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Research Article

High Data Rate FinFET On-Off Keying Transmitter for Wireless Capsule Endoscopy

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Wireless capsule endoscopy (WCE) is a painless diagnostic tool used by the physicians for endoscopic examination of the gastrointestinal track. The performance of the existing WCE systems is limited by high power consumption and low data rate transmission. In this paper, a 144 MHz FinFET On-Off Keying (OOK) transmitter is designed and integrated with a class-E power amplifier. It is implemented and simulated using 16 nm FinFET Predictive Technology Models. The proposed transmitter can achieve the data rate of 33 Mbps with average power consumption of 1.04 mW from a 0.85 V power supply in the simulation. This design outperforms the current state-of-the-art designs.

1. Introduction

Wireless capsule endoscopy (WCE) is a state-of-the-art technology for medical diagnoses of gastrointestinal diseases and illnesses [1]. This idea was originally conceived in 1950 [1, 2]. The very first attempts of WCEs used transmitters with low-frequency carrier and the diagnosis was based only on sensor's data like temperature, pH, and pressure [3, 4]. Later, WCEs were equipped with small cameras [5].

The most common diseases that WCEs can diagnose are some types of cancer [6], Crohn's disease [7], and obscure gastrointestinal bleeding [8]. Nowadays, there are capsules dedicated for specific investigation areas, such as esophagus (PillCam ESO) [5] and colon (PillCam COLON) [5]. WCE captures the signals from sensors and takes pictures with the camera. These data are compressed and sent outside of human body in real time through a Radio Frequency (RF) module inside of the WCE. Outside of the body, there is a receiver that decodes the compressed data and presents it to doctors.

Figure 1 shows the diagram of a typical WCE that includes sensors, a processor for signal processing, image compression, and a RF part for wireless communications. The sensors can be cameras, pH sensor, dissolved oxygen sensor, temperature sensor, and other biosensors. The processor receives the values from the sensors, performs analog-to-digital conversion, and then compresses and packetizes the data to be sent using RF transmission to an external RF receiver. Since the amount of the data from the use of a camera is huge, an image compressor is required. For medical applications, the compression of image data should be lossless as required by the doctors for accurate diagnosis. Lossless image compression means that more data is needed to be transferred than the standard lossy image compression methods such as JPEG. The overall performance of the system highly depends on the data communication capability of the RF transmitter. Higher data rates would provide the possibility to use higher resolution cameras. However, higher data communication normally means high power consumption of the system. Higher data rate of the RF transmitter as well as low power consumption would make a better WCE. In this paper, a transmitter is designed to work at a voltage as low as 0.85 V and run up to 12 hours with extremely low power consumption. The system includes an LC oscillator, a class-E amplifier with integrated modulator, and the matching circuit.

The rest of the paper is organized as follows: Section 2 reviews the existing designs and Section 3 gives the consideration of the design. Section 4 shows the proposed architecture and all the detailed information on its components and

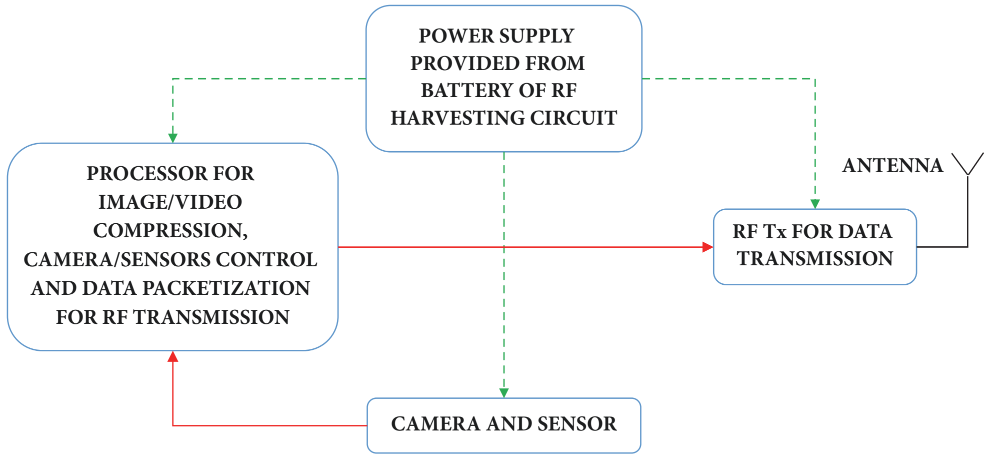

Figure 1: Block diagram of the part of an endoscopic capsule; with red color, data flow (solid line) is denoted, and with green color (dashed line), there is the power supply path.

Section 5 gives the detailed implementation and performance. Finally, Section 6 presents the conclusion.

2. Related Works

Several RF telemetry systems have been designed and simulated in recent years like [9–13]. The research effort focused on designs to reduce power consumption and increase the data rate. All of the designs we mention in this paper have only simulated results; no hardware implementation has been made, although some people have the facilities to implement their design in hardware.

Turcza and Mlynarczyk [12] have designed and simulated a wideband transmitter for biomedical applications based on OOK modulation and with a carrier frequency of 4.3 GHz. The achieved data rate is up to 20 Mbps with power consumption of 1.2 mW at 1.5 V.

Yousefi et al. [11] present an OOK transmitter that works at a voltage as low as 0.5 V with 1.52 mW of power consumption. The carrier frequency of this design is 430 MHz and the data rate is up to 40 Mbps. Using high carrier frequencies causes the signal transmitted to be weakened due to the human tissue absorption [14, 15]. This transmitter was designed in 0.18 μm CMOS technology.

Basar et al. [10] made a significant improvement for the data rate. This design can achieve up to 100 Mbps of data rate. Although no power consumption data are presented, only the power supply voltage is presented, which is 1.5 V. It is a novel design working at 450 MHz and designed in 0.18 μm CMOS technology.

The goal of this research is to provide a novel telemetry system that is able to transmit at high speed with low power consumption at specific modulation frequency for better penetration in human tissue.

3. System Consideration and Architecture

3.1. Data Rate. The data rate of the wireless link depends on the type of data to be transmitted. For data from simple sensors like pH, temperature, dissolved oxygen, and so forth, there is no need for high data rate transmitters. For WCE with a camera sensor, the amount of data to be transmitted is huge. The most effective way to transmit high-resolution image/video is to increase the wireless bandwidth. In existing commercial systems, VGA (640 × 480) and HD (1280 × 720) images are captured and transmitted. WCE with VGA resolution can achieve 5 to 12 frames per second, and HD capsules can transmit up to 2 frames per second. Since the capsule's movement is not self-propelled and is due to peristalsis, the capture of 2 to 4 images per second is enough to capture and synthesize a map of the intestine by connecting all of these images like a mosaic.

For the Full High Definition (FHD) (1920 × 1280) resolution images, the bandwidth needed to transmit one frame per second is 22.12 Mbps. With FHD resolution images, the lenses with 360-degree field of view can be used.

3.2. Frequency Selection. Several factors should be considered for the selection of the carrier frequency of the transmitter. The work in [16] suggests using a carrier between 450 MHz and 900 MHz for maximum radiation. However, from experiments reported in [14, 15, 17, 18], it was shown that the surrounding tissues do not attenuate the transmitted signal so much for lower frequencies, thereby obtaining higher signal-to-noise ratio (SNR). A lower carrier frequency also requires less power to propagate through the body tissue. In addition, if the carrier is used as the main clock of the capsule, the use of low carrier frequency results in a low power consumption system and good RF penetration in the human tissue. So the carrier frequency is selected in the 2 m amateur band that is between 144 MHz and 148 MHz.

3.3. Modulation Scheme. The transmission of compressed image data needs high data rate modulation schemes. Preferred schemes for such applications are Quadrature Phase Shift Keying (QPSK), FSK, and Amplitude Shift Keying (ASK). FSK modulation scheme is a popular choice because

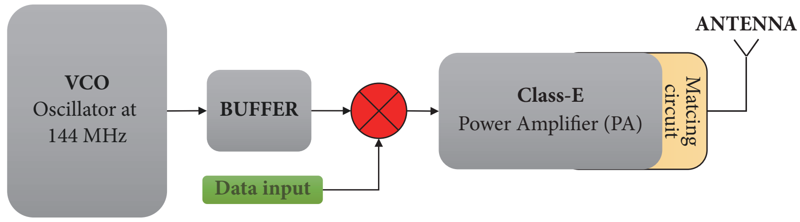

Figure 2: Block diagram of the transmitter.

nonlinear power amplifiers (PA) can be used. However, the need of pulse shaping to perform better spectrum efficiency tends to make the transmitter too complicated. QFSK modulation compared to OOK has double the bandwidth but needs more energy than OOK.

Transmitters based on OOK modulation scheme are used in [11–13, 19, 20] and those on FSK modulation in [18].

The main advantage of OOK modulation is low power consumption, due to the way it works. In OOK, the data transmission is made by modulating/mixing the digital data with a carrier frequency. For example, when a digital "1" is going to be transmitted, the output of the transmitter will be a signal oscillating at the carrier frequency and when the digital data are "0" the transmitter output will be zero, or it is not working. By this way, when the data are "0," the power consumption of the transmitter is almost zero. When the input data are "1," the output is oscillating in the carrier frequency and when the input is "0," the transmitter does not send anything. The OOK modulation scheme is the most feasible scheme to consume less energy. If FSK modulation is used, then the transmitter will work all the time and the power consumption will be increased.

3.4. 16 nm FinFET Technology. Bulk CMOS technology has some unwanted issues such as high power dissipation. While CMOS devices are shrinking, short-channel effects have increased and the performance of the device has decreased [21]. The solution is the use of the FinFET technology [21], a promising technology that can overcome the issues of CMOS technology. FinFET technology is a relatively new technology that has a 3D structure as compared to CMOS that has a 2D structure. The performance of this technology is increased mainly due to the low leakage current, which leads to lower threshold voltages, allowing FinFET devices to work with lower power supplies [22]. By using lower voltages, the power consumption of the device is decreased [23]. In our design, Predictive Technology Model (PTM) [24] is used.

4. System Design

The proposed design of the transmitter is shown in Figure 2. It includes an oscillator, a buffer stage, a modulator, and a class-E power amplifier with a matching circuit.

4.1. Low Power LC Oscillator. The main part of the transmitter is a differential LC oscillator using a cross-coupled transistor that produces the 144 MHz carrier frequency. The oscillator is designed with two nMOS transistors. Inductors $L1$ and $L2$ with the capacitor C compose the LC circuit. The values of $L1$, $L2$, and C are computed by the following equation:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

This design aims to achieve better phase noise. In LC oscillators, the quality factor of the resonator can improve the phase noise. So an LC circuit with a good Q-factor is needed, which is mainly dependent on the inductors Q.

Tail current source has been added to control and minimize the power consumption and increase the stability of the oscillator. A current source adds noise in the oscillator. So, an inductor and a capacitor are added to decrease the noise and improve the noise performance of the oscillator. The length and the width of the transistors are computed in a way that the current that flows inside them is high enough to induce oscillation and as low enough to keep the power consumption at low levels.

4.2. Modulator and Power Amplifier. In our design, the implementation of the modulator is integrated in the PA. In RF transmitters, there are some classes of amplifiers which can be used based on their performance and characteristics. The basic classes of PA are classes A, AB, B, C, D, E, and F. In this transmitter, the class-E PA is selected because the maximum efficiency can be achieved.

In the class-E amplifier, the main transistor "Switch 2," as shown in Figure 3, acts as a switch. Therefore, ideally the maximum efficiency can be 100%. An ideal switch has either zero voltage across it or zero current passing through it, and the power dissipation is zero. Since the ON-resistance of the transistor reduces the efficiency of the class-E amplifier from the ideal efficiency of 100%, a power efficiency of more than 85% is not feasible. This selection is based not only on the efficiency of this class but also on the selected OOK modulation. With class-E amplifier, a better performance can be obtained with less components for the design of the transmitter.

A nonlinear switching mode PA, whose operation is based on a switch, typically uses a transistor. When the transistor/switch is closed, the current flows into the switch; when the switch is open, the current flows into the output load, which causes a voltage. Ideally the output is a square wave without overlap, so there is no power dissipation over the switch/transistor.

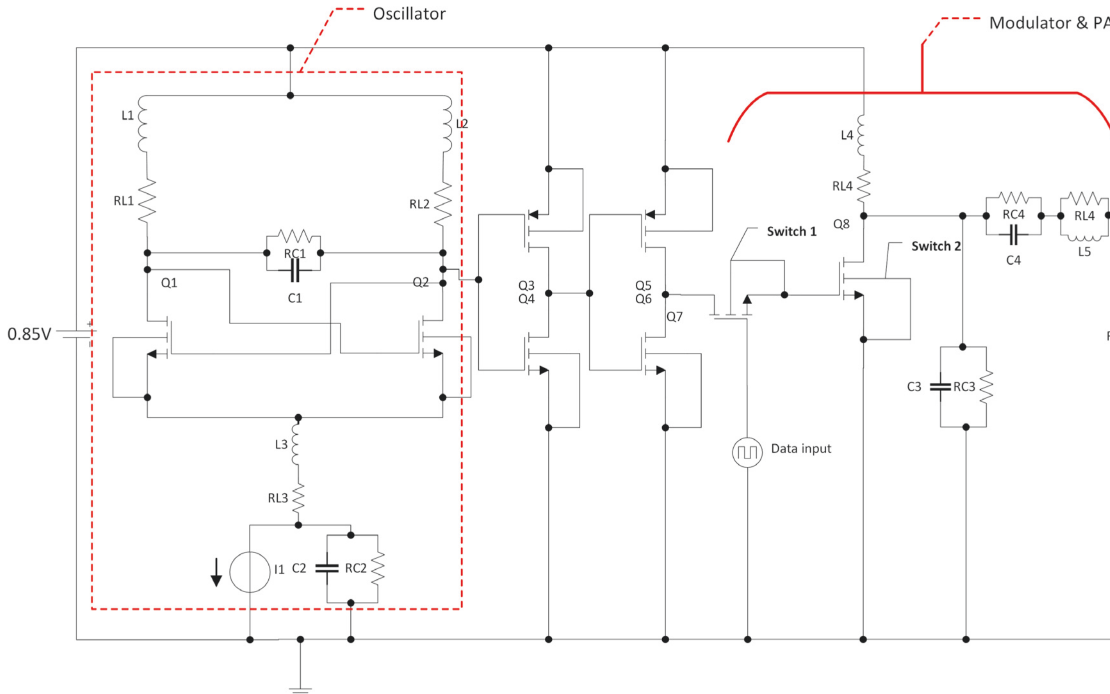

FIGURE 3: Circuit diagram of the proposed transmitter. It includes the LC oscillator, the class-E PA, and the matching circuit.

A lot of power is lost as a result of the harmonic frequencies because they are not transmitted. The solution to this problem is a resonator placed in the output of the PA. Resonator consists of a capacitor in series with an inductor, resonating in the fundamental (carrier) frequency which is 144 MHz. However, the use of resonator causes a new problem. When the transistor/switch is closed, the current flows into the switch. On the other hand, when the switch is open, the current flows into the output load, which causes a voltage. Since the switch is open, this is not possible. For this reason, a shunt capacitor is placed before the resonator and this problem is solved. The RF circuit used allows only DC current to pass and ideally has no resistance. Also the high Q of the resonator plays a major role in the performance of the PA, since it can provide high impedance conditions for the harmonics. The current that flows in sinusoidal form into the load can be computed from (2), where I_R is the maximum current and i_R is the sinusoidal current.

$$i_R(\omega t) = I_R \sin(\omega t + \varphi) \quad (2)$$

For the design of the entire system, the values of the L-C resonator, the shunt capacitor, and the load resistance need to be computed from (3)–(6).

$$R = 0.5768 \frac{V_{cc}^2}{P_{out}} \quad (3)$$

$$C = 0.1836 \frac{1}{\omega R}, \quad (4)$$

where, in (3), R is the optimum load resistance and it is obtained by supply voltage V_{cc} and the output power P_{out}.

For the resonator, the equations are

$$C_0 = \frac{1}{\omega^2 L_0} \quad (5)$$

$$L_0 = 1.026 \frac{R}{\omega} \quad (6)$$

4.3. Matching Network. The output of the amplifier is connected to the matching network before the load. The matching circuit is applied for the maximum transfer of power from stage to stage and its design is the same as the resonator described before. In our design, before the matching network, we use a shunt capacitor $C3$, which reduces the voltage across the switch Q8 after the drain current is reduced to zero. By this way, $C3$ eliminates the harmonic distortion produced by Q8.

In our case, an L-section is used to improve the matching efficiency. The values of $C4$ and $L5$ were computed from (7), (8), and (9) [25], where R_p resistance and R_s resistance are the equivalent coil resistance in parallel and in series, respectively, and f is the carrier frequency.

$$Q = \sqrt{\frac{R_p}{R_s} - 1} \quad (7)$$

$$C4 = \frac{Q}{2\pi f R_p} \quad (8)$$

$$L5 = \frac{Q R_s}{2\pi f} \quad (9)$$

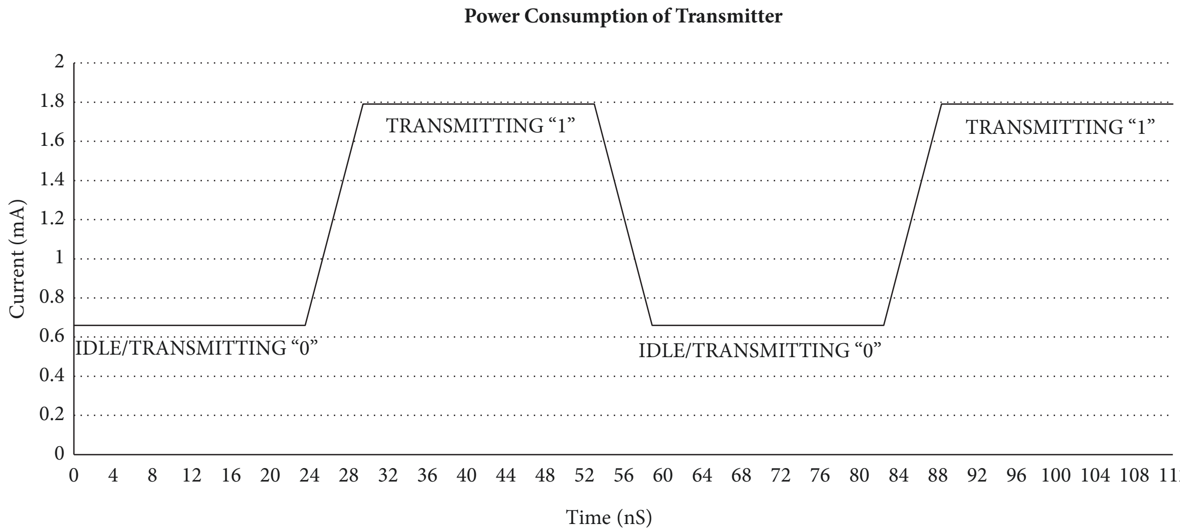

Figure 4: The transmitter tested with various data inputs and the result while transmitting "1" and "0" is shown. Here is the transmission of "0101" data sequence at 33 Mbps.

5. Implementation and Analysis

All the components of the system are designed with schematic editor of Cadence Virtuoso [26] and simulated with Spectre software [27]. Figure 3 shows the final circuit diagram of the whole design including oscillator, modulator, and transmitter.

5.1. Oscillator. An LC complementary oscillator is designed with FinFET and simulated with different tail currents. The current used by the oscillator to work is 0.66 mA.

$$V_{\text{amp}} = \frac{4}{\pi} R_p I_{\text{bias}}, \quad (10)$$

where R_p is the equivalent resistance of the inductors. It can be seen from (10) that the voltage amplitude of the oscillator is based on the equivalent resistance of the inductors used in oscillator circuit and the bias current is 0.66 mA.

5.2. Modulator. The final circuit of the PA modulator is presented in Figure 3. In this amplifier, two switches/transistors are used because the first one is for the carrier frequency and the second is for the data input. The first one is used to modulate the data with the carrier, where common gate mode is used.

The benefit of our design in comparison with other implementations is that, due to the low power design of our oscillator, we can keep it alive. In other designs of OOK transmitters, the oscillator part is switched ON and OFF. By this way, there is a start-up latency, which is taking part every time the data input changes from 0 to 1. This latency does not let us increase the data rate to the limit of every design. In our design, by modulating in the PA and keeping the oscillator on all the time, we eliminate this bottleneck.

5.3. Transmitter. The proposed low-power OOK transmitter is designed with 16 nm FinFET technology and the design is simulated with Cadence tools. The carrier frequency of the oscillator is 144 MHz for minimum energy loss and minimum tissue absorption.

The proposed design is able to achieve a data rate up to 33 Mbps. The average current flow is 1.223 mA at 0.85 V. The use of 16 nm FinFET technology gives us the opportunity to operate our design at a voltage as low as 0.85 V and decrease more the power consumption. As seen in Figure 4, the current flow while the transmitter is in idle/transmitting "0" mode is approximately 0.66 mA. When the transmitter is transmitting "1," the overall current of the circuit is 1.786 mA. Assuming that 50% of the data are "0" and the rest are "1," the average current is 1.223 mA.

5.4. PVT Analysis. PVT (Process, Voltage, and Temperature) analysis was done in order to examine the stability of the oscillation frequency of the proposed system. It is based on the variance of the Process, Voltage, and Temperature. Process corners mean the performances of devices due to variations in the die which have occurred in minor changes of humidity or temperature of the clean room when wafers are transported or due to the position of the die relative to the center of the wafer. The combinations used for process variation are SS, SF, FS, TT, and FF, where the first letter corresponds to the NMOS component and the second one stands for the PMOS component. State S stands for slow performance, F stands for fast performance, and T stands for typical performance. In our PVT analysis, SS, TT, and FF were used. For voltage variations, the simulation was done with a ±10% variation of the nominal power supply, which is 0.85 V. For temperature variation, three different temperatures were used, 30°C, 37°C, and 44°C. The device will be used in a capsule endoscopy inside human body, where the

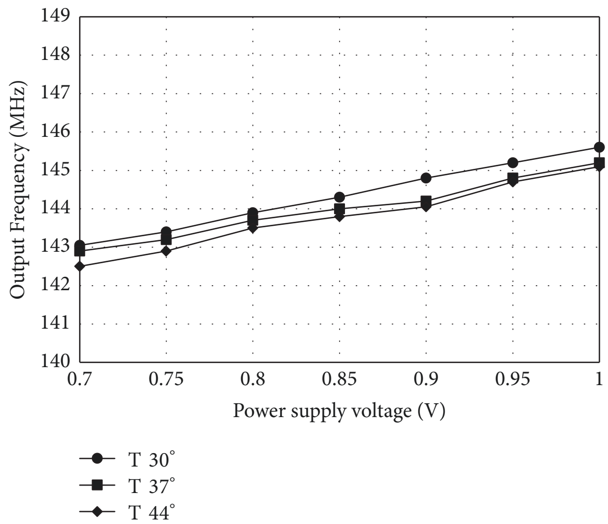

Figure 5: Frequency drift due to temperature and voltage variations.

Table 1: Oscillator frequencies based on PVT variations.

Voltage (V)	Temperature (°C)	SS	TT	FF
0.7	30	141.60	142.50	142.60
	37	141.90	142.90	142.80
	44	142.50	143.05	143.40
0.85	30	143.20	143.80	144.10
	37	143.90	144.00	144.30
	44	144.15	144.30	144.70
1	30	144.85	145.10	145.60
	37	145.00	145.20	146.20
	44	145.10	145.60	146.90

Table 2: Summary of transmitter's characteristics.

Vdd	0.85 V
Carrier frequency	144 MHz
Data rate	33 MB/s
Avg. current	1.223 mA
Avg. power consumption	1.04 mW
Phase noise of oscillator	0.144 dBm/Hz
Output power	−4 dBm

temperature is stable at approximately 37°C, except in cases like fever, where temperature is higher than 37°C. The results of voltage and temperature variations are shown in Figure 5.

The overall results of PVT simulation are shown in Table 1. The frequency variation achieved is around 2.1%. These results have shown a stable oscillator with predicted frequency drifts. For PVT simulation, Cadence ADE (Analog Design Environment) XL was used.

5.5. Performance Comparison. Table 2 presents a summary of the designed transmitter. From Table 2, it can be seen that the proposed transmitter has a relatively high data rate of 33 Mbps and lower average power consumption of 1.04 mW.

Table 3: Performance comparison of similar works.

	Basar	Yousefi	Turcza	This work
Process (μ m)/voltage (V)	0.18/1.5	0.18/0.5	0.18/1.5	0.016/0.85
Carrier frequency (MHz)	450	400	4300	144
Data rate (Mbps)	100	40	20	33
Modulation	OOK	OOK	OOK	OOK
Power (mW) (TX)	n/a	1.52	1.2	1.04

The transmitter is able to send up to 4 HD 1920 × 1080 images per second by the use of a compression scheme of an average compression rate of 2.5.

Table 3 shows the comparison between the proposed transmitter and other existing similar systems. In Table 3, the comparison is made between our design and other simulated designs, where no hardware implementation has been made. Overall, the proposed design has clear advantage with high data rate and low power consumption. Compared to the simulation of Yousefi et al. [11], the data rate of the proposed system is less, but the carrier frequency is lower than their design, so it has better performance in penetration of human tissue. Also the power consumption is almost 50% less than their design. In this design, the data rate is 33 Mbps per second, which can transfer up to 2 FHD high-resolution images per second without compression. With a compression rate of 2.5, it can transfer up to 4 images, which is good enough for WCE applications.

It should be mentioned here that there are designs implemented in hardware such as Ryu et al.'s. [20] who made a significant improvement for the data rate. This design can achieve up to 40 Mbps data rate. The carrier frequency is 440 MHz and the implementation process is 0.18 μm CMOS technology. The power source of the design is 3 V with 860 uA of current; it is a novel design with 2.58 mW average power consumption. Raja and Xu [28] implemented an OOK transmitter with adaptable data rate. The carrier frequency is 433 MHz and the implementation is 0.35 μm CMOS technology. The data rate is 3–10 Mbps with a power supply of 1 V at 560 uA current consumption.

6. Conclusion

In this paper, a new OOK transmitter with high-efficiency PA and low-power LC oscillator has been designed and simulated. The key point of this transmitter is that the modulation takes part at the PA and not in the oscillator. The meaning of this is that there is no start-up time in comparison to the other designs. Due to that, our design can push the data rate to the limit of the carrier frequency. If a typical OOK transmitter is designed, which modulates the data in the oscillator, the achieved data rate will be almost the half.

The proposed design is for next-generation WCE that needs to transmit high-resolution image/video. It is dedicated to be used inside an endoscopic capsule, where other subsystems work simultaneously, like image/video compressor.

The use of FinFET technology provides extremely low power consumption schemes in two ways. Firstly, the entire system is to be manufactured with the same technology in same wafer (image/video compressor), so the main processor gains the benefits of FinFET technology like low power consumption and low delay. Also, as explained, we were able to increase the data rate of the transmitter to 33 Mbps and reduce the power supply voltage down to 0.85 V. With these features, we are able to transmit higher-resolution images in WCE.

For future work, we will design a lossless image compression module and complete the whole WCE system using the same FinFET technology.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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