0.07 mm^2, 2 mW, 75 MHz-IF, fourth-order BPF using source-follower-based resonator in 90 nm CMOS

Y. Chen, P.-I. Mak, L. Zhang and Y. Wang

A highly-transistorised bandpass filter (BPF) using a source-follower-based (SFB) resonator is proposed. It benefits from the advantageous properties of the source follower (e.g. no parasitic pole, linear V_{GS} I/O relationship, high-input and low-output impedances), while combining it with a compact and low-power grounded differential active inductor to synthesise the complex poles. Fabricated in 90 nm CMOS, a fourth-order 75 MHz-IF BPF prototype merging two such SFB resonators measures a 10 MHz bandwidth at 2 mW of power. The die size is merely 0.07 mm^2.

Introduction: Heterodyne-type receivers rely on intermediate frequency (IF) filtering to suppress unwanted blockers and images alleviating the back-end demodulation. Off-chip SAW filtering is undesirable owing to its cost, and extra power required to provide the 50 Ω buffering [1]. On-chip IF filtering, alternatively, balances better the area and power with selectivity. The transconductance (g_m)-C bandpass filter (BPF) [1–3] has been widespread for its speed advantage over the operational amplifier (opamp)-based counterpart, but is still inefficient in leveraging the area and power with noise and linearity. In this Letter, a source-follower-based (SFB) resonator is proposed. It merges the advantageous features of the source follower with a grounded differential active inductor (GDAI) to realise a highly transistorised resonator being simple in structure and small in number of devices. The feasibility has been experimentally verified in 90 nm CMOS via cascading two similar SFB resonators to constitute a fourth-order BPF. The measured power and area efficiencies are superior compared with the prior arts.

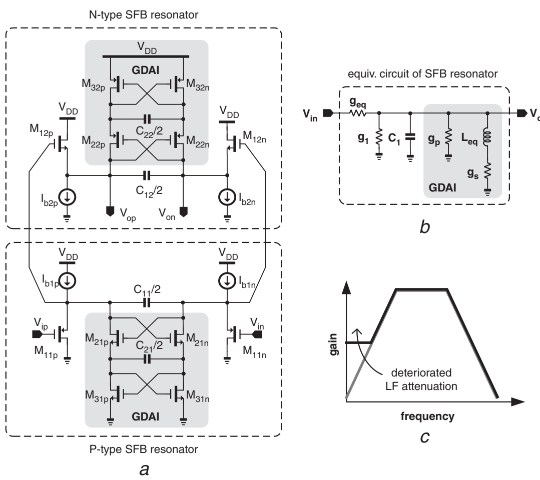

Fig. 1 *Fourth-order BPF using two SFB resonators in cascade*

a Full schematic
b Simplified half-circuit equivalent model of SFB resonator
c Problem of deteriorated LF attenuation

BPF using SFB resonators: As shown in Fig. 1*a*, the proposed BPF is structured by a P-type SFB resonator followed by an N-type one. Each of them is composed of an SFB integrator ($M_{11p,n}$) and a GDAI using positive feedback to synthesise the complex poles. The former features many advantageous properties suitable for high-frequency filtering such as no parasitic pole, no common-mode feedback in differential, linear V_{GS} I/O relationship, high-input and low-output impedances facilitating filter-order extension by simply cascading. For the GDAI, it is based on positive-feedback (PF) gyrators ($M_{21p,n}$), a negative-g_m stage ($M_{31p,n}$) and a capacitor ($C_{21}/2$). When the PF gyrators transform the capacitive effect of $C_{21}/2$ into inductive, $M_{31p,n}$ cancel the positive-g_m resulting from the source terminal of the PF gyrators. The simplified half-circuit equivalent model of GDAI is shown in Fig. 1*b*. Assuming that the GDAI is differentially symmetric, the equivalent parameters can be derived using small-signal analysis as follows:

$$L_{eq} = \frac{C_{21}}{(g_{m-M2} + g_{mb-M2} + g_{ds-M2})(g_{m-M2} - g_{ds-M2})} \simeq \frac{C_{21}}{g_{m-M2}^2}$$

$$g_p = -g_{m-M2} + g_{ds-M2} + g_{ds-M1} + g_{ds-Ib} \simeq -g_{m-M2}$$

$$g_s = \frac{g_{m-M2} + g_{mb-M2} + g_{ds-M2} - g_{m-M3} + g_{ds-M3}}{(g_{m-M2} + g_{mb-M2} + g_{ds-M2})(g_{m-M2} - g_{ds-M2})} \quad (1)$$

where $g_{m\text{-}Mx}$ and $g_{ds\text{-}Mx}$ are the transconductance and output conductance of the numbered transistors, respectively; $g_{mb\text{-}M2}$ is the body transconductance of $M_{2p,n}$. Although the term $-g_{m\text{-}M2}$ in the expression of the parallel conductance g_p can potentially lead to instability, the source-follower ($M_{11p,n}$) offers a positive equivalent transconductance g_{eq} that can be specifically sized to compensate it (Fig. 1*a*). The overall transfer for function *H(s)* of the SFB resonator is given by:

$$H(s) = \frac{g_{eq}/C_{11}(s + g_s/L_{eq})}{s^2 + s(g_s/L_{eq} + g_{eq} + g_p + g_1/C_{11}) + g_s(g_{eq} + g_p + g_1) + 1/L_{eq}C_{11}} \quad (2)$$

where g_{eq} ($=g_{m\text{-}M1}$) and g_1 ($=g_{ds\text{-}M1} + g_{ds\text{-}Ib}$) are the equivalent transconductance and parasitic conductance of the SFB integrator, respectively. The filter parameters of the SFB resonator are obtained as:

$$\omega_0 = 2\pi f_0 = \sqrt{\frac{g_s(g_{eq} + g_p + g_1) + 1}{L_{eq}C_{11}}}$$

$$G_{\text{resonator}} = \frac{g_{eq}}{g_{eq} + g_p + g_1} \quad (3)$$

$$Q = \frac{\sqrt{L_{eq}C_{11}[g_s(g_{eq} + g_p + g_1) + 1]}}{g_s C_{11} + (g_{eq} + g_p + g_1)L_{eq}} \simeq \frac{g_{m-M2}}{g_{m-M1} - g_{m-M2}}\sqrt{\frac{C_{11}}{C_{21}}}$$

where ω_0 is the angular pole frequency, Q is the quality factor and $G_{\text{resonator}}$ is the passband gain. Both Q and $G_{\text{resonator}}$ are highly insensitive to process and temperature variation as they are given by the ratios of components.

For bandpass filtering a general issue is the deteriorated low-frequency (LF) attenuation, as shown in Fig. 1*c*. When the frequency moves from LF (LF $< f_0$) to 0, the LF suppression is degraded. Equation (2) can be written as follows, to obtain the maximum attenuation at DC:

$$G_{LF \to DC} = H(s)|_{s \to DC} = \frac{g_{eq}g_s}{g_s(g_{eq} + g_p + g_1) + 1} \quad (4)$$

The negative-g_m stage ($M_{31p,n}$) can be properly added to reduce g_s, such that the LF attenuation can be mended. As long as the series conductance g_s in (1) maintains as a positive value over process variation and mismatch, the stability of the SFB resonator is guaranteed.

Experimental results: The proposed fourth-order BPF has been fabricated in a 90 nm CMOS technology which offers 2.2 fF/μm^2 density for the used capacitors. The BPF optimised for a 75 MHz IF occupies a die size of 0.07 mm^2 as shown in Fig. 2. The total capacitance is around 30 pF. The measured frequency response is shown in Fig. 3*a*. The BPF at a 75 MHz centre frequency shows an in-band gain of −2.5 dB. The bandpass ripple is <0.2 dB in a bandwidth of 10 MHz. The maximum group delay is 14.8 ns at 75.3 MHz (Fig. 3*b*). The noise figure (NF) including the test buffer is 22 dB (Fig. 3*c*). For the linearity tests (Fig. 3*d*), a two-tone test at 74 and 76 MHz yields an in-band IIP3 of −7.5 dBm. The out-of-band IIP3 is +3.6 dBm by applying two tones at 150 and 225 MHz (i.e. the third-order intermodulation distortion folds to 75 MHz). The total current consumption is 1.3 mA at a 1.5 V supply.

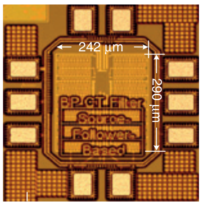

Fig. 2 *Chip photo*

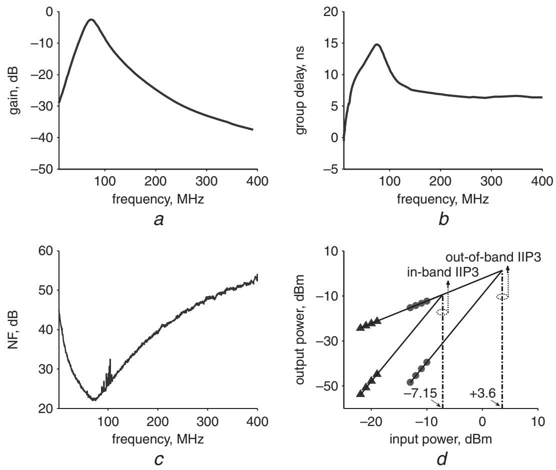

Fig. 3 *Measured performance*

a Magnitude response
b Group delay
c NF
d In-band and out-of-band IIP3

Table 1 compares the performance of this work with those [1–3] targeting a similar application. This work is advantageous for its much small power and die size.

Table 1: Performance summmmary and comparison

Parameters	[1]	[2]	[3]	This work
CMOS technology	65 nm	0.6 µm	90 nm	90 nm
Total current (mA)	11	10	10	**1.3**
Die size (mm^2)	0.25	0.44	N/A	**0.07**
Filter order	4	6	6	4
f_0 (MHz)	80	100	100	75
BW (MHz)	10	10	10	10
Passband gain (dB)	2	0	13.5	−2.5
In-band ripple (dB)	0.1	4	N/A	0.2
In-band IIP3 (dBm)	−2	N/A	2	−7.15
NF (dB)	21.5	N/A	N/A	22
Supply voltage (V)	1.2	2.95	1.4	1.5

Conclusion: This work has demonstrated that a source-follower-based (SFB) resonator is particulary power- and area-efficient in realising a high-IF BPF with a small number of device counts. A fourth-order 75 MHz-IF BPF prototype merging two such SFB resonators measures a 10 MHz bandwidth at 2 mW of power, while occupying a 0.07 mm^2 die size in 90 nm CMOS. The achieved results are favourably comparable with the prior arts.

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One or more of the Figures in this Letter are available in colour online.

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