Power Transfer/Uplink Techniques for Miniature Tag

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***Abstract*— This work introduces the smallest inductive wireless power transfer (IWPT) and uplink. The first 2-GHz system, with on-silicon coil size of 0.04 mm^2, harvests a 0.1-mW dc power with a Tx power of 21 dBm. The uplink data rate is 625 kb/s. The second IWPT includes selecting the best operation frequency and advances with a tag coil only of 0.01 mm^2. The 4.7-GHz/2-GHz tag generates a 0.1-mW dc power with Tx power of 31.4/38 dBm. The uplink is only 20 kb/s due to the weak coil coupling. To improve the uplink, a new method is proposed utilizing the rectifier nonlinearity for a new Rx channel at the Tx second-harmonic frequency. The Tx/Rx frequencies are well separated, so the Tx leakage at the Rx frequency can be effectively filtered. Prototype IWPT and rectenna, both implemented on PCB, shows the Rx signal-to-noise and signal-to-blocker ratio can be improved.**

***Index Terms*—Inductive power transmission, rectifiers, uplink.**

I. Introduction

New applications, such as implanted devices and miniature RFID [1] incorporate miniature electronics, and wireless power transfer has become a necessity. A new application is to have miniature tag on electronic devices to secure the supply-chain integrity [2]. The small tag footprint posts challenges to the power transfer efficiency and uplink communication.

First, we present a 2-GHz IWPT system with a CMOS tag with 0.04-mm^2 on-tag coil [3]. A 21-dBm reader power transfers 0.1 mW to the tag 1-mm away. The 625-kb/s direct backscattering signal can be directly sampled and ASK demodulated by a high-speed ADC. The operation frequency was selected arbitrarily. The second design demonstrates that an ultra-small tag with a 0.01-mm^2 coil, powered up by a reader 1.2 mm away, can generate a 0.1-mW dc power. The operation frequency was designed and the IWPT optimized at 4.7 GHz needs a Tx power of 31.4 dBm, better than that optimized at 2 GHz (38 dBm) and other IWPT frequencies. The direct backscattering and ADC sampling cannot be adopted, limited by the low signal-to-blocker ratio (SBR) at Rx, so a down-conversion chain is used for the IF-based backscattering.

Owing to the high Tx power, the Tx-to-Rx leakage degrades the Rx signal-to-noise ratio (SNR). In IWPT applications, the diode rectifier has been used only for the dc current. Inspired by the harmonic radars, we proposed a novel uplink (on PCB) exploiting the rectifier nonlinearity. The rectifier also works as a frequency doubler and the uplink is at 3.6 GHz, the second harmonic (SH) of the 1.8-GHz Tx. The coupled coils used for the IWPT are reused, so no additional area is required. Although the SH Rx signal is weaker, the effective filtering on the Tx leakage helps to improve the Rx spectrum.

II. IWPT and Uplink Results For Miniature Tag

For the first IWPT design at 2-GHz (tag coil of 0.04 mm^2) [3], the schematic is shown in Fig. 1. The rectifier is a four-stage

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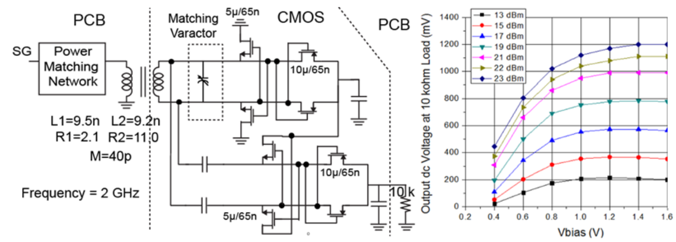


Fig. 1. IWPT block diagram and the tag output to the varactor bias.

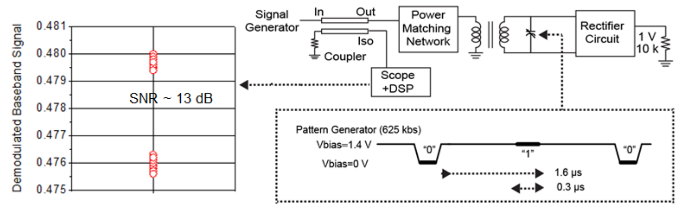
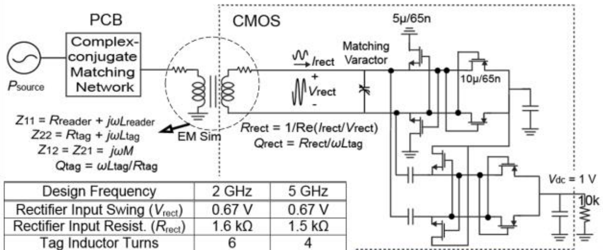


Fig. 2. Block diagram for backscattering uplink measurement.

differential Dickinson rectifier in 65nm CMOS. The PCB reader is optimized to generate the highest magnetic-field intensity 1-mm above the coil center (under a fixed reader power), and after that the tag is optimized to minimize the reader power for harvesting a 1-V dc voltage at a 10-kΩ load resistor. Details for designing for the lowest reader power can be found in [4]. The measured output dc voltage versus the on-tag varactor bias voltage is also plotted in Fig. 1, at different Tx power levels. With a bias voltage of 1.4 V, the varactor resonates with the tag inductance and results in the highest output voltage. For the uplink, a directional coupler is inserted at the reader input and the backscattering signal is measured at the coupler isolation port, as illustrated in Fig. 2. The tag-sent data toggles alternating between the two states “1” and “0” with bit rate of 625 kb/s. Only 3/16 of the 1.6-μs bit duration is used for the data and the rest is used solely for the power transmission. The backscattering signal was sampled by an Agilent 54855A oscilloscope. The two backscattering states are demodulated by self-mixing. After the digital filtering, the demodulated constellation is shown in Fig. 2 with SNR of -13 dB. The noise is dominated by the ADC quantization noise.

For the 2- and 5-GHz IWPT designs with the coil size of 0.01 mm^2 [4], the design parameters are listed in Fig. 3, along with the die photos and system illustration. The calculated reader powers are 34.4 and 29.4 dBm, respectively for the 2 and 5-GHz design. Fig. 4 shows the IWPT performances. The measured Tx power is 38 dBm for the 2-GHz tag and 31.4 dBm for the 4.7-GHz tag (with different reader designs). The output voltage is more sensitive to the varactor bias for the 4.7 GHz tag, where the coil quality factor is higher.

Successively, the uplink is characterized for the 4.7 GHz IWPT design. Fig. 5 illustrates the block diagram of the backscattering uplink adopting an IF frequency of 2 MHz and a baseband data rate of 20 kb/s. When the tag sends “0”, the tag varactor is driven by a 2 MHz sinusoidal waveform swinging between 0 and 1.2 V, whereas for a “1” the varactor is biased at



Design Frequency	2 GHz	5 GHz
Rectifier Input Swing (V_{rect})	0.67 V	0.67 V
Rectifier Input Resist. (R_{rect})	1.6 kΩ	1.5 kΩ
Tag Inductor Turns	6	4
Tag Inductor Width	3 μm	3 μm
Tag Coil Inductance (L_{tag})	3.3 nH	2.2 nH
Rectifier Quality Factor (Q_{rect})	35.3	21.5
Tag Inductor Quality Factor (Q_{tag})	5.4	10
Q_{rect} // Q_{tag}	4.7	6.8
Mutual Inductor (M)	7.3 pH	3.9 pH
Reader Resist. (R_{reader})	1.7 Ω	2.6 Ω
P_{source} according to (1)	34.4 dBm	29.4 dBm

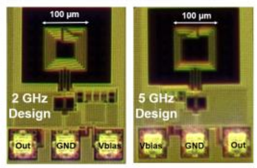
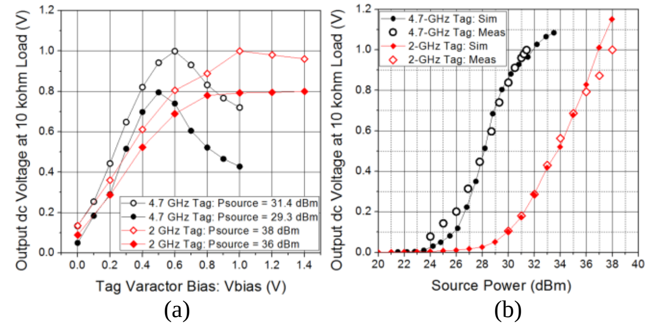


Fig. 3. IWPT schematic, design parameters, and die photos [4].

0.6 V. The dc voltage drops to 0.97 V when the tag sends an alternating "1" and "0". The 2-MHz frequency spacing between the backscattering signal and the Tx leakage protects the Rx spectrum from being contaminated by the Tx phase noise. The demodulated constellation, with the baseband signal a 20 kb/s PRBS sequence, is also shown in Fig. 5 with the constellation SNR of about 14 dB. The IF Rx signal is sampled by an 8-bit, 20 MS/s ADC. The ADC quantization noise can be neglected.

III. Novel Second-Harmonic Uplink

Fig. 6 illustrates the proposed SH uplink with both the rectenna and the reader coil realized on PCB [5]. Similarly, digital signal is applied to the tag varactor. When the *LC*-tank is in-resonance in the first tag state, the diode rectifier generates the dc current and a by-product SH current that returns to the reader through coil coupling. When the tag *LC*-tank is off-resonance in the second tag state, little SH current is generated. The low-pass filter at the Tx attenuates the SH frequency while passes the fundamental frequency, so the power transfer can work properly. The Tx-to-Rx leakage at the Tx frequency can also be easily filtered at the Rx input, without losing the Rx signal. Fig. 6 also shows the SH Rx spectrum at 3.6 GHz (under square-wave modulation) with bit rate of 1 Mb/s. The SBR is 4 dB and the SNR is 89 dBc*Hz. The Rx spectrum at the 1.8-GHz fundamental frequency (with the HPF removed) shows the signal strength is higher by 34 dB but the SBR degrades to -33 dBc, with a high Tx-to-Rx leakage of 6.3 dBm. The comparable SNRs (both 89 dBc/Hz) justify using the SH uplink due to the significantly better SBR.



(a) (b)

Fig. 4. Measured tag output voltage for the 2/4.7 GHz tags versus (a) varactor bias and (b) Tx power (under the optimal varactor biases).

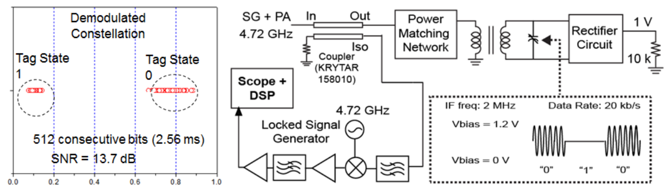


Fig. 5. Block diagram of the IF-based backscattering uplink and the demodulated constellation.

IV. Career Plans and Impact of the MTT-S Fellowship

I am grateful to receive the MTT-S graduate fellowship. This funding allowed me to attend the IMS2016. In the symposium, I was exposed to the latest microwave techniques and worldwide experts. I am looking forward to finishing the PhD study at UC Berkeley in early 2018 and would like to pursue an industrial career in the design of RF integrated circuits and systems. This fellowship guarantees an impressive resume.

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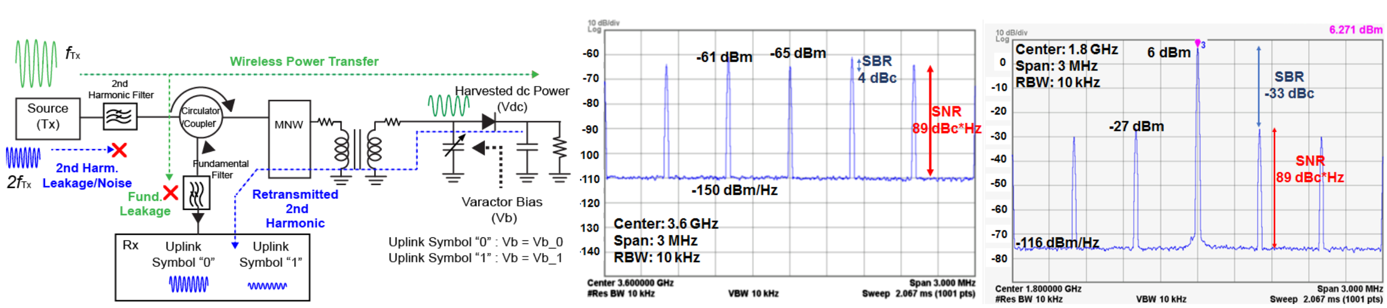

(a) (b) (c)

Fig. 6. (a) Bock diagram of the SH uplink. (a) Rx spectrum at the SH and (b) the fundamental frequency (conventional uplink).