Flexible milimeter-wave microstrip patch antenna array for wearable RF energy harvesting applications

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Article Info

Article history:

Received Sep 11, 2020
Revised Sep 22, 2020
Accepted Oct 14, 2020

Keywords:

Flexible antenna
Microstrip antenna
RF energy harvester

ABSTRACT

In this paper, a series-fed milimeter-wave microstrip patch antenna array operating at 28 GHz is presented for wearable radio-frequency (RF) energy harvesting applications. The antenna array is made of 4×4 rectangular microstrip elements on a polyethylene terephthalate (PET) substrate to provide conformability when directly attached on human body parts. A 4-way Wilkinson power divider is connected to the array for RF power combining. The overall size of the antenna is 47×28×0.25 mm. The half-power beamwidth (HPBW) of the antenna array can be increased up to 151.9° via structural deformation making it suitable for energy harvesting applications. The performance of the antenna array is investigated in terms of impedance matching, gain and radiation pattern. The average simulated specific absorption rate (SAR) of the antenna is 0.52 W/kg which is well below the safety limit of 1.6 W/kg averaged over 1 g of tissue for 100 mW of input power.

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1. INTRODUCTION

In the next few decades, Internet of Things (IoT) and wireless sensor networks (WSN) will become ubiquitous which will contribute to a significant increase in electronic devices worldwide [1-3]. These devices are designed to assist human in various aspects such as health and environment monitoring, diseases detection, communication and industrial process monitoring and control [4, 5]. To operate remotely, IoT devices are expected to be powered up by batteries. As a result, periodic placement of batteries are needed to ensure continuous operation of the devices. In addition, some of them might simply be replaced with a new one altogether. Over time, the accumulation of this electronics waste will become severe which would eventually lead to pollution. It is reported in [1] that there are about 50 million tons of electronic waste every year. As such, to achieve sustainable development in the long run, renewable energy resources such as radio frequency (RF) energy, solar energy, wind energy and thermal energy are required. One of the interesting options is by harvesting RF energy from ambient milimeter-wave signals that are expected to surround us due to future implementation of 5G standard [6-8]. It is also foreseen that future wireless communication will utilize the higher frequency range compared to the existing networks which currently rely on sub-6 GHz frequency band.

There are numerous research that have been carried out to develop an efficient RF energy harvester to date [9-32]. However, most of the works reported were conducted for current wireless networks such as GSM900, GSM1800 and Wi-Fi. To anticipate the implementation of 5G technology where more spectrum bands will be used particularly in milimeter wave range, a novel RF energy harvester is required to improve the efficiency, size and cost of the current devices. However, there are several fundamental challenges that need to be addressed in order to harvest RF signal at milimeter-wave frequencies.

In RF energy harvester systems, there are several key components mainly antenna, matching network, rectifying circuit and low pass filter. For harvesting ambient RF energy, the input RF signal is transmitted from the transmitters fat the base stations in the vicinity of the harvesting device. Due to the very low power density of the transmitted signals, an efficient RF harvesting device is needed. One of the methods to improve the efficiency of the rectenna and to increase the received power is by utilizing high gain and wide half-power beamwidth (HPBW) receiving antennas. Moreover, the need for flexible RF energy harvesters that can be comfortably worn and conformal to human body is vital to support the rapid development of wearable devices for various applications such as remote health monitoring, patient tracking and so on.

In this paper, a flexible microstrip antenna array with high gain characteristic operating at 28 GHz is proposed for wearable RF energy harvesting applications. First, we present the design methodology for the microstrip antenna and the 4-way power divider in section 2. To improve the gain of the antenna, a 4×4 array arrangement is employed in this design. The antenna elements are fed at the radiating edge of the antenna. The simulated operating frequency of the antenna is from 27.5 GHz to 28.4 GHz. A total of 900 MHz of impedance bandwidth will be sufficient for the antenna to harvest RF energy from the future implementation of 5G technology which will utilise the 28 GHz frequency band as part of the milimeter wave frequency bands [33]. Next, simulations have been carried out to investigate the performance of the flexible antenna array by deforming it based on various curvatures. In section 3, the results of the simulations are presented and discussed in detail. The numerical simulation results demonstrate that the antenna is suitable to be implemented as wearable RF energy harvesting device. Finally, conclusions are drawn in section 4.

2. ANTENNA DESIGN AND SIMULATIONS

The design of the proposed microstrip antenna array integrated with a 4-way Wilkinson power divider is carried out using a commercial electromagnetic wave solver, CST Microwave Studio. First, the 4×4 antenna array is optimized to operate at 28 GHz through parametric optimization based on the analytical calculation of the initial antenna dimension. Afterwards, a 4-way Wilkinson power divider is developed to be connected to the antenna array for power combining. The device is then deformed in several bending configurations to evaluate its effects on the antenna performance mainly its impedance matching, gain and radiation pattern. The use of 4×4 antenna array instead of just one single antenna is to increase the antenna gain even when the antenna is in bending configuration.

2.1. Microstrip antenna configuration

The initial dimension of the rectangular microstrip patch was calculated analytically by using the widely known closed-form equations described in [34]. The operating frequency of the antenna is defined at 28 GHz to exploit the implementation of 5G technologies in the future of which the ambient RF energy can be harvested using the antenna. To provide flexibility to the antenna structure, PET material was selected as the substrate. The dielectric constant, ε_r and the loss tangent, $tan\ \delta$ of the substrate are 2.1 and 0.03 respectively [35]. The thickness of the substrate is 0.25 mm. An array of 4×4 elements was chosen to increase the gain of the antenna without having to significantly increase the antenna footprint. The antennas were fed in series at the radiating edges to simplify the overall structure of the array. The radiating element is made up of silver with thickness of 250 nm. The final configuration of the rectangular microstrip antenna array is illustrated in Figure 1 where the antenna parameters are given in Table 1.

2.2. 4-way Wilkinson power divider

The antenna array designed previously has four separate ports where each separate port is connected to 4 series-fed antenna arrays. As such, to combine all the received power captured by the arrays, a power divider/combiner is required. To achieve this target, a Wilkinson power divider is proposed where it can function as a lossless network when its output ports are matched [36]. The typical configuration of an equal-split Wilkinson power divider is shown in Figure 2(a). The characteristic impedance of the Wilkinson power divider, Z_0 is set to 50 Ω to match with the impedance of the antenna port. The power divider is designed in microstrip form to provide seamless power transmission between the antenna array and the proposed power divider. The substrate used in this design is similar to that of the antenna array. The distance between the output ports is also set to match the separation distance in the designed array. Since the length of a quarter-wave arm in a typical design of Wilkinson power divider is only 2 mm at 28 GHz, it is very difficult to incorporate the required bends due to its limited length. As such, a 3λ/4 branch which corresponds to 6 mm is utilised instead of the quarter-wave transmission line. Moreover, to reduce the reflection of the propagating electromagnetic (EM) signal at the 90^0 bends in the design, mitering technique has been applied [37]. The optimized design of the 4-way Wilkinson power divider is shown in Figure 2(b). The values of the parameters of the structure is given in Table 2. Finally, the antenna array and the power divider are integrated as shown in Figure 3.

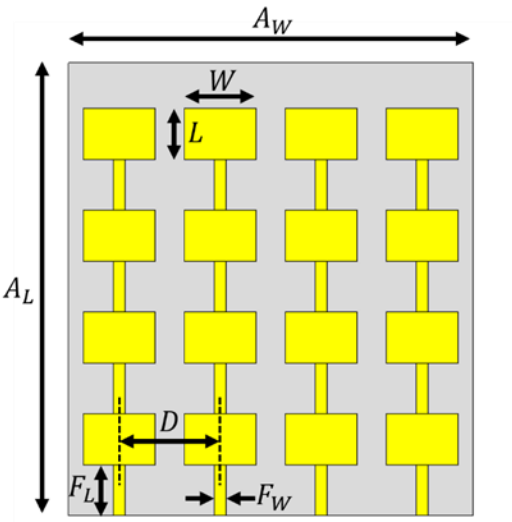


Figure 1. Configuration of the 4×4 microstrip patch antenna

Table 1. Geometrical parameter of the antenna

Antenna Parameter	Symbol	Values (mm)
Antenna length	L	3.47
Antenna width	W	5
Thickness of the substrate	T_S	0.25
Antenna separation distance	D	7
Feedline length	F_L	3.47
Feedline width	F_W	0.8
Array length	A_L	32
Array width	A_W	28

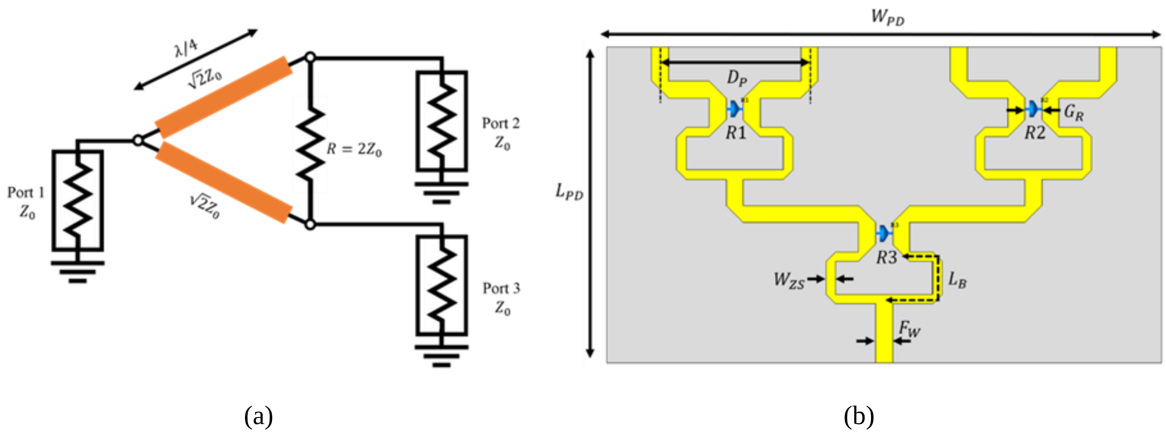


Figure 2. Wilkinson power divider (a) an equal-split Wilkinson power divider, (b) configuration of the proposed 4-way Wilkinson power divider

Table 2. Geometrical Parameter of the 4-way Wilkinson Power Divider

Parameter	Symbol	Values
Wilkinson power divider length	L_{PD}	15 mm
Wilkinson power divider width	W_{PD}	28 mm
Port separation distance	D_P	7 mm
Feedline width for 50 Ω transmission line	F_W	0.8 mm
Feedline width for 70.71 Ω transmission line	W_{ZS}	0.45 mm
3λ/4 branch length	L_B	6 mm
Branches gap	G_R	0.8 mm
Resistor 1	$R1$	100 Ω
Resistor 2	$R2$	100 Ω
Resistor 3	$R3$	100 Ω

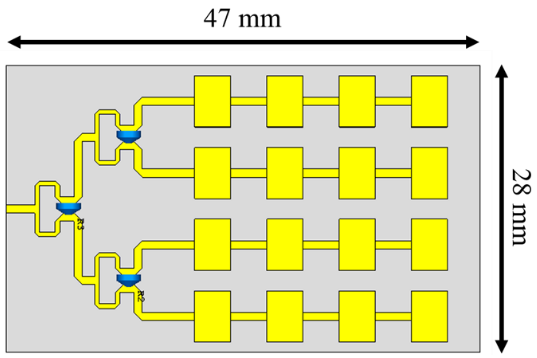


Figure 3. Microstrip antenna array integrated with 4-way Wilkinson power divider

2.3. Simulation model for antenna array structural deformation

Since the proposed wearable antenna array is aimed for harvesting RF energy by placing the device on the body, it will be subject to various structural deformations depending on the human body curvature. Therefore, the antenna was first evaluated by bending it according to several bending radius, R_b values mainly 10 mm, 20 mm, 30 mm and 40 mm where these values were chosen based on the reasonable representations of a typical human hand. The S_{11}, gain and radiation patterns of the antenna were evaluated. Figure 4 shows the diagram of the antennas in the simulations according to the bending radius values.

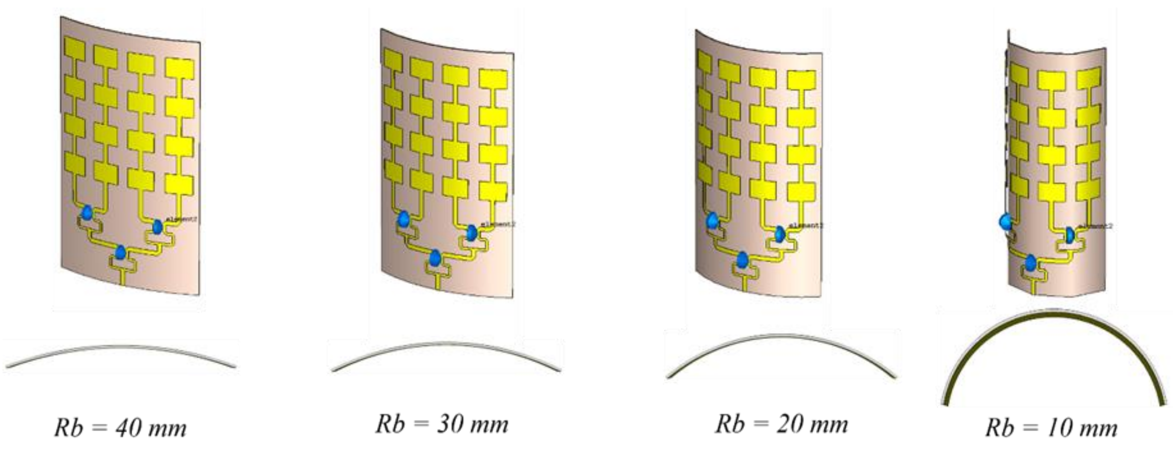


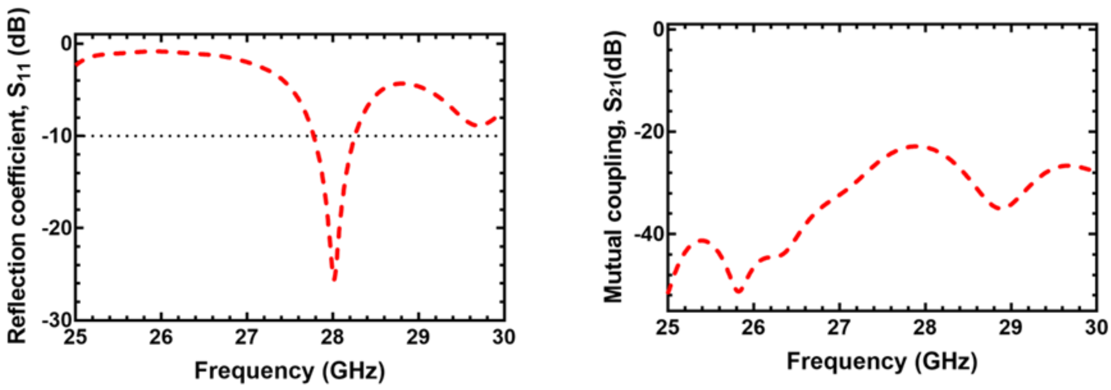
Figure 4. Bending configurations of the antenna with radius of curvatures of 40 mm, 30 mm, 20 mm and 10 mm

3. RESULTS AND ANALYSIS

The results of the simulations are divided into two parts based on the simulation environments described in the previous section. The first part presents the results for the planar configuration while the second part discusses the antenna performance due to structural deformations.

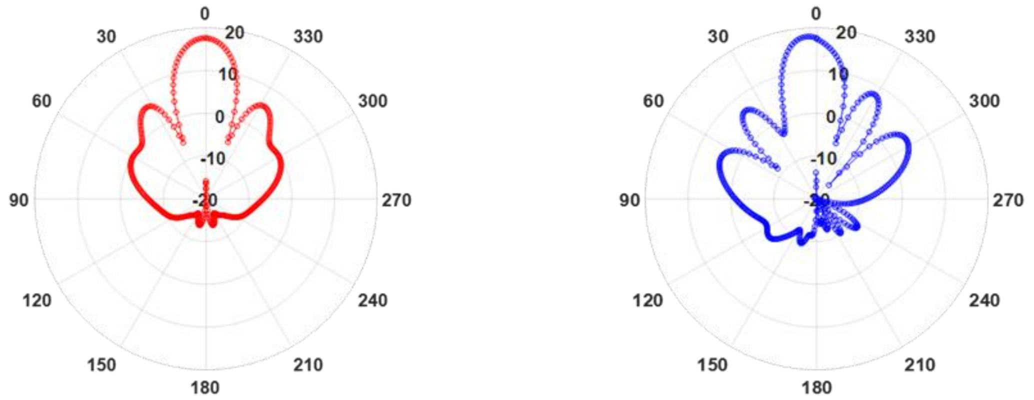
3.1. Performance of antenna in planar configuration

The simulated S_{11} of the antenna array in planar configuration is shown in Figure 5. It can be seen that impedance matching of the antenna is well below −10 dB at 28 GHz which is −25 dB. A good separation distance between the antenna elements is achieved indicated by mutual coupling of less than −20 dB. The impedance bandwidth is 1.71% ranging from 27.5 GHz to 28.4 GHz. The simulated gain of the array at the broadside direction is 18.9 dBi confirming the significant advantage over single element configuration. Figure 6 shows the H-plane and E-plane radiation patterns where half-power beamwidth (HPBW) of 18.3^0 across the H-plane is obtained.



(a) (b)

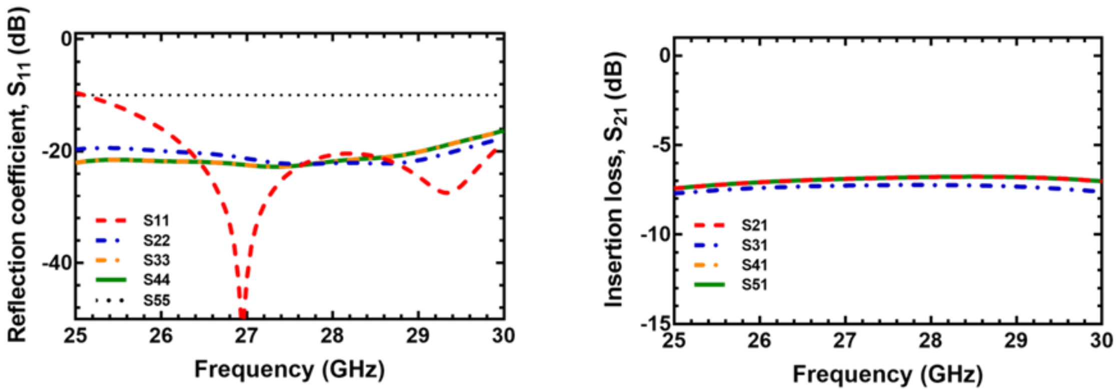
Figure 5. (a) Simulated reflection coefficient, (b) mutual coupling of the microstrip antenna array in planar configuration



(a) (b)

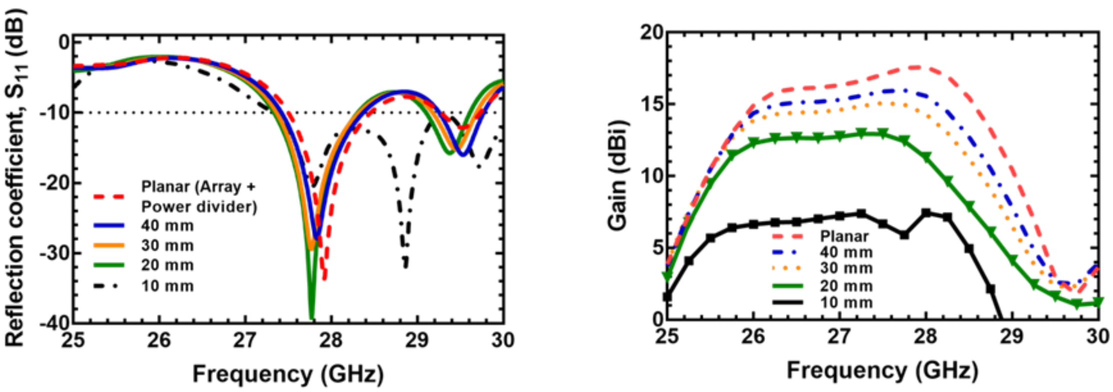
Figure 6. (a) Simulated H-plane, (b) E-plane radiation pattern of the antenna at 28 GHz for planar configuration

As for the 4-way Wilkinson power divider, the S_{11} for each port is less than −10 dB across the operating frequency indicating a properly designed input and output ports as depicted in Figure 7. The transmission loss, S_{21} between input port, P_1 and output ports (P_2, P_3, P_4, P_5) are around 6.68 dB to 7.72 dB where 1.72 dB loss (−6 dB for lossless equal split divider) is mainly due to finite conductivity of the metal and dielectric loss of the substrate material. As for the overall structure after integrating the antenna array and the power divider, the S_{11} result shows a slight shift in the operating frequency as shown in Figure 8(a). However, the impedance matching at 28 GHz is still intact thus no further optimization is required. As for the gain and the radiation patterns, the results are shown in Figure 8(b) and Figure 9 respectively. In conclusion, the gain and the radiation patterns are similar to that of the array without the power divider.



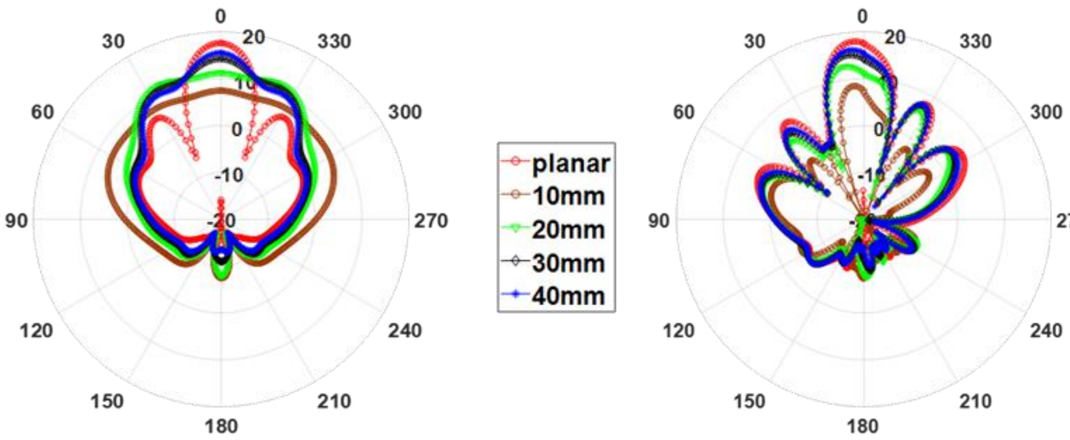
(a) (b)

Figure 7. (a) Simulated reflection coefficient, (b) insertion loss of the 4-way Wilkinson power divider



(a) (b)

Figure 8. (a) Simulated reflection coefficients, (b) antenna gains of the devices for various radius of curvatures



(a) (b)

Figure 9. (a) Simulated H-plane, (b) E-plane radiation pattern of the antenna at 28 GHz for various bending configurations

3.2. Effects of bending on antenna performance

The S_{11} of the antenna for various bending configurations are shown in Figure 8(a). The resonance of the antenna array shifts towards the lower frequency band as the values of the bending radius increase. As for the impedance bandwidth, an increase of the antenna bandwidth can be observed with the increase of the bending radius. Therefore, the bending configuration somehow improves the performance of the antenna. Figure 8(b) and Figure 9 show the maximum gains and radiation patterns for each bending configuration respectively. The gain of the antenna decreases as the bending radius increases. On the other hand, the HPBW of the antenna array increases with the decrease of the bending radius. Antenna with bending radius of 10 mm demonstrates the lowest gain compared to others with 7.45 dBi. Although the antenna has the least gain, its HPBW is the highest with 151.9º thus better suit for RF energy harvesting applications since RF sources will come from multiple directions instead from one particular direction. It can be concluded that through bending, the HPBW of the antenna can be significantly increased compared to planar form although with reduced gain. Finally, the average simulated specific absorption rate of the antenna is 0.52 W/kg which is well below the safety limit of 1.6 W/kg averaged over 1 g of tissue for 100 mW of input power making it as a feasible solution for wearable energy harvesting system in the future.

4. CONCLUSION

In conclusion, we have proposed and demonstrated a wearable milimeter-wave microstrip patch antenna array for RF energy harvesting applications. A 4 ×4 antenna array configuration has been utilised and integrated with a 4-way Wilkinson power divider to improve the overall gain of the antenna. The simulated impedance matching performance of the antenna for various bending forms are good with S_{11} values well below −10 dB at 28 GHz. As for the gain of the antenna, the value decreases from 18.9 dBi to 7.45 dBi as the bending radius decreases from 40 mm to 10 mm. Meanwhile, HPBW of the antenna improves from 18.3º to 151.9º as the bending radius decreases. It is worth noting that for RF energy harvesting purposes, the HPBW is very important design parameter to ensure the antenna can harvest RF sources coming from multiple directions. Therefore, by deforming the antenna array to operate in bending form can actually improve the HPBW significantly. This technique will be applied in future fabrication of the antenna where a foam spacer can be used to support antenna deformation. The antenna is intended to be fabricated using inkjet printing technology.

ACKNOWLEDGEMENTS

This work was supported by International Islamic University Malaysia (IIUM) under RMC 2020 grant. The authors would like to acknowledge NVIDIA for sponsoring the GPU, Quadro P6000 used in this work through GPU Grant Program.

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