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RESEARCH ARTICLE

Analog Backscatter Video Transmission for Wireless Capsule Endoscope

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ABSTRACT Wireless capsule endoscopy is a fast-growing technology in healthcare systems. Due to using battery for powering the camera, light source, wireless communication, and other electronics, it has substantial limitations with the image quality, frame rate, and operating time. In this work, we propose a wireless passive video transmission system for capsule endoscopy, in which the power consumption is reduced by using analog camera sensor, and implementing an innovative radar technique for remote reading of the analog video signal using radio frequency backscattering. The power consumption of the capsule communication system tends to zero. The communication electronics system is minimized to a single Varactor diode with appropriate matching circuits and the image sensor power consumption is reduced by eliminating the camera sensor's analog to digital converter. With these improvements the capsule system can operate for a longer period of time which enables the feasibility of continuous video streaming during the gastric tract screening. The design feasibility is demonstrated in a phantom experiment, and validated in an animal experiment for depths 6-11 cm using a bi-static radar system at 400 MHz, implemented using software defined radio platform.

INDEX TERMS Analog backscatter, battery-free video streaming, passive wireless communication, remote healthcare, wireless capsule endoscopy.

I. INTRODUCTION

Remote healthcare monitoring systems are changing diagnosis methods in many areas. These opportunities are because of enormous progress in miniaturizing, developing low-power electronics,and progress in information and communication technology. The established technique for visual diagnosing the gastric tract is by using the wired endoscopy or colonoscopy cameras that make an unpleasant experience for the patients, while being limited to the gastric tract's upper (stomach) and lower parts (colon). Wireless capsule endoscopy (WCE) is an approach to eliminate wire-related problems in conventional gastric diagnosing and to reduce the cost of such screening. The hardware of WCE mainly consists of a camera sensor for imaging, a light source, a wireless communication link for transferring the recorded camera data, a power supply, and a power management unit. In swallowable WCE, the image and video signal is transmitted wirelessly to an off-body device that stores the received data. The process, from swallowing the capsule to excretion, takes 8-12 hours. During this timeline, the image or video from different parts of the digestive system is taken and transmitted to the on-body receiver. A medical care center may be able to monitor or process the recorded imaging data to detect possible anomalies.

Efficient energy use in WCE is essential because of the capsule's limited battery supply and long operating time. The high data rate wireless transmission of the recorded data to

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an off-body system is power-consuming and can deplete the battery quickly. The current FDA-approved WCE systems use active RF transmission for communication. For instance, Medtronic PillCams use active RF transmitters with MSK modulation at 434.1 MHz frequency band [1]. The frame rate for this capsule is 2-6 f/s. Using RF communication is a straightforward solution for WCE because of the technological development and commercially available electronics. However, the system power efficiency is low, especially in the high-frequency bands in which the communication subsystems such as local oscillators, frequency synthesizers, and power amplifiers consume considerable energy.

For improving the power efficiency of the wireless communication in WCE several works have been done. In [2] a high data rate wireless link has been suggested using low-frequency signaling known as human-body communication (HBC), where the communication system power consumption is 3.2 mW utilizing a frequency of 16 MHz and a data rate of 6 Mbps. Wireless backscatter is another approach for saving the power consumption of the implant. This method has been implemented in low-data rate applications, mainly in RFID systems, where a reader system sends a tone signal to the battery-limited side; the tag electronics modulate the antenna impedance, which is sensed at the reader to extract data. Wireless backscatter is gaining attraction in biomedical implants, mainly for low data rate applications such as ECG signal monitoring or temperature monitoring of an organ [3]. The first demonstration of high data rate (more than 8 Mbps) backscatter communication for video signal streaming from a gastric capsule has been shown by the authors [4], [5], [6].

Although backscatter communication is a promising approach for eliminating the required energy for WCE, there are a few limitations such as: 1) the communication link faces round way path loss in the forward and backward, causing poor link quality, 2) the capsule antenna is small and suffers from a poor efficiency with low radar cross section (RCS), 3) large differential RCS must be created by the load switching to gain in communication link quality, 4) the channel and system nonlinearity cause inter-symbol interference that complicates the receiver for high data rates (above 20 Mbps), 5) the coupling between transmitter and receiver at the reader rise the signal to noise-interference ratio (SNIR) which decreases the sensitivity of the receiver. Although digital cameras have significant advantages in image quality, using analog-to-digital converters (ADC) limit power saving; thus, digital image sensor consumes a considerable amount of power. Therefore, limited quality, frame rate, and operation time are expected. Analog cameras have an advantage in terms of power consumption over the digital system that can be integrated with the backscatter system. In [7], a new approach for using free-space backscatter for streaming the analog raw pixel values has been presented, where the integrated ADC has been eliminated from the sensor; however, they use digital backscatter technique by converting the analog video signals to pulse wave modulation (PWM) signals.

In this paper, we target removing most parts of the power-hungry subsystems in the WCE. We implement a fully analog backscatter technique scheme for communication, where an analog camera is used. The analog output continuously loads a reverse-biased Varactor diode that constantly alters the capsule antenna RCS. The communication system is external to the body and can sense the capsule's analog signal using the designed analog backscatter reader implemented with software-defined radio (SDR).

II. SYSTEM DESIGN

Fig. 1 shows the overall view of the implemented system. It includes a mock-up capsule with a camera sensor and a remote wireless reader system for transmitting energy to the capsule and receiving the wave reflections from the capsule antenna for video recovery. We have integrated a wideband antenna in the form of two metal rings in both ends of the cylinder capsule [8]. The rings are not in direct contact with the physiological medium but have a small gap of 0.5 mm to create higher efficiency at the reader frequency. The antenna electrodes are connected to a variable capacitor which is controlled by the camera output voltage. The external reader system uses two antennas to realize a bi-static continuous wave (CW) radar. The reader antennas are two dipoles loaded

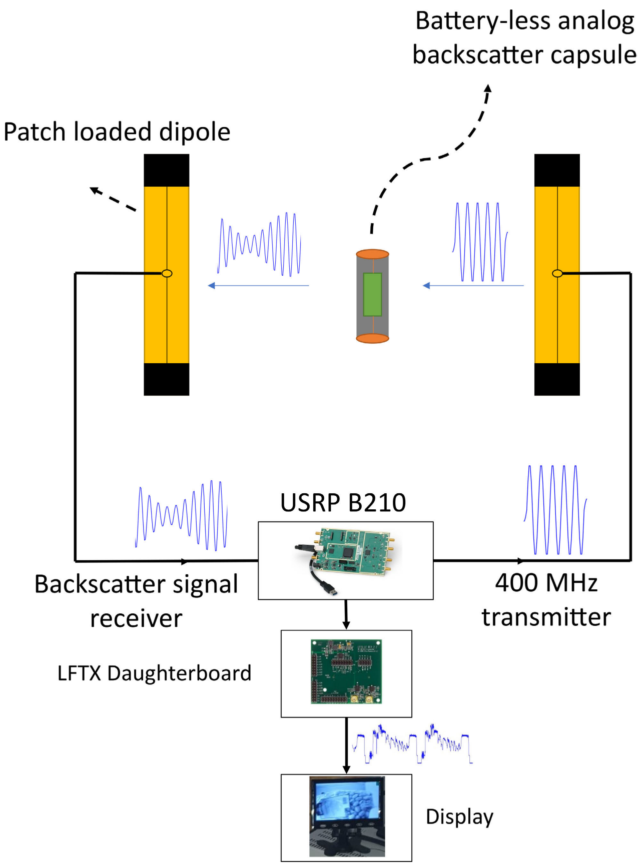

FIGURE 1. Block diagram of the proposed system. The battery-free capsule modulates 400 MHz carrier signal with NTSC video signal and the reader receives the backscattered signal to extract analog video signal.

with square patches at both ends [8]. The patches are placed on the body with a gap of 1 mm and can couple maximum RF energy to the subsequent tissues. We use the two dipoles in parallel with a separation distance of 10 cm to reduce the mutual coupling by 30 dB. The backscatter transceiver is developed using SDR (USRP B210); the transmitter emits a tunable level single-tone carrier at 400 MHz, while the receiver detects the reflections from the capsule to extract the baseband signal variations. The baseband signal is processed using FPGA of a second SDR (USRP N210) to convert the received video to a readable analog format for real-time monitoring of the video on a screen.

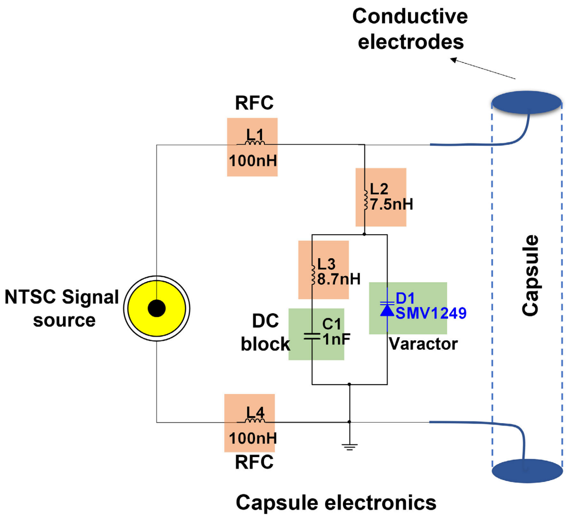

FIGURE 2. Battery-free video modulator schematic circuit. L1 and L2 act as RFC in 400 MHz in order to block RF leakage to the baseband signal path but allows NTSC signal to pass. C1 acts as a DC block to avoid low frequency short circuit of NTSC signal source to the ground.

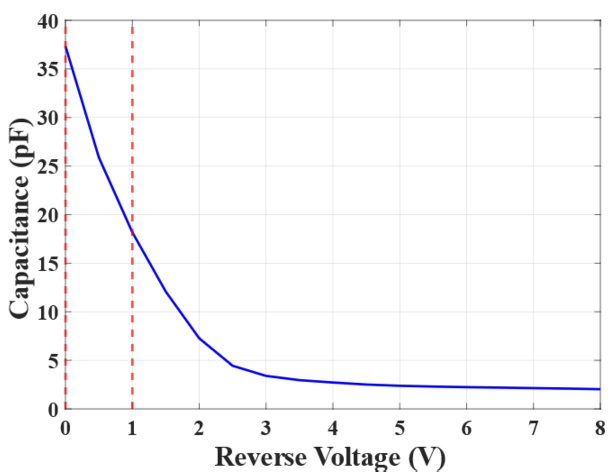

FIGURE 3. Capacitance variation of Varactor for different input reverse voltage. Maximum variation is in the voltage range of 0 – 1 V.

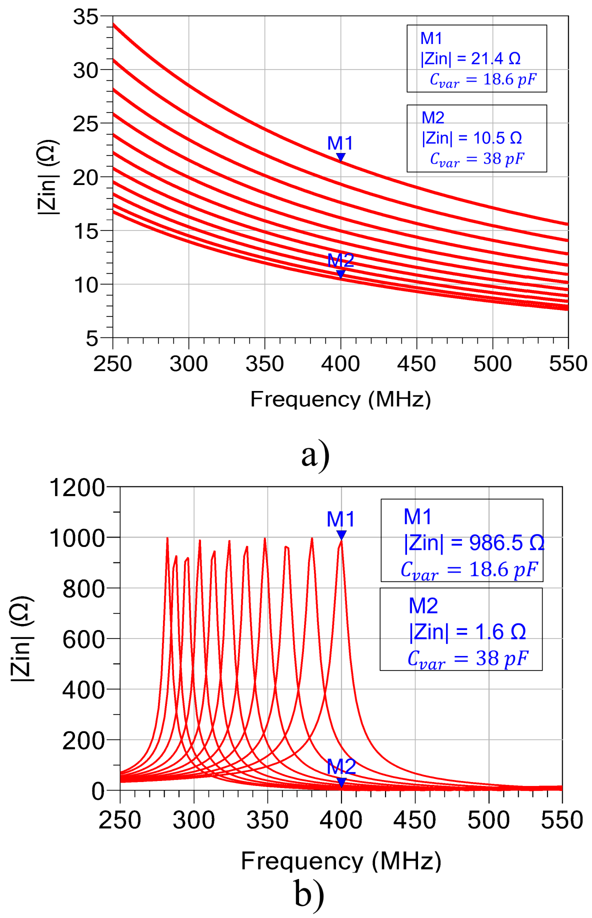

FIGURE 4. a) Impedance variation of the modulator circuit based on Varactor capacitance value, b) impedance variation after adding the resonance circuits to Varactor to increase the variation in order to improve the backscatter signal.

A. CAPSULE DESIGN

The available backscatter systems are based on the digital waveform and switching among multiple load impedance that increase the system bandwidth and have higher power consumption, which would not be appropriate for devices with significant power constraints. Our wireless backscatter system implements an analog approach, where continuous variations of the capsule antenna load are translated to successive RF reflections from the antenna that is observed as ΔRCS. The variations of ΔRCS should be a linear function of the applied source voltage or the antenna load variations, to reduce the backscatter signal distortion and preserve the transmitted waveform for optimum image reception. To realize analog backscatter, we use a Varactor diode in the reverse bias that performs as a variable capacitor, in which the diode capacitance is altered according to the camera's applied voltage. Fig.2 shows the schematic of the modulator circuits. The two plates show the electrodes that are used in the capsule device. We note that the capsule antenna is not in the resonance mode but has acceptable impedance changes by loading the antenna with the surrounded medium [8]. The diode modulator is fully passive and does not need any battery source. It consists of inductors and capacitors that set the diode's working point at the linear region and isolate the applied baseband signal from the external RF signals (see Fig. 2). The analog output voltage from the camera is applied to the Varactor diode, which changes the diode's capacitor proportional to the applied voltage from the camera. For an applied input voltage, maximum capacitance variation is required to maximize the antenna reflections because of the higher impedance variation. A low tuning voltage, and high capacitance ratio diode is selected for this purpose. In Fig. 3, the capacitance variation of the chosen diode (SMV1249) versus applied reverse voltage is depicted.

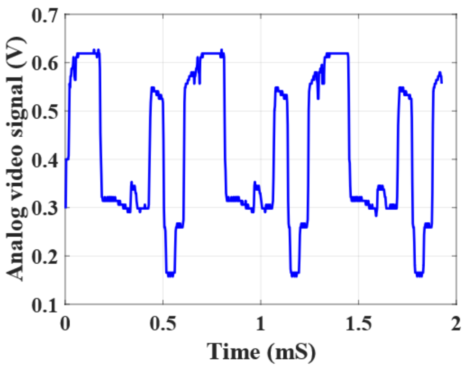

FIGURE 5. Recorded NTSC signal in time-domain used for emulating video signal for experimental measurements.

The camera output signal has standard NTSC format with the output voltage range of 0-1 V, as shown in Fig. 5. The diode capacitance variation is highest in the applied voltage range of 0-1 volt (see Fig. 3). The circuit is simulated in Advance Design System (ADS), KeysightB., to extract accurate impedance mismatch of the circuit at 400 MHz reader frequency. To maximize the impedance mismatch with the applied voltage for maximum backscatter, we have added L2 and L3 inductors to the diode circuit. The inductor L3 makes a parallel LC resonance with the Varactor, and L2 makes a series LC resonance with the diode. We ensure the maximum impedance variation at 400 MHz by using these two series and parallel LCs. As shown in Fig. 4, in the series resonance, the impedance is close to zero, and in the parallel resonance, the impedance is almost open. So considering the input voltage range of 0 – 1 V, the impedance of the circuit changes between almost zero (short circuit) and infinite (open circuit). As shown in Fig. 4, the impedance variation has improved by adding the series and parallel LC circuits to produce a backscatter signal. For the input signal in the range of 0 - 1 V, the diode capacitance changes from 38 pF to 18.6 pF, with this capacitance variation base on Fig. 4-a, the impedance changes from 21.4 Ω to 10.5 Ω. The impedance variation ratio is about two. By adding parallel and series LC resonance circuits, as shown in Fig. 4-b, the same input signal range, the impedance variation is within the range of 1.6 – 986.5 Ω. In this case, the impedance variation ratio is 617, which is improved significantly and results in higher modulation depth.

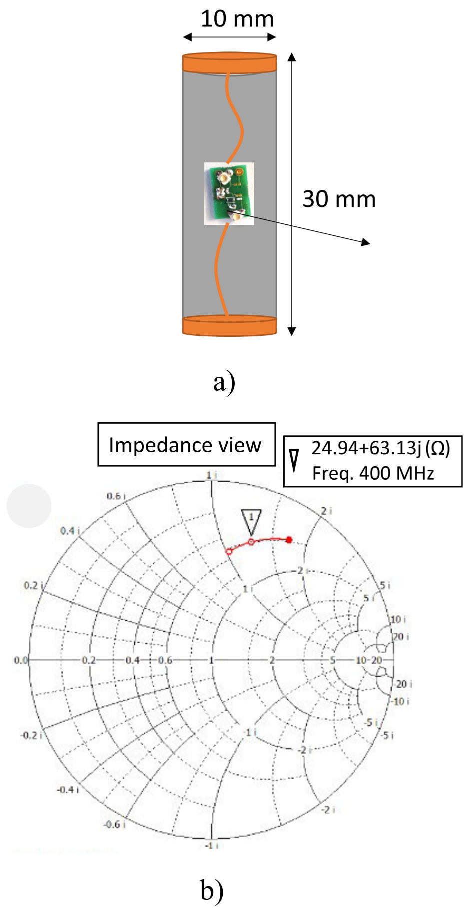

FIGURE 6. Impedance simulation of the capsule in CST, a) capsule geometry, b) simulation result of the capsule impedance.

Figure 5 shows the time domain signal of NTSC standard, which is used to drive the capsule's modulator. A recorded version of NTSC signal is used during the lab experiment to realize a bench-top test and assess the modulator and the communication link performance.

The modulator is connected to a pair of electrodes, as shown in Fig. 6-a. The capsule length is 28 mm with a diameter of 7 mm. The capsule antenna is simulated using numerical electromagnetic techniques in FDTD, considering a sample muscle tissue as the antenna surrounding. Fig.6-b shows the impedance graph of the embedded antenna. The muscle material properties of complex permittivity are used for computations using CST Microwave Studio. As shown, the capsule has the impedance Z = 24.94 + 63.13j, where the resistive part is due to the antenna loading with the conductive medium.

B. READER SYSTEM

We use an on-body transceiver system to transmit the carrier signal for the backscatter communication, and process the received signal for video recovery. The reader consists of a pair of conductive electrode patches for transmission and reception [8]. The transceiver is realized using SDR B210. In Fig. 7, the block diagram of the on-body setup is shown.

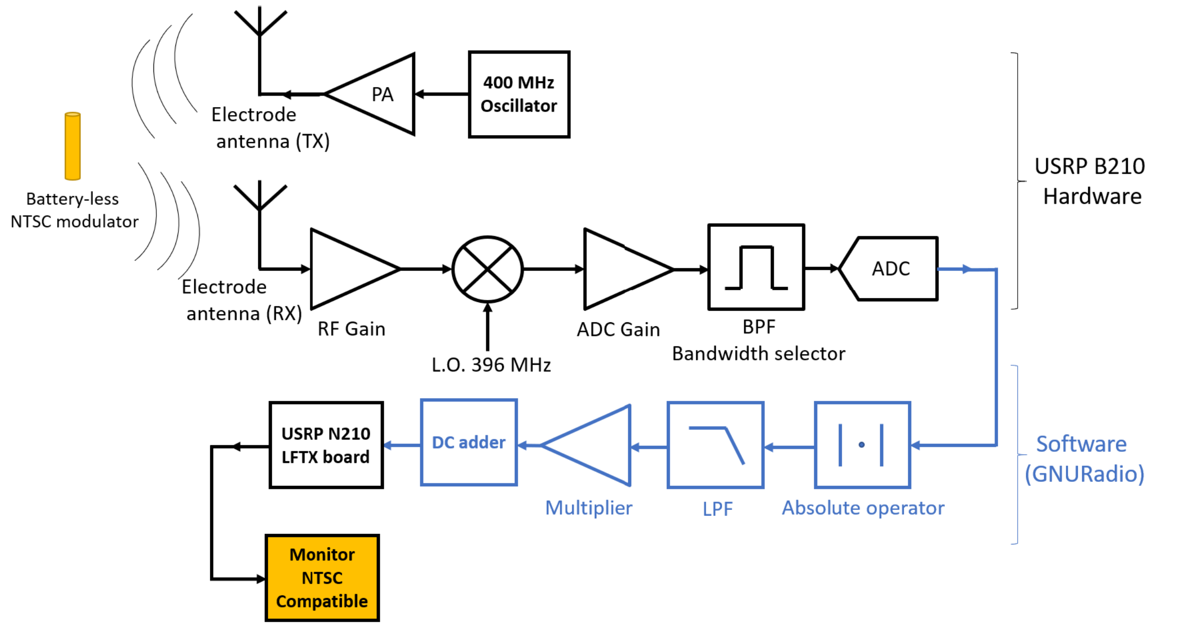

FIGURE 7. Block diagram of on-body system. Hardware based tasks are colored black and software-based units are colored blue.

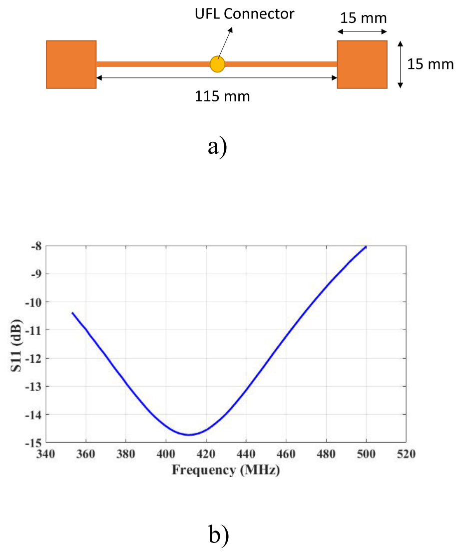

FIGURE 8. Return loss simulation of the antenna in CST.

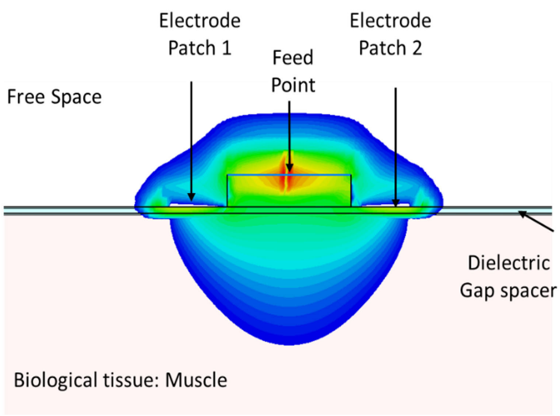

FIGURE 9. Electric field simulation of the patch antenna.

The transmitter is programmed to generate a single tone at 400 MHz that is fed to the transmitter antenna. The SDR gain is adjusted to generate power level of 10 dBm. The receiver uses the second dipole antenna connected to the front end. The receiver includes a low-noise amplifier and down-conversion using a mixer. The mixer's local frequency (LO) block uses the same reference source for the transmitter, so the phase variations are the same, and the down-converted signal is stable. The major challenge with zero-IF reception is the coupling and leakage from the transmitter via the antennas, which can saturate the AGC amplifier at the receiver and limit the ADC's dynamic range. To reduce the effect, the local oscillator for down-conversion is programmed to 396 MHz instead of the transmitted 400 MHz. By this frequency shift, the received signal is shifted to 4 MHz instead of zero. With this intermediate frequency (IF), we avoid DC saturation in the receiver before the ADC conversion because of substantial interference from the transmitter side. The ADC used in the receiver has a 12-bit resolution. The backscattered signal appears as an amplitude-modulated signal in the receiver baseband. For demodulating and decoding the video signal, we use an asynchronous structure. An absolute operator is used to down-convert the video signal from 4 MHz IF frequency. A low pass filter is applied after the absolute operation to remove the high-frequency elements due to the nonlinear behavior of the absolute operator. Once the decoded NTSC video signal is obtained, we have to apply several pre-processing tasks to make it compatible to show on a standard screen. A multiplier is used to increase the NTSC signal level, followed by a level shifter block to adjust the DC level of the NTSC signal. Finally, for connecting the decoded NTSC signal to the screen, an FPGA board with 12 bit DAC is used to generate the appropriate standard NTSC analog format. In the measurement process, the mutual coupling between the external antennas should be kept as minimum as possible to increase the ADC dynamic range. For this purpose, the antennas are separated with a spacing of 10 cm to keep the mutual coupling below -30 dB. Fig. 9 shows the simulated field inside a sample muscle tissue. The field intensity is focused at the center of the dipole between the patches. The E-field decays with the distance from the surface. The dipole and the patch sizes are selected and optimized that can provide optimum matching and field intensity in a distance of 10-15 cm that is our target inside the body.

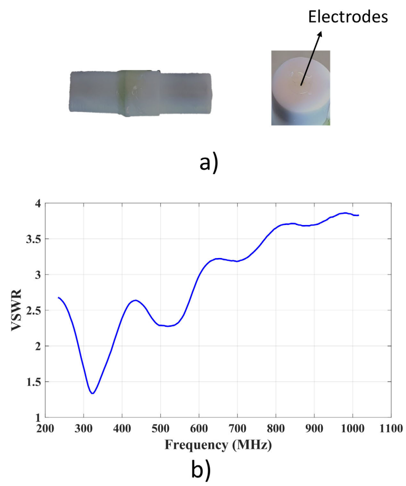

FIGURE 10. **a) Final version of the battery-less video modulator capsule, b) measured VSWR for the capsule electrodes when the capsule was placed inside the phantom.**

III. MEASUREMENTS SETUP AND RESULTS

To evaluate the system operation in a biological medium, we have prepared a liquid phantom with similar characteristics compared to the muscle tissue at 400 MHz. The phantom is realized by mixing water (55.4 %), sea salt (1.3 %), and Propanediol (43.3 %) to mimic the biological tissue characteristics at 400 MHz. A plastic container size 30 × 30 × 35 cm^3 with a thickness of 1.2 mm is used as the container. The implant electronics are encapsulated in a 3D printed capsule mimicking the use case. To evaluate the capsule antenna impedance, VSWR is measured as shown in Fig. 10, VSWR is less than 2.5 at 400 MHz, which means that more than 80 % of energy can be absorbed in this frequency.

The reader antennas are attached to the container surface. Fig. 11 shows the measured VSWR for the reader dipole antenna. The antenna is fabricated on a flexible FR4 material of thickness 0.25 mm. The measured VSWR of the antenna is

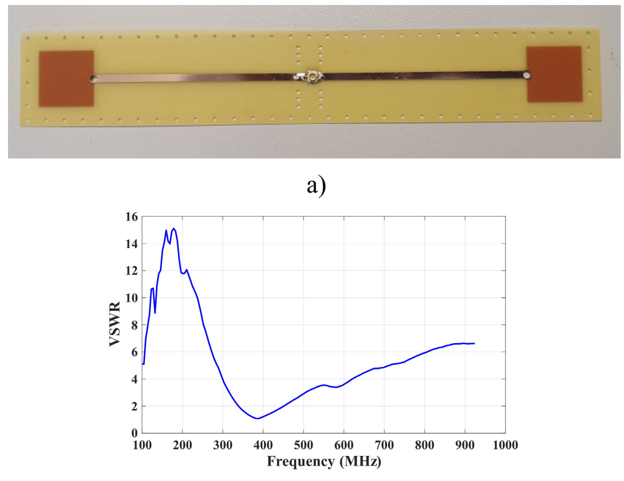

FIGURE 11. **a) Photograph of the manufactured patch antenna, b) measured VSWR for the patch antenna.**

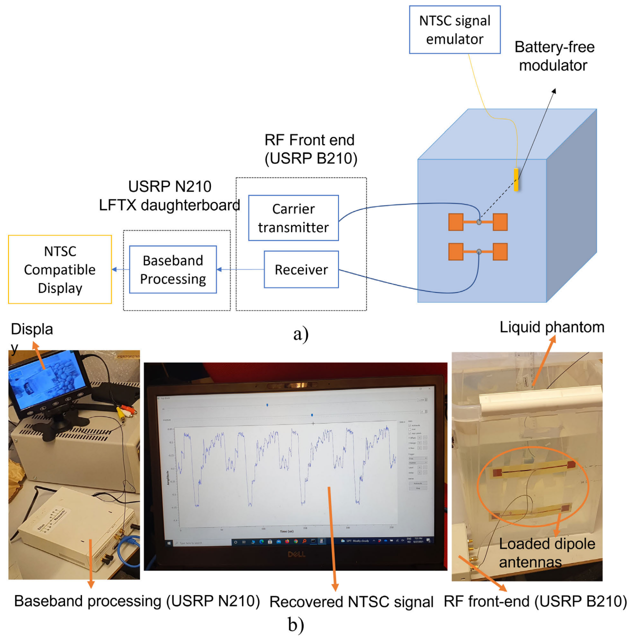

FIGURE 12. **a) Setup diagram for the experimental evaluation, b) picture of phantom setup and decoded video signal before applying to the monitor, and the decoded video signal is displayed by the monitor.**

shown in Fig. 11-b that is below 2 for a wide frequency range (350 – 450 MHz) at the center frequency of 400 MHz.

Fig. 12 shows the phantom measurement setup. The capsule is placed in a depth of 11 cm from the surface. RF front-end transmits 400 MHz carrier signal toward the capsule and receives the backscattered NTSC video signal. The original baseband signal is obtained from a 1.8 mm camera lens with 600 TVL resolution and 170-degree angle of view with 30 fps. In Fig. 14, the normalized received power for different capsule depth is shown. Based on the the graph, the channel loss is a linear function of the capsule depth in decibel

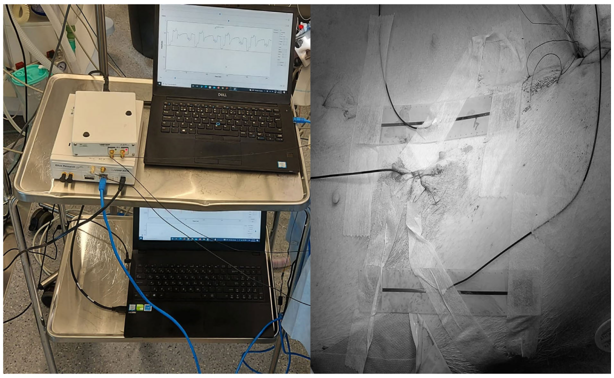

FIGURE 13. Photograph of the in-vivo experiment. The modulator capsule is placed at 6 cm depth in abdominal area. By sweeping a single frequency signal from 396 MHz to 404 MHz with 100 kHz resolution, the amplitude response of the system is measured.

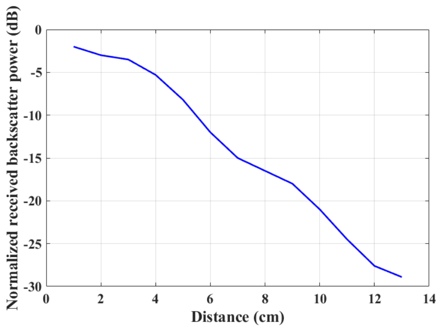

FIGURE 14. Normalized power of the received backscatter signal for different distances in phantom experiment.

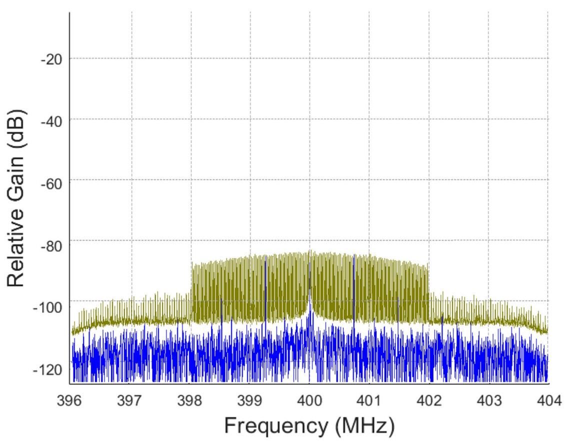

FIGURE 15. Measured amplitude response of the system in in-vivo experiment. The green spikes are the response of the system when a single tone signal is applied to the modulator. The frequency resolution of the measurements is 100 kHz.

scale. The baseband signal is recorded and processed, and the recovered NTSC video signal is transferred to the display. The display is a commercial multi-input display with NTSC support.

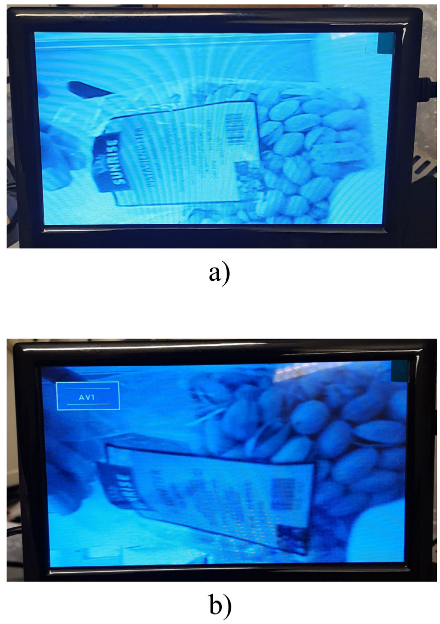

FIGURE 16. Comparison of NTSC video signals. a) Original NTSC signal, b) recovered video signal from the capsule at 11 cm distance.

The in-vivo animal experiment is performed to evaluate the communication system's amplitude response. The photograph of the animal experiment and the measurement setup is depicted in Fig. 13. The capsule is placed in the abdominal area while the backscatter antennas are attached to the body in a similar scenario as the phantom experiment. The capsule is at a depth of approximately 6 cm from the skin. The amplitude response of the system through the in-vivo experiment is shown in Fig. 15. The green graph is the measured system response when a single tone signal with 100 kHz resolution is applied to the modulator capsule and is sweeped from 100kHz to 2 MHz. As we can see in Fig. 15, the amplitude response of the modulator for a wide frequency range that covers the video bandwidth is linear, this ensures that the amplitude modulated backscatter signal can be used for analog video transmission without significant video signal distortion.

Fig. 16 shows the received video image for the backscatter system, recorded for the capsule in the depth of 11 cm in the phantom experiment. The image is compared to the originally transmitted signal. The visual inspection shows the potential of analog backscatter for wireless capsule video streaming. Regarding the required SNR value for the analog video signal, we can see that in Fig. 15, there is more than 20 dB distance between the noise floor and signal level which is at least 4 dB higher than minimum required SNR value for analog video signals [9].

Regarding the power consumption, we emphasize that the proposed backscatter modulator does not need any power supply and the camera output voltage alters the Varactor diode impedance. The applied diode is a device that needs a weak reverse bias current for a proper working point. The reverse

TABLE 1. Performance comparison of video transmission links for wireless capsule endoscopy.

	Frequency	Communication technique	Link distance	Frame rate	Effective radiated power (ERP)	Power consumption
[10]	920-925 MHz	RF - active	-	3	0.25 mW	5 mW
[2]	32 MHz	Galvanic HBC	6 - 11 cm	3.13	-	3.7 mW
[3]	1 -5 MHz	Ultrasound	6.5 cm	0.5 - 24	1 - 3 μW	-
[1]	434.1 MHz	RF - active	-	2 - 4	16 nW	-
[14]	490-510 MHz	RF - active	-	10.5	0.7 mW	2.5 mW
This work	400 MHz	Conductive backscatter	11 cm	30	0	1 pW

bias based on the datasheet is 20 nA at 12 V. However, in our test, the applied voltage to Varactor diode is maximum 1 V. We were not able to measure the reverse current at 1 V due to the limited sensitivity of our current measurement setup. However, we have simulated the reverse current at 1 V reverse bias that is maximum 1 pA. Thus, for the power consumption, we estimate that the proposed modulator sinks maximum 1 pA from the NTSC signal source, which has a maximum of 1 V amplitude. Thus, the power consumption of the modulator is maximum 1 pW.

Table 1 shows a comparison of our proposed battery-less video transmitter for capsule endoscopy with the state-of-the-art works. We can see that the proposed method is the most power-efficient system. Because of using the backscatter technique, the implant system does not radiate energy to the environment, which makes it safe from radiation concerns point of view. Also, the proposed method can be interfaced with any camera setting as far as the camera output is in analog format. So the higher frame rate and higher resolution video can be streamed without changing the system structure. Also, because of zero power consumption of the link, by using an ADC-less camera like the proposed camera in [7], the system can be used in a wirelessly powered capsule endoscope.

The proposed method removes the battery from the video transmission system in WCE. The simplicity and compact size of the modulator make it ideal for system integration. The proposed modulator is compatible with available endoscopy camera sensors with NTSC or PAL output, so there is no need to add any ADC converter and extra processing units such as compression, microcontroller, or FPGA for data preparation to the system. Also, the implant antenna can be easily mounted on the capsule shell. The current verification and demonstration version of the capsule endoscopy system has some limitations. The receiver part can be re-designed with ASIC technology in order to reduce the on-body system size and also improve the radio link parameters. In order to cover a wide volumetric area for video reception, the receiver part needs to have an array of antennas.

IV. CONCLUSION

A novel battery-less method for video signal transmission based on the backscatter concept is presented for WCE application. The proposed modulator consists of a Varactor diode, one series LC resonance, and one parallel LC resonance to maximize the backscattered signal amplitude. The modulator is battery-free. For driving the modulator, an NTSC video signal is connected to the modulator without any preprocessing tasks. The Varactor diode sinks maximum 1 pA current from the video signal source for reverse biasing. The operating frequency of the system is at 400 MHz. The proposed system has been evaluated in the phantom experiment with a 30 fps video signal at 11 cm distance. Amplitude response of the system is evaluated through an in-vivo experiment with 100 kHz frequency resolution, that is linear. Simplicity and compact form of the proposed battery-free modulator make it suitable for video transmission in wireless capsule endoscopy.

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