An Implantable Cardiovascular Pressure Monitoring System with On-chip Antenna and RF Energy Harvesting

Yu-Chun Liu Jiann-Shiun Yuan Ekavut Kritchanchai

Department of Electrical Engineering and Computer Science
University of Central Florida
Orlando, Florida 32816, U.S.A.
Email: ycliu@knights.ucf.edu, jiann-shiun.yuan@ucf.edu, ekavut1@knights.ucf.edu

Abstract—An implantable wireless system with on-chip antenna for cardiovascular pressure monitor is studied. The implantable device is operated in a batteryless manner, powered by an external radio frequency (RF) power source. The received RF power level can be sensed and wirelessly transmitted along with blood pressure signal for feedback control of the external RF power. The integrated electronic system, consisting of a capacitance-to-voltage converter, an adaptive RF powering system, an RF transmitter and digital control circuitry, is simulated using a TSMC 0.18 μm CMOS technology. The implanted RF transmitter circuit is combined with a low power voltage-controlled oscillator resonating at 5.8 GHz and a power amplifier. For the design, the simulation model is setup using ADS and HFSS software. The dimension of the antenna is 1 × 0.6 × 4.8 mm^3 with a 1 × 0.6 mm^2 on-chip circuit which is small enough to place in human carotid artery.

Keywords—energy harvesting; link budget block; RF rectifier

1. INTRODUCTION

Hypertension is a critical risk factor for cardiovascular morbidity and mortality in the general population and reduction of blood pressure (BP) with effective antihypertensive therapy significantly decreases cardiovascular morbidity and mortality [1]. Keeping observing BP is also a matter of concern for those who have hypertension, coronary heart disease, or other cardiovascular diseases [2]. BP measurement is also important for particular disease patients, such as hemodialysis patients [3]. Hence, in the daily life, BP measurement and management is very useful for handling health situation and plays a preventive function.

In recent years, a wireless implantable bio-sensor device and remote monitoring system are becoming important topics. The sensor is used to continuous monitor changes in blood pressure and provides feedback to help maintain an optimal heart status. Wireless communication is relied upon to transmit patient's data to a mobile phone or an access point and relay the information to a remote center via the Internet. Emergency situations are detected via data processing implemented throughout the system and an alarm message is sent to an emergency service center to provide immediate assistance to patients. For a long-term blood pressure monitoring, wireless powering has been widely employed as a critical enabling technology for advanced biomedical implant applications, where it is impractical or impossible to connect an implant device directly to an external power source or a processing unit. Because the patients are not able to replace the batteries or plug in an adaptor to charge the implanted device, utilizing of the wireless energy harvesting to run the system is the most important task. Therefore, small size and low power system are the two necessaries for implanting a device into human body.

In this paper, the design of implantable cardiovascular pressure monitoring system is presented. Section II presents the specification and sensitivity of the implantable system. Section III describes the design of the system including
RF receiver and transmitter circuit, wireless energy harvesting circuit and voltage rectifier circuit. In section IV, the antenna design for the system is described. The sensitivity of the antenna is simulated and evaluated using HFSS software. The performance and results of the system design are evaluated. Conclusions are given in section V.

2. SPECIFICATION

Recently, biomedical implantable device for such as Glaucoma or heart and eye pressure monitor are widely been researched and designed. [4] and [5] proposed a fully wireless implantable system for detecting cardiovascular pressure and eye pressure with MEMS and ASIC. That group explored the idea of integrating a medical stent with a fully wireless implantable cardiac monitor to take advantage of their well-established delivery methods that allow for placement nearly anywhere in the circulatory system. The integration of a miniature cardiac pressure monitor with a stent takes advantage of the maturity of stent technology, its delivery procedure, and its versatility in terms of implant location. The stent is used in the device as both structural support and an antenna for simultaneous wireless telemetry and powering. However, these antennas are designed separately with the main chip, which takes the risk to fail the whole system. In order to solve this problem, this section will provide a co-design integrated system solution with antenna, rectifier, and transmitting circuit in a single chip for cardiovascular pressure monitoring system.

The external source is a reader which can transmit RF energy to the RF rectifier inside the human body and power up the whole implanted chipset. The wireless system is designed to operate at 5.8 GHz of ISM band. This frequency chosen is based on two reasons. First, lower frequency causes longer wavelength and eventually the antenna has to occupy large area. Second, too high frequency degrades the RF to DC efficiency of a RF rectifier and decreases its input impedance, causing large power reflection from the receiving antenna. Therefore, 5.8 GHz is the best operation frequency to maintain enough efficiency and keep the size small.

According to Federal Communications Commission (FCC) rules for unlicensed wireless equipment operating in the ISM Bands (5.725 to 5.875 GHz), the maximum transmit output power, fed into antenna is 30 dBm (1 watt) and the maximum effective isotropic radiated power (EIRP) is 36 dBm (4 watt). Thus, the output power from the external source antenna has to be less than 36 dBm. Then, the path loss in the air from the source to the implanted device is given by Eq. (1)

$$path\_los(dB) = 20log\frac{4\pi d}{\lambda} \qquad (1)$$

where d is the distance between two devices and λ is the wavelength at operation frequency. At 5.8 GHz, we can simply calculate the loss is roughly 27 dB at 5 cm distance. 5 cm distance is maximum distance for the reader to power up the implanted IC.

Moreover, the loss in human body for the implanted antenna has to be taken into account. This section uses human chest model for example, the chip is placed inside a 3 × 3 × 9 mm^3 blood with high-permittivity (loss tangent (tanδ) = 0.384, relative permittivity (ε_r) = 52.54, conductivity (ρ) = 6.5057 S/m) box and the blood box is inside a 10 x 10 x 10 mm^3 muscle (loss tangent (tanδ) = 0.32, relative permittivity (ε_r) = 48.4, conductivity (ρ) = 4.962 S/m) box.

Fig. 1 illustrates the entire wireless system for biomedical sensing application. The output power of each function blocks are designed and predicted based on the loss mentioned above. An efficiency of the external and internal antenna and rectifier will be described in the following section. The external receiving sensitivity is usually at least -35 dBm by most wireless communication technology such as Zigbee which has -60 dBm sensitivity. Table 1 shows the designed link budget for the whole system. It shows the specifications and limitations of this design.

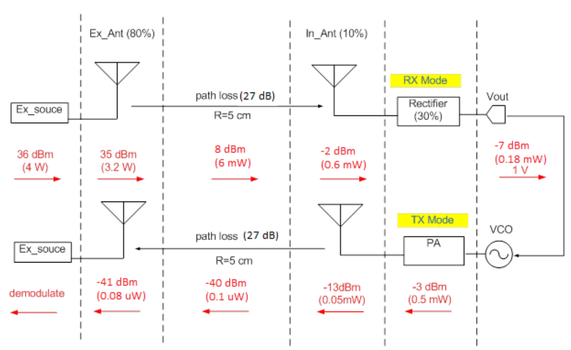


Fig.1 Link budget block diagram of the cardiovascular pressure monitoring system

Item	External source	External antenna	Internal Antenna	Internal rectifier/PA	Output voltage
Efficiency	-	80%	10%	30%	-
RX mode	36dBm	35 dBm	-2 dBm	RF/DC	1V
TX mode	A/D	-40 dBm	-13 dBm	-3 dBm	-

Table 1 Link budget table of the cardiovascular pressure monitoring system

3. DESIGN

Wireless powering techniques based on RF electromagnetic wave propagation has captured many research interest in applications such as RFID [6-8] and medical electronics [9-10]. One major goal of the harvesting system is to convert RF energy into usable DC power. Energy harvesting techniques for biomedical implantable applications have been widely researched [1,2] in this few years, for example, blood and eye pressure monitoring device. Because the patients are not able to replace the batteries or plug in an adaptor to charge the implanted device, utilizing the wireless energy to run the system is the most critical task.

RF energy harvester is mainly made of several elements: on-chip antenna, RF-DC rectifier, storage capacitor, and voltage regulator. The 13-stage voltage multiplier is shown in Fig. 2. This n-stage voltage multiplier consists of a cascade of n-low threshold p-channel MOSFETs, which gate and source terminals are connected. The coupling capacitor in each stage pumps the voltage to a high potential level. Each p-channel MOSFET here functions as a diode, which switches on and off by different cycles.

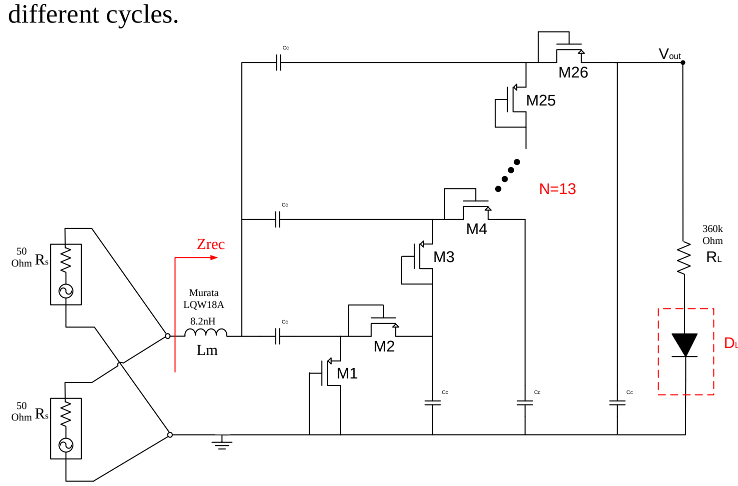


Fig. 2 Proposed three-port 13 stages diode-connected NMOS RF Rectifier with a load resistance compensation diode.

The implanted RF transmitter is combined with a low power VCO to resonate at 5.8 GHz and a PA to burst the resonated signal. The architecture of VCO uses a cross-coupled pair of PMOS and NMOS transistors. Transistor M1 and M2 are a PMOS cross-coupled pair of the VCO. Transistor M3 and M4 are used as capacitors. The drain and source terminal are connected to each other and a tuning voltage is applied to that connection. Transistor M5 and M6 are a NMOS cross-coupled pair of the VCO. The transistor M7 provides the bias current. Transistor M8 is used as a buffer and they produces the output signal. Both VCO and PA are supplied by 1-V V_{dd}. In Fig. 3, it shows the circuit components of the transmitter.

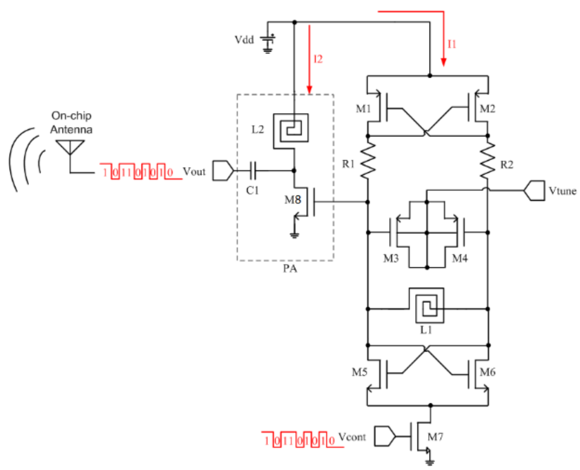
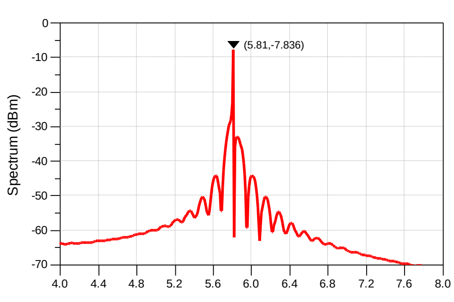
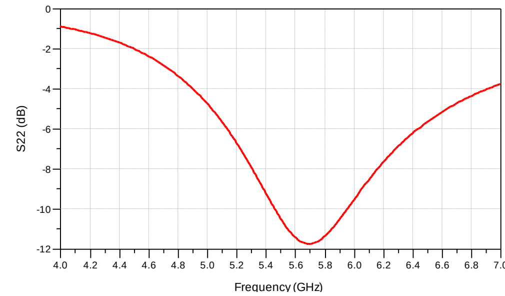


Fig. 3 Implanted transmitter include a VCO and a PA

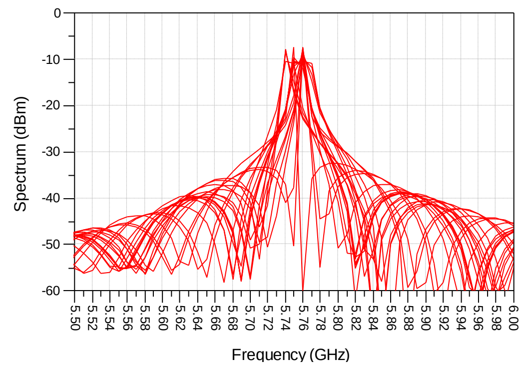
All the transistors and lump components are using TSMC 0.18-µm model. M_1 and M_2 are PMOS to provide a negative resistance. M_3 and M_4 are PMOS which body, drain and source are connected to form a controllable MOS varactor. The capacitance is tuned by the voltage V_{tune} and resonates with the inductor L_1. M_5, M_6 and M_7 are the current source to control the current through the VCO. R_1 and R_2 are two 10-Ω balance resistors to reduce the power consumption [11]. The PA, also can be seen as a buffer, is a single- stage NMOS. The current I_1 through VCO is 270 µA and I_2 is 300 µA for the PA. The overall current is only 570 µA which is able to generate -7.8 dBm to input on-chip antenna shown in Fig. 4(a). Fig. 4(b) shows the output matching is less than -10 dB at 5.8 GHz and Fig. 4(c) shows the tuning range of the VCO is around 40MHz by adjusting the tuning voltage form 2V to -2V.



(a)



(b)



(c)

Fig. 4(a) The output spectrum (b) return loss (c) voltage tuning range versus frequency of the designed RF transmitter

In the Fig. 5, the control voltage (V_{con}) is a digital signal from the sensing circuit to switch VCO on and off in order to send the data by OOK modulation to the external device. When V_{con} is high, M_7 is on and VCO start to transmit the data through V_{out} to the antenna, and in contrary, VCO is turned off while V_{con} is low. After the demodulation by external receiver, the patient will be able to read the data such as eye or heart pressure. As can be seen in Fig. 5, The data of V_{out} is the same as the signal generated by V_{con}. The amplitude of V_{out} is 0.2 V, and therefore, the external device has to have high sensitivity to detect the weak signal.

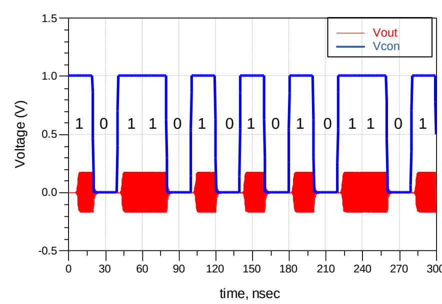
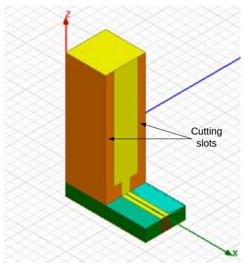


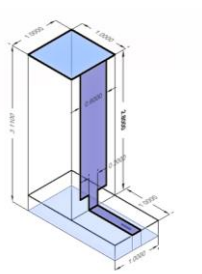
Fig. 5 OOK modulation by switching M_7 on and off through the control signal V_{con}

4. ANTENNA DESIGN, RESULTS AND DISCUSSION

For more accurate local blood pressure information, the monitoring system is directly put inside the pulmonary artery which is right next to the heart. The volume of pulmonary artery is larger than the carotid artery. Therefore it is convenient to place the designed on-chip system.



(a)



(b)

Fig. 6 3D-view of the proposed on-chip antenna for placing in pulmonary artery. (a) HSS model (b) Detail dimensions (Unit: mm)

The modified 3D on-chip antenna evaluated using HFSS software for placing in pulmonary artery to monitor local blood pressure is shown in Fig. 6. The dimension of the antenna is 1 × 1 × 3.1 mm3 with a 1 × 0.6 mm2 on-chip circuits. The cutting slots on the side wall of the antenna are used for impedance match to 50-Ω.

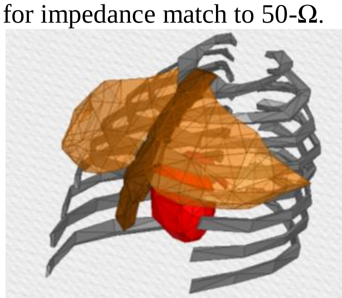


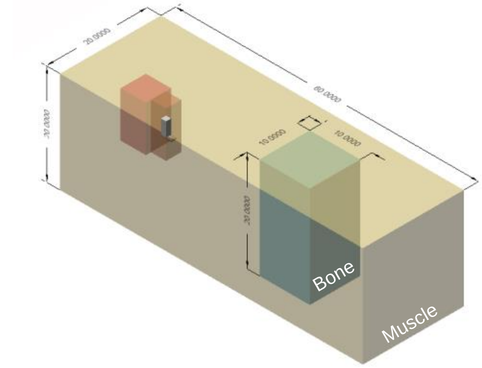
Fig. 7 Human chest model

Fig. 7 shows the model of human chest structure. The pulmonary artery locates in front of heart. In front of pulmonary artery, there are also sternum, ribs and chest muscle around. The model setup is shown in Fig. 8 (a) and the close view of simulated pulmonary which is right next to the heart is shown in Fig. 8 (b). The on-chip antenna is placed in a 3 × 3 × 9 mm^3 blood box and the blood box is inside a 20 x 60 x 20 mm^3 muscle box. All the material properties of human organs are shown in Table 2.

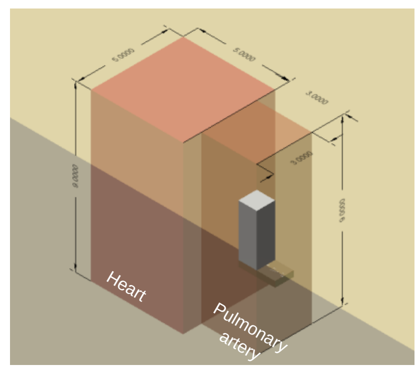
Frequency : 5.8 GHz			
Human organ	**Relative permittivity**	**Loss tangent**	**Conductivity (S/m)**
Muscle	48.49	0.317	4.96
Bone	9.67	0.369	1.154
Heart	48.95	0.371	5.86
blood	52.53	0.384	6.57
Aqueous humor	68	0.2677	6.67

Table 2 Material properties of human organs

The simulation results of radiation patterns (Fig. 9 (a)) and gain in E-plane and H-plane have been analyzed. Fig. 9 (b) shows the 3-D polar plot. Fig. 9 (c) shows the simulation result of the return loss which is around -17 db, and other detail results are listed in the table 3. As can be seen, the efficiency is 10% and the peak gain is -10 dB, which meets the required spec.

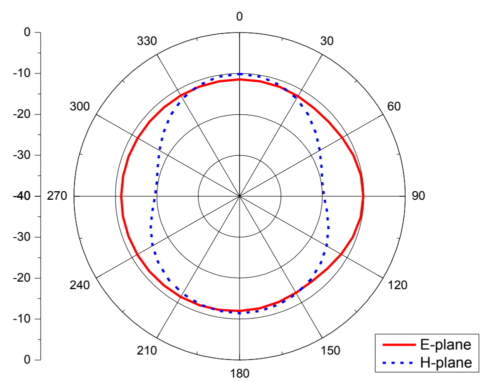


(a)

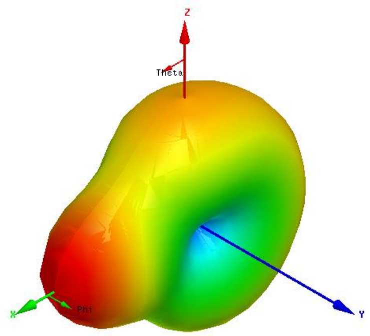


(b)

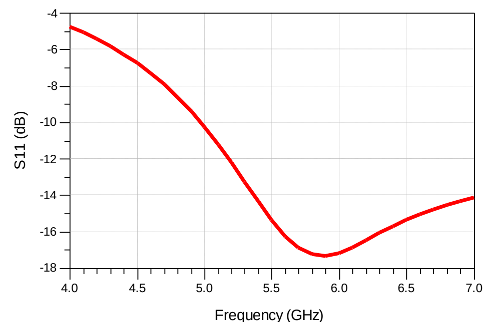
Fig. 8 (a) Simulation model for the on-chip antenna placed in blood with muscle and bone around (b) Close view of simulated pulmonary which is right next to the heart



(a)



(b)



(c)

Fig. 9(a) Radiation pattern (b) 3-D polar plot (c) return loss of the proposed on-chip antenna for local blood pressure monitor

Parameter	Value at 5.8GHz
S11 (dB)	-17
Peak Gain (dBi)	-10.1
Efficiency	9.3%

Table 3 Parameters of the designed on-chip antenna in pulmonary artery

The wireless system model for the local blood pressure monitoring is shown in Fig. 10. There are ribs and muscle between the external antenna and implanted antenna. The distance between the two antennas is 6-cm. For a person with thicker chest muscle might enlarger the distance. The simulation results of return loss and insertion loss are shown in Fig. 11. The return loss of the external antenna and the implantable antenna are -25 and -17 dB respectively. The overall system performance is shown in Fig.12. The receiving power from the external device is -39.3 dBm which is still higher than -40 dBm and therefore it demonstrated this receiving signal is able to be demodulated by the high sensitivity communication technology.

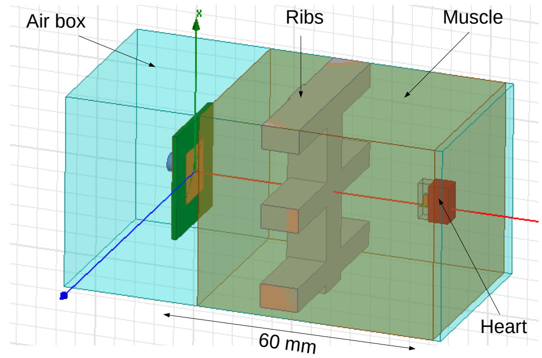
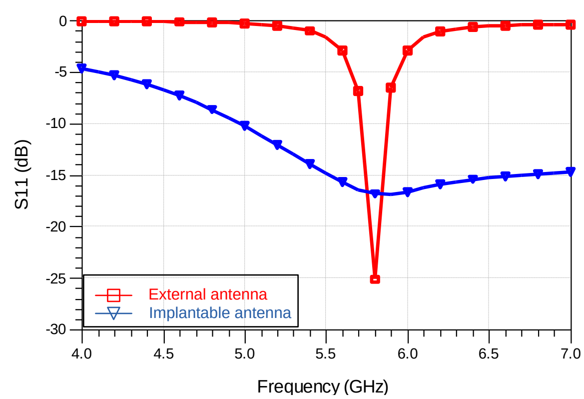
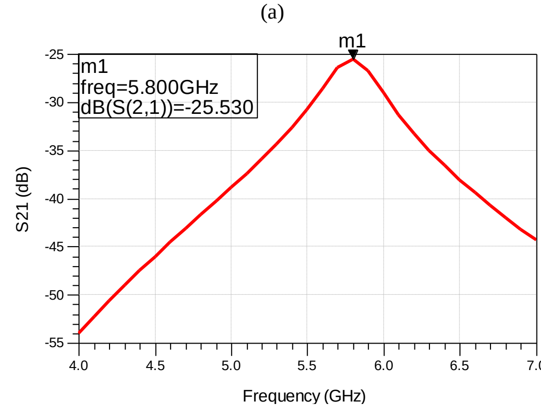


Fig. 10 External antenna is placed 6-cm away from the heart to communicate with the implanted on-chip antenna in pulmonary artery



(a)



(b)

Fig. 11 Simulation result of (a) Return loss of external and implanted antenna (b) insertion loss from the external to the internal antenna to the implanted on-chip antenna

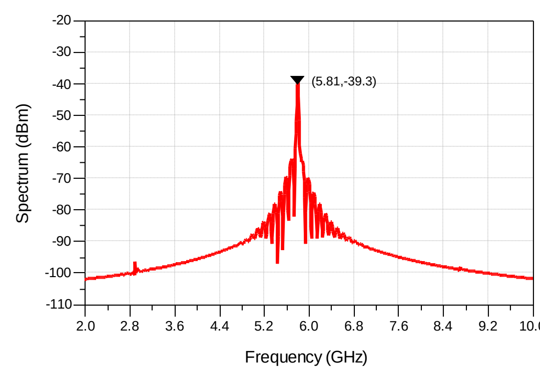


Fig. 12 Output power at external receiver of the cardiac monitor system

5. CONCLUSION

A fully implantable wireless system analysis and design including on-chip rectenna and low power RF transmitter for the biomedical application of cardiovascular have been presented. The designed harvesting circuit of 13-stage NMOS rectifier is able to drive a 1-kΩ load with 1-V and 1-mA by utilizing RF energy within a short distance, which makes the battery-less function possible

A new idea for the 5.8-GHz on-chip antenna solution to fit in a vessel with 10% efficiency has been proposed and co-designed with TSMC 0.18µm CMOS ICs.
The receiving power level at the external device is higher than -40 dBm at 36-dBm input from the external signal generator at 5.8 GHz. For the high sensitivity receiver such as Zigbee with sensitivity lower than -60 dBm, data with -40-dBm power level is able to be processed.

6. REFERENCES

[1] A. V. Chobanian et al., "The Seventh Report of the Joint National Committee on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure", **The Journal of American Medical Association**, vol. 289, no. 19, pp. 2560-2572, 2003.

[2]C. S. Wang, T. W. Wang, J. H. Lee, and C. W. Liu, "Mobile and Wireless Technologies on Sphygmomanometer and Pulsometer for Patients Setting Pacemaker and Complicating with Other Cardiovascular Disease", **The 2nd International Conference on Bioinformatics and Biomedical Engineering**, pp. 1347-1350, May 16-18, 2008.

[3]A. E. Lazar, M. C. Smith, and M. Rahman, "Blood Pressure Measurement in Hemodialysis Patients", **A Journal of Kidney Foundation**, vol. 11, no. 2, pp. 134-142, April, 2004.

[4] E. Y. Chow, A. L. Chlebowski, S. Chakraborty, W. J. Chappell and P. P. Irazoqui, "Fully Wireless Implantable Cardiovascular Pressure Monitor Integrated with a Medical Stent," **IEEE trans. Biomedical Engineering**, vol. 57, no. 6, June 2010.

[5] Eric Y. Chow, A. L. Chlebowski and P. P. Irazoqui, "A Miniature-Implantable RF-Wireless Active Glaucoma Intraocular Pressure Monitor," **IEEE trans. Biomedical Circuits and Systems**, vol. 4, no. 6, Dec 2010.

[6]J. Yin et al.,"A System-on-Chip EPC Gen-2 Passive UHF RFID Tag with Embedded Temperature Sensor", **IEEE ISSCC Dig. Tech. Papers**, Feb. 2010, pp. 308-309 .

[7]T. Le et. al, "Efficient Far-Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks", **IEEE J. Solid-State Circuits**,vol. 43, pp. 1287-1302, May 2008.

[8]S. Mandal and R. Sarpeshkar, "Low-Power CMOS Rectifier Design for RFID Applications," **IEEE Trans. Circuits and Systems I**, vol. 54, no. 6, pp. 1177–1188 , Jun. 2007.

[9]E. Y. Chow , S. Chakraborty, W. J. Chappell, and P. P. Irazoqui, "Mixed-Signal Integrated Circuits for Self Contained Sub-Cubic Millimeter Biomedical Implants", **IEEE ISSCC Dig. Tech. Papers**, Feb. 2010, pp. 236-237.

[10]C.W. Lin et al, " Pain Control On Demand Based on Pulsed Radio-Frequency Stimulation of the Dorsal Root Ganglion Using a Batteryless Implantable CMOS SoC", **IEEE ISSCC Dig. Tech. Papers**, Feb. 2010, pp. 234-235.

[11] Z. Wang, H. S. Savci, N. S. Dogan ,"1-V Ulatr-Low-Power CMOS LC VCO for UHF Quadrature Signal Generation" **Circuits and Systems**, 2006. ISCAS 2006. Pro. 2006 IEEE Int. Symp..