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On-chip ultra low power optical wake-up receiver for wireless sensor nodes targeting structural health monitoring

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Article Info

ABSTRACT

Wireless sensor network (WSN) consists of distributed nodes deployed for monitoring the physical conditions and organizing collected data at the central control unit. Power consumption is the challenges in WSN as the network consists of wireless sensor nodes becomes denser. By utilizing WSN and visible light technology, a simple health monitoring system design can be approached that are smaller in size, faster and lower power consumption. This work focuses on design a low power optical wake-up receiver to reduce the energy consumption of each node in WSN. A wake-up receiver is designed to be always-on for detecting incoming signal and switches on the stand by protocol controller and WSN network for data transmission process. The characteristic of optical transmission and functional circuit of a wake-up receiver has been investigated. A low power optical wake-up receiver has been designed in 180nm Silterra CMOS process technology. The proposed wake-up receiver consumes only 443pW in standby mode and 1.89nW in active mode. The proposed optical wake-up receiver drastically reduces the power consumption by more than one third compared to other wake-up receivers which could be a milestone in the medical field if successfully conducted.

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1. INTRODUCTION

Wireless sensor network is spatially distributed autonomous sensors deployed for monitoring the physical conditions and organizing the collected data at the central control unit [1]. The WSN includes large number of sensor nodes that cooperate with each other via a wireless connection and forms a network for collecting, propagating and analyzing environmentally received data [2] as shown in Figure 1 (a). Between the deployed sensor nodes and the end user, a sink with higher processing capacity is placed to serve as a gateway and communicate with the task manager node. A user retrieves information from the wireless sensor network by query and collect the results from the base station.

In term of implementation of the structural health monitoring, WSN can be embedded into a hospital building to track and monitor each patient and provide healthcare services [3] such as medical monitoring and

medical data access to a healthcare provider as shown in Figure 1 (b). Each sensor nodes can be implemented to monitoring equipment to transmit data. A sensor node that monitors the patient's physical condition can even be knitted into clothes or wear as a watch for remote nursing. This system is useful for tracking and monitoring patient's condition without the need to interrupt the normal life of the patient, thereby improving the quality of life.
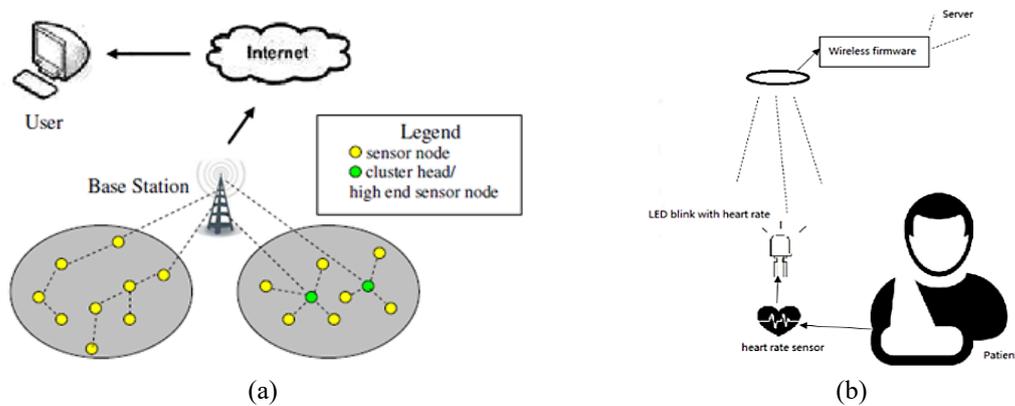

(a) (b)

Figure 1. Wireless sensor network (a) operation and (b) embedded with
optical communication targeting health monitoring

− Wake-up receiver

Development of optical wake-up receiver in wireless sensor node entails major design challenges and low power consumption issue. Each node is heavily duty-cycled in a wireless sensor network (WSN) to minimize power consumption resulting in nodes spending most of the time in sleep mode. A wake-up receiver has been proposed as one of the ways to solve this energy constraint and minimize the power consumption of each sensor nodes.

Comparison between previously reported wake-up receivers as shown in Table 1. According to previous research work, traditionally RF solutions exhibits high standby power which is more than 10µW. The ultrasound wake-up receiver [4-7] is much lower power consumption and smaller size compared to the radio frequency technique. However, the sensing accuracy of ultrasound wake-up receiver will be affected by soft or curved materials due to the difficulties in reading reflections from the material [8]. Moreover, it has 4.4µW standby power, which is still considered high compared to the previous research with 695pW standby power of optical wake-up receiver [9].

In this work, a demand trigger based on low power optical wake-up receiver in WSN has been proposed. To achieve low power consumption, WSN is in standby power at most of the time and activated when received the instructions from wake-up receiver. The wake-up receiver in the sensor has to always on to receive interrupt, synchronization, and reprogramming [10]. The design of the front-end of the analog circuit block has been optimized for lower power consumption further minimizing the wake-up receiver's power consumption.

Table 1. Performance summary and comparison

	[11]	[12]	[4]	[13]	[9]
Transmit Method	RF	RF	Ultrasound	Optical	Optical
Technology	180nm	130nm	65nm	No IC	180nm
Fully Integrated	-	-	No	No	-
Supply Voltage	1.8V	1.2V	0.6V	3.3V	1.2V
Standby Power	8.5µW/1078 µW	16.4 µW /22.9µW	4.4µW	317µW	695pW
Max. Data Rate	1k/200kbps	10k/200kbps	250bps	2kbps	91bps
Energy/Bit	8.5/5.39nJ/b	1.64/0.11nJ/b	18nJ/b	159nJ/b	140pJ/b
Range	-	-	8.6m	15m	-
Bit Error Rate	<10-8	<10-6	<10-5	-	<10-5

− Visible light communication

Optical wake-up receiver uses visible light for data communication instead of existing radio frequency (RF) technology [14]. Light fidelity or visible light communications (VLC) is an emerging technology that

operates at very high-speed wireless communication [15] inside building that humans cannot detect it and causing the light source appears to be alike continuously on. This invisible switching activity allows data transmission process through binary codes which binary '1' indicate switching on an LED while binary '0' indicates switching off [16]. Table 2 shows a comparison of parameter such as data transmission, coverage area, frequency band, speed, topology, spectrum range and obstacle range among Wi-Fi and VLC.

VLC provides an extremely high-speed data rate of 1 Gbps. Meanwhile, Wi-Fi router works on multiple bands that only supply 2.4 GHz or 4.9 GHz or 5 GHz [17, 18]. The light spectrum is 10,000 times wider than the radio spectrum, which provides more bandwidth than Wi-Fi. VLC technology resolved low bandwidth problem in radio frequency communication due to large bandwidth availability [19]. However, the visible light signal cannot penetrate through the wall which making VLC a safer environment that cannot be remotely hacked. VLC is not a substitute for Wi-Fi. It can be regarded as an incredible companion of Wi-Fi technology.

Table 2. Comparison between Wi-Fi and VLC

Features	Light Fidelity	Wireless Fidelity
Data transmission [14]	bits	radio waves
Coverage Area [14]	10 Meters	20 - 100 Meters
Frequency Band [14]	100 times of Tera Hz	2.4 GHz, 4.9 GHz and 5 GHz
Speed [15]	1 - 3.5 Gbps	54 -250 Mbps
Topology [15]	Point to Point	Point to Multi-point
Spectrum Range [15]	100000 times of Wi-Fi	Radio spectrum range
Obstacle Interference [20]	High	Low or almost negligible

2. RESEARCH METHOD

In this work, the optical wake-up receiver at wireless sensor node is deployed as shown in Figure 2 to detect incoming signal, activate the protocol controller and assist each patient by providing healthcare services such as medical monitoring and medical data access to a healthcare provider. The proposed optical wake-up receiver comprises of a decoder, protocol controller, reference generator, clock generator, and front-end circuits. The optical wake-up receiver stays on at all times and the protocol controller are power gated state in standby mode as shown in Figure 3. When the light detector is matched with the predefined global passcode, a signal will be sent out by the wake-up receiver to activate the protocol controller to operate in active mode through increasing the clock frequency. Otherwise, protocol controller will always in standby mode to reduce the power consumption.

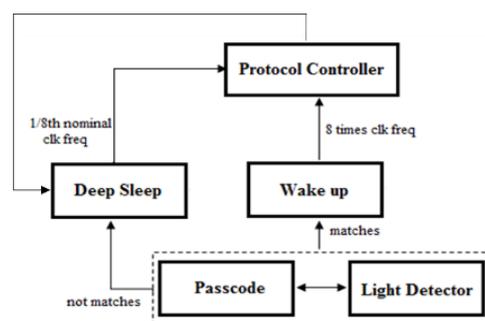Figure 2. Wireless sensor network implemented in hospital building

Figure 3. Block diagram of optical wake-up receiver in WSN

3. RESULTS AND ANALYSIS

3.1. Design of an on-chip optical wake-up receiver

The circuit functional blocks in the wake-up receiver as shown in Figure 4. The front-end receiver is used to transform incoming visible light into voltage. The outputs of the front-end circuits are fed into a comparator and compared with a reference value. The output with majority voters is selected and a signal called FL_DATA is generated accordingly. The accumulated FL_DATA are then compared with the 8-bit predetermined global passcode. A match of the passcode generates a signal called VALID which increases eight times the sampling frequency of the clock, thus turning the protocol controller into active mode. The main functional blocks have been presented in the following subsections.
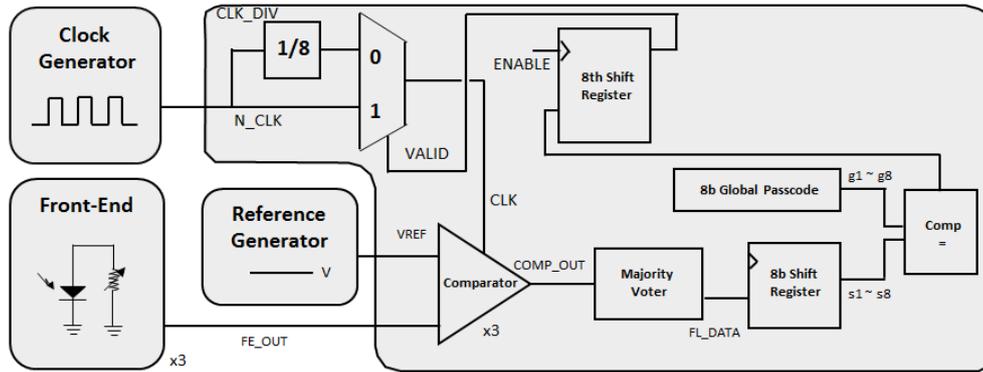

Figure 4. System block diagram of optical wake-up receiver

3.1.1. Front-end receiver

The front-end receiver is implemented using a parasitic diode as a PV cell to transform incoming visible light to voltage. For optical communication systems, a visible light signal that incident on the photodiode is transformed into an electrical voltage. The voltage which has the visible light signal's information is then compared and the majority voted is selected and stored into the shift register memory.

3.1.2. Voltage comparator

Figure 5 shows the simulation results of the developed comparator. When the front-end measured voltage exceeds a reference voltage of 105.1 mV, the comparator outputs a digital signal 1 [21]. At the end, visible light flashing on and off is successfully converted into binary form.
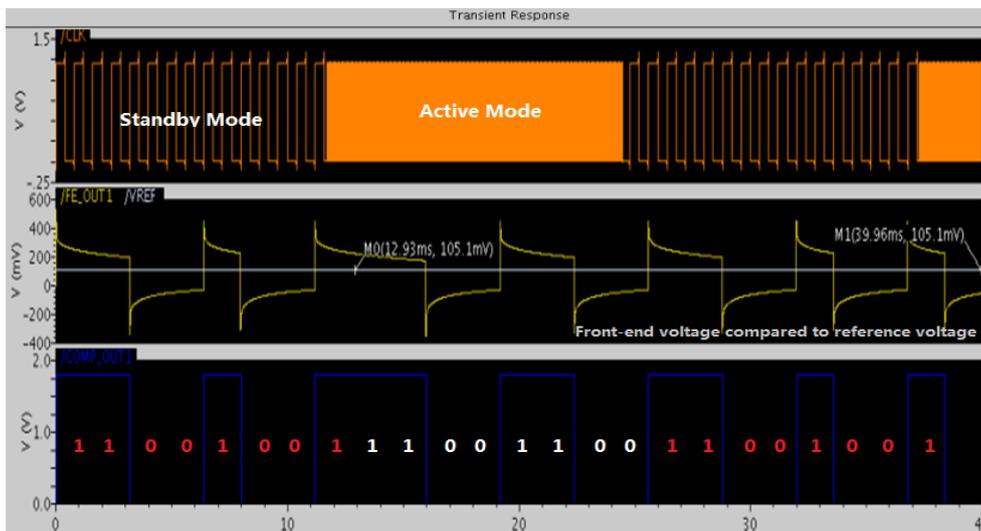

Figure 5. Performance of voltage comparator

3.1.3. Majority voter

Failure detection the incoming signal on the front-end receiver or wrong interpretation of the signal on the comparator will result in the protocol controller being misactivated. The majority voter is capable of successfully masking a single failure from being noticed by the external environment and also manages to keep the entire system operational. However, it is generally presumed that no faults can occur within the voter, which implies that the voter is assumed to be perfect [22-24]. In this work, majority voter has been designed to compare between three outputs from the front-end receiver and the majority voted of the input states determine the output state. Figure 6 shows the output waveform of majority voter in respect to three inputs produced by voltage comparator. As majority input from the comparator is one, the majority voter is routed to VDD and vice versa. The simulation results clearly demonstrate that the majority voter effectively prevented false triggering and produced an erroneous output against in response to the input.
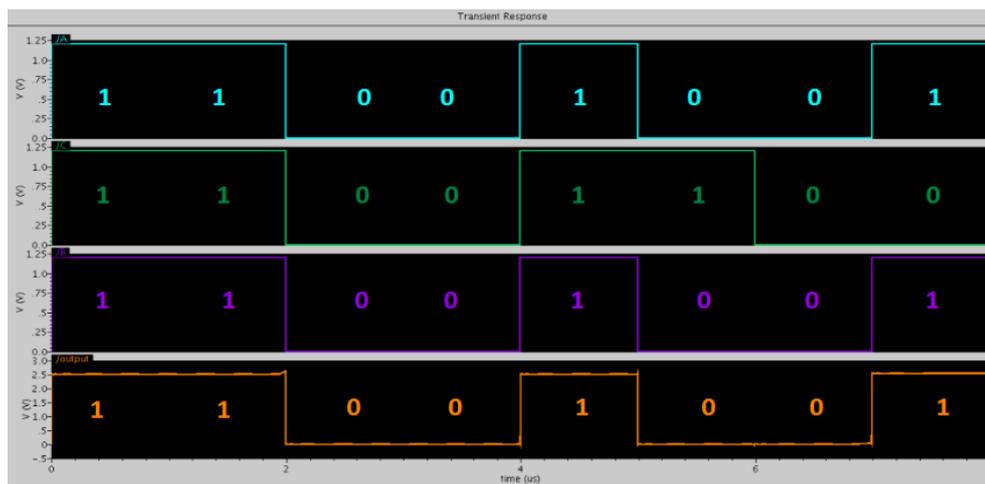

Figure 6. Majority voter electrical simulation results with three front-end receiver input

3.1.4. Gated latch memory

Gated enable memory is designed to store a single bit of information that generated by majority voter and as long as it remains on power. During the write operation, write enable is turned to 1 to latch the input data in the memory and the previous store data is replaced. The write enable wire is then turned off to prevents any memory changes. The eight gated latch memory is designed side-by-side in this work to store 8 bits of information and named as shift register memory. The first gated latch memory is used to store the first bit data, second gated latch memory stored the second bit data until the 8th bit data is stored.

3.1.5. 2-Input multiplexer

The two input multiplexer controlled by a signal called VALID [25]. When VALID is zero, the multiplexer propagates 20kHz high frequency clock pulse to the output CLK; When VALID is one, only 2.5 kHz low frequency clock pulse will be propagated. Multiplexer switches between multiple input lines at an extremely high rate which resulting in the potential of creating a glitch by a sudden increase or chopping the output clock. However, this glitch effect did not have a major impact on the final outcome.

3.1.6. Integrated on-chip optical wake-up receiver

Figure 7 and Figure 8 show the schematic diagram and simulation result of the optical integrated wake-up receiver. The parasitic diode at the front-end receiver is used to transform incoming visible light into voltage. Three front-end receivers are implemented to enhances detection effectiveness and prevent false triggering that may be caused by structural issues such as a dust particle blocking the photodiode detection part. The outputs of the three front-end circuits are digitized by each comparator and the majority voted input is routed to the output which generate FL_DATA. An 8-bit predetermined passcode is set and used as a global passcode to wake up the system and protocol controller to avoid false triggers from visible light. Once the FL_DATA is matched with the 8-bit global passcode at equality comparator, a VALID signal is generated and wakes up the protocol controller. The sampling frequency of both protocol controller and voltage comparator increase by eight times to enable full speed data transfer. The protocol controller is power-gated during standby mode until activates by the wake-up receiver to optimize system energy consumption.
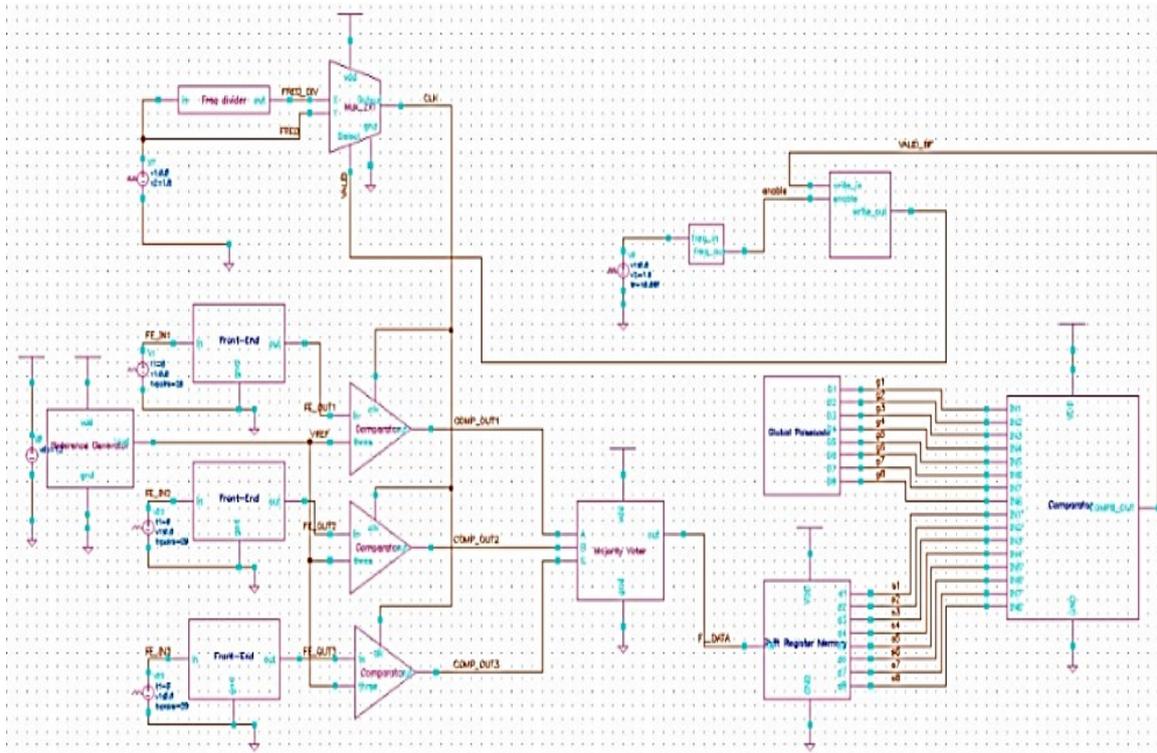
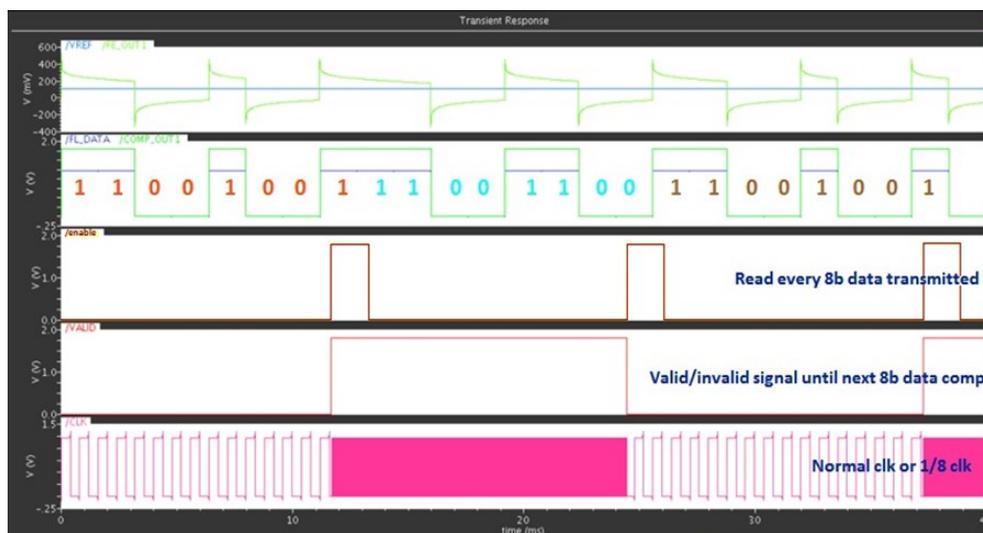Figure 7. Optical wake-up receiver schematic diagram

Figure 8. Performance of optical integrated wake-up receiver

3.2. Power consumption of proposed optical wake-up receiver

The proposed optical wake-up effectively reduces power consumption of each wireless sensor nodes by keeping protocol controller in standby state. The wake-up receiver activates the protocol controller once the incoming signal matched with global passcode and start full data sampling rate. The optical wake-up receiver consumes only 443 pW in standby mode and 1.89nW in active mode as shown in Figure 9.

The voltage comparator and clock frequency divider consume the most of the switching power in the proposed system during the standby mode. The power consumption is dominated by the sampling frequency defined during standby and active modes. The performance of the proposed wake-up receiver has been benchmarked with previous research work as shown in Table 3. The power saving of this work is 252 pW

which is more than one third compared to the previous optical wake-up receiver [10]. The proposed optical wake-up receiver consumes only 443 pW in standby mode which is 9000 times lower than the previously reported ultrasound wake-up radio [4] and 37,000 times lower than previously reported RF receivers [12].

Table 4 shows the comparison between WSNs with and without implemented wake-up receiver. For system without implemented wake-up receiver, it will always in active mode and consumes 1.89 nW for 8-bits data transfer. By implementing optical wake-up receiver, the daily power consumption for the system is about 3.44mW if no incoming signal, which significantly reduced 73.8% of power consumption of each sensor node per year.
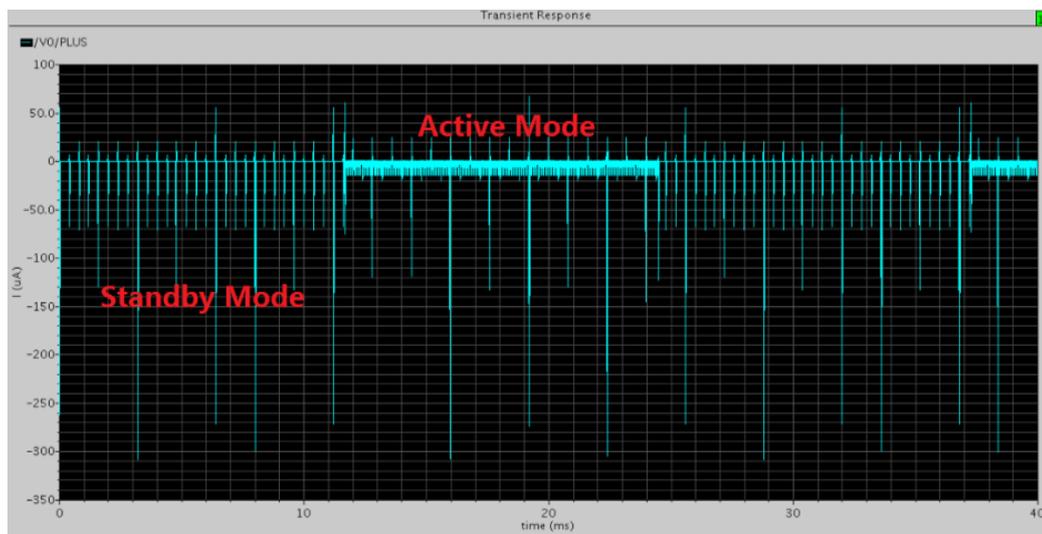

Figure 9. Power consumption during standby and active mode

Table 3. Comparison of power consumption

Transmit Method	RF [12]	Ultrasound [5]	Optical [10]	This Work
Technology	130nm	65nm	180nm	180nm
Supply Voltage	1.2V	0.6V	1.2V	1.2V
Standby Power	16.4μW	4.4μW	695pW	443pW/1.89nW

Table 4. Power consumption comparison for system with and without WuRx

Parameter	With Optical Wake-up Receiver	Without Optical Wake-up Receiver
Power Consumption	443pW / 1.89nW	1.89nW
Power consumption/day	3.44mW	13.12mW
Power consumption/year	41.28mW	157.44mW

4. CONCLUSION

An optical wake-up receiver utilising WSN technology for health monitoring in the hospital has been proposed. The optical wake-up receiver is developed in 180nm Silterra CMOS process technology. As the light detector matches the predefine global passcode, the optical receiver switched on the protocol controller which samples eight times faster after turning into active mode from standby mode. The power consumption of the proposed optical wake-up receiver is significantly less than one third compared to previously reported optical, RF and ultrasound wake-up receivers which consumes only 443pW in standby mode and 1.89 nW in active mode. The work shows a power saving of 73.8% compared to traditional WSN which without a wake-up receiver has been achieved. The proposed optical wake-up receiver demonstrates not only high-speed data rate and relatively secure data transmission, but also significant of power saving, showing a great potential in next generation healthcare monitoring system.

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