Research Article

Process Variation Aware Wide Tuning Band Pass Filter for Steep Roll-Off High Rejection

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A wide tuning band pass filter (BPF) with steep roll-off high rejection and low noise figure is presented. The design feature of steep roll-off high stopband rejection (>20 dB) and low noise figure (<6 dB) provides a wide tuning frequency span (1–2.04 GHz) to accept desirable signals and reject close interfering signals. The process variation aware design approach demonstrates robustness of the BPF after calibration from process variations, operating in 1.04 GHz tuning frequency span: almost zero deviation on center frequency, an average maximum deviation 1.16 dB on a nominal pass band gain of 55.6 dB, and an average maximum deviation 1.06 MHz on a nominal bandwidth of 12.3 MHz.

1. Introduction

When RF devices are upgraded to support future standards, IF amplifiers, mixers, band pass filters (BPFs), modulators, and demodulators are preferable to be tunable and cost-effective to meet different frequency band standards [1]. Reconfigurable RF minimizes duplicated RF front-end components and hence reduces energy and cost. Considering cognitive radio in the TV bands, there are narrow spectral holes between strong TV transmitter signals. To avoid blocking of the receiver, strong TV signals have to be rejected by tunable BPF of high linearity, high Q , and high stopband rejection. A typical example is $Q = 50$ for 10 MHz bandwidth in a wide tuning frequency range of 500 MHz in the TV bands. Reconfigurable RF devices include power amplifiers, antennas, band pass filters, and matching networks with high tuning speed and high linearity for reasons of size and cost.

Tunable BPF features include tunable frequency range, pass band gain, tuning center frequency span, bandwidth, noise figure, and stopband rejection. Several state-of-the-art CMOS design techniques such as gm-C filters, Q enhanced LC filters, N -path, and pseudo- N -path filters have been presented. Most of them have either low band pass gain, high noise figure, or low tuning frequency range [2–15].

The gm-C filters have the advantage of low power and high frequency. Their weak linearity is improved by applying linearization techniques such as resistive source degeneration, dynamic source degenerated differential pair, tunable feedback, and adaptive feedback. However, these techniques have low pass band gain and narrow tuning range [7, 10]. The Q -enhanced LC band pass filter through an adjustable negative-conductance generator is capable of operating in low-voltage supply but it has low pass band gain (-5 dB) and high noise figure (26.8 dB) [8]. Other Q -enhanced LC filter based designs were proposed in [9, 11]. The BPF in [9] consumes less power and has a tuning frequency range (400 MHz) with a pass band gain (23 dB). A low pass band distortion BPF proposed in [11] has a low pass band gain (0 dB). The high- Q integrated switched capacitor band pass filter [12] has a broad frequency band but a low pass band gain (-2 dB) and high power. A design using high- Q N -path band pass filter is proposed [13], which has a tuning frequency range (0.1–1 GHz) but low band pass gain (-2 dB). A novel inductorless tunable switched capacitor band pass filter based on N -path periodically time-variant circuit operates in a high frequency range (4–4.44 GHz) but has low pass band gain (-12 dB) and high noise figure (14 dB) [14].

FIGURE 1: Schematic of band pass filter.

In this paper, a tunable BPF is presented, which has a wide tuning range, high band pass gain, high stopband rejection, low noise figure, and low power. The paper is organized as follows. Section 2 presents the architecture and operation principle of the tunable BPF. Section 3 presents design approach to BPF for specified center frequency and bandwidth. Section 4 presents process variation aware design approach to BPF for tunable center frequency and bandwidth. BPF design calibration after process variation is also presented. Section 5 presents measurements and performance analysis of BPF after design calibration. Section 6 is the conclusion.

2. BPF Architecture and Principle Operation

The tunable BPF with differential cascade architecture is divided into two stages. Stage I is the transconductance stage. Stage II is the transimpedance stage. The transconductance stage converts input voltages V_{INP} and V_{INN} to output currents I_P and I_N while the transimpedance stage converts input currents I_P and I_N to output voltages V_{OPP} and V_{OPN} , as shown in Figure 1. The BPF is a type of double notch filter [2], which has two single notch filters with LC parallel series resonant combination, as depicted in Figure 2.

The input LC impedance for parallel series resonant combination is expressed as Z_N . Its small equivalent signal model is depicted in Figure 3, where the drain current I_D of transistor m_9 (Figure 1) serves as driver of the amplifier and I_N is the current feeding the LC parallel series resonant combination. I_L is the current through transistor m_1 . The transconductance of m_1 is g_{m1} and the load resistance seen

FIGURE 2: Schematic of single notch filter.

FIGURE 3: Small equivalent signal model for single notch filter.

from the source of m_1 is $1/g_{m1}$. The input impedance Z_{N1} is expressed in (1). Consider

$$Z_{N1} = \frac{1 + s^2 L_{N1} (C_{N1} + C_{P1})}{s C_{N1} (1 + s^2 L_{N1} C_{P1})}. \quad (1)$$

Considering the parallel series LC network, its parallel resonant frequency f_{P1} is higher than the zero frequency f_{Z1} , as shown below:

$$f_{P1} = \frac{1}{2\pi\sqrt{L_{N1}C_{P1}}}, \quad (2)$$

$$f_{Z1} = \frac{1}{2\pi\sqrt{L_{N1}(C_{N1} + C_{P1})}}. \quad (3)$$

As shown in Figure 3, the equivalent resistance of $1/g_{m1}$ and r_{ds1} in parallel is approximately $1/g_{m1}$ for $r_{ds1} \gg 1/g_{m1}$. The amplitude I_N is then expressed as

$$I_N = I_D \frac{1}{1 + g_{m1}Z_N} = \frac{g_{m1}V_{INN}}{1 + g_{m1}Z_N}, \quad (4)$$

where I_D is equal to $g_{m1}V_{INN}$. Similarly, the current I_P can be expressed by replacing v_{INN} with v_{INP} . The differential output current I_{out} ($= I_P - I_N$) of the transconductance stage is simply obtained after replacing v_{INP} with v_{IN} ($= v_{INP} - v_{INN}$). The same LC parallel series combination with different impedance L_{N2} , C_{N2} , C_{P2} is applied in the transimpedance stage with v_{out} ($= v_{o1} - v_{o2}$). Hence, the input impedance of the second LC stage is given by

$$Z_{N2} = \frac{1 + s^2 L_{N2}(C_{N2} + C_{P2})}{s(C_{N2} + s^2 L_{N2}C_{P2})}. \quad (5)$$

The resonant frequencies are expressed by

$$f_{P2} = \frac{1}{2\pi\sqrt{L_{N2}C_{P2}}}, \quad (6)$$

$$f_{Z2} = \frac{1}{2\pi\sqrt{L_{N2}(C_{N2} + C_{P2})}}. \quad (7)$$

The differential output voltage of the transimpedance filter stage is then expressed by

$$v_{out} = sL_D \frac{g_{m1}Z_{N2}}{1 + g_{m1}Z_{N2}} I_{out}. \quad (8)$$

When $f = f_{Z1}$ then $Z_{N1} \approx 0$. And when $f = f_{P1}$ then $Z_{N1} \approx \infty$. Therefore, the output current $I_{out} = I_P - I_N$ in (4) can be expressed as

$$I_{out} \approx \begin{cases} g_{m1}v_{IN} & \text{when } f = f_{Z1}, \\ 0 & \text{when } f = f_{P1}. \end{cases} \quad (9)$$

Similarly, $Z_{N2} \approx 0$ when $f = f_{Z2}$. And $Z_{N2} \approx \infty$ when $f = f_{P2}$. Hence the output voltage in (6) is given by

$$v_{out} \approx \begin{cases} 0 & \text{when } f = f_{Z2}, \\ sL_D I_{out} & \text{when } f = f_{P2}. \end{cases} \quad (10)$$

It is observed from (9) and (10) that the transmission zero happens at f_{P1} in transconductance stage and happens

FIGURE 4: Example of frequency response of the proposed band pass filter ($f_c = 1.7$ GHz, $BW = 12.4$ MHz, and stopband rejection = 27.4 dB).

at f_{Z2} in transimpedance stage. Meanwhile, the peak value happens at f_{Z1} in transconductance stage and happens at f_{P2} in transimpedance stage. Correspondingly, the peak conductance g_{max} and impedance Z_{max} are obtained at f_{Z1} and f_{P2} . Finally, the overall transfer function of the BPF is obtained from (3) to (9). Consider

$$v_{out} = v_{IN} \frac{g_{m1}^2 L_D Z_{N2} s}{(1 + g_{m1}Z_{N1})(1 + g_{m1}Z_{N2})}. \quad (11)$$

The peak output can be expressed in (12) when $f = f_{Z1}$, and also $f_{Z1} \approx f_{P2}$. Consider

$$v_{out} \approx \begin{cases} 0 & \text{when } f = f_{P1} \text{ or } f_{Z2}, \\ g_{max} Z_{max} v_{IN} & \text{when } f = f_{Z1} \approx f_{P2}, \end{cases} \quad (12)$$

where $g_{max} = I_{out}/v_{IN}$ and $Z_{max} = v_{out}/I_{out} = sL_D$.

From (12) the peak gain happens at center frequency (the pole f_{P2} and the zero f_{Z1}). A wide tuning range is realized by changing L_{N1} and L_{N2} . A high base band gain is achieved by maximizing g_{max} and Z_{max} , which are determined by the Q factor of the inductors and by location of the poles and zeros. The Q-factor of inductors is improved by using a cross-coupled transistor pair, creating negative impedance in parallel with the inductors. The location of poles and zeros can be adjusted by varying C_N and C_P .

The pole frequency can be adjusted to be slightly greater than the zero frequency by making C_{N1} much less than C_{P1} and making C_{N2} much smaller than C_{P2} . A steep roll-off can be achieved. Figure 4 demonstrates the frequency response of the proposed BPF at $f_c = 1.7$ GHz and $BW = 12.4$ MHz. Its stopband rejection is 27.4 dB. Meanwhile, the peak center frequency gain can be increased when $f_{P2} \approx f_{Z1}$ by making $C_{N1} + C_{P1} \approx C_{P2}$.

Given: BPF (Figure 1) with NMOS (m_1 to m_{17}), inductors (L_{N1} , L_{N2} , L_D), capacitors (C_N , C_{P1} , C_{N2} , and C_{P2}), current sources (I_1 , I_2 , I_3), power (pw)
Input: V_{inn} and V_{inp}
Objective: BPF to meet a specified center frequency and bandwidth
Output: NMOS sizes, capacitors and inductors value

Design approach: //BPF design to meet the specified center frequency and bandwidth//
(1) Specify DC power (pw_0), center frequency (f_{c0}), bandwidth (BW_0);
(2) Calculate I_1 , I_2 and I_3 based on pw_0 ;
(3) Set w_3 , w_4 , w_5 based on I_1 , I_2 and I_3 ;
(4) Set initial value $k_3(0)$, $k_4(0)$ and $k_5(0)$;
(5) Given C_{N1} , C_{P1} , C_{N2} , C_{P2} , L_{N1} , L_{N2} and L_D ,
 set $C_{N1} \ll C_{P1}$ and $C_{N2} \ll C_{P2}$ to make f_{p1} a little greater than f_{z1} and make f_{p2} a little greater than f_{z2} ;
 set $C_{P2} \approx C_{P1} + C_{n1}$ to make $f_{p2} \approx f_{z1}$;
(6) $i = 0$
(7) while ($i < N$) //Optimize k_3 , k_4 , k_5 in N iterations
(8) $\{k_3(i) = k_3(0) + (k_{3max} - k_3(0)) * i/N$;
 $k_4(i) = k_5(i) = k_4(0) + (k_{4max} - k_4(0)) * i/N$;
(9) do DC simulation;
(10) if $|pw - pw_0|/pw > 0.01$ then $i = i + 1$ and go to Step (7);
(11) else exit;
(12) end if;
(13) adjust C_{N1} , C_{P1} , C_{N2} , C_{P2} , L_{N1} , L_{N2} ;
 do AC simulation; //find f_c
(14) If $|f_c - f_{c0}|/f_{c0} < 0.01$ then go to Step (17)
(15) else go to Step (13)
(16) end if;
(17) adjust L_D ;
(18) do AC simulation; //find BW
(19) If $|BW - BW_0|/BW_0 < 0.01$ then exit;
(20) else go to Step (17)
(21) end if;

ALGORITHM 1: A BPF design to meet the specified center frequency and bandwidth.

TABLE 1: Transistor size information.

Transistor	m_1	m_2	m_3	m_4	m_5	m_6	m_7	m_8	m_9	m_{10}	m_{11}	m_{12}	m_{13}	m_{14}	m_{15}	m_{16}	m_{17}
Width	w_1	w_1	w_6	w_6	w_4	$k_4 w_4$	$k_4 w_4$	w_3	$k_3 w_3$	$k_3 w_3$	w_2	w_2	w_7	w_7	w_5	$k_5 w_5$	$k_5 w_5$
Length	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L

3. BPF Design with Fixed Center Frequency and Bandwidth

Algorithm 1 presents sizing approach of BPF (Figure 1) in 180 nm CMOS process. The power supply is 1.8 V. The desirable power consumption is denoted as pw_0 while the desirable center frequency and bandwidth are denoted as f_{c0} and BW_0 , respectively. With the relationship of current mirror circuit, the current I_1 drives branch currents I_{m6} and I_{m7} ; the current I_2 drives branch currents I_{m9} and I_{m10} ; the current I_3 drives branch currents I_{m16} and I_{m17} . Note that I_{mxx} is the current through the transistor m_{xx} . Normally, the driver current (I_1 , I_2 , I_3) is made by the tenth of its load current through transistor (m_6 , m_7 , m_9 , m_{10} , m_{16} , m_{17}) based on the power consumption pw.

The next step involves setting width and length of transistor m_1 to m_{17} and multiplicand k_3 , k_4 , k_5 for current mirror

load current through m_3 , m_4 , m_5 , which is precalculated and summarized in Table 1. The initial value for k_3 , k_4 , k_5 is 10. It is then optimized to have the load current through transistor (m_6 , m_7 , m_9 , m_{10} , m_{16} , m_{17}) as 1/10 of its driver current (I_1 , I_2 , I_3).

Using 180 nm CMOS process, the value of C_1 to C_4 and L_1 to L_4 is calculated based on (2), (3), (6), and (7). Given $C_{N1} \ll C_{P1}$ and $C_{N2} \ll C_{P2}$, f_{p1} and f_{p2} are set to be a little greater than f_{z1} and f_{z2} . Also, $f_{z1} \approx f_{p2}$ if $C_{p2} \approx C_{p1} + C_{n1}$. The initial parameter setting is completed in steps 1–5 in Algorithm 1. As shown in Algorithm 1, k_3 , k_4 , and k_5 are optimized in step 8 till power consumption is met. Next, adjust C_{N1} to C_{P2} , L_{N1} , L_{N2} and do AC simulation until the center frequency f_c is close to f_{c0} (<1% error). Finally, adjust L_D and do AC simulation until the bandwidth BW is close to BW_0 (<1% error).

Given: f_c , BW_0 , and initial values of L_{N1} , L_{N2} , L_D .

Input: V_{inn} and V_{inp}

Objective: tunable BPF to meet f_c and BW_0

Output: L_{N1} , L_{N2} , C_{P2}

Design approach: //Stage A to meet the specified f_c (Steps (1)–(10))//

(1) Find the range of f_c ($f_{c1} < f_c < f_{c2}$) in Table 2;

(2) Set initial values $L_D = L_{D2}$, $L_{N1} = L_{N2} = L_{N12}$, and set C_{N1} , C_{N2} , C_{P1} , C_{P2} , δ_1 , δ_2 , δ_3 , M , N , P , Q ;

(3) Repeat

(4) do AC simulation;

(5) decrease $L_{N1} = L_{N2}$ by $\Delta L_{N1} = (L_{N12} - L_{N11})/M$;

(6) Until $|f - f_c| < \delta_1$;

(7) Repeat

(8) do AC simulation;

(9) decrease C_{P2} by $\Delta C = (C_{P22} - C_{P21})/N$;

(10) Until $|f - f_c| < \delta_2$;

Design approach: //Stage B to meet the specified BW_0 (Steps (11)–(17))//

(11) Find f_c and its corresponding BW_{min} in Table 2;

(12) If $BW_0 < BW_{min}$ then break;

(13) Else

(14) Do {

(15) decreases inductor L_D by $\Delta L = (L_{D2} - L_{D1})/P$;

(16) do AC simulation to find the bandwidth BW ;

(17) } While $|BW - BW_0| < \delta_3$;

Design approach: //Stage C to calibrate BPF design after considering process variations (Steps (18)–(32))//

(18) Select N (i.e., $N = 100$) cases of BPF designs with different f_{c0} , BW_0 and A_v after Stage A and B;

(19) Perform Monte Carlo analysis to obtain μ and σ for BW ;

(20) Compute $(BW - (\mu - \sigma))$; //calculate the BW deviation

(21) Choose top 30% cases having the worst BW deviation and find their center frequency (f_c) and corresponding gain (A_v);

(22) Compute the average of center frequency (f_{avg}) and gain deviation (ΔA_v)

(23) Compute ΔL_D from (17);

(24) For $i \leftarrow 1$ to 30 //consider the top 30 cases

(25) $L_{D_new}(i) = L_{D_old}(i) + \Delta L_D$;

(26) do AC simulation;

(27) if $BW_{new}(i) > BW_{old}(i)$ then set $BW(i) = BW_{new}(i)$;

(28) else $\{L_{D_new}(i) = L_{D_old}(i) - \Delta L_D$;

(29) do AC simulation;

(30) set $BW(i) = BW_{new}(i)$;

(31) end if;

(32) End for;

ALGORITHM 2: Process variation aware tunable BPF design approach.

4. Process Variation Aware Tunable BPF Design

4.1. Tunable BPF with Specified Center Frequency and BW.

The design approach described in Section 3 is sequential and iterative loops for parameter setting and sequential results are affecting one another. The final design meets unique specifications and its design parameters are difficult to be changed to become tunable for different center frequency or bandwidth. In this regard, a design approach to make BPF tunable is proposed, which stores BPF design parameters as design reference and increases design space for wide tuning frequency range.

The design approach for tunable BPF is divided into three stages. Stage A is to meet the center frequency f_c . Stage B is to meet the BW. Stage C is to calibrate the BPF design to meet f_c and BW after process variations. They are shown in Figure 5. Algorithm 2 depicts detailed design approach in

FIGURE 5: Block diagram of process variation aware tunable BPF design.

the three stages and explains how to obtain design parameters for the tunable BPF. In stage A, it is desirable to narrow the range of design parameters, which are primarily related to the center frequency. By referring to a look-up table of

TABLE 2: Initial look-up table of inductors obtaining peak gain and minimum BW for different center frequencies.

L_{N1} (nH)	L_{N2} (nH)	L_D (nH)	f_c (GHz)	BW _{min} (MHz)	Peak gain (dB)
1.30	1.30	281.0	1.00	5.34	65.3
1.10	1.10	269.4	1.07	5.47	69.3
1.00	1.00	210.0	1.15	5.85	68.3
0.90	0.90	196.0	1.20	6.33	64.7
0.80	0.80	183.0	1.26	6.14	67.8
0.70	0.70	169.0	1.35	6.87	66.2
0.60	0.60	164.0	1.45	7.17	66.3
0.50	0.50	136.0	1.58	7.79	66.1
0.40	0.40	118.0	1.78	8.92	65.0
0.30	0.30	93.00	2.04	9.91	64.9
0.20	0.20	55.00	2.51	12.4	63.6
0.10	0.10	27.50	3.55	16.6	63.1
0.05	0.05	14.20	5.01	21.4	62.9

inductors (Table 2), peak pass band gain and minimum BW for different center frequencies in a wide tuning frequency range are obtained. These parameters are obtained by design approach in Algorithm 1. Given f_c to tunable BPF design, the first step is to find the adjacent center frequency (i.e., upper f_{c2} and lower f_{c1}) from Table 2. Next, find the upper L_{N12} and lower inductor L_{N11} from f_{c2} and f_{c1} , respectively. For example, if $f_c = 1.7$ GHz, then f_{c1} is 1.58 GHz and f_{c2} is 1.78 GHz. Also, $L_{N12} = 0.5$ nH and $L_{N11} = 0.4$ nH. Thereafter, set the initial value $L_D = L_{D2}$, $L_{N1} = L_{N2} = L_{N12}$. Calculate C_{N1} to C_{P2} value from equations in Section 2. Make $C_{P22} = 1.1C_{P2}$, $C_{P21} = 0.9C_{P2}$ and do AC simulation. L_{N1} and L_{N2} are the primary impact factors to determine the center frequency. If $|f - f_c| > \delta_1$ (i.e., 15 MHz), decrease L_1 and L_2 by $\Delta L_{N1} = (L_{N12} - L_{N11})/M$ and then conduct AC simulation. Otherwise, decrease the second primary impact factor C_{P2} by $\Delta C_{P2} = (C_{P22} - C_{P21})/N$ until $|f - f_c| < \delta_2$ (i.e., 1 MHz). Then, go to stage B to meet the specified bandwidth, as shown in steps 11–17 in Algorithm 2. If $BW < BW_{min}$, then BW is out of design range. Otherwise, decrease L_D by $\Delta L = (L_{D2} - L_{D1})/P$ and do AC simulation till $|BW - BW_0| < \delta_3$ (i.e., 0.1 MHz).

Then, the specified BW is met. M , N , and P are the number of repeats determined by the accuracy (δ_1 , δ_2 , δ_3) in simulation. Consider

$$\Delta L_{N1} = \frac{L_{\text{larger}} - L_{\text{smaller}}}{\text{number of repeats}} = \frac{L_{N12} - L_{N11}}{M}, \quad (13)$$

$$\Delta C_{P2} = \frac{C_{\text{larger}} - C_{\text{smaller}}}{\text{number of repeats}} = \frac{C_{P22} - C_{P21}}{N}, \quad (14)$$

$$\Delta L_D = \frac{L_{\text{larger}} - L_{\text{smaller}}}{\text{number of repeats}} = \frac{L_{D2} - L_{D1}}{P}, \quad (15)$$

$$A_v = \frac{v_{\text{out}}}{v_{\text{IN}}} = g_{\text{max}} Z_{\text{max}} = s g_{\text{max}} L_D, \quad (16)$$

$$|\Delta A_v| = 2\pi f_{\text{avg}} g_{\text{max}} \Delta L_D. \quad (17)$$

4.2. Design Example of a Tunable BPF for f_c (1.7 GHz) and BW (12.4 MHz). Table 3 summarizes transistor sizes and parameter settings based on the design approach in Section 3. Prior to implementing the tunable BPF design, the desirable center frequency f_c (1.7 GHz) and BW (12.4 MHz) are specified. The number of repeats depends on the design accuracies δ_1 , δ_2 , and δ_3 . For example, δ_1 , δ_2 , and δ_3 are given 15 MHz, 1 MHz, and 0.1 MHz and the number of repeats M , N , and P is 20, 40, and 25. As shown in Table 2, the center frequency f_c (1.7 GHz) lies between f_{c1} (1.58 GHz) and f_{c2} (1.78 GHz), the corresponding inductor L_D lies between L_{D1} (136 nH) and L_{D2} (118 nH), and the inductors L_{N1} and L_{N2} lie between L_{N11} (0.4 nH) and L_{N12} (0.5 nH). Therefore, set the initial value $L_D = L_{D2} = 136$ nH, $L_{N1} = L_{N2} = L_{N12} = 0.5$ nH, and $C_{N1} = 2$ pF, $C_{P1} = 18$ pF, $C_{N2} = 3$ pF, $C_{P2} = C_{N1} + C_{P1} = 20$ pF, $C_{P22} = 1.1C_{P2} = 22$ pF, $C_{P21} = 0.9C_{P2} = 18$ pF and do AC simulation. If $|f - f_0| > \delta_1$ (>15 MHz), decrease L_{N1} and L_{N2} by $\Delta L_{N1} = (L_{N12} - L_{N11})/M = 0.005$ nH and then do AC simulation. Otherwise, decrease the second primary impact factor C_{P2} by $\Delta C_{P2} = (C_{P22} - C_{P21})/N = 0.1$ pF until $|f - f_c| < \delta_2$ (<1 MHz). After the specified f_c is met, then go to stage B to meet the specified BW = 12.4 MHz.

As shown in steps 11–17 in Algorithm 2, the first step is to find f_c and its corresponding bandwidth (BW_{min}). If $BW < BW_{min}$, then BW is out of range. If $BW > BW_{min}$, decrease L_D by $\Delta L = (L_{D2} - L_{D1})/P = 0.84$ nH and run AC simulation. Repeat until $|BW - BW_0| < \delta_3$ (<0.1 MHz). Then, f_c (1.7 GHz) and BW (12.4 MHz) are met. The proposed BPF provides a high pass band gain between 45.2 and 65.1 dB and tunable pass band between 5.5 and 51.2 MHz, while the center frequency is varied from 1.0 to 2.04 GHz, which is depicted in Figure 6.

4.3. BPF Calibration after Process Variations. The BPF design calibration to meet the specified BW after process variation is presented in stage C in Algorithm 2. The initial step in stage C is to select N (i.e., $N = 100$) cases of different f_c , BW, and A_v and conduct Monte Carlo simulation to obtain BW's mean (μ) and standard deviation (σ). The top 30% design cases contributing to the worst deviation of $(BW - (\mu - \sigma))$ are selected to calculate the average center frequency (f_{avg}) and the corresponding gain deviation (ΔA_v). Then, ΔL_D can be calculated from (17). Note that ΔL_D is used to calibrate L_D , which in turn calibrates BW. Finally, calibrated L_D and calibrated BW for each case are obtained. Table 4 shows the tunable BPF BW comparison with and without calibration after process variations. Ten design cases of center frequency which varied from 1 to 2.04 GHz are compared. Their BW is close to 12.3 MHz. Considering the case example of $f_c = 1.35$ GHz and BW = 12.2 MHz in Table 4, the bandwidth deviation $BW - (\mu - \sigma)$ before calibration is 0.88 MHz and after calibration is 0.42 MHz, which accounts for 52.3% improvement. Consider all 10 case examples, the average bandwidth deviation $BW - (\mu - \sigma)$ before calibration is

TABLE 3: Transistor size and parameter setting.

m_1 (μm)	m_2 (μm)	m_3 (μm)	m_4 (μm)	m_5 (μm)	m_6 (μm)	m_7 (μm)	m_8 (μm)	m_9 (μm)
150	150	2	2	2	19	19	4	46.4
m_{10} (μm)	m_{11} (μm)	m_{12} (μm)	m_{13} (μm)	m_{14} (μm)	m_{15} (μm)	m_{16} (μm)	m_{17} (μm)	L (μm)
46.4	90	90	2	2	2	19	19	180
M	N	P	δ_1 (MHz)	δ_2 (MHz)	δ_3 (MHz)	I_1 (mA)	I_2 (mA)	I_3 (mA)
20	40	25	15	1	0.1	50	300	50

FIGURE 6: Pass band gain versus tunable bandwidth ($45.2 \text{ dB} \leq A_V \leq 65.1 \text{ dB}$, $5.5 \text{ MHz} \leq \text{BW} \leq 51.2 \text{ MHz}$) for $1.0 \text{ GHz} \leq f_c \leq 2.04 \text{ GHz}$.

0.58 MHz and after calibration is 0.292 MHz, which accounts for 49.6% improvement.

5. Measurement and Performance Analysis

The performance of ten tunable BPF designs with the pass band nearly constant (12.1–12.6 MHz) is shown in Table 5. The bandwidth is 12.1 MHz, 12.3 MHz, 12.1 MHz, 12.1 MHz, 12.2 MHz, 12.3 MHz, 12.2 MHz, 12.4 MHz, 12.5 MHz, 12.6 MHz, and 12.6 MHz, respectively. The center frequency is varied from 1.0 to 2.04 GHz: 1.0 GHz, 1.07 GHz, 1.15 GHz, 1.20 GHz, 1.26 GHz, 1.35 GHz, 1.45 GHz, 1.58 GHz, 1.78 GHz, and 2.04 GHz. The nominal pass band gain before considering process variations is between 53.4 and 59.9 dB. Considering process variations on t_{ox} , L_{eff} , and v_t with a maximum 10% variation on their nominal values, the Monte Carlo simulation results show robustness of the BPF:

TABLE 4: Tunable BPF BW comparison with and without calibration after process variations.

f_c (GHz)	BW (MHz)	$\mu - \sigma$		BW - ($\mu - \sigma$)	
		w/o calibration	w calibration	w/o calibration	w calibration
1.00	12.1	11.15	11.56	0.95	0.54
1.07	12.3	10.96	11.52	1.34	0.78
1.15	12.1	12.51	12.34	-0.41	-0.24
1.20	12.2	11.24	11.62	0.96	0.58
1.26	12.3	11.25	11.85	1.05	0.45
1.35	12.2	11.32	11.78	0.88	0.42
1.45	12.4	11.83	12.09	0.57	0.31
1.58	12.5	12.15	12.39	0.35	0.11
1.78	12.6	12.81	12.74	-0.21	-0.14
2.04	12.6	12.27	12.49	0.33	0.11

zero deviation on center frequency. The average maximum deviation on pass band gain is 1.16 dB on a nominal pass band gain of 55.6 dB. And the average maximum deviation on bandwidth is 1.06 MHz on a nominal bandwidth of 12.3 MHz.

Table 6 summarizes the calibrated performance of the ten tunable BPF designs after process variations. Figure 7 shows a low noise figure ($< 6 \text{ dB}$), while the center frequency is varied from 1.0 to 2.04 GHz.

6. Conclusion

This paper presented an effective design approach to optimize design parameters of a BPF to achieve tunable center frequency and bandwidth in a wide frequency span, for example, 1.04 GHz. Process variations on channel length, physical oxide thickness, and threshold voltage were considered in Monte Carlo simulation. The BPF design calibration to compensate bandwidth deviation from process variations was presented and evaluated. Considering process variations in 180 nm CMOS process and the central frequency which varied from 1.0 to 2.04 GHz, it was shown in Table 6 that the BW deviation (BW_σ) is 0.292 MHz on the pass band mean (BW_μ) of 12.01 MHz. The pass band gain variation ($A_{V(\sigma)}$) is

TABLE 5: BPF f_c , A_v , and BW considering process variations.

f_c after process variation					A_v after process variation					BW after process variation				
Nominal (GHz)	t_{ox} [min, max] (GHz)	L_{eff} [min, max] (GHz)	t_{ox} [min, max] (GHz)	All [min, max] (GHz)	Nominal (dB)	t_{ox} [min, max] (dB)	L_{eff} [min, max] (dB)	t_{ox} [min, max] (dB)	All [min, max] (dB)	Nominal (MHz)	t_{ox} [min, max] (MHz)	L_{eff} [min, max] (MHz)	t_{ox} [min, max] (MHz)	All [min, max] (MHz)
1.00	1.00, 1.00	1.00, 1.00	1.00, 1.00	1.00, 1.00	53.4	52.19, 53.21	52.75, 53.82	52.51, 53.02	53.64, 53.91	12.1	10.95, 13.91	10.65, 12.09	11.82, 12.46	10.24, 11.49
1.07	1.07, 1.07	1.07, 1.07	1.07, 1.07	1.07, 1.07	54.7	54.26, 55.25	54.77, 54.82	54.65, 54.91	54.14, 55.45	12.3	11.65, 12.81	11.36, 12.07	11.69, 12.39	10.93, 11.06
1.15	1.15, 1.15	1.15, 1.15	1.15, 1.15	1.15, 1.15	53.5	54.98, 55.68	55.59, 55.94	55.42, 55.87	54.22, 56.88	12.1	12.16, 12.30	11.81, 12.25	11.95, 12.35	11.51, 13.27
1.20	1.20, 1.20	1.20, 1.20	1.20, 1.20	1.20, 1.20	53.7	53.19, 54.20	53.77, 54.99	53.48, 54.08	54.89, 54.92	12.2	11.20, 13.78	10.91, 12.29	11.98, 12.59	10.47, 11.54
1.26	1.26, 1.26	1.26, 1.26	1.26, 1.26	1.26, 1.26	54.9	54.63, 55.40	55.03, 55.11	54.88, 55.17	55.03, 55.68	12.3	11.76, 12.78	11.49, 12.14	11.92, 12.42	11.20, 11.34
1.35	1.35, 1.35	1.35, 1.35	1.35, 1.35	1.35, 1.35	55.2	54.98, 55.44	55.24, 55.39	55.07, 55.40	54.89, 55.88	12.2	11.59, 12.73	11.39, 12.08	11.87, 12.29	11.29, 11.45
1.45	1.45, 1.45	1.45, 1.45	1.45, 1.45	1.45, 1.45	56.8	56.10, 57.67	56.44, 56.87	56.78, 56.96	55.57, 57.41	12.4	12.10, 12.19	11.87, 12.12	11.97, 12.32	11.64, 12.03
1.58	1.58, 1.58	1.58, 1.58	1.58, 1.58	1.58, 1.58	57.1	56.46, 57.92	56.77, 57.19	57.08, 57.29	55.94, 57.69	12.5	12.39, 12.63	12.03, 12.46	12.36, 12.62	11.87, 12.32
1.78	1.78, 1.78	1.78, 1.78	1.78, 1.78	1.78, 1.78	57.2	56.00, 58.40	56.05, 57.15	56.98, 57.31	55.21, 57.00	12.6	12.41, 12.94	12.67, 12.89	12.59, 12.67	12.74, 13.04
2.04	2.04, 2.04	2.04, 2.04	2.04, 2.04	2.04, 2.04	59.9	59.43, 60.20	59.34, 59.87	59.79, 59.93	58.93, 59.75	12.6	12.15, 12.67	12.27, 12.31	12.32, 12.33	12.10, 12.44
AMD	0.00	0.00	0.00	0.00		0.62	0.56	0.21	1.16		0.66	0.76	0.33	1.06

Note: * AMD denotes average maximum deviation in comparison with its nominal value.

FIGURE 7: Noise figure measurement for different center frequencies.

TABLE 6: Calibrated performance after process variation for the ten tunable BPF designs in Table 5.

Parameter	Our work
CMOS technology (nm)	180
Filter order	4
Supply voltage (V)	1.8
Frequency tuning range (GHz)	1.0–2.04
BW mean (BW_μ) (MHz)	12.01
BW deviation (BW_σ) (MHz)	0.292
Pass band gain mean ($A_{v(\mu)}$) (dB)	55.02
Pass band gain deviation ($A_{v(\sigma)}$) (dB)	0.58
NF (dB)	<6
Power (mW)	15

0.58 dB on the pass band gain mean ($A_{v(\mu)}$) of 55.02 dB. Low noise figure (<6 dB) and steep roll-off high stopband rejection (>20 dB) make the tunable BPF attractive in reconfigurable RF and cognitive radio in TV band applications.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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