A 20 to 560 MHz, Reduced Harmonic Selectivity and Harmonic Fold Back, 6-path Tunable Bandpass Filter

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Abstract. In this paper a 6-path tunable bandpass filter which is able to reduce both Harmonic Selectivity (HS) and Harmonic Fold Back (HFB) effect simultaneously is proposed. The filter contains two channels of 6-path switched capacitor filters with same circuit structure but different clocks and is designed and simulated in GSMC 180nm CMOS technology. The simulation result shows the center frequency of the designed filter f_s can be tuned from 20 to 560 MHz, reduction of HS at $3f_s$ is from -34 to -40 dB, and reduction of H6 in HFB is -21 dB at the same time. The filter can be useful in SDR systems because of its good tunability, high Q and high linearity.

Introduction

Software-defined radio (SDR) is one of the most promising solutions to meet the demand of multiband wireless systems, because of its programmable circuitry which can integrate circuits with multiple purposes. To design a programmable radio, a tunable, integrated bandpass filters in analog front-end circuit, is the key and is still in challenge. Off-chip filters, like SAW filters are unable to tune. On-chip LC filters only provide limited tunability with low Q and consume much more areas.

Recently, many researches have focused on the N-path switched capacitor filters due to their center frequency tunability realized by changing the frequency of clock [1-5]. Benefitted from the boost of CMOS technology, this structure has been more and more widely used in RF circuits. However, because of signal sampling, the N-path filters have two fatal drawbacks which are called Harmonic Selectivity (HS) and Harmonic Fold Back (HFB), respectively [2].

Many works have been done to reduce the HS and HFB in N-path filter. By using differential structure, all even parts of the HS can be eliminated [2]. Other HS can be suppressed when the N is decreased but the HFB will be increased at this moment [2,6]. By using the method of signal superposition, a 6-path filter can reduce the HS at $3f_s$ [7], and a structure which could significantly reduce HFB is proposed in [8]. But all these former proposed structures work poorly to reduce the HS and HFB at the same time.

In this article, a 6-path tunable bandpass filter which is able to reduce both HS and HFB effect simultaneously is proposed. This filter contains two channels of 6-path switched capacitor filters with the same circuit structure but different clocks. With method of signal superposition, this filter can reduce HS effect at $3f_s$ and H6, the largest HFB effect of all, is also reduced at the same time.

N-path Filter

Fig. 1 gives the structure of a typical N-path bandpass filter circuit [1,2,5,7]. Each switch in this circuit works as a mixer. The input signal is down-sampled by switch networks S1 to Sn, transferred into baseband and filtered by RC lowpass filters. Since N paths are sampled by clocks with the same pulse width but different clock phases, the baseband signals are transferred to the switch frequency again. So the circuit can be taken as a bandpass filter whose center frequency can be tuned by changing the clock frequency.

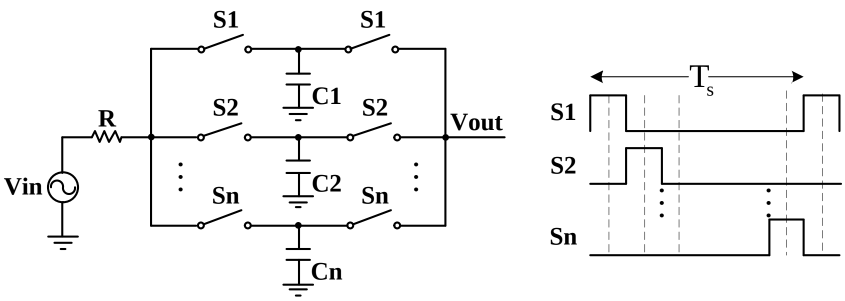

Fig. 1. N-path bandpass filter.

The theoretical approach for this N-path bandpass filter has been discussed in [2,7,8]. The frequency response of this N-path filter is [8]

$$H_{p\times N}(f)=\frac{N}{1+j\times\frac{f-pNf_s}{f_{rc}}}\times\left(\frac{1-e^{-2\pi p}}{j2\pi pN}+\frac{f_s\left(1+e^{\frac{j\pi(N-2)(f-pNf_s)}{Nf_s}}\right)\left(1-e^{-\frac{2\pi(f_{rc}+jf)}{Nf_s}}\right)}{2\pi(f_{rc}+j(f-pNf_s))\left(1+e^{-\frac{\pi\times(2f_{rc}+jN(f-pNf_s))}{Nf_s}}\right)}\right) \quad (1)$$

where N is the number of paths, f_s is the center frequency of the passband, $f_{rc}=1/2\pi RC$, $p=0,\pm1,\pm2...$ Here $H_{p\times N}(f)$ shows the ability that the filter can transfer the signals from around frequencies $(pN\pm1)f_s$ to f_s. When $p=0$, Eq. 1 can be written as [8]

$$H_0(f)=\frac{N}{1+j\times\frac{f}{f_{rc}}}\times\left(\frac{1}{N}+\frac{f_s\left(1+e^{\frac{j\pi(N-2)f}{Nf_s}}\right)\left(1-e^{-\frac{2\pi(f_{rc}+jf)}{Nf_s}}\right)}{2\pi(f_{rc}+jf)\left(1+e^{-\frac{\pi\times(2f_{rc}+jNf)}{Nf_s}}\right)}\right). \quad (2)$$

$H_0(f)$ is transfer function of the N-path bandpass filter without harmonics.

Although the above N-path filter can provide good tunability, it still has two drawbacks: Harmonic Selectivity (HS) and Harmonic Fold Back (HFB). Harmonic Selectivity means the filter has excess passbands around frequencies $Kf_s(K=2,3,4...)$. Harmonic Fold Back represents the phenomenon that harmonics around $(pN\pm1)f_s(p=\pm1,\pm2,\pm3...)$ are transferred to passband f_s [2,8]. In N-path filter, the largest HFB effect is HN with transfer function written as $H_N(f)$ [2,8]. These two drawbacks will introduce too many harmonics in the entire filtering process and severely degrade the performances of the filter.

Reduce HS and HFB

There are multiple methods to reduce HS and HFB. Since these effects are caused by signal up-sampling and down-sampling, we propose to use signal superposition to reduce HS and HFB at the same time.

As shown in Fig. 2, the proposed circuit structure is constructed by two channels of 6-path switched capacitor filters. Each channel uses the circuit structure introduced in previous section, but with a different control clock. Every path of filters contains an input switch, a capacitor and an output switch. The input and output switches of all paths are controlled by 6-path non-overlapping clocks S1-S6 and K1-K6 with the same frequency but different phase.

The period of all control clocks are marked as T_s. The clocks of Filter2 (K1-K6) are $T_s/12$ delayed than the clocks of Filter1 (S1-S6) respectively. For example, K1 is $T_s/12$ delayed than S1, K2 is delayed $T_s/12$ than S2, etc. In Filter 1, each path uses the same clock for both the input and output switches. In Filter2, for each path the clock of the output switch is shifted one phase than the clock of the input switch, like K2 to K1, K3 to K2 and etc. Finally, the outputs of two bandpass filters are added up together as final output.

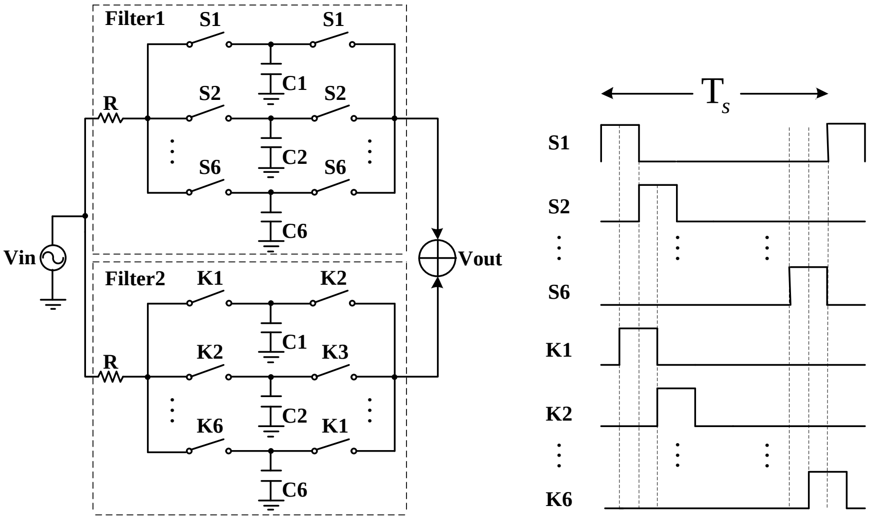

Fig. 2. Structure with reduced both HS and HFB.

Frequency response of typical 6-path filter can be written as $H_{p\times6}(f)$. Because Filter1 has the typical structure with no change, transfer function of Filter1 $H_{p\times6}(f)|_{Filtet1}$ at frequency of $M\times f_s(M=1,2,3...)$ is $H_{p\times6}(M\times f_s)$.

In Filter2, clock of output switches is shifted $\pi/3$ than clock of input switches, which result in $\pi/3$ phase shift on output signal [7]. So at this time transfer function of Filter2 at $M\times f_s$ can be white as

$$H_{p\times6}(M\times f_s)|_{Filter2}=H_{p\times6}(M\times f_s)\times(e^{-j\times\frac{M\pi}{3}}). \quad (3)$$

Then clock K is delayed $T_s/12$ comparing to clock S, so another phase shift is added on output [8]. The transfer function at $M\times f_s$ of Filter2 is

$$H_{p\times6}(M\times f_s)|_{Filter2}=H_{p\times6}(M\times f_s)\times(e^{-j\times\frac{M\pi}{3}}e^{-j\times\pi\times p\times12f_s\times\frac{1}{12f_s}}). \quad (4)$$

Finally the outputs of two filters are added together, so the transfer function of the proposed structure at $M\times f_s$ is

$$H_{p\times6}(M\times f_s)|_{Filter}=H_{p\times6}(M\times f_s)\times(e^{-j\times\frac{M\pi}{3}}e^{-j\times\pi\times p\times12f_s\times\frac{1}{12f_s}}+1). \quad (5)$$

Consider $p=0$, $M=3$, which means the frequency response H_0 at $3f_s$ is

$$H_0(3\times f_s)|_{Filter}=H_0(3\times f_s)\times(e^{-j\times\pi}+1)=0. \quad (6)$$

So the structure eliminates the HS effect at at $3f_s$.

Consider H6 of HFB when $p=1, M=1$, which is the largest HFB effect in 6-path filter [2,8]. Frequency response $H_6(f_s)|_{Filter}$ is

$$H_6(f_s)|_{Filter}=H_6(f_s)\times(e^{-j\times(\frac{\pi}{3}+\pi)}+1)=H_6(f_s)(0.5+j\times\frac{\sqrt{3}}{2}). \quad (7)$$

$H_6(f_s)|_{Filter}=1\times H_6(f_s)<2|H_6(f_s)|$, the structure reduces H6 of HFB effect.

Based on Eq. 6 and Eq. 7, the proposed structure can reduce HS effect at $3f_s$, and reduces H6 of HFB at the same time. Using differential architecture also can reduce the even part of HS, like HS effect at $2f_s$, which makes the filtering characteristic better.

Design and Simulation of 6-path Tunable Filter

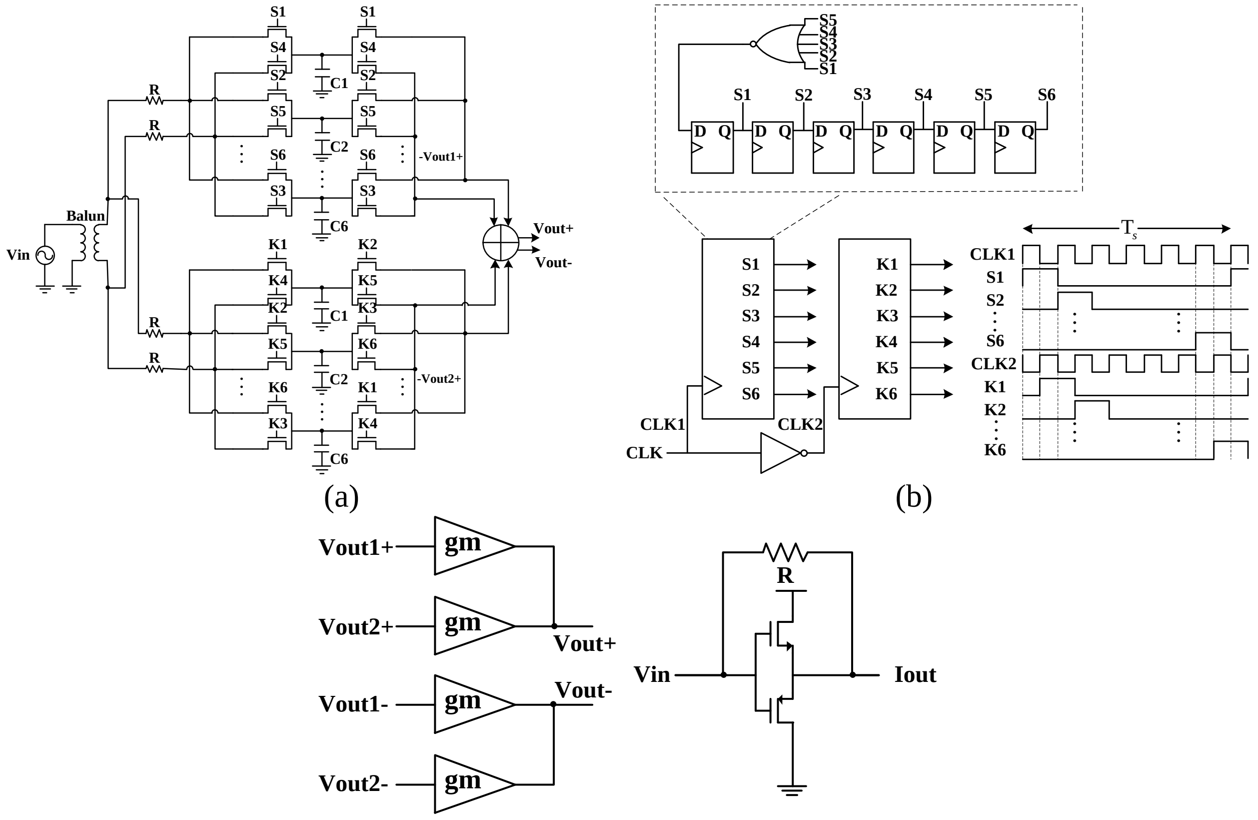

Fig. 3. (a) Transistor level schematic of filter. (b) Clock generation. (c) Add schematic.

A 6-path tunable bandpass filter which can reduce HS and HFB is implemented in GSMC 180nm CMOS technology to verify the proposed structure. Fig. 3(a) shows the transistor level schematic of this filter. The proposed filter contains two channels of 6-path switched capacitor filters in differential architecture and an add circuit. An ideal balun is used to convert single port to differential ports. Switches are made by single NMOS transistors whose W/L is $220/1.8$ and on-resistance is 8Ω. All capacitors are 50pf. These capacitors are made of MOS capacitor instead of MIM capacitor to save areas of chip.

A $1/6$ duty cycle 6-phase clock generator is shown in Fig. 3(b). The input system clock CLK which is 6 times faster than the switch frequency f_s comes from off-chip. CLK1 is identical to CLK and CLK2 is inverted CLK. The CLK1 and CLK2 are divided by 6 by a circuit consist of 6 cascade DFFs and a NOR gate feedback, to generate the control clocks S1 to S6 and K1 to K6.

Implementation of the add circuit is shown in Fig. 3(c). Four inverter transconductance amplifiers are used to add the outputs of the two bandpass filters together. A Feedback resistor R is used to reduce output resistance of the amplifiers.

The performance of this 6-path tunable bandpass filter is simulated by PSS-PAC simulation in Cadence Spectre-RF, and the transfer function of filter with different center clock frequencies is shown in Fig. 4. The center frequency f_s is set at 200MHz, 300MHz, 400MHz and 500MHz by different system clocks. Simulation result shows that the proposed filter achieves good bandpass filtering characteristic in different frequencies. In Fig. 4, the reduction of HS at $3f_s$ is from -34 to -40dB, and H6, the largest HFB effect of all, is reducing -21dB at the same time, which is in agreement with the analysis in previous section. The gain of this filter at 500MHz is 0.46dB lower than the gain of filter at 200MHz because of parasitic capacitances, which is very small around wide frequency span. The center frequency of the filter can be tuned from 20 to 560 MHz under 180nm CMOS technology. It’s a reasonable expect that the work frequency of the proposed filter can be even higher when using more advanced technology due to the improvement of DFFs.

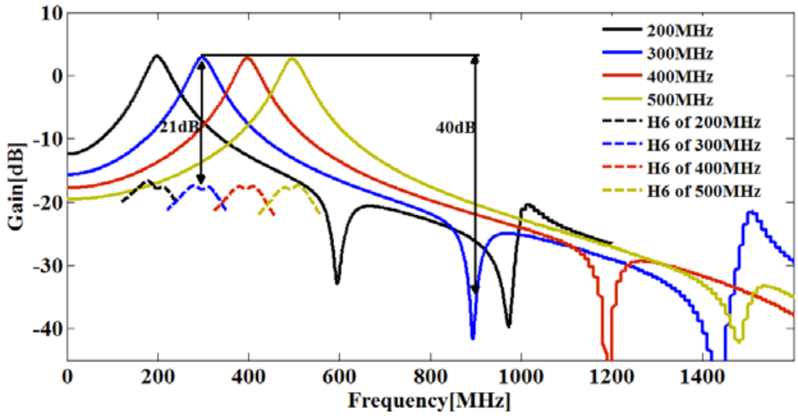

Fig. 4. The simulated transfer function of the filter in different center frequencies.

Fig. 5 shows the NF and S11 of the filter in different frequency. The noise figure of filter mainly comes from add circuits. NF can be reduced by increasing the value of g_m in add circuits, which need a large W/L size of transistors and consumes much more power and chip areas. In this work the method which could reduce HS and HFB is more important than NF.

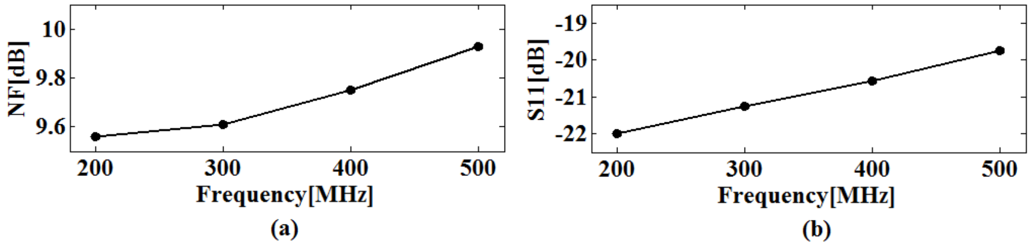

Fig. 5. (a) NF of the filter for different frequencies. (b) S11 of the filter for different frequencies.

Different design structures of 6-path switched capacitor tunable filter are simulated in same CMOS technology and same circuit design method, i.e., the proposed structure, the typical 6-path filter [2], the reduce HS filter [7], and the reduce HFB filter [8]. Fig. 6 (a) shows the gain of HS at $3f_s$ in different center frequencies, and Fig. 6 (b) shows the gain of H6 in different center frequencies. The proposed structure has achieved -34 to -40dB HS reduction at $3f_s$ and -21dB H6 reduction, which are all better than typical structure.

The structure of [8] provides -75dB reduction of H6, which is the best reduction of HFB in four filters, but the HS at $3f_s$ is only -6dB, which is the worst of all. Both proposed structure and the structure of [7] has achieved -34 to -40dB reduction of HS at $3f_s$ around different frequencies, but H6 reduction in proposed structure is -21dB, better than -14dB in [7]. Comparison result between four filters shows the proposed structure can reduce both HS and HFB effect together to get better filtering characteristic.

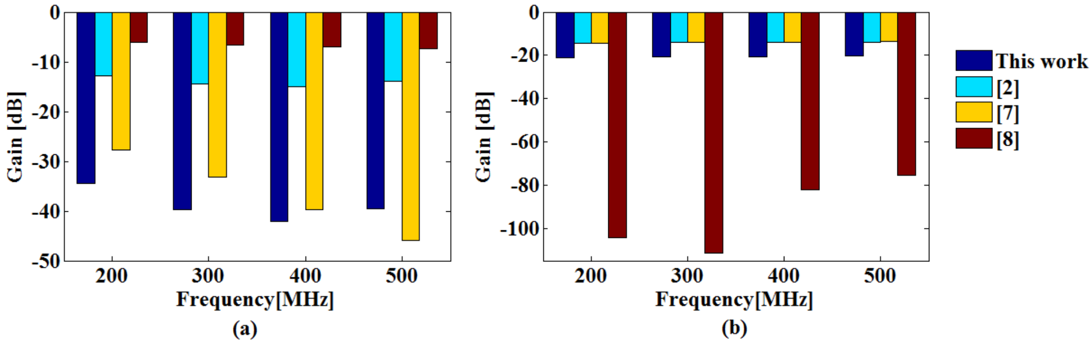

Fig. 6. (a) Gain of HS at $3f_s$ in different frequencies. (b) Gain of H6 in different frequencies.

Finally, Table 1 summarizes the main simulation results of the filter.

Table 1 Summary of simulation results

Gain [dB]	+2.57 - +3.03
Input CLK [GHz]	0.12 - 3.3
Frequency Band [MHz]	20 - 560
BW [MHz]	57 - 60
HS at $3f_s$ [dB]	-31.39 - -39.28
H6 of HFB [dB]	-17.66 - -17.90
S11 [dB]	< -19
Q	4.88 - 9.11
NF [dB]	9.56 - 9.93
IIP3 (333M±50MHz) [dBm]	18
Supply Voltage [V]	1.8
Power [mW]	82.89
CMOS Technology [nm]	GSMC 180

Conclusion

The paper has demonstrated the design of a 6-path tunable bandpass filter which is able to reduce both HS and HFB effect simultaneously. The proposed filter contains two channels of 6-path switched capacitor filters with the same circuit structure but different clocks, which is designed and simulated in GSMC 180nm CMOS technology. Simulation result shows filter achieve tuning rage from 20 to 560 MHz, from -34 to 40dB reduction of HS at $3f_s$, and -21dB reduction of H6 in HFB. Compared with other structures, this work achieves better filtering characteristic while considering reduction of HS and HFB together. With the advantages of good tunability, high Q and high linearity, this filter can be useful in SDR systems and the designed method can be adapted to designing other N-path filters.

Acknowledgment

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