A tunable Gm-C polyphase filter with high linearity and automatic frequency calibration

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Abstract: In this paper, a new CMOS Gm-C poly-phase filter used in Low-IF receiver is presented. As the requirements of multi-model and multi-band determine the frequency tunability, a master-slave transconductance control circuit is designed. Besides, a low power consumption automatic frequency calibrate circuit is used to resist the PVT. A novel 4\textsuperscript{th} order poly-phase filter is designed in SMIC 0.18 µm standard CMOS process. Consuming 1.1 mA from a 1.8 V voltage, simulation results show that the filter has a tunability of center frequency from 150 kHz to 500 kHz and bandwidth from 100 kHz to 900 kHz independently. Meanwhile, the polyphase filter achieves a IIP3 above 18 dBm.

Keywords: poly-phase filter, tunability, master-slave, frequency calibration

Classification: Integrated circuits

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1 Introduction

In recent years, the WSN (Wireless Sensor Network) technology has extensive applications such as Smart Home System, Wireless Medical Monitor and so on,
which increases the industry’s requirement for low cost, low power and full integrated wireless transceiver. Due to the good frequency separation, no DC offset and low 1/f noise, low-IF receiver is a good choice for one chip integrate. However low-IF receiver has the disadvantage of sensitivity to image signal. So a poly-phase filter is needed following the quadrature mixer to suppress both the image signal and the adjacent channel signal [1, 2]. A new CMOS Gm-C poly-phase filter is proposed in this paper.

The filter in this work is designed for a low power Sub-1 GHz transceiver, which is applied in Smart Home System. The transceiver works in 433 MHz, and has a flexible data rate from 2 kBaud to 250 kBaud. Correspondingly, the poly-phase filter must have a tunability of channel bandwidth from 100 kHz to 900 kHz and center frequency from 150 kHz to 500 kHz in detail circuit. Meanwhile, high linearity is also required. To meet these design requirements, a master-slave transconductance (Gm) control circuit is designed to control the Gm in the filter. Besides, a lower power consumption automatic frequency calibration circuit replaces the traditional architecture based on PLL to resist the PVT.

2 Circuit design and implementation
2.1 Gm-C poly-phase filter design

In Low-IF receiver, to pass the desired signal and reject the image and interferers from neighbor channels, the poly-phase filter is required following the quadrature mixer. Generally, poles of a real filter are symmetric with the real axis, and the responses of the filter to positive frequency and negative frequency are the same. So shifting the frequency transformation of a low-pass filter with a frequency \( \omega_0 \), we can get the frequency transformation of a poly-phase filter [3].

\[
H(j\omega) \rightarrow H(j(\omega - \omega_0))
\]

Fig. 1 shows the topology circuit of a 4\textsuperscript{th} order poly-phase filter. Both of upper and lower parts are low-pass filter prototype circuits, which are based on a multi-integrator feedback loop model. Grounded capacitors used in the filter avoid
producing internal poles. The cross-connected transconductors in the middle are used to shift the center frequency. To realize Butterworth lowpass filter, the equal capacitor design is adopted with the capacitor value being $C = 4 \text{pF}$, and the normalized transconductances are calculated as following:

$$g_1 : g_2 : g_3 : g_4 = 1.53 : 1.58 : 1.08 : 0.38$$  \hspace{1cm} (2)

Besides, the transconductors in frequency shifting circuit have the same $G_m$ value.

### 2.2 Linear transconductors design

Fig. 2 shows the circuit of linear transconductors used in the filter, which is an implementation of CCIIs [4]. Transistors MN1~MN10 and MP1~MP6 of input stage constitute a super source follower. The linearity of transconductors relies on the compliance of the X-Y voltage copy from input terminals. The passive resistor $R_g$ is properly included to implement V-I conversion. The converse result of the input stage is $I = \frac{V_{id}}{R_g}$. As the requirement of continuous tuning of the trans-conductance value, a MOS transistor MN5 works in the voltage-controlled resistance region to scale the output current of the input stage. So the $G_m$ value of the transconductor is $k/R_g$. $k$ is the current scaling ratio at nodes C and D.

![Fig. 2. The transconductor circuit based on CCIIs](image)

All the transconductors have the same transistor size except the resistor $R_g$, so transconductors in the filter have the same scaling ratio $k$, and different values of resistor $R_g$ are required as the transconductances value in Equation (2).

### 2.3 Frequency tuning and automatic calibration circuit design

The poly-phase filter frequency response is determined by the value of $G_m/C$. Since the capacitors have the same value, we can tune the values of $G_{mt}$ and $G_{mc}$ to change bandwith and center frequency separately. As mentioned above, the $G_m$ of the transconductor is determined by the resistor $R_g$ and the current scaling ratio $k$ controlled by the gate voltage of the transistor MN5. So we can control the gate
voltage to tune the frequency response of poly-phase filter. The required control voltage is generated in the tuning circuit shown in Fig. 3, which is based on the master-slave transconductance control principle. The tuning circuit includes a master transconductor, current mirrors, resistor $R_0$ and an error amplifier. A current source $I_g$ is applied at the output of the master transconductor. A constant reference voltage $V_{\text{ref}} (= V'_p - V_n = I_b \times R_0)$ is gained from a current $I_b$ flowing through the resistor $R_0$. The error amplifier magnifies the voltage error between $V_p$ and $V'_p$, and gives an output voltage to adjust the $G_m$ value of the transconductor. As negative feedback connected, $V_p$ equals $V'_p$, So the transconductor has an input voltage $V_p - V_n$, which equals $V_{\text{ref}}$. The whole tuning circuit works as a feedback loop, so the tuning result is obtained as

$$G_m = \frac{I_g}{V_p - V_n} = \frac{I_g}{V_{\text{ref}}} = \frac{I_g}{I_b \times R_0} = \frac{K_i}{R_0}$$  \tag{3}$$

The parameter $K_i$ equals $I_g/I_b$, which is the ratio of current mirror. The filter has the frequency characteristic as $f \propto G_m/C = K_i/R_0 C$, so we have three parameters to tune the frequency response: the ratio of current mirror $K_i$, the resistor $R_0$ and capacitors $C$ in the filter. Tuning the capacitors $C$ will degrade the linearity of the filter because of the switches in the signal chain. So tuning the current mirror ratio $K_i$ or the resistor $R_0$ is the best choice. In this paper, we change the current mirror ratio $K_i$ to tune the center frequency and bandwidth of the poly-phase filter. The current sources work as current mirrors, which are insensitive to the PVT and have relatively accurate values. The PVT of RC will affect the filter’s frequency response, so an automatic frequency calibration circuit is designed as shown in Fig. 4. The output frequency of the RC oscillator is determined as same as the filter:

![Fig. 3. The proposed master-slave transconductance control circuit.](image-url)
\( f \propto K_c/RC \), so the digital circuit detects the oscillation frequency to obtain the RC value and changes the resistor \( R_0 \) in Fig. 3 to compensate the PVT.

![Fig. 4. The RC oscillation circuit used in frequency calibration.](image)

### 3 Simulation results

The proposed poly-phase filter is simulated in SMIC 0.18 µm CMOS process and it draws a similar total current of 1.1 mA from a 1.8 V supply at different bandwidth. Simulation results show that the filter has a tunability of center frequency from 150 kHz to 500 kHz and bandwidth from 100 kHz to 900 kHz separately as showed in Fig. 5. Because of the automatic frequency calibration, the maximum frequency deviation is 5% at process corners.

![Fig. 5. The simulation amplitude-frequency response of the filter.](image)

*no application value because of a negative pass-band

Meanwhile, IIP3 indicates the linearity of Gm-C filters. In this work, the simulation IIP3 of the poly-phase filter varies from 18 dBm to 23 dBm. Fig. 6 shows the IIP3 @500 kHz/900 kHz by applying two-tone signals 450 kHz and 550 kHz. Table I summarizes the detail parameters for the other frequency situations. All of these parameters achieve the integrate transceiver’s requirement.
Table II summarizes the proposed poly-phase filter and the filter in [5]. The center frequency and bandwidth are lower than filter in [5], because they are used in different systems. To increase the frequency, we can decrease the capacitor or resistor value easily. The work in this paper has significant advantages in the frequency tunability and linearity.

**Table I.** Detail parameters of the ploy-phase filter for different situations

| Spec. | 150 k/100 k | 150 k/900 k* | 500 k/100 k | 500 k/900 k |
|-------|-------------|-------------|-------------|-------------|
| IIP3  | 19.7 dBm    | 21 dBm      | 18.2 dBm    | 22.6 dBm    |
| Image rejection ratio | 60 dB | * | 100 dB | 28 dB |
| Input referred noise uV/√Hz | 5.5@150 k | 0.4@150 k | 4@500 k | 0.2@500 k |
| Power (current) | 1.04 mA | 1.08 mA | 1.07 mA | 1.1 mA |

*no application value because of a negative pass-band

Table II summarizes the proposed poly-phase filter and the filter in [5]. The center frequency and bandwidth are lower than filter in [5], because they are used in different systems. To increase the frequency, we can decrease the capacitor or resistor value easily. The work in this paper has significant advantages in the frequency tunability and linearity.

**Table II.** The comparison of two type of ploy-phase filter

| Spec. | [5] | This work |
|-------|-----|-----------|
| Technology | 90 nmCMOS | 0.18 umCMOS |
| Power | 1.02 mA(2.4 V)@4th | 1.1 mA(1.8 V)@4th |
| Tunnable | no | Yes |
| Center frequency | 2.5 MHz | 150 k~500 kHz |
| Bandwidth | 3.6 MHz | 100 k~900 kHz |
| IIP3 | −3.4 dBm | 18~23 dBm |

**4 Conclusion**

In this paper, a new CMOS Gm-C poly-phase filter used in Low-IF receiver is presented. Because of the master-slave transconductance control circuit, the filter gains advantages on frequency tunability and automatic calibration. The transconductors based on CCIIs assure the high linearity of the poly-phase filter.