Scalable adaptive wireless powering of multiple electronic devices in an over-moded cavity

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***Abstract*—This paper presents a method for wireless powering of multiple electronic devices placed in an over-moded 2.2-GHz shielded microwave cavity using watt-level high-efficiency sources. Two transmitters based on a 77% efficient pHEMT PA to feed the cavity incoherently via strategically placed microstrip probes. The field patterns inside the cavity result from multiple excited modes ensuring a relatively uniform power density. Narrowband frequency modulation of the sources further improves uniformity. Each electronic device contains a rectenna, power management circuitry, and a rechargeable battery. A microcontroller performs power management and the available battery power is monitored using a low-power 900-MHz transceiver and communicated through a separate monopole probe and displayed external to the cavity. The approach is scalable in terms of power level, field profile, number of devices and overall size. Applications include personal electronics, powering of toys and powering of products in storage crates.**

***Index Terms*—wireless power, rectifier, resonator, power management.**

I. INTRODUCTION

THERE has recently been much interest in powering various devices without cords or batteries. Wireless powering methods can be categorized as near-field reactive powering, including tuned transformers [1-3], far-field beaming [4-7], and far-field scavenging of low power densities [8-12]. The applications have ranged from powering solar satellites and long-range terrestrial power transmission to cardiac implants, assistive technology devices, and structural sensors. Inductive powering products where the device is placed on a two-dimensional pad of inductors, have been commercialized for some time and are still under consideration by a number of companies, e.g. [13]. In [14], an alternative approach is presented using a cavity with meta-material walls.

In this paper, we present a metallic over-moded waveguide cavity operating at 2.2GHz for watt-level shielded wireless powering of multiple electronic devices. The position of the devices is not critical as they are powered by EM waves in a three-dimensional arrangement, and this volumetric approach is scalable in several parameters.

Figure 1 shows one possible version of the proposed approach using an over-moded rectangular waveguide resonator, with size shown for a 2.2GHz powering frequency. Two patch-type probe feeds are located on the cavity walls and fed incoherently by an efficient watt-level power transmitter. The transmitted waves can be frequency-modulated in order to improve the uniformity of the power density throughout the cavity and reduce sensitivity to device placement within it. Each device under charge (DUC) is equipped with an integrated rectenna and power management circuit similar to the ones described in detail in [9]. The low relative permittivity of polystyrene foam at RF frequencies is utilized on the bottom and walls of the cavity to prevent shorting to the conductive mesh. Each DUC may have a low-power wireless transmitter (here at 900MHz) which transmits power status to a monopole probe and receiver for processing and a status display external to the resonator (not shown for clarity). This three-dimensional approach is scalable in physical size, frequency, power and number of devices powered.

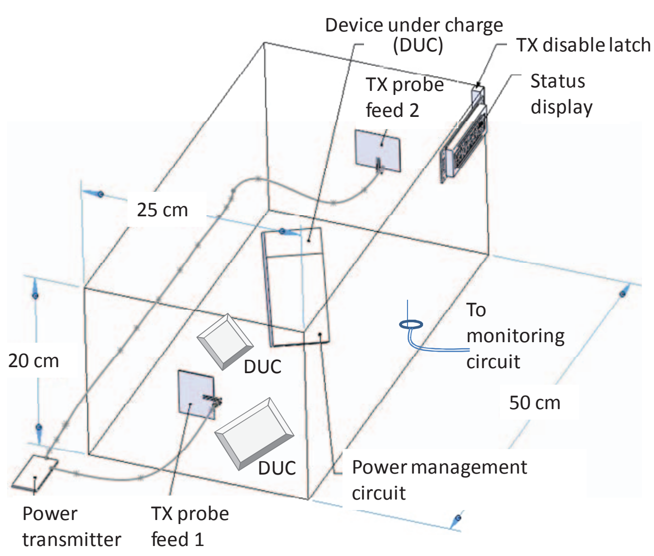

Fig. 1. Over-moded rectangular cavity for wireless powering of multiple electronic devices (DUCs). The size shown is for a 2.2GHz powering frequency. Two patch-type probe feeds are located on the cavity walls and fed incoherently by an efficient watt-level power transmitter. Each DUC has an integrated rectenna and power management and can have a low-power wireless transmitter (here at 900MHz) which transmits power status to a monopole probe connected to processing and a status display external to the resonator (not shown for clarity).

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For the remainder of the paper the relevant parts of the box powering system are described: (1) resonator and excited modes; (2) power transmit probes; (3) power transmitter; (4) DUC powering circuit (including rectennas), power management and battery charging; and (5) monitoring circuits.

II. Over-Moded Cavity and Excitation

A powering frequency of 2.2GHz was chosen, since the first prototype size of 20cm x 25cm x 50cm will support a number of modes at this frequency and thus have a very incoherent field profile, suitable for powering. This 2.2-GHz frequency is chosen to avoid interference with military and commercial GPS devices, mobile phone frequency allocations, and Bluetooth- and Wi-Fi-enabled devices that may be placed within the cavity.

A. Cavity modes

The size of the rectangular powering box is well above cutoff for a number of rectangular waveguide resonator modes. Expressions for the TE_{mnp} and TM_{mnp} modes can be found in various electromagnetic texts and the cutoff frequencies calculated for the dimensions of Fig. 1 are shown in Fig. 2. At 2.2GHz this resonator supports 61 modes with varying field profiles and polarizations allowing for more uniform power density throughout the cavity.

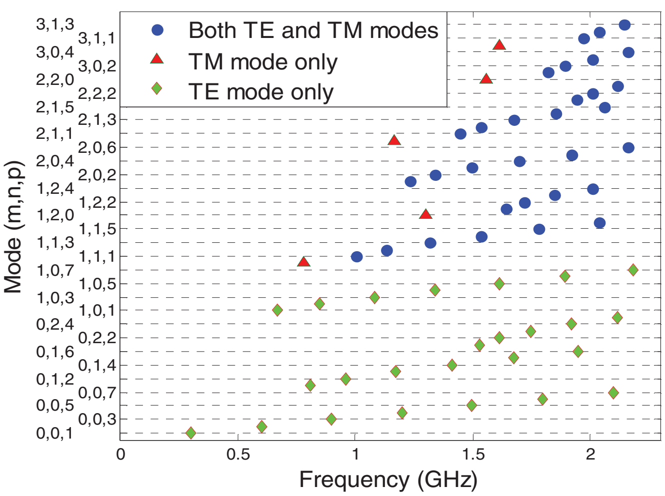


Fig. 2. TEmnp and TMnmp mode cutoff frequencies calculated for a rectangular metallic resonator 20cm x 20cm x 50cm in size.

B. Excitation probe

To excite the cavity, patch probes were designed and included in a full-wave simulation (HFSS) to find the fields in the unloaded resonator. Fig. 3 shows the detail of the probe. It is fabricated on a Rogers™ 4350B substrate. The linearly-polarized patch size is 3.7 by 4.6 cm and it is fed with a 50-Ω microstrip indented feed on the radiating edge. The patch dimensions are obtained by simulation inside the cavity for 2.2GHz input match, since it will not behave the same as a patch antenna in free space. Simulations were performed for the electric field distribution in the cavity with the two probes fed with 1W of power with varying relative phase. The electric field magnitude is about 1V/m, and the relative phase did not seem to have a large effect. For example, with the two sources in quadrature, the average electric field magnitude within the volume is 0.08 V/m less than with the sources in phase. The case in which the probes are fed 135 degrees out of phase yields the highest average electric field magnitude of 1.21 V/m, which is 0.28 V/m greater that with the sources in phase. The simulated electric field for this case is shown in Fig.4.

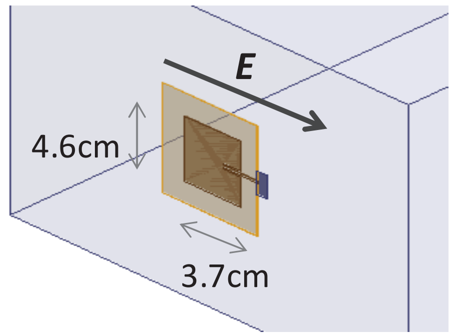


Fig. 3. Geometry of patch probe 1 from Fig.1 placed on the inside wall of the resonator, with the patch ground plane connected to the cavity walls. The microstrip radiating-edge indented feed is connected to the power transmitter which is external to the cavity. The second probe from Fig.1 is orthogonally-polarized relative to probe 1.

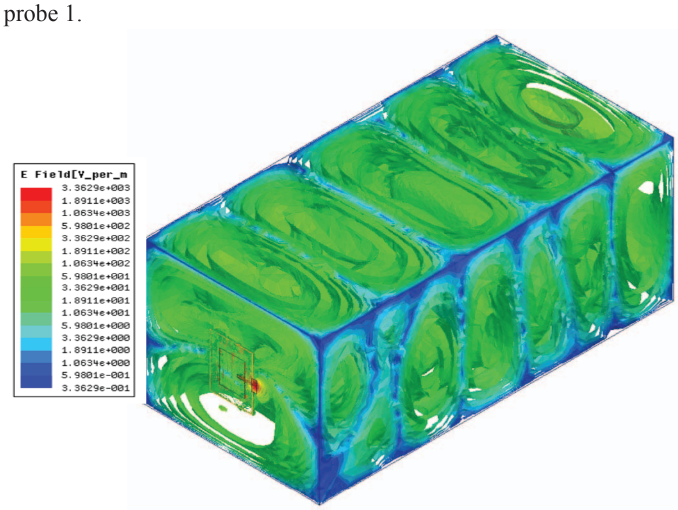


Fig. 4. Simulated electric field profile in the unloaded resonator when excited with the two patch probes fed 135 degrees out of phase. The sources are not modulated, resulting in a non-uniform field distribution.

C. Transmitter design

Each patch probe is fed through a two-way in-phase hybrid power divider (PS-2-4000F by RFMD) by a 1-W power amplifier (PA) having 77% power-added efficiency, designed using the methods in [15] with RFMD FPD3000SOT89 packaged pHEMTs. A VCO (CVCO55BE from Crystek) with 5dBm output power feeds a driver to enable 18dBm input power to the PA. For these results, the transistor is presented with input impedance of $4 - j0.4\Omega$ and an output impedance of $13.2 - j2.5\Omega$ at the fundamental. The circuitry is fabricated on Rogers 4350b™ 30-mil thick substrate.

III. POWER RECEPTION CIRCUIT

Each DUC contains a rectifier integrated with a linearly-polarized patch antenna. The rectifier uses a single Infineon BAT 68-08 diode for rectification, fabricated on the same dielectric as the antenna (Rogers 4350*b* 30-mil thick substrate) for greater integrability. Measurements conclude an RF-to-DC efficiency of 45% at 10 dBm input. Fig.5 shows a dependence of the rectified DC power on the load resistance, indicating that there exists an optimal load impedance for a given input power to maximize rectification efficiency.

Since the power received by the rectenna in the cavity will vary depending on placement, the power management circuit has the role of presenting this optimal DC resistance at the output of the rectenna. A similar approach has been adopted in [16]. A single MSP430 microcontroller processes for power management and the power converter, which actively adjusts the rectenna output impedance. The power converter implements an asynchronous DCM boost converter controlled by the MSP430 via a gate drive signal of adjustable period and duty cycle. The power reception circuit is described in more detail in [9] and associated references.

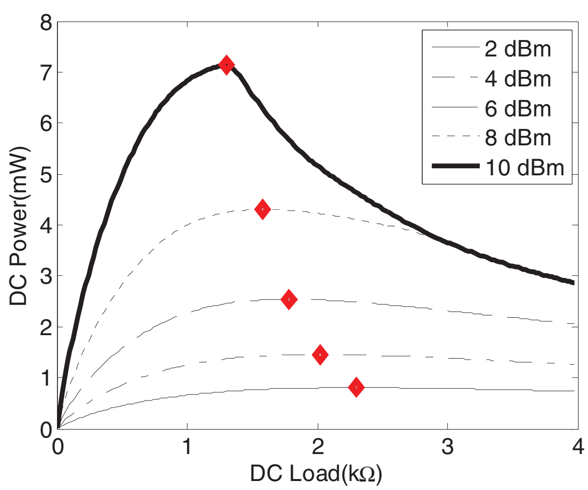
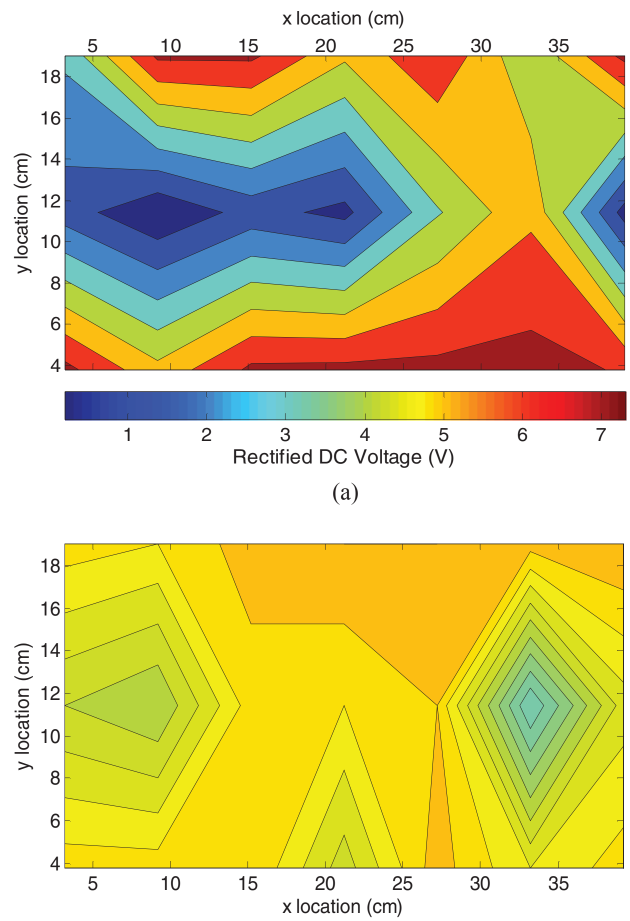


Fig. 5. Simulated load-pull plot of rectifier with RF input of varying power levels, with diamond markers indicating the optimal load resistance for maximum rectified power at each input power level. Note that the optimal load point varies with input power.

IV. RESULTS

To investigate the field distribution in the cavity, a receive patch probe is placed on the polystyrene shelf (displacing the probe by 24 mm from the cavity floor) at varying locations and is connected with a cable to a rectifier outside of the cavity. Measurements were performed using either a 1.5-kΩ resistor or an active load circuit (provided by the power management circuit) as the DC load to the rectenna. The purpose of the static 1.5-kΩ impedance is to measure the field magnitude independent of the power-maximizing algorithm in the power management circuit. A contour of the rectified DC voltages vs. probe placement is shown in Fig.6a. In this case, the probe was oriented such that its radiating edge is perpendicular to the radiating walls of the cavity. With this probe orientation the modes aligned such that there exists a constructive superposition of fields near the cavity side walls, and field nulls along the center of the cavity.

In comparison, Fig.6b shows the rectified DC voltage vs. probe placement with identical probe orientation but with an active load utilizing a maximum power point tracking (MPPT) algorithm that dynamically adjusts its input resistance to achieve maximum power. The fields within the cavity are not actively altered with frequency modulation or mechanical stirring, yet the rectified voltage as a function of location remained relatively constant. Similar observations were noted with different probe orientations and placements.



(a)

(b)

Fig. 6. Measured DC voltage rectified from receive probe placed at varying locations throughout the cavity, oriented such that its radiating edge is perpendicular to the radiating walls (x = 0 cm, 50 cm). The probe did not vary in any other dimension, resting on a 24 mm thick polystyrene shelf. The rectifier was loaded with a 1.5-kΩ resistor (a) and an active load with MPPT (b). The excitation probes remained fixed at y = 12.5 cm and x ≈ 0 cm, 50 cm.

V. SYSTEM INTEGRATION AND MONITORING

A prototype of the powering system for testing and is shown in Fig.7. The metal screening is used as a reflector that keeps all radiation within the box while the lid is closed but enables visual inspection. A switch is integrated with the lid permits operation only when the resonator box is closed. It is convenient that the excitation frequency does not overlap with common communications frequencies, allowing for easy wireless communication for monitoring. A low-power wireless transceiver (CC1101, 900MHz) and a microcontroller (MSP430) provides communication and power management functions. The data is coupled out of the resonator through a short monopole as shown in Fig.1.

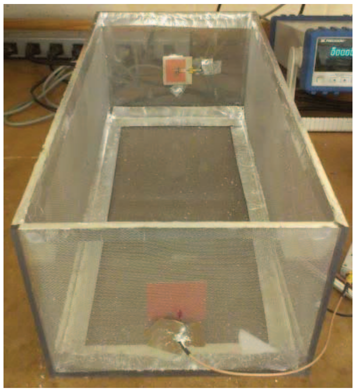


Fig. 7. Assembled prototype powering cavity with two probe feeds oriented orthogonally to each other. The metal screening is used as a reflector that keeps all radiation within the box while the lid is closed but enables visual inspection.

VI. Discussion

A shielded over-moded resonator powering cavity which includes power transmission, reception and monitoring devices is presented. The approach is scalable in terms of volume, and this is quantified in Fig. 8, where the cavity is enlarged by 5cm (a third of a powering wavelength) in each dimension to 25cm x 30cm x 50cm and the TE and TM mode cutoff frequencies are recalculated. The plot shows that at 2.2GHz, a larger number of modes are present in this larger cavity, enabling an even more uniform field distribution. Other wireless powering approaches use different field distributions: inductive and resonant coupling uses the near field, and beaming and scavenging receive power in the form of one or more plane waves. In the work presented here, a different type of field distribution is employed to deliver power in a three-dimensional configuration. The approach scales, and applications include charging personal electronic devices, while a scaled version can be used to powering toys in an "electromagnetic" toy box. Similar non-plane wave environments are found in HVAC pipes, where flow and vibration sensors can be placed for building monitoring. In this case, standard size pipes are over-moded waveguides at most microwave frequencies, and guided waves can be used to power the sensors. Monitoring room occupancy and flow in HVAC pipes can lead to significant savings in energy, as most rooms are designed for maximal occupancy but are rarely fully occupied.

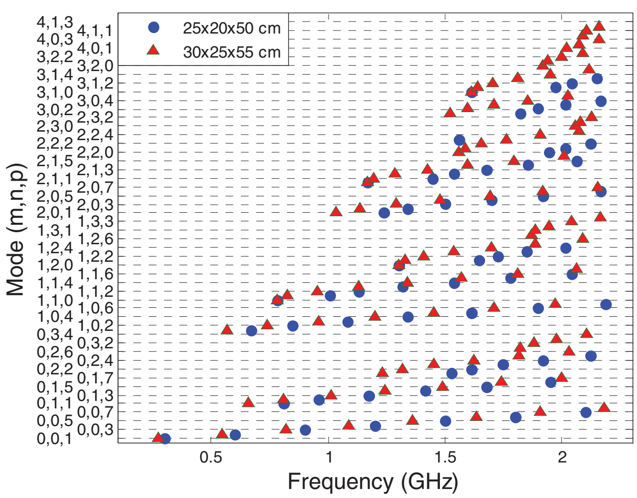


Fig. 8. TE and TM mode cutoff frequencies calculated for a 20cmx25cmx50cm and a 25cmx30cmx55cm rectangular resonator. The number of modes and spectral distribution increase when the cavity is enlarged by a third of a wavelength at 2.2GHz.

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