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Broadband dual linear polarized (DLP) antenna array for energy harvesting system

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Research Paper

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Abstract

A broadband linear polarized antenna is designed for radio frequency energy harvesting. The antenna covers the frequency range from 1 up to 6 GHz with relative impedance bandwidth of 126% at −6 dB reflection coefficient $|S_{11}|$ and extended from 1.1 to 3.3 GHz and from 4.2 to 5.6 GHz at $|S_{11}| \le -10$ dB. A 2×2 dual linear polarized (DLP) antenna array is designed based on the antenna element by using equal phase and equal power divider 1-to-4 Wilkinson power divider with 180° phase shifter. The DLP antenna array covers the frequency band from 1.8 to 2.9 GHz. This frequency band covers a wide range of modern wireless communication standards, including GSM 1800, UMTS 2100, Wi-Fi 2.4, and most of LTE bands. The developed array prototype was then used to experimentally validate the simulation results. The horizontally and vertically polarized gain of the designed array were found to be quite similar across the 1.8–2.9 frequency band with an average gain value of 5.5 dBi.

Introduction

Energy harvesting solution is proposed as a durable power source for different wireless sensor nodes distributed in a Wireless Sensor Network. This solution can bypass the main drawback for wireless sensor nodes, which is the life cycle of the primary batteries [1–2]. The ambient radio frequency (RF) energy harvesting can be obtained at all places and it could be found at the night times rather than other energy harvesting. RF energy harvesters include a receiving antenna, band pass filter, a matching network, a rectifier, and a terminal load [3–5]. A printed antenna was used to harvest the RF ambient power from the GSM system to feed the low power temperature sensor of STLM20 [6]. To increase the harvest power the array antennas are used [7–9]. However, the majority of the wireless communication systems are linearly polarized [10], as the complex environment and multipath effect of the polarization of the signal can be changed. Moreover, depolarized leads to the decrease of the efficiency of the harvest energy system. This problem can be solved by using a dual polarized receiving antenna because it can collect the electromagnetic waves regardless of the angle of polarization of the incident electromagnetic waves. Microstrip antenna is a better solution for the design of dual linear polarized (DLP) antennas and arrays because of this antenna element or array it has to be low profile and lightweight [5].

There are many publications on DLP arrays previously. However, majority of the works have multilayers, dual ports, large size and complex structure which is very difficult to be integrated with the rectifier and matching network in RF energy harvesting systems [11–14]. Table 1 shows the comparative designs between previous research and our designed DLP array.

In this paper, a low-profile dual polarized 2×2 planar monopole antenna array is shown in Fig. 1 with a single layer and a single feeding port, designed for RF energy harvesting. This array is simulated, fabricated, and measured. This paper is organized as follows. The section "Antenna design and results" presents the analysis of single antenna element design and its simulation and measured results. In the section "Dual linearly polarized 2×2 antenna array", the proposed antenna array design, and its simulation and measured results are discussed. The section "Conclusion" summarizes the results of the proposed array.

Antenna design and results

The starting point in the designing of the antenna array is the single antenna element as shown in Fig. 2. This figure shows the proposed single element design steps with the 3D configuration of the final design and its fabricated photo for upper and lower substrate layer, respectively. It consists of a modified ground plane with rectangular-shaped slot and *V*-shaped planar monopole radiator. The design steps start with conventional rectangular monopole as shown in Fig. 2(a). A *V*-shaped is etched on the monopole antenna as shown in Fig. 2(a) in order to reduce the antenna size and improve the antenna bandwidth by increasing the electrical length and creating closely staggered resonant modes. Then the modified ground plane has a rectangular-shaped slot with dimensions, $L_s \times W_s$, is used as shown in Fig. 2(a) to

Table 1. The comparison of the proposed antenna and other researches

Items	[11]	[12]	[13]	This work
BW VSWR	4:1 <3	1.5:1 <2	1.54:1 <2	1.6:1 <2
Element gain	3 dBi	–	–	3 dBi
Ave. array gain	17 dBi	13 dBi	9.4 dBi	5.5 dBi
Element size	$0.66\lambda_c \times 0.28\lambda_c \times 0.41\lambda_c$	$0.48\lambda_c \times 0.48\lambda_c \times 0.16\lambda_c$	$0.8\lambda_c \times 0.8\lambda_c \times 0.14\lambda_c$	$0.43\lambda_c \times 0.39\lambda_c \times 0.012\lambda_c$
Array size	$0.66\lambda_c \times 7.3\lambda_c \times 0.575\lambda_c$	$3.9\lambda_c \times 1.4\lambda_c \times 0.16\lambda_c$	$1.83\lambda_c \times 1.09\lambda_c \times 0.14\lambda_c$	$1.25\lambda_c \times 1\lambda_c \times 0.012\lambda_c$
Multi-layer	Yes	Yes	Yes	No

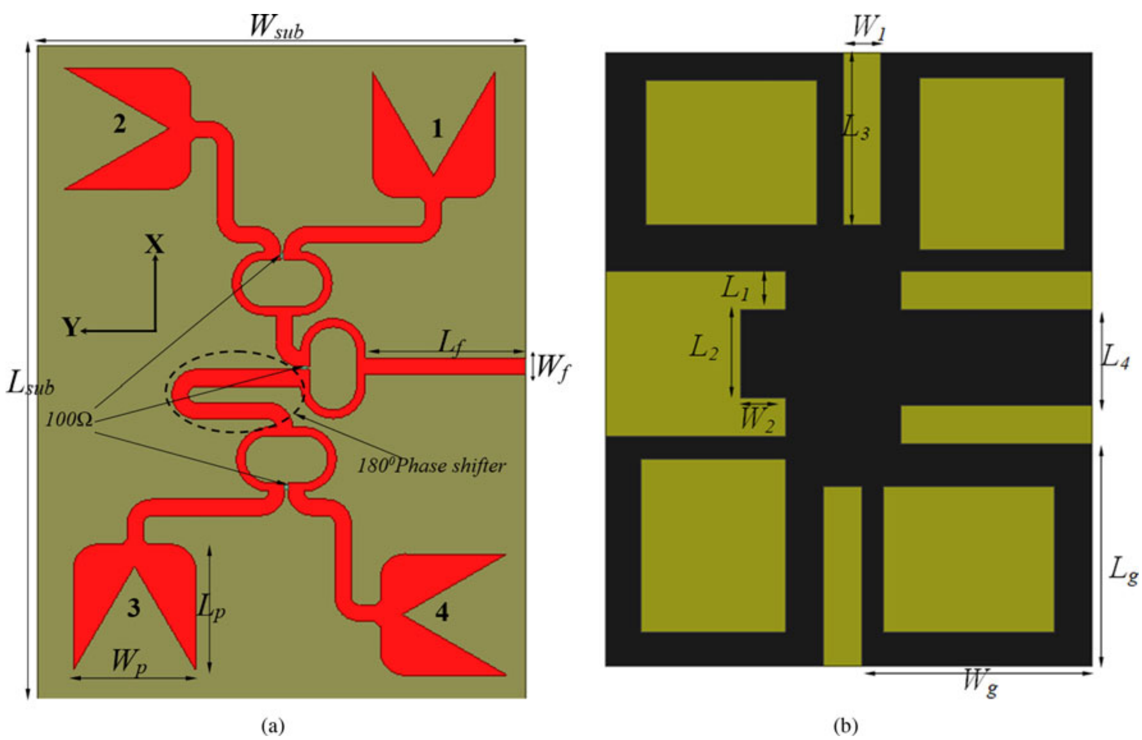

Fig. 1. The structure geometry of the proposed 2 × 2 array antenna. (a) Top view. (b) Bottom view.

improve the antenna matching and gain. The antenna is printed on a Roger RO4003 substrate with dielectric constant of 3.55, loss tangent of 0.002, and substrate thickness of 1.525 mm as shown in Fig. 2(b).

The reflection coefficient of the different design steps is shown in Fig. 3(a). Then the proposed monopole antenna dimensions are optimized by the changing angle Φ of *the V*-shaped and the length and width (L_s and W_s) of the slot on the ground plane. The parametric analysis states with angle Φ is changed from 30° to 90° with step 20°. Figure 3(b) shows that when Φ decreases, the impedance matching improves and the resonant frequency decreases. This is due to as the angle Φ increases, the electrical length and the current path decrease. In addition, the effect of the slot area in the ground plane reduces. The effect of length and width of the slot on the ground plane are shown in Figs 3(c) and 3(d), respectively. By increasing the slot length and width, the antenna impedance bandwidth and matching are improved. All simulations are done by using finite element 3D electromagnetic simulator, High-Frequency Structure Simulator Ansys ver. 19. The optimized antenna dimensions are listed in Table 2. To verify the simulation results the antenna element is fabricated and measured as shown in Fig. 2(c). Figure 4 presents the simulated and measured $|S_{11}|$ of the proposed antenna element, which the measured result agrees well with the simulation result.

Figure 4 also indicates that the operating frequency of the antenna ranges from 1.35 to 6 GHz for $|S_{11}| < -6$ dB, and ranges from 1.5 to 3.6 and 4 to 6 GHz for $|S_{11}| < -10$ dB. That is suitable for RF energy harvesting at GPS 1570, GSM 1800, UMTS 2100, Wi-Fi 2.4, LTE 2600 bands, and WLAN 5.2. The antenna gain is also measured and compared with the simulated results as shown in Fig. 4(b). The proposed antenna element has a maximum gain of 4.75 dBi at 2.5 GHz and average gain around 3 dBi over the operating frequency band.

Dual linearly polarized 2 × 2 antenna array

The design of the DLP antenna array should be simple and planar in order to integrate with the RF energy harvesting system. As a

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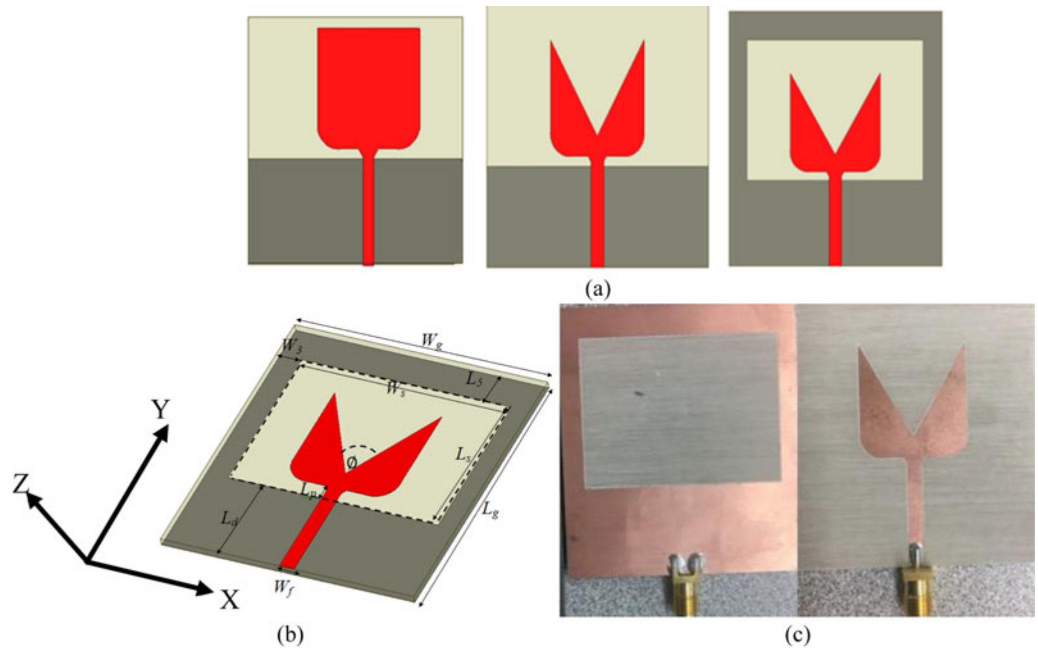

Fig. 2. (a) Design steps, (b) 3D-geometry, and (c) photo of the fabricated single antenna element, top, and bottom layer.

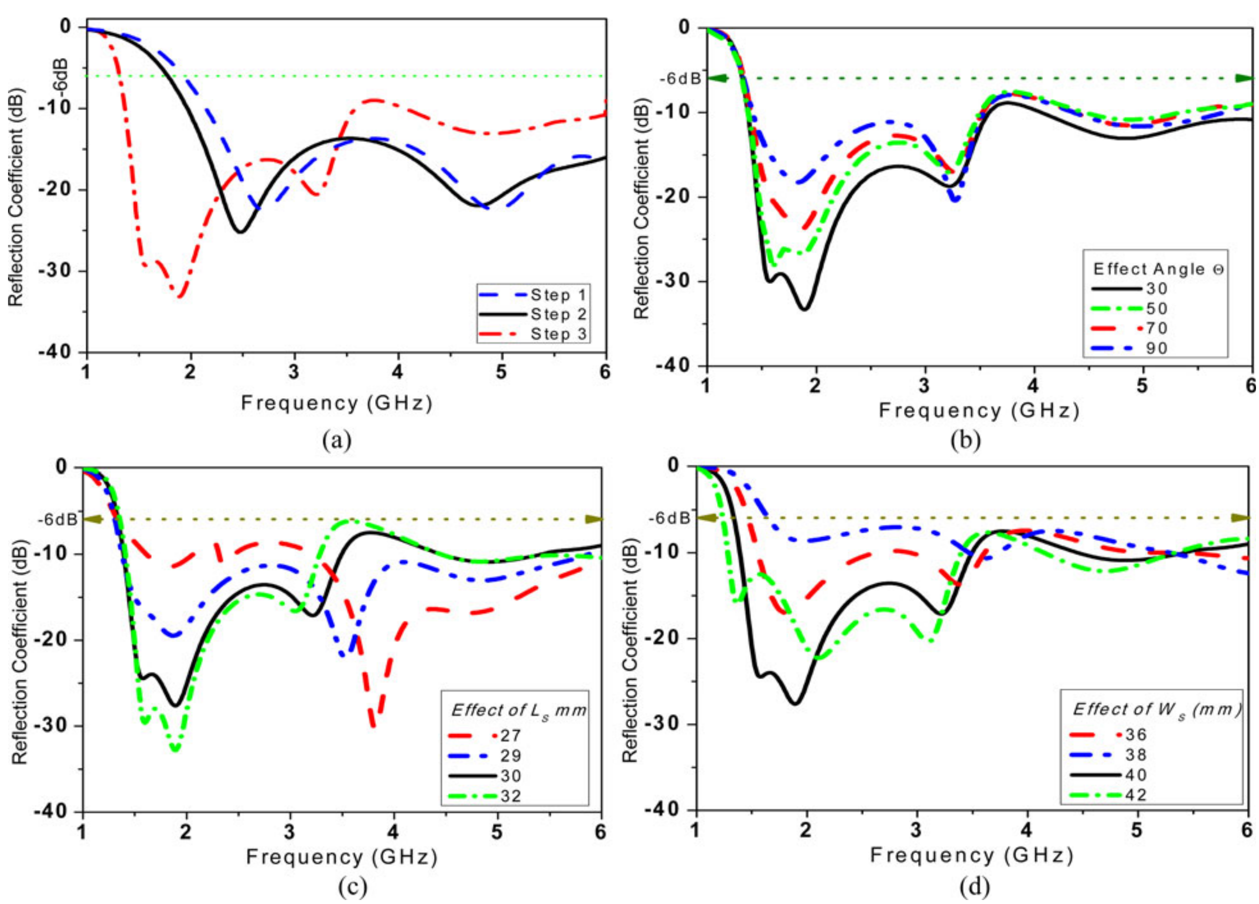

Fig. 3. (a)The simulated design steps and (b)–(d) the effect of $|S_{11}|$ of different values of Φ, L_s *and* W_s, respectively.

result, a 2×2 DLP antenna array is designed based on the antenna element in Fig. 2. The antenna elements are oriented such that the antenna array supports DLP as shown in Fig. 1.

The feeding network for the proposed 2×2 DLP antenna array is shown in Fig. 5(a). The distances between the antennas in vertical and horizontal polarization antenna are 124 and 136 mm as

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Table 2. Optimized antenna dimensions (unit in mm)

W_{sub}	L_g	W_g	L_d	L_p	W_f	L_2	W_1	L_3	W_p
120	55	50	15	2	3.4	23	10	50	22.4
L_{sub}	L_s	W_s	W_3	L_f	L_5	L_1	W_2	L_4	L_p
130	30	40	7	45	5	10	12	25	23.2

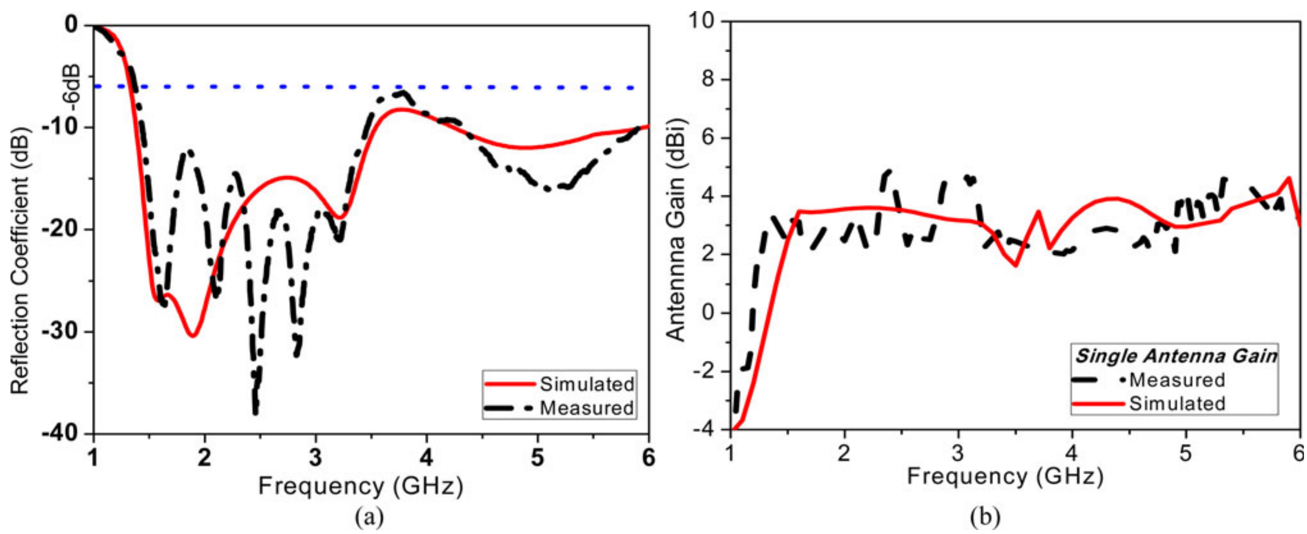

Fig. 4. (a) The comparison between the simulated and measured reflection coefficient versus frequency and (b) the antenna element gain.

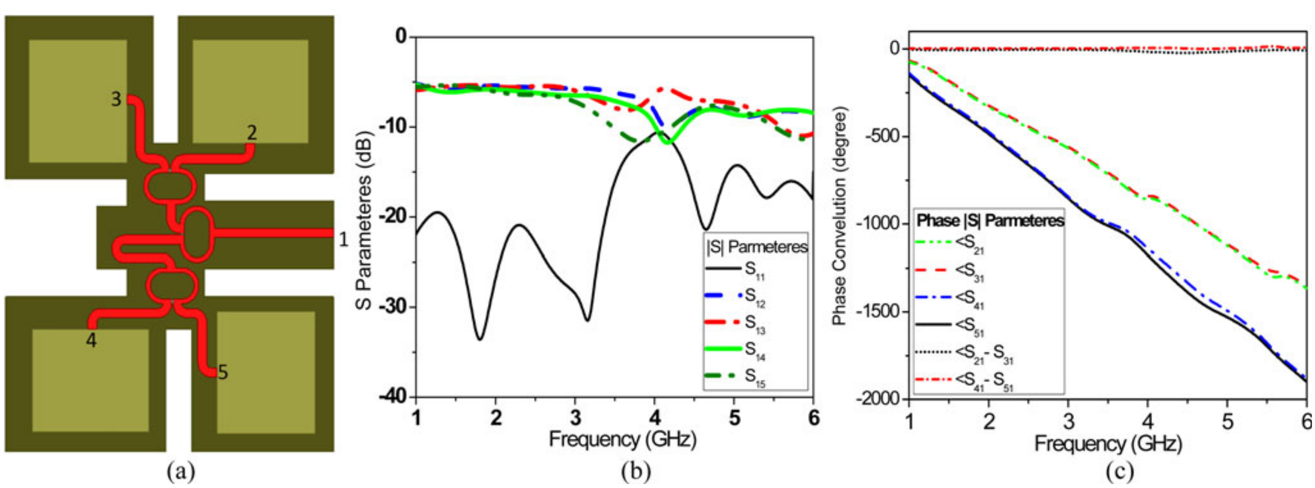

Fig. 5. (a) the feeding network for the 2 × 2 dual polarized antenna array, (b) reflection coefficient variation versus frequency for feeding network.

Table 3 The isolation between the different polarization antennas

Freq. (GHz)	1.8	2.1	2.4	2.7	3
V-pol (dB)	−30	−25	−37	−25	−21
H-pol (dB)	−6	−6	−7	−7.5	−7

$0.5\lambda_o$ and $0.55\lambda_o$, respectively, at 2.4 GHz. It consists of 1-to-4 Wilkinson power divider [15]. The power divider is designed to be broadband, as shown in S-parameters in Fig. 5(b), to cover the frequency bands from 1 to 3.8 GHz in order to include most of the required wireless communication standards' frequencies. Figure 5(c) shows that the phase response of the four ports and the difference between port 2 with port 3, and port 4 with port 5. This figure shows that port 2 is in phase with port 3 as well as port 4 is in phase with port 5 and these two ports are 180° phase difference and the first two ports at 2.4 GHz. Then the monopole antenna elements are added as shown in Fig. 1 where the four elements in the proposed array are arranged to produce vertical and horizontal polarized radiation patterns. There is 180° phase shift between antenna element number 1 and antenna element number 3 which makes E-field of these

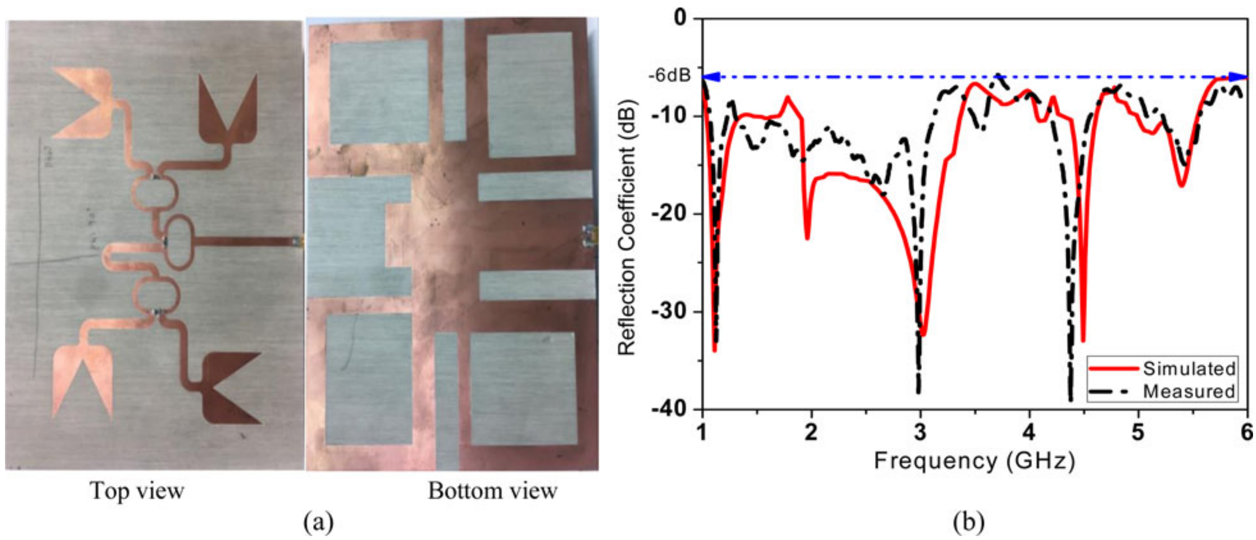

Fig. 6. (a) Photo of fabricated 2 × 2 dual polarized antenna array and (b) the array reflection coefficient variation versus frequency.

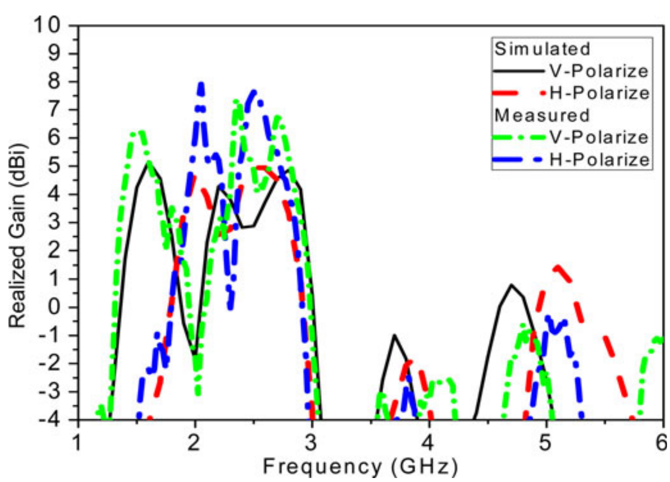

Fig. 7. Simulated and measured horizontally and vertically polarized gain in the broadside direction.

two elements in-phase with each other and radiate vertically. As well as, for antenna element number 2 and antenna element number 4 there is 180° phase shift between them and both of these antennas are located opposite to each other, so they are in-phase with each other and radiate horizontally. Thus, in this arrangement, a DLP antenna array is realized. The isolation between two different polarization antennas is changed over the operating band as shown in table 3. The isolation between the antenna elements is about 21 dB isolation over the interesting operating band.

The proposed array is fabricated using a CNC milling machine. The radiation characteristics of the antenna array are measured using Agilent Technologies E8364B vector network analyzer. Figure 6(a) shows the fabricated photo of array in both the top and bottom layer. Comparison between simulated and measured reflection coefficient of the antenna array is shown in Fig. 6(b). It can be seen that the array has good impedance matching in both simulated and measured results. The horizontally polarized (H-pol) and vertically polarized (V-pol) gain of the antenna array in the broadside direction is shown in Fig. 7. The peak antenna gain in V-pol and H-pol are 7.5 and 8 dBi, respectively, while the average gain is around 5.5 dBi for both V-pol and H-pol. The component gain values of the antenna array at the frequencies correspond to different wireless communication standards (GSM 1800, digital TV, WiFi, and LTE) and are listed in table 4. It could be noticed that at different wireless communication frequencies the H-pol and V-pol gain in the broadside direction are approximately the same. The differences in values between two polarizations are due to the misalignment on the vertical and horizontal antennas involved in the radiation.

Comparison of the measured and simulated 2-D radiation patterns of the proposed array at *XZ* and *YZ* planes at different frequencies of 1.8, 2.1, 2.4, 2.5, 2.6, and 2.8 GHz are shown in table 5. Table 5 shows that E_x *and* E_z components of radiation pattern are quite similar in the *XY* and *YZ* planes, the difference is due to the dissimilar of the ground plane. This means that the array is a DLP and the array can receive vertical and horizontal RF ambient power at different operating frequencies to collect more ambient power and solve the antenna alignment and the depolarization caused by the multiple path propagations which could have happened in the linear polarized signal.

To examine the received power of the designed single monopole element and DLP antenna array at certain frequencies, a DRG horn antenna (SAS-571) is used as Tx antenna and Anritsu MS27260 Spectrum Analyzer is used to measure the received power on the antenna element and the array for both vertical and horizontal polarizations. The input power of the Tx horn

Table 4. Values of the realized gain in the broadside direction at different wireless frequency applications

Freq.(GHz)	1.8	2.1	2.4	2.5	2.6	2.8	2.9
V-pol gain (dBi)	3.5	1.5	6.3	5.3	4.5	5.3	3.2
H-pol gain (dBi)	1	5.3	5.4	7.5	6.7	4	1

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Table 5. Simulated and measured normalized radiation pattern at different wireless communication frequencies; simulated (H-pol —, V-pol –.–) and measured (H-pol —, V-pol –.–)

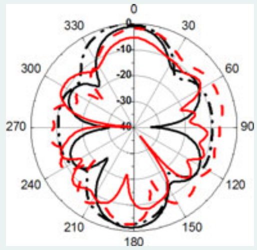
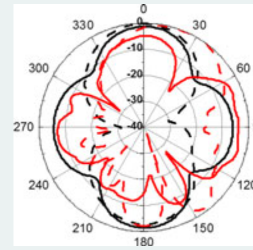
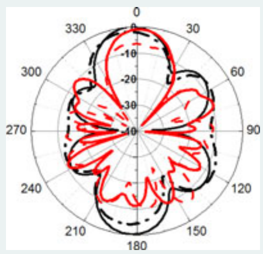
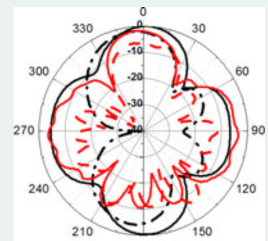
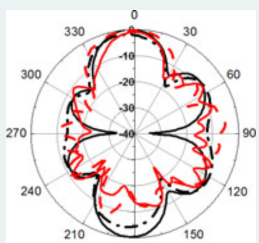
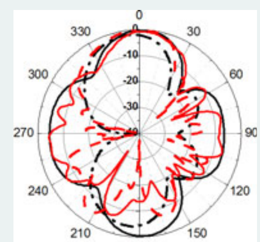
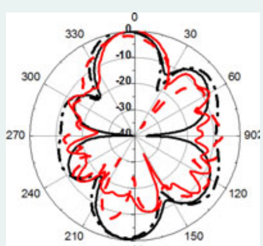
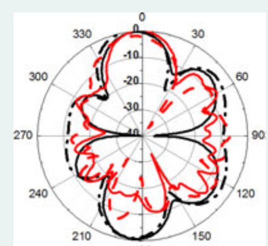
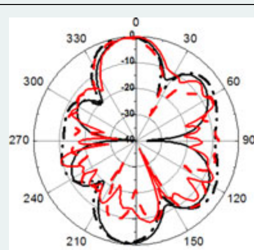
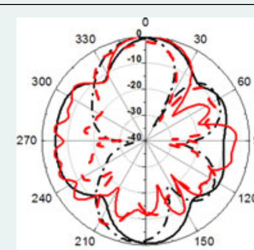
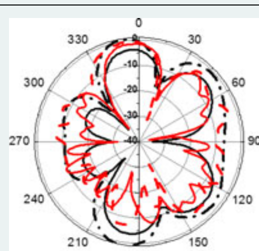
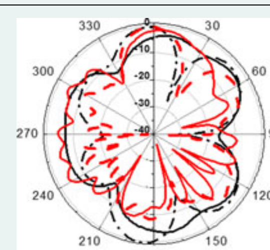
Freq. GHz	*XZ*	*YZ*
1.8		
2.1		
2.4		
2.6		
2.8		
2.9		

Table 6. The ambient received power at different frequencies for single element and array power in dBm.

Freq. (GHz)		1.8	2.1	2.4	2.5	2.6	2.7	2.8	2.9
Single antenna	V	−36	−35	−36	−36	−37	−38	−37	−38
	H	−51	−50	−49	−49	−51	−49	−48	−50
Array antenna	V	−34	−36	−34	−35	−36	−35	−36	−38
	H	−35	−33	−33	−34	−34	−36	−36	−39

is 3 dBm from the Agilent Technology N9918A which works as a spectrum analyzer with 2 m away from the Rx antenna. Table 6 shows the list of the received RF power in dBm for both the single element and the antenna array. The received power for V-pol and H-pol of the antenna array are almost the same in the frequency band of interest.

Conclusion

A 2×2 DLP antenna array is designed in this paper to harvest the ambient RF waves at the different wireless communication bands, such as GSM1800, UMTS 2100, Wi-Fi 2.4, and LTE. The single element of the array is designed to be wideband with reasonable antenna element gain 3 dBi on average. Then a wideband suitable feeding network is designed for the antenna array. The designed array is planar and uses a single substrate so that it can be easily integrated with the RF harvest system. The antenna array covers the frequency band from 1.8 to 2.9 GHz with an average gain of 5.5 dBi in both vertical and horizontal polarizations. Both of the antenna element and array are fabricated and measured. There are good agreements between the measured and simulated results.

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References

1. **Xie F, Yang GM and Geyi W** (2013) Optimal design of an antenna array for energy harvesting. *IEEE Antennas and Wireless Propagation Letters* **12**, 155–158.
2. **Muncuk U** (2012) Design optimization and implementation for RF energy harvesting circuits, M.Sc. Thesis, Northeastern University, Boston, Massachusetts.
3. **Tung N** (2016) Multi-band ambient RF energy harvesting rectifier for autonomous Wireless Sensor networks, *IEEE Region 10 Conference (TENCON), Singapore*, pp. 3736–3739, November, 2016.
4. **Din NM, Chakrabarty CK, Ismail AB, Devi KKA and Chen W-Y** (2012) Design of RF energy harvesting system for energizing low power devices. *Progress in Electromagnetics Research (PIER)* **132**, 49–69.
5. **Barcak JM and Partal HP** (2012) Efficient RF energy harvesting by using multiband microstrip antenna arrays with multistage rectifiers, *IEEE Subthreshold Microelectronics Conference (SubVT)*, Waltham, MA, USA, 9–10, pp. 1–3, October 2012.
6. **Din NM, Chakrabarty CK, Bin Ismail A, Devi KKA and Chen W-Y** (2012) Design of RF energy hravesting system for energizing low power devices. *Progress in Electromagnetics Research* **132**, 49–69.
7. **Elsheakh D, Elsadek HA, Abdallah E, Elhenawy H and Iskander MF** (2011) Ultra-wide bandwidth 2×2 microstrip patch array antenna by using electromagnetic band-gap structure (EBG). *IEEE Transaction on Antenna and Propagation* **59**, 1528–1534.
8. **Zhou S and Chio T** (2011) Dual linear polarization patch antenna array with high isolation and low cross-polarization, IEEE International Symposium on Antennas and Propagation (APSURSI), Spokane, WA, USA, pp. 588–590, July 2011.
9. **Woelders K and Granholm J** (1997) Cross-polarization and sidelobe suppression in dual linear polarization antenna arrays. *IEEE Transactions on Antennas and Propagation* **45**, 1836–1842.
10. **Guo Z, Yang S, Shi Z and Chen Y** (2016) A miniaturized wideband dual-polarized linear array with balanced antipodal Vivaldi antenna, IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Chengdu, China, pp. 1–4, 20–22 July 2016.
11. **Zhang H, Yang S, Chen Y, Guo J and Nie Z** (2018) Wideband dual-linear array of tightly coupled elements. *IEEE Transaction on Antennas and Propagation* **66**, 476–480.
12. **Lian R, Wang Z, Yin Y, Wu J and Song X** (2016) Design of a low profile dual polarized stepped slot antenna array for base station. *IEEE Antenna and Wireless Propagation Letteres* **15**, 362–365.
13. **Lin XQ, Nie LT, Yu JW and Fan Y** (2016) Wideband dual polarization patch antenna array with parallel strip line balun feeding. *EEE Antennas and Wireless Propagation Letters* **15**, 1499–1501.
14. **Liang J, Hong J-S, Zhao JB and Wu W** (2015) Dual band dual polarized compact log periodic dipole array for MIMO WLAN applications. *IEEE Antennas and Wireless Propagation Letters* **14**, 751–754.
15. **Eltresy N, Elsheakh D, Abdallah E and Elhenawy H** (2018) Multi band dual linearly polarized 2×2 antenna array for powering sensors in IoT systems, IEEE Global Conference on Internet of Things (GCIoT), Alexandria, Egypt, December 2018.

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