

Miniature Microwave Sensor for Detecting Vital Sign under Low Frequency Motion of Human Subject

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Abstract

In this paper, we propose a microwave sensor circuit that can detect vital sign close to human chest. It operates as a sensor in low frequency movement of human subjects, and circuitry is constructed to realize small size and low power consumption to fit wearable device. A self-oscillating detector and a feedback circuit were connected to the planar microstrip patch radiator designed at 2.4 GHz ISM band. The feedback circuit controls the oscillation frequency which changes in proportion to the movement, thereby stably detecting the heart rate signal through the nonlinear characteristic of the self-oscillating detector. The boards that implement the patch radiator and the circuit board where the active circuits are placed, share the ground plane. Owing to the miniaturized circuit architecture, the sensor consumes only about 20mA current at 5V DC voltage. Besides, measurement results confirm that the proposed sensor can detect the vital sign of the human subject moving with a low frequency within 40 mm from the sensor.

Keywords: Vital sign, microwave, miniature, microstrip, wearable device, oscillator

1. Introduction

RF and microwave sensors are of major interest in biomedical applications as they offer numerous compared to traditional techniques. Specially, the detection of non-invasive vital sign provides convenience for infants, adults, and burn patients who are vulnerable to skin contact. Microwave biosensor using Doppler radar system or existing frequency down-conversion becomes important as one of the alternative, and related studies [1-3] have progressed. However, it is difficult to structurally eliminate the interference of the multiple reflection signals coming from the surrounding object, and it suffers from a problem of size or power consumption to be used as a wearable device. For this purpose, microwave proximity sensors have begun to be studied as miniature sensors. Studies [4-6] have been reported in which the sensor circuit is positioned within a few tens of millimeters from the human body and the heart rate signal is detected at the near field. They extracted the heart rate signal at the fixed position of the near field, but did not consider the effect of human body in motion. On the other hand, recent attempts have been made to offset irregular movements of the human body. Microwave transmission and reception systems [3, 7] have also been used, and a study of a combination of cameras and other sensors has been reported [8]. Such a system is complicated in structure, resulting in large power consumption and hardware size.

In this study, we propose the microwave sensor with miniature architecture that can detect vital sign under the human motion at low speeds within a few tens of millimeters from the human body. A microstrip patch radiator with two mutually orthogonal feed ports in the 2.4 GHz ISM frequency band is implemented, and both a self-oscillating detector (SOD) and a feedback circuit with an RF signal magnitude detector is connected to each port, respectively. The output signal of the feedback circuit controls the oscillation frequency of the SOD, and the heart rate signal is

consequently detected by canceling the motion of the human body. Based on the circuits designed through simulation, prototypes are fabricated to demonstrate the possibility as a heart rate sensor

2. System Configuration

Figure 1 shows a block diagram of the heart rate sensor proposed in this study. The human body is located in the near field of the circular microstrip radiation patch. This sensor is applied to a wearable device whose distance from the human body is within 50mm. The radiation patch has two ports ($P1$, $P2$), which have mutually orthogonal characteristics isolated from each other by about 20 dB or more [9]. Port $P2$ implements a self-oscillating detector (SOD) with transistor $Q1$ and its peripheral circuits through coupling capacitance Cc . The radiation patch acts as a resonator for the 2.4 GHz oscillation circuit at the ISM band. The change of the distance (d) according to the movement of the human body located in the near field of the radiation patch causes the impedance change at the input of the radiation patch. This leads to a change in the SOD oscillation frequency, and then generates a baseband signal indicative of an oscillation frequency change by a self-mixing operation due to nonlinear operation of the transistor. Next, the frequency discriminator is connected to remove the high frequency oscillation signal, and the baseband signals reflecting the motion of the human body including the heart rate signal are output to the final output (V_{out}) through the data processor. On the other hand, the oscillation signal radiated into air through the port $P2$ of the radiation patch is received at the port $P1$ of the radiation patch depending on the distance (d) the near field. The received power is input to the RF detector. The RF detector and the feedback circuit output the voltage (V_c), and are applied to the Varactor diode to control the oscillation frequency of the SOD. This makes it possible to stably oscillate the SOD near a specific frequency within the range of the oscillation frequency, thereby ultimately extracting the heart rate signal

irrespective of respiration or the low frequency movement of the human body.

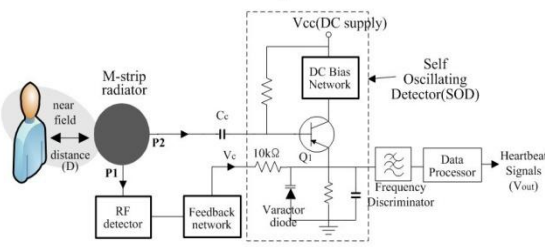


Figure 1: Conceptual architecture for the proposed heart rate sensor

2.1. Assembled Boards and Patch Radiator

The proposed circuit has a simple structure with miniature size and low power consumption. Figure 2 (a) shows side view of the assembled board consisting of three layers. In the top layer, the board for the circular microstrip radiation patch is located, and the control circuitry including the SOD is located in the bottom layer. They share a ground layer and are connected through two via holes. Figure 2 (b) shows the radiation patch structure and two feed positions. The diameter L_d is 48 mm so as to resonate in the

2.4 GHz ISM band. The two feed ports have a distance L_o from the center of the radiator. Both the impedance at the feed port of the radiation patch and the isolation between the ports are affected by the distance (d) away from the human body. Also, the impedance at the feed port is mainly determined by the distance L_o away. The ANSYS HFSS simulator was used to design the optimal feed point and to estimate the isolation level (S_{21}) when the distance (d) was 5 mm and 40 mm, respectively, and the results are shown in Figure 3. The Phantom box shown at the top of Figure 2 (a) mimics the tissues of the human chest where the sensor is located. The tissues are assumed to be mostly occupied by the muscle tissue rather than the skin or fat, and their permittivity and conductivity are listed in Table 1 with reference to the existing studies [10]. As a result of simulation, the optimized distance of L_o is 10mm. The reflection coefficient (S_{11}) and the degree of isolation were calculated based on this value. Finally, better results were obtained when the distance (d) was 40 mm than 5 mm. It is considered that the capacitive capacitance due to the dielectric property existing between the feed ports increases as the human body approaches, thereby affecting the impedance Z_r and enhancing the electric field between the ports. Especially, the isolation between the ports around 2.45 GHz ranges 19dB to 30dB, so that the electrical characteristics of each port are evaluated as independent.

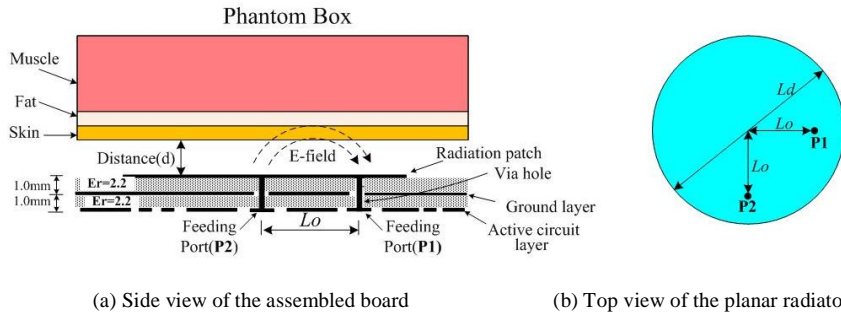


Figure 2: The architecture of the proposed sensor and the geometry of the planar radiator

Table 1: Dielectric characteristics of Human tissue

Tissue	Thickness	Relative Permittivity	Conductivity (S/m)
Skin(dry)	0.5mm	44.6	1.7
Fat	0.5mm	4.4	0.08
Muscle	30mm	54	2.2

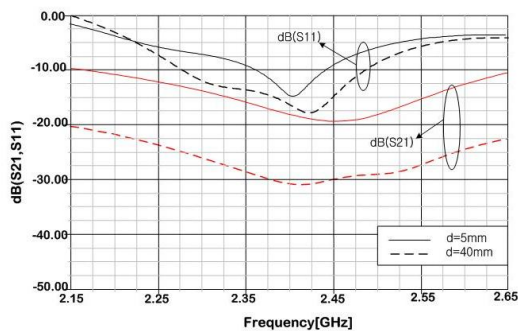


Figure 3: Simulation results of the optimized patch resonator

2.2. SOD Circuit Design

SOD is a circuit that performs both high frequency oscillation and baseband detection by frequency-mixing at the same time by a transistor. It is mainly used in the front-end of a high frequency receiver requiring a miniature circuit structure. Since the circuit structure is simple, power consumption can be drastically reduced. Figure 4 shows the SOD circuit configuration including the

circular radiator for this paper. The circular radiator acts as a resonator of the oscillation circuit and is affected by the phantom box in close proximity. The impedance of the emitter terminal in the BJT (Bipolar Junction Transistor) is fed back in series to satisfy the oscillation condition, and the resonant frequency of the radiator determines the oscillation frequency. In addition, it has a VCO (Voltage Controlled Oscillator) structure that moves the oscillation frequency by applying a voltage (V_c) to a Varactor diode connected to the BJT emitter terminal. The design of the SOD starts with a typical high-frequency oscillator circuit. A detailed design method is described in reference [11], using ANSYS Circuit Designer. Figure 5 shows simulation results to confirm the possibility of oscillation at 2.4 GHz, ISM band. The BJT used here is BFP420 and the voltage applied to the 10KΩ resistor in series with the Varactor diode (Skyworks SMV-1245) is 2V. The input impedance Z_r of the resonator changes according to the distance (d) to the phantom box, so that the oscillation frequency is shifted. The self-mixing effect can be obtained by the nonlinear characteristics of the BJT base and emitter junction diode while maintaining the oscillation condition [12, 13]. At this time, the DC bias at the base terminal of the BJT is set near the diode knee voltage by using the resistor (R_b), so that the nonlinear mixing effect is maximized. Since the circular radiator serves as the receiving antenna, the SOD extracts oscillation frequency variation only from the self-oscillation mixing result. As shown in Fig. 4, the demodulated signal obtained from the emitter terminal of the BJT is input to a low-pass filter where the high frequency signals including the oscillation signal are removed, and the frequency deviation due to the motion of the human body is converted into a low frequency voltage. The final output baseband

signal (V_{bb}) contains human motion information and vital signals.

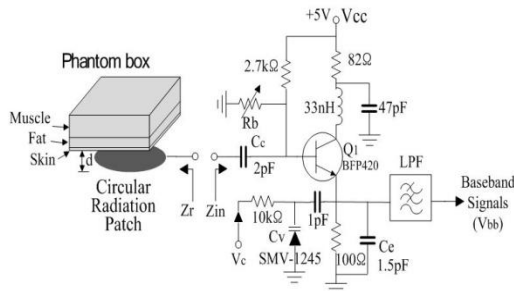


Figure 4: Schematic diagram of the Self-Oscillating Detector

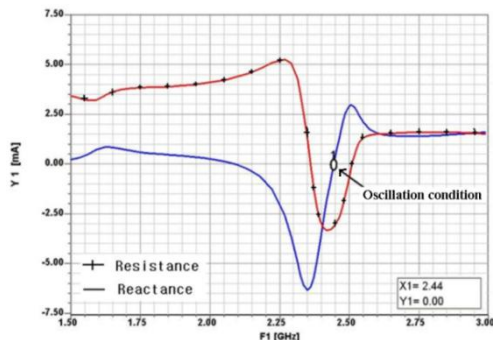
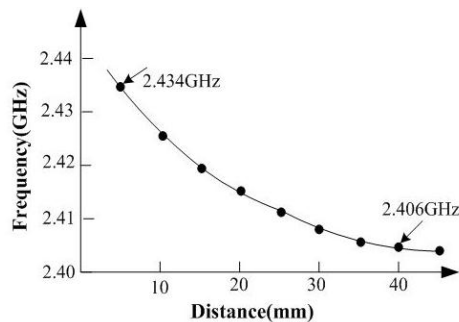


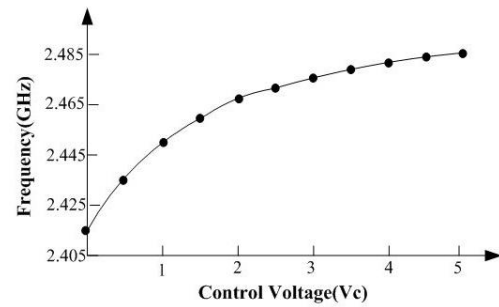
Figure 5: Simulation results to check oscillation condition of the SOD

2.3. Feedback Control Circuit

Heart rate signal has been measured at a fixed position near the human body as a proximate sensor [4]. However, when the human body is in motion, the distance (d) between the sensor and human increases, so that the amount of change in the oscillation frequency increases. In severe cases, the heart rate signal cannot be observed outside the signal processing range. Then, the VCO oscillation frequency can be brought within a detectable range by using a feedback circuit. In this study, the frequency of the human motion is assumed to be 0.5Hz, which is similar to or smaller than the respiration signal. Also, since the movement of the human body is generally much larger than the distance (d) variation caused by respiration, the maximum distance (d) is regarded as 40 mm. First, the simulation results for the distance-frequency variation of the SOD circuit within a distance (d) of 40 mm under the condition that the feedback circuit is not connected can be seen in Figure 6 (a). The frequency difference of about 28MHz can be seen in the 2.4GHz band, and the average distance-frequency variation is 700 KHz/mm. In Fig. 6 (b), the VCO frequency changes with the control voltage (V_c) at the fixed distance (d) of 20 mm and has an average gain of 14 MHz / V.



(a) Frequency variation over the distance (d)



(b) Frequency variation over a control voltage (V_c)

Figure 6: Simulation results for VCO frequency variation

On the other hand, since the two ports of the planar radiator are electrically isolated, port 1 receives electro-magnetic energy radiated from port 2 to air. Figure 7 shows the feedback circuits and the schematic diagram. The high-frequency signal input to the $P1$ port is input to an RF detector (AD8312 of AnalogDevice). The detector outputs the DC voltage V_{do} in proportion to the magnitude of the received high frequency signal power. As shown in Fig. 3, the bigger the distance (d) is, the smaller the isolation between ports (S_{21}) becomes, so the output voltage of the detector is small. The phase is inverted 180 degrees in the inverting amplifier and amplified to an appropriate size using a variable resistor R_{var} . The amplified signal passes through a low-pass filter (LPF) of a Sallen-Key type with excellent cut-off slope. Figure 7 shows the LPF transmission characteristics of OPAMP. Loss of low-frequency signals indicating respiration or movement of human body under 0.6Hz is small, and heart rate signal with higher frequency is removed more than 20dB around 1.3Hz. Therefore, the LPF output signal consists of respiration and human motion signals. However, among these, the signal indicating the motion of the human body is much larger. The LPF output voltage (V_c) is applied to the Varactor diode connected to the emitter terminal of the BJT in the SOD. Feedback circuits are designed to control the SOD oscillation frequency appropriately using the control voltage (V_c). Figure 9 shows both the output DC voltage (V_{do}) of the RF detector and SOD control voltage (V_c) signal when the distance (d) varies 5 to 40 mm. The V_{do} has a range of 0.25 to 0.5V. On the other hand, when the distance (d) is larger than 40 mm, the V_{do} is smaller than 0.25 V, and the SOD oscillation frequency also decreases. If it gets worse, it is outside the control range of the feedback circuit. The opposite case in which the distance (d) is reduced to less than 5 mm is similarly explained.

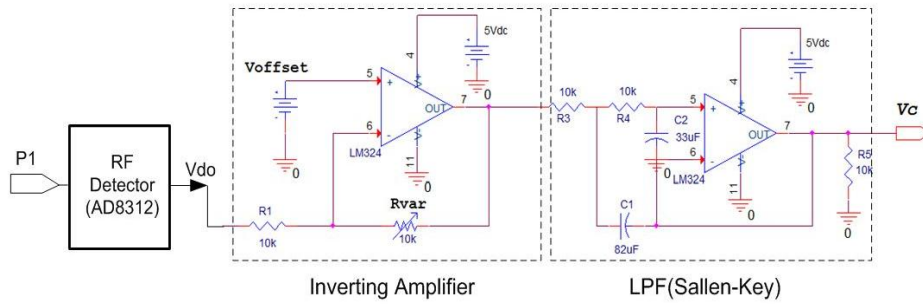


Figure 7: Schematic diagram of the feedback path

The magnitude of the V_{do} is controlled through R_{var} in the inverting amplifier circuit, and the center voltage of the waveform is adjusted using V_{offset} . It can be seen that a small spike type heart rate signal is placed on V_{do} waveform, and the control voltage (V_c) shows that the heart rate signal size is remarkably reduced. The voltage (V_c) whose phase is inverted is amplified about 5 times or more and has a range of 1 to 3V. At this time, the oscillation frequency of the SOD has a frequency range of 20MHz around 2.45GHz as shown in Fig. 5 (b), and thus it is possible to stably detect the heart rate signal in the SOD circuit. The detector output voltage (V_{do}) in figure 8 seems to show periodic motion, but it is estimated that irregular movement of the human body with low frequency can be controlled sufficiently.

the sensor is slowly moving forward and backward within 15 beats / min between 5 and 40 mm centered on the 20 mm point in front of the center of the human chest.

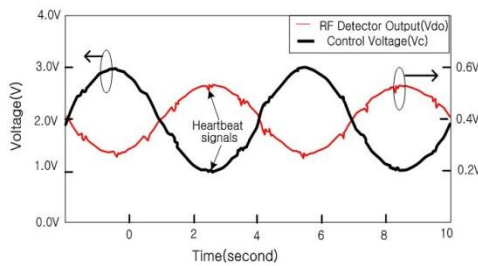
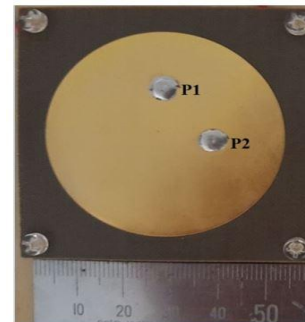


Figure 8: Electrical characteristics of the feedback circuit

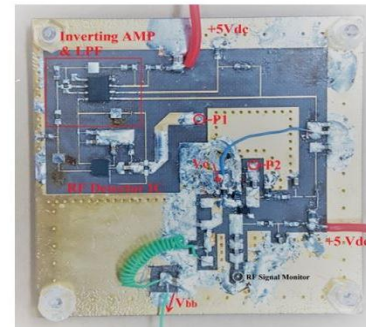
3. Test Results and Discussion

In the prototype of Figure9, the patch radiator and the active element circuit parts are independently fabricated on the printed circuit boards and stacked. They have size of 60 mm x 60 mm, and both of them has dielectric constant of 2.2, loss tangent of 0.0009, and thickness of 0.76 mm. Figure 9 (a) shows a photograph of a circular radiator with feeding ports ($P1$, $P2$). Figure 10 (b) shows that $P1$ and $P2$ ports are connected to each other via holes. On the board in Figure 9 (b), SOD circuit and feedback circuits are arranged, DC power consumed with +12mA at 5V is estimated to be small enough. In the final output signal V_{bb} of the board, the high frequency signal of the ISM band and noises are removed.

The oscillation signal spectrum of the prototype was observed at the RF signal monitor terminal during increasing the distance (d) from 5mm, as shown in Figure 10. In the meantime, the control voltage (V_c) has been fixed at 2 V. At the distance of 40mm, the frequency was the smallest and the 28MHz variation was measured around 2.42GHz. Figure 11 shows a system for measuring heart rate signal. The final output signal (V_{bo}) of the prototype is observed on the time axis by the oscilloscope and acquired by NI9234 (by National Instrument) with AC coupling mode. The analog signal is digitized with noise signal removed, and transformed into frequency domain. To verify the performance of the developed vital signal sensor, a reference heart rate signal by finger-pressure heart rate sensor (UFI-1010) is measured at the same time. The heart rate signal is observed while



(a) Radiation patch in the top layer



(b) Circuit layer in the bottom layer

Figure 9: Photograph of the fabricated prototype

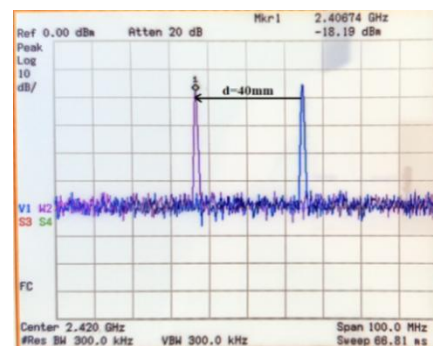


Figure 10: Oscillation frequency shift over the distance (d)

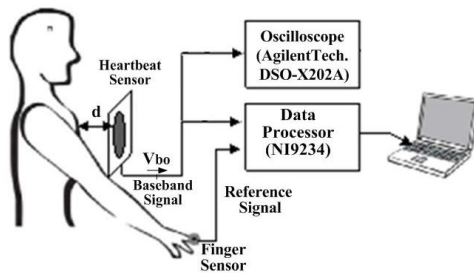


Figure 11: Measurement setup for heart rate signal detection

Figure 12 (a) shows the result of measuring the output signal (V_{do}) of the sensor by removing noise and averaging using an oscilloscope without connecting the feedback circuit. It is observed that periodic small spikes showing a heart rate centered on a DC offset voltage of 1.0 V are placed on a large voltage change indicating the motion of the human body. Figure 12 (b) shows the measured AC coupled output signal (V_{do}) compensated through the feedback circuit. Periodic heart rate signal with noise were measured. This is compared with the finger pulse sensor signal (frequency 1.3 Hz) of Figure 12 (c) used as the reference signal. Both signals show the same number of peaks implying the heart rate signal. Figure 13 shows the result obtained by converting the voltage signal of Figure 12 (b) into the frequency domain. It can be seen that the heart rate signal with 1.3Hz is relatively larger than that of the signal of 0.2Hz which indicates the motion of the human body, which proves the effectiveness of the feedback circuit. Thus, the measured heart rate signal is evaluated to be consistent with that of the pressure pulse sensor used as the reference signal, indicating that heart rate signal can be observed for human motion within the 40 mm range.

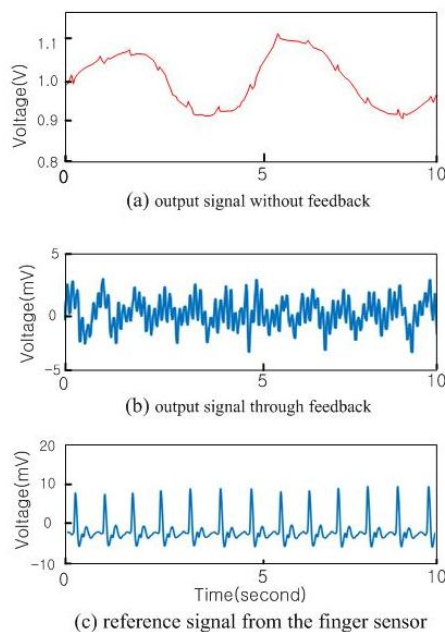


Figure 12: Measured results for heart rates

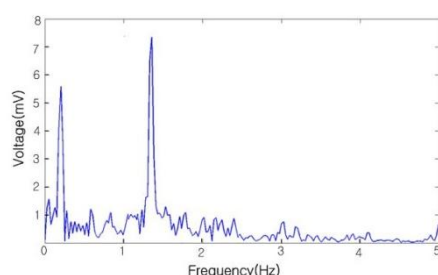


Figure 13: Frequency spectrum of the output signal (V_{bo}) with feedback

4. Conclusion

We proposed a compact proximity sensor that can detect the heart rate signal in the movement of the human body. The circular microstrip radiator operating in 2.4GHz band is combined with both self-oscillating detector and feedback control circuits. The self-oscillating detector works for detecting the heart rate signal, and the feedback circuit controls the oscillation frequency of the SOD. Thanks to simple hardware structure, the prototype size of the built board is small enough as $60 \times 60 \text{mm}^2$, and battery consumption can be reduced to low power consumption (DC current 20mA at 5V). The validity of the proposed structure is demonstrated by detecting the heart rate signal consistently even in human motion within a distance of 40 mm from the chest of a human body.

The proposed heart rate sensor can be used as a wearable device attached to the wrist of a human body, a seat belt of a human body, a blanket of a bed, or clothes as well as a chest area.

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