A Fully Integrated Q-enhanced LC Filter with 6 dB Noise Figure at 2.5 GHz in SOI

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***Abstract* — Q-enhanced LC filter technology offers a promising approach to remove the off-chip preselect filter still required in current transceivers. To date, previous designs fail to meet the stringent system specifications such as dynamic range and noise figure for existing wireless receivers. This paper presents an innovative prototype design targeted at Bluetooth in silicon-on-insulator (SOI) process. Drawing 5mA from a 3V supply, it achieves 17 dB voltage gain, approximately 6 dB noise figure, 153 dB 1-dB compression point dynamic range relative to 1 Hz bandwidth, and 70 MHz bandwidth at 2.5 GHz, suitable for industry applications.**

***Index Terms* — full integration, Q-enhancement, LC filter, SOI, SOS.**

I. INTRODUCTION

To cater lower cost and smaller size, the trend of wireless communication transceiver design has been pushed toward full integration from the antenna port to information source/sink on a single chip, eliminating discrete components without compromising performance such as power consumption, selectivity, noise figure and dynamic range. However, in current gigahertz-range receivers, a bulky and expensive off-chip bandpass filter before the LNA is still required to handle the existence of large out-of-band interferes. Great efforts have been brought to use an on-chip Q-enhanced LC filter to replace the off-chip preselect filter [1-9].

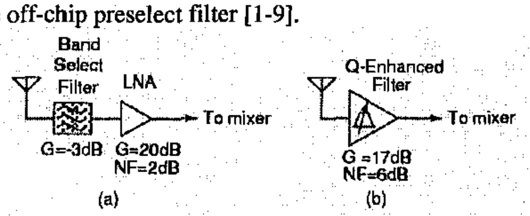

Fig.1. Receiver front-end designs (a) Traditional (b) Q-enhanced filter

As shown in figure 1, the Q-enhanced filter can theoretically be used to take place of the preselect filter and the LNA, providing similar gain with equivalent noise figure. Unfortunately, the use of on-chip bandpass RF filters has been limited so far by stringent system specifications such as high compression point, narrow bandwidth, low intermodulation distortion and noise figure, which have been determined based on excellent capabilities of off-chip filters [9]. The best documented examples [5,6] present 19 dB noise figure, far from the sensitivity requirement, even for Bluetooth which has very relaxed system specifications.

One reason for the poor dynamic range and noise figure in previous designs is that only low-Q (less than 10) inductors are available in standard CMOS or BiCMOS process. The solution is to use an SOI process with high bulk resistivity such as silicon-on-sapphire (SOS) where high-Q inductors are available (about 20-35 between 2-3 GHz). In this paper we present a Q-enhanced filter targeted at Bluetooth applications in a 0.5 μm SOS process. With the use of on-chip high-Q inductors and an innovative circuit topology, this filter achieves 17 dB voltage gain, approximately 6 dB noise figure, a normalized 1-dB compression point dynamic range of 153 dB-Hz, and 70 MHz bandwidth at 2.55 GHz, while drawing 5mA from a 3V supply. This performance is comparable to that of conventional LNA with an off-chip bandpass filter.

II. Q-INHANCED FILTER DESIGN

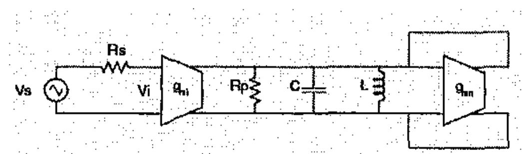

Fig. 2. Simplified Q-enhanced filter circuit-level diagram

The basic idea in Q-enhanced LC filters is to use negative resistance to boost the Q in a lossy LC tank. Figure 2 shows a simplified second-order (one pole) bandpass filter topology, where R_p represents equivalent parallel loss resistance from the finite Q tank inductor, tank capacitor, and parasitic capacitance at resonance. Negative conductance g_{mn} compensates the loss in the tank. The effective quality factor Q_{eff} of the filter at the resonant frequency can be shown to be [1]

$$Q_{eff} = Q_0 \frac{1}{1 - g_{mn} R_p} \qquad (1)$$

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2004 IEEE Radio Frequency Integrated Circuits Symposium

where Q_0 is the base quality factor of the LC tank, which is dominated by the inductor in the low gigaherz range. 1-dB compression point dynamic range (DR) in a second-order Q-enhanced filter can be expressed as [5]

$$DR = \frac{P_{1dB\_out}}{P_{n\_out}} = \frac{P_{1dB\_out}}{4KT(\gamma' + 1)B_{IF}Q_{eff}} Q_0^2 \qquad (2)$$

where P_{1dB_out} is the 1-dB output compression point power on the effective parallel resistance $R_p(Q_{eff}/Q)$ at resonance, P_{n_out} is the output noise floor, B_{IF} is the final IF bandwidth, and γ' is a noise factor associated with g_{mi} and g_{mn}. To compare circuits independent of bandwidth, the 1-dB compression DR relative to a 1-Hz bandwidth is applied to define a figure of merit (FOM) [9]

$$FOM = \frac{P_{1dB\_out}}{P_{n1Hz\_out}} \frac{1}{P_{dc}} \qquad (3)$$

where P_{dc} is the DC power.

To date, the best FOM achieved is 121 dB-Hz/mW. The filter reported here achieves 141 dB-Hz/mW through the use of high Q inductors and careful attention to noise figure issues.

III. Circuit Architecture

Figure 3 shows the schematic of the newly developed Q-enhanced filter targeted at Bluetooth applications. The filter is composed of an input matching network constructed by L2 and C2, input transconductor FETs M1a/b, cascode FETs M2a/b, and tank L1, C1, while the negative resistance is implemented by cross coupled FETs M3a/b (plus more switched copies). Two output buffers M5a/b are located on the differential output of the filter core.

One innovation in this filter is to adopt an LC input matching network, which can decrease the noise figure significantly and also provide part of band select filtering. A 6:1 voltage step-up balun formed by L2 and C2 is employed here to convert the unbalanced 50 Ω source to a differential source for the following amplifier. Due to the series resistance from finite Q inductor L2 (around 20 in implementation), the actual ratio is 4.6:1. This conversion increases the percentage of the total output noise contributed by the source, and hence minimizes the noise figure [10].

The differential input transconductor M1a/b use a grounded-tail configuration to provide maximum possible signals swing within the amplifier. M1 uses a special zero-threshold device offered by the target IC process, both to minimize the noise figure and to optimize the dynamic range performance in the filter [9,10]. With the resulting 0.5V V_{gs}-overdrive at 0.5V bias voltage, signals of up to 1V peak differential can be tolerated at the filter input, translating to approximately -9dBm input compression for out-of-band signal at the antenna terminals. Additional protection comes from the input balun at large frequency offsets.

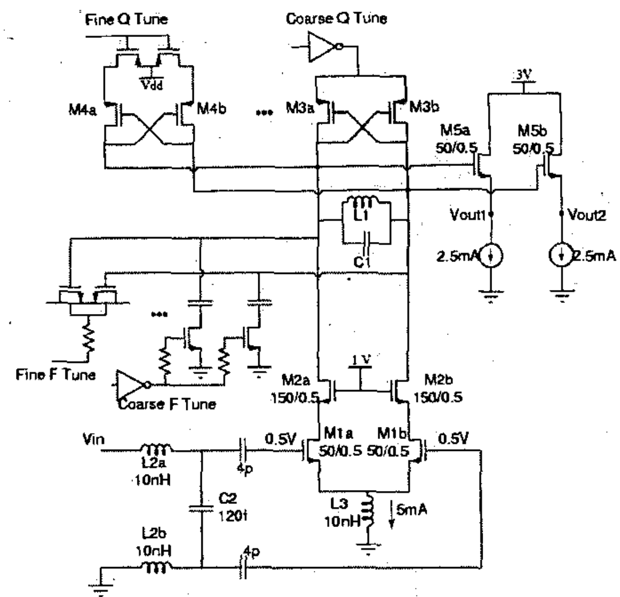

Fig. 3. Schematic of Q-enhanced filter

Different from conventional Q-enhanced filter, a current reuse strategy is employed to implement negative conductance. In the filter, negative transconductor FETs M3a/b share the same DC current with input FETs M1a/b, without sacrificing dynamic range. M3a/b are implemented with low-noise, regular-threshold (0.8V) PFET devices to provide approximately 1V peak differential signal swing across the LC tank's 800 Ω effective resistance at resonance before leaving the active region (onset of output compression). In simulation, around 0.7V peak differential swing is achieved at the compression point, translating to an output compression point of –6.6 dBm, and to an in-band input-referred compression point of –14.6 dBm at a voltage gain of 17dB (8dB power gain).

A bank of switched transconductors is applied here to provide coarse digital Q control, while analog fine-tuning control of Q is achieved through controlling the input gate voltage of long channel FETs, which act as degenerative resistors when operated in triode region. A bank of switched capacitors provides coarse frequency tuning, and a MOS varactor contributes to fine frequency tuning, all of them achieve a 400MHz tuning range.

Two buffers are positioned on the differential output of the filter to isolate the LC tank from the following loads during test. M5a/b function as source followers with 200Ω output impedances.

IV. LAYOUT

The filter described above is implemented in a 0.5 μm SOS process with one poly layer and three metal layers. A photograph of the chip is shown in figure 4. The area consumed by the filter is approximately $2.5\,mm^2$. The one turn spiral inductor positioned on the right of the die is the inductor in the LC tank. The single spiral inductor on the left of the die is the tail inductor. Two parallel spiral inductors next to the tail inductor are used for the input matching network, in which the layout polarity of inductors is chosen to cancel mutual inductance between them.

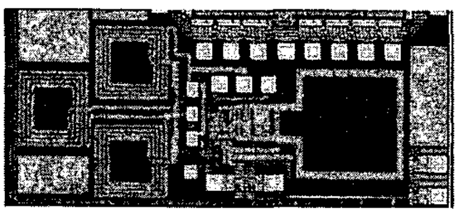

Fig. 4. Die photograph

V. MEASURED RESULTS

The design targeted a tuning range from 2.25 GHz to 2.65 GHz. The measured frequency range is from 2.45 GHz to 2.85 GHz, due to the difference in inductor values between field solver simulation and fabrication. In our measurement for noise figure and dynamic range, the frequency controls were set to 2.55 GHz and the desired selectivity Q_{eff} was achieved through manual setting of the coarse Q controls. Current consumption is around 5mA (excluding buffer) at 3V power supply. The filter response (S21) measured from one output buffer by a 250Ω (5:1) probe is shown in figure 5. Due to a voltage loss of about 6 dB in the buffer and 6 dB on single-sided measurement, the actual differential voltage gain is about 12 dB higher than the value shown on network analyzer. Note that there is about 14dB attenuation of voltage gain in the probe, which is cancelled out by calibration.

The hot/cold source method with a 15 dB ENR source was applied to measure the noise figure of the filter. The differential voltage gain of the filter was set to 17 dB (8 dB power gain) by coarse Q control, obtaining a bandwidth of 70 MHz (Q_{eff}=36). A 4.9 dB noise floor variation at resonance is achieved, which gives a noise figure of 11.8 dB for the total cascaded stages including the attenuating probe and subsequent LNA, translating to a noise figure of 5.8 dB for the filter. The actual noise figure may be up to 1 dB higher than the measured value due to inaccuracy in the measurement. Operating at high gain and high Q mode, the filter presents slightly higher noise figure, but the measurement can be more accurate because the gain appearing after the probe exhibits a few dB instead of loss in low gain mode. As shown in figure 6, a noise floor power variation of 7.6 dB was recorded with a voltage gain of 26 dB and 27 MHz bandwidth, translating to a noise figure of 7 dB for the filter.

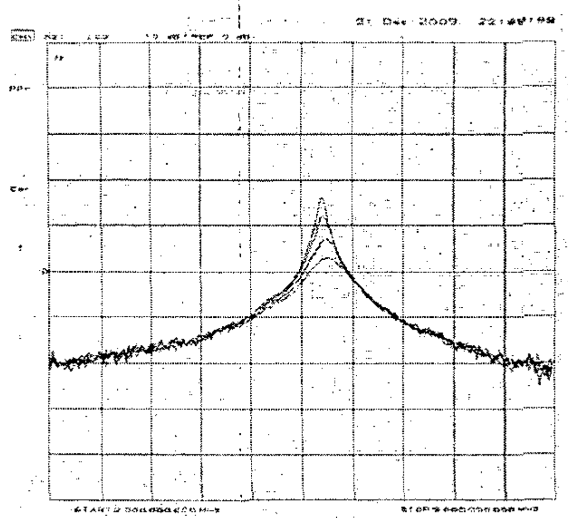

Fig. 5. Filter response versus Q-tuning at 2.55GHz

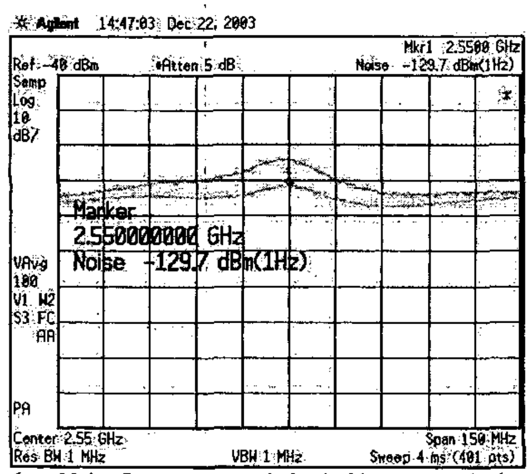

Fig. 6. Noise floor spectrums in hot/cold source method

The measured input 1-dB compression point is –15 dBm at a voltage gain of 17 dB at 70 MHz bandwidth, resulting in a normalized DR of 153 dB-Hz and a FOM of 141 dB-Hz/mW. As predicted by equation (2) and (3), the filter theoretically presents a normalized DR of 153.4 dB-

Hz and a FOM of 141.4 dB-Hz/mW for P_{dc} =15mW, P_{1dB_out}= -6.6 dBm, γ'=1, Q_{eff}=36.4, and Q_0=20. The measured values of DR and FOM match the theoretical values very well.

A summary of measured performance is provided in table 1. Table 2 presents comparisons between this design and other designs. Note that in [7] there is no gain and FOM will be significantly degraded (at least 10 dB lower) if the LNA stage is included.

TABLE I

SUMMARY OF FILTER PERFORMANCE

Parameter	Performance
Supply voltage	3V
Current	5mA
Frequency	2.45-2.85 GHz
Voltage gain	17 dB
Bandwidth	70 MHz
Effective Q	36
1-dB input compression point	-15 dBm
Noise figure	6 dB
DR	153 dB-Hz
Die area	2.5 mm^2

TABLE II

PERFORMANCE COMPARISON BETWEEN THIS WORK AND INTEGRATED LC FILTER IN THE LITERATURE

Ref	f_0 (MHz)	BW (MHz)	Q_{eff}	NF (dB)	DR(dB-Hz)	FOM(dB-Hz/mW)
[4]	1000	25	40	37	114	96
[5]	840	18	47	19	130	111
[7]	2140	60	35	19	142	129
[8]	2190	53.8	40	26.8	117	114
[9]	900	20	45	21	137	121
This work	2550	70	36	6	153	141

VI. CONCLUSION

The prototype design described in this paper implements a practical one-pole Q-enhanced filter in a 0.5 μm SOS process. With the help of high Q inductors and the on-chip input matching network, it achieves a FOM significantly exceeding that of previous filters, 20 dB higher than the best reported result, mainly due to the low noise figure. The filter provides a 1-dB compression point DR of 153 dB relative to 1 Hz bandwidth and 6 dB noise figure for a 70 MHz bandwidth at 2.55 GHz, with 5mA current and 3V supply. The result is comparable to that of existing commercial front-end designs with off-chip bandpass filter and LNA. With simple Q and frequency tuning circuits, Q-enhanced filter is practical for industry applications.

ACKNOWLEDGEMENT

The authors would like to acknowledge Peregrine for fabrication. This work is supported by the National Science Foundation under grant 9875770.

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