A CMOS Q-Enhancement Bandpass-Filter for use in Paging Receivers

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Abstract—**Paging receivers often have to work in a dense signal environment. This poses high demands on the preselection filter. One of the most difficult aspects is the large image rejection demand, which only can be satisfied by use of a narrow-band or high-Q filter. The practical restrictions for possible filter implementations are the low cost, low power and the small size of the pager. By use of positive feedback around a cheap off-chip low-Q inductor we obtain an enhanced quality factor. We are therefore able to construct selective filters using cheap small-size inductors. The price paid for Q-enhancement is a larger noise and higher sensitivity to component variations. The higher noise influence is eliminated using a high gain in the preceding LNA-stage, which is considered a part of the filter. Simulated results are: Q enhanced from 30 to 100, Image-rejection = 48dB, f_0 = 280MHz, Voltage-gain = 20dB, Noise- figure = 2.4dB, IMFDR = 66dB, I_{DD} = 1mA, V_{DD} = 2V. The original contribution of this work is the application of the enhancement principle to off-chip components, which benefits the minimization of size and cost.**

Keywords—**Q-enhancement, Filters, LNA, CMOS**

I. Introduction

This paper deals with the application of Q-enhancement technique, a rather simple and old principle of compensating resonator loss by use of positive feedback. The reason that this technique did not become very important until recently was due to the good performance of off-chip inductors. Today, relative small inductors can be reliable fabricated with quality factors up to 100 however at considerable cost. The trend of miniaturization and cost reducing has introduced the use of on-chip inductors implemented in more or less standard CMOS processes. These on-chip inductors suffer from large losses because of the high metal trace resistance and the conductive substrate [1,2]. These high losses cause the on chip inductor to have inevitable low Q-values making them not suitable for use in selective filters like the pre-selecting filter of a heterodyne paging receiver. In the past numerous papers [3-9] have been published which demonstrate the application of Q-enhancement technique in order to compensate the high losses of on-chip inductors. The benefits achieved come at the cost of higher sensitivity to component variations which limits the achievable enhancement factor to low values and/or demands some sort of control loop to overcome this sensitivity problem. The use of on-chip inductors in paging receivers is not feasible because of the relative low frequency bands which would cause the inductor to occupy to much die area. The idea is to apply Q-enhancement to low-Q, low-cost and small external inductors. The benefits compared to a conventional RLC-bandpass filter are the reduction in cost and occupied space. From a Q-enhancement point of view the relative high start Q_0 (taken here 30) reduces the needed enhancement factor and it is therefore expected to make the application of Q-enhancement potentially feasible. The paper is organized as follows: First the principal of Q-enhancement is presented followed by the extraction off specific Q-enhancement relations concerning noise, distortion, stability and the sensitivity to component variations. A practical test-case circuit is presented and nominal simulation results are presented. Finally the conclusions are drawn.

II. The Q-Enhancement Principle

We can represent the pre-selecting bandpass filter by a simple second order parallel resonant circuit [3,4] as shown in fig.1 where R_S represents the inductor loss.

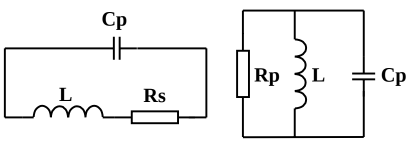

Fig. 1. Two ways of representing the loss in a RLC resonator.

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The loss in the capacitor is not considered here because it is typically orders of magnitude smaller, it can however be treated likewise. Under the condition of resonance the series resistance can be transformed to a parallel loss resistance Rp according to:

$$Rp = Q_0^2 Rs \tag{1}$$

Then the relation to the Q_0 of the resonator becomes:

$$Q_0 = Rp\sqrt{\frac{Cp}{L}} \tag{2}$$

The subscript 0 of Q_0 is introduced to define the not-enhanced Q-factor of the resonator. From (2) we see that the Q-factor is proportional to the parallel resistance of the resonator Rp. The simplest method to enhance the Q-factor is to compensate part of the loss represented by Rp by applying a negative resistance in series with R_s [5] or parallel to Rp. The latter is used because this yield the most practical circuit values knowing that the value of Rp is Q_0^2 larger than R_s. The negative resistance can be obtained by applying positive feedback around the resonator as is illustrated in fig. 2.

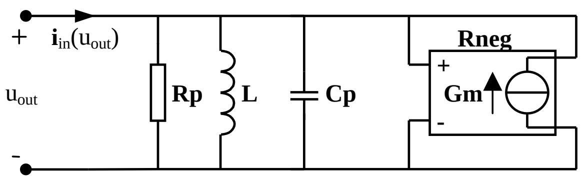

Fig. 2. Parallel mode Q-enhancement resonator, negative resistor created by use of a VCCS.

The analyzed total circuit in this paper also includes the LNA stage preceding to the circuit presented in fig. 2. The LNA can also be represented as a simple VCCS with transconductance value: Rp_{enh}/A_v where Rp_{enh} means the enhanced resonator impedance at resonance.

III. Noise Consideration

The noise behavior of a Q-enhanced RLC-resonator can be considered using the simplified circuit given in fig. 3

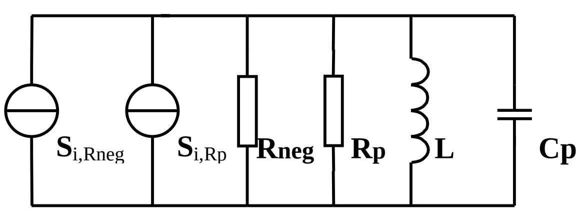

Fig. 3. Representation of the noise sources in a Q-enhanced RLC-resonator.

Here a fundamental difference occurs if we compare this Q-enhanced resonator with a resonator having the same Q-factor but without enhancement.

The latter will produce the well-known wideband noise power of $\frac{kT}{Cp}$. As the negative resistance contributes additional noise, it can be derived that the Q-enhanced resonator produces a factor F_{Q_enh} more noise power [11]. The noise factor can be expressed as:

$$\frac{Rp_{enh}}{Rp_{enh}} = \frac{Q}{Q_0}(F_{negR} + 1) = F_{negR} = F_{Q\_enh} \tag{3}$$

Where Rp_{noise} represents $Rp//|Rneg|$ and F_{negR} represents the noise factor of the negative-R circuit compared to an ordinary resistor of the same absolute value. So for the Q-enhanced resonator we expect the noise power to be increased proportional to the enhancement factor Q/Q_0.

If we take into account the influence of the LNA-stage we can derive the total pre-selecting LNA noise figure to be:

$$\begin{aligned} F_{\mathrm{Pre}-sel.LNA} &= \frac{\overline{u_{n\_in,eq}^2}}{\overline{u_{n\_ant}^2}} \\ &= 1 + \frac{F_{Gm,LNA}}{Gm_{LNA}Rp_{ant}} \\ &\quad + \frac{1}{Gm_{LNA}^2 Rp_{ant} Rp_{noise}} \end{aligned} \tag{4}$$

Where Gm_{LNA} is the transconductance of the LNA-stage, $F_{Gm,LNA}$ is the noise factor of the transconductance of the LNA-stage compared to $4kTGm$ and Rp_{ant} represents the antenna equivalent parallel resistance at resonance.

If we substitute Q and Q_0 and use the relation: $A_v = gm_{LNA} \cdot Rp_{enh}$ we arrive at the following expression for $F_{Pre-sel.LNA}$:

$$F_{Pre-sel.LNA} = 1 + \frac{Q}{Q_0}\frac{R_p}{Rp_{ant}}\left(\frac{F_{Gm,LNA}}{A_v} + \frac{F_{Q\_enh}}{A_v^2}\right) \tag{5}$$

From this expression we see that the influence of the extra noise power due to Q-enhancement can be made low for reasonable values of the voltage gain A_v.

IV. Distortion Consideration

The distortion level obtained in the pre-selecting LNA stage can be fully assigned to the negative-R circuit because of the large signal level difference between the input of the LNA stage and the input of the negative-R stage. The distortion enhancement due to the non-linear negative-R can be illustrated as is done in fig. 4. The R-values are converted to conductance values for convenience.

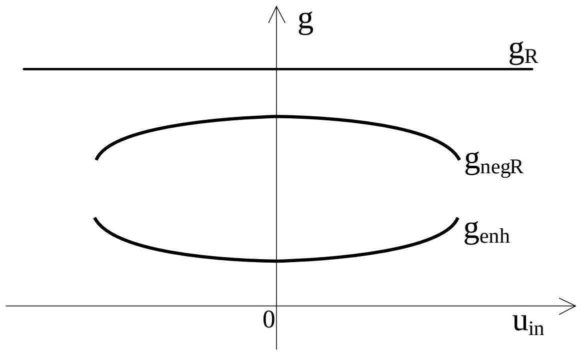

Fig. 4. Representation of the linear loss gR and non-linear g_{negR} conductances leading to a non-linear total conductance g_{enh}.

A measure for the distortion is the relative deviation in the g_{enh} value at certain input voltage level, which become larger if the enhanced-Q becomes larger. The IM3 level can if we assume balanced circuits be expressed as [11]:

$$IM3 = \frac{3}{4}\hat{v}^2_{in,ant} A_v^2 gm_3 Q\sqrt{\frac{Lp}{Cp}} \tag{6}$$

Where gm_3 represents the third order coefficient of a Taylor approximation of the $g_{enh}(u_{in})$ relation. Note that the distortion level does not depend on the enhancement factor but only on the final enhanced-Q value.

V. Stability Considerations

From the simplified representation given in fig. 4 we can also deduce some stability criteria concerning relative large input voltages. The resulting conductance g_{enh} may never become zero or negative for any input voltage, this means that the function describing $g_{enh}(u_{in})$ must have a positive minimum larger than zero. We can approximate the g_{enh} value by use of a Taylor series:

$$g_{enh} = \frac{1}{Rp} + gm_1 + gm_2 u_{out} + gm_3 u^2_{out} \tag{7}$$

Where we assume that the considered large input signals are still small enough to let the approximation be valid.

From the calculus we know that the extreme can be found by taking the derivative of the function $g_{enh}(u_{in}) > 0$ and equate it to zero, the found extreme value of the total conductance than becomes:

$$\frac{1}{Rp} + gm_1 - \frac{gm_2^2}{4gm_3} > 0 \tag{8}$$

We also know from calculus that to ensure that the found extreme function is a minimum, the second derivative has to be larger than zero which requires $gm_3 > 0$.

By recalling that the coefficient gm_1 denotes the transconductance of the negative-R circuit we can write:

$$\frac{1}{Rp} + gm_1 = \frac{1}{Rp_{enh}} = \frac{1}{Q\sqrt{\frac{Lp}{Cp}}} \tag{9}$$

Because Rp is smaller than Rp_{enh} we see that gm_1 must be negative. Because of (8) this therefore requires opposite signs between gm_3 and gm_1.

Summarizing, the derived constrains to maintain stability for large input voltages are found to be:

- $gm_1 < \frac{gm_2^2}{4gm_3} - \frac{1}{Rp}$
- $gm_2 < 2\sqrt{gm_3\left(\frac{1}{Rp} + gm_1\right)}$
- $gm_3 > \frac{1}{4Q\sqrt{\frac{Lp}{Cp}}} gm_2^2$

Note that: gm_2 and gm_3 can also be zero both at once, also gm_2 can be zero independent of the value of gm_3 but gm_3 may not be zero if gm_2 is not zero as can be seen from the last constrain. The explanation is that the total conductance can actually be decreased without causing instability depending on the value of conductance left to zero after enhancement. This remaining conductance depends on the final-Q value as can be seen from (9).

The conclusions drawn from this evaluation are:

- We need a transconductor for implementation of the negative-R with opposite signs for gm_1 and gm_3. *This restricts the implementation possibilities to strong inversion non-saturated common gate circuits and the strong inversion saturated common source circuit* [12].
- If we use a transconductor with low third order distortion, then we need an even lower second order distortion. So very tight IM3 requirements can make Q-enhanced resonators more subject to instability.
- If we have a second order term then, enlarging the final Q can cause instability for large inputs. The final enhanced impedance has to be low enough to maintain stability for the expected input levels. This means that for a given final-Q value the maximum enhanced resonator impedance is restricted.

A general recommendation that can be made is to use balanced circuits to minimize the even order distortion.

These circuits do need good matching in order to be able to gain the full benefit of even order canceling. The choice of balanced circuits was already made based on the need of high common-mode signal rejection to suppress interference from the digital part of the paging receiver.

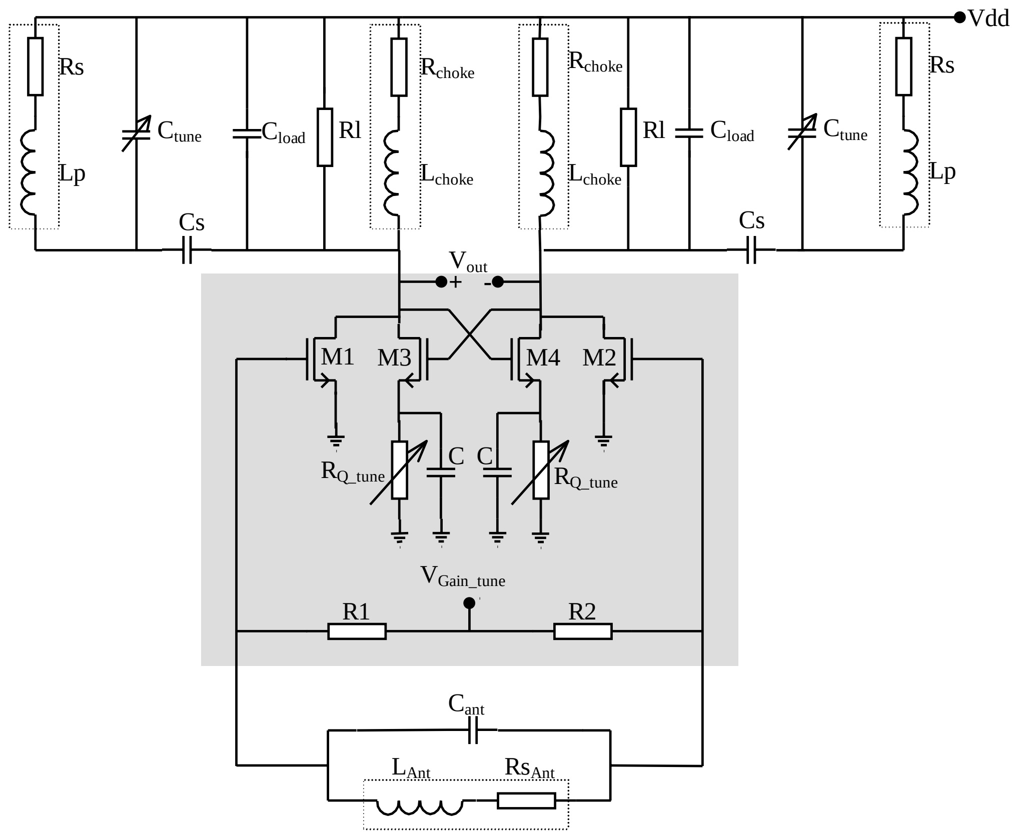

Fig. 5. The proposed Q-enhanced pre-selecting LNA circuit that is simulated to verify the found relations.

VI. The Sensitivity To Component Variations

It is common knowledge that the sensitivity to component variations in a negative feedback system is lowered. In the case of Q-enhancement presented here the negative resistance used for compensating the resonator losses is obtained by using positive feedback. So besides the Q-value we also expect to enhance the sensitivity for component variations. The sensitivity coefficient can be expressed as:

$$S_x^y = \frac{\frac{dy}{y}}{\frac{dx}{x}} = \frac{x}{y}\frac{dy}{dx} \tag{10}$$

Where S_x^y means the sensitivity of output y to component value variations of x. After calculations it becomes clear that the sensitivity of the center frequency can be neglected for reasonable Q_0 values (> 10) and that only the voltage gain A_v and the final Q-value are affected by enhancement. We can derive that the sensitivity to component variations is roughly proportional to the enhancement factor Q/Q_0. This is a serious problem. For given tolerances this sets the maximum usable enhancement factor. Without the application of a control-loop e.g. as proposed in [13] this maximum enhancement factor can be to low for certain applications.

VII. Possible Prototype Circuit

The relations found are verified by means of simulation of a representative prototype circuit as is given in fig. 5. The resonator in this circuit is extended with an extra series resonance which improve the image rejection. The transistors M1 and M2 form the LNA stage while M3 and M4 provide the negative resistance. The tuning possibility of Q and A_v are represented by variable resistors for simplicity. The most important specifications for the pre-selecting LNA system for use in paging receivers are given in table 1:

It is found using (2) in (5) that to design for maximum allowed noise figure, which is necessary if we want to minimize power consumption, this yield only one solution for

TABLE I

Specification	**Desired value**
Noise figure	2dB
Voltage gain A_v	20dB
IMFDR	>61dB
Image Rejection	>40dB ex. Ant.
Final Q	100
Supply current	1mA @ 2V

the resonators L and C value. The impedance level is therefore determined and the transconductance values of the transistors can be derived. The only non-determined parameter in the circuit is the effective gate-source voltage. The effective gate-source voltage has to be chosen to satisfy the dynamic range and the low-power demand. The dynamic range is expressed by means of the InterModulation Free Dynamic Range which defines the input range starting from the equivalent input noise level until the input level at which the intermodulation products are equal to the noise level. This dynamic range definition relates the third-order intermodulation distortion level to the noise level and is therefore very useful in characterizing narrowband filters. From simulations done using the Spectre-RF simulation tool and using a MM9 model for the 0.35 μm CMOS process, the obtained nominal results are displayed in table 2 below.

TABLE II

Specification	Simulated value
Noise figure	2.39dB
Voltage gain A_v	20dB
IMFDR	66dB
Image Rejection	48dB ex. Ant.
Final Q	100
Supply current	1.05mA @ 2V

These results indicate that the desired performance can be closely met. The slightly higher noise figure can be lowered by simply choosing a different L,C set. This is an iterative process because of the capacitive tap formed by C_s and C_{load} and is therefore not performed here.

VIII. Conclusions

The application of the Q-enhancement principle to a pre-selecting LNA stage using small low-Q off-chip inductors is investigated. The impact of Q-enhancement on the performance is made clear and a practical circuit is dimensioned and simulated. The simulations are promising and show quite feasible performance. It has become clear that the application of Q-enhancement to a RLC-resonator introduces three problems:

1. The enhanced sensitivity to component variations proportional to the enhancement factor.
2. More noise also proportional to the enhancement factor.
3. More distortion proportional to the final Q-value under the condition of constant gain.

It is found that the extra noise influence can be minimized if the LNA-gain is sufficiently large. The final Q-value is not subject to chance so if we apply Q-enhancement, the distortion obtained will not be increased if the enhancement factor is increased by lowering the Q_0-value. This implies that the only real problem of Q-enhancement applied to a pre-selecting LNA stage is the enhanced sensitivity to component variations. The main conclusion drawn is that the full benefits of Q-enhancement can be obtained if a control loop is applied. For paging receivers, Q-enhancement can be more interesting if other reasons like automatic frequency tuning already demand a control loop.

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