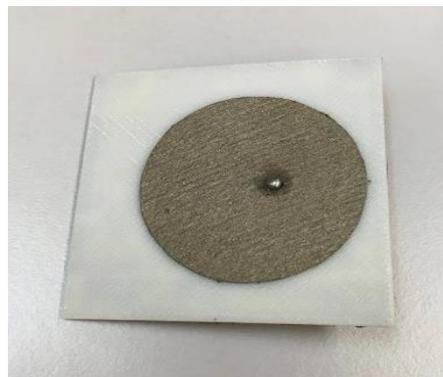
Figure 7. A circular patch antenna at 2.4 GHz

Figure 8 shows the return loss for both simulation (in dash-red curve) and measured (blue curve). It shows that both are in good agreement with each other. While, the ripples and the differences observed at S11 measured result at the lower frequency is possibly due to the fabrication inaccuracies resulting from the cutting process of the copper tape for the radiating patch and ground plane of the antenna. The simulated and measured S11 at 2.4 GHz is -21dB and -12dB respectively.
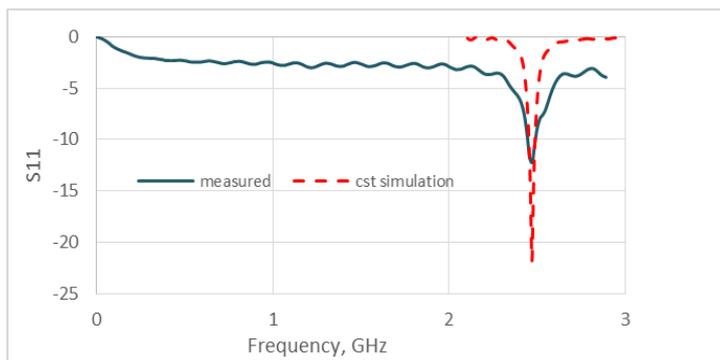
Figure 8. S11 comparison between measured and simulation of ABS

Table 4 summarizes the overall performance of the patch antenna. The most important parameters that are being taken into consideration are the return loss, VSWR, directivity, gain, radiation efficiency, total efficiency and resonant frequency.

Table 4. Overall Performance Parameters of Circular Patch Antenna at 2.44 GHz using ABS as the substrate.

Parameters	Circular Patch Antenna
Return Loss (dB)	-21.11 (simulated) , -12.5 (measured)
VSWR	1.13 (simulated)
Impedance (Ω)	30.1 (simulated)
Bandwidth	1.62%
Directivity (dBi)	6.163 (simulated)
Gain (dB)	5.398 (simulated)
Radiation Efficiency (dB)	-0.77(simulated)
Total Efficiency (dB)	-7.48 (simulated)
Resonant Frequency (GHz)	2.44 (simulated), 2.44 (measured)

4. Conclusion

As a conclusion, the characterization of the ABS type of material of a substrate for a patch antenna at 2.44 GHz has been determined. Furthermore, those parameters of dielectric constant and loss tangent have been used in the circular patch antenna design. Indeed it is showed that the results of S11 for both simulation and measurement are match to each other. By judging its performance, it is clearly states that ABS could be used as a substrate for antenna and thus it is suitable to be built as conformal antenna in 3D for further research.

Acknowledgement

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