A Frequency-Shift Readout System for FPW Allergy Biosensor

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***Abstract*— In this paper, an IgE antigen concentration measurement system using a frequency-shift readout method for a two-port FPW (flexural plate-wave) allergy biosensor is presented. The proposed frequency-shift readout method adopts a peak detecting scheme to detect the resonant frequency. A linear frequency generator, a pair of peak detectors, two registers, and an subtractor are only needed in our system. According to the specification of the FPW allergy biosensor, the frequency sweep range is limited in 2 MHz to 10 MHz. The sensitivity of the peak detector is 0.8 mV. The proposed frequency-shift readout circuit is verified on silicon by using a standard 0.18 μm CMOS technology. The maximal power consumption is 12.94 mW@0.1 MHz clock given by HSPICE simulations.**

***Keywords*—IgE antigen, frequency-shift readout circuit, FPW, resonant frequency, peak detection.**

I. Introduction

Due to rapid growth of the biomedical electronics market, *in vitro* bio-analytical applications are quickly developed to help medical staffs to perform pathologic analysis. Many people have been suffered by many allergic diseases, e.g., allergic rhinitis, which may cause uncomfortable feeling. In human serum, concentration of immunoglobulin E (IgE) is an important indicator to show the allergic level therein [1]. Conventionally, many commercial allergy measurement instruments are adopted to measure IgE concentration, e.g., enzyme-linked immunosorbent assay (ELISA) [2], surface plasmon resonance (SPR) [3], and quartz crystal microbalance (QCM) [4] sensing techniques, etc. Unfortunately, these commercial allergy measurement devices require multifarious testing samples, long operation time for sampling analysis procedures, expensive analysis instruments, and lot of analysts. Therefore, a low cost, high speed, and high precision for allergic level estimation is very much needed for those who are suffered.

A two-port allergy biosensor based on an ultrasonic flexural plate-wave (FPW) technique was proposed in [5]. The FPW allergy biosensor adopts the Cr/Au interdigital transducers (IDTs) to be a transmitter and a receiver, which are, respectively, placed on the right and left side on a thin plate. According to the investigation results, the sensitivity of the FPW allergy biosensor is $-8.5 \times 10^7 cm^2 g^{-1}$. Notably, the resonant frequency of the FPW allergy biosensor is variable, which is roughly anti-proportional to the purified human IgE antigen concentration. Thus, the FPW-based allergy biosensor shows another IgE antigen concentration measurement method. In this investigation, a frequency-shift readout system for the two-port FPW allergy biosensor is presented to reduce the operation time and cost. The proposed frequency-shift readout system is realized by a standard 0.18 μm CMOS technology. According to the resonant basics, the output signal amplitude of the FPW allergy biosensor will be maximum when the input frequency is equal to the central resonant frequency. Therefore, a high sensitive peak detector is needed to detect the maximum peak voltage and generate an enable signal to trigger a register to snapshot the frequency value. By calculating the difference between resonant frequencies of sensor1 (with antigen) and sensor2 (without antigen), the frequency-shift value is attained such that the IgE antigen concentration can be estimated. The power consumption of the proposed frequency-shift readout circuit is found to be 12.94 mW at a 0.1 MHz system clock.

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II. Frequency-Shift Readout Circuit

The FPW allergy biosensor propagates an acoustic wave via a mechanical thin plate as shown in Fig. 1. Refereing to [5], the resonant frequency of the FPW device can be expressed as follows.

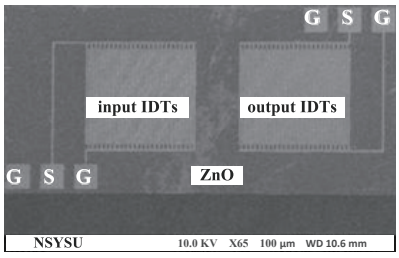

Fig. 1. Photo of the FPW sensor

$$\frac{\Delta f}{f_0} = S_m \Delta m = S_m (MW \times C_S) \tag{1}$$

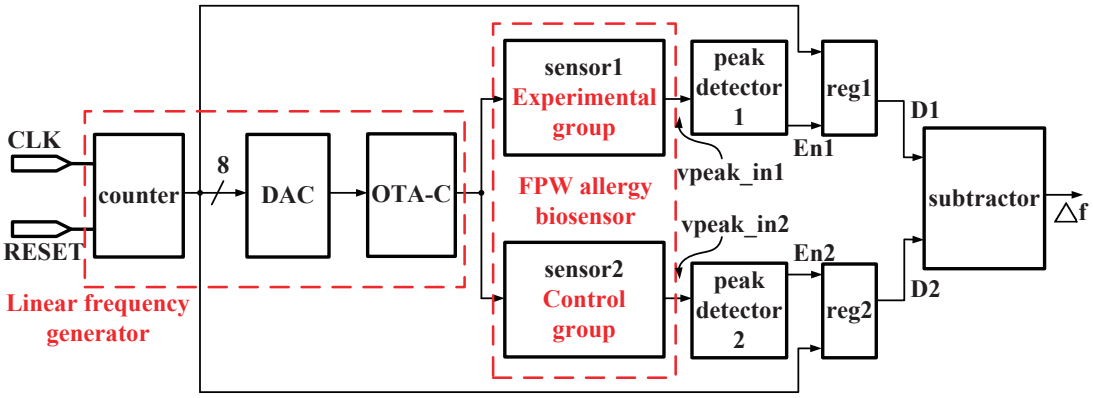

Fig. 2. Schematic of the frequency-shift readout system

where f_0 is the initial resonant frequency, Δf denotes the variation of the resonant frequency, and the mass per unit area and the mass sensitivity are, respectively, denoted as S_m and Δm. MW is the molecular weight and C_S is the surface concentration of the absorptive moleculars. Therefore, Δf can be changed by C_S as well as the IgE antigen concentration . According to the phenomenon of FPW allergy biosensor's frequency shifting, we propose a novel frequency-shift readout circuit to estimate the amount of the frequency shifting. Fig. 2 shows the proposed frequency-shift readout system, which is composed of a counter, a DAC (digital-to-analog converter), an OTA-C oscillator, a pair of peak detectors, two registers, and a subtractor. The detailed description of each subcircuit is explained in following subsections.

A. Linear frequency generator

A sine wave generator is required for the FPW biosensors to generate all of the frequencies in the pre-defined range. As shown in Fig. 2, the counter is a typical digital 8-bit up-counter generating 0 to 256 up counting signal to the DAC. The 8-bit DAC utilizes a current-steering structure with a current complement circuit as shown in Fig. 3. The 8-bit DAC requires only 8 current sources with different sizes instead of $2^8 - 1$ sources. To reduce the error of the 8-bit DAC output voltage, the current complement circuit generates an appropriate complement current to vout. Therefore, the performance of the proposed DAC can be enhanced regarding integral non-linearity (INL) and differential non-linearity (DNL). Given an input binary code, vout can be set to an appropriate potential to provide the OTA-C oscillator a bias voltage.

The schematic of the tunable OTA-C oscillator is shown in Fig. 4 [6]. OTA_VB is given a proper bias voltage to ensure correctness of each OTA's functionality.

Gm1, Gm2, Gm3, and Gm4 are the same operational transconductance amplifier (OTA) as the one shown in Fig. 5. Assuming MP502=MP503 and MN502=MN503, the drain-source currents of MP502 and MP501, i_{dP502} and i_{dP503}, are expressed as follows.

$$-i_{dP502} = i_{dP503} = \frac{g_m}{2}(VP - VN) \tag{2}$$

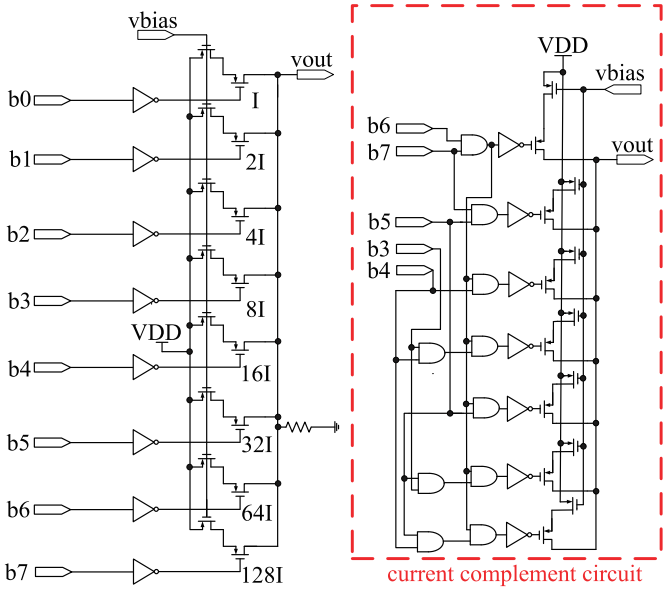

Fig. 3. Schematic of the 8-bit DAC

Furthermore, the gain of the OTA is given by

$$Av = \frac{Vo}{VP - VN} = g_m(r_{oP501}||r_{oN501}) \tag{3}$$

If the impedance of output load is smaller than OTA output resistance at a higher frequency, the output current, *io*, can be written as Eqn. 4.

$$io = i_{dP501} - i_{dN501} \tag{4}$$

Finally, we can derive the OTA's transconductance as follows.

$$g_{mOTA} = \frac{io}{VP - VN} \tag{5}$$

However, the transconductance of Gm1 can be adjusted by tuning the bias, Vtune, from output of DAC. Referring to Fig. 4, Gm1-C1 and Gm2-C2 constitutes a 2nd-order RC oscillator with a positive feedback to generate an oscillation signal. On the other hand, Gm3 and Gm4 is used to keep the peak-to-peak

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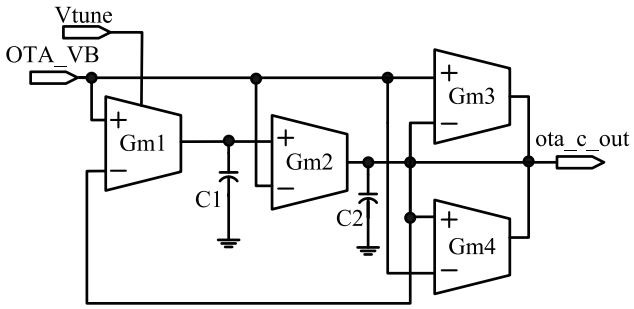

Fig. 4. Schematic of the OTA-C oscillator

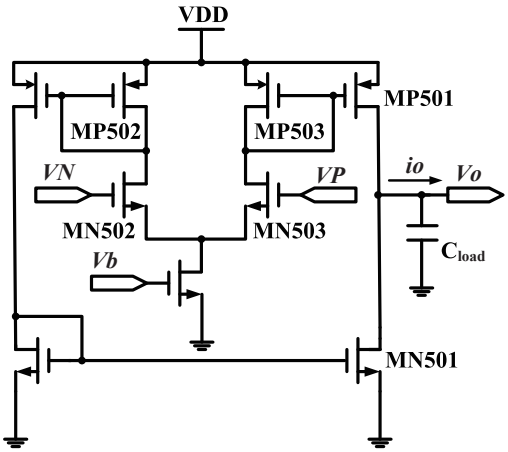

Fig. 5. Schematic of the operational transconductance amplifier

amplitude of the generated sine wave. The frequency tuning range of tunable OTA-C oscillator is limited from 2 MHz to 10 MHz according to the specification of the FPW allergy biosensor.

B. Peak detector

The output signal of the FPW allergy biosensor will reach its peak value when the input frequency equals to the resonant frequency. A peak detector is, then, used to detect the maximum peak from the FPW allergy biosensor output and the determine the frequency value. Fig. 6 shows the proposed peak detector. The detailed operating steps of the peak detector is explained as follows.

Step1: Initially, RESET1, RESET2, and RESET3 are biased at high to discharge C1, C2 and reset the D flip-flop.

Step2: The sine wave from FPW allergy biosensor's output is fed to VIN. When VIN is higher than VPEAK1, OPA1 will turn on MN603. Then, C1 is charged until VPEAK1 $\geq$ VIN.

Step3: MN603 is off to isolate VPEAK1 from VPEAK2. If VPEAK1 is higher than VPEAK2, OPA2 will trigger the D flip-flop. Then, EN is pulled high to turn MN603 on. Hence, VPEAK2 is pulled close to VPEAK1 through MN603. If VPEAK1 is not higher than VPEAK2, VPEAK2 keeps the prior high voltage value.

Step4: When VPEAK2 is equal to VPEAK1, RESET3 will be pulled up high to reset the D flip-flop to set EN=0. VPEAK1 and VPEAK2 are isolated again by MN603.

By the above steps, the peak detector can generate the enable signal, EN, to enable the register and store the current counting number in the counter. Therefore, the resonant frequency of the FPW allergy biosensor is detected by the proposed peak detector. The sensitivity of the peak variation is 0.8 mV. By the subtraction reg1 from reg2, the frequency-shift variation, $\triangle$f, can be derived.

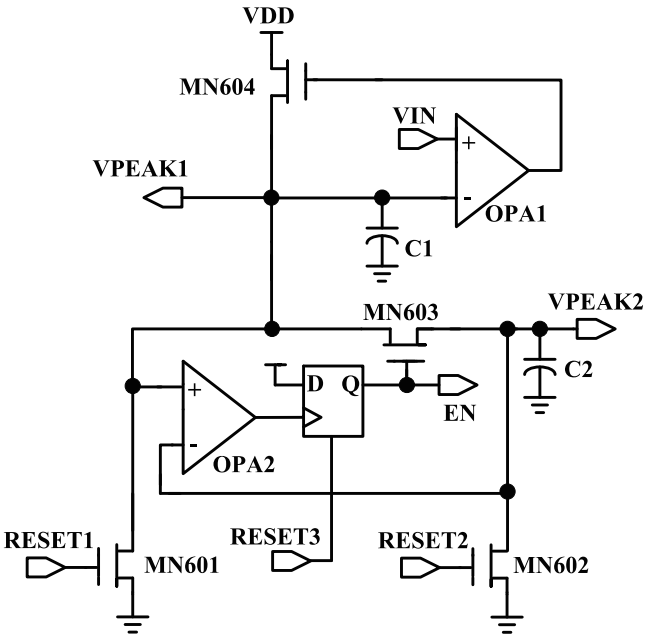

Fig. 6. Simulation of the peak detector

III. Implementation and Simulation

The proposed frequency-shift readout circuit for FPW allergy biosensor is realized on silicon by TSMC (Taiwan Semiconductor Manufacturing Company) standard 0.18 μm CMOS technology. Fig. 7 shows the whole chip layout including I/O PADs of the proposed design. The chip area of the proposed RC5 is 1148 $\times$ 1148 μm^2. The FPW allergy biosensor is converted into an equivalent RLC model, which is added in the proposed frequency-shift readout system to run the HSPICE simulation. The simulation results of the peak detector are illustrated in Fig. 8. When the amplitude of vpeak_in1 is higher than the prior peak, vpeak2 will be pulled to the same position as vpeak1 and $\overline{\text{En1}}$ becomes low. Therefore, the register, reg1, is renewed to store the current frequency of the

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Experimental group FPW allergy biosensor. On the other hand, reg2 is renewed to take the current frequency of the Control group FPW allergy biosensor. The frequency-shift variation is calculated by the subtractor. The power consumption is 12.94 mW at a 0.1 MHz clock. The comparison with a similar prior work is tabulated in Table I.

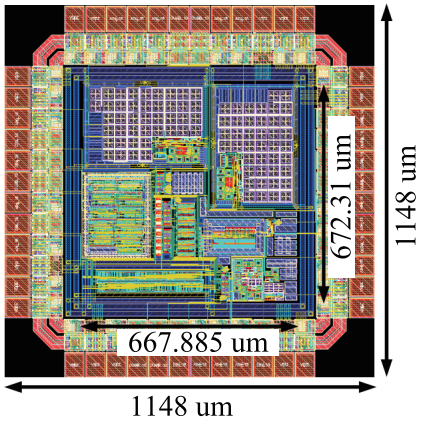

Fig. 7. Layout view of the proposed frequency-shift readout circuit

TABLE I

COMPARISON WITH PRIOR WORK

	proposed	[7]
Implementation technique	system on chip	on PCB discretes
Detecting method	peak detection	phase detection
Process (μm)	0.18	N/A
Supply voltage (V)	1.8	N/A
Frequency (MHz)	0.1	4.2
Power (mW)	12.94	N/A
Year	2010	2008

IV. CONCLUSION

This paper presents a frequency-shift readout circuit for a two-port FPW allergy biosensor. The linear frequency generator generates a linear frequency sweep fed into the FPW allergy biosensor. The peak detectors are adopted to detect the resonant frequencies of the Experimental group and Control group of the two-port FPW allergy biosensor. The detected resonant frequencies are stored in the registers, reg1 and reg2, respectively. The frequency-shift value is derived by the subtraction of reg1 from reg2. By using the semiconductor technique, the proposed frequency-shift readout circuit is fabricated on a chip by TSMC standard 0.18 μm CMOS technology.

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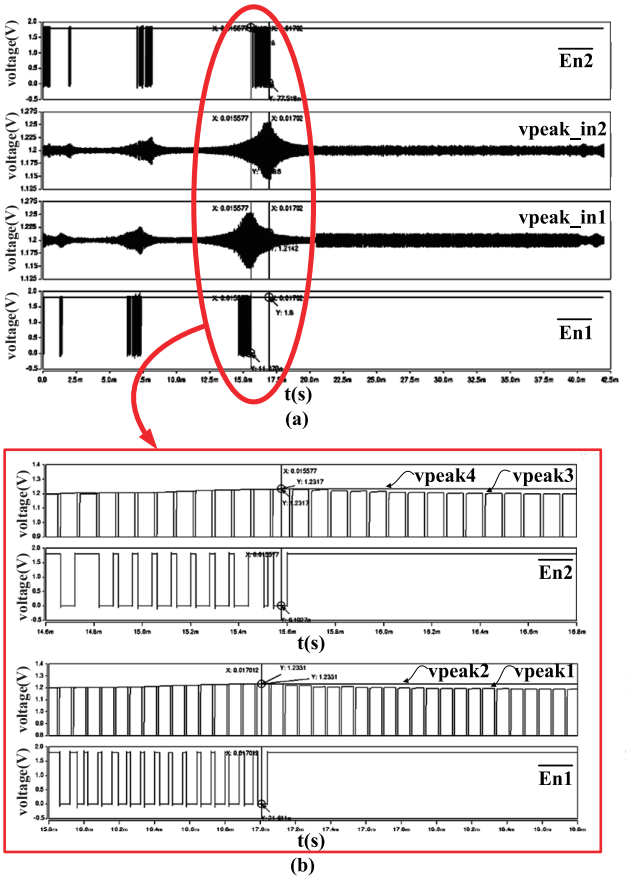

Fig. 8. Simulation of the frequency-shift measurement

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