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Microwave antennas—An intrinsic part of RF energy harvesting systems: A contingent study about its design methodologies and state-of-art technologies in current scenario

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Abstract

With the significant rise of low power embedded devices in various applications of both consumer and commercial usage, the surge for continuous power requirements has initiated promising research toward alternative sources of energy. It includes the domain of wireless power transmission, internet-of-things, wireless sensor nodes, machine-to-machine, and radio frequency identification. Thus, the overall scope of this review article is to witness microwave antennas and its implementation in RF energy harvesting system through ambient RF signals. For this reason, unified understanding of classical electromagnetism is needed; beginning with the fundamentals of RF transmission and the exploration of concepts such as Fraunhofer's Distance and Friis Transmission Equation. It is followed up by the analogy of dependency of parameters like circuit build-up, conversion efficiencies and amount of power harvested, which is quite crucial from the rectifier point-of-view. For better improvisement in RF energy harvesting systems, five different cases of monopole antennas are explored with reflector surfaces such as PEC (perfect electrical conductor) and AMC (artificial magnetic conductor) integrated with the rectifier circuit. Implementation with wide diversity has proposed a generalized solution for achieving tradeoffs: polarization and pattern diversity with consistent system efficiency; leads to clean and sustainable energy for low power-embedded devices.

KEYWORDS

classical electromagnetism, low power embedded devices, microwave antennas, power conversion efficiency, rectifiers

1 | INTRODUCTION

The intent of this review article is to get a comparative focus about the possible utilization of microwave antennas built with rectifier circuits for Radio Frequency (RF) energy harvesting applications. It bids to feature performance capabilities and versatility for low power embedded devices. A comprehensive study is carried for the prospective of devices in conjecture with wireless power transmission (WPT), internet-of-things (IoTs), wireless sensor nodes (WSNs), wake-up radios, machine-to-machine, and radio frequency identification (RFIDs). As a result, the intuitiveness of RF energy harvesting using ambient RF energy has opened a new way-out for reducing cost and need for periodic maintenance from device point-of-view.[1] In addition, context of different available sources of energy in the environment are taken into consideration. Among all of them, potentials of RF energy as a possible alternative source of energy for replacing batteries in different spectra of low power-embedded devices are explored. From the instances in open literature; it can be implemented with proper facilitation of WSNs and IoTs.[2-6] The major intuition is to step forward regarding the improvement of lifespan of multi-functional electronic components. However, RF energy harvesting is viable and characterized by application requirements and intuitiveness in design philosophy. The viability of entire system vastly depends on integration of modules: microwave antennas, impedance matching network, rectifying circuit, DC booster, and power management techniques. Thus, the design of such systems are characterized through critical tradeoffs. These tradeoffs are utilized by researchers for creating an optimal system for a given paradox of application. The focus of this review article is to give a detailed analogy, along with comprehensive study of microwave antennas built-in with rectifier. Due to the inherent nature, microwave antennas are often considered as the intrinsic part of RF energy harvesting systems. Before getting into the physical insights of microwave antennas, the mainstream of understanding of its physics is required. It begins with fundamentals of RF transmission, is a naïve for understanding classical electromagnetism. Conjecture is through, in pursuit to microwave antennas. The designing aspects depends on evaluation metrics,[7-10] with prior to the utilization of ambient RF signals.

Here, various cases like planar antennas, nonplanar antennas, high performance antennas, metamaterial-inspired antennas, circularly polarized antennas, array antennas, reconfigurable antennas, and reflector antennas with special mentioning to low power embedded devices for a miniaturized system are studied. The nature of such type of energy harvesting involves utilization of energy sources available in ambient RF environment. It can be applied to power low power embedded devices (sensors), without the hassle of disrupting and/or even discontinuing their normal operation for a longer period of time. Given available extension surveys in literature,[11-16] analysis carried out in this review paper will focus on the realization of reflector surfaces (PEC/AMC) for planar antennas. Besides, due credit in understanding frequency of operation, impedance bandwidth, axial bandwidth, realized gain, antenna efficiency, and radiation traits are quite significant. Prior to the understanding of basic concepts, other parameters such as polarization diversity, pattern diversity, and initial tradeoffs are scrutinized before going toward the optimal solution. With due analysis about pros and cons of proposed antenna models, the incorporation of rectifiers would make this review article more helpful for researchers; as it explains the realization of five different cases of rectenna models. They are designed, simulated, analyzed, and reported by using FDTD domain solver and ADS circuit solver which clears the objective for RF energy harvesting. This is the first instance, where generalized solutions are proposed in terms of classical electromagnetism with the progressive research presented for solving the tradeoffs in modern RF communication systems, especially RF energy harvesting systems. The current analogy was not earlier available in the open literature.[2,3,11-16]

The review article is segregated into following sections. Section 2 and 3 deals with the fundamentals of RF and the operationalibility of microwave antennas. It also highlights their basic link up with classical electromagnetism, meant to understand its behavioral traits in real-time scenarios. In addition, detailed analogy about various evaluation metrics related to the rectifier circuit build-up, conversion efficiencies and amount of power harvested are explored and investigated. Section 4 introduces about the study and characterization of different breeds of microwave antennas used in RF energy harvesting. Prior to that, a summary of design setup and performatory analysis of various microwave antennas are tabulated. With that, the design methodologies and its state-of-art technologies for the microwave antennas in RF energy harvesting are also explored. In Section 5, design prospective regarding the usage of PEC and AMC reflector surfaces for planar antennas, as a possible generic solution for microwave antennas in achieving tradeoffs for RF energy harvesting system are presented. It is prepared along with the scope of theoretical context and its physical insight. Finally, Section 6 summarizes overall investigation and relates with the exploration of proposed solutions for RF energy harvesting. Appendix is provided to highlight generic idea about technical aspects, glossary of abbreviations, evaluation metrics for microwave antennas, and brief insights about the electromagnetic optimization techniques by using FDTD domain solver.

2 | RF FUNDAMENTALS

With the conceptualization of Maxwell's equation,[17] the understanding of electromagnetic waves comes into reality and provided a way-out for realizing the physics behind microwave antennas. Transmitting and receiving functionalities of antenna are explained by Maxwell; as he was the one, who characterized the properties of electric and magnetic fields in terms of electromagnetic waves. Due to which, the concept of classical electromagnetism comes into existence. It predicted that these infinite number of frequencies of electromagnetic waves are traveling at the speed of light, gives the very first indication for existence of electromagnetic spectrum.[18] The demonstration of electromagnetic waves is predicted with behavior of a valence electron losing energy and moving from higher-energy state to a lower-energy state at same point-of-time. Due to principles of conservation of energy[19,20]; it will radiate as the photon. Still, it will continue its journey indefinitely until it encounters an atom that is, electron, along its path. When it hits an electron and if that electron absorbs the energy, which the photon is carrying; then it will become more energetic and will travel from valence band to conduction band. Hence, the force that the photon carries is transferred to electron and due to which, the photon vanishes. The type of waves created by photons is defined as electromagnetic waves for which the medium can be of any form: solid, liquid or gas. The RF energy can be transported through electromagnetic waves.[11] Due to ambient RF characteristics,[21-25] it solved the need for self-sustainable powering of multifunctional electronic components and extracted by the surrounding wireless RF energy sources such as cell phone towers, broadcast stations, RF emitting devices, and Wi-Fi hotspots. The continuous availability and implantable in nature is a bigger advantage; when it is compared with other conventional source of energy such as solar energy, wind energy, thermal energy, mechanical energy, and vibration energy.[26-31]

Taking the above schema into generalization, microwave antennas are considered as the intrinsic part of RF energy harvesting systems.[32-34] Since, overall ideology of the system depends on utilization of freely available RF energy in the environment; where the behavior of electromagnetic waves varies according to distance, frequency and conducting environment.[35,36] Depending on the requirements from applications point-of-view; antenna designers need to select possible traits for characterization of electromagnetic waves. Loss of power in space is characterized by free space path loss (FSPL). Calculating FSPL requires information about gain, frequency of transmitting wave, and distance between transmitting and receiving antenna.[37,38] The behavior of electromagnetic waves depends upon distance from transmitting antenna and is categorized into far-field[39,40] and near-field.[41,42] The electromagnetic waves pattern at far-field is relatively uniform to near-field; but electric and magnetic field components are strong and independent in such a way that, one component dominates the other component. The near-field region is considered with space, lies within the Fraunhofer's distance; whereas far-field region lies outside of Fraunhofer's distance, respectively. For transmitter and receiver antenna in the far-field free space, power propagation at receiver side is expressed with the understanding of Friis transmission equation.[43,44] It provides an upper limit for the maximum possible range available for a given transmitted power. However, the Friis Transmission Equation assumes ideal free space without the presence of any environmental attenuation; where, in real world measurements; it experiences out higher order distance attenuation; thereby, causing lower power levels in the urban spaces.[45]

EIRP and Friis Transmission Power defines two important upper limits for RF energy harvester design. Available power at the antenna side can never exceeds EIRP, regardless of the range and when evaluated at a distance, falls almost below of Friis power density, except for highly reflective environments. It is analyzed by considering path loss to indicate the signal power at the far field region.[46-48] Despite of its continuous availability, radio waves arises concern of EMI/EMC of penetrating through human body; subjected to risk by World Health Organization.[11-16,49] At the midst of it, RF energy harvesting[50-53] is still considered as robust, trustworthy and feasible solution for meeting the increasing power requirements of low power embedded devices in both consumer and commercial usage.

3 | A THEORETICAL ANALOGY OF RECTIFIER CIRCUITS

Now coming to the analogy of rectifier circuits[13] for various evaluation metrics like power conversion efficiency (PCE), sensitivity (P_{dBm}), peak passive voltage (V_{peak}), rectifier output voltage (V_{out}), regulator dropout voltage (V_{dropout}), load voltage (V_{DD}), load current (I_{DD}), and overall system power conversion efficiency (η_0). PCE refers to the proportion of power received at antenna, successfully relayed through harvester rectifier circuitry and applied to the load. It also refers to the part of circuit that needs a steady DC voltage for its operation. A high-power conversion efficiency percentage indicates efficient rectifier circuit, but power losses due to the nonlinear component such as threshold, leakage currents, and parasitic exist in practical circuit. PCE is defined as relationship between absorbed power and load power, where signal reflection coefficient at antenna terminal is not considered.[54] It is mathematically expressed as:

$$\text{PCE} = \eta_c = \frac{P_{\text{load}}}{P_{\text{absorbed}}} = \frac{P_{\text{load}}}{P_{\text{incident}} - P_{\text{reflected}}}. \tag{1}$$

The minimum power required for integrated circuit of the receiving device to perform its task is defined as sensitivity.[55] Maximizing sensitivity and efficiency are not mutually exclusive goals, their relationship is complicated by the fact that PCE is often dependent upon input power. Operating at absolute minimum possible input power usually results in lowered PCE; since conversion efficiency tends to increase with input power and voltage amplitude. Designing of circuits with zero threshold CMOS increases sensitivity, but the leakage currents inherent to processes shift the circuit efficiency toward unacceptable levels. A circuit will have to balance in between these two metrics, dictated by the application assigned to circuitry components with an ideal range at which the circuit should perform[13] in a best possible manner.

Parameters such as PCE and sensitivity of a standard power harvester circuit are highly proportional to amplitude of sinusoid between LC matching network and rectifying stage ladder. For understanding its analogy, peak passive voltage (V_{peak}) is defined as the peak amplitude of the voltage sinusoid observed at output of antenna impedance matching network (input terminals of rectifier). V_{peak} defines sensitivity and PCE of the rectifier via its relationship with voltage threshold (V_{th}) at the rectifier input terminal. It is related to rectifier output voltage, as rectifier ladder witness multiplication of the V_{peak} based upon the number of stages. This property is proposed as a solution for converting RF input into DC voltage. The DC voltage amplitude at output stage of rectifier is defined as output voltage (V_{out}). In general, it is seen as the technical requirement; since operating voltage cannot be further improved without any significant power loss. The essence of voltage limiter is to reduce V_{out} down to V_{DD} and regulate it at the stable DC value. Internally, it requires voltage difference between V_{DD} and $V_{dropout}$, in such a way that $V_{out} > V_{DD}$ is always a way-out for good regulation.[56]

$$\text{Regulator dropout voltage} = V_{dropout} = V_{out} - V_{DD}. \quad (2)$$

The entire digital portion of the RF circuit is typically fed from the stable DC voltage (V_{DD}). The current drawn from V_{DD} is referred as I_{DD}. For majority of the cases, the circuit needs to be collectively examined for efficiency. Overall system PCE (η_0) is examined based on the incident power[57] and on a performance scale, including efficiency losses from impedance mismatch and reflection scattering at the antenna level.

$$\text{Overall system PCE} = \eta_0 = \frac{P_{load}}{P_{incident}} = \frac{V_{out}^2}{P_{in} \times R_{load}} \times 100\%. \quad (3)$$

Since, η_0 is dependent on antenna and circuit process precision for the passive components, it may vary between different accomplishments of the same circuit design.[13] It incorporates efficiency losses due to three distinct stages that incident antenna power must transfer through to turn into the stable load power @ $V_{DD} \times I_{DD}$. Thus, antenna and impedance matching network efficiency is defined as ratio of incident antenna power to the power delivered into rectifier input. It is theoretically characterized as in Equation (4); where, V_{rect} and I_{rect} are the RMS voltage and current at the input of rectifier. Similarly, η_{ant} includes the power loss due to backscattering. On the same path, rectifier efficiency is defined as ratio of incoming rectifier power to the output DC power from the rectifier to the regulator, as in Equation (5); where, I_{DD} is the load current, approximately equal at the input and output of the regulator. V_{out} is output voltage of rectifier. The regulator efficiency (η_{reg}) is defined in Equation (6). Combining Equations (4), (5), and (6); the overall system power conversion efficiency can be characterized as (Equation (7)):

$$\text{Antenna network efficiency} = \eta_{ant} = \frac{V_{rect} \times I_{rect}}{P_{incident}}, \quad (4)$$

$$\text{Rectifier efficiency} = \eta_{rect} \approx \frac{V_{out} \times I_{DD}}{V_{rect} \times I_{rect}}, \quad (5)$$

$$\text{Regulator efficiency} = \eta_{reg} \approx 1 - \frac{V_{dropout}}{V_{out}}, \quad (6)$$

$$\eta_0 = \frac{P_{load}}{P_{incident}} = \eta_{ant} \times \eta_{rect} \times \eta_{reg} = \frac{V_{out}^2}{P_{in} \times R_{load}} \times 100\%, \quad (7)$$

where, η_{ant}, η_{rect}, and η_{reg} are the individual efficiency of antenna and the LC matching network including reflective power losses at the antenna terminal, rectifier ladder, and voltage limiter.[58] A detailed analogy about the evaluation metrics of rectifier circuits and their tradeoffs are referenced in the literature.[11,13]

4 | MICROWAVE ANTENNAS IN RF ENERGY HARVESTING SYSTEMS

In Figure 1, the different components of RF energy harvesting systems are shown. Microwave antennas are considered as the intrinsic part, relates with utilization of electromagnetic waves. As, they are heavily responsible for collecting the incoming RF signals as input, that is available freely in environment from commercial RF energy sources such as intentional, anticipated, and unknown. Before going around, the readers must have a quick overview about the operating frequencies of mobile communication bands,[59] presented in Table 1. In the present context, such types of radio waves are abundantly

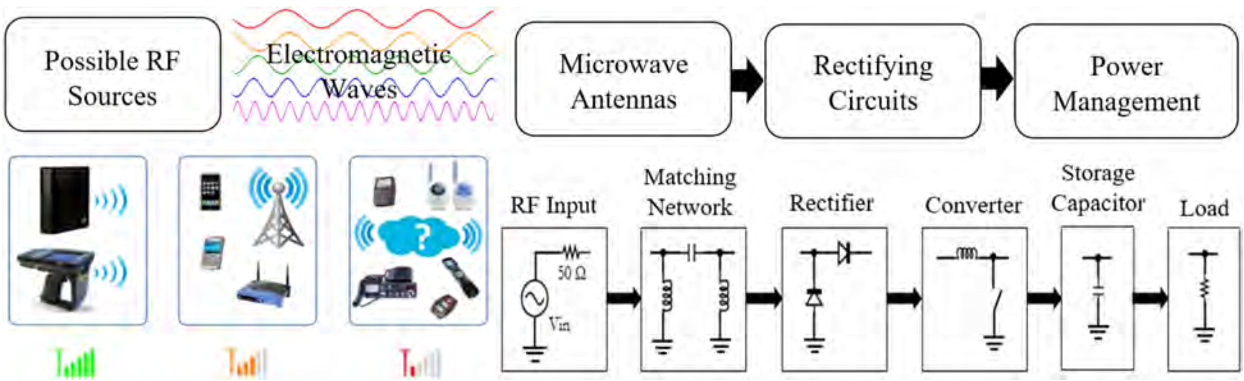

FIGURE 1 Block diagram of constituent elements of RF energy harvesting systems

available and it is utilized in a continuous manner. Thus, an inference can be modeled out from literature study that "RF energy harvesting technology is useful for medical and healthcare devices," because of its sensational growth in internet-of-things and wireless sensor nodes in recent period-of-times. All these facilitations are possible due to mobility of use. This creates new horizon and introduces a wider aspect with promising research for greater productivity. Analogy about IoTs and WSNs are given in Appendix (Table A1).

To-date, the growth in this technology has paved the way for variety of antenna designs and from the progressive research done here, suggests that with intuitiveness in theoretical/physical characterization, that is, fabrication, measurement, and implementation; there is a need of more compactness, effectiveness & maturity from applications point-of view. To have percussion in functionality, designing of microwave antennas plays a significant role. Not only with the multiband and/or broadband qualities,[60,61] it should be capable of achieving miniaturization[62] and importantly, suppression of the unwanted harmonics. [63] In a bid to these tradeoffs, that is, achievement of circular polarization, broad impedance and axial bandwidth, high realized gain, consistent antenna efficiency with pattern diversity of these microwave antennas are the top most priorities; before incorporating them with the "rectifier circuits," that is, rectenna.[64] Prior to it, complete illustration about the microwave antennas in RF energy harvesting are presented with complete design perspective. A comparative study along with performatory analysis of microwave antennas[65-158] are presented in Table 2; keeping intact with rectenna characteristics: operating frequency, realized gain, polarization diversity, input power levels, and RF-to-DC power conversion efficiency, which was not in the scope of review papers[11-16] for RF energy harvesting available in the open literature. Technically, to pursue clear understanding about tradeoffs of modern RF systems; five different cases of planar antennas

TABLE 1 Commercial RF energy sources available in the ambient environment

Sources of RF energy	Frequency ranges	Emission power levels[a]
FM tower	88-108 MHz	Upto ±36 dBm
TV tower	180-220 MHz	Upto ±36 dBm
AM tower	530-1620 MHz	Upto ±36 dBm
CDMA band	824-890 MHz	Upto ±36 dBm
GSM 900 band	890-915 MHz	±5-39 dBm
	935-960 MHz	±5-39 dBm
GPS (Global Positioning System)	1575 ± 10 MHz	Not available
GSM 1800 band	1710-1780 MHz	±2-36 dBm
	1810-1900 MHz	±2-36 dBm
3G	1920-1980 MHz	±2–33 dBm
	2110-2170 MHz	±2–33 dBm
4G	2300-2400 MHz	Upto ±36 dBm
Wi-Fi band	2400 MHz	Upto ±36 dBm
Bluetooth band	2450 MHz	Upto ±36 dBm
ISM (Industrial, Scientific and Medical)	2400-2484 MHz	Upto ±36 dBm
IEEE 802.11 b/g/n/j/ac/y/p standard	2400 MHz	Upto ±36 dBm
	3600 MHz	Upto ±30 dBm
	5000 MHz	Upto ±41 dBm
	5200 MHz	Upto ±41 dBm
	5500 MHz	Upto ±41 dBm
	5800 MHz	Upto ±41 dBm
	5150-5725 MHz	Upto ±41 dBm
	5725-5875 MHz	Upto ±41 dBm
Wi-MAX	3300-3700 MHz	Upto ±30 dBm

[a]The information regarding emission power levels is taken from the datasheet of various mobile bands, as decided by the FCC.

TABLE 2 A comparative study of different microwave antennas for RF energy harvesting[65-158]

	Properties of microwave antenna					Properties of rectenna		
Ref.	Frequency of operation	Realized gain	Radiation traits	Antenna efficiency	Pol.	Input power levels	RF-to-DC PCE	Harvested voltage
65	Theoretical analysis and characterization of the corresponding dipole antenna							
66	1.8 GHz 2.45 GHz	6.38 dBi 6.52 dBi	Omni-directional	78%[d]	LP	7 dBm	46.8%	NR
67	2G, 3G, ISM IEEE 802.11	<5.1 dBi[a]	Omni-directional	75%	LP	Can be utilized for RF-EH		
68	1.7-3.6 GHz	9.05 dBi[b]	Omni-directional	80%	LP	−20 dBm	70%	<1 V
69	2.6-3.2 GHz	1.73 dBi[b]	Omni-directional	78%	LP	0 dBm	48.9%	2.35 V
70	Theoretical analysis and characterization of the corresponding monopole antenna							
71	0.8-2.5 GHz	>1.5 dBi[a]	Omni-directional	80%[d]	LP	−5.7 dBm	> 75%	3.8 V
72	0.85-1.94 GHz	2.1 dBi	Omni-directional	78%	LP	30 dBm	60% 17%	1.26 V 0.68 V
73	0.93-0.96 GHz 1.81-1.88 GHz	3.5 dBi 4.1 dBi	Omni-directional	85%	CP	Can be utilized for RF-EH		
74	0.9-9.9 GHz	<3.2 dBi[a]	Omni-directional	82%	LP	Can be utilized for RF-EH		
75	Theoretical analysis and characterization of the corresponding loop antenna							
76	1.8 GHz	3.9 dBi	Omni-directional	86%	LP	23 dBm	61%	1.5 V
77	0.868 GHz	1.38 dBi	Omni-directional	80%[d]	LP	−17 dBm	40%	2.2 V
78	1.83 GHz	2.2 0dBi	Omni-directional	86%	LP	Can be utilized for RF-EH		
79	810-849 MHz	1.83 dBi	Omni-directional	80%	LP	−20 dBm	NR	1.72 V
80	Theoretical analysis and characterization of the corresponding slot antenna							
81	0.85-0.95 GHz	4.9 dBi	Broadside	~80%[d]	LP	−8.2 dBm	25%	< 3.3 V
82	WLAN	< 6.2 dBi[b]	Broadside	82%	LP	Can be utilized for RF-EH		
83	IEEE 802.11	< 4.1 dBi[b]	Broadside	78%[d]	LP	0 dBm	57%	< 1.8 V
84	WLAN	3.85 dBi	Broadside	80%[d]	LP	Can be utilized for RF-EH		
85	Theoretical analysis and characterization of the corresponding microstrip antenna							
86	2.45 GHz	~4 dBi[a]	Omni-directional	88%[d]	LP	2.5 dBm	70%	1.6 V
87	GSM 900	8.5 dBi	Omni-directional	80%	LP	3 dBm	65.3%	1.8 V
88	6.07-7.52 GHz	9 dBi	Omni-directional	85%	LP	Can be utilized for RF-EH		
89	35 GHz	19 dBi	Omni-directional	90%	LP	8.45 dBm	67%	2.18 V
90	Theoretical analysis and characterization of the corresponding microstrip antenna							
91	Theoretical analysis and characterization of the corresponding Vivaldi antenna							
92	1.8-3.2 GHz	9 dBi	Broadside	> 80%	LP	20 dBm	NR	2 V
93	0.8-1.2 GHz	7 dBi	Broadside	> 80%	LP	Can be utilized for RF-EH		
94	2.3-2.85 GHz	2 dBi	Broadside	85%	LP	0 dBm	68%	1.6 V
95	0.7-2.7 GHz	7.41 dBi	Broadside	> 90%	LP	Can be utilized for RF-EH		
96	Theoretical analysis and characterization of the corresponding dielectric resonator antenna							
97	1.67-6.7 GHz	8 dBi	Broadside	> 90%	LP	−20 dBm	61.4%	NR
98	1.84-2.44 GHz	4.5 dBi	Broadside	> 90%	LP	Can be utilized for RF-EH		
99	5.5 GHz	NR	Broadside	> 90%	LP	0 dBm	70%	NR

(Continues)

TABLE 2 (Continued)

	Properties of microwave antenna					Properties of rectenna		
Ref.	**Frequency of operation**	**Realized gain**	**Radiation traits**	**Antenna efficiency**	**Pol.**	**Input power levels**	**RF-to-DC PCE**	**Harvested voltage**
100	4.19-6.94 GHz	7.2 dBi	Broadside	> 90%	LP	Can be utilized for RF-EH		
101	Theoretical analysis and characterization of the corresponding helical antenna							
102	GSM 900	NR	Omni-directional	NR	LP	−10 dBm	NR	0.3 V
103	2.45 GHz	3.8 dBi	Omni-directional	NR	LP	0 dBm	52%	NR
104	Theoretical analysis ad characterization of the corresponding Yagi-Uda antenna							
105	0.915 GHz 2.45 GHz	6 dBi	Omni-Directional	NR	LP	−13 dBm −11 dBm	40.7% 56.2%	NR
106	1.8-2.2 GHz	10.9 dBi 13.3 dBi	Omni-Directional	NR	LP	−13 dBm	40%	224 mV
107	Theoretical analysis and characterization of the corresponding log-periodic antenna							
108	0.57-2.75 GHz	6.7-7.7 dBi	Broadside	NR	LP	−4.2 dBm	NR	3 V
109	0.65-2.5 GHz	<7.2 dBi[b]	Broadside	NR	CP	Can be utilized for RF-EH		
110	2.5 GHz	NR	Broadside	NR	0 LP	15 dBm	61%	NR
111	LTE Bands	4-6 dBi	Broadside	NR	LP	−20 dBm −15 dBm	5-16% 11-30%	~1.02 V
112	2.45 GHz	5.6 dBi	Omni-directional	80%[d]	LP	5 dBm	68%	3.24 V
113	2.45 GHz	8.1 dBi	Broadside	> 95%	LP	−7 dBm	28.7%	3 V
114	0.7-2 GHz	1.5 dBi[a]	Broadside[c]	NR	LP	−7 dBm	< 90%	NR
115	~0.24-0.9 GHz	NR	Broadside[c]	NR	LP	20 dBm	NR	2.24 V
116	2.45 GHz	11 dBi	Broadside[c]	NR	LP	−20 dBm	NR	28 mV
117	2.72 GHz	11 dBi	Broadside	>95%	CP	−2 dBm	55%	NR
118	3.32-4.76 GHz	7-7.5 dBi	Broadside	>80%	CP	Can be utilized for RF-EH		
119	5.04-7.2 GHz	7 dBi	Broadside	>80%	CP	Can be utilized for RF-EH		
120	ISM Bands	4.5-5 dBi	Broadside	80%	CP	Can be utilized for RF-EH		
121	2.31-2.56 GHz	6.32 dBi	Broadside	90%	CP	Can be utilized for RF-EH		
122	4.48-5.9 GHz	> 8 dBi[b]	Broadside	90%	CP	Can be utilized for RF-EH		
123	1.8-2.5 GHz	9 dBi	Broadside	~85%	CP	20 dBm	24%	1.8 V
124	1.8 GHz 2.45 GHz	4.54 dBi[a] 4.64 dBi[a]	Broadside	80%	CP	−15 dBm	40.6%	150 mV
125	2.45 GHz	5.5-6.4 dBi	Broadside	80%	CP	−15 dBm	37.7%	189 mV
126	5.8 GHz	10.2 dBi	Broadside	85%	CP	0 dBm	70%	2.2 V
127	5.05-7.45 GHz	< 6 dBi[b]	Broadside	90%	CP	Can be utilized for RF-EH		
128	1.6 GHz 2.4 GHz	0.23 dBi 1.94 dBi	Broadside	85%	LP	15 dBm	NR	21 V 22 V
129	WiMAX WLAN	NR	Broadside	> 78%	LP	28 dBm	NR	4.9 V
130	4.5-5.1 GHz	< 4 dBi[b]	Broadside	90%	CP	Can be utilized for RF-EH		
131	WiMAX	< 6 dBi[b]	Broadside	~85%	CP	16.5 dBm	37-46%	NR
132	WiMAX	6.4 dBi	Broadside	80%	CP	Can be utilized for RF-EH		
133	2.16-2.63 GHz	11.3 dBi	Broadside	80%	LP	Beam-steering for RF-EH		

(Continues)

TABLE 2 (Continued)

	Properties of microwave antenna					Properties of rectenna		
Ref.	**Frequency of operation**	**Realized gain**	**Radiation traits**	**Antenna efficiency**	**Pol.**	**Input power levels**	**RF-to-DC PCE**	**Harvested voltage**
134			2.45 GHz	NR		Broadside	80%	LP
	6 dBm 5 dBm 5 dBm	64.5% 65.3% 64.5%	6.51 V 1.58 V 3 V					
135	2.45 GHz	>4.5 dBi[b]	Broadside	> 90%	LP	−5 dBm	S < 70%	NR
136	5.8 GHz	>4.3 dBi[b]	Broadside	> 80%	LP	13.8 dBm	38.4%	NR
137	ISM bands	<4 dBi[b]	Broadside	80%	CP	Can be utilized for RF-EH		
138	Mobile bands	<6 dBi[b]	Omni-directional	90%	CP	Can be utilized for RF-EH		
139	2.45 GHz	5.9 dBi	Omni-directional	> 80%	LP	−4 dBm	55.3%	3.3 V
140	ISM X-band	NR	NR	NR	LP	−15 dBm	20%	NR
141	Theoretical analysis and characterization of EM-based genetic algorithm (GA)							
142	Theoretical analysis and characterization of EM-based particle swarm optimization (PSO)							
143	0.5 + ISM	>4.1 dBi[b]	Broadside	70%	LP	It can be improved with implicit technique.		
144	Mobile bands	>1.3 dBi[b]	Broadside	70%	LP	It can be improved with implicit technique.		
145	0.9-2.4 GHz	~5 dBi[a]	Omni-directional	> 90%	LP	−10 dBm	35%	~2.5 V
146	2.45 GHz	6.44 dBi	Broadside	< 75%	LP	−10 dBm	55%	~215 mV
147	GSM 900	3.2 dBi	Broadside	~82%	LP	−20 dBm 0 dBm	21.2% 63.6%	~1.5 V ~3.5 V
148	0.9-2.1 GHz	>7 dBi[b]	Omni-directional	~75%	LP	4 dBm	40%	~600 mV
149	ISM	7.4 dBi	Omni-directional	NR	CP	−15 dBm	NR	2.8 V
150	5.71-5.99 GHz	NR	Broadside	85%[d]	LP	15.2 dBm	~70.1%	< 3 V
151	2.45 GHz	NR	Broadside	80%	LP	−5 dBm −15 dBm	61.4% 38%	NR
152	2.26-2.61 GHz	~3.2 dBi[a]	Omni-directional	~82%[d]	LP	0 dBm	70%	2.2 V
153	0.89-5.53 GHz	>3 dBi[b]	Broadside	75%	LP	0 dBm	62.5%	NR
154	GSM 1800 2.4 GHz	~4.6 dBi[b]	Broadside	80%	LP	5 dBm	41% 15%	0.6 V
155	Theoretical analysis & characterization about reducing transmission loss by using single structure							
156	Theoretical analysis and characterization about spectrum sharing in cellular system and IoTs for 5G							
157	Theoretical analysis and characterization about communication channel models for the RF utilization							
158	Theoretical analysis and characterization about sensitivity and nonlinearity far-field RF harvesting							

Note: Realized gain: antenna. There are certain cases, where the phenomena of metamaterial absorber is considered for RF energy harvesting systems. Here, maximum absorption efficiency is considered as the identification factor. All the necessary parameters for understanding the concept of RF-EH are presented as “properties of microwave antenna” and “properties of rectenna”.

Abbreviations: Amount of power harvested, rectenna (volts); CP, circularly polarized; Input Power Levels, rectenna (Ambient RF Sources); LP, linearly polarized; NR, not reported in the paper; Pol., polarization (antenna); RF-to-DC PCE: power conversion efficiency (%).

[a]Realized gain: antenna (in terms of average).

[b]Realized gain: antenna (approximate value of gain); radiation trait: antenna- omni-directional and directional.

[c]From the observation point-of-view.

[d]Antenna efficiency: antenna (calculated manually).

(monopole antennas) at different bands with reflector surfaces and integrated with rectifier circuits are designed, simulated and analyzed by using FDTD domain solver (CST microwave studio) and circuit solver (advanced design system). The results are reported in accordance with achievement of tradeoffs. The relevant description about different evaluation metrics[7-10] are presented in the Appendix (Table A2).

The different breeds of microwave antennas in RF energy harvesting are shown in Figure 2; it includes the basic form of antennas such as dipole antennas,[65-69] monopole antennas,[70-74] loop antennas,[75-79] slot antennas,[80-84] microstrip antennas,[85-90] Vivaldi antennas,[91-95] dielectric resonator antennas,[96-100] helical antennas,[101-103] Yagi-Uda antennas,[104-106] and log-periodic antennas.[107-109] The relevant theories of basic forms of antennas are available in open literature.[36,65,70,75,80,85,91,96,101,104,107] It is further classified into high performance antennas,[110-113,159] metamaterial antennas,[114-117,160-162] CP antennas,[118-127,164-177] reconfigurable antennas,[128-134] and array antennas.[135-140] It is a strong belief that prerequisites need to be cleared before using the implicit technique in proposed antenna models. The various EM optimization techniques are shown in Table 11, used in the prospective of FDTD/FEM/MoM domain solver.[141,142] It can be taken as wider research aspect for microwave antennas in RF energy harvesting.[143-145,163] During the course-of-study, there are fewer instances of electromagnetically optimized antennas, available for RF energy harvesting. Hence, it can be taken as the broader area of exploration for research, where RF researchers can pursue modeling of antennas through soft computing techniques. A comparative focus on recent developments of microwave antennas in RF energy harvesting[146-158] with concurrent analysis are shown in Table 2. The characteristics of microwave antennas are normally dealt with frequency of operation, realized gain, radiation characteristics, and antenna efficiency; followed by the properties of rectenna characterized with parameters such as input power levels, RF-to-DC PCE, and harvested voltage.

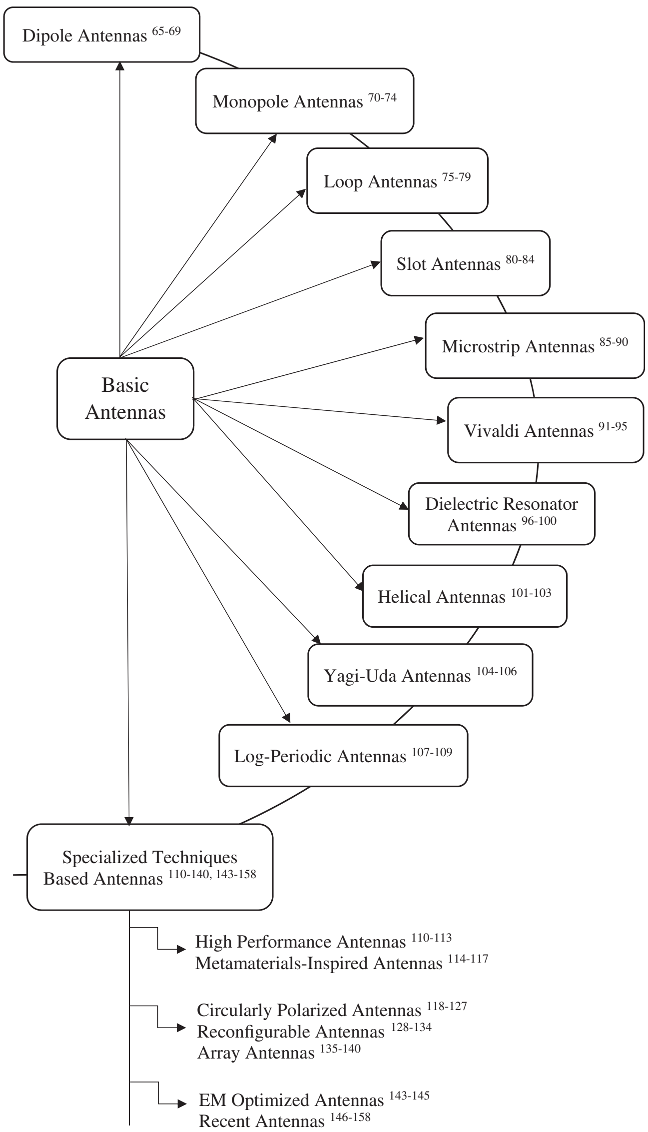

FIGURE 2 A complete illustration of microwave antennas for RF energy harvesting systems

5 | DESIGN PROSPECTIVE OF MICROWAVE ANTENNAS IN RF ENERGY HARVESTING SYSTEMS

Here, five cases of printed monopole antennas loaded with AMC and PEC reflector surfaces integrated with rectifier circuits are investigated and reported in Figures 3–7 and Tables 3–7. Prior to that, a detailed analogy regarding the incorporation of reflecting surface on the proposed antenna models are highlighted in Table 8A. Table 8B demonstrates RF-to-DC PCE (%) and amount of voltage harvested for the proposed antennas. It demonstrates the achievement of design tradeoffs such as polarization diversity,[164-177] wide/broad axial bandwidth, high realized gain, consistent antenna efficiency, and directional pattern diversity.

1. U-shaped monopole antenna for GSM 900 bands loaded with PEC and AMC reflector
2. Circular-shaped monopole antenna with AMC reflector for wideband circular polarization
3. Circular-shaped monopole antenna with PEC reflector for broadband circular polarization
4. Y-shaped monopole antenna with PEC reflector for wideband circular polarization
5. Y-shaped monopole antenna with AMC reflector for broadband circular polarization

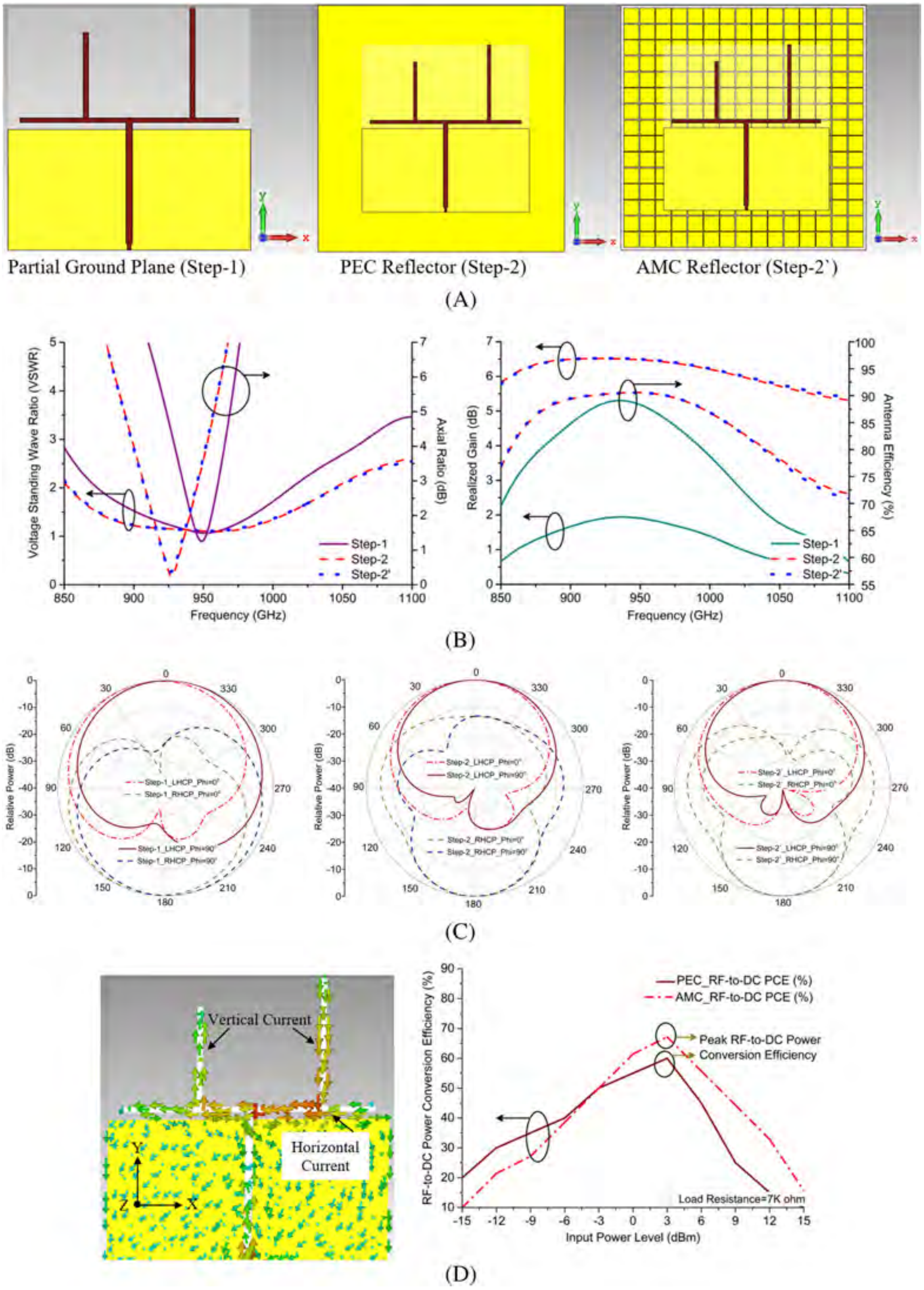

FIGURE 3 A, Geometrical Evolution; B, Antenna parameters: VSWR, axial ratio, realized gain, antenna efficiency; C, normalized radiation pattern of proposed CP antenna (ie, step 1, step 2, and step 2′ at $f = 915$ MHz); D, surface current distribution for circular polarization (ie, at $f = 915$ MHz) and rectenna parameters: RF-to-DC conversion efficiency with a load resistance of 7 KΩ

5.1 | Case of a U-shaped monopole antenna for GSM 900 bands with AMC and PEC reflector integrated with a 4-stage rectifying circuit

Here, a circularly polarized asymmetrical U-shaped antenna integrated with 4-stage rectifier is proposed for RFID applications. It consists of an impedance matching device that is, quarter-wave transformer, 50-Ω microstrip feed line, two asymmetrical metallic strips, making a U-shape on top of the substrate with the partial ground plane. With reference to the behavior of current density, detailed analogy about circular polarization is refined. The asymmetrical U-strips of monopole antenna generate

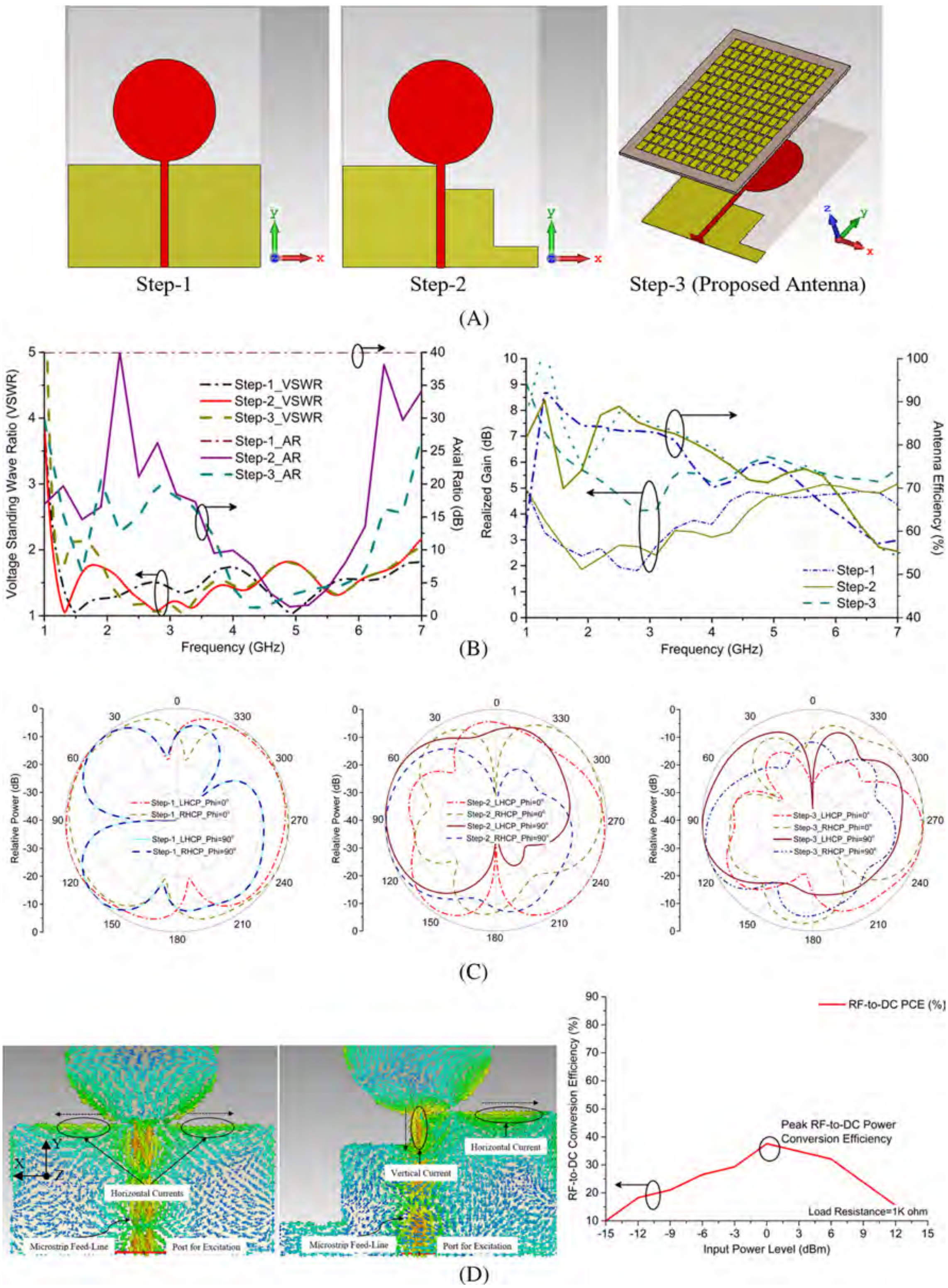

FIGURE 4 A, Geometrical evolution; B, Antenna parameters: VSWR, axial ratio, realized gain, antenna efficiency; C, normalized radiation pattern of proposed CP antenna (ie, step 1, step 2, and step 3 at $f = 4.5$ GHz); D, surface current distribution for circular polarization (LP vs CP) (ie, at $f = 4.5$ GHz) and rectenna parameters: RF-to-DC conversion efficiency with a load resistance of 1 KΩ

vertical currents. In the same, there is an existence of maximum horizontal current on the ground plane. Thus, the combination of horizontal and vertical currents indicates the existence of circular polarization. With the conversion to partial ground plane, the impedance bandwidth is enhanced with moderate improvement of axial

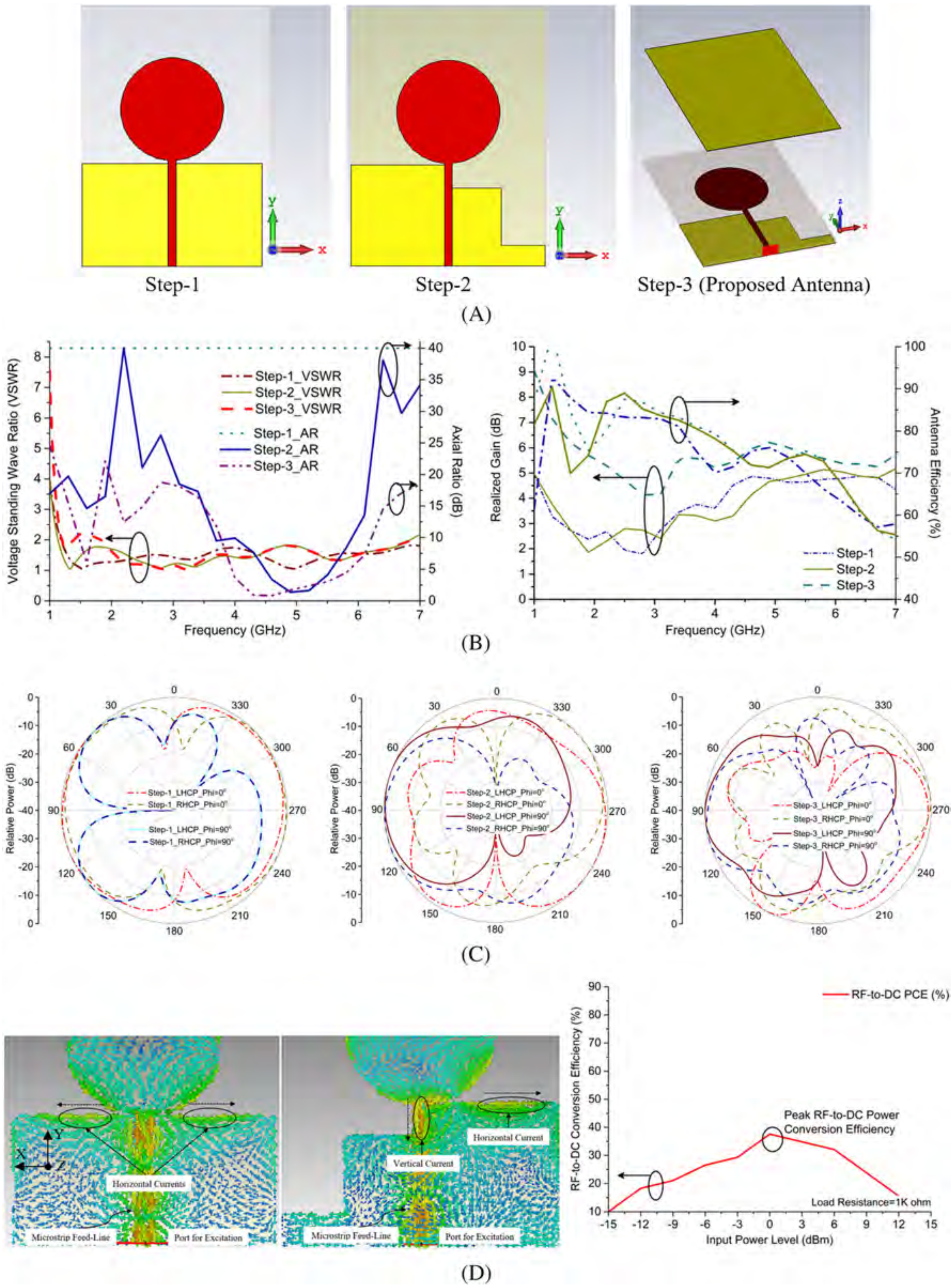

FIGURE 5 A, Geometrical evolution; B, Antenna parameters: VSWR, axial ratio, realized gain, antenna efficiency; C, normalized radiation pattern of proposed CP antenna (ie, step 1, step 2, and step 3 at $f = 4.8$ GHz); D, surface current distribution for circular polarization (LP vs CP) (ie, at $f = 4.8$ GHz) and rectenna parameters: RF-to-DC conversion efficiency with a load resistance of 1 KΩ

ratio bandwidth. But the realized gain was still very low. AMC and PEC reflector (separately) are placed below patch for improving parameters. For conversion of RF-to-DC, a 4-stage rectifier is incorporated with the proposed CP antenna (step 2 and step 2′). The RF-to-DC power conversion efficiency (%) is calculated on the basis of Equation (3).

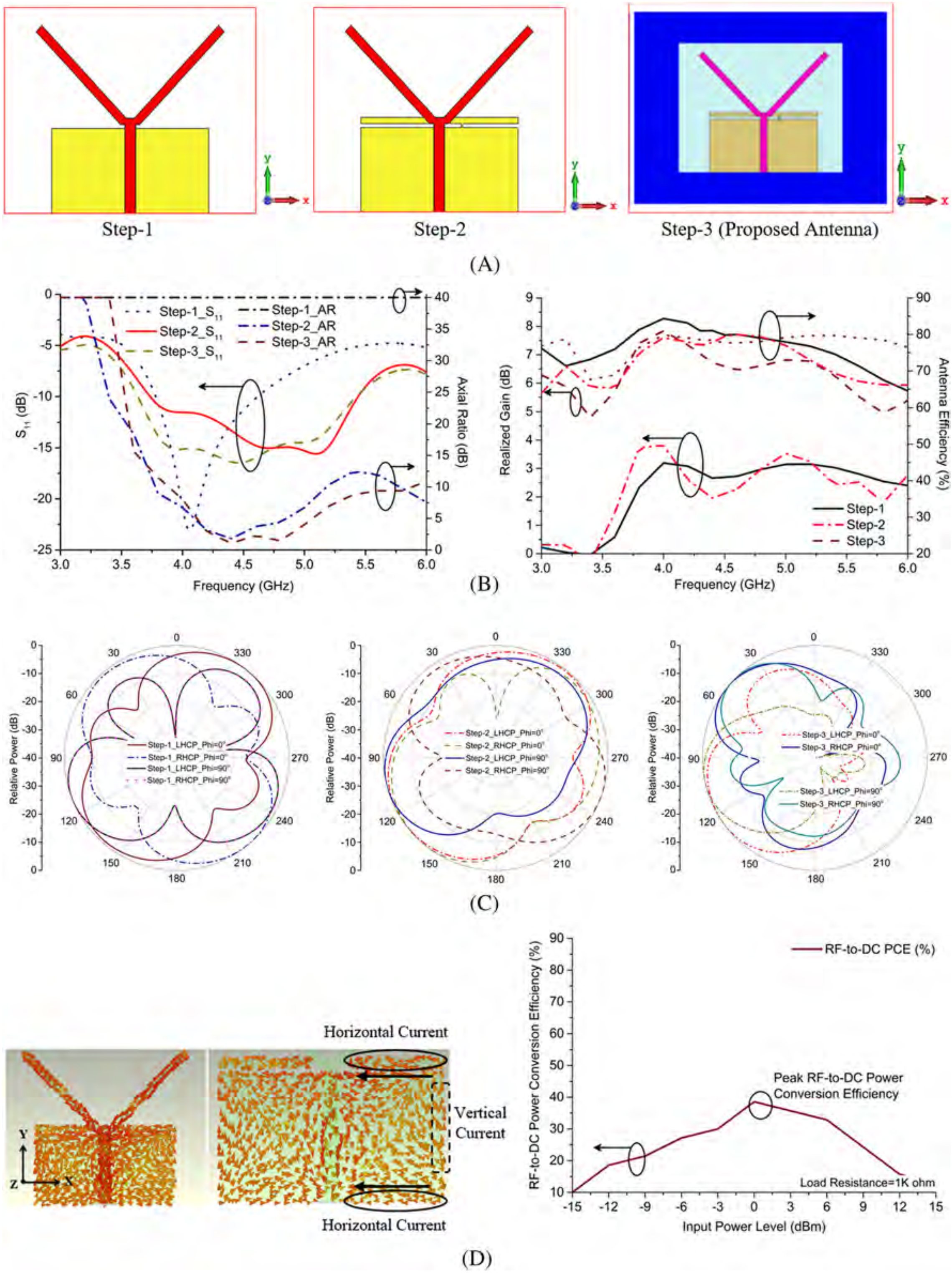

FIGURE 6 A, Geometrical evolution; B, Antenna parameters: S_{11}, axial ratio (AR), realized gain, antenna efficiency characteristics; C, normalized radiation pattern of proposed CP antenna (ie, step 1, step 2, and step 3 at $f = 4.5$ GHz); D, surface current distribution for circular polarization (ie, at $f = 4.5$ GHz) and rectenna parameters: RF-to-DC conversion efficiency for a load resistance of 1 KΩ

In step 2 and step 2′, value of V_{out} is referenced on the basis of first stage of rectifying circuit, with load resistance of 7 KΩ. From these outcomes, the proposed U-shaped monopole antenna with PEC/AMC reflector integrated with 4-stage rectifying circuit becomes a suitable candidate for GSM 900 bands.[163,164] A detailed state-of-art is shown

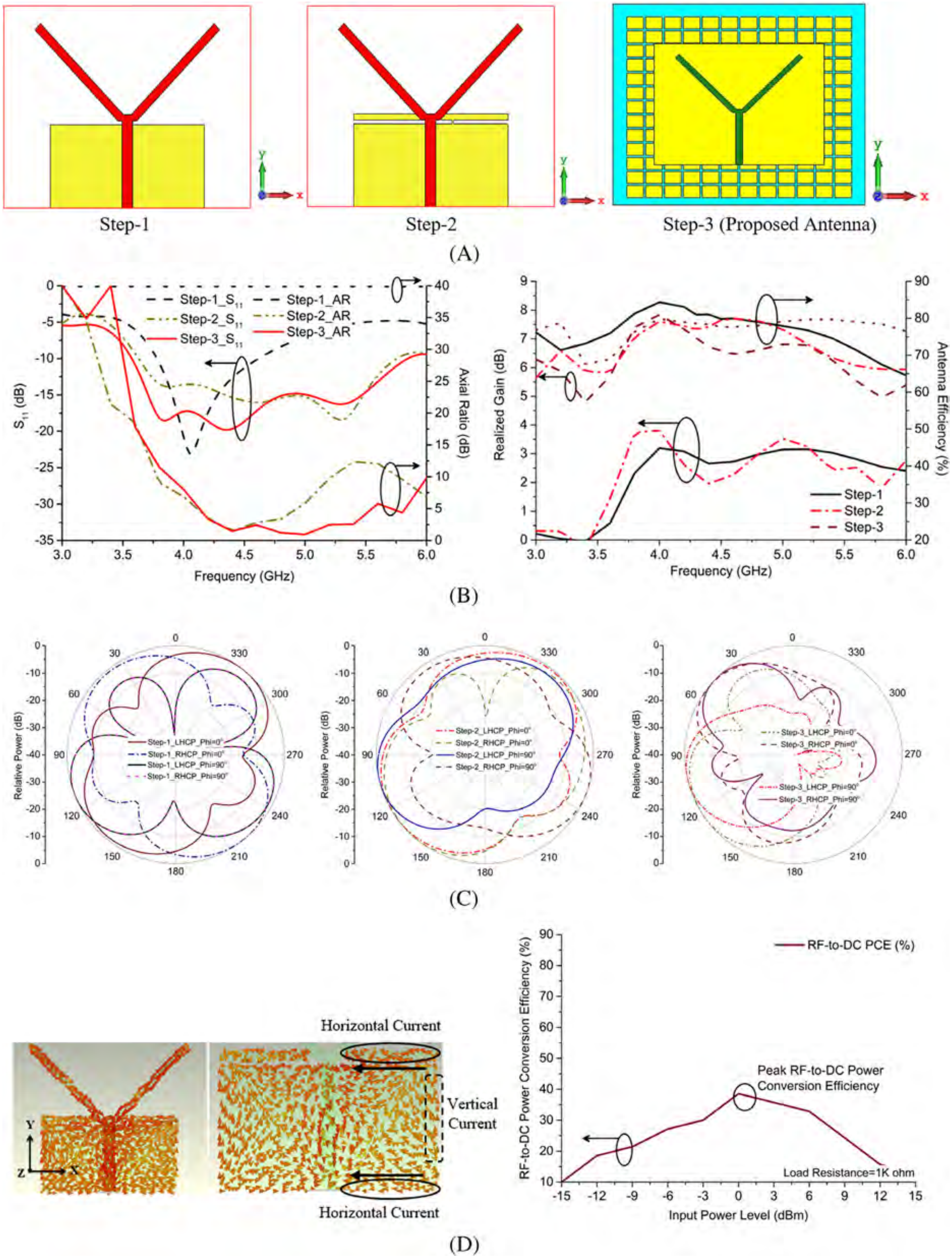

FIGURE 7 A, Geometrical evolution; B, Antenna parameters: S_{11}, axial ratio (AR), realized gain, antenna efficiency characteristics; C, normalized radiation pattern of proposed CP antenna (ie, step 1, step 2, and step 3 at $f = 4.8$ GHz); D, surface current distribution for circular polarization (ie, at $f = 4.8$ GHz) and rectenna parameters: RF-to-DC conversion efficiency for a load resistance of 1 KΩ

TABLE 3 Performance Index of U-shaped monopole antenna for GSM 900 bands with PEC and AMC reflector integrated with a 4-stage rectifying circuit

Parameters	Step 1	Step 2	Step 2′
Frequency of operation	GSM 900 bands		
Antenna size	100 mm × 100 mm × 0.8 mm		
Substrate	FR-4 (epoxy) with Epsilon = 4.4 and thickness = 0.8 mm		
Geometrical feature	Partial ground	PEC reflector	AMC reflector
Reflector size	Not applicable	$150 \times 150 \times 0.2$ mm^3	$150 \times 150 \times 1.6$ mm^3
Air gap (Height)	Not applicable	80 mm	
S-parameters (VSWR ≤2)	877-1010 MHz	851-1045 MHz	851-1045 MHz
Impedance bandwidth	133 MHz (14%)	194 MHz (20.5%)	194 MHz (20.5%)
Axial ratio (AR ≤3 dB)	935-960 MHz	905-945 MHz	902-944 MHz
Axial ratio bandwidth	25 MHz (2.6%)	40 MHz (4.3%)	42 MHz (4.55%)
Polarization	Circular polarization	Circular polarization	Circular polarization
Radiation pattern	Omni-directional	Directional	Directional
Realized gain[a]	Avg. ≥ 1.83 dB	Avg. ≥ 6.33 dB	Avg. ≥ 6.5 dB
Input power level (dBm)	Not Applicable	5 dBm ($f = 915$ MHz)	5 dBm ($f = 930$ MHz)
RF-to-DC PCE (%)		57.75% (stage 1)	58.7% (stage 1)
Harvested voltage (V)	—	Stage 1: 3.54 V	Stage 1: 3.57 V
	—	Stage 2: 3.71 V	Stage 2: 3.89 V
	—	Stage 3: 3.89 V	Stage 3: 4.02 V
	—	Stage 4: 4.04 V	Stage 4: 4.24 V

[a]The realized gain is calculated on the basis of average of lower bound and upper bound frequency points of 3-dB axial bandwidth.

in Table 3 and Figure 3. For the placement of reflectors (PEC/AMC), an empirical formula (Equation (8.1)) is proposed:

$$h_{\text{air-gap}} = 0.26\lambda - h_{\text{sub}}\sqrt{\varepsilon_r}. \tag{8.1}$$

5.2 | Case of a circular-shaped monopole antenna with AMC reflector for wideband circular polarization integrated with a 4-stage rectifying circuit

Here, circularly polarized circular-shaped monopole antenna is proposed for wideband applications. It consists of circular-shaped patch, asymmetrical staircased ground plane, and 50-Ω microstrip feed line for input excitation. Conventional UWB antennas with partial ground plane has a limitation of achieving circular polarization. Thus, asymmetrical staircased ground plane is considered, capable of generating both the horizontal and vertical components, needed for CP generation. It can be confirmed by surface current distribution (LP vs CP). To meet tradeoffs, AMC reflector is placed above patch. For conversion of RF-to-DC, 4-stage rectifier is added (step 3). RF-to-DC power conversion efficiency (%) is calculated on basis of Equation (3). In step 3, value of V_{out} is referenced from the fourth stage of rectifying circuit with 1 KΩ load resistance. The rectifier designed in this case, can be further improvised in terms of RF-to-DC PCE (%). From the outcomes;

TABLE 4 Performance index of circular-shaped monopole antenna with AMC reflector for wideband circular polarization integrated with a 4-stage rectifying circuit

Parameters	Step 1	Step 2	Step 3
Frequency of operation	GSM 1800, UMTS, LTE, Wi-Fi/Bluetooth, ISM, LTE-advanced, Wi-MAX, WLAN, IEEE 802.11, and 5G		
Antenna size	75 mm × 100 mm × 1.6 mm		
Substrate	FR-4 (epoxy) with Epsilon = 4.4 and thickness = 1.6 mm		
Geometrical feature	Partial ground	Asymmetrical ground	AMC reflector
Reflector size	Not applicable		$75 \times 100 \times 1.6\ \text{mm}^3$
Air gap (height)	Not applicable		45 mm
S-parameters (VSWR ≤2)	1.2-7.0 GHz	1.1-6.8 GHz	1.87-6.77 GHz
Impedance bandwidth	5.8 GHz (141.4%)	5.7 GHz (144.3%)	4.9 GHz (113.4%)
Axial ratio (AR ≤3 dB)	—	4.65-5.37 GHz	4.09-4.96 GHz
Axial ratio bandwidth	—	720 MHz (14.3%)	870 MHz (19.24%)
Polarization	Linear polarization	Circular polarization	Circular polarization
Radiation pattern	Omni-directional	Omni-directional	Directional
Realized gain[a]	Avg. ≥ 3.2 dB	Avg. ≥ 4.6 dB	Avg. ≥ 5.8 dB
Input power level (dBm)	Not Applicable		0 dBm ($f = 4.5$ GHz)
RF-to-DC PCE (%)	Not Applicable		36.72% (Stage 4)
Harvested voltage (V)	Not Applicable		Stage 1: 3.08 V
	—		Stage 2: 4.08 V
	—		Stage 3: 5.07 V
	—		Stage 4: 6.06 V

[a]The realized gain is calculated on the basis of average of lower bound and upper bound frequency points of −10 dB impedance and 3-dB axial bandwidth.

it is essential for GSM 1800, UMTS, LTE, Wi-Fi/Bluetooth, ISM, LTE-advanced, Wi-MAX, WLAN, IEEE 802.11, and 5G. A detailed state-of-art is shown in Figure 4 and Table 4. For the placement of reflector, an empirical formula (Equation (8.2)) is proposed:

$$h_{\text{air-gap}} = 6.53\lambda - h_{\text{sub}}\sqrt{\varepsilon_r}. \tag{8.2}$$

5.3 | Case of a circular-shaped monopole antenna with PEC reflector for broadband circular polarization integrated with a 4-stage rectifying circuit

Here, circularly polarized circular-shaped monopole antenna is proposed for wideband applications.[165] It consists of the circular-shaped patch, asymmetrical staircased ground plane and 50-Ω microstrip feed line used for input excitation. Conventional UWB antennas with partial ground plane has the limitation of polarization agility. Thus, asymmetrical staircased ground plane is considered, capable of generating both the horizontal and vertical components, needed for CP generation. It can be confirmed by surface current distribution (LP vs CP). To meet tradeoffs, PEC reflector is placed above patch. For conversion of RF-to-DC, a 4-stage rectifier is incorporated with the proposed CP antenna (step 3). The RF-to-DC power conversion efficiency (%) is calculated on the basis of Equation (3). In step 3, the value of V_{out} is referenced on the basis of fourth stage of rectifying circuit with load resistance value of 1 KΩ. The rectifier designed can be further improvised in terms of RF-to-DC PCE (%). From these outcomes; it is essential for GSM 1800, UMTS, LTE, Wi-Fi/Bluetooth, ISM, LTE-Advanced, Wi-MAX, WLAN, IEEE 802.11, and even 5G. A detailed state-of-art is presented in Figure 5 and Table 5. By adding PEC reflector, axial bandwidth is improved nearly 2.28 times (ie, at step 3). In addition, it satisfies the criteria of broadband explained in IEEE standards; where, fractional bandwidth should be greater than 20%[35] in the desired operating bands. For the placement of reflector, an empirical formula (Equation (8.3), which is same as that of previous one) is utilized in this case, as follows:

$$h_{\text{air-gap}} = 6.53\lambda - h_{\text{sub}}\sqrt{\varepsilon_r}. \tag{8.3}$$

TABLE 5 Performance index of circular-shaped monopole antenna with PEC reflector for broadband circular polarization integrated with a 4-stage rectifying circuit

Parameters	Step 1	Step 2	Step 3
Frequency of operation	GSM 1800, UMTS, LTE, Wi-Fi/Bluetooth, ISM, LTE-advanced, Wi-MAX, WLAN, IEEE 802.11, and 5G		
Antenna size	75 mm × 100 mm × 1.6 mm		
Substrate	FR-4 (epoxy) with Epsilon = 4.4 and thickness = 1.6 mm		
Geometrical feature	Partial ground	Asymmetrical ground	PEC reflector
Reflector size	Not applicable		$75 \times 100 \times 0.2$ mm^3
Air gap (Height)	Not applicable		45 mm
S-parameters (VSWR ≤2)	1.2-7.0 GHz	1.1-6.8 GHz	1.87-6.77 GHz
Impedance bandwidth	5.8 GHz (141.4%)	5.7 GHz (144.3%)	4.9 GHz (113.4%)
Axial ratio (AR ≤3 dB)	—	4.65–5.37 GHz	4.08-5.49 GHz
Axial ratio bandwidth	—	720 MHz (14.3%)	1.41 GHz (29.4%)
Polarization	Linear polarization	Circular polarization	Circular polarization
Radiation pattern	Omni-directional	Omni-directional	Directional
Realized gain[a]	Avg. ≥ 3.2 dB	Avg. ≥ 4.6 dB	Avg. ≥ 5.6 dB
Input power level (dBm)	Not Applicable		0 dBm (f = 4.8 GHz)
RF-to-DC PCE (%)	Not Applicable		39.18% (Stage 4)
Harvested voltage (V)	Not Applicable		Stage 1: 3.58 V
	—		Stage 2: 4.72 V
	—		Stage 3: 5.66 V
	—		Stage 4: 6.26 V

[a]The realized gain is calculated on the basis of average of lower bound and upper bound frequency points of −10 dB impedance and 3-dB axial bandwidth.

5.4 | Case of a Y-shaped monopole antenna with PEC reflector for wideband circular polarization integrated with a 4-stage rectifying circuit

Here, a circularly polarized Y-shaped monopole antenna is proposed for wideband applications.[166] It consists of Y-shaped patch, shorting of partial ground plane and parasitic conducting strips by using a metallic strip; with 50-Ω microstrip feed line for input excitation. Conventional UWB antennas of partial ground plane has limitation of polarization agility. Thus, the partial ground plane is shorted with parasitic conducting strips. Due to shorting, it is capable of generating both the horizontal and vertical components, needed for CP generation. It is confirmed by surface current distribution (LP vs CP). To meet tradeoffs, PEC reflector is placed above patch. For the conversion of RF-to-DC, 4-stage rectifier is incorporated at step 3. RF-to-DC power conversion efficiency (%) is calculated on the basis of Equation (3). In step 3, V_{out} is referenced on the basis of fourth stage of rectifying circuit with 1 KΩ load resistance. The rectifier designed can be further improvised in terms of RF-to-DC PCE (%). From the outcomes; it is essential for Wi-MAX, WLAN, IEEE 802.11, 5G, and initial satellite applications in C band. A detailed state-of-art is in Figure 6 and Table 6. For placement of reflector, empirical formula (Equation (8.4)) is proposed:

$$h_{\text{air-gap}} = 0.36\lambda - h_{\text{sub}}\sqrt{\varepsilon_r}. \quad (8.4)$$

5.5 | Case of a Y-shaped monopole antenna with AMC reflector for broadband circular polarization integrated with a 4-stage rectifying circuit

Here, circularly polarized Y-shaped monopole antenna is proposed for wideband applications. It consists of Y-shaped patch, shorting of partial ground plane and parasitic conducting strips by using a copper strip; with 50-Ω microstrip feed line for input excitation. Conventional UWB antennas of partial ground planes has limitation of CP. So, the partial ground plane is shorted with parasitic conducting strips. Due to shorting, it is capable of

TABLE 6 Performance index of Y-shaped monopole antenna with PEC reflector for wideband circular polarization integrated with a 4-stage rectifying circuit[166]

Parameters	Step 1	Step 2	Step 3
Frequency of operation	WLAN, WiMAX, IEEE 802.11, 5G, and Initial C-band satellite applications (3 GHz-to-7 GHz)		
Antenna size	80 mm × 59.5 mm × 1.6 mm		
Substrate	FR-4 (epoxy) with Epsilon = 4.4 and thickness = 1.6 mm		
Geometrical feature	Partial ground	Shorting with ground	PEC Reflector
Reflector size	Not applicable		$120 \times 99.5 \times 0.2\ mm^3$
Air gap (height)	Not applicable		20 mm
S-parameters ($S_{11} \le -10$ dB)	3.7-4.6 GHz	3.7-5.46 GHz	3.6-5.47 GHz
Impedance bandwidth	900 MHz (21.6%)	1.76 GHz (38.4%)	1.87 GHz (41.2%)
Axial ratio (AR ≤3 dB)	—	4.21-4.52 GHz	4.19-4.92 GHz
Axial ratio bandwidth	—	310 MHz (7.1%)	730 MHz (16.04%)
Polarization	Linear polarization	Circular polarization	Circular polarization
Radiation pattern	Omni-directional	Omni-directional	Directional
Realized gain[a]	Avg. ≥ 2.4 dB	Avg. ≥ 2.3 dB	Avg. ≥ 7.1 dB
Input power level (dBm)	Not Applicable		0 dBm (f = 4.5 GHz)
RF-to-DC PCE (%)	Not Applicable		35.52% (Stage 4)
Harvested voltage (V)	Not Applicable		Stage 1: 3.02 V
	—		Stage 2: 3.96 V
	—		Stage 3: 4.94 V
	—		Stage 4: 5.96 V

[a]The realized gain is calculated on the basis of average of lower bound and upper bound frequency points of −10 dB impedance and 3-dB axial bandwidth.

generating the horizontal and vertical components, needed for CP generation. It is confirmed by surface current distribution (LP vs CP). To meet tradeoffs, AMC reflector is placed above patch. For the conversion of RF-to-DC, 4-stage rectifier is incorporated (step 3). RF-to-DC power conversion efficiency (%) is calculated on the basis of Equation (3). In step 3, value of V_{out} is referenced on the basis of fourth stage of rectifying circuit with a load resistance value of 1 KΩ. The rectifier designed can be further improved in terms of RF-to-DC PCE (%). From the outcomes, it is essential for Wi-MAX, WLAN, and IEEE 802.11, 5G and initial satellite applications in C band. A detailed state-of-art is shown in Figure 7 and Table 7. While adding on AMC surfaces, the axial bandwidth is improved nearly to 3.56 times (step 3). In this case maximum enhancement in the 3-dB axial bandwidth is observed. It is crucial for proposing generic solution regarding incorporation of AMC reflector for achieving broadband CP. In addition to that, it satisfies the criteria of broadband explained in IEEE standards; where the fractional bandwidth should be greater than 20%[35] in the desired operating bands. For the placement of reflector, an empirical formula (Equation (8.5), which is same as that of previous one) is utilized in this case, as:

$$h_{\text{air-gap}} = 0.36\lambda - h_{\text{sub}}\sqrt{\varepsilon_r}. \tag{8.5}$$

The above outcomes are in correlation with input power level (dBm), RF-to-DC PCE (%) and harvested voltage (V), related to rectifying circuit. It consists of a simple LC matching circuit and 4-stage voltage doubler circuit; meant for converting RF-to-DC. Since, the power densities of RF signals are very low; multi-staged circuits are designed.[181] Keeping with the need of modern RF applications, it can be further improved; especially RF-to-DC PCE (%) (cases B to E). Table 8A and B highlights the performance of proposed antenna with reflector surfaces, integrated with the 4-stage rectifying circuit. It relates with critical tradeoffs; 3-dB axial bandwidth, realized gain and number of rectifier stages, power conversion efficiency and sensitivity; where maximizing one parameter may lead to degradation of other parameter. Hence, a

TABLE 7 Performance index of Y-shaped monopole antenna with AMC reflector for broadband circular polarization integrated with a 4-stage rectifying circuit

Parameters	Step 1	Step 2	Step 3
Frequency of operation	WLAN, WiMAX, IEEE 802.11, 5G and initial C-band satellite applications (3 GHz-to-7 GHz)		
Antenna size	80 mm × 59.5 mm × 1.6 mm		
Substrate	FR-4 (epoxy) with Epsilon = 4.4 and thickness = 1.6 mm		
Geometrical feature	Partial ground	Shorting with Ground	AMC Reflector
Reflector size	Not applicable		$120 \times 99.5 \times 1.6$ mm^3
Air gap (height)	Not applicable		20 mm
S-parameters ($S_{11} \leq -10$ dB)	3.7-4.6 GHz	3.7-5.46 GHz	3.57-5.85 GHz
Impedance bandwidth	900 MHz (21.6%)	1.76 GHz (38.4%)	2.28 GHz (48.4%)
Axial ratio (AR ≤3 dB)	—	4.21-4.52 GHz	4.24-5.42 GHz
Axial ratio bandwidth	—	310 MHz (7.1%)	1.18 GHz (24.43%)
Polarization	Linear polarization	Circular polarization	Circular polarization
Radiation pattern	Omni-directional	Omni-directional	Directional
Realized gain[a]	Avg. ≥ 2.4 dB	Avg. ≥ 2.3 dB	Avg. ≥ 6.8 dB
Input power level (dBm)	Not Applicable		0 dBm ($f = 4.8$ GHz)
RF-to-DC PCE (%)	Not Applicable		34.69% (Stage 4)
Harvested voltage (V)	Not Applicable		Stage 1: 3.12 V
	—		Stage 2: 3.78 V
	—		Stage 3: 4.86 V
	—		Stage 4: 5.89 V

[a]The realized gain is calculated on the basis of average of lower bound and upper bound frequency points of −10 dB impedance and 3-dB axial bandwidth.

proper balance needs to be maintained among the designing tradeoffs of individual modules.

6 | CONCLUSION

This review article provides a comprehensive study about state-of-art technologies for the microwave antennas integrated with built-in rectifiers for RF energy harvesting. Since, the primitive source of input is electromagnetic waves; microwave antennas are the intrinsic part of RF energy harvesting technology. So, its practical realization and consideration of tradeoffs such as achievement of wideband/broadband circular polarization, wide/broad impedance & axial bandwidth, high realized gain and consistent antenna efficiency is quite significant from the applications point-of-view. Before going into design prospective, a unified understanding on fundamentals of RF transmission (such as Fraunhofer's distance and Friis transmission) are required. Besides progressive development in recent years; there are still a variety of rooms toward achievement of polarization diversity, higher realized gain, consistent antenna efficiency; targeting contingent research outcomes for RF energy harvesting. Hence, the antenna modules integrated with a 4-stage rectifying circuit is discussed. A brief theoretical insight and its possible interpretation for RF energy harvesting applications are presented in Figures 3–7 and Tables 3–7, respectively. The incorporation of reflector surface is governed by empirical formulae. With significant improvement in axial bandwidth and realized gain; Table 8A shows promising outcomes toward implementation of reflector surfaces in microwave antenna for RF energy harvesting. Table 8B gives information about the amount of harvested energy (ie, RF input to DC output) for the case of proposed microwave antennas. A maximum harvested voltage of 6.26 V is obtained for case-C, with a minimum harvested voltage of 4.04 V is witnessed for case-A with PEC reflector. Therefore, it can be a possibly considered as alternative source of energy for low power embedded devices; thereby, facilitating the

TABLE 8 A, Comparative focus on performance index (microwave characteristics) of proposed antennas along with incorporation of reflector surfaces (PEC/AMC). B, Comparative focus on performance index (rectifier characteristics) of proposed antennas along with incorporation of reflector surfaces (outcomes from fourth stage of rectifying circuit)

A

Proposed antennas[A-E]	Without reflector		PEC reflector		AMC reflector	
	Axial bandwidth	Realized gain[a]	Axial bandwidth	Realized gain[a]	Axial bandwidth	Realized gain[a]
Antenna 1[A]	25 MHz	≥1.83 dB	40 MHz	≥6.33 dB	42 MHz	≥6.5 dB
Antenna 2[B]	720 MHz	≥4.6 dB	Not applicable		870 MHz	≥5.7 dB
Antenna 3[C]	720 MHz	≥4.6 dB	1.41 GHz	≥5.5 dB	Not applicable	
Antenna 4[D]	310 MHz	≥2.3 dB	730 MHz	≥7.1 dB	Not applicable	
Antenna 5[E]	310 MHz	≥2.3 dB	Not applicable		1.18 GHz	≥6.8 dB

B

Proposed antennas	Rectifier properties	Without reflector surfaces	With reflector surfaces	
			PEC	AMC
Antenna 1 (Case A)	Input power level	Rectifier circuit is not applied in these stages.	5 dBm (f = 915 MHz/930 MHz)	
	RF-to-DC PCE		75.2%	82%
	Harvested voltage		4.04 V	4.24 V
Antenna 2 (Case B)	Input power level	Rectifier circuit is not applied in these stages.	0 dBm (f = 4.5 GHz)	
	RF-to-DC PCE		Not applicable	36.72%
	Harvested voltage			6.06 V
Antenna 3 (Case C)	Input power level	Rectifier circuit is not applied in these stages.	0 dBm (f = 4.8 GHz)	
	RF-to-DC PCE		39.18%	Not applicable
	Harvested voltage		6.26 V	
Antenna 4 (Case D)	Input power level	Rectifier circuit is not applied in these stages.	0 dBm (f = 4.5 GHz)	
	RF-to-DC PCE		35.52%	Not applicable
	Harvested voltage		5.96 V	
Antenna 5 (Case E)	Input power level	Rectifier circuit is not applied in these stages.	0 dBm (f = 4.8 GHz)	
	RF-to-DC PCE		Not applicable	34.69%
	Harvested voltage			5.89 V

[a]The realized gain is calculated on the basis of average of lower bound and upper bound frequency points of 3-dB axial bandwidth.

development of WSNs/IoTs by mobility of use. It is a hope from the authors side, that the information provided in this review article would prove to be a new way-out for benefitting the researchers and practicing RF engineers; who are unfamiliar about RF energy harvesting. They would be able to acquire a better understanding of its potentials and perhaps its possible consideration for utility in medical and health-care devices, as alternative provision of power.

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APPENDIX A.

Here, explanations are provided on different counterparts. Table A1 provides a complete list of the index terms and its descriptions. Table A2 correlates with the fundamental antenna characteristics presented with respect to classical electromagnetism. In Table A3, brief insights about the optimization techniques and their possible implementation by using EM solver[178] are referenced.

TABLE A1 List of abbreviations used in the review paper[2-6,12,13,179,180]

Terms	Description of abbreviated terms
WSNs	A connected network of active sensors typically operating within the UHF band.
IoTs	An internet-connected network of self-addressable devices.
M2M	The automated communications between networked devices.
RFIDs	1-100 μW powered-devices capable of performing dedicated simple tasks.

TABLE A2 Evaluation metrics[a] for microwave antennas in RF energy harvesting systems[7-10,15-18,36]

Evaluation metrics[a]	Description of evaluation metrics[a] of microwave antennas
Input impedance	It is the ratio of voltage to current at the terminals of the antenna.
Antenna bandwidth	It is the range of frequency over which microwave antenna can operate correctly.
Antenna directivity	It describes how well an antenna directs energy in a certain direction.
Antenna gain	It is the amount of energy radiated in a direction, as compared to isotropic antenna would radiate in the same direction when driven with same input power.
Radiation pattern	A mathematical function of the radiation properties of the antenna; as function of space coordinates.
Antenna efficiency	It accounts for the amount of losses at terminals and within the structure of antenna.
Polarization diversity	It is the property of EM wave relating direction/magnitude of electric field vector.

[a]To conceive the configuration of an antenna that meets with a set of RF and mechanical specifications.

TABLE A3 Optimization techniques and their possible implementation at the EM platform[167,178]

Optimization techniques	Description of EM-based optimization techniques
Classic Powell[a]	It is useful for single-parameter problems.
Interpolated quasi Newton[a]	It uses interpolation to approximate the gradient of parameter space.
Trust region framework[a]	It builds a linear model on primary data in a trust region around the starting point.
Nelder mead simplex algorithm[a]	It uses multiple points across the parameter space to find the optimum.
Particle swarm optimization[b]	It treats points in parameter space as that of moving particles. At each iteration, the position of particles changes, according to a best known position of each particle; along with the best position of entire swarm.
Genetic algorithm[b]	It generates points in parameter space, refines them through multiple generations with random parameter mutation. By selecting fittest sets at each generation, the algorithm converges to a global optimum.
CMA evolution[b]	It remembers previous iterations and can be exploited to improve the performance of algorithm; thereby, avoiding local optimum.

[a]Comes under local optimizers, are considered for the smaller parameter range.
[b]Comes under global optimizers, evenly considered for larger parameter range. These techniques are referenced under the domain of electromagnetic solvers (MoM/FDTD/FEM domain solver).
Note: The above optimization techniques are segregated into local optimizers and global optimizers.