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Abstract: This paper describes a new association of a high-Q pseudo 8-path switched-capacitor (S-C) bandpass filter and its command circuit made up by a ring VCO with 'XOR' gates. The proposed circuit presents the possibility of tuning over a radio-frequency (RF) broadband allowing to sweep different channels with a high quality factor. Designed with CMOS process (0.35 μm, for instance), this circuit is intended to replace the surface acoustic wave (SAW) filters in modern wireless receivers. Measurements carried out on a circuit demonstrator show a tunable center frequency range of 200 MHz [300–500 MHz], with a quality factor higher than 300.

Keywords: high-Q, tuned, switched-capacitor, bandpass filter, ring VCO

Classification: Integrated circuits

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1 Introduction

Pseudo N-path S-C filters have been widely used for a few years, for the realization of stable, accurate and high quality filters at operating frequencies below the megahertz range [1, 2]. Another attractive feature of these filters is their feasibility in low-cost CMOS technology, which results in a great increase in their operating frequency range [2, 3]. Moreover, they can be fully integrated (on-chip) unlike SAW filters which are generally off-chip. The critical limitation of these filters is related to the construction of the command circuit of the switches, which was generally carried out using a shift register. This solution that requires a clock frequency equal to the center frequency of the filter multiplied by the number of cells to commutate (here, eight cells) is exclusively used at low frequencies. The solution proposed in this paper uses a ring VCO associated with 'XOR' gates. This original solution provides the possibility of tuning within a broadband in the RF range, allowing to sweep different channels with a high quality factor. Furthermore, it might be a very attractive solution for the design of zero IF receivers used in radio-communication systems.

2 Circuit design and simulation results

Figure 1 (a) shows the architecture of the pseudo 8-path S-C filter. This filter can be used for clock recovering by filtering the harmonic components. It can also be used as bandpass filter at the center frequency Fo = 1/To. This last application will be discussed in this paper. The number of eight cells that is

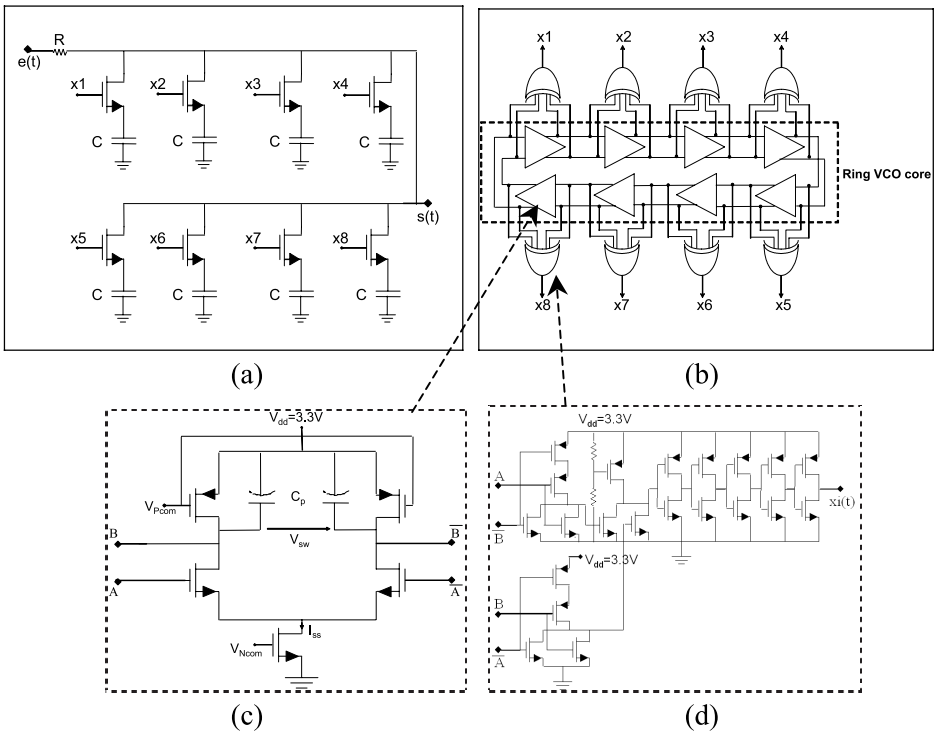

Fig. 1. Architectures of : (a) pseudo 8-path S-C filter, (b) proposed command circuit, (c) delay cell with NMOS differential amplifier, and (d) 'XOR' gate.

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chosen for this study seems to be a good trade-off between the quality factor (in first approximation [4], Q = π N R C Fo) and chip complexity, which quickly increases with the cell number (N).

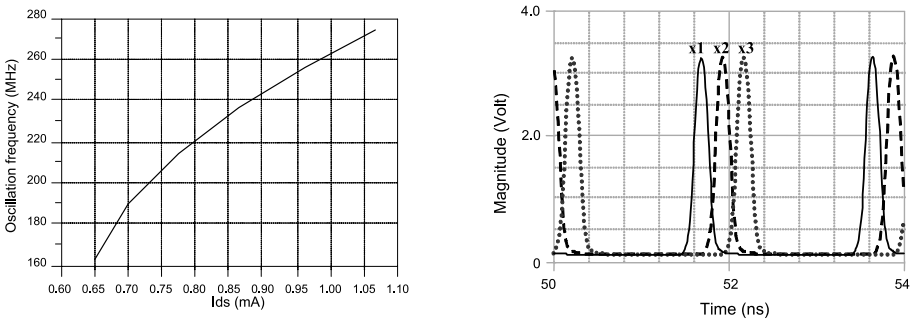
The switches are performed with NMOS transistors sequentially controlled in ON-OFF states. The switches size is critical and should be optimized. Indeed, the transistors used in this design are channel N MOSFETs composed of six fingers with an elementary gate width of 25 μm and a length of 0.35 μm. These transistors present a resistance R_{on} of 30 Ω and a drain-source capacitance C_{ds} of 0.06 pF, to give an optimal dynamic range [5].

To command the filter (Fig. 1 (a)), an eight-cell command circuit is sufficient. Figure 1 (b) shows the proposed command circuit, which composed by a ring VCO with 'XOR' gates.

The ring VCO comprises eight identical differential delay cells. Each cell is based on two NMOS transistors composing a differential amplifier (Fig. 1 (c)), to provide both the gain and the delay required for the oscillation phenomena. The total delay cumulated with the eight cells is equal to 2 To, and leads to Fo/2 oscillation frequency. The delay generated by one cell depends of the time-constant Rp Cp. The Rp resistance corresponds to the differential resistive load, which is obtained by PMOS transistors working in triode operation region, and the Cp capacitance is due to the 0.35 pF capacitor placed between drain and source of each PMOS transistor. The oscillation frequency is tuned by contolling both the common current source and the bias point of the PMOS transistors which modify the Rp value between 800 Ω and 1.5 KΩ.

The 'XOR' gates (Fig. 1 (d)) generate command signals from the delay cells inputs and outputs. This is achieved by using NMOS transistors of $1 \times 1 \times 0.35\,\mu m^2$ gate size. Nevertheless, the low gate size of these transistors cannot provide the necessary current to drive the switching transistors, which have a gate width of $6 \times 25\,\mu$m for length of 0.35 μm. Consequently, a five-stage buffer was implemented to ensure the switching.

The output frequency of this ring VCO is adjustable between 160 and 270 MHz (Fig. 2 (a)) by controlling the current source of the delay cells. A special attention was given to the temporal waveform signals in order to



(a) (b)

Fig. 2. Simulation results: (a) frequency versus bias current, and (b) command signals for the first three successive switches.

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Table I. Summary of simulation and measurement performances.

Parameters	Simulation	Measurement
Voltage supply (V)	3.3	3.3
Current consumption (mA)	26	26-27
Tuning frequency range (MHz)	320-500	300-500
−3 dB Frequency Bandwidth (MHz)	0.9	0.97-3.4
Quality factor	355-550	310-140
Insertion loss (dB)	2.5	4-1
Dynamic range (dB)	25.5	18-12
1 dB input compression point (dBm)	-5	-9

limit the time jitter, in this condition, the simulated phase noise obtained is roughly −111 dBc/Hz at the offset frequency of 1-MHz. From this result, it's appears important to have only one source that provides all command signals, which reinforces our choice of this ring VCO to command the filter. In theses conditions, the command circuit generates correlated signals and the time jitter doesn't have significant influence on the filter response [5].

Figure 2 (b) presents the simulated command signal waveforms x1(t), x2(t) and x3(t) respectively applied to the first, second and third switches for switching frequency closed to 500 MHz. The impulse magnitude is higher than 3 Volts, allowing to get a low R_{on} value of the switch. During switches design, it is necessary to avoid insertion losses generated by impulses overlap.

The main simulation results of this filter with its command circuit are summarized in Table I.

The filter presents an adjustable center frequency ranging between 320 and 500 MHz with a bandwidth of 900 kHz, and a quality factor better than 355 on the tunable frequency band.

3 Experimental results

To validate the proposed design approach, a circuit demonstrator composed by a pseudo 8-path S-C filter with its command circuit (Ring VCO with 'XOR' gates) was fabricated using a standard 0.35 μm CMOS process.

The measurements realized on this circuit demonstrator show a measured oscillation frequency range of 100 MHz [150–250 MHz], i.e. a tunable center frequency band of 200 MHz [300–500 MHz]. The measured results at both 300 MHz and 500 MHz switching frequencies are summarized in Table I.

Figure 3 shows the pseudo 8-path S-C filter transfer characteristic measured at a switching frequency closed to 300 MHz. Measurements at 300 MHz demonstrate interesting performances; the bandwidth is equal to 0.97 MHz, and the quality factor is roughly 310. However, the quality factor is reduced for the higher switching frequencies; thus, a quality factor of 140 is obtained for a switching frequency close to 500 MHz. The difference observed between simulated and measured results is due to the lack of accuracy the models present at high frequency harmonics of the switching signals. For higher

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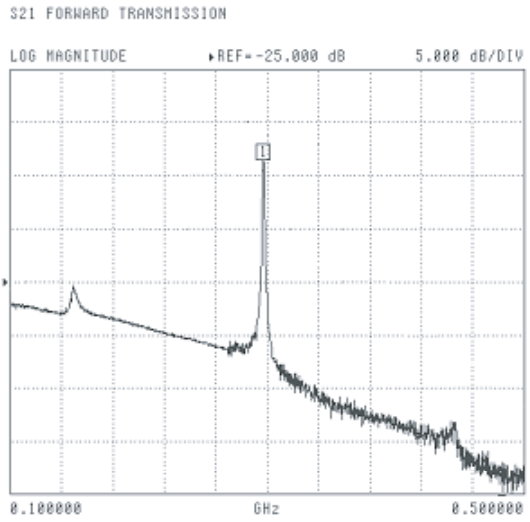

Fig. 3. Measured frequency response around a switching frequency closed to 300 MHz.

frequencies applications, a CMOS technology with a higher f_T (transit frequency) would be suitable to improve the performance of this circuit.

4 Conclusion

A new command circuit design for tuning high-Q pseudo 8-path S-C filter has been presented. This high-Q filter can be tuned over a broadband in the RF range by using a ring VCO with 'XOR' gates in 0.35 μm CMOS process. The experimental results demonstrate the validity of the proposed design approach; They are comparable with those of SAW filters. This circuit could be used in the field of low-cost wireless communications as a subset of professional mobile phone.

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