RF Energy Harvesting using Complex-Conjugate Rectennas Along Single-Wire Transmission Lines

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***Abstract*—Goubau Single-Wire Transmission Lines (SWTL) enable low-loss long-distance links using surface waves confined to a single conductor. Here, the concept of harvesting RF energy in the near-field of a high-power SWTL is proposed, showing up to 25 mW and 30 V DC output from a wire excited with under 30 dBm of 902 MHz signals. The leakage from the SWTL is harvested using a flexible single-layer rectenna array based on six complex-conjugate electrically-small antennas with series power summation between the elements. 15 mW of DC power could be harvested at 4 m distance from the transmitter in proximity of an SWTL, compared to under 150 µW in space. It is shown that SWTLs could enable long-range low-loss hybrid wireless power transmission (WPT).**

I. Introduction

Wireless power transmission (WPT) and harvesting will enable the next generation of battery-free and sustainable devices [1]. The fundamental limitation of radiative WPT, the spherical spreading of power resulting in an inverse-square relation with distance, constrains the power deliverable to the receiver [2].

Several approaches have been reported for minimizing the losses due to spherical spreading in WPT applications. Surface waves are among the promising approaches for guiding WPT signals [3]. For example, textile-based spoof-surface plasmons (SSPs) were used to connect wearable devices in a body-area network (BAN) enabling non-line-of-sight (NLOS) coverage [4], and avoiding the losses of radiative transmission around the absorptive on-body medium [5]. However, this was limited to a range under 1 m and only demonstrated at 2.4 GHz [4]. Single-wire transmission lines (SWTLs) were recently proposed for UHF to mmWave links up to 50 GHz, but were only explored for communication with wired coplanar launchers [6]. Several approaches relied on quasi-optics for long-range WPT, but they suffer from a high complexity owing to the need for large antennas [7] or electromagnetic (EM) surfaces [8].

In this paper, we present the first demonstration of RF energy harvesting from a Goubau SWTL. Using a six-element rectenna array, over 10 mW of DC power could be received at 4 m from a 1 W source.

II. SWTL Analysis and Characterization

The investigated SWTL uses tapered "Vivaldi" flexible coplanar waveguide (CPW)-based launchers from [6], implemented on a flexible polyimide substrate. The SWTL uses a stranded <0.3 mm^2 wire with a plastic dielectric insulating coating, soldered directly onto the CPW line. The high electric E-field confinement of the SWTL is illustrated in Fig. 1. From Fig. 1(b), it can be seen that under 10 mm from the the wire, the highest E-field density is observed and a WPT receiver would observe a high power density.

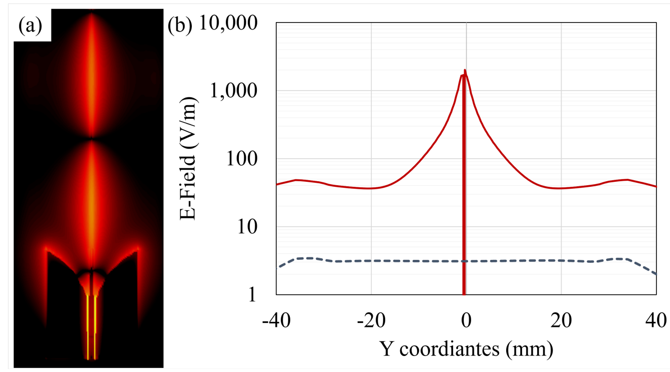

Fig. 1. The SWTL used in WPT [6]: (a) simulated E-field distribution from the CPW launchers; (b) E-field magnitude around the wire for a 0.5 W input.

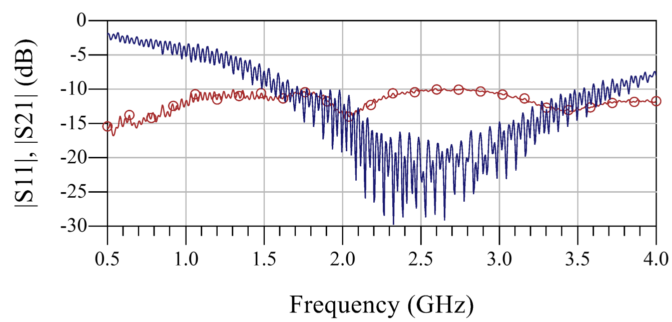

Fig. 2. Measured S_{11} (blue) and S_{21} (red, with markers) of the 5 m-long SWTL with a 90° bend.

The measured S_{21} response of the SWTL is shown in Fig. 2. While the line is not well matched at sub-1 GHz frequencies, the high S_{21} above -15 dB indicates that it could still guide the waves over the distance of 5 m. The SWTL was disconnected between the launchers and the S_{21} was under -70 dB, verifying that the SWTL supports the link. A 90° bend was added at d=1 m from the transmitting (first) power.

III. WPT Rectenna Performance

To receive RF power in proximity of with the SWTL, a six-element rectenna array based on matching network-free complex-conjugate dipoles was used. By using electrically-small antenna elements in a finite array with a limited number of elements and DC combining, an effective energy harvesting area surpassing the array's physical size can be achieved [9]. A photograph of the array, implemented on a flexible single-sided polyimide substrate, is shown in the inset of Fig. 3. The array combines the DC output of the elements in series leading

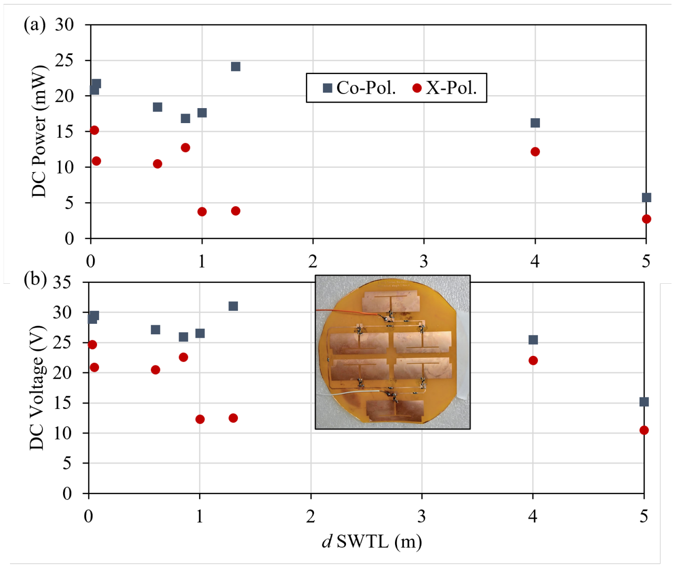

Fig. 3. DC output of the array in proximity with the SWTL over different points along its length: (a) DC power; (b) DC voltage across the 40 kΩ load.

to voltage summation, which improves the sensitivity in low-power operation enabling a boost converter-free operation.

A 1 W 902 MHz signal was used as a source using a BGA6130 power amplifier, using the transmitter from [10]. The second port of the SWTL was terminated using a broad-band 50 Ω load to emulate an active receiver in a data link. The rectenna array was positioned at 1 cm above the line at various distance points d. The received power was measured across the optimum load impedance of 40 kΩ. Fig. 3(a) and (b) show the measured DC power and voltage output for varying separation d from the transmitter. The DC output was measured with the dipoles aligned with the the SWTL (i.e., co-polarized), and with the dipole's orthogonal to the line (cross-polarized. While the co-polarized component exhibits a higher power output, the low polarization purity of the array implies that a DC output exceeding 1 mW can be received in both orientations at all distances investigated. Furthermore, the end-to-end efficiency relative to the power source at 4 m is over 1%, which is significantly higher than radiative unguided WPT where the path-loss would exceed 40 dB.

In a radiative WPT experiment with indoor ground reflections, under 150 µW/cm^2 were received by the array from a 3 W EIRP source [9]. Thus, it can be seen that by using SWTLs in an engineered EM environment a ten-fold improvement in the DC output can be achieved. While the achieved voltage levels are too high $>$10 V, an array with parallel combining (current summation) could increase the RF-DC efficiency and allow direct interfacing with 3.3-5 V devices.

IV. Conclusions

In this paper, a surface wave-enabled WPT concept is proposed based on Goubau SWTLs. The SWTL was fed directly using the WPT transmitter, operating at 1 W, and the power was received using a state-of-the-art six-element rectenna array in close proximity with the SWTL. Over 15 mW can be received up to 4 m away from the transmitter, owing to the high E-field confinement of the guiding SWTL. A ten-fold DC power output improvement over radiative WPT is demonstrated, showing that future WPT surfaces could be implemented based on SWTLs.

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