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Finite Element Method Modelling of Microstrip Patch Antenna (S Band) for Return Loss Based on Material Permittivity

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ABSTRACT

This paper presents the use of Finite Element Method in modelling the use of microstrip patch antenna in the S band frequencies, i.e. 2 GHz to 4 GHz, in close contact with materials of various permittivity in the shape of a cube to obtain the return loss measurement and its corresponding frequency. Observation is made to where the return loss value is the lowest for each frequency step in the band. The goal of the research here is to model the effect of changing permittivity using different antenna frequencies and studying the effects on the sample materials chosen. The main goal is to establish the use of the microstrip patch antenna for use in measuring and determining the strength of concrete of varying mix ratio which are casted in standard moulds. If the concrete mix ratio changes, it is expected that the permittivity would change as well. As concrete is not a standard material in the modelling software, materials of various permittivity are selected in place of concrete. The results of this modelling show the permittivity of materials affect the return loss measurements of the antenna across the S band, with considerations to the antenna design parameters, the patch dimensions and the desired frequencies. The results show that, for use in measuring concrete samples in cube moulds, actual testing would need to be conducted as the permittivity of concrete changes from the time casting is done and throughout the curing process.

1. Introduction

1.1 Background

This paper presents the results of Finite Element Method (FEM) for the modelling of microstrip patch antenna on various materials and the measurements of the return loss value and frequency on each material. This research output serves to determine the material permeability can affect the return loss value of the microwave S-band frequencies between 2 GHz and 4 GHz. This current research serves to establish the use of microstrip patch antenna to determine the strength of

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concrete samples of different and varying grades used in the industry. Prior to conducting actual testing on concrete samples, this stage of the research is to establish the use of microstrip antenna in obtaining the return loss values of materials with different permittivity values. A patch antenna by itself can be modelled easily using electromagnetic (EM) software packages such as CST Studio Suite by Dassault Systèmes and Ansys HFSS by Ansoft Corporation. Comparing these two software packages, both are equally useful and suitable for designing and simulating antennas. CST is based on the Finite Integration in Technique (FIT), whereas HFSS is based on Finite Element Method (FEM). The FEM is selected due to the availability of software to the user, which is used for the purpose of the antenna testing and modelling, plus obtaining data on the measurements.

1.2 Overall Research Scope and Purpose of This Modelling

Generally, the wider research scope is to use microstrip patch antenna to determine the strength of concrete via the measurement of the return loss value. Due to the various mixture of materials used to form concrete, typically cement, sand, aggregate and water, the proportion or mix ratio can be pre-determined before the casting process. From previous research and studies, it is possible to use EM wave signals to relate the permittivity, and permeability of concrete, which shall vary according to the concrete strength grade, and in turn also is due to the mix ratio of materials used during the casting process. Therefore, the use of microstrip patch antenna in measuring the return loss of concrete has the potential to be further researched and investigated. However, before the antenna can be designed and fabricated, the use of modelling software packages can be first used to simulate potential designs of various antenna types, as well as determine the specific frequency or range of frequencies suitable for the antenna to be fabricated and further integration with a measurement system. The physical system can later be tested, and the measurement results can be compared.

1.3 Modelling of Materials with Varying Permittivity

In the Ansys HFSS software, there are per-defined materials within the library that can be specified in the model when designing an antenna. However, concrete is not included in the library of materials. Therefore, the initial results from modelling of various materials are required to determine the feasibility of the patch antenna in correlating the relationship of material permittivity with the return loss value. If the different permittivity of various materials can be shown to influence the return loss value, it can be hypostasized that similar outcome can be reached when testing on concrete of different grades, or varying strength. In the industry, concrete moulds are casted in cubes of 15 cm x 15 cm x 15 cm or 10 cm x 10 cm x 10 cm. In this paper, the dimensions of the materials to be modelled are using the size of 15 cm x 15 cm x 15 cm. This is to reduce the variable of the shape of the material under test when switching to concrete samples.

1.4 Gap and Significance of This Study

This research study seeks to fill the gap in non-destructive testing of concrete whereby the use of microstrip patch antenna can be applied onto the surface of the concrete to determine and predict its strength grade, without the need to do the destructive testing. In the construction industry, it takes 4 weeks for concrete to be cured, and only then would achieve its highest strength value. Thus, the use of this type of antenna can be beneficial in reducing the time required to do concrete strength testing, as it is proposed to be able to predict the strength based on the measured return loss of the antenna.

2. Literature Review

2.1 Microstrip Patch Antenna

In a typical microstrip patch antenna, the design parameters are already well established. These antennas are compact in design and have a variety of applications. They can be easily modelled using simulation software. The design parameters of the antenna can be optimized to achieve the suitable dimensions, resonant frequency, gain and radiation efficiency, as per these studies by Shimu and Anis [1] and Rana *et al.,* [2]. There are various types of microstrip patch antenna with different feed mechanism, such as inset feed, edge feed and probe feed. Various research has been published on the performance of these antennas, and the testing results show that each type has its own strengths and weaknesses. Comparisons between modelling and simulation to the actual antenna have shown that the latest modelling software is able to generate the results which closely matches that of the design parameters, typically the antenna patch dimensions and the substrate or ground plane dimensions, from these studies [3-6]. In this study by Azman *et al.,* [7], the comparison between line feed and coaxial feed antenna has been made. The suitability of the antenna feed mechanism is based on the results of measurements and the intended application.

2.2 Using Microwave to Investigate Permittivity and Dielectric Properties of Materials, e.g. Concrete

Concrete is a material of interest which is the main goal for this research on using microstrip patch antenna to determine its strength. In this research by Jamil *et al.,* [8], concrete with different mix ratios and compressive strength are found to have different dielectric properties during the curing process. It is observed that microwave non-destructive testing can be used for in situ measurements to obtain data for transmission coefficients, reflection coefficients, dielectric constants, and loss factors. In the findings, this research uses transmit and receive horn lens antennas. Similarly, in another research, it was found that the permittivity of cement-based materials is strongly affected by the water-to-cement ratios, types of cement, pozzolans and aggregate types. During the hydration process, the water quantity in the cement mixture will decrease, therefore the permittivity also decreases [9]. Consequently, the dielectric constant can be related to the water content of concrete [10]. As concrete is a mixture of various components it has been found that the water content influences the dielectric property the most, citing He and Na [11].

2.3 Non-Destructive Testing on Concrete

Typically, the compressive strength property of concrete is obtained by a destructive test method, on cubes or cylinder specimens. This is a tried-and-true method even for newly developed cement-based materials [12]. In some cases, samples of concrete need to be bored out from the casted material, which involved the use of heavy machinery and equipment, referring to this study by Yikici and Hung-Liang [13]. In this research, the study made use of open coaxial probe in using electromagnetic non-destructive testing to obtain the dielectric constant via the porosity and the composition of the concrete mixture. The study by Guihard *et al.,* [14] used a concrete element model in place of the full composite material for concrete to establish a relationship between the porosity with the dielectric constant. In another research using capacitive probes, it is also described that the dielectric permittivity is affected by water content of concrete. Thus, there are results obtained using an inversion method to get the permittivity profile of reinforced concrete. The inversion process applied use two forms of parametrizations, i.e. discrete and continuous, taken from Fares *et al.,* [15].

3. Methodology

3.1 Microstrip Patch Antenna Design

The microstrip patch antenna designs follow that of an inset fed type, as shown in Figure 1. As the research intends to use S band frequencies, the modelling for each of the antenna are using frequencies from 2.0 GHz to 4.0 GHz in steps of 0.2 GHz. The basic antenna design is according to the design equations outlined in this resource from Altium [16]. Thus, the following antenna sizes in Table 1 are to be modelled.

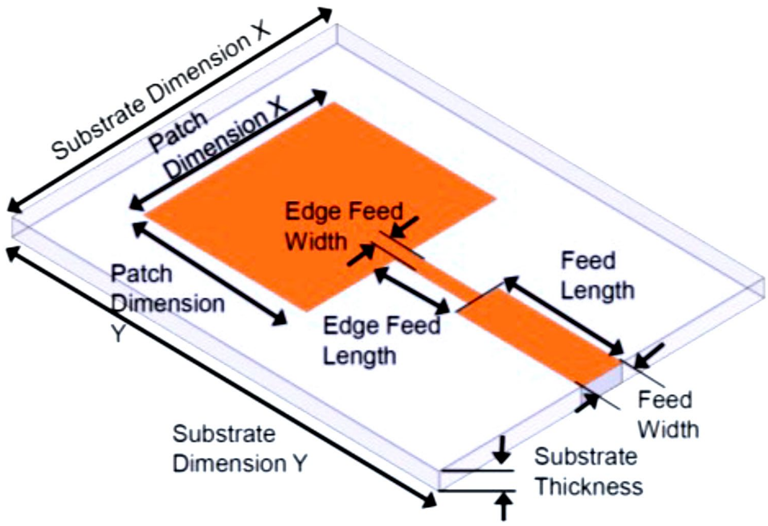


Fig. 1. A typical patch antenna using inset feed [17]

Table 1
Antenna and substrate size (S band frequencies)

No.	Frequency (GHz)	Antenna size		Substrate size	
		Patch dimension X (cm)	Patch dimension Y (cm)	Substrate dimension X (cm)	Substrate dimension Y (cm)
1	2.00	4.56	3.54	7.80	10.91
2	2.20	4.15	3.22	7.20	9.92
3	2.40	3.80	2.94	6.70	9.09
4	2.60	3.51	2.71	6.20	8.38
5	2.80	3.26	2.52	5.90	7.78
6	3.00	3.04	2.34	5.50	7.25
7	3.20	2.85	2.19	5.20	6.80
8	3.40	2.68	2.06	5.00	6.39
9	3.60	2.54	1.94	4.80	6.03
10	3.80	2.40	1.84	4.60	5.71
11	4.00	2.28	1.74	4.40	5.42

3.2 Selection of Materials

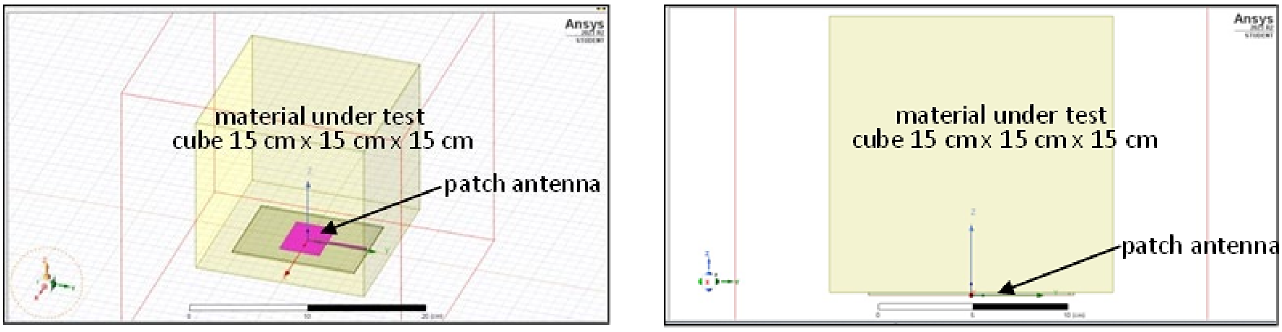
Next, the selection of materials used in the modelling and testing on the effects on return loss is centered around the permittivity value of concrete. From this study, the value of permittivity is shown to vary based on the frequency used in the measurement. In the S band frequencies, the real part of permittivity values obtained are between the ranges of 4 and 10, based on these studies [18,19]. Thus, the chosen materials from the software library are as listed in Table 2. These materials have relative permittivity ranging from 3.5 to 5.7, randomly chosen from the simulation software library as they are available from the software application library, and the fact that these values are close to the permittivity of concrete described in the references from literature. The description of these materials is obtained from ScienceDirect and Altium sites [20-24].

Table 2
Antenna and substrate size (S band frequencies)

No.	Material		
	Type	Relative permittivity	Description
1.	Polyimide	3.5	High-performance thermoplastic polymers [20].
2.	Silicon dioxide	4.0	Covalent compound and exists mainly in three forms: quartz, tridymite, and cristobalite [21].
3.	Polyamide	4.3	Well known as nylons, and are defined as polymers [22].
4.	FR4 epoxy	4.4	most popular type of printed circuit board laminate [23].
5.	Porcelain	5.7	Quartz partially dissolves into silicate glass which then gained strength by crystal precipitation on cooling [24].

3.3 Model Design

The modelling assumed that the setup for measuring the permittivity values of concrete is using the standard mould dimensions of 15 cm x 15 cm x 15 cm. Thus, the model of the antenna designed using the software package would also have the cube of material placed at proximity to it at the centre, as shown in Figure 2. The initial testing would be setting the cube to be of vacuum, i.e. no material present nearby. The return loss value is obtained from each of the simulation for the range of S band microwave frequency values set previously. Once the above is done, each cube is assigned to be the material selected above and the series of simulation is conducted using the same frequency range. Therefore, the value of return loss and the accompanying frequency is obtained for each material at each set of frequencies. Observation is made to the values of return loss, and the frequency at which the lowest value occurs for each material at each frequency which every antenna has been designed for. These shall be discussed in the next sections, Results and Discussions.



(a) (b)

Fig. 2. Model of microstrip patch antenna in Ansys HFSS (a) Microstrip patch antenna, 2.0 GHz (in purple) (b) Front view with material cube 15 cm x 15 cm x 15 cm above antenna (yellow box)

4. Results

The result for each material is tabulated in the tables below. Table 3 to Table 8 shows the return loss values for the microwave S band at intervals of 0.2 GHz, for vacuum and the five other materials selected from the modelling software library. Typically, the results of the modelling would produce a graph like the one shown in Figure 3, which is produced from the simulation at 2.0 GHz. The lowest value of the curve is the return loss value, and the corresponding frequency at which it occurs. Table 3 shows that when there is no material present, i.e. with antenna in free space. The microstrip patch antenna performs significantly well, almost close to each of its designed value. This is as expected, since the design of the antenna follows that of the standard literature.

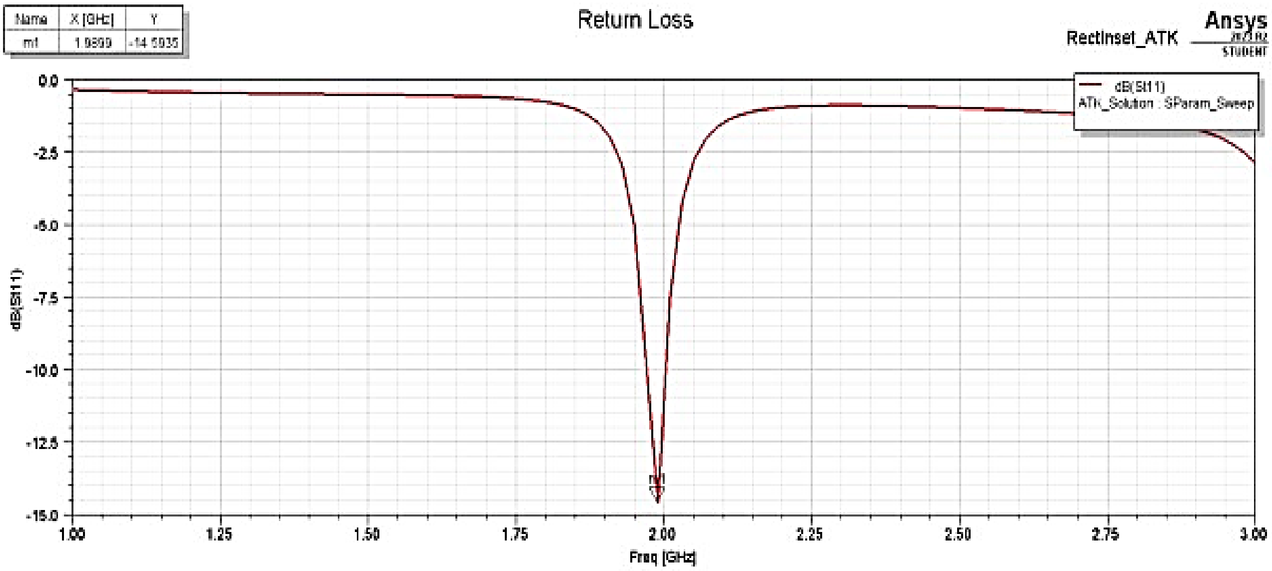


Fig. 3. Return loss at 2.0 GHz with antenna in free space

Table 3
Results of simulation with antenna in free space

No.	Designed frequency (GHz)	Simulation results	
		Return loss (dB)	Measured frequency (GHz)
1	2.00	-14.59	1.99
2	2.20	-13.16	2.19
3	2.40	-15.96	2.39
4	2.60	-16.21	2.59
5	2.80	-14.93	2.79
6	3.00	-15.49	2.98
7	3.20	-16.04	3.18
8	3.40	-16.59	3.38
9	3.60	-15.52	3.58
10	3.80	-16.12	3.78
11	4.00	-15.41	3.99

The values of return loss obtained from the modelling shows similar pattern across all materials. It is observed that when the frequency increases, the return loss for each material is different, with the lowest return loss usually occurring at a lower frequency. For polyimide, Table 4, there is no clear pattern which emerged from the simulation results. The return loss values fluctuate between -4.81 dB (at 2.86 GHz) to -8.48 dB (at 2.62 GHz) in the S band frequencies. For silicon dioxide, Table 5, there is also no clear pattern with increased frequencies, and the return loss values ranges from -4.09 dB (at 1.87 GHz) to -8.72 dB (at 2.46 GHz). Furthermore, with the other three materials, i.e. polyamide (shown in Table 6), FR4 epoxy (shown in Table 7), and porcelain (shown in Table 8), the pattern across various frequencies do portray similar results. These materials show the trend similar to polyimide and silicon dioxide.

Table 4
Results of simulation with polyimide

No.	Designed frequency (GHz)	Simulation results	
		Return loss (dB)	Measured frequency (GHz)
1	2.00	-6.89	1.89
2	2.20	-6.49	2.10
3	2.40	-7.48	2.27
4	2.60	-5.32	2.51
5	2.80	-8.48	2.62
6	3.00	-4.81	2.86
7	3.20	-6.63	2.99
8	3.40	-6.04	3.25
9	3.60	-6.00	3.40
10	3.80	-6.11	3.59
11	4.00	-5.63	3.78

Table 5
Results of simulation with silicon dioxide

No.	Designed frequency (GHz)	Simulation results	
		Return loss (dB)	Measured frequency (GHz)
1	2.00	-4.09	1.87
2	2.20	-8.22	2.08
3	2.40	-4.20	2.22
4	2.60	-8.72	2.46
5	2.80	-4.86	2.56
6	3.00	-5.19	2.83
7	3.20	-4.55	3.05
8	3.40	-5.59	3.18
9	3.60	-5.71	3.36
10	3.80	-5.39	3.51
11	4.00	-5.80	3.78

Table 6
Results of simulation with polyamide

No.	Designed frequency (GHz)	Simulation results	
		Return loss (dB)	Measured frequency (GHz)
1	2.00	-4.67	1.91
2	2.20	-6.97	2.06
3	2.40	-5.05	2.29
4	2.60	-6.48	2.43
5	2.80	-4.06	2.59
6	3.00	-4.97	2.77
7	3.20	-5.10	2.99
8	3.40	-4.86	3.21
9	3.60	-5.27	3.36
10	3.80	-5.16	3.44
11	4.00	-5.87	3.73

Next, the observation is made on the change of change of permittivity towards the return loss values. When permittivity increases, the return loss tends to worsen. This happens to all frequencies the antennas have been designed for. Overall, the change in the permittivity of a material is found to be able to produce a change in the return loss value regardless of which frequency is used. Nevertheless, there are other parameters to consider when deciding on the suitable frequency of the antenna. Antenna size is one consideration to make, as it cannot be larger than one face of the cube, i.e. 15 cm x 15 cm because then the antenna EM field cannot fully cover the intended cube surface.

Table 7
Results of simulation with FR4 epoxy

No.	Designed frequency (GHz)	Simulation results	
		Return loss (dB)	Measured frequency (GHz)
1	2.00	-4.72	1.91
2	2.20	-6.42	2.03
3	2.40	-5.12	2.29
4	2.60	-5.87	2.40
5	2.80	-4.30	2.62
6	3.00	-4.29	2.80
7	3.20	-4.60	2.99
8	3.40	-4.63	3.18
9	3.60	-4.98	3.33
10	3.80	-4.60	3.34
11	4.00	-4.72	3.82

Table 8
Results of simulation with porcelain

No.	Designed frequency (GHz)	Simulation results	
		Return loss (dB)	Measured frequency (GHz)
1	2.00	-4.54	1.83
2	2.20	-5.27	2.06
3	2.40	-3.89	2.17
4	2.60	-4.77	2.40
5	2.80	-4.10	2.56
6	3.00	-3.49	2.74
7	3.20	-3.86	2.93
8	3.40	-5.16	3.18
9	3.60	-5.28	3.40
10	3.80	-5.17	3.55
11	4.00	no results*	no results*

*Note that for 4.00 GHz, there was no result obtained due to error in the limitation of mesh size exceeding the limit of the software

5. Discussions

In designing a suitable microstrip patch antenna that can be used to produce a change in the reading of the return loss value when placed in proximity to a material under test, the consideration on the frequency is also important. The antenna size will decrease as the frequency increases. When compared to other studies, there no direct comparison as the experimental setup is different. Nevertheless, there is an effect of changing dielectric constant (dielectric constant is the ratio of the permittivity of a substance to free space) being observed with concrete of various mixes, based on the study by Jamil *et al.,* [8]. If the material is concrete, it is observed that the initial 24 hours of concrete setting has a significant change of the dielectric constant value [9].

In another study, the paper described the use of an open coaxial probe to measure the dielectric constant via the porosity of concrete, they can estimate the compressive strength using a strength model and a dielectric model, based on Guihard *et al.,* [14]. It can be seen from this study by He and Na [11], the dielectric constant value has been used to form a relationship with the curing process of the concrete. During the early stages of the curing process, the water content of the concrete is high.

This gives a high value for the dielectric constant. The concrete strength increases when the dielectric constant value decreases, since the water content of the concrete decreases as well over the period of curing. Thus, the proposed use of microstrip patch antenna is seen as a potential way for also determining the concrete strength from the relationship between the antenna return loss and the concrete dielectric constant value.

Though the approaches of different studies use methods which are dissimilar to the modelling method of this paper, the observations are in line with the results obtained here. It can be seen from the modelling results above that using materials of varying permittivity, the microstrip antenna is found to be able to give significant return loss values and frequency readings that are measurable. Fabrication of the antenna is limited by the manufacturing capabilities of the printer circuit board facility and equipment at the university. Secondly, the substrate size is also important as this is where the ground plane of the antenna is typically at. Thus, the lower ranges of the S band frequencies are more suited to be used when designing the antennas, if they are to be used in measuring cubes of 15 cm x 15 cm x 15 cm size.

6. Conclusions

In this paper, the results of modelling and simulation of microstrip patch antenna using S band frequencies have been conducted on materials with varying permittivity. As the intended goal is to establish the suitability of using the microstrip patch antenna to determine the strength of concrete in a real-life environment, the purpose of this research is to ensure simulation on cubes of materials with permittivity that is within the range of concrete first. Within each of the materials selected, there is an indication of change of return loss with respect to the measured frequency. Through each material, there is a lower measured value as compared to the initial designed frequency as the S band frequency steps higher. The notable change that is observed in this research shows that as the frequency increases, the return loss has an increasing trend.

Thus, should this method of measurement is to be applied similarly for the use in the testing of concrete, the proposal is that the antenna should be designed using the lower S band frequencies. Consequently, the antenna would be easier to fabricate at the university laboratory because of the patch dimensions and substrate size for lower S band frequencies. Since the simulations here are conducted on cubes of materials measuring 15 cm x 15 cm x 15 cm dimensions, the actual real-life testing can then be also performed on physical concrete moulds which are commonly used in the industry or (civil engineering) laboratory. The research established that future work of designing the antenna and performing actual testing on concrete of various strengths.

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