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DESIGN AND IMPLEMENTATION OF A RF SENSOR WITH SINGLE-CHANNEL AND NONORTHOGONAL IQ SIGNALS FOR NON-CONTACTING MONITORING

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Abstract. In this article, a design of RF (radio frequency) sensor which is based on PCB (Printed Circuit Board) antenna for monitoring physiological parameters is proposed. In order to remotely monitor the activities of heartbeat, respiration and body movement, this article designed and implemented a RF sensor with single-channel and nonorthogonal IQ signals whose working central frequency is 2.4 GHz. Considering of low cost, simple structure and the ease of fabrication, the antenna is designed to be integrated into a circuit on a PCB to form a single antenna system. The gain of the sensor is 7.7 dB. The return loss is -22.7dB at 2.4GHz and the directionality of the antenna is satisfactory for monitoring vital signals. After simulation and some experiments, it was validated that the sensor could detect the respiration and movements signals.

Index Terms: Non-contact RF sensor, Yagi antenna, nonorthogonal IQ signals, Monitoring physiological parameters.

I. INTRODUCTION

The cost in healthcare is an important portion of each government's budget and it's increasing rapidly every year. In America, it is estimated that one hundred million Americans suffer from chronic diseases including heart disease, lung disorders, and diabetes, and the treatment for these conditions accounts for three-fourths of total US healthcare costs [l]. If there is a way that can prevent the disease at a very early state, the costs of healthcare will be limited. With the advent of big data, daily vital signs become very essential for disease prevention and medical diagnosis. By analyzing daily physiological parameters, doctors are able to diagnose the illness accurately. Monitoring sleeping infants can reduce the mortality of Sudden Infant Death Syndrome (SIDS) [2]. Consequently, there is a growing market for appliances which allow monitoring daily health parameters for convenience and cost reduction [3].

Among most of the existing devices, wearable devices can detect our daily physiological parameters precisely. However, considering the coherence and conveniences are not suited for our daily monitoring of physiological signals. Wearable devices take a lot of space and limit wearers' action. Furthermore, most people may be shameful to wear equipment every day [4].

Therefore, there is a great demand for monitoring physiological parameters expediently and with low costs in our daily lives [5-6]. Recently, a wireless bio-radar sensor, fabricated using Doppler theory, has drawn a great deal of attention as a non-contact monitoring system for human healthcare and vital-sign monitoring, such as in cardiopulmonary monitoring for sleep apnea syndrome detection [7]. Since the 1970s, microwave Doppler radar has drawn attention for new applications on human healthcare because it offers a non-contact alternative for healthcare monitoring, such as physiologic movement, volume change sensing, life detection for finding human subjects trapped in earthquake rubble [8-9], and cardiopulmonary monitoring for sleep apnea syndrome detection [10-11]. Remote non-contact detection of vital signs, i.e., the respiration and heartbeat, based on microwave Doppler phase modulation effect has been studied for many years [12].

Nevertheless, Doppler radar used for detecting vital signs has not been commoditized available and is still under studying. The most important limitation in Doppler radar measurement of periodic motion is the presence of null detection points [13]. When vital signs become weak and with a lot of background noise caused by walking and talking of people nearby, it will be hard for the radar sensor to detect the relative weak vital sign signals from high level background noise, unless smaller carrier wavelength is used to improve the sensitivity [14]. In consequence, single-channel receivers cannot be used and a multiple antenna system is required, which means the Doppler radar system is always complex [15-16].

In summary, there is a huge market for a new kind of sensor which can ensure simple structure, accurate detecting. Compared with Doppler radar, this article analyzed and designed a RF sensor working at the 2.4 GHz for monitoring physiological parameters, which can form a single-antenna system. In principle, our antenna detects movements by the shift of phases however Doppler radar detects movements by the change of frequency [17]. Therefore, our antenna can form a single-antenna system and provide a high accuracy detecting method with low noises [18]. Due to the ease production of PCB antenna, our design also ensures the possibility of mass production with low costs.

II. PRINCIPLEOF DETECTING MOTIONBY MICROWAVE

According to the microwave principle, the phase of signal and the location of the time-varying moving target will be modulated in a linear scale and reflected again by a time-varying moving target whose rate close to zero. A human body's periodic breathing speed compared with the electromagnetic wave speed almost close to zero in quiet state. Therefore, A microwave radar targets in thoracic will receive the phase modulation signal with time varying movement of thoracic position similar to launch signal. This signal contains information with breathing and heartbeat. According to this principle, the RF sensor is designed.

For single frequency microwave radar, signal can be expressed as follows:

$$S(t) = A_0 \cos\left(2\pi f t + \phi(t)\right) \tag{2-1}$$

The total distance that Radar signal comes from the transmitting antenna to the receiving antenna is $2d(t) = 2d_0 + 2x(t)$, so the echo signal is launched by the body as follows:

$$S_F(t)=\cos[2\pi f(t - \frac{2d(t-\frac{d(t)}{c})}{c})+ \phi\left(t - \frac{2d(t-\frac{d(t)}{c})}{c}\right) \tag{2-2}$$

The chest movement cycle caused by breathing is $T \gg \frac{d_0}{c}$, so in $x(t - \frac{d(t)}{c})$, $\frac{d(t)}{c}$ can be neglected. So the received echo signal can be expressed as follows:

$$S_F(t) \approx \cos\left[2\pi f t - \frac{4\pi d_0}{\lambda} - \frac{4\pi x(t)}{\lambda}\right) + \phi\left(t - \frac{2d_0}{c}\right)] \tag{2-3}$$

By contrasting this function with (2-1), we found that the received radar echo signal is very similar with the transmitting signal. The reason is the phase of the echo signal is modulated by ups and downs of the thorax movement, as well as the delay caused by the distance between people and radar.

After the echo signal and the local oscillator signal are mixing demodulation and low-pass filtering, we can get the following baseband signal $BD(t)$:

$$BD(t) = \cos(\theta + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)) \tag{2-4}$$

Among, $\Delta\phi(t) = \phi(t) - \phi\left(t - \frac{2d_0}{c}\right)$ is the rest of the phase noise, $\theta = \frac{4\pi d_0}{\lambda} + \theta_0$ is the inherent phase shift, it is determined by the distance between radar and the body; θ_0 is caused by the phase shift of the reflection plane, mixer and the distance between the antennas so on.

If θ is an odd number of times of $\frac{\pi}{2}$, and $x(t) \ll \lambda$. According to the principle of small Angle approximation, baseband signal can be approximation for the following type:

$$BD(t) = \frac{4\pi x(t)}{\lambda} + \Delta\phi(t) \tag{2-5}$$

In this case, the best phase demodulation result will come true. When we ignore the influence of the remainder term$\Delta\phi(t)$， baseband signal and the periodic thoracic movement displacement $x(t)$ form a linear ratio. Whenθ is an even multiple of $\frac{\pi}{2}$, baseband signal can be approximated for the following type:

$$BD(t) = 1 - \left[\frac{4\pi x(t)}{\lambda} + \Delta\phi(t)\right]^2 \quad (2\text{-}6)$$

In this case, the baseband signal and time-varying displacement is can't form a linear ratio. When the vibration signal and echo signal are in phase or 180 degree phase shift, it will produce a null point. It could be solved by obtaining two signals which have a 90°phase difference to eliminate the disturbed redundancy. This article designed a special circuit which could catch these signals in the sensor and it will be introduced in next part.

III. DESIGN AND ACHIEVEMENT

The article designed and implemented a RF sensor. The block diagram is presented at figure 1. Crucial parts of the sensor will be introduced in this part.

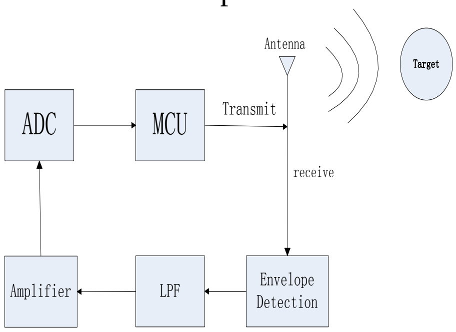


Fig. 1 Block diagram of our sensor design

A. Yagi Antenna Design

With the electronic systems becoming more and more complete, the trend in antenna engineering is tending toward the designs which can realize significant dimension reduction. Printed antennas have the tendency to fit in many fields due to compact sizes, light weight, low cost and ease of fabrication. The Yagi patch antenna has a high directivity, low profile and in recent years has become a hot research. Considering of the simple structure and high directivity, Yagi patch antenna is a fine choice for detecting physiological parameters such as the heartbeat in our daily life.

According to the principle of Yagi antenna design, a higher gain is associated with a larger size. It was balanced between the gain and the size of this sensor. The transmission distance was also taken into account. Yagi antenna was designed as depicted in Figure 1, which consisted of a radiator, a reflector and three director patch elements.

Radiator is the main factor of Yagi antenna. The length of Yagi radiator is equal to half wavelength. For the sake of a suitable size and universal feasibility, the antenna was designed for working at 2.4 GHz ISM band.

According to the work frequency f_0 and the speed of light C_0， we could get the wavelength in vacuum:

$$\lambda = \frac{C_0}{f_0} \quad (3\text{-}1)$$

The original antenna patches are based on the FR4 substrate with the thickness of 1.2 mm. The permittivity of FR4 substrate is ε_r =4.4. When the electromagnetic wave transmits in the dielectric, the speed of light will change:

$$c = \frac{C_0}{\sqrt{\varepsilon_r}} \quad (3\text{-}2)$$

Therefore, the length of the radiator should be shorter than the half wavelength. Using electromagnetism simulation software-HFSS (Version 14.0), this article designed a Yagi patch antenna based on the FR4 substrate with the thickness of 1.2 mm, and size of $154.5*54mm^2$. For a satisfied directivity and higher gain, it adjusted the reflector longer and the three directors shorter at the meanwhile. In general, the width of each element is designed to be the same. This article designed some improvements to reserve space for circuits.

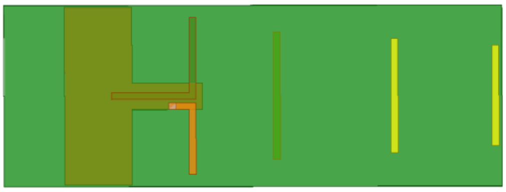


Fig. 2 Yagi antenna design

As Figure 2 shows, this article enlarged the area of reflector and shorted it at the meanwhile which can guarantee the performance.

B. Circuit Design

With the emerging of smart phone, Bluetooth and Wi-Fi become very helpful and effective in our daily lives. Whether Bluetooth or Wi-Fi, which are at the ISM band. Therefore, this paper has designed a Yagi antenna which works at ISM band. The devices and platform for healthcare are always communicate by Bluetooth or Wi-Fi. The sensor was designed for connecting with common facilities. At present, a RF MCU of Nordic company is implemented in our sensor. The features of this MCU are low consumption and embedded transmission protocol. The sensor was designed for working long time in our daily lives, which means low consumption is very important. Those features are very suitable for monitoring and acquiring daily sleeping data.

Design of high frequency circuit is very different from normal circuit design. There might be a variety of unexpected issues emerged because of inappropriate high frequency circuit design. This sensor is an integration of antenna and circuit, which means the circuit part, will be disturbed by the high frequency part. Therefore, it is of vital importance to reduce the disturbance caused by high frequency.

One of the most effective ways is Balun(balanced-to-unbalanced). Usually, the transmitter is regarded as unbalanced and the antenna is regarded as balanced. Balun is a convertor to get the resistance matched. Furthermore, the standing wave will be reduced obviously by the Balun. It is represented on the MCU datasheet about how to design a Balun for this MCU. However, this paper has designed a new Balun to match our antenna. As figure 3 depicted, the layout of components were arranged elaborately to lower power dissipation.

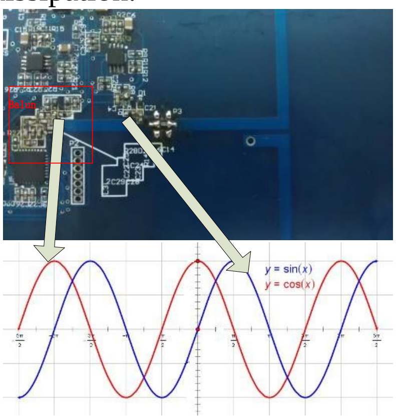


Fig. 3 Special circuits design

It is shown at figure 3. There is a wire whose length is equal to eighth wavelength arranged at the PCB. The width of this wire is 2mm which matches the 50Ohm impedance at the frequency of 2.4GHz. The wire was laid between the MCU and the Yagi antenna. When the MCU transmits and receives a signal through this wire, two different phases signal will be acquired by this line. The signal will get a 90 degree phase difference by the process. After reconstruction, a new signal without null spot will be generated.

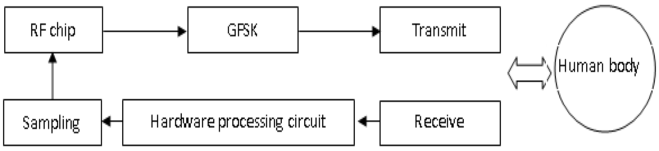


Fig. 4 Block diagram of software design

As it is shown in figure 4, the RF chip was set to transmit a pulse-square wave whose period is 10ms, under the carrier frequency of 2.4GHz. According to previously described, the echo signal has some information about body movement. The design of the circuit can remove high frequency components and demodulate the human dynamic information of low frequency component. And the signals were filtered, amplified. Using the chip with digital converter (ADC) converts signals into 8 hex decimal number coding and encodes into a pulse by GFSK - Gauss frequency Shift Keying. Finally, the pulse is sent under the carrier frequency of 2.4GHz.

In high frequency circuits, the phase of signal changes with the length of the wire. This article has taken advantage of this special characteristic to get two echo signals in one sensor.

C. RF Sensor Implementation

One of the main reasons of using a PCB antenna is to reduce cost. Since the antennas are printed directly on the board, they are generally considered to be free. Integration of antenna and circuits means that the size of the sensor will be optimized, so as to detect the physiological parameters more convenience and take up less space.

Well-implemented PCB antennas will have similar performance to that of a ceramic antenna. However, the performance of the antenna will be changed after adding circuits to the board. In order to make it work at 2.4GHz and have a high gain at the same time, we adjusted the length of radiator and rebuilt ground for the circuits.

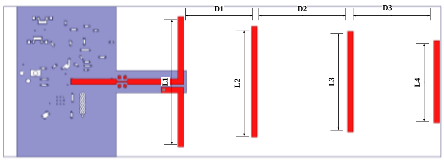


Fig. 5 Main parameters in integration of antenna and circuits

Adding circuits to the original antenna makes the model very complex. For the lines in these circuits are of great subtle and the components are different in irregularity shapes which add a lot of burden to the simulation, especially in the amount of calculation. In order to improve the computing speed and considering our computer's ability, This paper has made some simplification, while simulating such as reducing lines which is of weak effect and reserving the via holes which have a strong influence to the results.

Table1: Main Parameters of the Yagi Antenna

Parameter	L1	L2	L3	L4	D1	D2	D3
Size(mm)	42.6	39.7	36	29.5	24	32	28.45

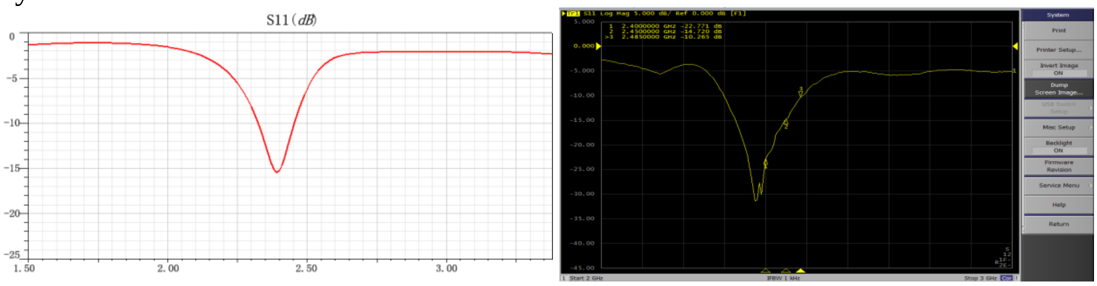
Having simulated by using HFSS, it is notable that if the distance (D1) between radiator and the first wave-guider is shorter than the distance (D2, D3) between the other wave-guiders, then the antenna will get a higher gain. Figure 5 and Table 1 shows the main parameters of the Yagi antenna.

IV. RESULTS AND DISSCUSSION

A. Parameter S11

When the impedance of the antenna mismatches from the feeder line of transmitter or receiver, the system performance will be declined due to the reflection. The sensor is an integration of the antenna and circuits, so it is of great vital of examining the return loss of this design. Parameter S11 is a distinct factor to examine the performance of a RF component.

The software HFSS was employed to simulate and process the data. Figure 6 (a) shows the simulated S11 parameters at different frequencies with a single Yagi antenna which is designed above. The value of S11 is -15.52dB in 2.4 GHz and resonance point is placed exactly at 2.4 GHz as demonstrated. This value is a considerable result which means most of the electromagneticwave is transmitted by designed antenna and only few are returned back. The results demonstrate that the Yagi patch antenna has a nice match in 50*Ω*. It is predicted to have a nice performance in transmitting especially in 2.4 GHz.



(a) Simulated results of the sensor; (b) S11 of the sensor

Fig.6 S11 of simulation and experimental results

Figure 6 (b) shows the experimental S11 results of designed sensor measured by a network analyzer. These are the final results after some experiments. By analyzing the simulated results, some improvements were taken. For instance, the resonance point was deviated from 2.4GHz thus this article enlarged the area of the ground to make the sensor working at the frequency of 2.4GHz.Table 2 shows RL (return loss) of the original antenna and the integrate system at different frequencies.

Table 2: Return Loss of simulation and experiment

Frequency(*GHz*)	2.4000	2.45000	2.485
RL of integration(*dB*)	-15.5225	-10.3145	-7.2068
RL of real sensor(*dB*)	-22.771	-14.720	-10.265

From table 2, the return loss of the sensor evidently shows our improvements' effect. At the frequency of 2.4GHz, the return loss of the sensor reach -22.771dB. The experimental results are better than simulated results after our adjustment.

B. Radiation pattern

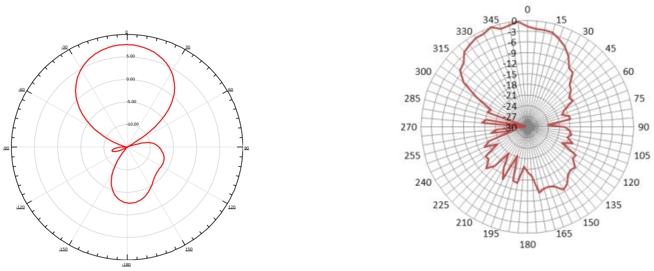
Radiation pattern is another indicator which can depict the performance of an antenna. The results about radiation pattern of sensor were obtained by using software-HFSS to get the simulated results. And the experimental results were obtained at a professional darkroom for microwave measurement. Figure 7 shows the environment of the experiment.

Figure 8 (a) shows the simulated result about co-polarization at electricfieldplane from the sensor. It can be found that there is a maximum gain of 7.71*dB* in the front. And the directionality which concentrates most power in the front and is satisfactory for detecting physiological parameters.

Considering the different method and standard of measurement between the real experiment and HFSS, Figure 8 (b) shows the experimental result about co-polarization at electricfield plane from the sensor.

The parameters of the original antenna were settled after simulating, however, the performance of the antenna was changed totally after adding circuits to it. For the wires and components influenced the antenna profoundly. This paper took some adjustments to improve the performance. The S11 parameter was placed at the first position thus there will be a compromise about radiation pattern.

Fig. 7 Experimental Environment



(a)Simulated result (b)Experimental result

Fig. 8 Radiation pattern of the sensor

Comparing the results, both have a huge front lobe. That means the sensor could concentrate more power on the front and will promote sensitivity effectively. The back lobe of the sensor is larger than simulated result, which might be caused by electronic components. The result is under our consideration and acceptability.

C. Function proving experiment

Some results will be demonstrated in this part. Figure 9 shows sensor and figure 10 show the results of different situation.

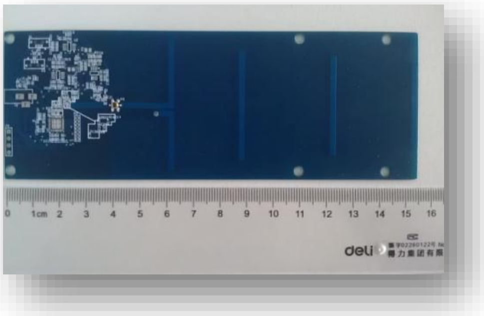
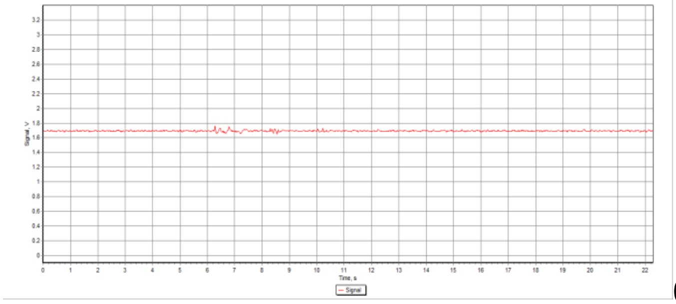
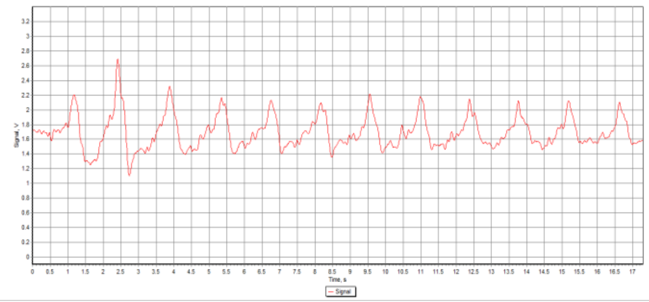


Fig. 9 RF sensor

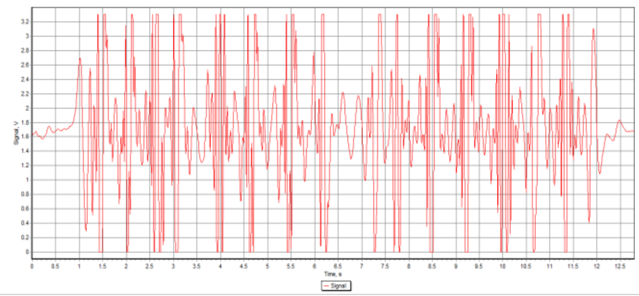
All the results were obtained by the sensor directly and transmit to PC with a receiver. These are original results without any processing. Figure 10 (a) shows the RF sensor working with no objects. Figure 10 (b) presents the respiration test， those peaks represent several breath. Figure 10 (c) shows movements captured by the sensor.



(a) No-object test



(b) Respiration test



(c) Movement test

Fig. 10 results of sensor at different situation.

The sensor could be used for monitoring vital signals during one night. The results can be considered as a collection by a great many of respiration, movements and noises. With appropriate processing and arithmetic, the sleeping condition could be analyzed by this sensor.

V. CONCLUSION

This paper, a RF sensor with single-channel and nonorthogonal IQ signals was designed for contactless monitoring the physiological signs. The maximum gain of our designed sensor in the front is 7.7 dB and VSWR<2. And the chip separates the transmittable signals and received signals by writing program. Also, the directionality of the antenna is satisfactory. After simulation and experiment, it was validated that the sensor could detect the respiration and movements signals.

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