Challenges in the Design of Integrated Circuits for Wireless Power Delivery and Information Transfer in Implantable Medical Applications

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Context

- Medical devices vs Semiconductors industries
- How to develop a medical instrument, equipment, or device
- Design considerations of a transceiver used for implemented medical device
- The possible application and research directions of the Wireless Transceiver
- Wireless Power Transfer for Miniaturized Medical Devices

Medical devices vs Semiconductors industries

Similar annual sales of top 20 companies , but different in …

The total market size of the medical device industry is similar to that of the information industry

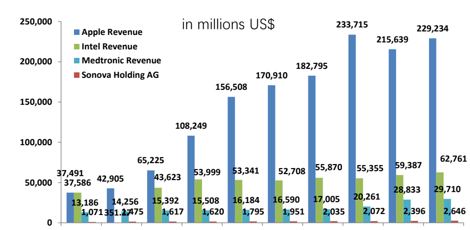
Top Medical Devices and Semiconductor Companies in 2017

Rank	*Medical Device*	*US$ B*	*Rank*	*Semiconductor*	*US$ B*
1	Medtronic plc	28.8	1	Samsung Electronics	61.2
2	Johnson & Johnson	25.1	2	Intel	57.7
3	GE Healthcare	18.3	3	SK Hynix	26.3
4	Siemens Healthineers	15.2	4	Micron Technology	23.1
5	Becton Dickinson	12.5	5	Qualcomm	17.1
6	Cardinal Health	12.4	6	Broadcom	15.5
6	Philips HealthTech	12.4	7	Texas Instruments	13.8
8	Stryker	11.3	8	Toshiba	12.8
9	Baxter	10.2	9	Western Digital	9.2
10	Abbott Laboratories	10.1	10	NXP	8.7
	Sub total	156.3		Sub Total	245.3
	Others	232.8		Others	174.4
	Total Market	389.1		Total Market	419.7

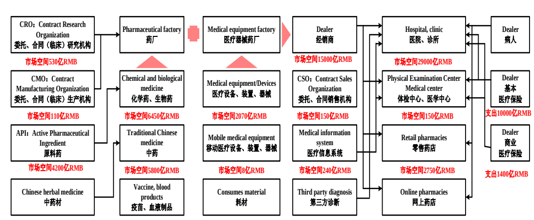
Sales in US exceed 60% China's imports more than 60%

A single enterprise in the medical device industry is smaller than the information industry

in millions US$



The market or medical devices is still large enough



Sourec: CITI, WIND

- Make medical device smarter and smaller

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How to develop a medical instrument, equipment, or device

With the Integrated Circuit is Enabling Technology

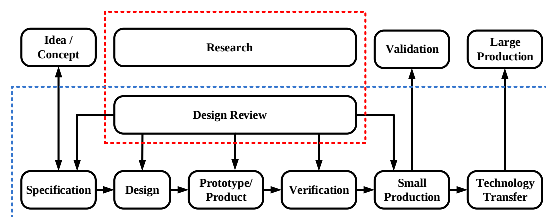
What is a medical device

- An instrument, apparatus, implement, machine, contrivance, implanted in vitro reagent, or other similar or related article, including a component part, or accessory which is:
  - Recognized in the official National Formulary
  - Intended for use in the diagnosis of disease or other conditions
  - Intended to affect the structure or any function of the body of man or other animals

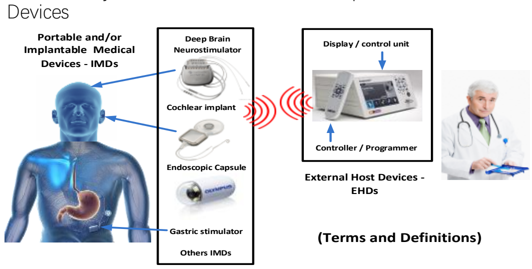
Classification of medical Devices

- Class I: General controls
- Class II: General controls with special controls
  - infusion pumps, and surgical drapes…
- Class III: General controls and premarket approval
  - implantable pacemaker, pulse generators, automated external defibrillators…

Research and Development of an medical system



A Medical System with Portable and/or Implantable Medical Devices



Composition or Development Platform

- Communication protocols and modules
- information security
- Sensing modules
- Pacing modules
- Wireless battery recharge module
- Lead impedance measurement modules
- Accelerometer modules
- FW download module
- RTC module

A Portable and/or Implantable Device

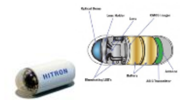
- Electronic implantable medical devices (IMD) are designed to be fully or partially implanted in the human bodies through surgeries[1], and remain in bodies for several hours to several years or even permanently after the surgical intervention.

What is a Portable and/or Implantable Medical Device?

[1] R. Ritter, J. Handwerker, T. Liu, and M. Ortmanns, "Telemetry for Implantable Medical Devices," IEEE SOLID-STATE CIRCUITS MAGAZINE, vol. 6, Issue. 2, pp. 47-51, Spring 2014.

Examples of Portable and/or Implantable Medical Devices


Total hip replacement


capsule endoscopy

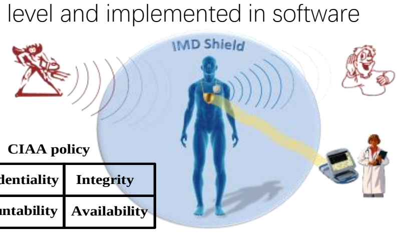

Robot hand


Cochlear implants


Nerve Stimulator


Total Knee replacement

About the information security - Mostly at the system level and implemented in software



CIAA policy

Confidentiality	Integrity
Accountability	Availability

Enabling Technology is Integrated Circuit

- Information Sciences:
  Acquisition
  processing,
  Storage
  Transmission

  of (medical and life) signals

Design considerations of a transceiver used for implemented medical device

Well known implemented medical devices in clinical application

- cardiac pacemakers,
- implantable defibrillators,
- Cochlear implants,
- nerve stimulators (Functional Electrical Stimulation-FES),
- limb function stimulation,
- bladder stimulators,
- Sphincter stimulators,
- diaphragm stimulators,
- implantable infusion pumps,
- bio-monitoring devices such as the capsule endoscope.

Two options to power an implemented medical devices

- miniature battery, ***and wireless power***.
  - lowering the circuit power consumption,
  - to evaluate the available space for power supply components inside IMDs,
- The lifetime and reliability requirement, before choosing the power type.
  - For example, a cardiac pacemaker relying on a reliable energy source may choose a battery, while an intraocular IMD usually choose wireless power since there is no room for a battery. The requirements on the wireless transceivers for different IMDS are quite diverse, in terms of data rate, signal transmission distance, and communication directions (single direction or two-way). The data integrity and bit-error rate (BER) tolerance are also of great importance, and the poor performances on these aspects may lead to harmful and even fetal malfunction.

implemented medical devices power and wireless data requirements

IMDs	Power consumption	Target data rate	Life-Time	Energy Source
Biomonitoring System	<100 μW	< 10 kb/s	a few days	Primary Battery
Capsule endoscope	<15mW	>1 Mb/s	10 Hours	Primary Battery
Pacemaker	<100 μW		10 Years	Primary Battery
Cardioverter-Defibrilator	Cont: <100 μW; Peak: 5–10 W		10 Years	Primary Battery
Cochlear Processor	200 μW	>100Kb/s	1 Week	Rechargeable Battery
Hearing Aid	100–2,000 μW	200 kb/s	1 Week	Rechargeable Battery
Retinal Implant	40–250 mW	> 500kb/s	NA	Inductive Power
Neural Recorder/Stimulator	1–100 mW	<1 Mb/s	NA	Inductive Power
Artificial Heart	10–100 W		NA	Inductive Power

Frequency band selection for implemented medical devices transceiver design

- considering the huge variation of EM signal propagation characteristics through human tissues with different frequencies. Based on FCC frequency regulations, the MedRadio band (composed of several inconsecutive bands in 401–457 MHz) has superior propagation characteristics for implants, quiet channel properties, and worldwide availability, which are the primary reasons for its popularity for implant applications. The 2.45GHz ISM band, with the mature circuit technologies, wide support for connecting to smart phones and other mobile devices, convenient access to the network, is also widely used for implantable medical systems.

Table 2. Radio standards - Implantable Medical devices

Global Frequency bands	Category	Comments
9 – 315 kHz	EU medical implant	Not so allocated outside EU
13.56 MHz	ISM and SRD	RFID transponders for patient ID
27.12 MHz	ISM and R/C	Congested
40.68 MHz	ISM and SRD	Protocol restrictions in USA
402 – 405 MHz	Medical Implant Comm.	Reserved for implants
2.45 GHz	ISM and SRD and microwave oven	802.11b/g (BT, Wi-Fi)
5.8 GHz	ISM	802.11a

IMD antenna design for IMDs

- IMD antenna design is also very challenging due to the size and shape restrictions, and the complicated working environment in human bodies. Since the electrical properties of the human tissues varies a lot with the patients' weight, age, posture changes, etc., the IMD antennas may adopt different sizes and shapes depending on the implantation location, which further limits the freedom of the designer

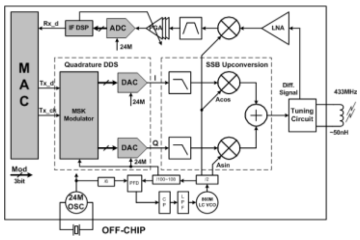
Implemented Transceivers for IMD

- 400 MHz RF transceiver
- 2.4 GHz RF transceiver
- Reconfigurable Sliding-Intermediate-Frequency (IF) Transceiver for 400 MHz/2.4 GHz IEEE 802.15.6/ZigBee
- 400 MHz/2.4 GHz TRX for dual-band communication

Asymmetrical RF Transceiver in 400MHz Band

- The data transmission from IMD to EHD sometimes requires very high burst data rate, while the control/command information receiving requires much lower data rate
- Asymmetrical wireless transceiver for IMD
  - High speed transmitter, very careful low power design
  - Low speed receiver
- TX: 3Mbps MSK modulation
  - High data rate → low duty cycle for battery
  - MSK chosen for bandwidth, performance & circuit complex.
- RX: 64kbps OOK demodulation
  - Low circuit complexity

A 400MHz IMD Transceiver



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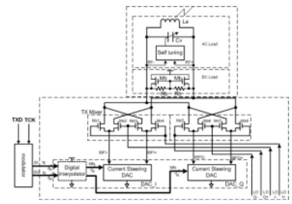
Low Power Transmitter with Current Sharing



- Zero-IF MSK modulator
- DC current sharing between IF DAC and mixer
  - Traditionally mixer and IF DAC are cascaded
- No traditional power amplifier
- Mixer directly loaded by antenna

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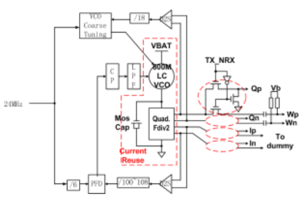
Frequency Synthesizer w/ Current Reuse



- 800M LC VCO w/ self calibration on tuning range
  - Double as the carrier frequency to generate quadrature carriers
- Current Reuse between VCO & Quadrature frequency divider [1]
- Current budget: VCO 0.6mA, all other blocks 0.2mA

[1] Park, et. al., "Current reusing VCO and divide-by-two frequency divider for quadrature LO generation," IEEE Microwave & Wireless Comp. Let., Jun. 2008

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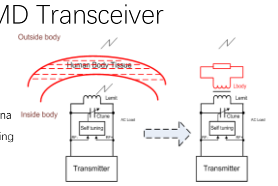
Antenna Design for IMD Transceiver



- Difficult to achieve good antenna matching for implantable SID with traditional antenna
  - Surrounding environment affects the antenna characteristic a lot
  - Difficult to characterize antenna's surrounding environment
- In this design, an inductor serves as antenna
  - C_{tune} is calibrated so that the RF port achieves resonance
  - no traditional antenna, therefore no traditional antenna matching
- A virtual transformer works as antenna
  - Inductor L_{emit} serves as the primary coil
  - Human body serves as the secondary coil
- The transformer has very low coupling
  - The transmitter sees very steady load, good for circuit design (positive)
  - The transmitting loss is high (negative)
- Our experience: if inductor L_{emit} has an RF ac current of 10mA (peak to peak), PBS receiving antenna can receive >-75dBm RF signal from outside body

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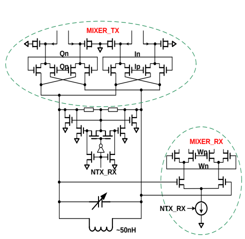
Switch between RX & TX



- RF I/O port is calibrated for resonance at TX mode
  - A RF peak detector is used to set the tuning capacitor such that to have highest RF output at the RF I/O port
- At RX mode, the load (inductor) will see different capacitance from TX mode
  - Transistors' working regions change a lot → parasitic capacitance changes a lot
- The dummy circuits in the center of this figure is toggled to compensate for the capacitance difference
  - The dummy circuit is a duplicate of the transistors connected to RF I/O port

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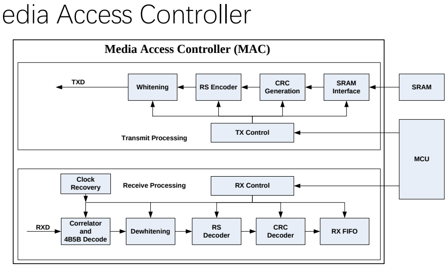
Media Access Controller



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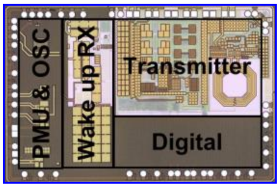
400 MHz Transceiver for IMD's



Parameters		This work
Supply voltage		2.5V~3.3V
External Components #		7
Frequency Band		400-432 MHz
Number of Channels		8
TX	Bit Rate	3Mbps
	Power Consumption	3.9mW
	Power Efficiency	1.3nJ/bit
RX	Bit Rate	64kbps
	Power Consumption	12mW

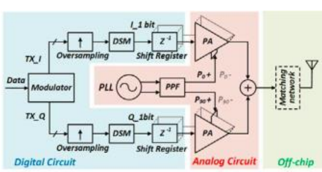
400 MHz Transceiver for IMD's

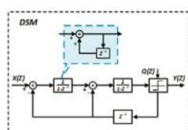
- 400 MHz wireless transmitter in 0.18 μm CMOS process
  - ✓ Low duty cycle ratio
  - ✓ Reduced average power consumption (average 27 μA)
  - ✓ 3 Mbps MSK modulation
  - ✓ Carrier frequency 416 MHz
  - ✓ Peak current 2.7 mA
  - ✓ Turned on for 14 ms every second
  - ✓ Sampling rate = 1 sps

Parameters		This work	ZL70081
Supply voltage		2.5V~3.3V	2.6V~3.2V
External Components #		7	10
	Type of RF link	Bi-directional	Transmit only
TX	Bit Rate	3Mbps	2.7Mbps
	Power Consumption	3.9mW	5.2mW
RX	Bit Rate	64kbps	*none*
	Power Consumption*	12mW	
MCU Power Consumption		240μW	*none*
Image Compressor		Yes	*none*
Image Compressor Power*		1.1mW	
Technology		0.18um CMOS	0.35um CMOS
Die area		13.3mm^2	*n/a*

H. Jiang *et al., "A SoC with 3.9 mW 3 Mbps UHF transmitter and 240 μW MCU for capsule endoscope with bidirectional communication," in Proc. IEEE Asian Solid-State Circuits Conf., Beijing, China, 2010, pp.* 1–4.
H. Jiang *et al.*, "*Implantable Wireless Intracranial Pressure Monitoring Based on Air Pressure Sensing*", *Trans. Bio. Circuit and System*, 2018
P. Bradley, "RF Integrated Circuits for Medical Implants: Meeting the Challenge of Ultra Low-Power," available online: http://www.cmoset.com/uploads/Peter_Bradley.pdf

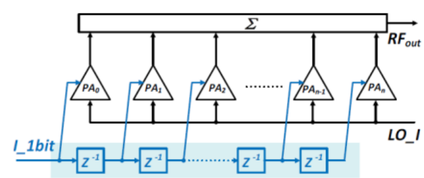
2.4 GHz IMD Transceiver



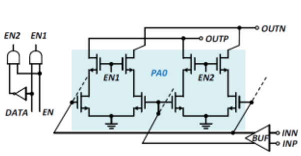


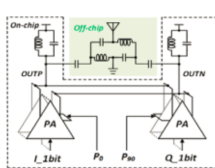
Y. Guo et al., "A 120 pJ/bit ΔΣ-Based 2.4-GHz Transmitter Using FIR-Embedded Digital Power Amplifier," IEEE Trans. Circuit and System-II., 2018

Realization of the FIR filtering using Digital Power Amp. and shift register



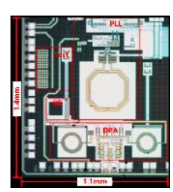
Implementation of PA network





- An embedded 16-order FIR filter(for OOB noise attenuated by at least 20 dB)
- 16 digitally controlled class-AB PA cells with each I/Q path
- The cascode transistors as the switches of the PA cells to avoid voltage breakdown issue.
- Each PA cell: two pseudo-differential amplifiers controlled by two internal signals EN1 and EN2

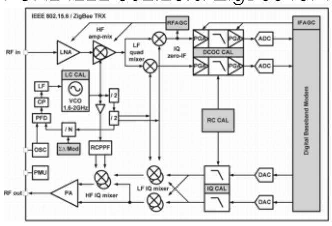
2.4 GHz Transceiver for IMD's



Parameters	This work	ISSCC 2012	JSSC 2017	TCAS-I 2017
CMOS Process	180 nm	90 nm	28 nm	90 nm
Supply voltage/V	1.2	1.2	0.5/1	1
Modulation	64-QAM	HS-OQPSK	GFSK	OOK
Carrier Frequency/GHz	2.4	2.4	2.4	2.4
Data Rate/Mbps	20	2	1	1
EVM/%	11	2.3	--	5.5
Power Consumption/mW	2.37	5.4	3.7	2.17
Power Efficiency	120 pJ/bit	1.10 nJ/bit	1.14 nJ/bit	2.17 nJ/bit
TX Pout/dBm	-15	-1	0	0/-10

Y. Liu, X. Huang, M. Vidojkovic, et al., "A 2.7nJ/b multi-standard 2.3/2.4GHz polar transmitter for wireless sensor networks," IEEE International Solid-State Circuits Conference, Feb 2012, pp. 448-450.
F. W. Kuo et al., "A Bluetooth Low-Energy Transceiver With 3.7-mW All-Digital Transmitter, 2.75-mW High-IF Discrete-Time Receiver, and TX/RX Switchable On-Chip Matching Network," in IEEE Journal of Solid-State Circuits, vol. 52, no. 4, pp. 1144-1162, April 2017.
S. J. Kim; C. S. Park; S. G. Lee, "A 2.4-GHz Ternary Sequence Spread Spectrum OOK Transceiver for Reliable and Ultra-Low Power Sensor Network Applications," in IEEE Transactions on Circuits and Systems I: Regular Papers , vol.PP, no.99, pp.1-12

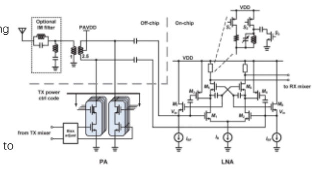
Reconfigurable Sliding-IF Transceiver for 400 MHz/2.4 GHz IEEE 802.15.6/ZigBee for IMDs



L. Zhang, et al., "A Reconfigurable Sliding-IF Transceiver for 400 MHz/2.4 GHz IEEE 802.15.6/ZigBee WBAN Hubs With Only 21% Tuning Range VCO," J. Solid State Circuit, vol. 48(11), 2013, pp. 2705-2716

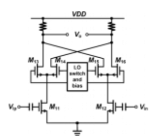
Wideband RF Front-end and off-chip matching circuits

- Active shunt feedback LNA with multiple gm enhancement
  - M1/2 provides gm
  - M3/4 enhances gm
  - M5/6 feedback for wideband matching
  - M7/8 widen resistance
- Class AB/B/C reconfigurable PA
  - Conduction angle adjustable
  - DBPSK/DQPSK-class AB
  - OQPSK/MSK-class B/C
- Matching circuits shared by TX/RX
  - An off-chip 1:2.5 balun needed
  - Reasonable input impedance <350 Ω to flatten the input reflection
  - Optimum load 320 Ω
  - External 2nd order LC filter suppressing 1.4-1.5 GHz

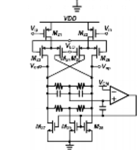


Reconfigurable RX Mixer

RX HF amp-mix: Gilbert mixer
- High frequency LO input (an amplifier while DC LO input)
- Pseudo-differential cascode amplifier mode:
  - M14/15 off, and M13/16 biased, M11/12 common-source input stage
- Mixer mode
  - M13-16: active switches driven by LO.
  - LNA's resistor load switched to a LC tank
    - filter out in-band interference
    - suppress the IM

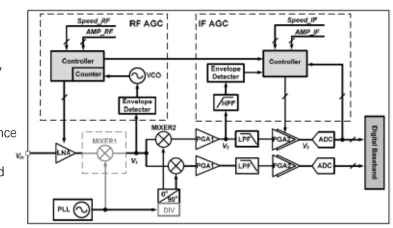


One path of the RX LF quadrature mixer
- PMOS input and switch transistors: good flick noise performance
- NMOS active load: high output voltage swing
- Common mode (CM) feedback
  - collect the redundant current
  - stabilize the output CM voltage.



Automatic gain control (AGC) method

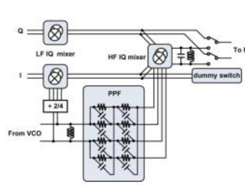
AGC flow
1. Set maximum RF gain
2. Turn VA1 to 30~60mV
3. Pre-determine IF gain
4. Adjust IF gain by N dB according to interference magnitude of VA2
5. Check ADC output and adjust VA3 to 200~600mV



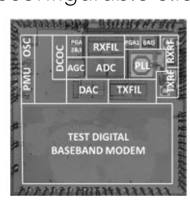
J. Dong, et al. "A Fast AGC Method for Multimode Zero-IF/Sliding-IF WPAN/BAN Receivers," IEEE International Symposium on Circuits and Systems, 2015, pp. 1310 - 1313.

TX up-converter with PPF IQ/LO generator

- A second order PPF
  - generate the IQ Local Osc. signals for the HF mixer.
- The Poly Phase Filter order and RC values
  - trade-off: image rejection ratio VS LO driver power consumption
- An inductor resonate S with the PPF equivalent capacitor
  - deliver large amplitude IQ LO signals to the HF mixer.
- LC tank
  - load filter out 1.4~1.5 GHz IM signal



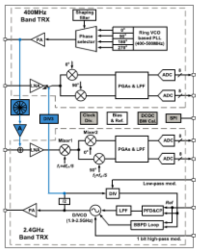
Reconfigurable Sliding-IF Transceiver IMDs

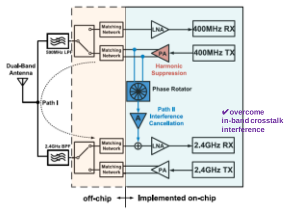


L. Zhang et al., "A low-power reconfigurable multi-band sliding-IF transceiver for WBAN hubs in 0.18 µm CMOS," in 2010 IEEE Asian Solid State Circuits Conf., A-SSCC, 2012, pp. 77–80.

	This work	
	2012 ASSCC 2013 JSSC	
Process (nm)	180	
Frequency (GHz)	0.36-0.51	2.36-2.5
Supply voltage (V)	1.55	
RX NF (dB)	3.9	4.4
RX in-band IIP3 (dBm)	-29.4	-26.6
ABB bandwidth (MHz)	0.15-3	
RX power (mW)	15.8	16.6
RX *FOM*[+]	**5.8**	
TX Max P_{out} (dBm)	+4.7	+3.1
TX power (mW) @ Max P_{out}	13.2	18.0
TX *FOM*[+]	**1.8**	
VCO range	21%	
Phase noise @ 1 MHz (dBc/Hz)	-121.5	-109.5[4]
Area (mm²)	6.1	

400 MHz/2.4 GHz TRX for dual-band communication





Z. Weng et al., "400-MHz/2.4-GHz Combo WPAN Transceiver IC for Simultaneous Dual-Band CommunicationWith One Single Antenna, " IEEE Trans. Circuit and System-I, vol. 65(2), 2018, pp. 745-757

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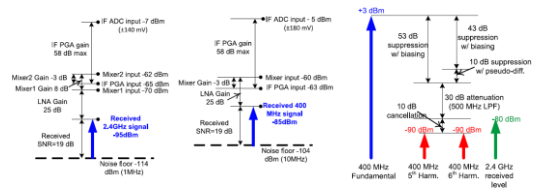
Signal levels and Harmonic Suppression



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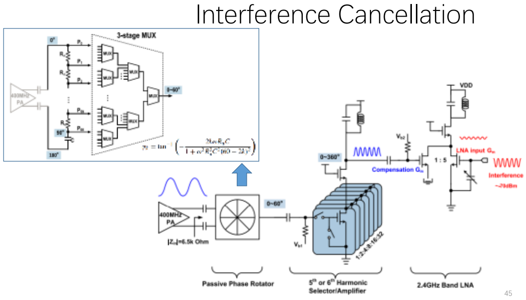
Interference Cancellation



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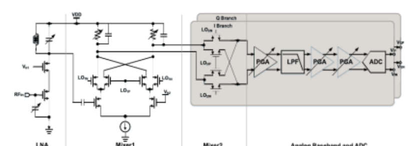
2.4 GHz band RX RF frontend and analog baseband circuit design



RF frontend
- Single-ended cascode LNA
- Gilbert cell based mixer
- Passive quadrature mixer

1st mixer
- LO signal frequency: 4/5 of the desired carrier frequency

I/Q branches
- 2nd mixer: 1/5 of the desired carrier frequency
- Quadrature analog baseband circuits
  - ✓ 3 programmable gain amplifiers
  - ✓ Active-RC 3rd-order Bessel LPF
  - ✓ 8-bit SAR ADC with programmable sampling rate up to 80 Msps

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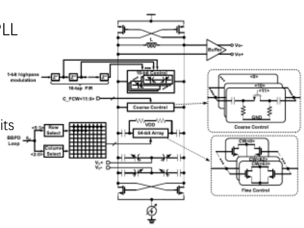
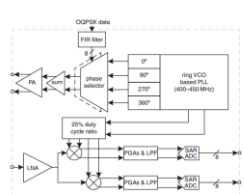
Frequency Synthesizer for 2.4 GHz

A 1.9-2.5 GHz semi-digital Δ-Σ PLL
- •Bang-bang phase detector (BBPD) loop
  - ✓Decreases the integration capacitor
  - ✓Generates 6-bit digital input bits
- •The VCO
  - ✓The analog input VC by PLL
  - ✓ 40 MHz/V VCO gain



47

400 MHz TRX Design



The 400 MHz TX
- 350-500 MHz ring VCO based fractional-N PLL synthesizer
- Digital intensive modulator
  - ✓Inverter-based phase selecter
  - ✓Shaping filter suit for low-power design
- PA

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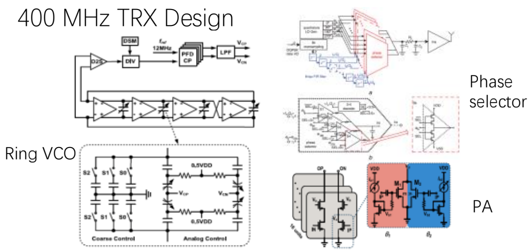
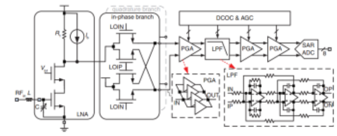
400 MHz TRX Design



H. Jiang et al. "10 Mbps 0.3 nJ/bit OQPSK transceiver IC for 400–450 MHz medical telemetry," Electronics Lett., vol. 52(22), 2016, pp. 1830-1832
Z. Weng et al. "400–450 MHz power amplifier with high-order harmonic suppression for multi-protocol transceiver, " Electronics Lett., vol. 52(23), 2016, pp. 1927-1929

49

400 MHz TRX Design



The 400 MHz RX
- Single-end LNA
- Passive quadrature mixer
- Analog baseband
  - ✓3 PGAs: 4 parallel units, 3 of them can be shut down
  - ✓3rd order LPF (bandwidth programmable between 1.2-5 MHz).
  - ✓DC offset calibration (DCOC) and automatic gain control (AGC) circuits

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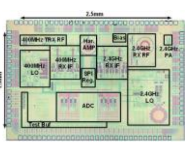
2.4 GHz/400 MHz Dual-band TRX for IMD's



		This work		ISSCC'14 [25]	ISSCC'15 [24]	ISSCC'15 [27]
Dual-band simultaneously operation		Yes		No	No	No
Shared antenna		Yes		No	No	No
Protocol		proprietary	BLE 802.15.4	802.15.6	BLE 802.15.4	BLE
Frequency band	MHz	400-457	2400-2483.5	402-457	2400-2483.5	2400-2483.5
Data rate	Mbps	3-10	1/2/3	0.01-4.5	1/2	1
RX sensitivity @data rate	dBm	-86 @10Mbps	-94 @1Mbps	-93 @562.5kbps	-94 @1Mbps	-94.5 @1Mbps
TX maximum P_{OUT}	dBm	2	1.8	-10	1	0
RX Power Consumption**	mW	3.1	3.3	2.19	3.3	6.3
RX energy efficiency	nJ/bit	0.31	1.1	0.33	1.65	6.3
TX Power Consumption** @ P_{OUT}	mW	2.98 @-15dBm	3.18 @-19dBm	2.28 @-17dBm	4.2 @-2dBm	10.8* @0dBm
TX energy efficiency	nJ/bit	0.298	1.06	0.4	2.1	5.4
Technology	nm	65		40	40	40

M. Vidojkovic *et al., "A 0.33 nJ/b IEEE 802.15.6/proprietary*-MICS/ISM-band transceiver with scalable data-rate from 11 kb/s to 4.5 Mb/s for medical applications," in *ISSCC Dig. Tech. Papers,* Feb. 2014, pp. 170–171.
Y.-H. Liu *et al., "A 3.7 mW-RX 4.4 mW-TX fully integrated Bluetooth* low-energy/IEEE 802.15.4/proprietary SoC with an ADPLL-based fast frequency offset compensation in 40 nm CMOS," in *ISSCC Dig. Tech Papers, Feb. 2015, pp. 236–237.*
T. Sano *et al., "A 6.3 mW BLE transceiver embedded RX* image-rejection filter and TX harmonic-suppression filter reusing onchip matching network," in *ISSCC Dig. Tech. Papers, Feb. 2015,* pp. 240–241.

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The possible application and research directions of the Wireless Transceiver

Case studies

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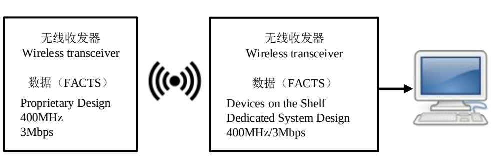
Assuming that we have this transceiver, what can we do to use it for a medical devices?



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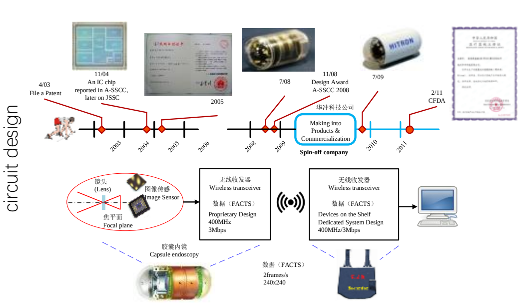
capsule endoscope and integrated circuit design



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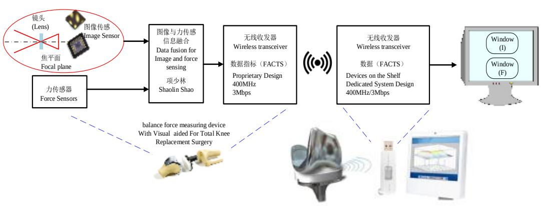
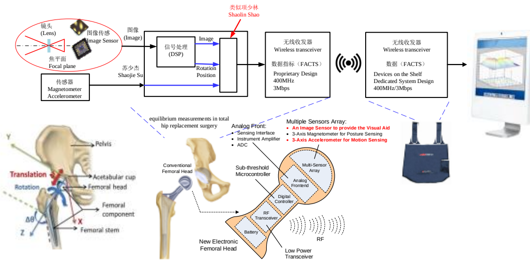
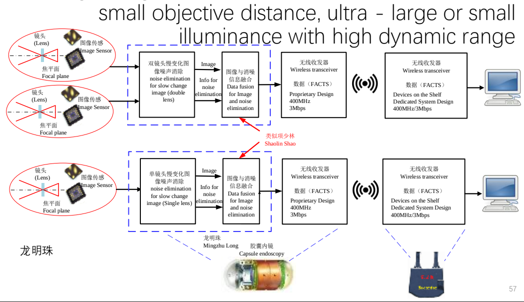
Balance measuring device for total knee replacement operation



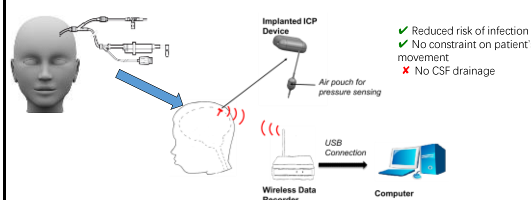
Balance measuring device for hip replacement surgery



range image enhancement under the conditions of small objective distance, ultra－large or small illuminance with high dynamic range

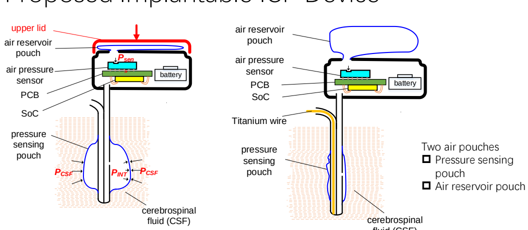


Implantable Intracranial Pressure (ICP) Sensing



- Implantable ICP Device + Wireless Data Recorder + Computer
- Wireless date link: 416 MHz

Proposed Implantable ICP Device

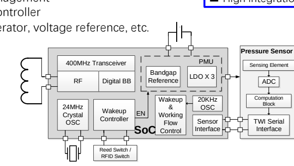


✔ No contact between CSF and sensor– good biocompatibility
✔ No CSF in the tube

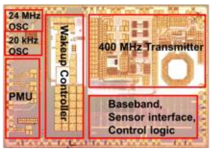
Electronics in the ICP

- The ICP device is composed of an air pressure sensor & a System-on-a-Chip (SoC)
- The SoC has the following function blocks
  - Sensor interface
  - Working flow controller
  - 400 MHz wireless transmitter
  - Power management
  - Wakeup controller
  - Clock generator, voltage reference, etc.

- ☐ Measurement accuracy
- ☐ Low power consumption
- ☐ High integration level



ICP SoC Implementation Result



SoC Die Photo

SoC Performance SUMMARY

Technology	0.18-μm 1P6M CMOS
Die size	3.04 mm x 2 mm
Supply voltage	3V(button batteries)
Off-chip components	6 off-chip capacitors 24MHz crystal oscillator
Logic gates	145k
Current consumption (communication idle)	240 μA
Average power (1 sample/second)	260μA

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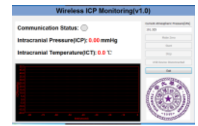
Prototype System of Implantable ICP Sensing

Implantable Device 22x17x8 mm³

Wireless Data Recorder



Computer Software

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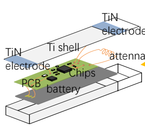
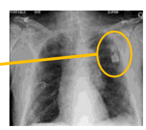
Implantable ECG monitoring system

- Implantable ECG monitor
  - Advantages:
    - Easy for implant operation
      - Small and single incision, subcutaneous insertion
    - Long-time continuous low-noise monitoring
    - Automatic abnormal ECG identification
    - Recording in certain point
- Patient/APP
  - Upload data
  - Start recording while feeling sick
- Doctor/APP
  - ECG data download and analysis
  - Decide parameters for ICM algorithm





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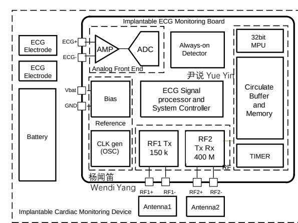
Electronics in the Implantable ECG monitoring system

- The Implantable ECG monitoring device is composed of a System-on-a-Chip (SoC)
- The SoC has the following function blocks
  - 400 MHz wireless transmitter for data communication
  - LF wireless transmitter for instruction communication
  - Analog front end
  - ECG signal processer and system controller
  - CLK management block
  - Power management block
  - Circulate buffer and memory



- ☐ High detection specificity
- ☐ Ultra-low power consumption
- ☐ Small size

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Prototype Implantable ECG monitoring system

- Circuit
  - 400 M TRX chip
  - Commercial chips
- ICM prototype
- PC software
  - Configure & display
- Wireless NFC r/w device

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Wireless Power Transfer for Miniaturized Medical Devices

Wireless power transfer (WPT)

- Advantages
  - Contactless, convenient to use 非接触、方便使用
  - Waterproof, readily used in adverse conditions 防水、适用于恶劣环境
  - Safe, easy to power implant and movable devices… 安全、适用于植入式及移动物体

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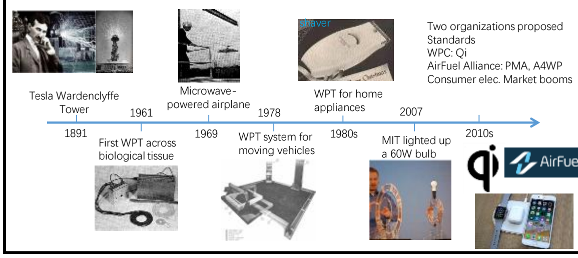
WPT timeline

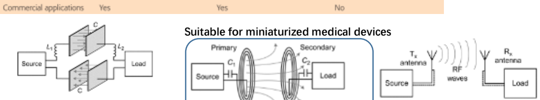


Main WPT mechanism

	NF-WPT		FF-WPT
	Resonant	Nonresonant	
Transmission mechanism	Coupling, no wave propagation	Coupling, no wave propagation	Wave propagation
Interacting device	Coils/electrodes	Coils/electrodes	Antennas
Tx–Rx antenna interaction	Strong interaction	Medium interaction	No interaction
Operating frequency	LF, HF	LF, HF	Microwave, millimeter-wave
Power level	Medium (mW–W), High (kW)	Medium (mW–W), High (kW)	Ultralow (µW–mW) High (MW)
Efficiency	High (70–90%)	Medium (30–60%)	Low (10–50%)
Commercial applications	Yes	Yes	No

A. Costanzo and D. Masotti, "Energizing 5G: Near- and Far-Field Wireless Energy and Data Transfer as an Enabling Technology for the 5G IoT", IEEE Microwave Magazine, vol. 18, no.3, pp. 125-136, May 2017

Suitable for miniaturized medical devices



Electric, capacitive: L1/L2 for resonant, non-resonant without L1/L2

Magnetic, inductive: C1/C2 for resonant, non-resonant without C1/C2

Far-field, waves

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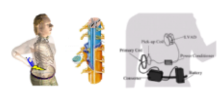
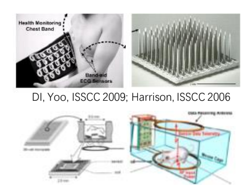
WPT for miniaturized medical devices

- Classified by clinical application 按临床应用分类
  - Diagnostic Instrument (DI) 诊断仪器
  - Treatment Instrument (TI) 治疗仪器
  - Auxiliary Instrument (AI) 辅助仪器



TI, Lin, ISSCC 2010; Ping, TBCAS 2008



DI, Yoo, ISSCC 2009; Harrison, ISSCC 2006

AI, Yazawa, ISSCC 2005; Cong, ISSCC 2009

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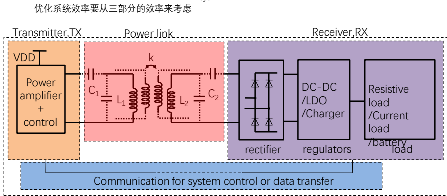
WPT architecture

- A typical WPT system is mainly composed of transmitter, power link and receiver
  通常由能量发射端、耦合部分、接收端组成
- Maximize the system efficiency: $\eta_{sys} = \eta_{TX} * \eta_{link} * \eta_{RX}$
  优化系统效率要从三部分的效率来考虑



A typical WPT system

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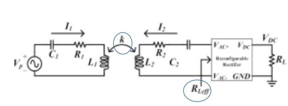
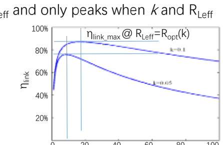
Power link

- 4 basic compensation arrangements for resonance: SS, SP, PS, PP
- Variables in power link
  - Coupling factor (k) variations resulting from variable link distance, link misalignment and orientation angle, etc.
  - Effective resistance (R_{Leff}) variations resulting from loading, receiver efficiency and topo, etc.
- Link efficiency η_{link} depends on k and R_{Leff} and only peaks when k and R_{Leff} match with each other



Power link with SS compensation



Link efficiency versus R_{Leff} for different k

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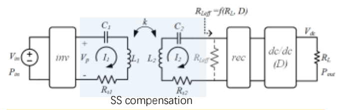
Maximum efficiency tracking in SS compensation



With boost dc/dc:

$$R_{Leff} = 8R_L/\pi^2 \cdot (1-D)^2$$

Theoretical analysis

$$\left.\frac{dD}{dV_{p,rms}}\right|_{opt} \le \frac{\pi}{2\sqrt{2}V_{dc}}\sqrt{\frac{R_{s2}}{R_{s1}}} = \alpha$$

✓ The maximum efficiency can be easily tracked just by measuring V_p and D, without a current or power sensor

X. Tang, J. Zeng, K. P. Pun, S. Mai, C. Zhang, and Z. Wang, "Low-cost Maximum Efficiency Tracking Method for Wireless Power Transfer Systems", *IEEE Trans. on Power Electronics*, vol. 33, no. 6, pp. 5317-5329, 2018.

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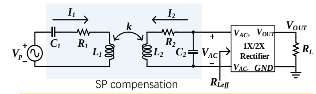
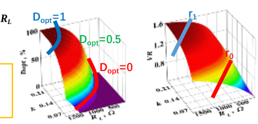
Maximum efficiency tracking in sp compensation





✓ The efficiency can be easily optimized by measuring output voltage ratio in 1X and 2X modes, without a current or power sensor

the optimal duty cycle D_{opt}

$VR = A_{sys,2X}/A_{sys,1X}$, A_{sys} means system voltage gain

G. Zhu, S. Mai, X. Tang, and Z. Wang, "Enhancement Method of Efficiency and Working Range in Bio-Implant Wireless Power Transfer", *IEEE MTT-S WPTC, 2018, invited paper*

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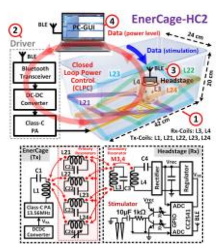
Multiple coils technique

- Include: primary coil(L1) – primary resonators (L2s)– secondary resonator(L3) – secondary coil(L4)
- Novel primary multi-resonator coil design
  - all L2s have strong coupling with L1 by fully overlapping it
  - one or more resonators that are best coupled with the Rx is/are the resonator(s) that transfer power to L3 and L4
  - obviate the need for a tracking system or switching the coils



System architecture

S. A. Mirbozorgi, Y. Jia, D. Canales and M. Ghovanloo, "A Wirelessly-Powered Homecage With Segmented Copper Foils and Closed-Loop Power Control", IEEE Trans. BCAS, 2016

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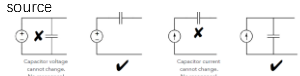
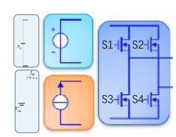
Transmitter design

- Typical circuit: power source+ power amplifier
- Pay attention to basic connection of power source



- Class-D PA is widely used. Carefully design the switch control timing for high transmitter efficiency



power source power amplifier

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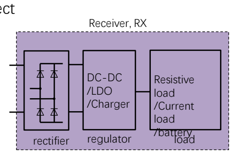
Receiver design

- Typical circuit: rectifier + regulator + load
- The load can be modeled as resistor with filtering capacitor, current source, or battery
- Coupling factor and load variations will affect output voltage
- Objectives: output voltage regulation and high efficiency
  - Transmitter-side controls
  - Receiver-side controls
  - Merge several stages into one stage, etc.



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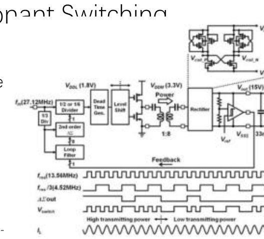
Sub-Harmonic Resonant Switching

- The hysteretic comparator in RX compares output voltage with a reference voltage, and the result is fed back to TX
- In TX, based on the feedback info, PA's switching frequency is controlled as f_{res} or $f_{res}/3$ to deliver different power level
- Output voltage is regulated with the system control



System architecture

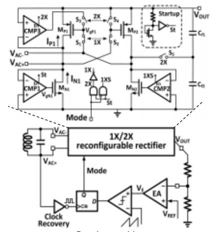
R. Shinoda, K. Tomita, Y. Hasegawa, H. Ishikuro, "Voltage-Boosting Wireless Power Delivery System with Fast Load Tracker by ΔΣ-Modulated Sub-Harmonic Resonant Switching", ISSCC, 2012

78

Reconfigurable Rectifier for SP compensation

- Two modes: it is a full-bridge rectifier in 1X mode and a voltage doubler in 2X mode
- Local PWM loop in RX controls the duty cycle of mode-switching of the rectifier between 1X and 2X
- Suitable for Series-Parallel compensation

X. Li, C.-Y. Tsui, and W.-H. Ki, "A 13.56 MHz Wireless Power Transfer System with Reconfigurable Resonant Regulating Rectifier and Wireless Power Control for Implantable Medical Devices", IEEE JSSC 2015.



Receiver architecture

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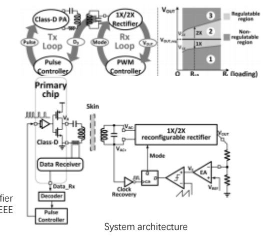
Global control for range extension

- In order to extend the regulatable region, global control was proposed
  - Obtain the mode info in RX and send it back to TX via additional detection coil
  - Adjust the transmitter power in TX based on detected info
- Two novel backscattering uplink techniques were proposed

X. Li, C.-Y. Tsui, and W.-H. Ki, "A 13.56 MHz Wireless Power Transfer System with Reconfigurable Resonant Regulating Rectifier and Wireless Power Control for Implantable Medical Devices", IEEE JSSC 2015.



System architecture

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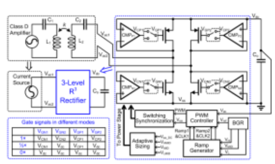
reconfigurable Rectifier for SS compensation

- Three modes: full-bridge rectifier in 1X mode, half-bridge rectifier in ½X mode and no current to load in 0X mode
- Local PWM loop in RX controls the duty cycle of mode-switching of the rectifier between 3 modes
- Suitable for Series-Series compensation



System architecture

L. Cheng, W. H. Ki, T. T. Wong, T. S. Yim, and C. Y. Tsui, "A 6.78MHz 6W Wireless Power Receiver with a 3-Level 1X/½X/0X Reconfigurable Resonant Regulating Rectifier", ISSCC, 2016

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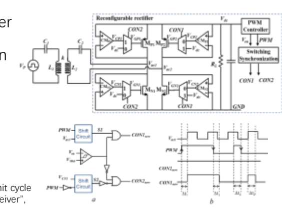
Output voltage ripple reduction

- Based on reconfigurable Rectifier with 1X/½X/0X modes switching
- Reduce the limit cycle oscillation effect
  - Output voltage ripple is reduced
- New switching synchronization method
  - Only one switching edge needs synchronization
  - Realized with a shift circuit

X. Tang, J. Zeng, Y. Zheng, K. N. Leung, and Z. Wang, "Limit cycle oscillation reduction in high-efficiency wireless power receiver", Electronics Letters, 2017



System architecture and proposed method

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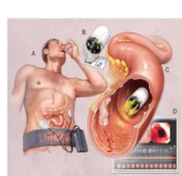
Capsule Endoscopy

- To diagnose gastrointestinal conditions without the need for any sedation
- Advantages: easily swallowed, painless, no harmful radiation, etc.
- Our achievements by Tsinghua group
  - Digital IC design techniques
  - Image enhancement technique
  - Transceiver design techniques
  - Wireless powering techniques
  - Have been applied into industrial production



Capsule Endoscopy

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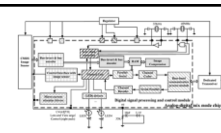
Digital IC design



System diagram in [1]

- Achieved low-power[1]
  - Multi-stage clock management
  - Stoppable ring oscillator
  - New image compression algorithm
  - 8 frames/s, 320*288 pixels, 2MB/s, 6.2mW
- Multiple Cameras for miss rate reduction [2]
  - Master-slave architecture with efficient bus design and 4-level clock management
  - Movement sensitive control and camera selection

Micro-ball prototype in [2]

Data reader in [2]

[1] X. Xie, and Z. Wang etc., "A Low-Power Digital IC Design Inside the Wireless Endoscopic Capsule", IEEE JSSC, 2006
[2] Y. Gu, X. Xie, and Z. Wang etc., "Design of Endoscopic Capsule With Multiple Cameras", IEEE Trans. BCAS, 2015

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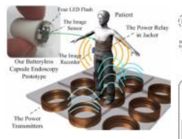
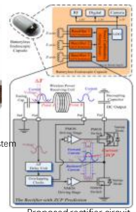
WPT for Endoscopic Capsule

- **Two wirelessly powered system: transfer power from floor and jacket to capsule in digestive track, respectively** [1][2]
- **Proposed a optimization method for loose-coupling**
- **Proposed three power converters and three power management circuits**



Wirelessly powered capsule endoscope system

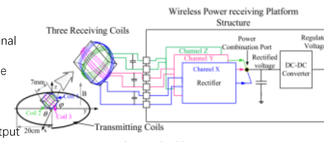


Proposed rectifier circuit

[1] T. Sun, X. Xie, and Z. Wang, etc., "A Two-Hop Wireless Power Transfer System With an Efficiency-Enhanced Power Receiver for Motion-Free Capsule Endoscopy Inspection", IEEE Trans. BCAS, 2012
[2] T. Sun, X. Xie and Z. Wang, "Wireless power transfer for medical microsystems", Springer, ISBN 978-1-4614-7701-3, 2013

Multiple receiving coils

- Proposed a power harvest circuit
  - combine power from three orthogonal receiving coils
  - Derived theoretical expression for the power flow from the transmitter
  - Verified the power combination mechanism
  - Contains three rectifiers and one output capacitor

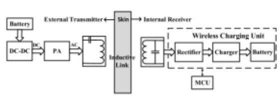


Proposed architecture

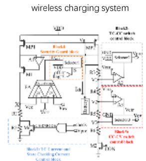
H. Li, G. Li, X. Xie, Y. Huang and Z. Wang, "Omnidirectional Wireless Power Combination Harvest for Wireless Endoscopy", IEEE Conf. BCAS, 2014

Wireless charging

- Proposed a wireless charging unit
  - Consisting of a rectifier and a lithium-ion battery charger
  - designed a dynamic offset-controlled comparator to attenuate multiple pulse
  - proposed a mode-division control method to realize smooth CC to CV transition
  - Use a state-checking operation to ensure the security



wireless charging system



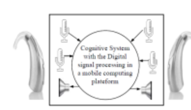
Proposed circuit

Y. Lu, H. Jiang, S. Mai, Z. Wang, "A Wireless Charging Circuit With High Power Efficiency and Security for Implantable Devices", IEEE ISCAS, 2016

Hearing aids

- Approximately 360 million people in the world live with a debilitating hearing loss
- Our group proposed a smart binaural hearing aid system
  - Apply advanced binaural DSP algorithms to the acoustic signals received from both ears
  - Contains a low-power low-delay radio transceiver
  - Real-time DSP software analyzes 4-channel audio signals simultaneously

Hearing aids application

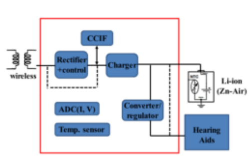


Proposed smart binaural hearing aid

Y. Li, F. Chen, Z. Sun, Z. Weng, X. Tang, H. Jiang and Z. Wang, "System Architecture of a smart binaural hearing aid using a mobile computing platform", IEEE ASICON, 2017

power management unit for hearing aids

- Wirelessly charge the built-in rechargeable batteries and generate voltage for hearing aid devices
- Include a charger communication interface (CCIF) to provide the battery charging info for user interaction
- Rectifier control technique and charging algorithm were proposed for high efficiency



Proposed wireless power management unit

Y. Li, F. Chen, Z. Sun, Z. Weng, X. Tang, H. Jiang and Z. Wang, "System Architecture of a smart binaural hearing aid using a mobile computing platform", IEEE ASICON, 2017

simultaneous power and data transfer

- Several methods for simultaneous power and data transfer
  - RFID: low power level
  - Via extra Wi-Fi or Bluetooth: high cost
  - Through common coil path: pay attention to the crosstalk
- Our group has proposed a new data modulation method in which power and data transfer simultaneously through the common coil path with small crosstalk

Conclusion

The requirements of application are the source of innovation

Long time persistence is the key fact of for success

A picture used by Chris Cloninger (Analog Devices Inc.) in a talk in Tsinghua University, 2008

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