Digitally-Controlled Gm-C Bandpass Filter

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***Abstract*—This paper describes digital auto-tuning schemes for second-order Gm-C bandpass filters which are suitable for fine CMOS implementation. We propose a switched Gm-C analog filter and two digital tuning schemes: a center frequency tuning scheme using the phase information and a Q factor tuning scheme using the magnitude information. We present circuits, describe their operations, and present SPICE simulation results.**

Keywords-Gm-C bandpass filter; Auto-tuning; Center-frequency tuning; Q-factor tuning

I. INTRODUCTION

In recent years, wireless communication technology has evolved dramatically due to the rapid advancement of LSI technology, and analog bandpass Gm-C filters play a crucial rule in mobile phone, wireless LANs, and Bluetooth transceivers [1]-[6]. This paper describes a digitally-controlled Gm-C bandpass filter which is suitable for several communication standards and fine CMOS implementation.

II. SWITCHED Gm-C BAND-PASS FILTER

1) OTA circuit.

There are two methods used to implement continuous-time analog filters; one is to use operational amplifiers (highly linear, power hungry, limited bandwidth) and the other is to use operational transconductance amplifiers (OTA, Gm cell; limited linearity, low power, wideband). Here we consider the use of OTAs for implementing a continuous- time analog filter.

Fig. 1 shows a differential OTA circuit, and the OTA is a voltage-controlled current source. Note that the term "operational" comes from the fact that the amplifier takes the difference of two voltages as its input for current conversion, and its ideal transfer characteristics is given as follows:

$$I_o = I_{o+} - I_{o-} = gm(V_{i+} - V_{i-}) \quad (1)$$

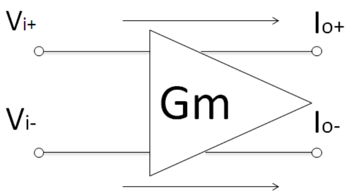

Fig. 1 Differential transconductance amplifier.

A Gm-C integrator can be implemented by connecting a capacitor to the OTA output. Fig. 2 shows a Gm-C integrator, which is the basic element of the Gm-C bandpass filter, and works by converting the input voltage difference to two currents Io+ and Io-. These two currents then flow into the capacitors and their difference results in a differential output voltage. The transfer function is express as follows:

$$V_{o+} = \frac{I_{o+}}{sC} = \frac{gm}{2sC}(V_{i+} - V_{i-}) \quad (2)$$

$$V_{o-} = \frac{I_{o-}}{sC} = -\frac{gm}{2sC}(V_{i+} - V_{i-}) \quad (3)$$

$$V_o = V_{o+} - V_{o-} = \frac{gm}{sC}V_i \quad (4)$$

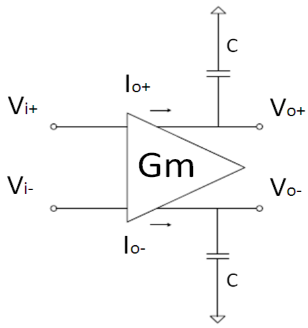

Fig. 2 Gm-C integrator.

2) Proposed Switched Gm-C Integrator

Fig. 3 shows a Gm-C configured using switches to make the Gm characteristic digitally controllable. The fraction part of Gm is adjusted by the first switch (which is controlled by ΔΣ modulation) and the integer part is adjusted by the other switches. Thus continuous adjustment can be realized.

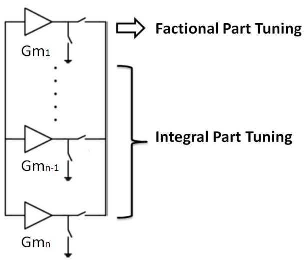

Fig.3 Switched Gm-C integrator.

The integer part adjustment module can be achieved in a straightforward manner: ON-OFF states of the switches are fixed. To realize fractional adjustment of Gm, we use a 1-bit ΣΔ modulator (Fig.4) to take advantage of fine CMOS switching speed. Fig. 5 shows MATLAB simulation results.

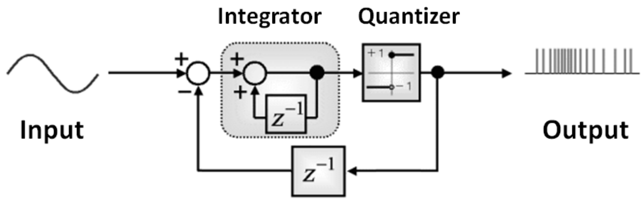

Fig. 4 1bit Δ Σ converter.

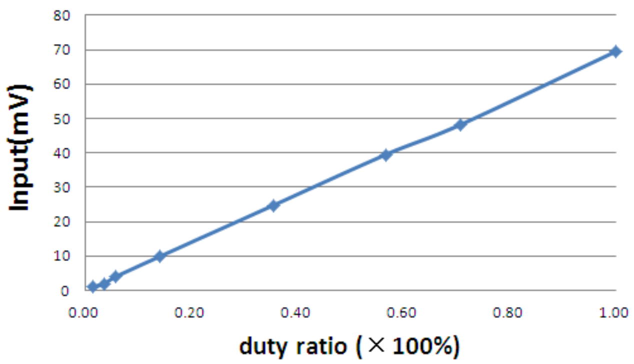

Fig. 5 Relationship between input voltage amplitude and duty ratio (simulation results).

A. Gm-C Bandpass Filter.

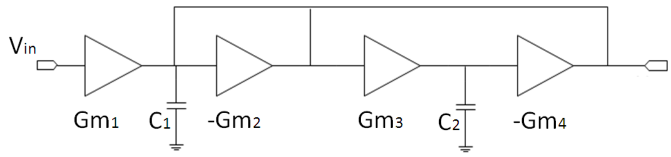

Fig. 6 Gm-C second-order bandpass filter.

Fig. 6 shows the structure of a second-order Gm-C bandpass filter. By implementing Gm cells with CMOS inverters (Nauta OTAs), this can operate at high frequencies with a low-voltage supply. Its transfer function is given by

$$H(s)=\frac{gm_1C_2s}{s^2C_1C_2+sC_2gm_2+gm_3gm_4} \quad (5)$$

which can be generalized as

$$H(s)=\frac{K\omega_0 s}{s^2+\omega_0 s/Q+\omega_0^2} \quad (6)$$

Poles ($p1$, $p2$) of the transfer function are as follows:

$$p_1=-\frac{\omega_0}{2Q}+j\omega_0\sqrt{1-\frac{1}{4Q^2}} \qquad p_2=-\frac{\omega_0}{2Q}-j\omega_0\sqrt{1-\frac{1}{4Q^2}}$$

where

$$\omega_0=\sqrt{\frac{gm_3gm_4}{C_1C_2}},\ Q=\sqrt{\frac{C_1gm_3gm_4}{C_2gm_2^2}},\ K=\sqrt{\frac{C_2gm_1^2}{C_1gm_3gm_4}}$$

Notice in the above equation that the frequency ω_o and the value of Q are determined by C and Gm. That is to say, the characteristics of band-pass filter can be adjusted by the value of C and Gm. Adjusting the value of C may affect circuit noise performance (the noise performance of the Gm-C filter is determined by the capacitor values). Therefore, we adjust only the value of Gm while keeping the value of C constant. We use a switched Gm-C integrator in order to adjust the value of Gm. In other words, to permit fine CMOS implementation, Gm value adjustment is performed in the digital domain instead of in the analog domain. The switched Gm-C integrator can be realized by replacing a Gm cell (Fig. 6) by a Gm array (Fig. 3), where the switches are composed of MOS transistors.

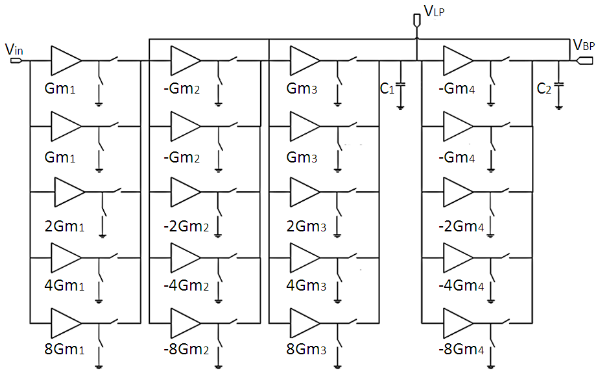

Fig. 7 Digitally-controllable bandpass filter.

B. Center Frequency Tuning

Automatic tuning of the filter characteristics is an important issue in continuous-time analog bandpass filter design. The center frequency and Q-value can be adjusted over a wide range by changing the Gm value. This section discusses automatic center frequency tuning in digital domain.

1) Description of Center Frequency Tuning Method.

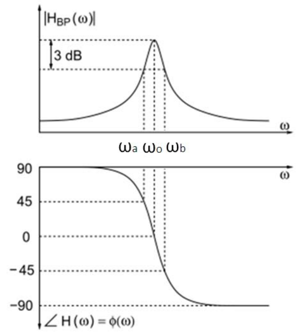

Fig.8 Magnitude and phase characteristics of the second order bandpass filter transfer function.

Fig. 8 shows the magnitude and phase characteristics of the second-order bandpass filter. Its phase response is given as follows:

$$\phi(\omega_i) = \frac{\pi}{2} - \arctan \frac{\omega_i \omega_0}{Q(\omega_0^2 - \omega_i^2)} \tag{7}$$

Here ω_i, ω_o are the input frequency and the center frequency of the filter. As shown in (7), the phase difference between the input and output signal will become zero when ω_i is equal to ω_o. Center frequency tuning can be done using this phase property.

We provide the sinusoidal input with the desired center frequency and observe the filter output in tuning mode; we compare the phases of the input and output and adjust the gm_3, gm_4 values so that the phases are equal. For example, if the phase difference θ is negative, the phase of the output will be ahead that of the input, and we make the values of gm_3, gm_4 smaller. The automatic center-frequency tuning scheme is shown in Fig. 9.

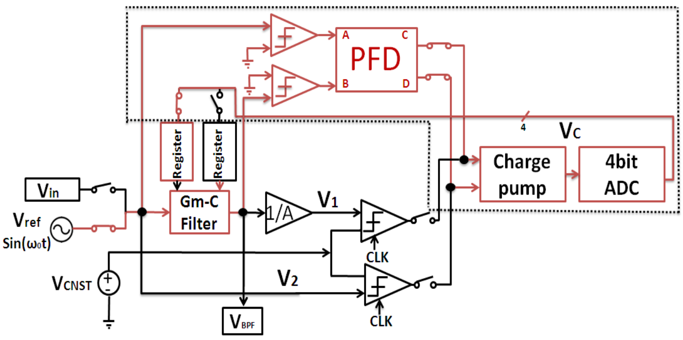

Fig. 9 Frequency tuning scheme.

The sinusoidal input V*ref* (whose frequency is the center frequency to be set) and the output of the bandpass filter are turned into pulse signals by the comparator, and the pulse signals become the inputs of the phase frequency detector (PFD) (Fig. 10). The output node C, D will be high if there is a phase difference between nodes A and B.

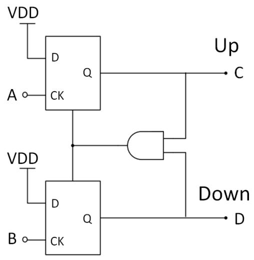

Fig. 10 Phase frequency detector (PFD).

The charge pump output voltage V_{CP} is changed by the output signals of the phase detector as follows:

$$V_{CP} = \frac{\theta}{2\pi} \cdot \frac{I_{CP} t}{C} \tag{8}$$

Note that the charge pump output voltage continuously changes as long as there is a phase difference between the input nodes A, B of the PFD. Tuning of the center frequency decreases the phase difference θ the change rate of the charge pump output voltage also decreases, and finally the center frequency reaches the input frequency and the charge pump voltage V_{CP} is constant. Fig. 11 shows the relationship between the charge pump output voltage and the output signals of the PFD.

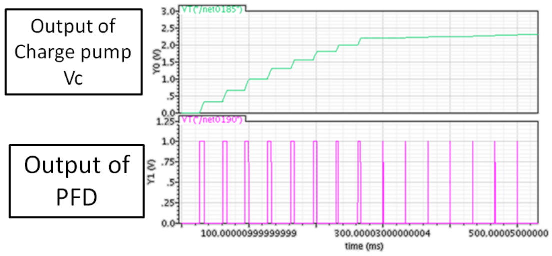

Fig. 11 Frequency control voltage and output signal of PFD.

Fig.12 shows the charge pump and associated circuits; the ADC reads the value of the charge pump output voltage, and the filter center frequency is controlled based on the ADC output. ω_o can be calculated as follows:

$$\omega_0 = \sqrt{\frac{gm_3 gm_4}{C_1 C_2}} \tag{9}$$

As shown in (9), the center frequency can be changed by gm_3 and gm_4, and the automatic tuning circuit controls the switches of gm_3 and gm_4 based on the ADC output.

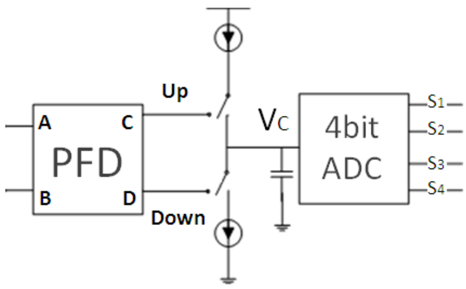

Fig. 12 Charge pump and associated circuits for center frequency tuning.

2) *Simulation Results.*

We have performed SPICE simulation with 4 OTA-arrays, a 4-bit ADC, a center frequency adjustment range of 50kHz-750kHz and gm_3 = gm_4, C_1 = C_2. Fig. 13 shows the simulation results of the bandpass filter magnitude response for a sine wave at three different frequencies, which demonstrate the validity of our method.

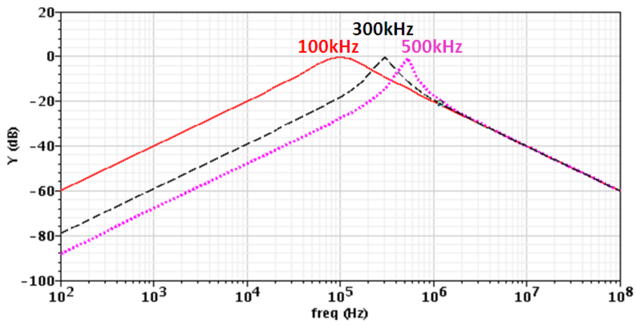

Fig.13 Simulation results of the bandpass filter magnitude response for varying reference frequency.

C. Q-Value Tuning

1) Description of Center Frequency Tuning Method.

We describe here the Q-value tuning method, which is carried out after the center frequency adjustment described in the previous section.

The transfer function can be represented as follows when the center frequency ω_0 is adjusted to the input frequency ω_i.

$$H(\omega_0)=\sqrt{\frac{gm_1^2C_2}{gm_3gm_4}}\cdot\sqrt{\frac{gm_3gm_4}{gm_2^2C_2}}=K\cdot Q \qquad (10)$$

We see in (10) that the gain at ω_o is proportional to the Q-value. The Q-value can be set to the desired value *A/K* after the center frequency is tuned and *K* is fixed. gm_3, gm_4 are fixed after the center frequency tuning and then K is determined by $gm1$ (or the ratio of and gm_3 and gm_1 when $gm_3 = gm_4$ and $C_1 = C_2$). For simplicity, we consider here the case that $K = 1$ ($gm_1 = gm_3 = gm_4$, $C_1 = C_2$).

Fig. 14 shows the regulator circuit for Q-tuning. V_1 ($=Q*K*Vref/A$) and V_2 ($=Vref$) in Fig. 14 can be described as follows: When V_1=V_2, the desired Q as *A* (*A/K, K=1*) can be obtained. When Q is smaller than the desired value *A*, V_1 is larger than V_2 and amount of the current that flows into the capacitor is larger than that which flows out. So the output voltage of the charge pump increases. By controlling the switches of gm_2 based on the ADC output, the value of Q increases (Q is proportional to $1/gm_2$). Conversely, V_1 is smaller than V_2 when the value of Q is larger than the desired value, and the charge pump output voltage decreases. This causes Q to be decreased. Fig. 15 shows simulated Q-factor control voltage (or charge pump output voltage).

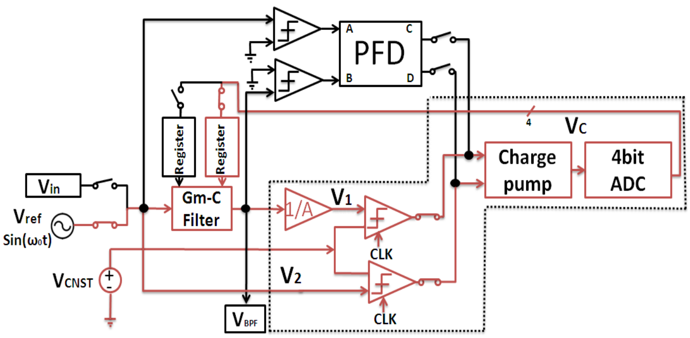

Fig. 14 Q factor tuning circuit.

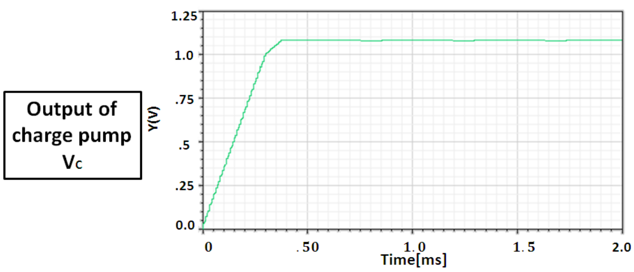

Fig. 15 Simulation results of Q factor control voltage.

2) Simulation Result.

We have performed SPICE simulation and results are shown in Fig. 16. As expected, the values of Q are tuned to 1.0, 3.0 and 6.0 at an input frequency of 600kHz.

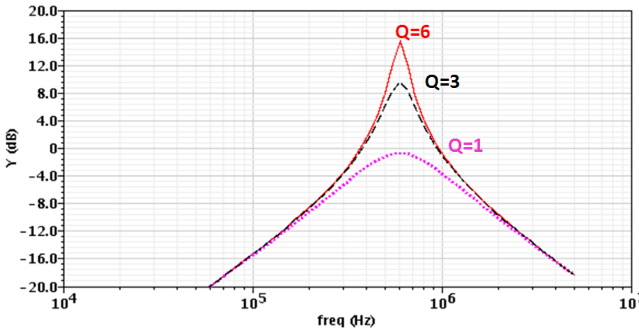

Fig. 16 Simulation results of the bandpass filter magnitude response for a fixed desired center frequency and varying Q.

III. CONCLUSIONS

This paper presents a digitally-controlled Gm-C bandpass filter using Gm arrays, and proposed schemes for digital tuning schemes of center frequency and Q-factor. The reference input signal in tuning mode is a sine wave whose frequency is set to the desired center frequency. SPICE simulation results confirmed the automatic tuning of the center frequency and Q value. The proposed approach is suitable for low-voltage fine CMOS implementation. The tuning circuit presented in this paper only adjusts the integer part of Gm-C integrator. A detailed investigation of the fractional part is left for future work.

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