Implantable Biomedical Signal Monitoring Using RF Energy Harvesting & On-chip Antenna

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Abstract— This paper presents the design of an energy harvesting wireless and battery-less silicon-on-chip (SoC) device that can be implanted in the human body to monitor certain health conditions. The proposed architecture has been designed on TSMC 0.18µm CMOS ICs and is an integrated system with a rectenna (antenna and rectifier) and transmitting circuit, all on a single chip powered by an external transmitter and that is small enough to be inserted in the human eye, heart or brain.

The transmitting and receiving antennas operate in the 5.8-GHz ISM band and have a -10dB gain. The distinguishing feature of this design is the rectenna that comprises of a single-stage diode connected NMOS rectifier and a 3-D on-chip antenna that occupies only $2.5 \times 1 \times 2.8$ mm^3 of chip area and has the ability to communicate within proximity of 5 cm while giving 10% efficiency. The external source is a reader that powers up the RF rectifier in the implantable chip triggering it to start sending data back to the reader enabling an efficient method of health evaluation for the patient.

Keywords—Biomedical Monitoring, Eye-pressure monitor Implanatble CMOS IC, Rectenna, TSMC, 3D on-chip antenna

1. INTRODUCTION

Biomedical sensing has gained significant amount of attention in the recent years owing to the increasing demand of frequent patient monitoring without professional medical intervention which in turn lead to the demand growth of personal health monitoring systems. In our work we have presented the idea of an energy harvesting based personal health monitoring system. Energy harvesting methods derived from sources such as wind, solar and tidal power have long since been employed in low power applications, however with technological progress there has been seen an increased application of RF energy harvesting in numerous medical and small-scale applications. [1-4] In this research work, effort has been made to incorporate the concept of RF energy harvesting in a biomedical application on an SoC device. Micro silicon chips can be implanted by minimally invasive surgeries at many different locations of the human body to monitor a wide range of factors such as blood pressure, blood glucose level, heart pressure, eye pressure, neural activity.In this paper, the design of an implantable silicon device has been presented which is small enough to be inserted in the eye to monitor the intraocular pressure at any given time by the doctor or patient itself and its battery-less nature eliminates future surgery requirements. This design is broadly split in two parts, an internal unit which is the implantable silicon chip that is inserted in the human eye and the external reader which wirelessly communicates with the internal device. The implantable chip comprises of the rectenna (3-D on-chip antenna and rectifier), IC sensing circuit and the external reader which combines a patch antenna and a signal generator. The entire circuit layout has been made on TSMC 0.18um CMOS ICs. In Section 2, Energy harvesting techniques and applications are discussed along with wireless utility. In Section 3, we have presented the case study that we carried out on an eye pressure monitoring device. Section 4 encompasses the results along with comparisons. In Section 5, we have discussed simulation result. The paper concludes with Section 6, where we have discussed future improvement in the design.

2. ENERGY HARVESTING AND WIRELESS CONTROL OF SOC DEVICE

In imaging the activity of a body part the primary concerns arise in case of invasive methods especially if the monitoring of a certain sensitive organ requires a complicated and possibly risky surgical procedure. There has been extensive research done in the area of biomedicine which enables monitoring of a certain organ using an implantable device connected wirelessly to an external reader or gauging circuitry. Although, this method is also invasive, however once a chip in implanted in the body it allows for continuous and long term, sometimes everlasting monitoring of a health condition without a need of replacement or alteration of the device.

To achieve the aforementioned benefit, this device must not only be wireless but have battery-less functionality as well. A number of studies have been carried out on implantable chips and have been implemented on mice as well but these devices are wired and connected to an external monitor which inhibits free movement of the subject. An added advantage to such a design would be using energy harvesting technique whereby energy from environmental sources such as solar energy, tidal power, winder energy and RF microwaves are captured and converted into usable electrical energy. The power generated from energy harvesting techniques is ideal for substitution of batteries in designs which could be impractical, infeasible, costly or dangerous. In the field of biomedicine, especially in case of implantable devices, the ideal requirement would be a battery-less design that uses energy from cost-free environmental resources thereby bypassing the need to change, replace or charge batteries. We have studied the case of a blood pressure monitor and intraocular pressure monitor. In a blood pressure monitor, the silicon chip is implanted in either the carotid artery or the pulmonary artery. This chip is powered up by an external reader upon which it begins to transmit data about the pressure of the heart. For a detailed case study, we choose the intraocular pressure monitor which is based on a similar structure as the heart pressure monitor and is small and effective enough to be implanted in an organ as sensitive and complicated as the eye.

3. CASE STUDY: INTRAOCULAR PRESSURE MONITOR

The proposed Intraocular Pressure Monitor comprises of an Implantable IC and an external reader. The block diagram of the eye pressure monitor is shown in Fig 1.
The primary components of the implantable device are the Rectenna (Diode Rectifier and the 3-D on chip) and transmitting circuit comprising of the Power Amplifier (PA), Voltage Controlled Oscillator (VCO) and Duplexer. The dimensions of the entire chip with all the mounted components is 2.5 × 1 × 2.8 mm3 which is placed 5 mm inside the anterior chamber of human eye. The key components of the design are the diode rectifier and the 3-D on-chip antenna. In the following sections we shall explain the key components in detail along with experimental results.

4. RECTENNA DESIGN

This work presents an integrated system solution with an antenna, a rectifier, and a transmitting circuit on a single chip for biomedical applications. As opposed to previous research work, where antennas are not mounted on the main chip, the presented design obviates the risk of chip failure. The external reader transmits RF energy to the RF rectifier on the chip placed inside the human body to power up the whole implanted chipset. When the chipset wakes up, it starts to work and sends data back to the reader. Then, the patient or the doctor can read the data to evaluate the health condition. In order to put the chipset inside the human body, the first requirement is to employ a battery-less technique thereby bypassing the need for future surgeries to remove the chip from the body. The second requirement is that the RF rectifier must generate enough voltage and current to drive the whole transmitter and sensing IC. Therefore, the efficiency is the most important aspect to be taken in consideration. This design operates at 5.8 Ghz which is the optimal frequency because too low a frequency results in longer wavelength and consequently larger antenna size while too high frequency degrades the RF to DC efficiency of the RF rectifier causing large power reflection from the receiving antenna.

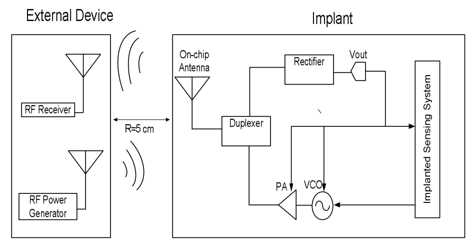


Fig 1. Simplified block diagram of the intraocular pressure monitor system.

Diode Connected MOSFET RF Rectifier

A detailed link budget analysis has been carried out for the proposed design, based on which it was decided that the Native NMOS with almost zero threshold voltage is the best candidate for the RF rectifier in biomedical applications. The designed RF rectifier can provide 1-V output voltage and 1- mA output current with 30% efficiency as shown in Figure 2, which is sufficient to drive a 1-kΩ load. The input impedance (Rrec) is 26 Ω and S11 at 5.8 GHz is -10 dB and shows 10% power reflected at 5.8GHz.

3-D on-chip Antenna Design

The rectenna (antenna plus rectifier) system for intraocular pressure monitor has to be implanted into the human eye which is why compactness is the key concern in addition to other limitations. We have listed down all the challenges we faced along with proposed solutions that we incorporated in our design.
Challenge 1: According to recent researches [6 - 9], on-chip antenna commonly operates in the range of millimeter wave; (35-GHz, 60-GHz and 94-GHz are popular frequency ranges) however in RF rectifier design, higher frequency degrades RF to DC efficiency.
Challenge 2: The large loss on silicon substrate and metal, which degrades the antenna efficiency.
Challenge 3: The high propagation loss inside the human eye which can be seen as additional dielectric loss.
Challenge 4: The mismatch between RF rectifier and antenna.
Challenge 5: Another issue is the inductive impedance of the antenna which limits the design of antenna.

In order to overcome the limitation of the on-chip antenna placed in aqueous humor, this work proposes a new 3D structure solution to achieve high efficiency, small size and simple design that operates in low frequency range and matches to 50-Ω standard network.

The proposed 3D antenna is built on the polymer-ceramic dielectric and silicon substrate. According to studies carried out by [10], by using a polymer and ceramic mixture is predefined quantities, it is possible to obtain a high permittivity (εr = 20) and low loss tangent (tanδ < 0.02) dielectric substrate. Also, based on the concept of DRA on silicon wafer, it is possible to integrate poly-ceramic substrate with the silicon chip. Instead of using dielectric material as a resonator, this design uses poly-ceramic as a dielectric substrate for the patch antenna thus isolating the radiated element from the lossy silicon.

Fig. 3 shows the stack-up of the proposed structure. In contrast with, conventional CMOS technology, additional dielectric substrate (DS) with 2.5-mm height is placed on the silicon dioxide and Metal 6 (M6), bent into an elongated L-shape is placed at the borders of DS to act as a patch radiator. At the bottom of the chip, a ground layer is placed to form an electrical field path from the top to the bottom. Implementation of this design makes it possible to achieve high efficiency and small size of the on-chip antenna.

This is due to the high-permittivity of DS owing to which, the size of the patch can be shrunk. Secondly, 2.5- mm height of DS creates a dielectric shielding to isolate it from the Si-substrate. Because of 3D structure, M6 can be elongated to have enough electrical length to operate at 5 GHz. Lastly, the antenna structure is simple and can be matched to 50-Ω only by adjusting the width of the antenna.

Therefore, with 50-Ω system, it would be possible to integrate the proposed RF rectifier with other RF circuits.

Fig. 4 (a,b) shows the proposed on-chip 3D patch antenna. The feeding is a 0.7-mm long 50-Ω Microstrip line (width: 0.2 mm) connected to the radiator with 1-mm width and 3.8-mm length (1.3-mm on the top + 2.5-mm on the side of DS). Between the radiator and the feeding line is a 0.3-mm long T-junction, and a 2.5 mm × 1 mm ground plane is placed under Si-substrate. The size of the antenna itself is only 1 mm × 1.5 mm × 2.8 mm which is extremely small and can be implanted within the human eye.

In the application under discussion, which is monitoring an ocular condition such as Glaucoma, the on-chip antenna has to function in the aqueous humor and therefore, the ambience has to be taken into account when carrying out HFSS simulation.

The on-chip antenna locates inside a 6 mm × 6 mm × 6 mm aqueous humor (εr = 68, tanδ = 0.2677). The boundary between near and far field of is given by Eq (1)

$$R_f = \frac{2D^2}{\lambda_a} \text{ ---------------------- (1)}$$

Where, 'Rf' is the boundary of near field, 'D' is the longest dimension of the antenna, and 'λa' is the propagation wavelength in a given material. In this design, 'λa' is around 3 mm at 5.8 GHz.

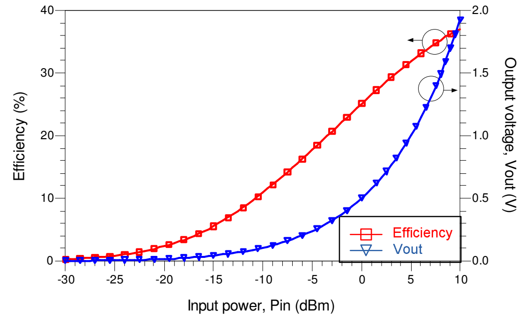


Fig. 2 Output voltage and efficiency of the designed RF rectifier.

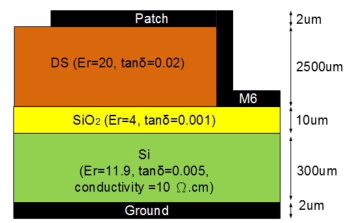


Fig. 3 Cross view of the proposed 3D- structure for on-chip antenna.

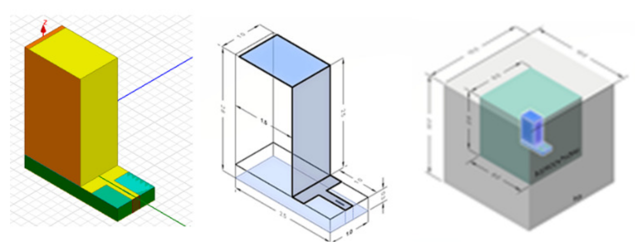


Fig. 4. 3D-view of the proposed on-chip antenna. (a) HSS model b) Detail dimensions (Unit: mm) (c) Simulation model built up of the proposed on-chip antenna.

Integration with Rectenna

In the rectenna design we have combined the single stage diode-connected Native NMOS Rectifier with the on-chip antenna as depicted in Figure 5. After the integration of the aforementioned segments, the matching could be slightly tuned by the on-chip spiral inductor. Fig. 6 shows the placement of an example wireless system on the proposed on-chip antenna. The rectifier is located inside the wireless system chip which occupies roughly 1 mm × 1mm on a wafer. Thus, the overall wireless system might be 2.5 × 1 × 2.8 mm3.

The performances of the rectenna system is shown in Fig. 7 (a,b,c). At the frequency range from 4.6 GHz to 5.8 GHz with 5-dBm input, the rectenna could achieve

1-V and 1-mA output with at least 30% RF to DC efficiency, which is sufficient to generate enough power to run the modern low power wireless system. The input power to the rectifier is 5 dBm (3.2 mW), with 30% efficiency of the on-chip antenna using which we can calculate the input power into the entire retenna which roughly 10.3 dBm (10.7 mW). The performance parameters have been compared with previous research studies and the tabulated results in Section VI indicate superior performance and power efficiency.

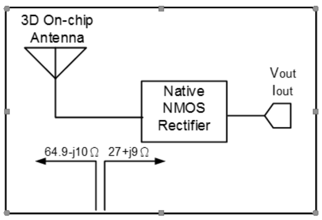


Fig. 5 Rectenna system block diagram.

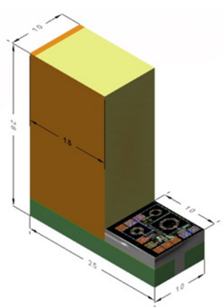


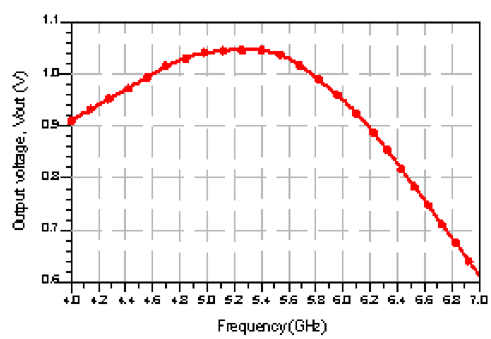
Fig. 6 On-chip antenna integrated with an example RF wireless system.

5. RESULTS AND DISCUSSIONS

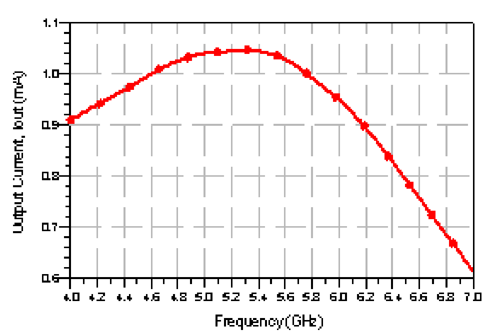
The size of the entire rectenna is 2.5 × 1 × 2.8 mm3 which is small enough to be placed in the human eye. The performance of the proposed rectenna in comparison with previous research works has been discussed in this section. The results show an improved performance compared with previous studies. Fig. 8 shows the entire wireless system circuit. The signal generator provides 36 dBm to the system and the loss between the two antennas is 26 dB. Therefore, the power input to the rectifier is roughly 10 dBm which can generate a voltage Vrec at around 1.1 V and a current Irec at 3 mA to power the VCO and PA. It may also be observed that the values of Vrec and Irec are sufficient to not only provide supply to the transmitter but also other implanted circuits.

The return loss and input impedance has been simulated on Agilent ADS as shown in Figure 9. Looking at the graph, it can be seen that the resonant frequency occurs at 5.8 GHz with minimum S11 equal to -16 dB and the impedance is (64 - j10) Ω, which indicates a good matching to 50-Ω network. The bandwidth is 600 MHz (5.5 GHz-6.1 GHz) which covers the entire 5.8 GHz ISM band (5.75 GHz - 5.85 GHz). The simulation results of radiation patterns and gain in E-plane and H-plane at 5.8GHz have also been analyzed as depicted in Figure 10. By studying the figure it can be seen that the peak gain is -10 dBi both on E and H plane.

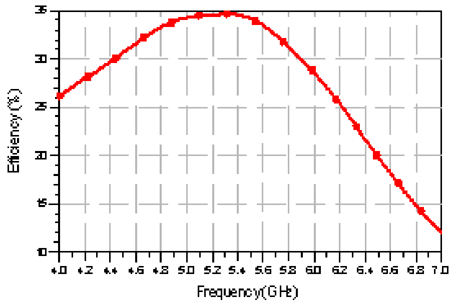
We have also simulated the current and E-field distribution on the metal of the on-chip antenna as shown in Fig. 11, There is a zero current spot on the side wall and away from the spot, the current reaches zero again on the top edge to form a quarter wavelengths as seen in Figure 11.The overall current path is around 7.3 mm which is roughly ¾ λ. 'λ' is roughly 10 mm due to part of the E-fields located in aqueous humor. Therefore, the top patch contributes towards the radiation and the 3/4 wavelength generates the resonated frequency at 5.8GHz. As can be seen in the Fig. 12(a), The proposed on-chip antenna is a patch antenna because the top patch radiator contributes to the main electrical field. The fringing field causes the antenna to radiate and thus the magnitude of E-field is stronger on the edge of the top patch and ground plane. However, due the small ground plane, this antenna resonates in a ¾ λ dipole mode. Fig. 13 shows the radiation efficiency and peak gain of the proposed on-chip antenna. At the ISM band from 5.725 to 5.875 GHz, the efficiency is 10% the gain are greater than -10 dBi, which mean the proposed antenna could achieve the 150-MHz bandwidth criteria. Table 1 shows the comparison with the similar on-chip antenna design. As can be seen, in this work, -10-dBi peak gain and 10% efficiency are the highest one compared with similar frequency range.



(a)



(b)



(c)

Fig. 7 (a) Output voltage (b) output current (c) efficiency of the proposed rectenna system at 5 dBm input the RF rectifier.

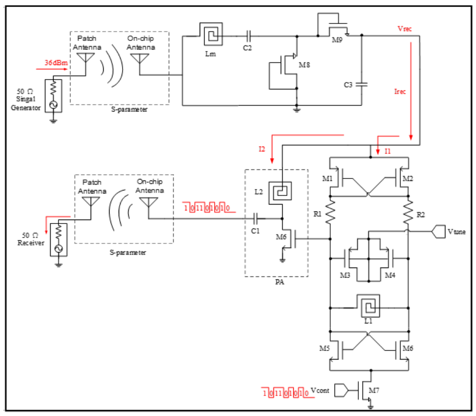
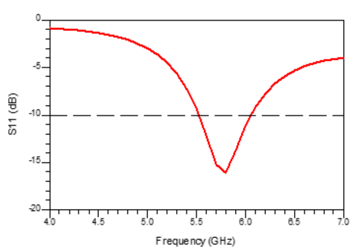
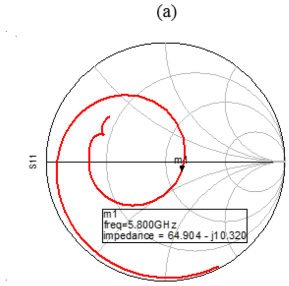


Fig. 8 Schematic of the entire biomedical system.



(a)



(b)

Fig. 9 Simulated (a) return loss and (b) input impedance of the proposed on-chip antenna.

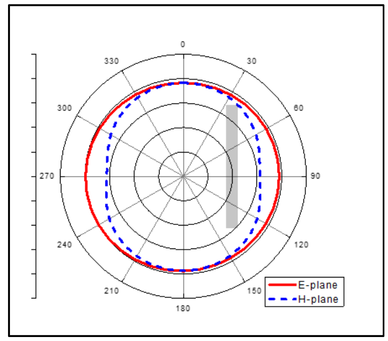


Fig. 10 Simulated radiation pattern and gain in the E-plane and H-plane of the proposed on-chip antenna (Unit: dB)

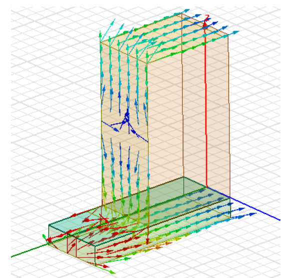


Fig. 11 Surface current on the conductor of the proposed on-chip antenna.

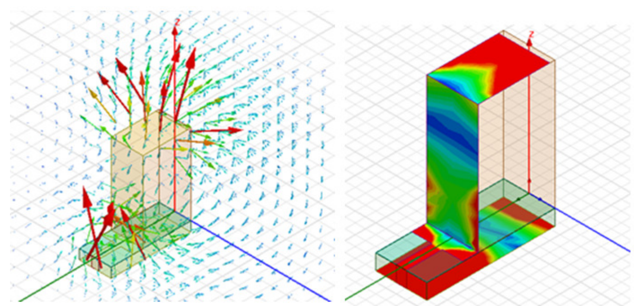


Fig. 12 (a) E-field distribution around the on-chip antenna (b) E field magnitude on the radiator and ground.

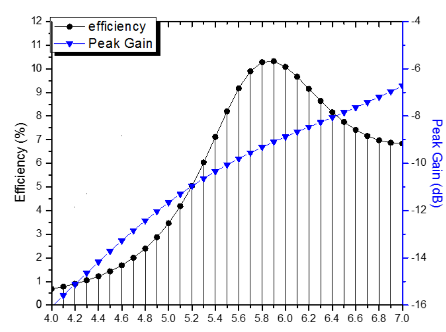


Fig. 13 Efficiency and peak gain versus frequency of proposed on-chip antenna.

6. CONCLUSIONS

This paper presents a fully implantable wireless system design including an on-chip rectenna and low power RF transmitter for pressure monitoring of human organs such as eye, heart and brain. The designed harvesting circuit of Native NMOS rectifier drives 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.In addition, we have proposed a new solution for the 5.8-GHz on-chip antenna to be fitted in a place with severe space and environmental constraints such as the human eye. The proposed solution has been designed on TSMC 0.18um CMOS ICs and displays 10% efficiency and -10 dBi gain.

Finally, based on the built-up environment model for imitating human heart and eye, the system simulation results show that at least -40-dBm receiving power can be utilized within 5-cm distance of external reader device, which demonstrates the feasibility of future on-demand easy-to-design implantable SoC.

This work can be further improved by optimizing the design possibly by using the state-of- art low power MEMS sensing circuits for pressure detection that may consume as low as 0.5 V. Moreover, the sensitivity of the external receiver can also go lower than -60 dBm or even -90 dBm using high sensitivity technology and design parameters thus reducing the output power of the VCO/PA as well as the size of antenna.

Table 1 Performance summary and comparison with papers

Ref	This work	[4]	[3]	[12]	[13]	[14]	[11]
Frequency (GHz)	5.8	5.2	4	9	5.8	60.5	60
Peak Gain (dBi)	-10	-14.5	-25	-10	-29.5	-3.32	0
Efficiency	10% (30% @ near field)	Below 10%	Below 10 %	9%	Below 10%	15.87 %	NA
Size (mm^2)	1.5 × 1 (H= 2.8)	2.9 × 1.1	3 × 3	0.6 × 0.6	3 × 1.5	1.2 × 1.6	2 × 1.5 (H= 1.7)
Antenna type	Patch	Monopole	Loop	Slot	Scavenging	Patch	Slot dipole
Technique	3D	Loop load	Single loop	Meander	Inductive stubs	Ground shielding	DRA
Application	Aqueous humor	Aqueous humor	Free space	Free space	Free space	Free space	Free Space
Year	2013	2012	2010	2009	2010	2010	2012

REFERENCES

[1] 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.

[2] 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.

[3] H. Le, N. Fong, H. C. Luong, "RF Energy Harvesting Circuit with On-chip Antenna for Biomedical Applications", Communications and Electronics (ICCE), 2010

[4] L. Marnat, M. H. Ouda, M. Arsalan, K. Salama, and A. Shamim, "On-Chip Implantable Antennas for Wireless Power and Data Transfer in a Glaucoma-Monitoring SoC," IEEE Antennas And Wireless Propag. Lett., vol. 11, 2012

[5] H. -K. Chiou, I. -S. Chen, "High efficiency Dual-band On-chip Rectenna for 35- and 94-GHz Wirless Power Transmission in 0.13um COMS technology," IEEE Trans.Microwave Theory and Techniques, vol. 58, no. 12, Dec 2010

[6] Y. Gao, and Z. Feng, "High-Gain Silicon Based On-Chip Dielectric Resonator Antenna at 60GHz," Microwave and Millimeter Wave Technology, pp. 1-4, May 2012

[7] M.-R N.-Ahmadi, M. Fakharzadeh, B. Biglarbegian, and S. S.-Naeini , "High-Efficiency On-Chip Dielectic Resonator Antenna for mm-Wave Transceivers," IEEE Trans. Antennas and Propag., vol. 58, no. 10, Otc. 2010

[8] W. Yang, K. Ma, K. S. Yeo and W. M. Lim, "A 60GHz On-chip Antenna in Standard CMOS Silicon Technonolgy," Circuits and Systems, 2-5 Dec. 2012

[9] Y. Zhou, "Polymer-Ceramic Composites for Conformal Multilayer Antenna and RF Systems," PhD DISSERTATION, The Ohio State University, 2009.

[10] Y. Gao, and Z. Feng, "High-Gain Silicon Based On-Chip Dielectric Resonator Antenna at 60GHz," Microwave and Millimeter Wave Technology, pp. 1-4, May 2012

[11] N. Behdad, "Single- and Dual- Polarized Miniaturized Slot antenna and their application in on-chip integrated radios," Antenna Technology, 2009. iWAT 2009. IEEE International Workshop, 2009, pp. 1-4

[12] S. Radiom, M. B.- Nejad, K. M.- Aghdam, G. A. E. Vandenbosch, L.- R. Zheng, and G. G. E. Gielen, "Far-field on-chip antennas Monolothically integrated in a wireless-power 5.8GHz Downlink/UWB uplink RFID Tag in 0.18um Standard CMOS," IEEE journal Solid-state Circuits, vol. 45, no. 9, Sep. 2010, pp. 1746-1758

[13] K. -K. Huang and D. D. Wentzloff , "60 GHz On-Chip Patch Antenna Integrated in a 0.13-μm CMOS Technology" Pro. of 2010 IEEE Int. Conf. Ultra-Wideband (ICUWB2010), pp. 1-4