Wireless Power Transmission: R&D Activities Within Europe

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***Abstract*—Wireless power transmission (WPT) is an emerging technology that is gaining increased visibility in recent years. Efficient WPT circuits, systems and strategies can address a large group of applications spanning from batteryless systems, battery-free sensors, passive RF identification, near-field communications, and many others. WPT is a fundamental enabling technology of the Internet of Things concept, as well as machine-to-machine communications, since it minimizes the use of batteries and eliminates wired power connections. WPT technology brings together RF and dc circuit and system designers with different backgrounds on circuit design, novel materials and applications, and regulatory issues, forming a cross disciplinary team in order to achieve an efficient transmission of power over the air interface. This paper aims to present WPT technology in an integrated way, addressing state-of-the-art and challenges, and to discuss future R&D perspectives summarizing recent activities in Europe.**

***Index Terms*—Computer-aided design (CAD) techniques, energy harvesting, inductive power transfer (IPT), Internet of Things (IoT), machine-to-machine (M2M) communication, power management, rectenna, RF identification (RFID), wireless power transmission (WPT).**

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I. Introduction

Wireless communications, battery-free sensors, passive RF indentification (RFID), passive wireless sensors, Internet of Things (IoT), and machine-to-machine (M2M) are systems and concepts that benefit from the use of wireless power transmission (WPT) and energy harvesting solutions to remotely power up wireless devices.

While recent advances in smart phones and wireless utensils appear to be unlimited, the dependence of their operation on batteries remains a weakness, mainly because batteries have a limited lifetime and require a fast charge time to achieve continuous operation. This is where the concept of WPT is useful, bringing together energy and wireless data transmission. This substitutes the traditional powering concept, where a cable or a battery is connected to the wireless device by the transmission of energy over the air in an efficient way to power-up the device.

WPT is, by definition, a process that occurs in any system where electrical energy is transmitted from a power source to a load without the connection of electrical conductors. This is not a new idea, attributed mainly to the work of Nikola Tesla in the late 19th Century. Tesla also made a WPT demonstration, similar to the more recent one at the "World's Columbian Exposition," Chicago, IL, USA, where it was shown that WPT could be used to "light" incandescent lamps [1], [2].

The long distance coverage of WPT was also demonstrated in 1975 by William Brown [3], when he transmitted a microwave beam converted to dc power by an RF–dc converter at a distance of 1.6 km. Specifically, the concept of a rectenna has been initially proposed by William Brown, where the combination of an antenna with a rectifier (RF–dc converter) made it possible to efficiently convert RF energy to dc energy. In his experiment, he achieved an efficiency of 84% [3].

Nevertheless, there are other methods of transmitting energy wirelessly. For example, the inductive power transfer (IPT) is gaining a lot of attention, primarily for short-range charging of devices, avoiding the need of power cables; a well-known and commercially successful example is the induction powered toothbrush, or recent mobile phones being charged by inductive coils. This method achieves a range of a few millimeters to a meter, and its low efficiency for higher distance imposes certain constraints in terms of possible applications. However, IPT has evolved in the last 20 years into a $1 billion industry [4], with notable applications in factory automation, biomedical implants and instrumentation; pioneered by research works such as the ones by the University of Auckland [4], [5]. A group at the Massachusetts Institute of Technology (MIT) recently demonstrated a new approach for transmitting energy over larger distances using resonant inductive coupling, providing 60 W to a lamp placed 2 m from the transmitter with an efficiency of 40% [6]. This experiment was further tested by Intel, achieving an efficiency of 75% at a distance of 60 cm [7].

These success stories define a new area of research, where the objective is to remove and eliminate all the power cables connected to the electronic utensils, but also to eliminate or at least reduce the charging needs of batteries in mobile devices. This technology is considered essential for the industry in several areas of expertise, including consumer electronics, automotive, and industrial control process. Consequently, the energy sector is investing substantially in research and development for wireless energy transfer technologies. Recently the "Wireless Power Consortium" was created [8] with support from a large community of companies. The purpose of this consortium is to establish an international standard for creating wireless battery rechargeable stations, compatible with electronic products. Other consortia have also been created, with a notable example being the Wireless Power Alliance. Toward maximizing the autonomous operation of low power wireless sensors, significant research efforts are also devoted to energy harvesting technologies, which include ambient electromagnetic (EM) energy harvesting. The latter explores existing radiated EM waves from sources not intended for the purposes of the specific wireless sensor application under consideration. A good practical example of RF energy harvesting from a multitude of ambient sources has been recently reported by Imperial College London [9].

With the growth of portable applications, many companies, such as eCoupled, WiPower, and Powermat [10]–[13] have developed solutions for the commercial market of wireless energy transfer. These initial developments drive the growth of commercial technological solutions, such as the ones able to charge electric vehicles without connecting to an outlet [14]. In terms of health-related applications, wireless transmission of power will charge the battery of pacemakers, without the need for further surgery to replace them [14]. The growth of applications in home automation, with the need to place individual devices or disguised without any physical connection, such as surveillance cameras, will be a reality and an application for this type of power transmission. In academia, WPT has been investigated to power up RFIDs, or to create a space-based satellite system that sends microwave energy to earth (e.g., the Microwave-based Space Solar Power System (M-SSPS) mission, proposed by JAXA in Japan).

Recently, companies have begun to evaluate the feasibility of using near-field WPT (also known as IPT or inductive-WPT) by using resonant highly efficient inductive coupling, where transfer efficiencies can be up to 90%, to power up implantable sensors, mobile phones, home utensils, monitoring sensors in buildings, etc. The optimal operating frequency is still to be established, depending on the environment, specific application, available switching speed of the power amplifier (PA) transistors, and required re-charging time. In the case of far-field wirelessly powering (also known as radiative-WPT), longer distances can be reached, but the achievable system efficiency still needs to be optimized. The problems researchers are facing include the size and weight of the transmitter and receiver coils, the amount of transmitted energy, the distance and directionality between the transmitter and receiver, the power electronics at high frequency, losses, efficiency, etc.

Finally, although WPT is possible, there is concern regarding the impact of the EM field on the health of the users of the technology. In order to accelerate the adoption of WPT, it is absolutely necessary that it operates within a regulatory framework. In order to expedite the regulatory process, companies, universities, scientists and original equipment manufacturers (OEMs) must work together to establish agreements, so as to incorporate a unified charging system for a wide range of products.

This paper presents the state-of-the-art in WPT technology, highlighting selected research activities across Europe. The number of European research groups with dedicated research activity in the field of WPT is large. In this paper, a characteristic sample of the works from a selected nonexhaustive set of research groups is presented, namely, the University of Perugia, Perugia, Italy, and the University of Bologna, Bolagna, Italy, the University of Aveiro, Aveiro, Portugal, the University of Ghent, Ghent, Belgium, Imperial College London, London, U.K., the Czech Technical University, Prague, Czech Republic, and the Centre Tecnologic de Telecomunicacions de Catalunya (CTTC), Castelldefels, Spain, and the University of Cantabria, Santander, Spain. These research groups have recently formed a research network, the European Cooperation in Science and Technology (COST) Project IC1301 on WPT for sustainable electronics [15] with an aim to create a reference framework among research and regulatory bodies in this challenging and exciting field worldwide. This paper is organized in terms of dynamic research areas, such as flexible electronics and wearable systems, inductive power transmission, dc–dc converters, computer-aided design (CAD) and signal optimization, energy harvesting systems, and RFID.

II. Flexible Substrate Materials and Wearable Antennas for WPT

A low-cost contactless assembly method for flexible substrate antennas and RFID chips has been developed at the University of Perugia [16]. Such methods exploit a magnetic coupling mechanism, thus not requiring ohmic contacts between the chip and the antenna itself. The coupling is obtained by a planar transformer; the primary and secondary windings of which are fabricated on the antenna substrate and chip, respectively. The proposed assembly method leads to a solution that requires only a placing and gluing process. In addition, such a transformer can tolerate misalignments.

The proposed approach has been validated with several practical applications; in particular, in [16], a bow-tie UHF antenna on a paper substrate was fabricated and its coupling to a hypothetical RFID chip was studied. The antenna was modeled by using a Thevenin equivalent circuit, whereas the chip is described by a resistor R_c (mainly the rectifier input impedance). To maximize the power transfer between the antenna and the chip, a suitable shunt capacitor (C_m) is placed at the terminals of the secondary winding. An overall power transfer ratio ($P_{\rm out}/P_{\rm in}$) of -1.5 dB was achieved at the 868-MHz design frequency with $R_c = 350\ \Omega$ and $C_m = 1.9$ pF.

Another example is reported in [17] where a bow-tie UHF antenna with the primary winding on a flexible substrate (Pyralux) was coupled to the secondary winding fabricated on a printed circuit board (PCB) substrate (Rogers RO4003). Fig. 1(a) shows a photograph of the fabricated structure and Fig. 1(b) reports the reflection coefficient measured at the secondary winding terminals with respect to the design optimum impedance. The same circuits can be replicated on paper substrates exploiting conductive adhesive tapes, as demonstrated in [18]–[20], where devices of comparable complexity are presented.

An example of concurrent technologies for the IoT is given in [21], where a shoe-mounted sensor for monitoring the human health is fabricated and measured. The sensor module consists of a novel shoe sole that serves the double role of a medical-grade temperature probe and a renewable energy scavenger. The temperature probe is used to monitor the condition of the human body. The scavenger transforms the human motion to usable electrical energy through a piezoelectric transducer (PZT). This way it complements a Li-ion rechargeable battery technology forming a hybrid power system approach. Additionally, a near-field reader is also placed in the shoe for purposes of localization. All collected data is preprocessed by a microcontroller unit (MCU) and transmitted through two transceivers at 900 MHz or 2.4 GHz, or both, through a dual-band antenna.

At Ghent University, flexible and wearable systems as enabling technologies for wireless power transfer have been studied in a body-centric context. In the past decade, the group has been in the forefront, in terms of research on experimental smart fabric interactive textile (SFIT) systems, a domain that has evolved tremendously during that time. Yet, at this moment, not many SFIT systems are used by industry, and market penetration is not in line with the research investment made in these systems. Current research efforts focus on removing the remaining impediments to allow SFIT systems to come to market.

One of the problems that must still be solved is that commercial SFIT systems should exhibit large autonomy and low maintenance cost. Therefore, efficient wireless power transfer is of primary importance. Existing wearable systems already rely on inductive near-field power transfer, making, for example, use of an embroidered coil integrated into the garment [22]. Near-field

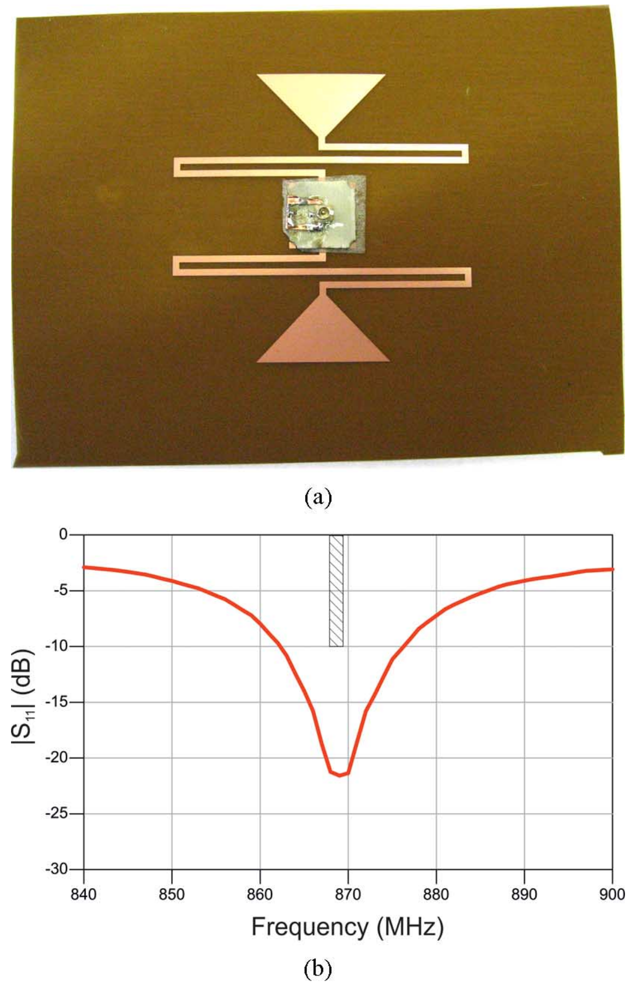
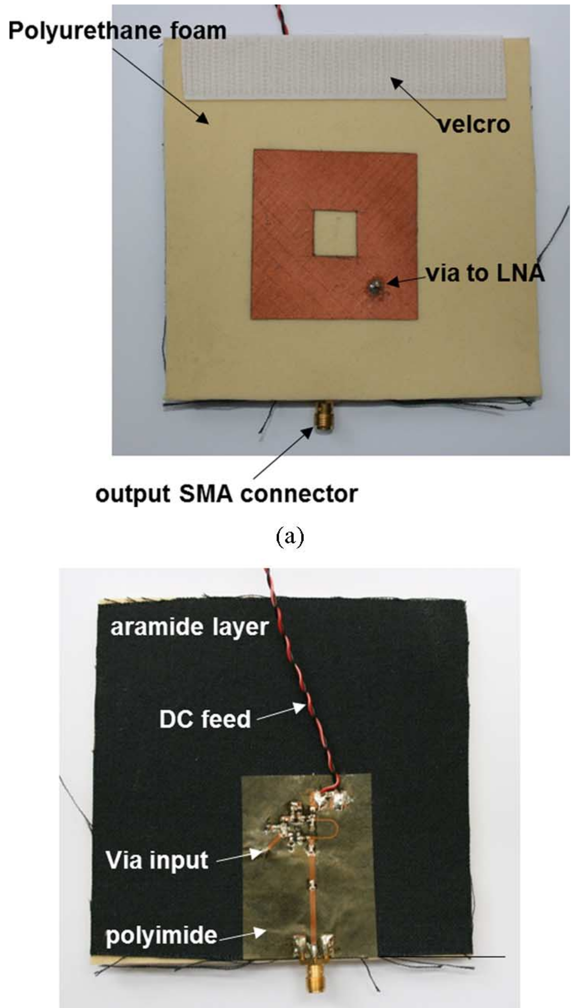


Fig. 1. (a) Prototypes of the antenna-transformer: flexible substrate with dipole antenna and primary winding, and Rogers substrate with UFL connector and secondary winding separated by biadhesive tape. (b) Measured reflection coefficient $|S11|$ plotted with respect to $32.4 - j80.5\ \Omega$ (optimal load impedance transformer); S_{11} magnitude is below -10 dB in the frequency band of 868–869.2 MHz.

systems clearly suffer from limited operating ranges, requiring the wearer to position the system at a well-defined location and in a well-defined orientation for recharging. Far-field wireless power transfer may overcome this problem, provided the energy efficiency of these systems is improved.

Another important recent evolution, as an enabling technology for WPT, was the development of electronic microwave systems on low-cost ecofriendly organic substrates, such as paper [23]–[26]; plastics that include liquid crystal polymers (LCPs) [27], polyethylene terephthalate (PET) [28], and polyimide [29]; textile fabrics [30] and foam materials [31]. Combining these substrates with low-cost screen [32] and inkjet printing [33] of conductive inks, embroidering using conductive yarns [34] or patterning of off-the-shelf electro-textiles [35] to produce interconnects, ground planes, and antennas, leverages the cost-effective fabrication of conformal large-scale energy harvesting surfaces that allow invisible and unobtrusive integration into their environment, which may be a piece of clothing, a wall, or the surface of a vehicle or aircraft. Moreover, the emergence of novel (semi-)conducting materials, such



(b)

Fig. 2. Active textile antenna developed by combining hybrid fabrication techniques with advanced full-wave/circuit co-design strategies. (a) Antenna patch on protective foam substrate. (b) Integrated low-noise amplifier on copper-on-polyimide feed plane assembled on an aramid feed substrate [39].

as carbon nanotubes (CNTs) [36], graphene [37], and pentacene [38] opens up some new perspectives to further improve the performance and/or the functionality of these systems. In addition, the judicious combination of hybrid fabrication techniques with advanced full-wave/circuit co-design [39], [40] results in highly efficient active antenna systems, where short RF interconnects allow optimal exploitation of the available energy. An example of an active wearable antenna designed based on this formalism is shown in Fig. 2.

New integration paradigms, such as substrate integrated waveguide (SIW) technology [41], [42], facilitate the direct integration of complete microwave systems into organic carriers, entailing passive microwave components, antennas, and microwave and low-frequency circuits composed of active and passive lumped elements. Such systems will combine sensing, communication, power harvesting, and management functionalities, and they will ultimately be fully autonomous.

In a body-centric context, specific challenges as well as opportunities arise. The direct proximity of the human body leads to a very complex propagation channel [43] in which correlated body shadowing introduces an additional level of received power fluctuations on top of the multipath fading due to the environment. Yet, in a wireless off-body communication setup, it has been well established that the large area of a garment may be exploited to integrate multiple textile antennas and to implement multiple input/multiple output (MIMO) schemes [44], [45], providing very reliable off-body communication links. In a similar fashion, multiple antennas cleverly distributed over the body may capture transferred power, leveling out fluctuations and providing a more continuous energy source. In addition, a garment provides enough space to deploy antennas tuned at different frequencies, paving the way for multiband or wideband energy transfer. Moreover, wearable antenna arrays [46] may efficiently harvest from concentrated power beams. Yet an important issue to bear in mind at all times is the wearer's safety given the specific absorption rate (SAR) exposure limits. Therefore, we advocate a distributed joint communication, harvesting, and exposure monitoring system, by extending the topology proposed in [47].

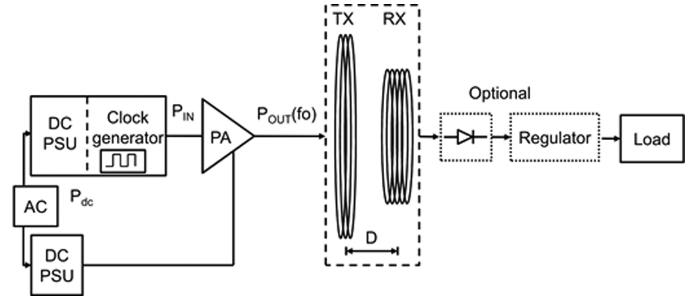


Fig. 3. IPT systems architecture [51].

III. IPT

Near-field WPT uses a principle of inductive coupling [48], [49]. A principle of capacitive coupling is utilized less often [50]. In the case of IPT, transmission is mediated between coupling elements represented by different structures of inductive coils on the side of a source and an appliance. The harmonic signal from a few kilohertz to a few megahertz is used for transmission between inductive coils.

At Imperial College London, recent studies on high-efficiency IPT systems have been reported [51]. Fig. 3 shows the typical architecture for an IPT system, with its transmitting (TX) coil separated by a distance D from its receiving (RX) coil. The maximum output power and efficiency can be improved by integrating the PA's impedance matching into the driver. The Class-E amplifier was adopted, however, working at 100 W and switching at $\sim$ 6 MHz is nontrivial; made possible with suitable power RF MOSFETs and high-Q capacitors. Furthermore, to achieve a good efficiency, a semi-resonant mode to match to the coils' impedance characteristics was found to be the most suitable solution [51].

Fig. 4(a) shows the circuit of a semi-resonant Class-E amplifier for the transmitter's loaded resonant tank (represented by the TX coil's self-inductance L_p, series resistance R_{ps}, and effective receiver resistance R_{seq}). Increasing both driver and link

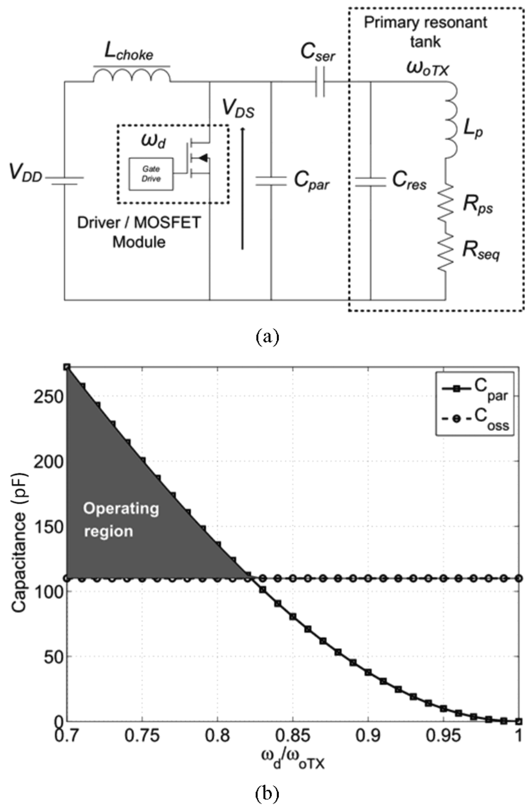


Fig. 4. (a) Semiresonant Class-E topology with $\omega_d < \omega_{o\mathrm{TX}}$ and (b) simulated C_{par} values against $\omega_d/\omega_{o\mathrm{TX}}$ for Class-E MOSFET selection with a drain-source voltage of 230 V [51].

efficiencies is achieved by tuning the primary resonant tank to a higher resonant frequency, $\omega_{o\mathrm{TX}}$, than the receiver's resonant tank driven resonant frequency, $\omega_{o\mathrm{RX}}$, at which the MOSFET gate driver switches at an operating frequency ω_d, i.e., $\omega_{o\mathrm{TX}} > \omega_{o\mathrm{RX}} = \omega_d$.

For a coil separation of arbitrary distance $D = 30$ cm and perfect coil alignment, PSpice simulations were performed to validate the semi-resonant mode of operation. The IXYSRF IXZ421DF12N100 module was employed because it includes the best available MOSFET for high power handling and with nanosecond switching and has a relatively low output capacitance C_{oss} at a drain–source voltage $V_{\mathrm{DS}} = 230$ V (required for 100-W operation).

In practice, C_{oss} is effectively absorbed by the parasitic capacitance C_{par} and is a limiting factor for selecting the maximum value of $\omega_d/\omega_{o\mathrm{TX}} = 0.82$, required for high efficiencies, as shown in Fig. 4(b). At this sweet spot, for the same desired power level, V_{DS} will increase and I_{DS} will decrease, resulting in a greater Class-E efficiency.

In summary, realizing low-cost high-Q coils and implementing a complete design and operational analysis of a semi-resonant Class-E driver for this IPT system was investigated [51]. For a load power of 95 W, an overall dc-to-load efficiency of 77% were demonstrated at 6 MHz, in a perfectly aligned scenario for $D = 30$ cm, having a coil-to-coil link efficiency of 95%.

Other challenging problems of IPT consist of the optimization of the transmission efficiency in the sense of reducing heating losses in the induction coils and ensuring relatively homogeneous and strong coupling, even if the appliance is moved. An investigation of structures of the induction coils and their EM field, with respect to these goals, is necessary. In addition, understanding of the heating losses of different geometries is important. The structures of induction coils that possess relatively homogeneous and strong coupling for arbitrary placement and orientation of an appliance have to be explored and strategies for their excitation have to be found. These structures can be then optimized for different scenarios like close-range defined coupling or random free-space coupling. The circuit model given by extraction of circuit parameters based on EM field analysis can be usually used for optimization. The important goal is to generalize the results and create recommendations for design.

The coupling elements represented by induction coils can be created by different structures according to their purpose [52]. For close-range transmission, the induction coils are usually flat and can be organized in arrays on the side of the source, to support movement of an appliance along this surface created by the source's coils [48]. Such systems are suitable for powering small appliances, such as smart phones and other mobile utensils. Another system is intended for the powering of low-power appliances, such as sensors placed in free space or any medium like concrete or human tissue [49]. In this case, the transmitting coils are considerably bigger than the receiving coils and surround the given space, where a powered appliance is located. The purpose is to ensure relatively homogeneous transmission for arbitrary placement and orientation of the appliance. Researchers at the Czech Technical University, Prague, Czech Republic, are working on optimization of the power balance of IPT systems with respect to structures of induction coils. Their study shows the relation between transmission efficiency and amount of transmitted power for resonance IPT systems [53]. Further, they are developing effective algorithms for the description of the magnetic fields for the induction coils [54] and extraction of their integral parameters like self and mutual inductance [55].

IV. Multi-Domain CAD Approach for the Design of RF Energy Harvesting Systems

At the University of Bologna, the focus has been on the use of a multi-domain CAD approach for the design of RF energy harvesting systems. The optimum design of an RF energy harvesting system is a nonlinear optimization problem and is a delicate task due to the strong interactions between the different subsystem parts. This is mainly due to the influence of the frequency-dependent antenna impedance on the nonlinear operation of the rectifier; this is particularly true when multiband antennas are required and multilayered compact layouts are used. Furthermore, a wide range of received power levels need be accounted for, which usually requires the design of different rectenna loading conditions. For these purposes, a multi-domain CAD approach, integrating EM, nonlinear simulation, and baseband design is used to simultaneously optimize antenna/rectifier matching network together with the load/storage circuit. At RF, the subsystem, consisting of the receiving antenna loaded by the rectifier and the antenna-rectifier inter-stage network is designed in a steady-state nonlinear regime by means of the concurrent use of nonlinear/EM CAD tools in optimum loading conditions. At baseband, the optimum loading conditions can be dynamically tracked by the transient design of a dc–dc converter with the rectenna circuit equivalent, derived in the previous step, representing the converter load. In this way, the maximum overall system efficiency is dynamically guaranteed in real time [56]. Thus, integration of RF nonlinear harmonic balance (HB) and time domain (TD) design techniques can be successfully implemented.

In the design of the entire rectenna, to augment the effectiveness of the CAD procedure, it is important to include the channel effects and the actual antenna received power. The only way to account for these aspects is to resort to rigorous EM theory, by the application of reciprocity theorem [57]. This approach can be described by referring to a general RF harvesting scenario, where a number of (un)known RF sources may exist and are described in terms of their respective radiated fields incident on the rectenna. Frequency, direction of arrival, and polarization of each incident field may be arbitrary. Assuming that the RF sources are located in the far-field region of the harvester, a kth incident field at the harvester location may be described as a uniform plane wave, and thus by a constant complex vector $\mathbf{E}_{\mathrm{inc}}(\omega_k)$. If the source location and polarization are known, $\mathbf{E}_i(\omega_k)$ is measured at the harvester position, as is the case of on-demand wirelessly powering scenarios. If unknown ambient sources are exploited, any possible amplitude, direction of arrival, and polarization of $\mathbf{E}_i(\omega_k)$ can be adopted to statistically predict the rectenna operating conditions.

Let $\mathbf{E_A}\left(\mathbf{r}\,;\omega_k\right)$ be the far-field vector radiated by the harvester antenna operating in the transmitting mode, when powered by a voltage source of known amplitude U and internal resistance R_0,

$$\mathbf{E_A}\left(\mathbf{r}\,;\omega_k\right) = \mathbf{E_{A\theta}}\left(\mathbf{r}\,;\omega_k\right) + \mathbf{E_{A\varphi}}\left(\mathbf{r}\,;\omega_k\right). \tag{1}$$

Here, $\mathbf{r}$ is the spatial vector, defining the RF source direction of arrival in the receiver-referred spherical reference frame. By a straightforward application of the reciprocity theorem

$$\begin{aligned} &J_{\mathrm{eq}}\left(\omega_k\right) \\ &= j\,\frac{\left[1+R_0Y_A(\omega_k)\right]}{U}\,\frac{2\lambda_k r e^{j\beta r}}{\eta}\mathbf{E}_i(\mathbf{r}\,;\omega_k)\bullet\mathbf{E}_A\left(\mathbf{r}\,;\omega_k\right) \end{aligned} \tag{2}$$

where $\bullet$ indicates the scalar product, η is the free-space wave impedance, and $Y_A(\omega)$ is the frequency-dependent antenna admittance computed by EM analysis. By computing the scalar product in the spherical coordinates reference system (r,θ,ϕ) and by defining the transadmittance functions,

$$\begin{aligned} G_\theta\left(\boldsymbol{r},\omega_k\right) &= j\,\frac{\left[1+R_0Y_A(\omega_k)\right]}{U}\,\frac{2\lambda_k r}{\eta}e^{j\beta r}E_{A\theta}\left(\boldsymbol{r},\omega_k\right) \\ G_\phi\left(\boldsymbol{r},\omega_k\right) &= j\,\frac{\left[1+R_0Y_A(\omega_k)\right]}{U}\,\frac{2\lambda_k r}{\eta}e^{j\beta r}E_{A\phi}(\boldsymbol{r},\omega_k). \end{aligned} \tag{3}$$

Equation (2) may be rewritten in the form

$$J_{\mathrm{eq}}\left(\omega_k\right) = G_\theta(\boldsymbol{r},\omega_k)E_{i\theta}(\boldsymbol{r},\omega_k) + G_\phi(\boldsymbol{r},\omega_k)E_{i\phi}(\boldsymbol{r},\omega_k). \tag{4}$$

Fig. 5 shows the circuit representation of (4), consisting of a three-port network obtained by the parallel connection of two

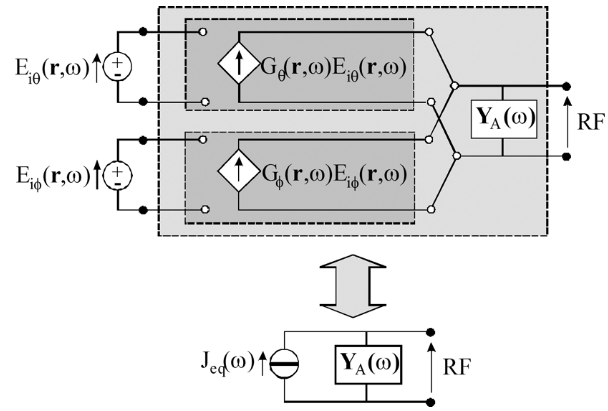


Fig. 5. Norton equivalent circuit of the receiving antenna.

field-driven current sources with internal admittance $Y_A(\omega)$; the driving fields being the scalar components of the incoming RF source ($\mathbf{E_i}$). This network is general and allows the actual receiver excitations (at port RF in Fig. 5) to be rigorously computed for any possible incident wave frequency and polarization. It is thus a powerful tool, to be adopted inside a nonlinear circuit simulator, to compute the actual received power (P_{RF}) of the antenna in the receiver front-end co-simulation.

Note that, with this approach, there is no need for an approximate rectenna effective area definition and the polarization mismatch between the rectenna and the incident field is automatically and rigorously taken into account. Furthermore this approach allows one to handle multi-source (multi-frequency) incident fields, and most of all, to straightforwardly compute, by means of a multi-tone HB analysis, the rectenna nonlinear regime for simultaneous incidence of various ambient RF sources.

In Fig. 6(a) and (b), the layout of the RF part of a multi-band rectenna is shown; it consists of a four-band circularly polarized antenna to harvest from ambient sources, designed by exploiting genetic algorithm optimization tools [58]. The phase shifter and the power-divider stages are designed for the four bands of operation to guarantee circular polarization, which is a fundamental requirement in harvesting scenarios, where the incoming signal direction and polarization may be undefined *a priori*. In Fig. 6(c), the rigorous circuit equivalent current source representation is connected to the rectifier.

In this way, the actual received power from the rectenna is computed and used during the HB-based optimization process (first step) to maximize the RF–dc conversion efficiency

$$\eta_{\mathrm{RF-DC}} = \frac{V_{\mathrm{DC}}\cdot I_{\mathrm{DC}}}{P_{\mathrm{RF}}} \tag{5}$$

where V_{DC} and I_{DC} are the dc components of the rectified voltage and current at the optimum and fixed load port, while P_{RF} is the available power at the rectenna location, and represents the maximum power the antenna is able to deliver to the rectifying circuit. Due to the rigorous approach previously described, the available power can be accurately accounted for in the HB simulation by means of

$$P_{\mathrm{RF}} = \frac{\left|\,J_{\mathrm{eq}}\left(\omega\right)\right|^2}{8\,\mathrm{Re}\left[Y_A(\omega)\right]}. \tag{6}$$

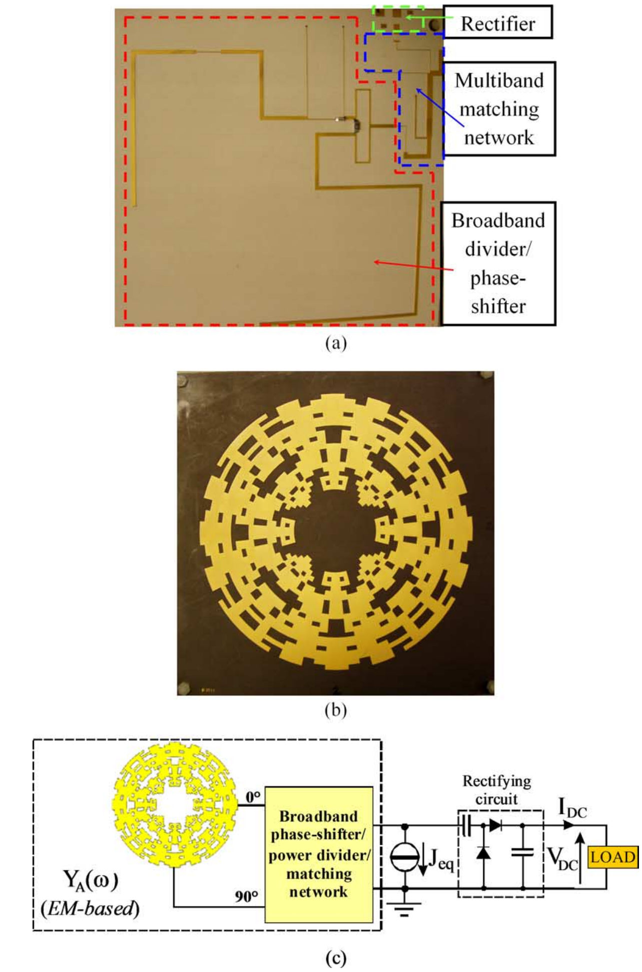


Fig. 6. Photograph of the: (a) bottom and (b) top sides of the prototype with different sections highlighted. (c) Rectenna equivalent circuit.

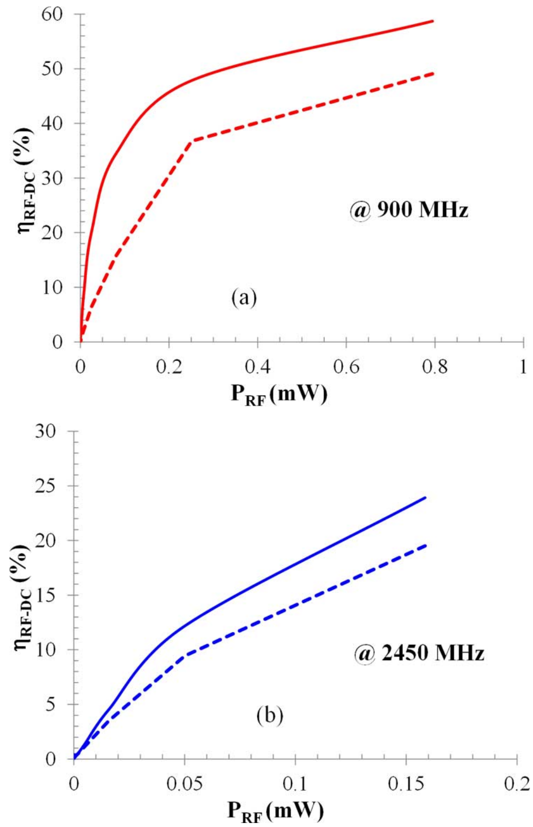


Fig. 7. Measured and simulated conversion efficiencies of the rectenna of Fig. 6(a) at: (a) 900 MHz and (b) 2450 MHz.

This design is carried out in RF stationary conditions, under the assumption of a fixed (optimum) load at the rectifier output port. The overall power conversion efficiency of the rectenna system of Fig. 6(a) is shown in Fig. 7, as a function of the actual received available power. The evaluated and measured results are obtained in the same realistic office scenario for two operating frequencies, but in the presence of a single RF source at a time.

In those applications where a power management unit is allowed and the harvester need not be directly connected to a defined load, the system efficiency may be further increased by dynamically tracking the optimum loading conditions, which vary with the nonlinear rectenna regime being a function of the actual received power P_{RF}. In this case, a second optimization step is then carried out at baseband, where the load must be replaced by an ultra-low power switching converter, whose possible topology can be found in [54], able to dynamically track the maximum power point (MPP) condition for any frequency and power level. This is obtained by keeping the rectified voltage V_{DC} at about one-half of the open-circuit voltage, which has been demonstrated to be close to the MPP [59]. A novel dual-branch rectifier concept has been recently proposed to comply with energy harvesting platforms with startup circuits [60]. In order to properly dimension the converter components, a SPICE-like time-domain model of the dispersive rectenna is used to represent the converter source during its time-domain optimization. The converter duty cycle is set according to the entire system efficiency maximization, which means by minimizing the converter power consumption.

A suitable definition of the dc–dc conversion efficiency is used as the baseband design specification

$$\eta_{\mathrm{DC-DC}} = \frac{F \cdot E_{\mathrm{HARV}}}{P_{\mathrm{DC}} T_C} = \frac{P_{\mathrm{HARV}}}{P_{\mathrm{DC}}} \tag{7}$$

where a fraction ($F < 1, \sim 90\%$) of the maximum energy stored in the capacitor (E_{HARV}) is consider during the charging time T_C is evaluated.

Some representative measured results obtained by the rectenna reported in Fig. 6(a) are shown in Fig. 8(a) and (b) [58]. The ambient source consists of a GSM900 phone call at a distance of 0.5 m: in Fig. 8(a), the registered bursts of the rectified voltage (V_{DC}) are plotted for a 300-ms time slot of the phone call, showing the actual rectenna dc output voltage due to a nonsinusoidal RF incoming signal. Fig. 8(b) shows the corresponding transient waveform of the actual harvested voltage (V_{HARV}) at the converter storage capacitor.

V. Multi-Band Rectennas

Employing simulation techniques where both EM and nonlinear simulations are jointly considered, the Centre Tecnologic de Telecomunicacions de Catalunya (CTTC), Castelldefels, Spain, has performed an optimized design of single-band and

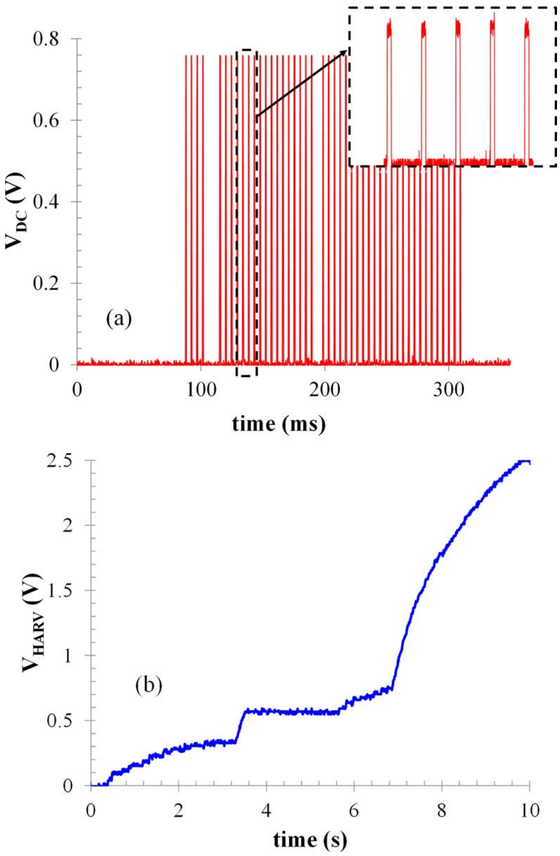


Fig. 8. (a) Rectified and (b) harvested voltage waveform during a GSM phone call.

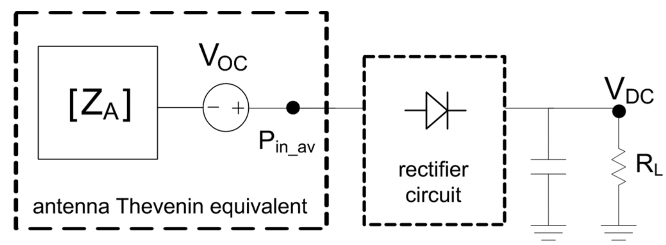


Fig. 9. Equivalent circuit used to design the rectenna elements.

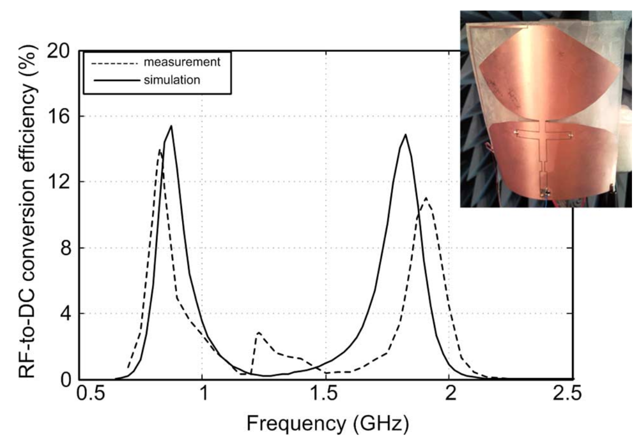


Fig. 10. Dual-band rectenna design using joint EM and HB simulations.

multiband rectenna elements [61]–[65]. In these designs, the Thevenin equivalent circuit, which represents the antenna as an impedance matrix $[Z_A]$ in series with a voltage source $V_{\rm oc}$ is used to simulate the presence of the antenna in a circuit simulator. The impedance matrix of the antenna is obtained in an EM simulator and the value of $V_{\rm oc}$ is calculated using reciprocity theory (Fig. 9) [63], [66]. Once the Thevenin equivalent of the antenna is introduced in the circuit simulator, it is possible to maximize the RF–dc conversion efficiency of the rectenna element by using nonlinear simulations such as HB in combination with optimization goals. In the case of single-band rectennas, only one optimization goal at a single frequency is imposed to maximize the RF–dc conversion efficiency. In multi-band rectenna designs, one goal per frequency band has to be imposed. Fig. 10 shows an example of a dual-band rectenna design in a flexible PET substrate performed using this technique [61], [62]. The antenna element is a printed monopole antenna and the two operation frequencies of the rectenna are 850 MHz and 1.85 GHz. The performance of this rectenna is optimized for low input power levels (-15 dBm) for which the obtained RF–dc conversion efficiency is around 15%.

VI. Synchronous Low-Loss Rectifiers

A rectifier is designed with carefully selected Schottky diodes, either with a low knee voltage ("zero bias") and low power-handling capabilities, when interested in ambient energy scavenging, or with a low resistance and high breakdown voltage in the case of dedicated power transfer applications. The resulting rectenna may provide a very good RF–dc conversion efficiency, but usually under a limited power range.

In order to reduce conduction losses, the rectifying diode may be replaced by an actively controlled switching element (a transistor), leading to a synchronous or active rectifier [67]. Despite being common practice for low voltage dc–dc converters [67], the use of these topologies in RF/microwave wireless powering applications is still rare. Besides cost and power density considerations, the available transistors at these bands are generally of the depletion-mode (normally ON) type. This is the reason why properly driving their gate for switched-mode operation would demand an auxiliary negative biasing supply.

The University of Cantabria has been evaluating the use of synchronous rectifiers as an alternative to diode-based topologies for WPT applications. In [68], advantage was taken of the low positive threshold voltage of enhancement-mode pHEMT (E-pHEMT) technology for its first introduction in a rectenna. Combining a lumped-element multi-harmonic class-E topology with an external self-driving network, competitive efficiency figures have been recently demonstrated for power beaming applications, but at the expense of a complex and noncompact implementation [69].

For simplifying the topology, while also assuring the desired synchronous class-E operation, a drain terminating network based on a self-resonant coil [70] may be combined with the use of the device intrinsic gate-to-drain capacitance $C_{\rm gd}$ [71]. The efficiency at lower power levels may be also improved with a bootstrap-type connection of the rectified voltage to the gate terminal. The proposed schematic is represented in Fig. 11(a),

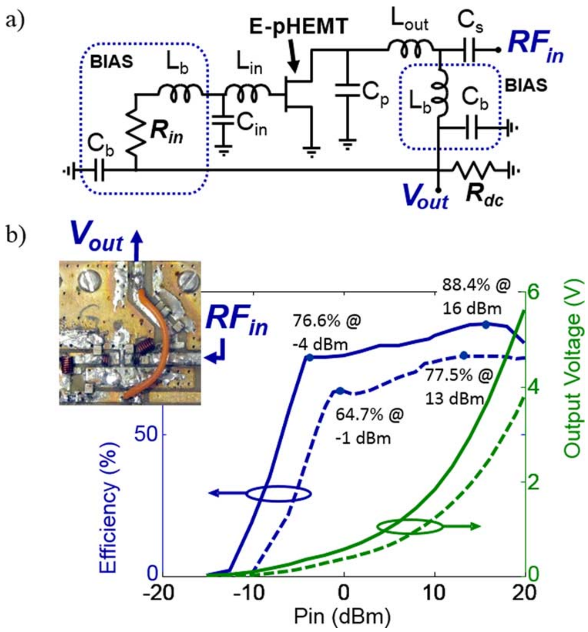


Fig. 11. Class-E self-synchronous E-pHEMT rectifier. (a) Circuit schematic. (b) Details of the implementation at 2.45 GHz, together with a comparison of measured results for rectifiers at (—) 900 MHz and (– –) 2.45 GHz.

together with details of its implementation with a VMMK-1218 E-pHEMT from Avago at 2.45 GHz in Fig. 11(b).

Having a low ON-state resistance, $R_{\rm on} = 3.6\ \Omega$, and a very small output capacitance, $C_{\rm out} = 0.19$ pF, the nominal zero voltage switching (ZVS) condition and zero voltage derivative switching (ZVDS) condition may be approximated with a simple $C_p L_{\rm out}$ network at drain side of the VMMK-1218. The $L_{\rm in} C_{\rm in}$ combination allows properly driving the gate terminal through the $C_{\rm gd}$ intrinsic path. The slightly positive gate biasing voltage, required for improving the low-level conversion efficiency (in the small-signal regime, the device output conductance has its maximum variation just at the threshold value [72]), is derived from the output voltage. When increasing the input power, the gate-to-source voltage is conveniently lowered or adapted through the introduction of an appropriate biasing resistor, $R_{\rm in}$, taking advantage of the small rectified current appearing at the gate terminal.

In Fig. 11(b), the measured results for the 2.45-GHz rectifier are also plotted together with those for an implementation at 900 MHz. As can be appreciated, high-efficiency figures (over 64% and 76%, respectively) may be assured along a significant power range (above 20 dB), with measured peaks of 77% and 88%. Using transistor-based topologies, the rectifier may be easily reconfigured to an oscillating (inverse rectenna) mode, as recently proved in [73]. E-pHEMTs are also amenable for the design of the required fast response MPP tracking dc–dc converters.

VII. Signal Design for Maximum WPT Efficiency

At the University of Aveiro, the research focus is in the field of WPT on the design of special waveforms, tailored to increase the RF to dc energy conversion efficiency in the rectifier circuits. In this respect, the use of multi-sine signals has been evaluated

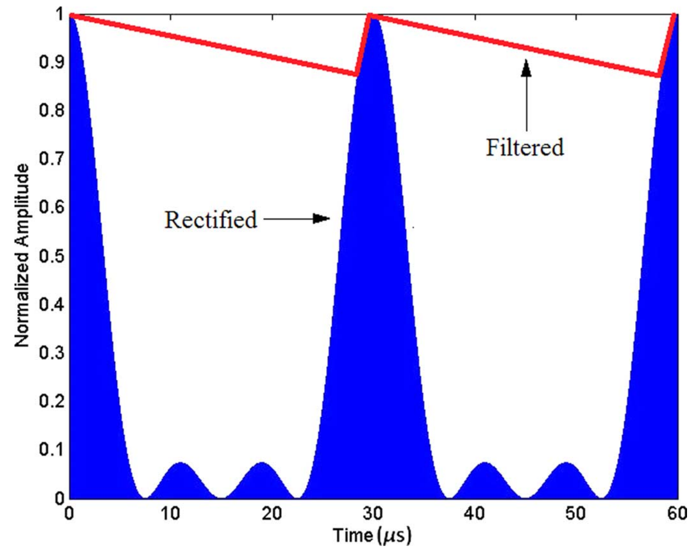


Fig. 12. Multi-sine signal rectification.

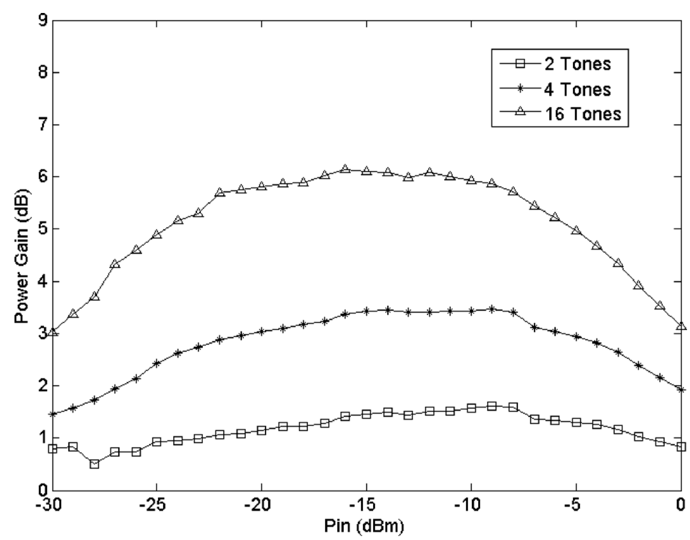


Fig. 13. Improvement in RF–dc efficiency by using different multi-sine signals.

as an alternative to single carrier generation. Fig. 12 presents the predicted behavior of the multi-sine, after passing through a diode-based RF–dc converter. As can be seen, the peaks of the multi-sine create a rise of the average voltage being rectified and converted back to dc [62].

These specially designed signals can later be applied to RF–dc converters efficiently. Fig. 13 shows the power gain obtained when comparing the obtained dc voltage when using a multi-sine signal and when using a single-tone signal [74]. This power gain is shown versus the input power level and for different number of tones in the multisine signal.

Activities in this field have also been carried out by CTTC, where chaotic waveforms were studied, to be used in WPT systems to increase the RF–dc conversion efficiency in rectifier circuits [62], [75]. Fig. 14 shows an example where using chaotic waveforms is possible to increase the rectifier conversion efficiency up to 20%, when compared to a single tone

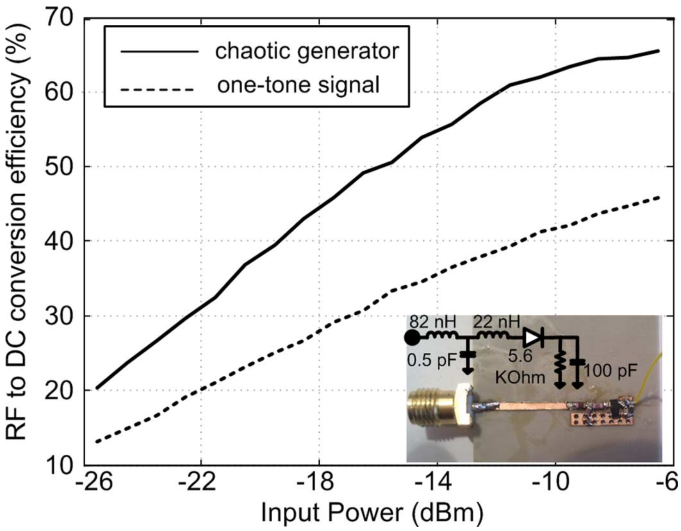


Fig. 14. RF–dc conversion efficiency using chaotic waveforms and a one-tone signal.

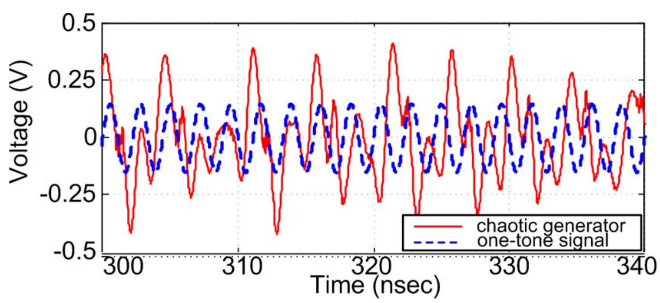


Fig. 15. TD waveforms for the chaotic generator and a one-tone signal.

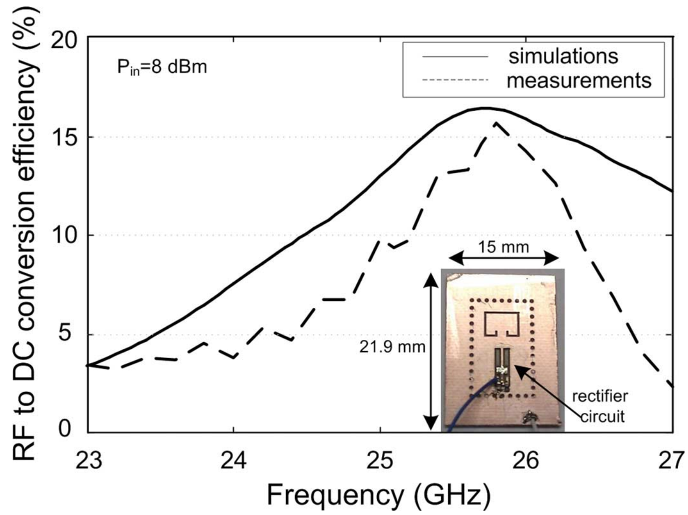


Fig. 16. 24-GHz SIW rectenna element.

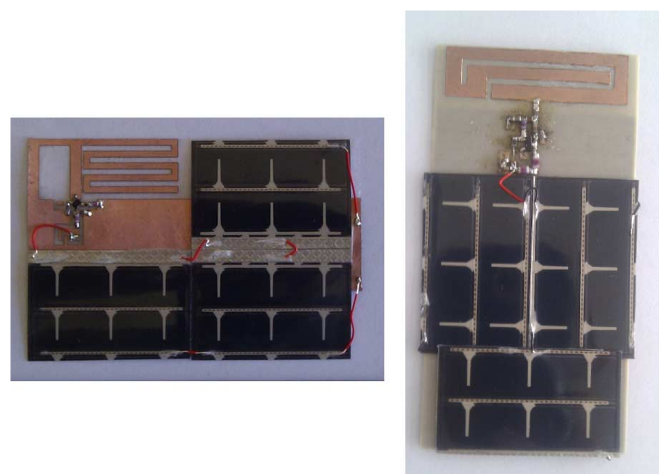


Fig. 17. Solar-to-EM converters for WPT operating at 868 MHz.

signal. The used chaotic generator is a single transistor circuit that creates a waveform with a higher peak-to-average power ratio (PAPR) in comparison with the one tone signal (Fig. 15), which allows reaching the threshold voltage of the Schottky diode for lower average input power levels if compared to the single-tone signal.

In the same area, further work has been performed to synthesize high PAPR signals using different schemes, such as the one in [76], where mode-locked oscillators are used to efficiently create a multi-tone signal to be used in WPT systems.

VIII. 24-GHz and Millimeter-Wave Rectennas

RFID and sensing at the 24-GHz industrial, scientific, and medical (ISM) frequency band and at millimeter-wave frequencies [millimeter-wave identification (MMID)] presents a great potential for short-range large-bandwidth communication, identification, and sensing systems [77]. Toward this goal, Fig. 16 shows a prototype of a 24-GHz rectenna element implemented in SIW technology, where the antenna element is an SIW slot antenna and the rectifier circuit is integrated inside the SIW cavity [78]. The rectenna achieves 15% RF–dc conversion efficiency for 8-dBm input power. This type of structure is also suitable for integration in rectenna arrays.

Further research in Europe related to millimeter-wave rectennas includes on-board harvesting in satellites [79], where it is demonstrated that power from the satellite antenna sidelobes can be harvested.

IX. Solar-to-EM Converters and RFID

Toward creating low-power, low-cost, and fully autonomous WPT systems to wirelessly power up low-power devices, CTTC has worked on the design of solar to EM converters [80]–[82]. These circuits collect solar energy that is converted to dc electrical power; the dc power is used to bias active antenna oscillators that are generating and radiating an EM signal at the oscillation frequency and that will be used for WPT. With these types of designs, it is important to design efficient oscillator circuits. Fig. 17 shows several credit card size prototypes of solar to EM converters. These designs are quite compact, as the solar cells share the same area as the antenna elements or ground plane. By properly avoiding key areas of the antennas, the effect that the placement of the solar cell has over its performance can be minimized [80], [81].

Following the same concept, solar assisted RFIDs have been designed [82], where a solar cell is used to power-up an oscillator that feeds an RF signal to the rectifier circuit of the RFID

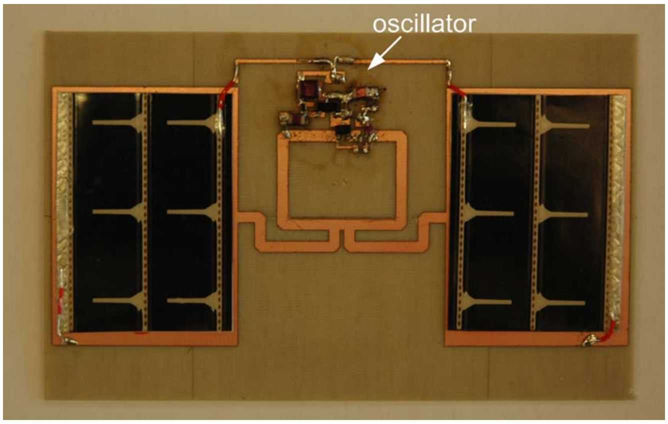


Fig. 18. Solar-assisted RFID tag.

(Fig. 18). In this way, in addition to the received signal from the reader, the RFID tag is receiving the RF signal from the oscillator, which leads to a reduction in the amount of power that the reader needs to transmit to power up the RFID tag.

X. Conclusion

This paper has presented a nonexhaustive list of recent activities dedicated to the field of WPT. WPT is an interesting and challenging field attracting contributions from several areas including material science and nanotechnology, power electronics, applied electromagnetics, and RF and microwave electronics. Additionally, it spans over a wide range of frequencies from kilohertz to millimeter waves, as well as a wide range of power levels from microwatts to kilowatts, posing a variety of challenges to the designer, some of which have been highlighted in this paper. Recent research and technological advances demonstrate its potential toward many engineering applications, and as an enabling technology for the IoT.

Acknowledgment

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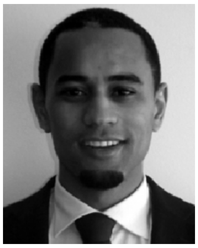

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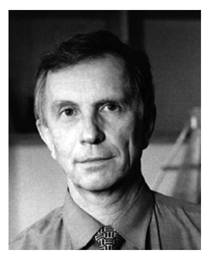

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