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ON THE POSSIBILITY OF USING CMOS ACTIVE INDUCTORS FOR TELECOMMUNICATIONS FILTERS IMPLEMENTATION

BY

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Abstract. The possibility of implementing pseudo-passive preselective filters for RF front-ends based on active inductors is investigated in this paper. Starting from a passive filter prototype synthesized for 2.4 GHz band, *e.g*. Bluetooth and WiFi, a pseudo-passive filter using transistor only simulated inductors (TOSI) is designed and simulated in Cadence. Frequency response, noise and power consumption are the parameters of major interest. It is found that a 6th order bandpass filter can fulfil the frequency requirements for 2.4 GHz band, a higher order having increased noise and power consumption. In addition, not all TOSI architectures are suitable for this kind of filter implementation. The circuits are biased from a 2.5 V supply voltage and simulations are carried out in Spectre RF using 0.25 μm QUBIC4x NXP BiCMOS process.

Key words: active inductor; bandpass; Bluetooth; CMOS; filter; RF.

1. Introduction

The emergence of multi-standard radio architectures and software defined radio concept pushes more and more pressure on the reconfigurability of the RF devices. If for the digital part we assist to a continuous process

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scaling, this is not the case for analog circuits (RF front-end in particular) where it is difficult to manage certain constraints such as noise, power consumption and linearity for smaller and newer technologies. This is the reason why the single freedom degree that still remains for the RF part is the general transceiver architecture adopted for a particular application. In this regard, an older matter of concern the designers had to deal with during the last decades is represented by the RF filtering part, currently implemented with SAW filters. Being external and with no possibility of tuning, these passive filters are a problem in implementing a fully integrated RF front-end. Three solutions have been proposed during the last decade as follows:

1. The first approach is to include the filtering function in the low noise amplifier (LNA) structure so that the interstage SAW filter (Yanduru *et al*., 2006) or preselective one (Darabi, 2007; Seo *et al*., 2009) is no more necessary. Such configuration is also known as *bandpass filtering LNA*.

2. The second possibility is to implement a pseudo-passive filter, consisting of a prototype passive filter implemented with TOSI. Only one topology using two sections was proposed in literature (Liang *et al*., 2005). Since all filter capacitors are sized depending on the inductance value, using an active inductor with good properties over the frequencies of interest (*e.g*. L = ct. and $Q \rightarrow \infty$) is critical. However, its main advantage is that it does not need any external matching network.

3. The third one is to implement an entire active filter, consisting of capacitively coupled active resonators. In all cases it makes use of TOSI, either having an input capacitor (Thanachayanont & Payne, 1996) or active buffer to have the input matched (Wu *et al*., 2003). The SAW preselective filter can be avoided when such active topology follows the LNA and has a minimum gain of 5 dB (Gao *et al*., 2008).

Active implementation has an important advantage over the passive one (SAW) with respect to impedance matching. Thus, a multi-standard receiver using SAW filters (preselective and interstage filters) needs two external impedance matching networks for each SAW filter. Contrary to this, active filter comes with integrated input/output impedance matching when a common gate/drain stage is used at the input/output. Therefore, there is no need to use on-chip impedance matching networks for active implementations at the price of some *extra* power consumption. This is an important detail that must be taken into account when dealing with the filtering part. In addition, incorporating the filtering function in the integrated active area minimizes not only the chip area but also the final cost.

This paper deals with the second approach, investigating the pseudo-passive filters. It aims also to study the performances and limitations of TOSI type active inductors when implementing such pseudo-passive configurations. The Bluetooth/WiFi case is taken into account since lower order bandpass filters are required (two or three sections), an increased order strongly deteriorating the noise factor.

The paper is organized as follows. Section **2** discusses the concept of transistor only simulated inductor and details the architecture used in our research. Section **3** investigates the possibility of implementing passive filters of minimum order, ideally 4^{th} order, and fulfilling the Bluetooth standard specifications. Butterworth and minimum ripple Chebyshev filters are taken into account. Section **4** investigates the possibility of implementing Bluetooth passive filters with active inductors (TOSI). Issues regarding the noise figure and scattering parameters are primarily envisaged. Finally, conclusions are drawn in Section **5**.

2. Active Inductor Topology

As mentioned previously, one possibility to implement active or pseudo-passive filters is to use TOSI inductors. These active inductors are based on the gyrator principle, being implemented with at least two transistors. There are also some circuits proposed in literature exhibiting an inductive behavior (Carreto-Castro *et al*., 1999; Sackinger & Fischer, 2000; Wu *et al*., 2004) but they are not based on the gyrator concept. Particular for these implementations is that they are using the transistor parasitic capacitor (C_{GS} in particular) as the gyrator loading capacitor. In fact, on-chip capacitors are not required since parasitic capacitors are always associated to the chip layout and therefore can be useful for gyrator implementation. This not only saves the chip area but also facilitates high self resonant frequencies for simulated inductor.

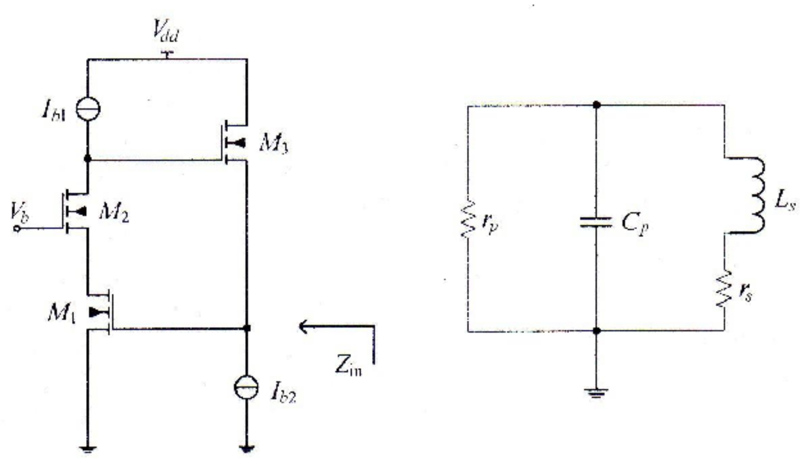

Fig. 1 – CMOS transistor only simulated inductor (left) and equivalent model (right).

The active inductor used in our study is shown in Fig. 1 (Thanachayanont & Payne, 1996). It consists of a common source stage, M_1, cascode transistor, M_2 , and common drain transistor, M_3. The gyrator is implemented as follows: M_1 is the inverting transconductor, M_3 is the non-inverting transconductor and C_{GS3} (or equivalently the total node capacitance) represents the gyrator loading capacitance. The capacitance seen at the input node (~ C_{GS1}) is the active inductor parasitic capacitance (C_p) that sets the inductor self resonant frequency (ω_0). Taking into account the transistors output resistance (r_{ds}), an equivalent *RLC* resonator is seen at the input node (as in Fig. 2). M_2 is used to increase the output resistance of M_1, thus minimizing the inductor series resistance (r_s). A supplementary resistance may be inserted to the gate of M_3 to improve the inductor quality factor (Hsian *et al*., 2002), but for the sake of simplicity no gate resistance is used.

As it can be seen from the equivalent model, the active inductor is affected by resistive losses. In fact, all active inductors possess this drawback, having very low intrinsic quality factors. This is the reason why a negative resistance must be used to compensate the resistive losses (Wu *et al*., 2003).

This active inductor is the single one proposed in literature that does not require a negative resistance. By using the cascode stage, sufficient quality factors might be achieved. In addition, inserting a supplementary resistance to the gate of M_3 increases the quality factor with the price of *extra* thermal noise. Being simple and having high quality factor, this active inductor may be useful for implementing pseudo-passive filters if the inductance value and quality factor do not have large deviations over the bandwidth of interest. This is a critical aspect when dealing practical implementations. In this regard, eight versions of active inductors were designed with different transistor sizes, currents and number of fingers. The inductance value ranges between 1 nH and 32 nH, with very small deviations in the bandwidth of interest (2.4…2.5 GHz). All circuits were biased from a 2.5 V power supply with a constant V_b ($V_b =$ $= 2$ V). As simulations show, smaller current consumption and transconductance value corresponds to larger inductances.

3. Prototype Bluetooth Filters

Among wireless standards, Bluetooth and WLAN have the most relaxed spectrum specifications. This facilitates the design of minimum order passive filters fulfilling the spectrum specifications regulated for these two standards, with the main benefit of reduced chip area. Thanks to the technology development, the SAW filter area reduced constantly during the last two decades, relative small size being currently achieved for Bluetooth filters: $1.4 \times$ $\times\ 1.1 \times 0.4$ mm^3 for B9413/B9447 (Epcos) and $1.4 \times 1.2 \times 0.4$ mm^3 for part 856539 (Triquint). Yet, the filter might seem bulky compared to the RF front-end chip area as it is the case of the low-power 2.4 GHz RF transceiver CC2500 which is four times only larger than Bluetooth filters (Texas Instruments). When taking into account also the (E)GSM/WCDMA SAW preselective filters, it is obvious that the ratio between RF front-end (active) area and the entire

(SAW) passive area tends to be by far less than 1, thanks to the continuous scaling of the CMOS process. In addition, the SAW filter chip size is not the single drawback since, being external, *extra* space is also required for supplementary inductors that must be added for matching purpose. Moreover, the PCB layout and parasitics affect the filter impedance matching which is the most critical aspect in filtering design. Taking into account the supplementary price paid for each Bluetooth filter when implementing a mobile terminal, it is obvious that the good frequency selectivity particular to SAW filters is traded off against chip area and cost. Therefore, the idea of avoiding the SAW filter by integrating the filtering part into the active part of the RF front-end is welcome.

In this section, the frequency behavior of several particular prototype filters is studied and the minimum order for which the passive filter fulfills the spectrum requirements is established. The frequency characteristics for these particular filters are reported to the spectrum mask reported for the SAW filter B9413, the main constraint consisting in achieving an attenuation $\alpha \geq 25$ dB ($f \leq 2.3$ GHz) and $\alpha \geq 18$ dB ($f \geq 2.55$ GHz).

The prototype architecture chosen for our study contains capacitively coupled resonators, this offering simultaneous impedance matching and AC coupling. Moreover, the input capacitor allows the use of active inductors, which is not the case of top C or top L topology. All filters are single-ended architectures, being 50 Ω input and output matched in a bandwidth of 83.5 MHz. Two approximations are taken into consideration, Butterworth (maximally flat) and Chebyshev respectively. 4th and 6th order filters are taken into consideration, these being designed for three particular inductance values (0.2 nH, 1 nH and 10 nH). Since practical implementation is envisaged, the chip area is the first design issue that must be considered when choosing a particular configuration. For passive filters, the chip area is mostly set by the inductance size, directly determined by its value. However, in our case, since the passive inductors are replaced with active topologies, the chip area constraint may be neglected since active inductors have very small chip area in comparison with the passive ones.

In general, larger inductances are obtained with smaller transconductance values and chip area, low power consumption being expected. In addition, smaller capacitance is required when using a large inductance value, which makes the filter design much easier for higher orders. However, a reasonable compromise must be achieved since smaller transconductance value means also larger noise which in turn degrades the pseudo-passive filter performances. This is the reason why the prototypes only implemented with $L =$ $= 1$ nH are chosen for comparison. The attenuation achieved by these filters at 2.3 GHz and 2.55 GHz are summarized in Table 1. The frequency characteristics corresponding to 4th and 6th order filter prototypes are shown in Figs. 2 and 3.

Table 1

Butterworth and Chebyshev Filters Gain

Filter		Attenuation, [dB]	
		f =2.3 GHz	f = 2.55 GHz
4th order, Butterworth		22.14	14.96
4th order, Chebyshev	α = 0.1 dB	12.14	5.23
	α = 0.5 dB	19.34	11.22
	α = 1.0 dB	22.67	14.29
6th order, Butterworth		33.84	22.43
6th order, Chebyshev	α = 0.1 dB	29.08	16.98
	α = 0.5 dB	37.24	22.51
	α = 1.0 dB	39.73	27.37

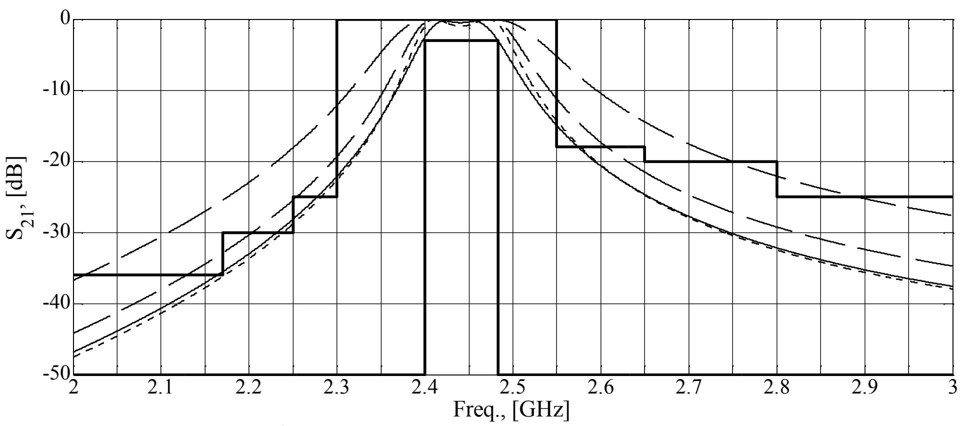

Fig. 2 – 4th order passive prototypes frequency response.

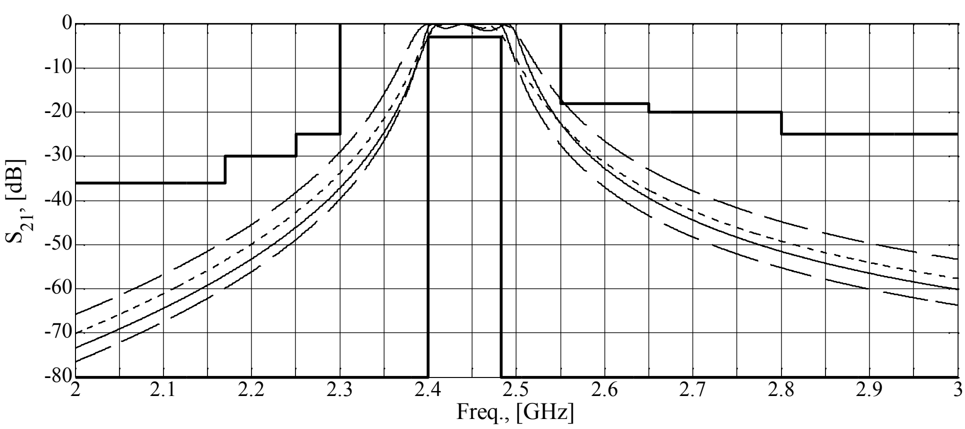

Fig. 3 – 6th order passive prototypes frequency response.

According to these figures, a 4^{th} order bandpass filter cannot fulfill the Bluetooth spectrum regulations even though a 1-dB ripple Chebyshev filter has the attenuation close to 25 dB at 2.3 GHz. In the same time, the spectrum requirements are satisfied by a 6^{th} order Butterworth or Chebyshev ($\alpha > 0.1$ dB) filter. All these theoretical results demonstrate that the minimum order a filter must have is at least 6^{th} in order to fulfil the Bluetooth requirements, higher orders being necessary for $2G/3G$ applications.

4. Pseudo-Passive Filter with TOSI

Two passive filter topologies fulfilling the Bluetooth specifications are presented in Fig. 4. They are also simulated in Cadence with the passive inductors replaced by active ones (as in Fig. 1). The simulated inductor quality factor, S_{21}, S_{11} and NF, are shown in Figs. 5,…,8. BPF1 is the Butterworth filter in Fig. 4 *a* implemented with high-Q active inductor, having better frequency response, while BPF2 is the Chebyshev filter in Fig. 4 *b* implemented with low-Q active inductor ($Q \sim 5$).

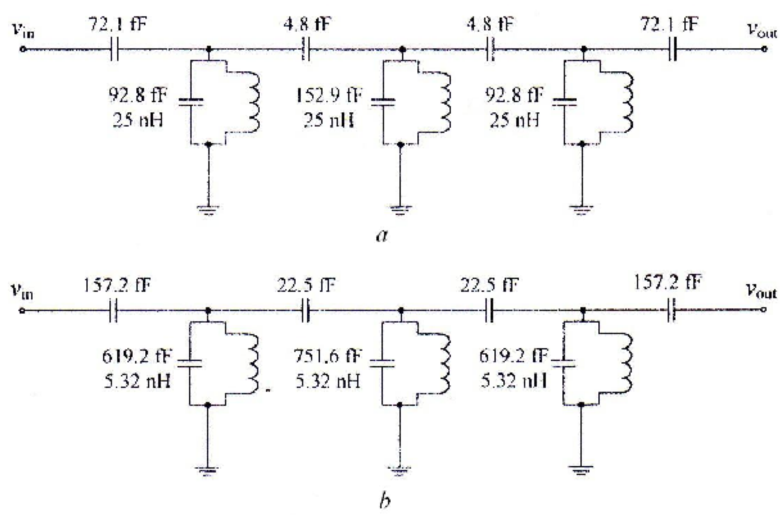

Fig. 4 – Two Bluetooth prototype filters.

The major problem when dealing with simulated inductors, besides implementing high-Q active inductors, is to know the right value of the inductor parasitic capacitance. In Fig. 4, any change of the parallel capacitance value deteriorates the filter frequency performances. In this respect, a common error obtained in our design was the extraction of a smaller parasitic capacitance than the real one used by the simulator. The main effect was not only a decrease of the filter bandwidth and central frequency but also the smoothing of the characteristic shape. This signifies that the supplementary inductor parallel capacitor must be smaller, with the main benefit of reduced chip area. Thus, it is interesting to note a second benefit when using the TOSI parasitic capacitances: the first parasitic capacitor is used to implement the gyrator, the second one is used as parallel capacitor when designing passive filter prototype.

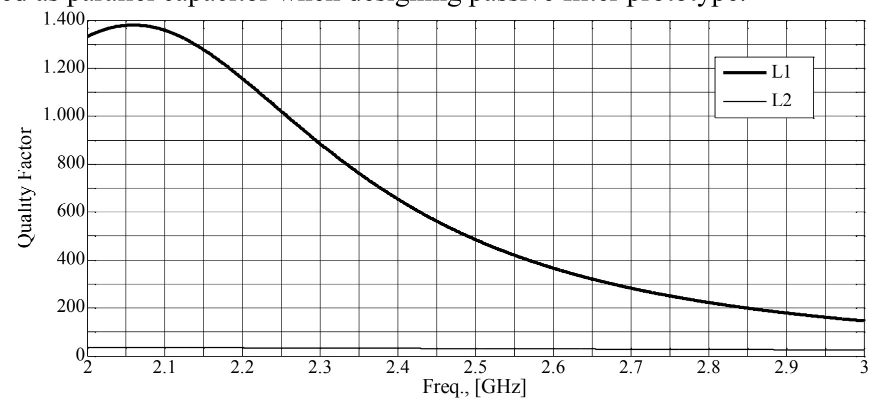

Fig. 5 – Simulated quality factor (L_1=25 nH, L_2=5.3 nH).

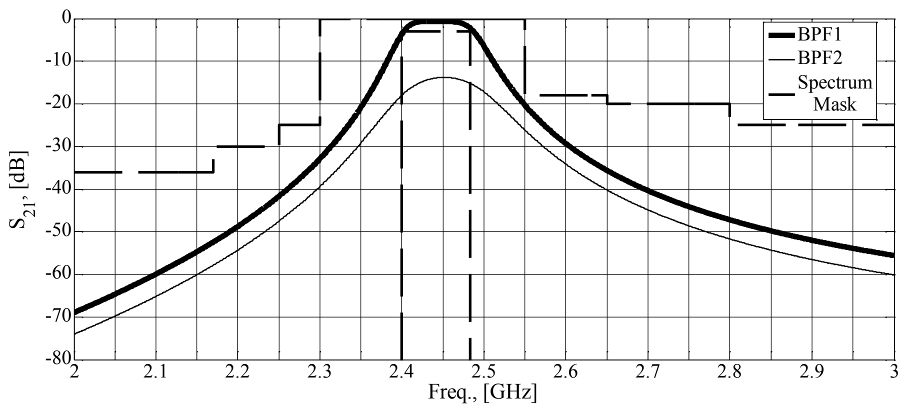

Fig. 6 – Frequency response for Bluetooth pseudo-passive filters.

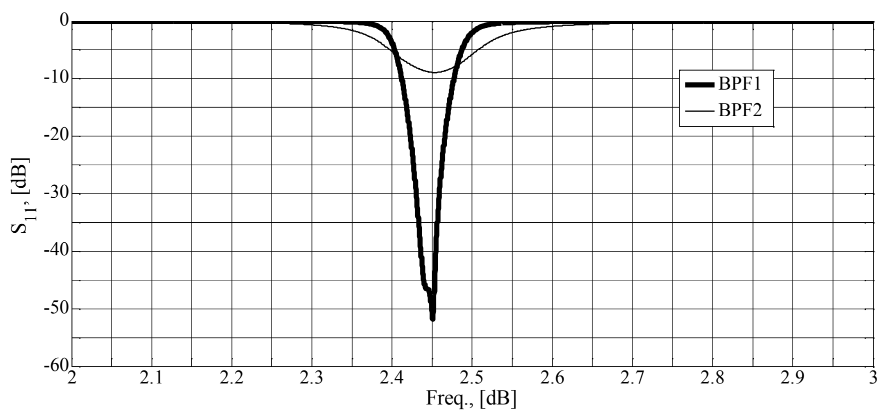

Fig. 7 – S_{11} *vs*. frequency.

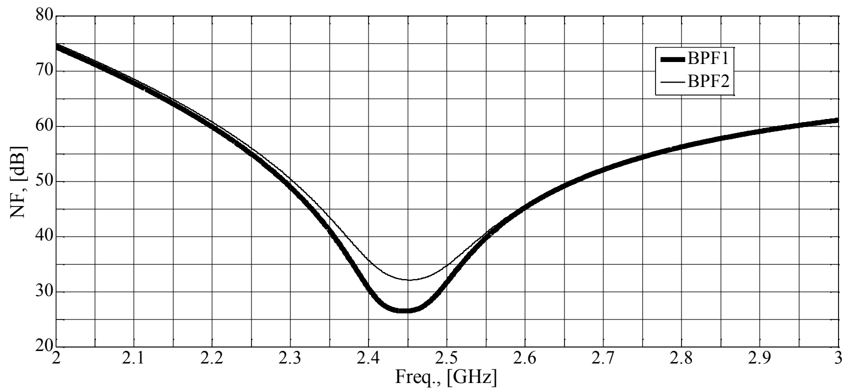

Fig. 8 – Noise figure (NF) *vs*. frequency.

Supplementary simulations showed that for a 6th order Butterworth topology, by replacing only one or two passive inductors with TOSI, the noise factor, NF, gradually increases up to about 16…20 dB. This seems to agree well with other TOSI based second order passive filters topologies proposed in literature, reporting 18 dB (Gao *et al*., 2008; Krishnamurthy *et al*., 2010). However, the structure reported by Gao *et al*., (2008) has a supplementary gain of 6 dB. Linearity is not taken into account since the first primary issues regarding this implementation are the spectrum mask and noise figure. The filters in Fig. 4 consume 1.98 mW and 12.6 mW, respectively.

5. Conclusions

The design of active inductor based passive filter prototypes of 4th and 6th order, fulfilling the Bluetooth standard spectrum requirements, was investigated. Preliminary results prove that a 6th order Bluetooth passive filter can be implemented with active inductors at the price of increased noise. The implementation of Bluetooth pseudo-passive filters using thermal noise canceling CMOS active inductors is under investigation.

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ASUPRA POSIBILITĂŢII DE UTILIZARE A INDUCTANŢELOR ACTIVE CMOS LA IMPLEMENTAREA FILTRELOR DE TELECOMUNICAŢII

(Rezumat)

Se studiază posibilitatea de implementare a filtrelor de preselecţie pseudo-pasive pentru partea radio front-end, bazate pe inductanţe active. Pornind de la un prototip pasiv sintetizat pentru banda de 2.4 GHz (Bluetooth şi WiFi), un filtru pseudo-pasiv bazat numai pe inductanţe de tip TOSI (implementat numai cu tranzistoare) este proiectat şi simulat în Cadence. Parametrii de interes cei mai importanţi sunt: răspunsul în frecvenţă, zgomotul şi puterea consumată. S-a stabilit faptul că un filtru trece bandă de ordin 6 poate satisface specificaţiile în frecvenţă pentru banda de 2.4 GHz, un ordin mai mare determinând zgomot şi consum semnificative. În plus, nu toate arhitecturile TOSI sunt potrivite pentru acest tip de implementare a filtrului. Circuitele sunt polarizate de la o sursă de tensiune de 2.5 V iar simulările au fost efectuate în SPECTRE RF cu tehnologia BiCMOS QUBIC4X 0.25 μm.