

A WIDEBAND ANTENNA ARRAY FOR RF ENERGY HARVESTING

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Abstract: *In this paper, we introduce a wideband antenna array for RF energy harvesting from 3G/4G and Wi-Fi. The array consists of four parallelly linked wideband antenna elements and a metallic reflector to enhance gain and suppress back lobe radiation. In measurement, the antenna array possesses a wide bandwidth spanning from 1.6 GHz to 2.5 GHz, fully cover the three harvested bands, and the high gains between 13.5 dBi and 14 dBi. The antenna is employed in a multiband rectenna for energy harvesting and placed in the ambience. The rectenna was able to collect up to 0.27 mW power.*

Keywords: Antenna arrays; Monopole antennas; Wideband; Rectennas.

1. INTRODUCTION

Harvesting energy from RF signals in the ambient environment is a potential solution to replace batteries as the primary power supply for low-powered electronics devices. Due to the low power density of RF waves in the ambient environment, only around $1 \mu\text{W}/\text{cm}^2$ [1], it is essential to use antenna array as the receiver instead of a single antenna in order to harvest enough power to supply any device. In addition, it is desirable for the antennas to operate at multiple frequencies instead of only single band because there are many communication bands exist in the environment, namely 3G/4G, GSM, Wi-Fi,...

However, due to the complication in feeding and matching circuits, few previous works have been able to realize a wideband antenna array. The impedance of the antenna array can be matched at one frequency while being strongly mismatched at others. Therefore, most previous works on multiband energy harvesting employ a single multiband or wideband antenna instead of an array [2]-[4]. For example, in [5], the quad-band rectenna uses a single bow-tie antenna with slots for receiving energy, which is able to operate at 840 MHz, 1.8 GHz, 2.1 GHz and 2.45 GHz. The classical monopole antennas are also frequently employed to provide ultrawide bandwidths. Yet, they have low gains due to their intrinsic natures. In one of a few works on multiband/wideband antenna array for energy harvesting, a 1x4 array of quasi-Yagi antennas is able to achieve a bandwidth that fully covers the 1.8 GHz and 2.1 GHz, and a high gain around 12 dBi [6]. However, the nearby 2.45 GHz, 2.6 GHz or 900 MHz are still not covered.

In an effort to enhance the amount of power harvested, we present a wideband antenna array for energy harvesting from 3G/4G and Wi-Fi sources. The bandwidth of the proposed antenna spans wide enough to fully cover the 1.8 GHz, 2.1 GHz and 2.45 GHz bands, while the antenna gain stays higher than 11 dBi at all of those frequencies.

The following parts of the paper are arranged as follow: section 2 provides the design of the antenna, section 3 provides the antenna measurement, section 4 is the antenna in a rectenna for energy harvesting, and finally section 5 is the conclusion.

2. ANTENNA DESIGN

The array consists of 4 elements, each one is a circular monopole antenna,

horizontally arranged on a RO4003C substrate ($\epsilon = 3.55$, $\tan\delta = 0.0027$) of 1.5mm thick. The four antennas are linked together via a corporate feeding network. A metallic reflector is put at the back of the antenna array as shown in figure 1.

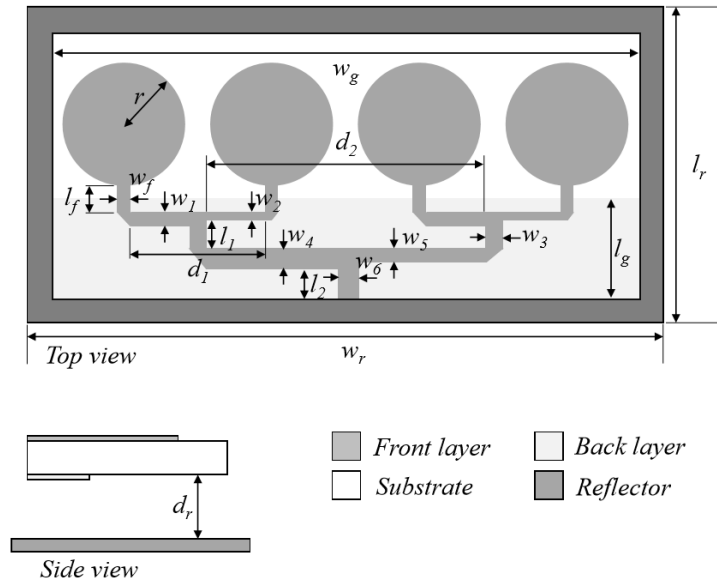


Figure 1. Schematic and image of the antenna array.

The monopole antenna is well known for its wideband property. Therefore it is the right candidate for the role of element antenna in this array. By optimizing the geometrical dimensions, namely patch's radius r , feed length l and width w , a desirable bandwidth, covering the intended frequency bands can be achieved. However, the antenna's omnidirectional pattern means its gain cannot be very high. By connecting the monopole antennas together via a T-junction power combiner, a 1×4 array is formed and, in theory, will significantly enhance the antenna gain. The task is to maintain the bandwidth as the elements are linked together. This can be carried out as follow: after simulating a single element in CST software, its input impedance is extracted and then the 4-to-1 power combiner is designed using ADS software with the 4 input ports having the same input impedance of the antenna element. The effects of each parameter w_1 to w_6 , d_1 , d_2 , l_1 , l_2 , w_g and l_g on the combiner's performance can be observed and changed using CST software, and from that, optimized parameters is obtain to achieve desirable result.

The monopole array, due to the omnidirectional pattern of each element, possesses the equally large front lobe and back lobe. To further enhance the gain, a reflector is placed at a distance d_r behind the array, completely quenches the back lobe. Parameter d_r along with the reflector's size l_r and w_r are optimized to achieve the maximum gain possible without significantly affecting the bandwidth. A deeper insight on the role of the optimal distance d_r can be understood as follow: By assigning d_r as $\lambda/4$ of frequency f , the reflected waves from the reflector cancels the radiated waves at the antenna, thus does not affect the S_{11} . Here we choose d_r as $\lambda/4$ of the central frequency 2.1 GHz. At other frequencies, the S_{11} will be affected at a certain level. As seen from fig. 3b, as d_r increases, the bandwidth is

broadened and becomes narrower, the picked d_r achieves a good compromise between deep S_{11} and wide bandwidth.

The antenna dimensions are respectively: $r = 28$ mm, $l_f = 14$ mm, $w_f = 4$ mm, w_1 to w_6 are 6, 2.1, 4.8, 3, 1.3, 6 mm, $d_1 = 57.6$ mm, $d_2 = 125.8$, $l_1 = 7.5$ mm, $l_2 = 15$ mm, $l_g = 35.8$ mm, $w_g = 253.2$ mm, $l_r = 142.6$ mm, $w_r = 293.2$, and $d_r = 35$ mm. With those dimensions, the array possesses a wide bandwidth in CST simulation, spanning from 1.75 GHz to 2.55 GHz, fully covers the 1.85 GHz, 2.1 GHz and 2.45 GHz bands.

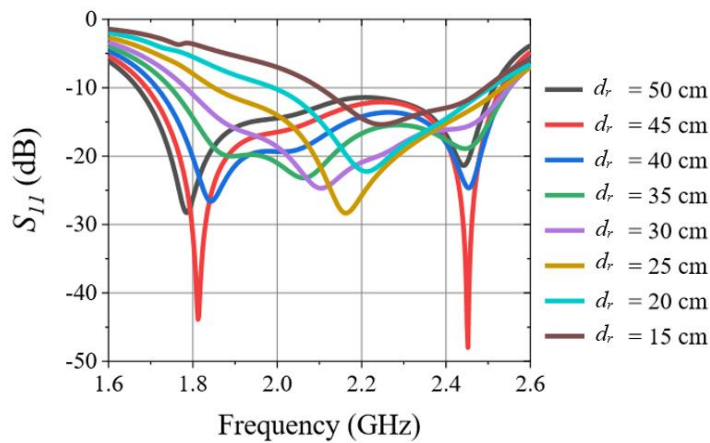


Figure 2. Simulated S_{11} at different values of d_r .

Figure 2 presents the reflection coefficient of the proposed antenna array with different value of d_r from 15 cm to 50 cm. This optimal distance of 35 cm is chosen because the antenna bandwidth at -10 dB of reflection coefficient is from 1.75 GHz to 2.55 GHz as required. At the distance of 40 cm to 50 cm, the reflection coefficient is smaller than but the antenna array size is increase.

3. ANTENNA MEASUREMENT

Figure 3 presents the simulated and measured reflection coefficient of the antenna array. The simulated and measured antenna radiation pattern at three frequencies of 1.85 GHz, 2.1 GHz and 2.45 GHz is shown in figure 4.

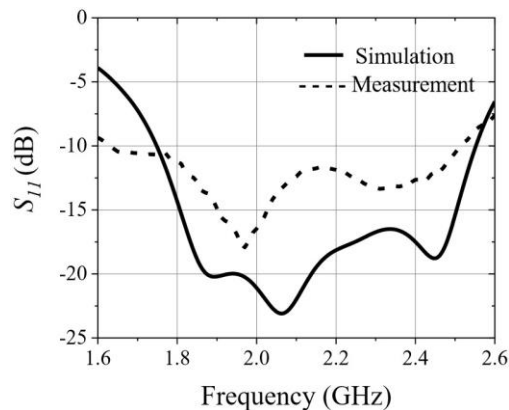
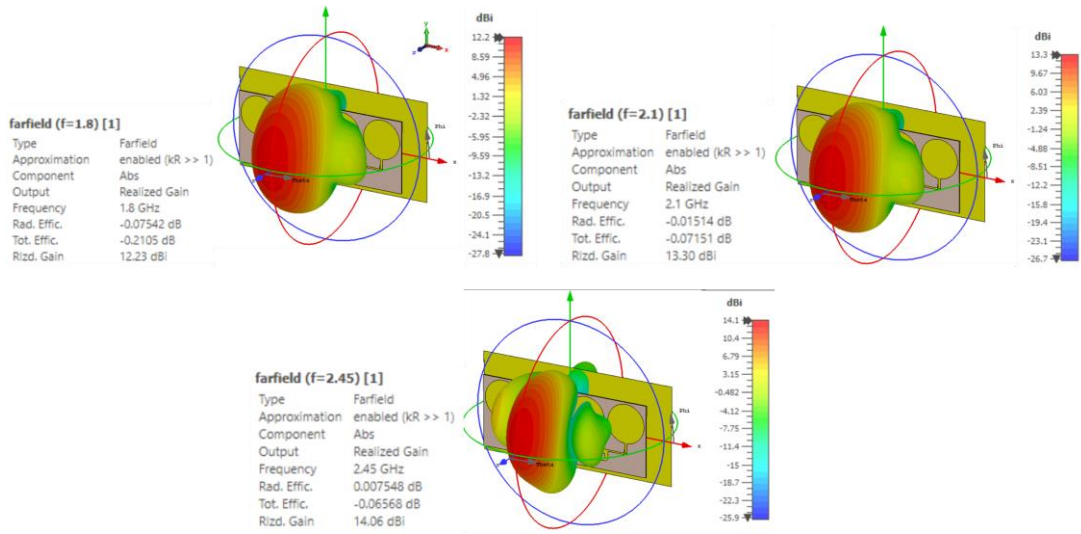
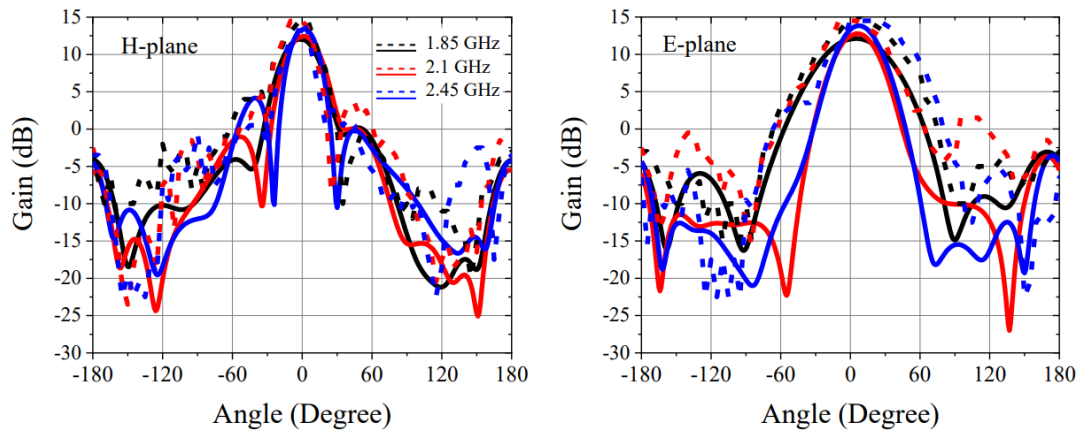


Figure 3. Simulated and measured S_{11} of the antenna array.



a)



b)

Figure 4. (a) 3D Simulated radiation pattern of antenna array at 1.85 GHz, 2.1 Ghz and 2.45 GHz; (b) Simulated and measured radiation pattern of the array. Solid lines are simulation results and dash lines are measurement results.

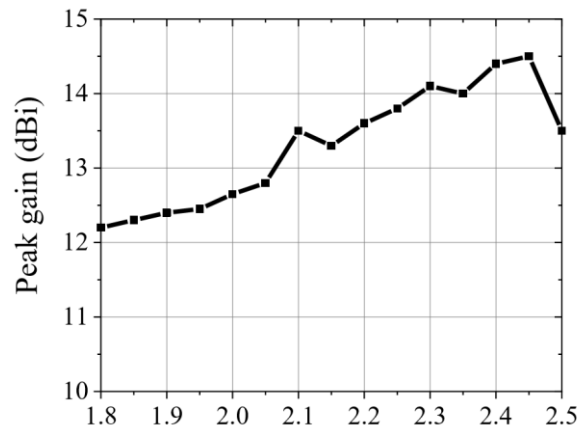


Figure 5. Simulated peak gain of the antenna array.

The peak gain over the bandwidth from 1.8 GHz to 2.5 GHz is illustrated in figure 5. As can be observed, the peak gain is from 12.2 dBi to 14.5 dBi over the wide frequency band.

Measurement agrees well with simulation, with the measured gains being 13.5 dBi, 14 dBi and 13.8 dBi at 1.85 GHz, 2.1 GHz and 2.45 GHz, respectively, and the bandwidth spanning from 1.55 GHz to 2.5 GHz in measurement. Such wide bandwidth is enough to fully cover the 3G/4G and Wi-Fi bands while the high gains ensure a large amount of harvested power. The half-power beam-widths in *H*-plane are around 30° to 40° for all three frequencies. Meanwhile, in *E*-plane are 45°, 40°, and 60°, respectively. The measured radiation patterns have some differences from the simulated results due to unideal testing condition. The difference is more significant at larger angle, and the measured beamwidths are somewhat larger, especially in *E*-plane. However, at normal direction, we can still observe a good agreement between simulation and measurement.

The antenna array performances are comparable to earlier works [2-4] in table 1. As shown, this proposed antenna has wider bandwidth and higher gain at three center frequencies 1.85 GHz, 2.1 GHz and 2.45 GHz.

Table 1. A comparison between the proposed antenna and earlier works.

Ref.	Frequencies	Bandwidth	Gain
[2]	2.45 GHz, 5.5 GHz	≈ 50 MHz at 2.45 GHz, ≈ 100 MHz at 5.5 GHz	7.52 dBi at 2.45 GHz 7.26 dBi at 5.5 GHz
[4]	0.9 GHz, 1.8 GHz, 2.1 GHz	100 MHz at 0.9 GHz, 400 MHz from 1.8 GHz to 2.2 GHz	8.15 dBi at 0.9 GHz 7.15 dBi at 1.8 GHz, 8.15 dBi at 2.1 GHz
[6]	1.8, 2.1	≈450 MHz from 1.8 GHz to 2.25 GHz	10.9 dBi at 1.8 GHz, 13.3 dBi at 2.1 GHz
This work	1.85 GHz, 2.1 GHz and 2.45 GHz	≈880 MHz from 1.62 GHz to 2.5 GHz	13.5 dBi at 1.85 GHz 14 dBi at 2.1 GHz 13.8 dBi at 2.45 GHz

4. ANTENNA ARRAY IN ENERGY HARVESTING APPLICATION

The antenna array is connected to a triple band rectifier and put under the real ambience testing. The consuming device is replaced with an equivalent resistive load of 2.7 kΩ. The rectenna was placed at a certain position inside the campus, 30 metre away from a base station, which transmit the 1.85 GHz and 2.1 GHz bands, while the 2.45 GHz bands was collected from ambient Wi-Fi. The maximum voltage recorded was 482 mV, correspond with around 0.27 mW power. In most of the time, the output voltage fluctuated between 250 mV and 300 mV. One may expect the amount of harvested power to be much higher when the rectenna is placed closer to the base station. Due to the three frequencies were harvested simultaneously, it was difficult to tell how much power belongs to each bands. These amounts of power is still insufficient to fully supply an electronic devices, however, it is enough for some low-powered wireless sensor in sleep mode or some limited function.



Figure 6. The antenna array inside a rectenna in the ambience.

In ambient energy harvesting, it is believed that an antenna with wide beamwidth or even omnidirectional radiation pattern is more suitable compared to high gain antennas, because such antenna may operate under arbitrary direction of incidence. However omnidirectional antennas have low gains. In our testing scenario, the power source was known and static. In urban area, base station towers are everywhere, and dedicated positions near the towers are the ideal places for rectennas. The direction of arrival is no longer uninformed but in fact already known. Therefore, high gain antennas can also work well for energy harvesting application.

5. CONCLUSIONS

In this paper, we propose a wideband antenna array for ambient energy harvesting from the 3G/4G and Wi-Fi sources, corresponding with 1.8 GHz, 2.1 GHz and 2.45 GHz bands. The antenna array is formed by four monopole antennas parallelly linked via a corporate feed, and backed by a metallic reflector. Measurement shows a wide bandwidth spanning from 1.55 GHz to 2.5 GHz, fully cover the three harvested bands. The array also yields high gains, from 13.5 dBi to 14 dBi. Such advantages make it suitable for ambient energy harvesting. The array was connected to a triple-band rectifier and placed in the ambience, where it was able to harvest up to 0.27 mW. That amount of power is enough for some low-powered electronic devices such as wireless sensors in sleep mode and limited functions.

Acknowledgement: This research is funded by the Ministry of Education and Training (MOET) under grant number B2020-BKA-11.

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TÓM TẮT

MẢNG ĂNG TEN BĂNG THÔNG RỘNG CHO ỨNG DỤNG THU HOẠCH NĂNG LƯỢNG TỪ SÓNG ĐIỆN TỪ

Bài báo này đề xuất một mảng ăng ten băng thông rộng cho ứng dụng thu hoạch năng lượng từ sóng điện từ ở dải tần 3G/4G và Wi-Fi. Mảng ăng ten được tạo nên từ bốn ăng ten đơn cực băng thông rộng, kết nối với nhau qua mạch cấp nguồn song song, với một tấm phản xạ bằng kim loại ở phía sau để ngăn chặn bức xạ ở mặt sau. Kết quả chế tạo và đo đạc cho thấy mảng ăng ten có băng thông rộng trải dài từ 1.55 GHz đến 2.5 GHz, hoàn toàn bao trùm ba băng tần mong muốn, và độ lợi cao từ 13.5 dBi đến 14 dBi. Mảng ăng ten được kết nối với một chỉnh lưu ba tần số, và thử nghiệm bên ngoài môi trường. Kết quả là hệ thống thu hoạch năng lượng có thể thu được tới 0.27 mW công suất.

Từ khóa: Mảng ăng ten; Ăng ten đơn cực; Ăng ten băng thông rộng; Ăng ten chỉnh lưu.

Received Apr 14th 2021

Revised Apr 23th 2021

Published May 10th 2021

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