Effect of Substrate Scaling on Microstrip Patch Antenna Performance

Ahmad Esmaeilkhah[1], Changiz Ghobadi[1], Javad Nourinia[1], Maryam Majidzadeh[2]

[1] Electrical Engineering Department, Urmia University, Urmia, Iran.
[2] Department of Electrical and Computer Engineering, Urmia Girls Faculty, West Azarbaijan branch, Technical and Vocational University (TVU), Urmia, Iran
*Ahmad Esmaeilkhah, E-mail: a.esmaelkhah@urmia.ac.ir

Abstract

The Maxwell field equations (MFEs), as an ecumenical model of electromagnetic phenomena, are scale-invariant under Lorentz Transformation (LT). To apply LT, some considerations are required which are not all practically available or technologically attainable; hence, the scale-invariant feature may not be reached effectively. Paving the way to focus on this issue, the effect of substrate thickness scaling as an uncontrollable parameter, is explored on eight identical patch antennas with different substrate thicknesses. In this way, the resonant frequency and complex value of S_{11} are measured. The effect of manufacturing tolerances of dielectric thickness on resonant frequency deviation and S_{11} magnitude are carefully studied, too. Also, the unwanted distortive effect of selected electrical connection, say as a female SMA connector, is investigated at higher frequencies. The obtained results are comparatively analyzed which confirm the practical bottlenecks in meeting the antenna parameters scaling.

1. Introduction

The inherent contradictions arising from applying the Galilean Transformation (GT), which manipulates the three Euclidean physical dimensions of the universe, to Maxwell equations [1, 2, 3] stimulated Lorentz [4] and Minkowski [5] to launch a more suitable transformation. Lorentz transformation (LT) which ties up the three-dimensional space and the time, redefines the analytical structure of physics by space-time coordination system to which Maxwell equations (MEs) are scale-invariant [3, 4]. The validity of MEs is independent of structural size, complexity, and speed (including time). Also, this is why a half-sized antenna is expected to resonate at frequencies which are twice the resonant frequency of originally-sized antenna. The advent of radio detection and radar technology and also the development of scaling methods for radar cross section (RCS) measurement, motivated some theoretical investigations on the scale-invariant property of MEs and its applicability both in measurement and prototyping of electromagnetic structures [5, 6]. Although the attained results revealed some difficulties with these methods; they are still in use especially in the design and simulation of huge antennas and some measurement techniques in anechoic chambers [7].

So far, little attention has been paid to study and research on effect of antenna parameters scaling on scale-invariant nature of Maxwell field equation (MFEs) [8. 9]. Easy and cost-effective manufacturing nature of microstrip RF structures opens an interesting research topic on limitation and advantages of structural scaling. The results provide the opportunity for the future attempts in scaled-prototyping of microstrip-based structures. This paper aims at studying the effect of substrate scaling on microstrip patch antenna performance, focusing on some technical considerations and paving the way for future studies. In this way, section 2 addresses the applied methods and materials. Then, section 3 discusses the obtained results. Eventually, section 4 concludes the paper.

2. Methods and Materials

Scaling procedure, both in simulation and manufacturing, requires some special considerations which ensure the correct transformation of dimensions, parameters, calculations, and also controls the level of errors [8].

2.1. Simulation and Pre-manufacturing Considerations

The validity of MFE is independent of physical properties, complexity, and structure type. Hence, the expected electrical properties such as resonant frequency, S_{11}, etc. are not a matter of interest. With the aim of preserving the generality of study, a simple microstrip-fed rectangular patch antenna is studied. Figure. 1 illustrates the antenna configuration and dimensions. It is supposed that this antenna is a scaled down version of an original one. The proposed antenna is printed on FR4 substrate with $\varepsilon_r \approx 4.4$ and thickness of 1.6 mm. As shown in Figure. 1, the overall size of the antenna is 39.74×23.00mm^2. The 11.50×11.50mm^2 square radiating patch is excited by a simple rectangular 22.49×0.70mm^2 feed line.

Note that the simulation studies are carried out with Ansoft High Frequency Structure Simulator (HFSS) version 13.0, using detailed information listed in Table 1. In this table, further explanations could be found regarding the simulation studies details.

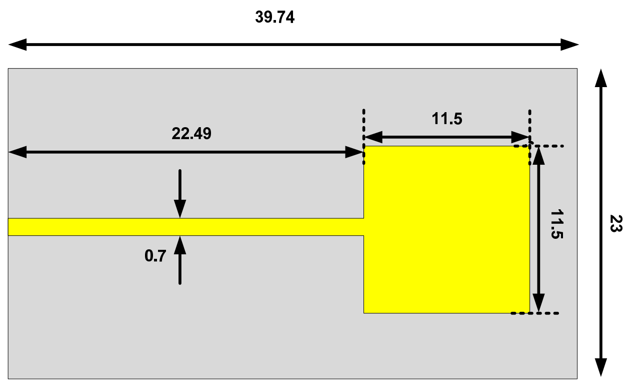

Figure. 1. Configuration and dimensions of the microstrip antenna. All the dimensions are in millimeters.

Table 1: The investigated system specifications in simulation studies

Simulation Parameter	Selected Value or Option	Description
Maximum Number of Passes	20	The value selected experimentally to ensure good convergence of simulation for all SFs.
Maximum Delta S	0.01	To control the S-parameters errors and its convergence.
Simulation Bandwidth	$0.01f_s$	To equalize the computation effort of numerical calculation among all SFs.
Absolute f_r deviation	$<\%0.086f_s$	To ensure the f_s and f_r are adjacent sufficiently and calculated experimentally.♣
Metallic layer Thickness	0.35µm	Standard for available PCB production technology (not Scaled).
Surface Roughness	0.017µm	Standard for available PCB production technology (not Scaled) [11].
Conductivity	$5.8\times10^{+7}$ (S/m)	Not Scaled due to lake of replacement materials for various SFs.
Air Box	Scaled automatically, using the value of f_s, to eliminate unwanted reflection from boundary.	
Waveport	Scaled automatically, using SF's value, to ensure appropriate coverage of feed line's excitation area.	

♣ f_s is simulation frequency, HFSS uses this value for mesh operation and the f_r is the calculated resonant frequency of antenna.

Eight antennas, named as B_1 to B_8 correspond to antennas with substrate thickness of 3.2 mm (SF=1 or B_1) to a substrate thickness of 0.25mm (SF=0.078125 or B_8). There are three factors which could not be scaled at all. These are discussed in the following subsections 2.1.1 and 2.1.2 Also, some other factors are scaled in a different way such as the one in the subsection 2.1.3.

2.1.1. *Electrical Conductivity*

As there is difficulty in scaling up the conductivity of metals and also a limited range of conductivity offered by metals, the conductivity parameter is left unchanged for different SFs. Of course, it should be mentioned that conductivity scaling is significant because of its effect on metals surface resistance [5].

2.1.2. *Surface Roughness*

As the roughness of the metallic surfaces affects its resistive properties at higher frequencies [10, 11], it is also required to be scaled. There are many practical techniques to reduce the roughness such as chemical or laser etch [12, 13]. However, these techniques are not cost-effective. The typical RMS roughness of metallic surface is considered to be about 0.017µm for different SFs.

2.1.3. *Simulation Boundary and Truncation Error*

The simulation boundary is also scaled without direct use of SFs. The absolute difference of f_r and f_s, for different SFs are tuned to be less than %0.086 of f_s. In this case, if the size of the simulation boundary is tuned by f_s, the reflection from surrounding boundaries would be negligible.
The digital electrical measurement devices generally utilize quantization method to truncate the least significant digits of a real number. To equalize the final truncation errors in measurement and simulation, the number of retained digits is considered to be 10 for measurement and 16 for simulation. Based on the results obtained in [14], the unbalanced number of significant digits avoids the unwanted ~%0.01 truncation error in simulation results as calculated in (1).

$$E_{t_{Max}}(16,10) = 100 \times \left(1 + \frac{10^{10}}{10^{16-10} - 1}\right)^{-1} \approx \%0.01 \qquad (1)$$

This value is also the upper limit of normalized truncation error while measured and simulated results are compared.

2.2. Antennas Manufacturing

The challenging issues during the initial ordering and manufacturing process of antennas are as follows:

2.2.1. *Keeping ε_r Constant for Different SFs.*

Glass-reinforced epoxy laminated sheets such as FR4 are typically low-cost flame redundant sheets. Hence, their compositions differ slightly for different manufacturers, even in different product batches of the same manufacturer. This is while; the antennas should be printed on sheets with constant ε_r for all thicknesses. To retain the best possible conditions, the FR4 sheets were chosen form a single and known vendor and from a single batch of production. So use of identical materials during the manufacturing process of FR4 sheets is assumable.

2.2.2. *Variation of Dielectric Thickness for Different SFs*

Manufacturing tolerances of FR4 sheets are a very critical issue in the present study. This is mostly due to the sensitivity of capacitance of rectangular patch and its final resonant frequency to the thickness of the substrate. The length and width tolerances affect the total size of the antenna at the edge of the antenna's structure and far from the patch center. To minimize the effect of this tolerance on the results, all the eight antennas are printed on a nearly identical dielectric with different thicknesses and are cut off using standard Computer Numerical Control (CNC) router device.

2.2.3. The SMA Connector

As a well-known fact, the SMA connector is required in the measurement process. As all of the standard RF connectors have predefined mechanical size, there is no way to scale them up or down. A female SMA connector with minimum available size is selected and soldered carefully. As all of the antennas use the same connector, its effect on performance would be the same for all the SFs. Figure 2. illustrates the manufactured antennas.

Figure. 2. The eight manufactured antennas. The standing one is B_8, SF=0.078125.

3. Results and Discussion

The fabricated antennas were connected to a calibrated Vector Network Analyzer (VNA) to conduct the measurement process. The acquired results are sorted, post-processed, and compared to the simulation results. Five different sets of data are extracted as follows.

3.1.1. S_{11} Variation

The minimum points in S_{11} curves of the proposed antenna vary while the substrate thickness and the SF change. Figure. 3 compares the S_{11} curves of the antennas obtained at 400MHz (±200MHz) span around their resonance. Interestingly, the magnitude of S_{11} decreases as SF changes from 1 to 0.15625 and the curves seem to be flatter. Due to scale invariability of MEs, this flatness is definitely predictable while the frequency axis is not normalized to expected fractional bandwidth.

3.1.2. Deviation of Measured Frequency

Deviations of the simulated and measured resonance frequencies for different SFs are shown in Figure. 4. Close agreement of the simulated and measured results result in slight deviations. As shown, this deviation is SF-dependent and is partially due to the unscaled SMA connector, especially at higher frequencies. The minimum and maximum deviations are measured at SF=0.6875 (B_3) and SF=0.078125 (B_8), respectively. Decreasing the substrate thickness yields in +%17.18 drift in resonance frequency. The manufacturing tolerances resulted in unexpected fluctuation of the measured curve around SF=0.6875(B_3) and SF=0.3125(B_6), as will be discussed later.

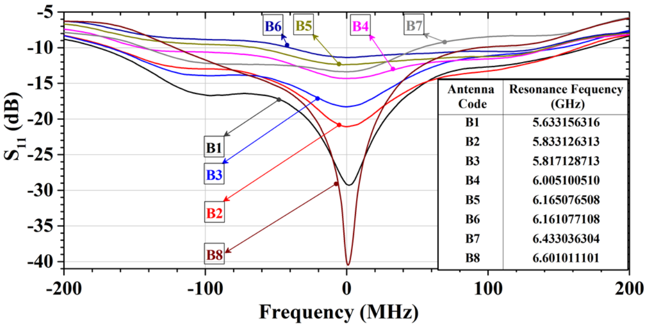

Figure. 3. Measured magnitude of S_{11} for various SFs in 400MHz span around the resonant frequency of various antennas.

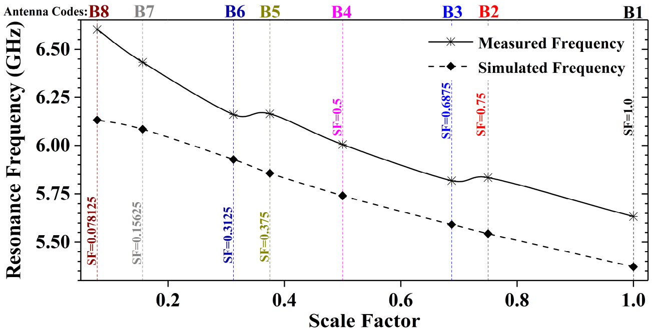

Figure. 4. Deviation of measured resonance frequencies from simulation results.

3.1.3. Mechanical Tolerance Effects

The associated mechanical tolerances of the manufacturing process for length and width of antennas and raw FR4 sheet are measured using two calibrated calipers and then are averaged. The acquired data, normalized at each measurement axis, are separately shown in Figure. 5.

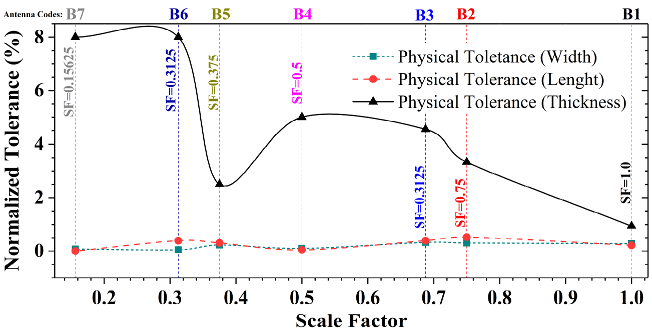

Figure. 5. The normalized physical tolerances of manufactured antennas.

As can be seen, the normalized mechanical tolerances are less than %0.53of their exact values. This is while; the maximum normalized tolerances are obtained for substrate thickness as high as %8. The raw FR4 sheets with different thicknesses have constant manufacturing tolerances which are more evident as the SF decreases. The measured and normalized thickness tolerances for SF=0.15625 is eight times of its counterpart for SF=1. The measurements for the antennas with SF=0.078625 are not performed due to the disability of measurement device to measure the tolerances.

3.1.4. S_{11} Magnitude Deviation

As frequency increases, the measured S_{11} for different SFs deviate considerably from the simulation results, as seen in Figure. 6. As the overall behavior of two curves from SF=1 to SF=0.15625 are similar, the measured deviation can be explained by un-scaled SMA connector and its non-ideal frequency response. For B_7 and B_8, deviation reduces and reaches to ~%-275 of its initial value (SF=1). As well, %25.16 drift in S_{11} magnitude is observed for B_1 to B_7.

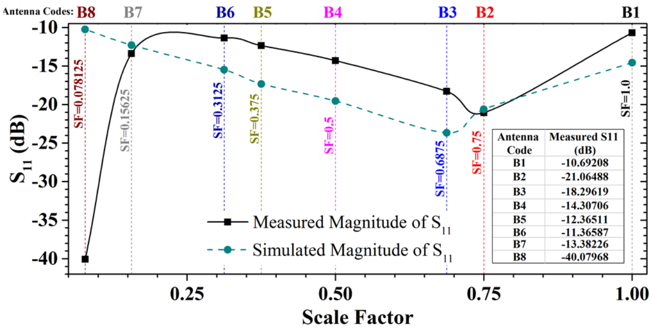

Figure. 6. Dependency of measured and simulated S_{11} magnitude to the scale factor.

Figure. 7 illustrates the normalized frequency deviation between simulated and measured results. Up to B_6 (SF=0.3125), the changes of simulated and measured curves are smooth and to some extent, are predictable. But the unusual changes of measured S_{11} for B_7 (SF=0.15625) and B_8 (SF=0.078125) increases the deviations, unexpectedly. +%0.47 drift in deviation between measurement and simulation is observed. As it was shown in Figure. 4, SF variation between 1 and 0.0078125, (Thickness= 3.2mm to 0.25mm), relocates the resonance frequency of antenna around 0.9678GHz, starting from about 5.633GHz. As can be seen in this figure, the relocation rate of f_r is linear, but the actual resonant frequencies and their normalized deviation from the simulated ones exhibit exponential-like variation, as shown in Figure. 7.

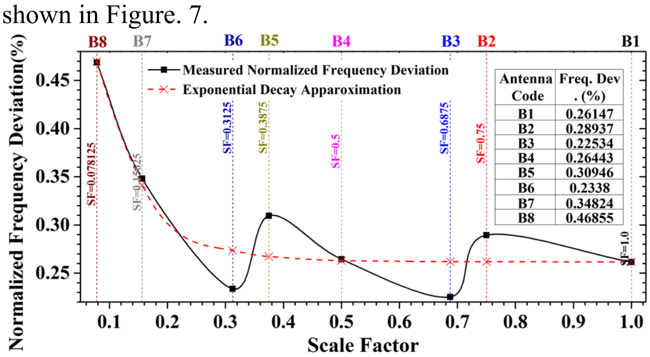

Figure. 7. The normalized frequency deviation between simulation and measurement results.

To reproduce the results, the associated parameters of the decaying exponential approximation were calculated as:

$$NFD(\%) = 0.262 + 0.208e^{-(S-0.078)/0.081} \quad (2)$$

Which *NFD* is the normalized frequency deviation and *S* is the scale factor. As shown in Figure 7, this type of approximation shows good convergence at its two ends and also is stable enough.

Fluctuation of S_{11} curve of no-load SMA connector in a wide range of frequencies is an inherent characteristic of these connectors. Obviously, excitation at higher frequencies results in unwanted radiation from its metallic surfaces. Figure. 8 illustrates the no-load S_{11} of the SMA connector which demonstrates a considerable reduction in S_{11} magnitude at higher frequencies. Also, to illustrate the decaying behavior of S_{11}, the associated parameters of logistic approximation curve were calculated. The curve could be expressed mathematically as:

$$S_{11}(dB) = \frac{-2.035+3.577}{1+\left(f/5.742\times10^{9}\right)^{10.87}} - 3.57; 4 \le f \le 7 \quad (3)$$

Which f is the frequency in gigahertz and $4 \le f \le 7$.

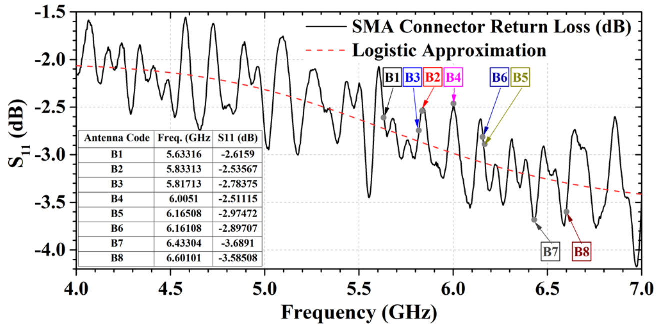

Figure. 8. The magnitude of measured S_{11} without any EM load.

As can be seen in Figure. 9, unusual change in substrate thickness (i.e., between SF=0.65 and SF=0.75) causes unusual changes in S_{11} magnitude and also in deviation of measured resonant frequency from simulation results.

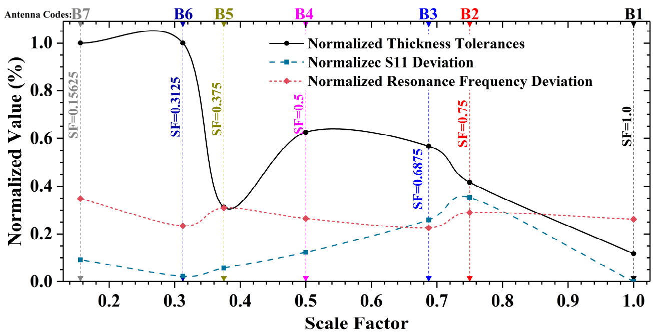

Figure. 9. Thickness tolerances and its effect to f_r and its S_{11}.

The effect also can be seen in Figures. 4, 6, and 7 for B_3 and B_6 antennas. For lower SFs, substrate thickness decreases and any small tolerances are more significant.

The measured values of the S_{11} phase are differentiated in respect to frequency between f=5.57GHz and 6.67GHz. Results are illustrated in Figure. 10. The local extrema of each curve have occurred at the resonance frequency of that antenna. The typical absolute values of dθ/df, for all of the antennas in the mentioned frequency range, are less than 2.5μdeg/Hz. However, this value increases up to 3 times of its typical value at their corresponding resonant frequency.

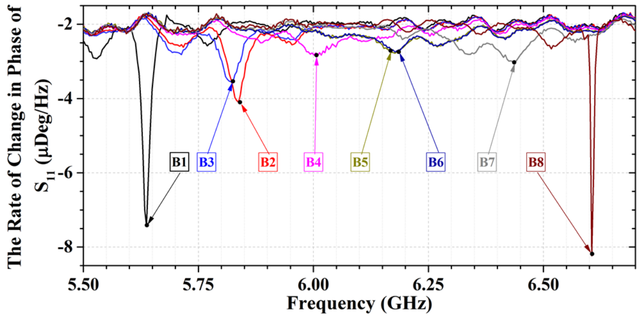

Figure. 10. S_{11} change-rate versus frequency. The marked points are the measured phase at the resonant frequency of their corresponding antennas.

4. Conclusion

The thickness scaling of the FR4 substrate in microstrip-fed rectangular patch was investigated. Obtained results for eight antennas with different substrate thickness revealed that decrease of substrate thickness from 3.2mm (SF=1) to 0.25mm (SF=0.078125) causes +%17.18 drift in resonance frequency and %25.16 drift in S_{11} magnitude for B_1 to B_7. Moreover, +%0.47 drift in deviation between measurement and simulation was observed. The manufacturing tolerances of FR4 sheets for different SFs resulted in a meaningful impact on the variation of simulation accuracy. On the other hand, PCB production tolerances in length and width of antennas have almost no considerable effects (less than ~%0.52 of the measured dimension). In contrast, the maximum normalized tolerances are obtained for substrate thickness as high as %8. Undesirable effects, especially at higher frequencies, were observed for SMA connector. The phase of measured S_{11} was differentiated and the extrema was noticed in the vicinity of the resonance frequency of that antenna. This notice validated the measured results. The generality of Maxwell Equations, as the best ever-known analytic description of harmonious behaviors of electric and magnetic fields, generalize the documented attempt to other microwave active or passive structures.

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