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Performance Comparison between the FR4 Substrate and the Rogers Kappa-438 Substrate for Microstrip Patch Antennas

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Abstract— In this paper, theoretical modelling of the microstrip patch antenna parameters is presented. The modelling is backed by simulations and measurements results. The novelty lies in the comparison in performance between the new Rogers Kappa-438 substrate and the FR4 substrate, based on the dissipation factor, is made. Specifically, the novelty is in the comparison targeted at the electromagnetic energy harvesting patch antenna performance affected by the dissipation factor (loss tangent). Two circular microstrip patch antennas at the 1.8GHz cellular band were designed; one based on the FR4 substrate; the other based on the Kappa-438 substrate. The comparison is based on both simulations and measurements results. The performance metrics are overall size, return loss, radiation patterns and gain.
Keywords— electromagnetic energy harvesting, microstrip patch antenna, antenna return loss, plane radiation, antenna gain, antenna impedance, FR4 substrate, Rogers Kappa-438 substrate.

I. Introduction

The sources of the RF electromagnetic energy are quite few. The dominant ones that are around us are those used for wireless mobile communications implemented at radio frequencies. This makes their harvesting practical from a product point of view. Of those wireless mobile communications are the cellular carrier bands that are oriented around 900MHz, 1800MHz and 2.1GHz. Moreover, with the advent of 4G, there are 3.5GHz and 5GHz bands. In addition to the cellular service bands, there are the WiFi and Bluetooth bands oriented around 2.4GHz. The levels of these ambient energies vary considerably according to their band of operation; theoretically, the lower the frequency band is, the higher the level is.

Harvesting these energies is a challenging task yet it can be accomplished. The two major components that are used to accomplish this feat are the microstrip patch antenna and a rectifier circuit; called a rectanna.

Several factors and parameters dictate antenna design in general and microstrip antenna design in particular. Of the parameters that affect antenna design are gain, polarization, and return loss among many. Of the parameters affecting microstrip antenna design are shape (structure) and bandwidth. Several factors and parameters affect the rectifier circuit design. Of those factors are the harmonic generation, RF-to-DC conversion ratio or efficiency, and matching among others. An optional part is a voltage booster or a step up converter

Microstrip antennas found many applications in communications. Their compact size, ease of fabrication, ease of installation, performance; among many attributes; have found usage in government and commercial applications and products such as aircraft, satellite, missile, mobile and wireless communications. These microstrip antennas can be synonymously referred to as patch antennas. When they are combined with PIN diodes and varactor diodes at the load, they can add another dimension to their importance, which is versatility, versatility in terms of variable resonant frequency, impedance, polarization, and radiation pattern [2] in what is known as adaptive antenna elements. The most popular of all are the rectangular and the circular.

Of particular application microstrip patch antennas have found usage, is RF energy harvesting. In RF energy harvesting, RF and electromagnetic ambient energy can be collected, recycled and converted to DC to charge low voltage devices and products such as RFID tags and scanners/readers, wireless sensors such as those used in medical devices, and to many extents, mobile handsets. These examples are among many where microstrip patch antennas have found usage.

The theory, background and analysis of microstrip patch antennas have been treated extensively in the literature and many books. Of the many parameters that affect the patch antenna design are the substrate parameters that include its thickness h, its dielectric constant ϵ_r and its loss tangent denoted as $tan\delta$. Also, of the parameters are the conductor (patch) parameters such as the thickness of the conductor t, the width w and the length L. Of the parameters that affect the patch antenna design as well is the type of antenna feed i.e. the source/sink of the antenna. There are four antenna feed types or configurations: microstrip feed, coaxial feed, aperture-coupled feed and proximity-coupled feed.

Several energy-harvesting prototype antenna designs have already been published in the literature [3]–[20], [22]. In [3], several different patch antenna designs targeted at RF energy harvesting applications were reviewed. The designs were compared based on re-configurability, miniature size, and harmonic rejection. While the re-configurability designs in this comparison covered frequencies from two to seven GHz, it did not cover frequencies below two GHz where RF power is larger and therefore the energy harvesting is potentially larger. The cost of designing at lower frequencies is a larger size antenna.

II. THEORETICAL MODELING

The new Rogers Kappa-438 substrate (ε_r = 4.38, tanδ = 0.005) is supposed to be an alternative in performance to the FR4 substrate (ε_r = 4.25, tanδ = 0.015) since they both have similar characteristics in terms of the dielectric constant (ε_r), both have the same substrate height, h = 1.524mm. When both have the same substrate thickness, the dielectric constant and the loss tangent affect the overall size, return loss, radiation pattern and gain of the microstrip antenna patch. The advantage of Kappa-438 over FR4 is in terms of the loss tangent. The loss tangent of Kappa-438 is 0.005 while that of FR4 is 0.015. This affects the performance parameters mentioned above. The loss tangent is the ratio of the real part of the displacement current to the imaginary part [1],

$$\tan\delta = \frac{\omega\epsilon'' + \sigma}{\omega\epsilon'} \quad (1)$$

where it reduces to:

$$\tan\delta = \frac{\sigma}{\omega\epsilon} \quad (2)$$

when characterizing microwave materials at a certain frequency. A low loss tangent is a quality of a good dielectric and a high loss tangent is a quality of a good conductor. Therefore, the Rogers Kappa-438 substrate is a better dielectric than the FR4 substrate.

A. Conductance due to Losses

The loss tangent controls the conductance due to dielectric losses in the substrate [2]. The total radiation is accounted for through the radiation conductance, Grad, of the parallel plate structure at hand. The parallel plate structure is composed of the top conducting patch, the dielectric substrate and the ground plane, which is the patch antenna.

$$G_{rad} = \frac{(k_0 a_e)^2}{480} \int_0^{\frac{\pi}{2}} [J_{02}'^2 + \cos^2\theta J_{02}^2] \sin\theta d\theta \quad (3)$$

where Jn(x) is the Bessel functions of first kind of order n and J'n(x) is its derivative, ko is the wave number of free space, ae is the effective radius of the circular patch antenna and θ is the H-plane angle.

$$J'_{02} = J_0(k_0 a_e \sin\theta) - J_2(k_0 a_e \sin\theta) \quad (4)$$

$$J_{02} = J_0(k_0 a_e \sin\theta) + J_2(k_0 a_e \sin\theta) \quad (5)$$

There is also the conductance due to conduction losses Gc and the conductance due to dielectric losses Gd where:

$$G_c = \frac{\epsilon_{m0}\pi(\pi\mu_0 f_r)^{-3/2}}{4h^2\sqrt{\sigma}}[(ka_e)^2 - m^2] \quad (6)$$

and,

$$G_d = \frac{\epsilon_{m0} \tan\delta}{4h\mu_0 f_r}[(ka_e)^2 - m^2] \quad (7)$$

ε_{mo}= 2 for m = 0, ε_{mo} = 1 for m ≠ 0, The total conductance, Gt, is:

$$G_t = G_{rad} + G_c + G_d \quad (8)$$

It is seen from the above equations, that the total conductance due to losses for the FR4 substrate is greater than that of the Rogers Kappa-438 because of the lower loss tangent.

B. Radiation Efficiency

The antenna losses mentioned in section 2.1, are also related to the total quality factor of the antenna such that:

$$\frac{1}{Q_t} = \frac{1}{Q_{rad}} + \frac{1}{Q_c} + \tan\delta + \frac{1}{Q_{sw}} \tag{9}$$

Where; Q_t is the total quality factor Q_{rad} is the quality factor due to radiation (space wave) losses:

$$Q_{rad} = \frac{\iint |E|^2 dA}{\oint |E|^2 dl} \frac{2\omega l \varepsilon_r}{hGt} \tag{10}$$

Q_c is the quality factor due to conduction losses:

$$Q_c = h\sqrt{\pi f \mu \sigma} \tag{11}$$

Q_d is the quality factor due to dielectric losses:

$$Q_d = \frac{1}{\tan\delta} \tag{12}$$

Q_{sw} is the quality factor due to quasi-TEM mode surface wave losses. The radiation efficiency (η) of an antenna, in terms of the quality factor, is:

$$\eta = \frac{Q_t}{Q_{rad}} \tag{13}$$

The gain (G) is related to the radiation efficiency through the directivity (D), such that:

$$G = \eta D \tag{14}$$

C. Resonant Input Resistance (Z_{ant})

The input resistance is related to the total conductance by:

$$R_{in} = \frac{1}{G_t} \tag{15}$$

$$\Delta f^2 {Q_t}^2 VSWR = f_o^2 VSWR^2 - f_o^2 \tag{16}$$

$$f_o^2 VSWR^2 - \Delta f^2 {Q_t}^2 VSWR - f_o^2 = 0 \tag{17}$$

$$VSWR = \frac{-\Delta f^2 {Q_t}^2 \pm \sqrt{(\Delta f^2 {Q_t}^2)^2 - 4(f_o^4)}}{2 f_o^2} \tag{18}$$

Since VSWR cannot be complex and is greater than or equal to 1, this stipulates that:

$$(\Delta f^2 {Q_t}^2)^2 - 4(f_o^4) \geq 0 \tag{20}$$

$$Q_t \geq \frac{4f_0}{\Delta f} \tag{21}$$

The return loss (RL) is:

$$RL = 20\log\left|\frac{\frac{-\Delta f^2 {Q_t}^2 \pm \sqrt{(\Delta f^2 {Q_t}^2)^2 - 4(f_o^4)}}{2f_o^2} - 1}{\frac{-\Delta f^2 {Q_t}^2 \pm \sqrt{(\Delta f^2 {Q_t}^2)^2 - 4(f_o^4)}}{2f_o^2} + 1}\right| \tag{22}$$

$$Z_{ant} = \frac{\Gamma + 50}{\Gamma - 50} \tag{23}$$

III.FR4 AND KAPPA–438 ANTENNA DESIGN

In this paper, the circular patch antenna is used due to its overall reduced size over the rectangular shape. The design frequency is the 1800MHz cellular band, which extends from 1820MHz to 1880MHz in the locality. Fig. 1 shows the FR4 design. Total dimensions are 53.04x59.3mm. An open stub of size 18.6x3mm was employed for matching purposes. The Kappa-438 design is shown in Fig. 2. Total dimensions are 44x44.8mm and no open stub was needed. A total size reduction of almost 9x15mm was achieved.

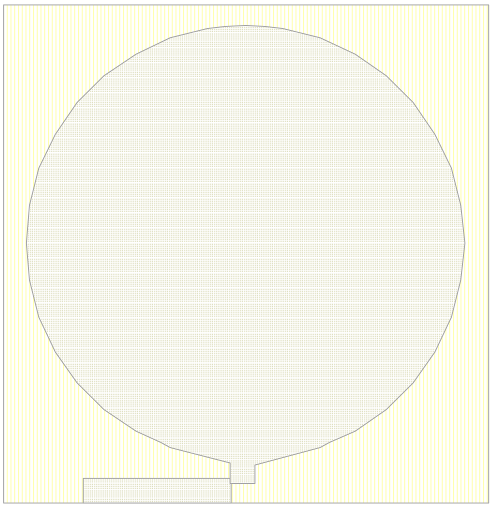

Fig. 1. Simulated FR4 antenna

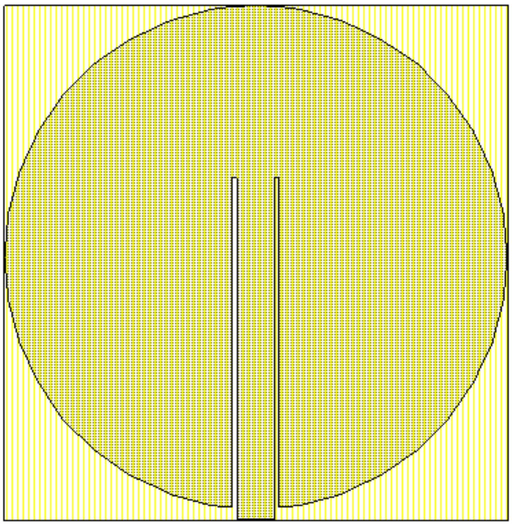

Fig. 2. Simulated Roger's Kappa-438 antenna

IV. SIMULATION AND MEASUREMENTS RESULTS

A. Results for FR-4

Substrate Fig 3 shows the simulated and measured impedance for the FR-4 substrate antenna. It is clearly seen the disparity between the simulated vs. the measured results. In the simulated results, the closest frequency to 50 ohms is at 1860MHz, while that of measured is at 1759MHz. Fig. 4 shows simulated and measured return loss for the FR4 substrate antenna, which is a reflection of the impedance measurements in Fig. 3. While the measured results show good return loss at -17.43dB, it is at a frequency outside the intended operational bandwidth.

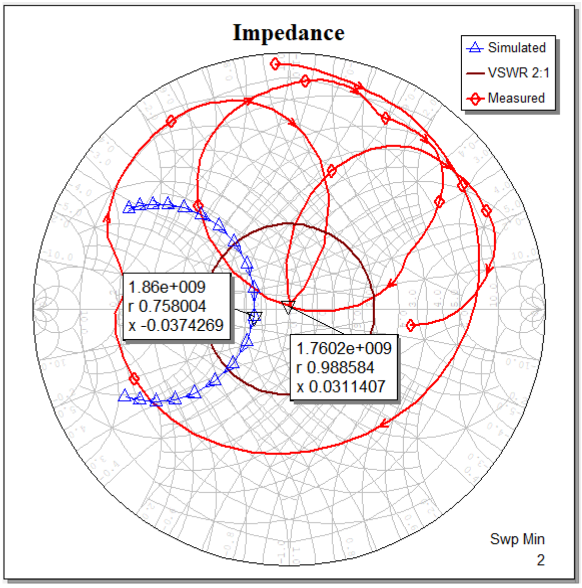

Fig. 3. Simulated and measured impedance for the FR4 substrate antenna

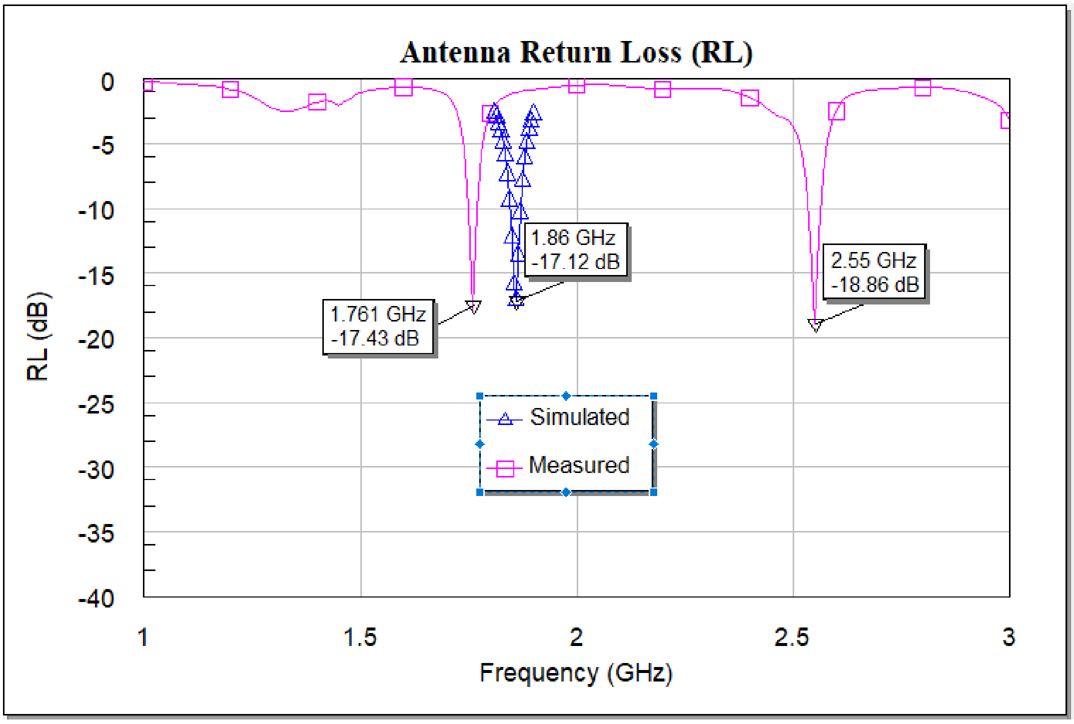

Fig. 4. Simulated and measured return loss for the FR4 substrate antenna.

Fig. 5 shows the simulated broadside gain for the FR4 substrate antenna. A measured value of -1.1dB was obtained. At 1800MHz, there was no received power. At 1900MHz, the received power was -45dBm. At 950MHz, the received power was -43.84dBm.

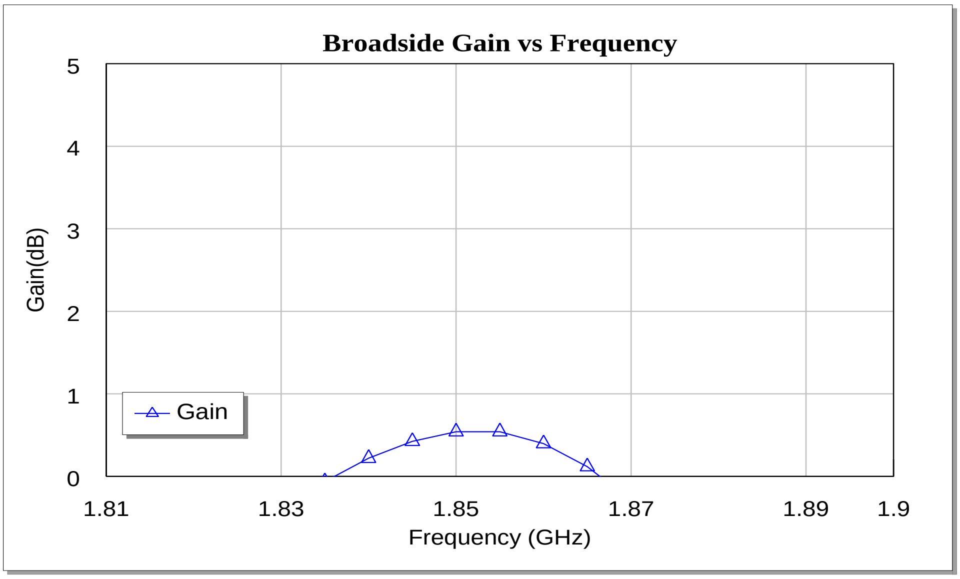

Fig. 5. Simulated broadside gain for the FR4 substrate antenna.

B. Results for Roger's Kappa-438 substrate

Fig. 6 shows the simulated and measured impedance for the Kappa-438 substrate antenna. In the simulated results, the closest frequency to 50ohms, is at 1860MHz, while that of the measured results, it is at 1869MHz; a very good correlation. The difference is only 9MHz. With some inspection of eqns 14-19 and 21, it is evident that the substrate with lower loss tangent has better matching impedance to 50ohms than the one with higher loss tangent at the resonance frequency within the design bandwidth. This explains the better performance of the Kappa-438 substrate over that of the FR4 substrate in terms of the simulated and measured impedances in Figures 3&6. In these two figures, it is shown that, within the bandwidth of operation, the simulated and measured performances agree with the theoretical modelling presented above. Figure 3, shows that a measured impudence is very close to the 50-ohm point, however, this impedance is at a resonance frequency outside the bandwidth of operational design. While Figure 6 shows a measured impedance that matches the 50ohm point and at a resonance frequency that is within the bandwidth of operational design. The results of Figures 3&6 are reflected in Figures 4&7 in terms of the return loss (RL). A better match to 50ohms results into lower return loss for the intended bandwidth of operational design. This is the intended goal of the design of the antenna. As equations (13&14) entail, the radiation efficiency is higher for the antenna with lower loss tangent, and therefore the gain is maximized for maximum radiation efficiency. This is evident from the fact Figure 7 show superior simulated gain performance for the Kappa-438, across the intended design bandwidth, over that of the FR-4 as shown in Figure 5. The above arguments are also reflected on the radiation field patterns where there was barely any received power for the FR4 substrate antenna during measurements. The opposite is not true for the case of the Kappa-438 substrate antenna. This is shown in Figure 9 where it emphasises that the radiation efficiency for the Kappa-438 antenna is better than that of the FR4 antenna.

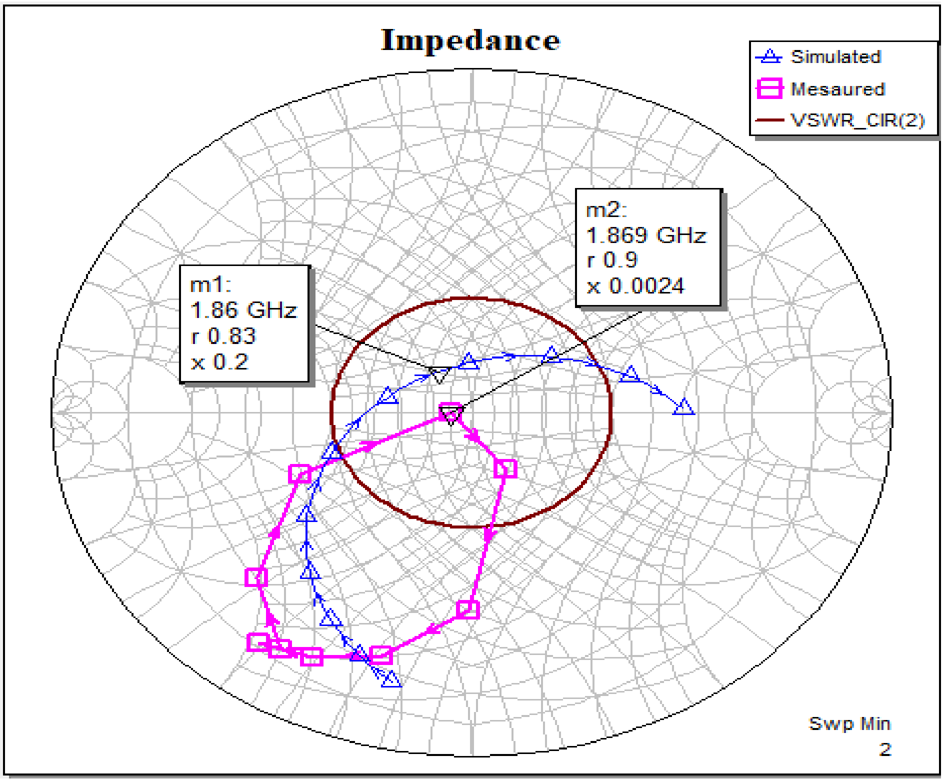

Fig. 6. Simulated and measured impedance for the Kappa-438 substrate antenna

Fig. 7 shows the simulated and measured return loss for the Kappa-438 substrate antenna. The simulated results are - 16.78dB at 1860MHz while that of the measured results, is - 12.94dB at 1869MHz.

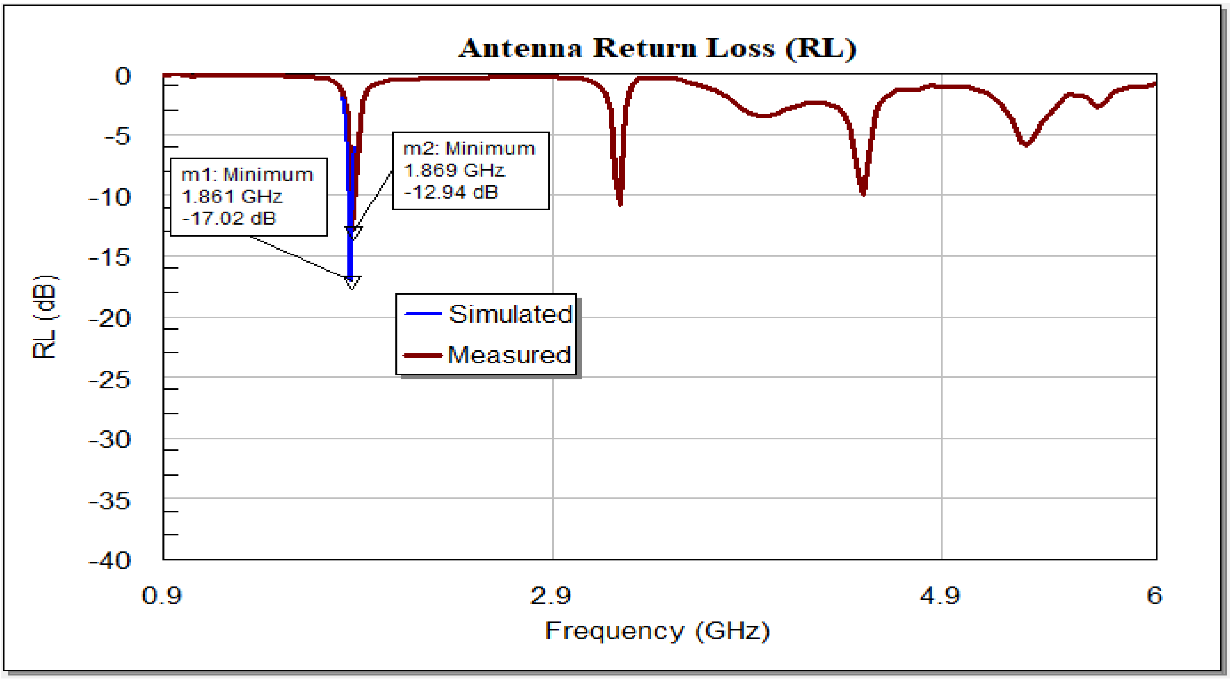

Fig. 7. Simulated and measured return loss for the Kappa-438 substrate antenna.

Fig. 8 shows the simulated broadside gain for the Kappa438 substrate antenna. The measured gain at 1869MHz was 2.9dB, which strongly correlates with the simulated results. Fig.9 shows the simulated and measured horizontal plane field radiation of Kappa-438 substrate antenna. The agreement between the simulated and measured results is apparent in the upper hemisphere of the radiation, suggesting the Kappa-438 substrate measured performance is well suited to correlate with the simulation tool. From Fig. 9, it can be seen that the measured beamwidth is almost 90° which matches, with extreme correlation, that of the simulated results. The measured front to back ratio was - 20dB. Figs. 10&11 show the fabrication of Kappa-438 and FR4 substrate antennas respectively. Please note that the images do not reflect the actual size of the antennas. The actual size is as reported above.

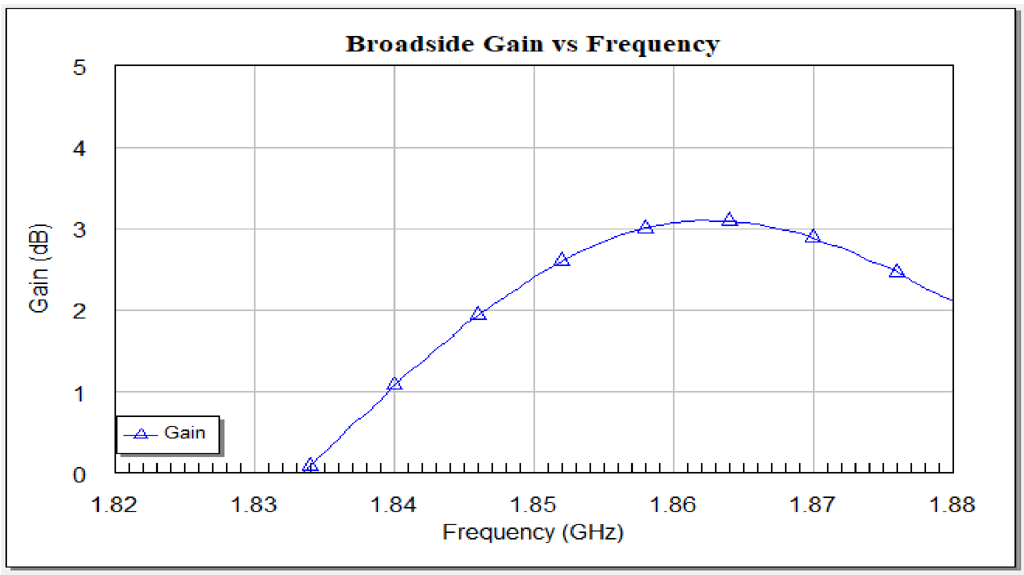

Fig. 8. Simulated broadside gain for the Kappa-438 substrate antenna

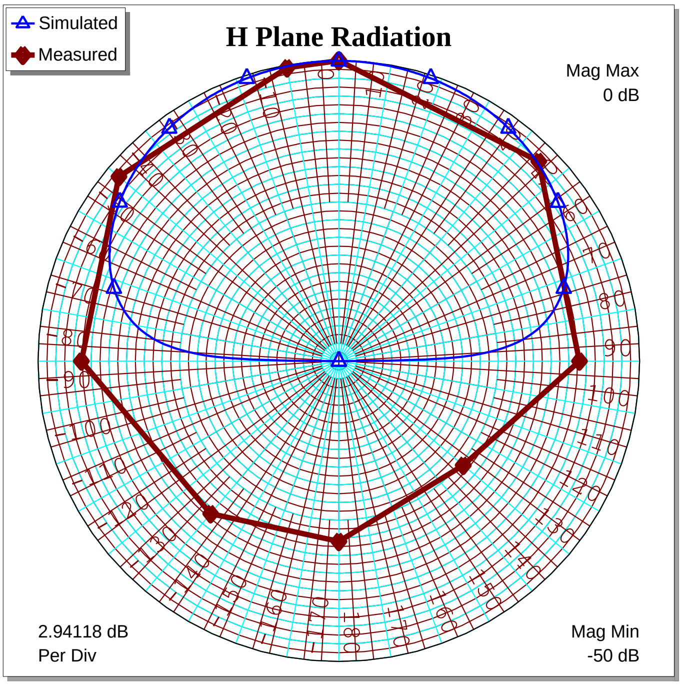

Fig.9. Simulated and measured horizontal plane radiation of the Kappa-438 substrate antenna

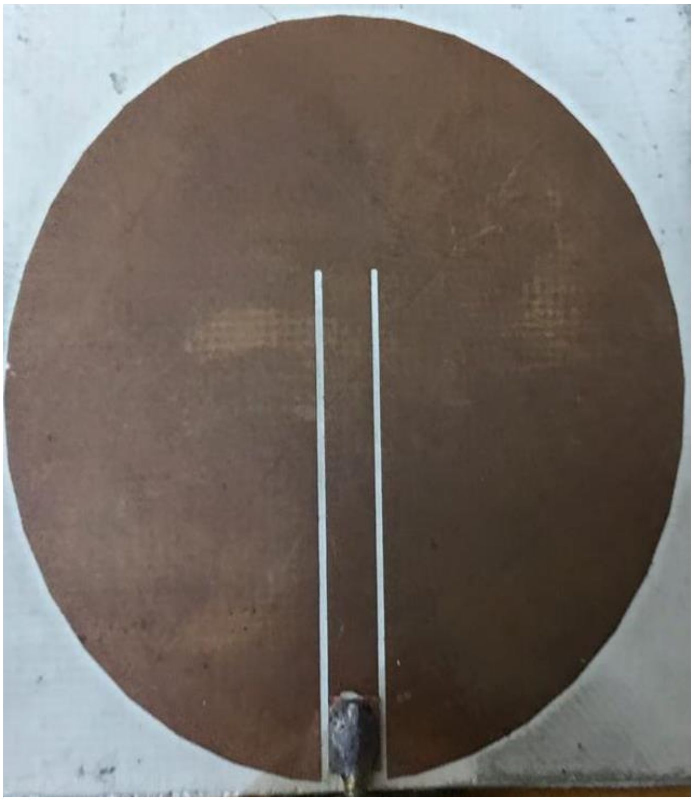

Fig. 10. Fabrication of the Roger's Kappa-438 substrate patch antenna

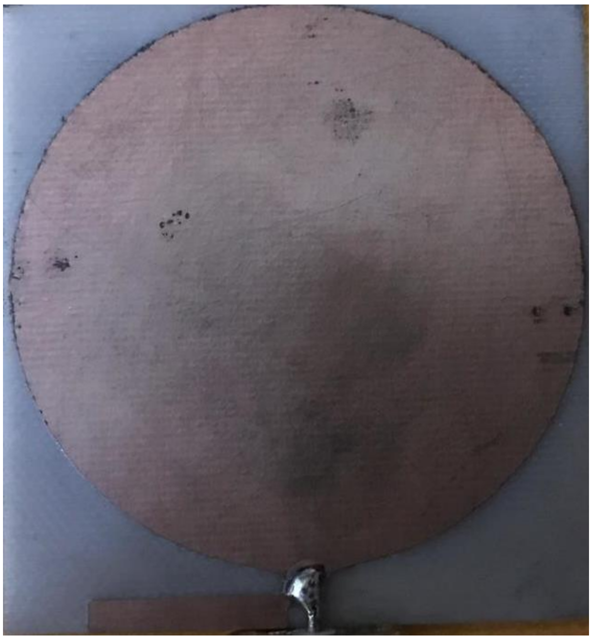

Fig. 11. Fabrication of the FR4 substrate patch antenna

V. CONCLUSION

In this paper, a performance comparison between the FR4 substrate and the Roger's new Kappa-438 substrate was made. The performance comparison included the parameters: size, impedance, return loss, gain and radiation pattern. As presented in the results section, the Kappa-438 substrate antenna outperformed the FR4 substrate antenna in all performance parameters mentioned above, making the new Kappa-438 more suitable for patch antennas dedicated for electromagnetic energy harvesting.

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