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Simplified wrist-worn heart rate sensor using microwave VCO

C. McFerran, A. McKernan, and N.B. Buchanan

This paper presents a novel, wrist worn heart rate sensor, which is comprised of only a passive resonator and a voltage controlled oscillator (VCO). It is clearly demonstrated that valid heart rate data can be extracted off the DC bias circuit of the VCO, making this sensor one of the simplest of its kind ever reported. Experimental results are shown for successful measurements of the user's heart rate when the VCO was tuned to 2.42GHz, with a DC bias voltage fluctuation of up to 10 mV representing the heart rate. These results are in agreement with those taken using a commercial optical sensor based heart monitor.

Introduction: Over the past number of years, there has been a large number of studies made into the field of measuring physiological information like heart rate, respiration, blood pressure and oxygen saturation levels (SPO₂). The tracking and monitoring of this information can lead the diagnosis of cardiovascular disease and other serious heart conditions. For these sensors to be able to work most effectively in any care environment they are required to be non-invasive, low-cost, reliable and robust for long term long patient monitoring.

There has been considerable studies in employing sensors using microwaves to detect vital signs [1-3]. These can be subdivided into two main categories of wearable and non-wearable. In this paper we focus on the wearable sensor, which has the advantage of 24/7 health monitoring, whilst the patient goes about their everyday activities. With non-wearable sensors the user is required to be a short distance away from the sensor antennas and must not move during the measurement, which usually detects vital signs around the chest area. The architectures for the microwave sensors vary considerably in complexity. In [1] a 5.8 GHz transceiver architecture was employed with full IQ demodulation capability on the receiver. In [2], a much simpler wearable architecture which utilised a Doppler Radar sensor coupled with an envelope detector was shown. In this paper we present what we believe to be the simplest microwave sensor configuration reported, requiring only a simple VCO circuit coupled to a passive resonator. Although a commercial off the shelf VCO device is used, the VCO could potentially be fabricated from a single active device and be extremely low powered. Typical power consumptions obtained from 2.4 GHz VCOs are in the range of 0.35 mW [4].

The wrist worn pulse sensor reported here proposes considerable simplifications to other reported variants, such as [3]. In [3] the configuration involved a sensor oscillator, which within its feedback loop had an interdigitated resonator placed on the patient's wrist. Variations in resonance caused by the pulse created changes to the oscillation frequency. By injection locking the sensor oscillator to a PLL circuit, the frequency variations on the VCO could be picked up by variations on the PLL control voltage. In this paper we are proposing a much simpler circuit, shown in Fig. 1. Here we use the known relationship [5] that a change in the load impedance of an oscillator will cause a corresponding change to its free running frequency and consequently a change to its DC bias current. To extract the pulse data from this circuit we simply measure the voltage variation across the resistor placed in series with the DC power supply. This variation, after some low frequency amplification and post processing, provides the measured pulse rate. The VCO used was a Mini-Circuits ROS-3000-819+, chosen for its large frequency range and also high rate of frequency pullability, which should provide the largest change in DC supply current with variation in bias current.

Design: The passive wrist mounted interdigitated resonator followed a design similar to that reported in [3]. The important property of this resonator is that it provides a large variation in impedance with variations of the pulse. The return loss of the resonator is shown in Fig 2. Here, the optimum frequency of 2.42 GHz provides the steepest gradient of the resonance curve, when the sensor is worn on the skin, therefore small dielectric variations caused by the radial artery on the

wrist dilating and non-dilating (pulses) produce changes to the frequency response of the resonator and consequently a change in the S11. This then changes the load impedance of the VCO, providing a corresponding change to the VCO bias current, which can be measured via the oscilloscope. It is possible that the S11 of the resonator can vary within a certain range due to variations in the mounting to the skin and also due to different skin compositions such as moisture content. Since the sensor system uses a VCO it is possible to counteract this effect by always tuning the VCO's frequency to the steepest point in the resonance curve, dependant on the subject being measured. It is likely this could be automated in future designs, where the VCO can be varied within a predefined range until the optimum pulse response is obtained, this could allow the system to be "recalibrated" to allow for variations if the sensor is worn for a long period of time.

Fig. 1 Wrist worn VCO based pulse sensor circuit.

Measured Results: The aim of these measurements is to provide results to show that the VCO based pulse sensor is able to produce similar heart rate data in comparison to results taken when the wrist worn resonator was connected to a Vector Network Analyser. Reference measurements were also taken using an optical pulse sensor on a "smart watch" device.

In order to measure the user's heart rate, the resonator was required to be consistently placed on the user's wrist. Figure 3 shows the mounting that was used which allowed the resonator to be coupled to the user's wrist without the sensor moving. This also allowed the user to stay in the test position for prolonged periods without too much discomfort. The plastic housing was setup such that the sensor could be positioned where there was a small air gap left between the resonator the user's wrist. The location where the resonator was in contact with the skin was chosen to be directly over the radial artery [6].

Fig. 2 S11 measurement of resonator.

At the commencement of the measurement, with the user's wrist placed over the sensor, an S11 frequency sweep was carried out to the resonator to determine the frequency where the resonance curve was steepest, thus providing the greatest sensitivity to small changes in S11 caused by the users pulse. The frequency used was 2.42 GHz, as per the graph of Fig 2. After this, an S11 Vs time sweep for a constant frequency was performed to measure the changes to S11 with respect to time. The results were then post processed using Matlab software where two separate filter functions were applied to remove both low frequency

and high frequency noise signals. The data was also normalized to allow a peak counting algorithm to be employed. This result, shown in Fig. 4(a) shows that the user had an average heart rate of 60 beats per minute (BPM). This was in agreement with measurements taken with a commercial wearable heart monitor, which stated their heart rate was in the range 60 – 64 BPM during the course of the experiment.

Fig. 3 Pulse measurement setup
a Resonator in free space
b Wrist placed on resonator

Fig. 4 Measured results from pulse sensor
a VNA S11 Vs time
b VCO DC voltage variation Vs time

Once heart rate pulses were measured from the VNA, the next step was to connect the resonator to the VCO, as per the block diagram of Fig 1. With the user's wrist placed over the sensor, the VCO was first tuned to a free running frequency of 2.42 GHz, confirmed by using a spectrum analyser. This was achieved by applying approximately 5.5 V to the V_{TUNE} port of the VCO circuit. The level of frequency pullability of the VCO was also confirmed as there was found to be a frequency shift of the free running frequency of 4.608 MHz when the sensor was connected to the user's wrist, compared to the sensor in free space. With the free running frequency correctly set and the users wrist placed over the sensor, the variations in DC bias current were measured using the digital oscilloscope. These results were post processed using Matlab software in a similar manner to the VNA results from before. The results of Figure 4(b) shows that the user had an average heart rate of 60 beats per minute (BPM). This was in good agreement with a commercial wearable heart monitor, which stated that their heart rate was in the range 59 – 65 BPM for the duration of the experiment. A comparison of the results of Figure 4 clearly show that the simple VCO/resonator detector is able to produce a similar quality result compared to the same wrist worn resonator connected to a VNA.

Conclusion: This paper describes a novel Voltage controlled oscillator based sensor for wrist pulse heart rate detection. The proposed sensor is comprised of a microstrip interdigital capacitor which employs the concept of proximity coupling with the user's radial artery to produce a change in DC voltage at the VCO to model the pulse of the user's heartbeat. This change in DC voltage occurs because the S-parameters, particularly S11, are affected by the change in tissue characteristics when the radial artery dilates and non-dilates due to the pulses of the users heartbeat. The pulses can cause a change in DC voltage of the VCO of about 10 mV. The proposed sensor would be an excellent candidate for a non-invasive type heart rate monitor for 24/7 ambulatory health care, with a potentially very low power consumption.

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