Parallel Dual-slot PIFA for 2.45GHz Rectenna Applications

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***Abstract*— Energy harvesting has gained a lot of attention lately especially in the area of miniaturization where the target is smaller devices. The PIFA antenna known for its compact frame is explored here for use in Rectennas. A PIFA antenna was carefully studied and designed in this text yielding agreeable results. Going even further, a pair of slots placed in parallel with each other was included on the patch based on the concept of U-Slots. This specific technique (parallel slots) has not been recorded anywhere to the best of our knowledge. A significant improvement in return loss at the figure of about -42dB was obtained over a bandwidth of 3.02%. Subsequently, results obtained were compared without any slots and with conventional U-Slot for observation. Additionally, the theory outlined helps the reader in appreciating the opportunities offered by the PIFA both in size and possible applications.**

Keywords—PIFA antenna; Miniaturization; U-Slot; Parallel slot; CST

I. INTRODUCTION

The past few years have seen a rise in demand for small antennas to serve in wireless technology. As antenna performance is often tied to its physical dimensions, researchers have concentrated efforts in pushing the limits of miniaturization. The term miniaturization, in essence, involves a surgical reanalysis and adaptation of antenna parameters while retaining the essential features in order to have performing antennas in smaller frames [1]. PIFA antennas have gained wide acceptance in that regard due to their small size, multiband capabilities and ease of mass production [2]. It is for this reason that this document presents an outline of the design of a PIFA to operate within the ISM band at 2.45GHz. This design is intended to be incorporated with a rectifier as part of a rectenna for energy harvesting which will be discussed in a future document. Also discussed are the critical design considerations when modelling the PIFA in Computer Simulation Technology (CST) design studio, a software that enables 3D modelling and simulation of a broad range of RF applications [15]. For an early researcher, this will serve as a platform to understand some of the advancements recorded in miniaturization. Theory of the PIFA is outlined in sections II&III while the U-Slot is introduced in section IV. A discussion of the parallel slot PIFA and subsequent variations of the slot ensues in section V while section VI concludes the text.

II. MICROSTRIP PATCH ANTENNA

Patch antennas are very popular due to their ability to conform to irregular profiles and inexpensive manufacturing costs using modern PCB technology. Their applications are prominent in aviation, satellite, mobile phones and more recently in biomedical implants [3]. Perhaps the most popular among this group is the Microstrip patch. Microstrip antennas are patch antennas that consist of a very thin resonating surface (patch) made of metal and a grounded plane, the two are separated by a dielectric substrate of known thickness. There is no standard form for the radiating patch as it can take almost any shape, although variations of the rectangular, dipole, square, and circular patches are more popular due to their simplicity in both analysis and design [1]. The PIFA discussed in this text is a form of patch antenna.

Table 1: A comparison of some existing antenna types

Antenna Type	Monopole	Slot	Microstrip patch	PIFA
Parameters				
Radiation pattern	Omnidirectional	Averagely omnidirectional	Directional	Omnidirectional
Gain	High	Moderate	High	Moderate to high
Design and Manufacturing	Somewhat difficult	Less difficult	Easy	Easy
Application	Mostly UHF/VHF applications	Radar, base stations	Satellite communication, aviation	Handheld devices
Merits	Compact size, low cost, large bandwidth	Simplicity in form, tuneable	Low cost, low weight, easily integrated	Small size, low cost, low SAR
Cons	Difficult fabrication at higher frequencies	Size constraint when intended for handheld devices	No band pass filtering effect, delicate matching requirement	Narrow bandwidth

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III. HOW PIFA RESONATES

A relatively new entrant into the antenna formation (around 1984) [4], the PIFA is widely used in handheld devices due to its small, lightweight profile which complies with current trends in the mobile industry. It also has good SAR records within regulator standards [5]. The name comes from it being shaped like the letter 'F' facing downwards and it may be considered a variation of the earlier IFA antenna. The concept of the PIFA antenna is derived from a half wavelength antenna with a square patch sitting on top of a dielectric of known ε_r. At the center of the square patch, the voltage is zero which means a short circuit is present between the patch and the ground plane, which in turn means that the other half of the patch is rendered ineffective, whether it exists or not will not matter to the radiation of the antenna. Since the dimension is halved, we now have the antenna length at $\lambda/4$ placed at a height, h above the substrate with the same current and voltage distribution as the $\lambda/2$ patch. A shorting pin or plate made of conducting material connects the patch to the substrate and its width, w_s controls the resonating frequency of the PIFA. Location of the feed relative to the shorting pin in turn controls the impedance seen at the input of the antenna [1]. Therefore in designing a PIFA, it is assumed that the average combination of both distances at the edge of the antenna will equal $\lambda/4$. Thus its design formula is generally given by:

$$L + W - w_s = \frac{\lambda}{4} + h$$

with w_s as the width of the shorting plane.

The height, h is very small and often is neglected. With that assumption and adding the convenient scenario when the shorting plane runs along the entire width, we would obtain the value of the length to be equal to $\lambda/4$. If the reverse is taken to be true, i.e. the shorting is just a pin, then the L and W would sum up to give $\lambda/4$. To solve for the resonant frequency;

$$f = \frac{v_0}{4(L + W - w_s - h)\sqrt{\varepsilon_r}}$$

Despite its merits, the PIFA has a narrow bandwidth of operation. Some researchers have addressed this by using a fractal antenna design as the resonant patch [7],[8], while in [9], characteristic mode theory was used to study the pattern of ground plane size with regards to bandwidth and then apply that theory to enhance bandwidth. Even though just an experimental study under impractical conditions, a promising report nonetheless, suggests PIFA miniaturization using magneto-dielectric and dielectric fillings to study the radiation mechanism of the PIFA heavily reliant on the position of the filling [10]. To further reduce the size of the PIFA, the radiating patch can simply be brought closer to the substrate, i.e. by shortening the height, however this method directly affects the antenna impedance. Although the drawbacks in this method of reducing the height can be compensated by adding a capacitor to enhance the match in a process called capacitive top loading. The capacitive loading reduces the resonance length from $\lambda/4$ to less than $\lambda/8$ at the expense of bandwidth and good matching [11].

IV. U-SLOTS

Improving the bandwidth by creating slots on the antenna was first introduced in a 1995 paper by Huynh and Lee [6]. They conducted several experiments and concluded in their report that there exists an added resonance caused by a U-shaped defect deliberately carved on the patch. It was established thereafter that bandwidths of up to 40% for air/foam substrates of thickness about $0.08\lambda_0$ and in the region of 30% for material substrates of similar thickness may be realised [12]. The U-slot may also be used to extend the antenna operation to more than a single band which eliminates the need to use stacked patches, further aiding the reduction in antenna size [13]. However, as mentioned earlier, the U-slot was a result of experimental studies, thus initially there was no empirical formula derived to aid in a seamless design process as is commonly obtained in other variations of the patch antenna. After an extensive study of previous experimental results and methods of moment (MoM) simulations, an attempt at coming up with a design procedure in a series of twelve steps was outlined in [14] and showed some promising equations, albeit only limited to electrically thin substrates. After that, another attempt to capture the complex relationship between the slotted antenna geometries and characteristics have been reported in [12].

V. PIFA WITH PARALLEL SLOTS AT 2.45GHZ

Using the design equations from the last two sections, a PIFA resonating at 2.45GHz was modelled with a length, L and width, W in the value range of 16.5mm and 30.0mm respectively. These parameters were obtained and then manually toggled to select the best performing ones. CST design studio was used to model the structure, a ground plane made of conducting material was the lowest point on the z-axis, a common thickness of the ground is 0.035mm. An FR-4 substrate of height 1.6mm and $\varepsilon_r = 4.4$ was built from the ground plane to serve as the medium. The FR-4 substrate is popular for its inherent fire-resistant (FR) property, low-cost, and modest performance for this range of frequencies. Unlike a regular Microstrip, the resonating patch of the PIFA rests at a height above the substrate whilst being connected to the ground via the shorting pin/plate, for this design the height was initially set at 3mm before being chosen as 2.43mm for best performance. Likewise, width of the shorting was settled at 3.0mm after some iterations. This is observed to directly affect the frequency at which the PIFA would radiate. The unique thing about this design however is the parallel slots of length 2mm and 26mm width that allow for a capacitive coupling. Based on electromagnetic theory, a crowding of currents will exist around the slot edges thereby resolving with the existing patch resonance for an improved antenna performance. The dimensions of the slots were optimized from equations given in [14], partially reproduced below.

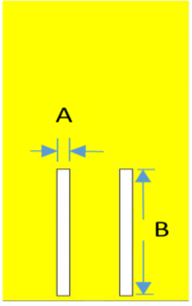

Figure 1: Plan view of the patch showing two slots in parallel

Starting value of slot thickness, A is selected using the following rule of thumb [14]

$$A = \frac{\lambda_r(air)}{60}$$

While the slot length, B, is selected such that

$$\frac{B}{1.5\left(\frac{v_0}{2\sqrt{\varepsilon_{eff}}f_r}\right)} \geq 0.3$$

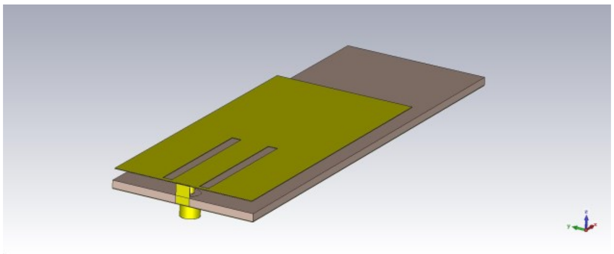

Figure 2: PIFA model with parallel slots

To further help in maintaining the antenna geometry, and also for its ease of impedance matching, a coaxial feed was chosen to be the feeding method of this antenna. It consists of an inner conductor that connects the patch via the dielectric while the outer conductor is connected to the ground plane. The Macros function is an automated computation algorithm which enables us to estimate the dimensions of the feed, here considered as 0.7mm and 2mm for the inner and outer cylinders respectively. For this design the position of the feed to the shorting was adjusted to obtain an optimum match.

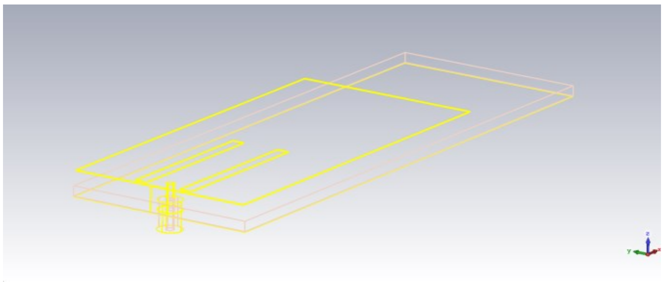

Figure 2: A wire representation showing the coaxial feed

Teflon is the material used for the coaxial cable modelling. Figure 3 shows the simulated return loss for this antenna with the plot minimum at 2.45GHz while figure 4 is the smith chart impedance representation.

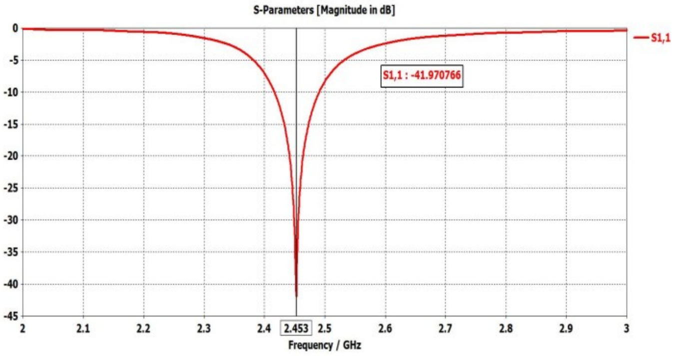

Figure 3: Simulated S-Parameter, RL of about -42dB

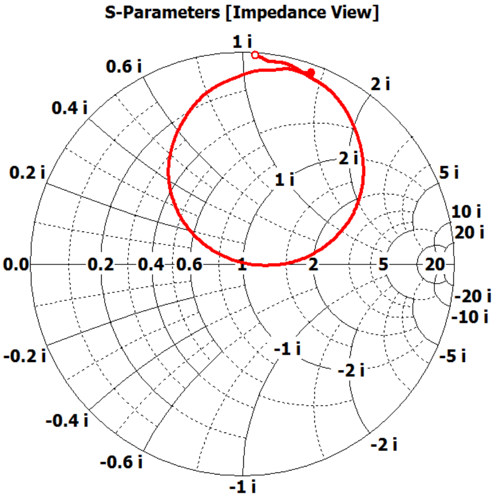

Figure 4: Impedance plot of S11

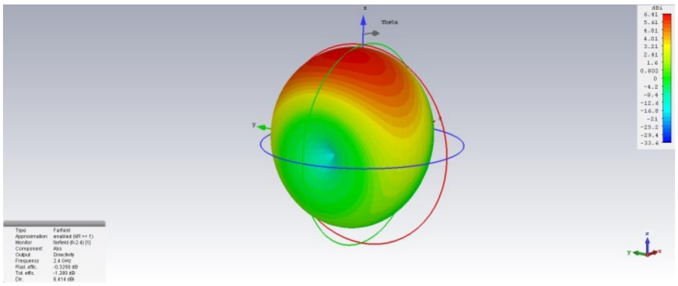

Figure 5: Radiation pattern at 2.45GHz

Our -10dB markers show a bandwidth of 3.02%. Keeping the patch dimensions fixed, the parallel slots were replaced with annealed copper to make the entire patch area of uniform material. This was observed to shift the resonating frequency of the antenna further up close to 2.5GHz while at the same time affecting the return loss.

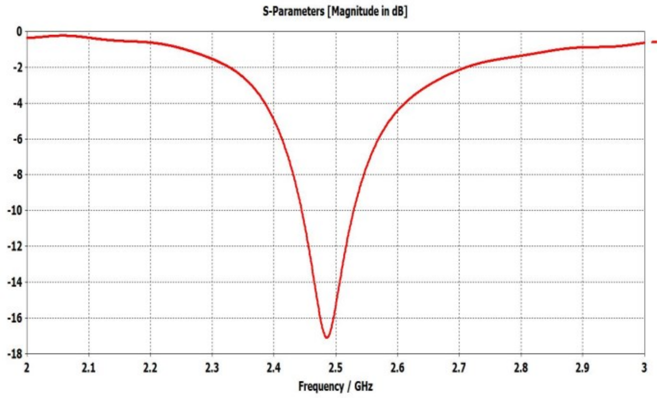

Figure 6: Return loss for no slots

For comparison with the conventional U-slot antenna, a U-slot was added on the patch of this antenna and as shown below, it retained the resonating frequency of the parallel slot but showed a weaker return loss than that of the parallel slot. It should be noted that the U-slot yielded better results than the same antenna without slots.

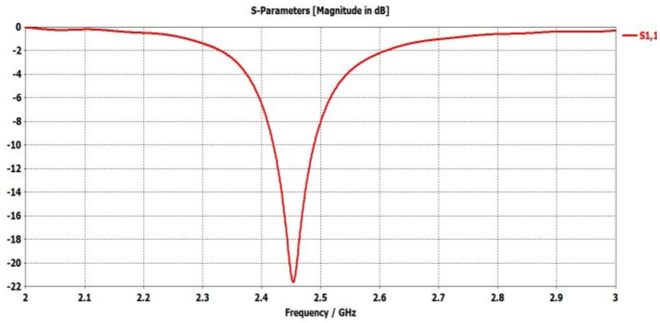

Figure 7: Return loss for U-Slot

VI. CONCLUSION

Taking from the conventional U-Slot approach to improving PIFA performance, herein we introduce a parallel Dual-slot PIFA that surpasses the U-Slot in performance and also in ease of manufacturing. This was derived from a close observation into the equations attempting to come up with a standardized design method. With the performance obtained at this desired geometry, the parallel dual-slot looks like a promising alternative to the U-Slot for this scenario. At the next stage of the assembly, a rectifier will be built to convert received RF energy into DC power at the centre frequency. At the same time while aiming to achieve direct impedance matching which will further reduce the amount of planar circuitry that will be needed to realise the Rectenna.

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