A UWB Wireless Capsule Endoscopy Device

Kasun M.S. Thotahewa, Jean-Michel Redouté and Mehmet Rasit Yuce

***Abstract*— Wireless capsule endoscopy (WCE) presents many advantages over traditional wired endoscopic methods. The performance of WCE devices can be improved using high-frequency communication systems such as Impulse Radio-Ultra-Wideband (IR-UWB) to enable a high data rate transmission with low-power consumption. This paper presents the hardware implementation and experimental evaluation of a WCE device that uses IR-UWB signals in the frequency range of 3.5 GHz to 4.5 GHz to transmit image data from inside the body to a receiver placed outside the body. Key components of the IR-UWB transmitter, such as the narrow pulse generator and up-conversion based RF section are described in detail. This design employs a narrowband receiver in the WCE device to receive a control signal externally in order to control and improve the data transmission from the device in the body. The design and performance of a wideband implantable antenna that operates in the aforementioned frequency range is also described. The operation of the WCE device is demonstrated through a proof-of-concept experiment using meat.**

I. INTRODUCTION

Wireless Capsule Endoscopy (WCE) has many advantages compared to traditional wired endoscopic methods. It does not require sedation of the patient or close monitoring of the procedure by a trained hospital staff. It can potentially be used for remote monitoring of the patients from isolated locations away from hospitals. One of the most important aspects of WCE is that it is the only method of obtaining images of the small intestine, whereas the wired endoscopy devices can only reach the colon or the upper part of the digestive tract [1-3]. Many reported designs for wireless endoscopy system use a narrow-band wireless link in order to transmit image data [3, 4]. Compared to wired endoscopy methods, existing narrowband WCE devices suffer from limited battery life, low frame rate and low resolution [5]. Impulse Radio-Ultra-Wideband (IR-UWB) can be identified as a wireless technology that can cater the demand for high data rate, low power consumption and small form factor requirement in the WCE devices [6-8]. UWB signals are defined as signals having a fractional bandwidth larger than 0.2 or a bandwidth of at least 500 MHz. UWB is allowed to operate in the 0-960 MHz and 3.1-10 GHz bands with the indoor effective isotopic radiated power (EIRP) kept below -41.3 dBm/MHz [9]. IR-UWB signals use short pulses to transmit data. One of the major drawbacks of IR-UWB technology is its receiver complexity [10]. This is mainly due to the low power level of UWB signals and their narrow pulse width. In order to detect low power, narrow IR-UWB pulses, IR-UWB receivers employ power hungry hardware components, such as high speed Analog to Digital Converters (ADC) and high gain Low Noise Amplifiers (LNA), in the front-end circuitry. Synchronization of narrow IR-UWB pulses requires extensive signal processing leading to additional power over heads. These adverse properties of the IR-UWB receivers make them unsuitable for battery powered WCE applications.

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This paper presents the hardware implementation and experimental evaluation of an IR-UWB based WCE device. The WCE device captures video images from a miniature in-body camera and transmits those data to an outside coordinator node. This design uses a dual-band transceiver architecture that employs IR-UWB signals to transmit high-speed image data from the WCE device and a narrowband receiver to receive control messages from the coordinator node. IR-UWB signals occupy the signal band of 3.5 GHz to 4.5 GHz. This signal band is chosen in order to avoid the possible interference from other wireless networks, such as 5 GHz Wi-Fi. The narrowband receiver uses the 433 MHZ Industrial, Scientific and Medical (ISM) band. Use of a narrowband receiver significantly reduces the hardware complexity and signal processing requirements of the WCE device resulting in low power consumption. It also enables simultaneous data transmission and reception capability in the WCE device due to the use of two non-interfering frequencies for data transmission and reception. This paper also describes the design of an implantable wideband antenna used to transmit IR-UWB signals. The narrowband receiver section uses a helix coil antenna to receive 433 MHz ISM band signals. Fig. 1 depicts the basic operation of the proposed WCE communication system.

This paper is organized as follows: Section II presents the design and implementation of key components in the WCE device, such as IR-UWB transmitter, narrowband receiver and implantable antennas. Section III presents the experimental evaluation of the WCE device. Finally, Section IV concludes the paper.

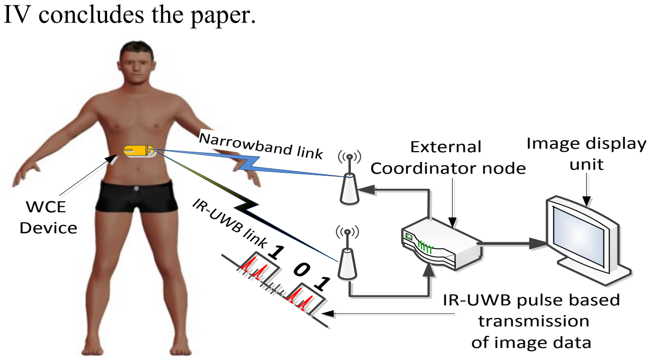

Fig. 1. Proposed WCE communication system.

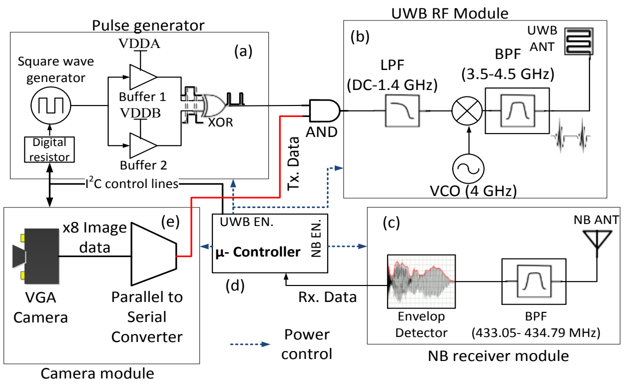

Fig. 2. Key components of the WCE device (a) IR-UWB pulse generator (b) IR-UWB RF section (c) narrowband receiver (d) micro-controller (e) camera module.

II. Hardware Implementation of the WCE Device

The proposed WCE device comprises of several key modules as shown in Fig. 2. IR-UWB transmitter consists of two sub modules: IR-UWB pulse generator and IR-UWB RF section (Fig. 2 (a) and (b)). The IR-UWB pulse generator is responsible for generating a narrow pulse stream in the base band domain.

The narrow pulse stream is generated by passing a periodic square wave and its time delayed version through a XOR gate. The delay circuit of the pulse generator comprises of two identical buffers. The time delay introduced by a buffer to a particular signal path depends on the supply voltage applied to that buffer [11, 12]. Supply voltages of 3 V and 3.3 V are used for the buffer elements in the pulse generator circuit. This results in a narrow base band pulse stream with a pulse width of 2 ns. A pulse width of 2 ns is sufficient to create a pulse stream with a spectrum that covers the intended bandwidth of 3.5 GHz – 4.5 GHz after the up-conversion stage in the UWB RF module [13]. The reference square wave signal that is fed in to the delay circuit is generated using a programmable square wave oscillator. The time period of this signal can be programmed using the micro-controller module through Inter-Integrated Circuit (I^2C) communication. Hence, the Pulse Repetition Frequency (PRF) of the output pulse stream can be varied according to the control messages received by the narrowband receiver module of the WCE device. The pulse generator is capable of generating pulses up to a PRF of 100 MHz.

The base band pulse stream is modulated by the image data bits originating from the camera module using a high speed AND gate. On-Off-Keying (OOK) is used as the modulation scheme for data transmitted on the IR-UWB channel due to its simplicity and low processing power requirement. The amplitude of the data modulated pulse stream can be controlled by varying the supply voltage of the AND gate. This property is used in this design to control the peak spectral amplitude of the output pulse stream. The WCE device presented in this paper is designed to use a higher spectral power than the FCC regulated spectral mask of -41.3 dBm/MHz for UWB signals [14, 15] while still meeting the safety requirements. A peak spectral amplitude of -25 dBm/MHz is used for the experiments presented in this paper. The received image quality highly depends on the transmit power level of the UWB signal. Higher transmit power levels results in lower bit error rates that lead to higher image quality. Modulated pulse stream is then fed into the UWB RF module, where a Low Pass Filter (LPF) with a cut-of bandwidth of 1.4 GHz is used to filter out the base band portion of the signal spectrum. The filtered pulse stream is then up-converted using a mixer and a Voltage Controlled Oscillator (VCO) operating at 4 GHz. The up-converted pulse stream is passed through a Band Pass Filter (BPF) with a pass band of 3.5 GHz to 4.5 GHz in order to ensure that the output pulse stream is contained within the intended bandwidth. Fig. 3 depicts the UWB pulse stream (with a PRF of 100 MHz) emitted by the UWB transmitter module and it's transmit spectrum.

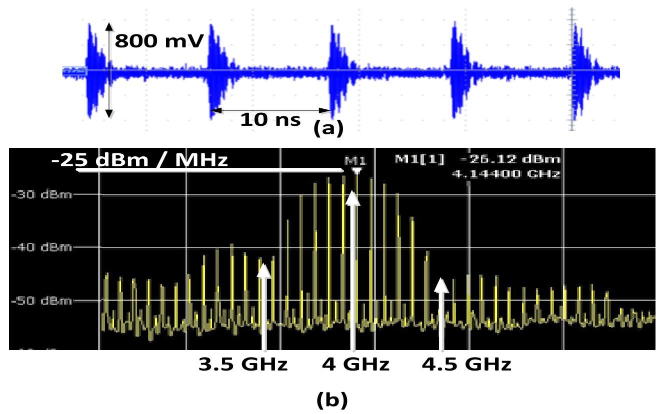

Fig. 3. (a) Output IR-UWB pulse stream (b) IR-UWB transmit spectrum.

The narrowband receiver in the WCE device uses *RX5500,* which is a 433 MHz ISM band amplifier sequenced hybrid receiver chip by RFM [16]. The receiver chip is set to operate using ASK modulation with low power mode. Under these conditions, the narrowband receiver operates with a power consumption of 5 mW. The power overhead introduced by this addition is much lower than using an IR-UWB receiver.

The micro-controller module acts as the central controller of the WCE device. *PIC18F14K22* micro-controller is used in the WCE device because of its low power consumption and the ability to operate with very few external components [17]. It can control power to all the other modules of the WCE device allowing optimized power consumption. It also communicates with the camera module using I^2C communication in order to issue various setting commands, such as image resolution and signaling format. Additionally, the micro-controller controls the operation of the Light Emitting Diodes (LED) in the camera module. Two LEDs are turned on only when the camera is acquiring images in order to preserve power.

The camera module (TCM8230MD by Toshiba) provides 8-bit parallel image data in an RGB format. It can operate in several video resolution formats, such as VGA (resolution of 640×480) and QVGA (resolution of 320×240). The 8-bit parallel data generated by the camera is converted in to a serial bit stream using a high speed parallel to serial converter and directly modulated with the IR-UWB pulse stream.

The implantable UWB antenna plays an important role in providing a feasible communication link for high frequency IR-UWB signals within the in-body communication environment. This antenna model is a further miniaturized version of our previous antenna models [15, 18]. The wide-slot antenna design with a U-shaped feed forms a magnetic dipole, which is less susceptible to variations in the near field propagation environment. Use of an insulating material with an approximate relative permittivity to the surrounding tissue materials facilitates efficient transfer of electromagnetic signals between the antenna-transmitting element and the tissue medium [14,15,18, 19].The antenna is immersed in a glycerin based gel medium, which has a relative permittivity value of 50. The glycerin based gel forms a non-flowing insulating medium at the bottom part of the WCE capsule. Rogers TMM 10i with a dielectric constant of 9.8 is used as the substrate material for the antenna. The antenna is 11.85 mm in height, 9 mm in width and has a thickness of 1.27 mm. Fig. 4 depicts the modelled UWB antenna immersed in the glycerin based gel medium together with its fabricated prototype and dimensions.

A helical coil antenna (Fig. 6 (e)) is used for the 433MHz ISM band signal. The antenna is constructed using a copper wire with a diameter of 0.7 mm. The helix has a diameter of 16 mm, a pitch of 1mm and seven turns. The antenna coil is attached to the inner wall of the WCE capsule using an adhesive material. The antenna operation frequency for the narrow band antenna can be manually adjusted by changing the height of the antenna until it provides an optimum performance in the operating environment. Fig. 5 shows the S-parameters for both wideband and narrowband antennas implanted in supermarket pork.

Fig. 6 depicts the main components of the WCE device All the circuits are fabricated in four layer circular Printed Circuit Boards (PCB) with a diameter of 15 mm. Individual modules are placed inside a thin walled plastic capsule with an internal diameter of 16 mm and a length of 30 mm according to the arrangement depicted in Fig. 7. A transparent opening at the front of the capsule allows the camera to capture images. Camera board and narrowband/ micro-controller board are attached using a stack-up board connector as shown in Fig. 7. UWB transmitter board is connected to the narrowband and control board using a flexible cable.

III. Experimental Evaluation of the WCE Device

The WCE device communicates with an external coordinator node; its main operational blocks are shown in Fig. 8. A data rate of 10 Mbps is configured with the PRF of 100 MHz. Thus, the communication system uses multiple pulses to represent a data bit and dynamic Bit Error Rate (BER) control [11, 12], in order to achieve a reliable two-way communication link between the WCE device and the coordinator node. The WCE device is capable of transmitting image data up to a frame rate of 20 fps. The coordinator node can choose the resolution of the received images using the narrowband communication link.

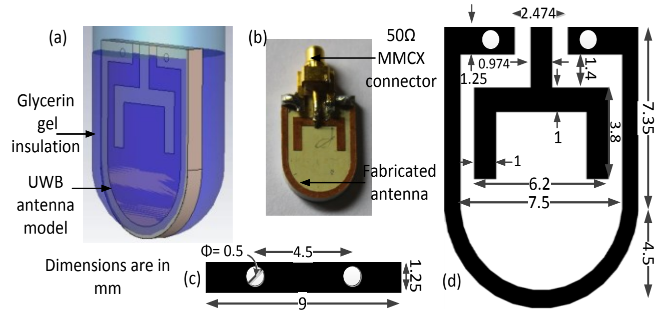

Fig. 4. (a) Antenna model inserted in glycerin-based gel (b) fabricated UWB antenna (c) UWB antenna bottom side (d) UWB antenna top side.

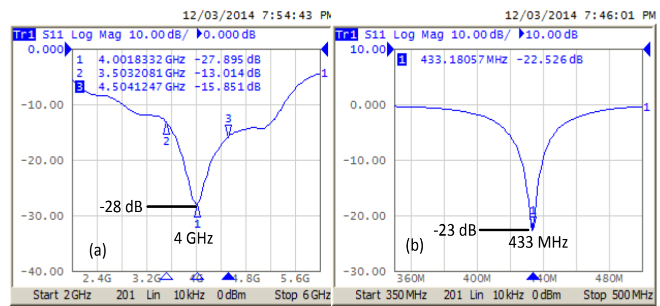

Fig. 5. S-parameters (a) implanted UWB antenna with glycerin insulation (b) implanted narrowband helix antenna.

Fig. 9 (a) depicts the laboratory set up used for the proof-of-concept experiments. In order to simulate the in-body communication environment, the WCE device is completely wrapped in the pork meat. During the experiments, it was observed that an IR-UWB signal with a peak spectral amplitude of -25 dBm/MHz was sufficient to be detected at the UWB receiver (in the coordinator node). The receiver is placed 5cm away from the meat. The received images are stored in a memory card attached to the FPGA module. Fig. 9 (b) shows an example image with a resolution of 640×480 obtained using the proposed UWB WCE device. Table I presents the maximum power consumption figures for the main modules of the WCE device.

IV. Conclusion

This paper presents the implementation and evaluation of an IR-UWB based WCE device. The WCE device provides significant advantages in terms of low power consumption and high data rate communication link. The WCE device is evaluated in a proof-of-concept experiment using a sample of meat. It is capable of transmitting images with a resolution of 640×480 at a frame rate of 20 fps. It was observed that the WCE device consumes a total maximum power of 57 mW under continuous operation including lighting sources (LEDs).

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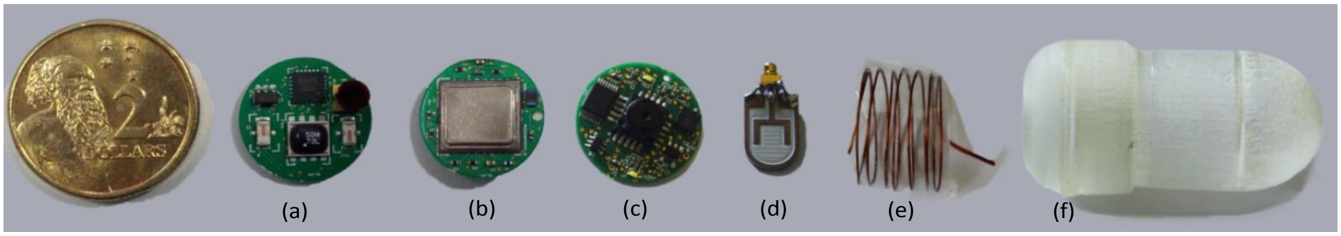

Fig. 6. (a) UWB board (b) narrowband and micro-controller board (c) camera board (d) UWB antenna (e) narrowband antenna (f) prototype capsule.

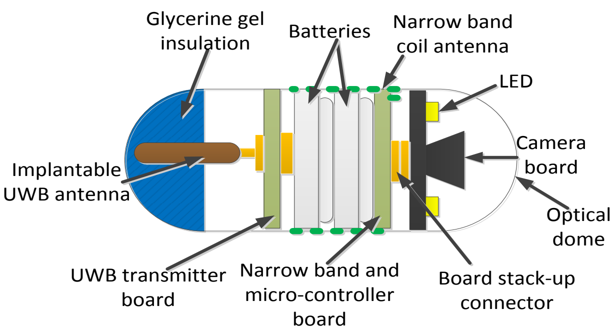

Fig. 7. Positioning of key modules inside the WCE device.

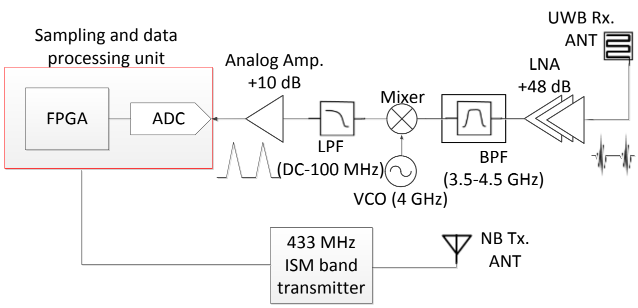

Fig. 8. Block diagram of the coordinator node.

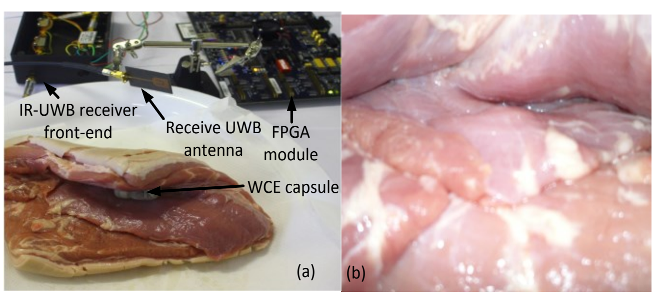

Fig. 9. (a) Experimental set up for evaluation of the WCE device (b) an image obtained using the WCE device.

Table I POWER CONSUMPTION FIGURES.

UWB transmitter	Narrowband Receiver	Micro-controller	Camera board (with LEDs)	Total
4 mW	5 mW	10 mW	38 mW	57 mW

REFERENCES

[1] A. Moglia, A. Menciassi, M. O. Schurr, and P. Dario, "Wireless capsule endoscopy: from diagnostic devices to multipurpose robotic systems", *Biomedical Microdevices*, vol. 9, no. 2, pp. 235-243, April 2007.

[2] J. L. Toennies, G. Tortora, M. Simi, P. Valdastri, and R. J. Webster, "Swallowable medical devices for diagnosis and surgery: the state of the art", *IMechE Proceedings*, vol.224, no.7, pp.1397-1414, 2010.

[3] X. Chen, X. Zhang, L. Zhang, X.W. Li, N. Qi, H. Jiang, and Z. Wang, "A Wireless Capsule Endoscope System With Low-Power Controlling and Processing ASIC," *IEEE Transactions on Biomedical Circuits and Systems*, vol.3, no.1, pp.11-22, Feb. 2009.

[4] L. Dung, Y. Wu, "A Wireless Narrowband Imaging Chip for Capsule Endoscope," *IEEE Transactions on Biomedical Circuits and Systems*, vol.4, no.6, pp.462-468, Dec. 2010.

[5] G. Pan, and L. Wang, "Swallowable Wireless Capsule Endoscopy: Progress and Technical Challenges," *Gastroenterology Research and Practice*, vol. 2012, Article ID 841691, 9 pages, 2012.

[6] Y. Gao, Y. Zheng, S. Diao, W. Toh, C. Ang, M. Je, and C. Heng; , "Low-Power Ultrawideband Wireless Telemetry Transceiver for Medical Sensor Applications," *IEEE Transactions on Biomedical Engineering*, , vol.58, no.3, pp.768-772, March 2011.

[7] M. R. Yuce, and T. Dissanayake, "Easy-to-swallow wireless telemetry," *IEEE Microwave Magazine*, vol. 13, pp. 90-101, September-October 2012.

[8] D. Anzai, K. Katsu, R. Chavez-Santiago, Q. Wang, D. Plettemeier, J. Wang, and I. Balasingham, "Experimental Evaluation of Implant UWB-IR Transmission with Living Animal for Body Area Networks," *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, pp. 183-192, 2014.

[9] FCC 02-48 (UWB First Report and Order), 2002.

[10] A. Gupta, and P. Mohapatra, A survey on ultra wide band medium access control schemes, *Computer Networks*, Volume 51, Issue 11, pp. 2976-2993, 8 August 2007.

[11] K. M. Thotahewa, J-M. Redoute and M. R. Yuce, "Implementation of a dual band body sensor node, "IEEE MTT-S International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications**,** Singapore, 2014.

[12] M. R. Yuce, K. M. Thotahewa, J-M. Redoute, Ho Chee Keong, "Development of low-power UWB body sensors," *IEEE International Symposium on Communications and Information Technologies* (ISCIT), pp. 143-148, October 2012.

[13] J. Colli-Vignarelli and C. Dehollain, "A discrete-components impulse-radio ultrawide-band (IR-UWB) transmitter," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, pp. 1141-1146, 2011.

[14] K. M. Thotahewa, J-M. Redoute and M. R. Yuce, "Electromagnetic power absorption of the human abdomen from IR-UWB based wireless capsule endoscopy devices, *IEEE International Conference on Ultra-Wide Band* (ICUWB), Sydney, Australia, Sept. 2013.

[15] K. M. Thotahewa, J-M, Redoute, and M. R. Yuce, "SAR, SA and temperature variation in the human head caused by IR-UWB implants operating at 4 GHz," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, pp. 2161-2169, May 2013.

[16] http://www.rfm.com, 2014.

[17] http://www.microchip.com, 2014.

[18] T. Dissanayake, K. P. Esselle , M. R. Yuce, " Dielectric loaded impedance matching for wideband implanted antennas," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, Part 2, pp. 2480-2487, October 2009.

[19] T. Dissanayake, M. R. Yuce and Ho Chee Keong, "Design and Evaluation of a Compact Antenna for Implant-to-Air UWB Communication," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp.153 - 156, 2009.