RF and Microwave Filter Design By Means of Single Transistor Active Inductor: a Review

Vincenzo Stornelli, *Member, IEEE,*

Leonardo Pantoli, *Member, IEEE,* Alfiero Leoni, *Student Member, IEEE, and* Giorgio Leuzzi

Abstract — **RF and Microwave active filters design by the use of grounded active inductor (AI) is here presented. The proposed single transistor AI emulates an inductor behaviour by implementing a passive variable phase and amplitude compensating network and amplifiers, forming a similar gyrator-C architecture allowing its use in LC filters architectures at high frequencies with high quality factor and reduced occupied chip area. The design method can be applied with success, in particular, for the design of bandpass filters with very high performances in terms integration and application from RF to Microwave frequency range achieving active filters with relatively high dynamic range, constant Q and also easy frequency tuning capability.**

Index Terms — **Filters, Active Filters, Active inductor.**

I. INTRODUCTION

RECENT advancements in integrated circuits (IC) and communications systems, in conjunction with the great increasing request for miniaturisation and size reduction of wireless systems and devices, have led to an increase of performances and space reduction of modern telecommunication apparatus. As a consequence most RF and microwave system blocks have been successfully implemented as IC with different technologies. In this scenario, analog tunable filters working, in general, at RF and microwave frequencies still remain the most difficult part to be integrated in a single chip [1-10], due to requirements in input and output impedance matching, stability, and dynamic range and noise. In fact most commercial wireless receivers only use off-chip filters that are typically implemented with discrete components, being in IC circuits most of the semiconductor area occupied by passive elements, while active devices play a marginal role in area occupation. Spiral inductors, in fact, require large amounts of substrate area, have limited bandwidth, high series resistance, and crosstalk problems. In this scenario, in the last decades Active Inductors (AI) [11-20] have demonstrated to be good candidates for high-frequency operation, therefore, considerable interest has been shown in their use in active filters. In this perspective, in particular, band-pass filters

Vincenzo Stornelli, Leonardo Pantoli, Alfiero Leoni and Giorgio Leuzzi, are with the Department of Industrial and Information Engineering and Economics, University of L'Aquila, via Gronchi 18 - L'Aquila, 67100, Italy. (e-mail: Vincenzo.stornelli@univaq.it).

designed by means of active inductor, usually suffer from a very low dynamic range due to the combination of a high noise level introduced by the AI and the relatively low compression power level of the AI itself. For all these reasons there are only a few commercial solutions available on the market based on active inductors. Based on the same author experience in the field [21-39], this work describes an approach to design single transistor active inductor based filters characterized by high quality factor and high dynamic power range. As an example application already developed a RF bandpass filter is also reported and discussed both at IC and discrete element board level.

II. THE SINGLE TRANSISTOR AI

The first high-Q AIs were reported over two decades ago and the use of these inductors for the implementation of *L-C* resonator-type active filters was presented both in several papers and conferences. The classical gyrator-C architecture, as shown in Figure 1, is the most well-known method to design an AI.
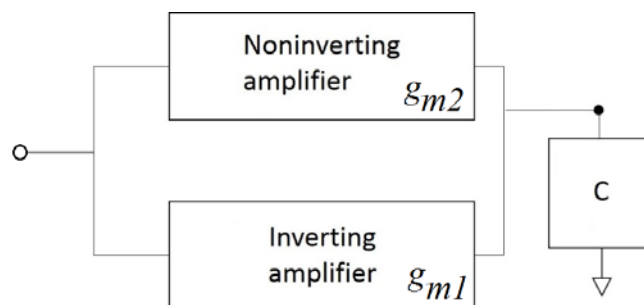

Fig. 1. Classical Gyrator-C Structure

In this case the equivalent inductance of the gyrator-based active inductor can be expressed as:

$$L_{eq} = \frac{C}{g_{m1}g_{m2}} \qquad (1)$$

If we consider a real case non idealities in the amplifiers must be taken into account and two unwanted effects appears. In particular a parasitic resistance arises in series to the

equivalent inductance and the bandwidth of the inductive impedance becomes finite. Fig. 2 shows that a phase relation between voltage and current at the system input less than 90° gives positive resistance, while a phase relation in excess of 90° causes a negative resistance.
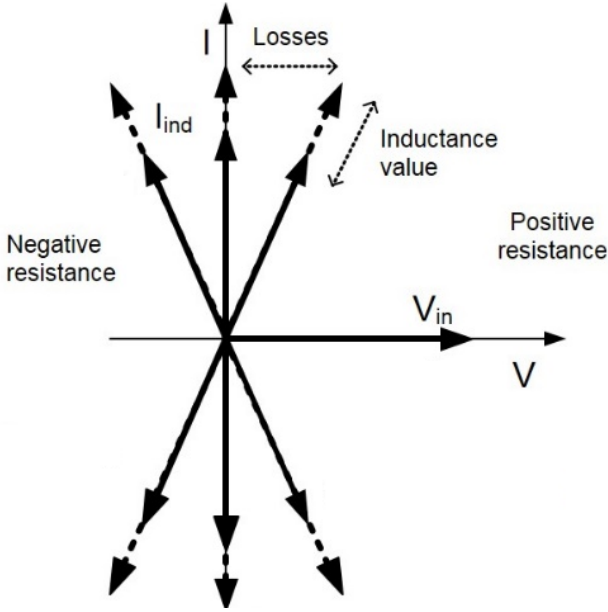

Fig. 2. AI voltage and current relations

If we were able to control both these phase relations, without acting on the bias condition of the amplifiers, the linearity of the active component of the gyrator will not be affected. This condition can be reached by the insertion of a suitable variable passive compensation network, moreover, in order to simplify the design, a single active block AI with a compensation network can be also adopted as shown in Fig. 3. In this case a simplified model of the capacitance gyrator with a single active block is designed.
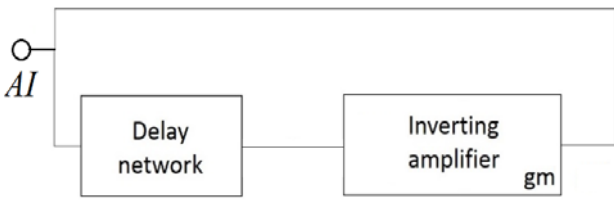

Fig. 3. Single active block AI block scheme

In the ideal case starting from Fig. 3 block scheme and, considering the simplified Fig. 4 equivalent circuit linear model of a single transistor AI, the circuit input impedance is given by the following relation:

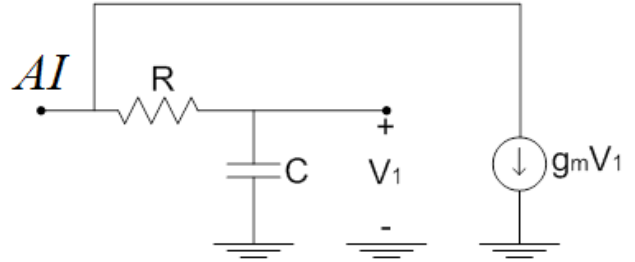$$Z_{in} = \frac{1 + j\omega RC}{g_m + j\omega C}$$

(2)

Fig. 4. Simplified schematic model of the single-transistor AI.

Now it can be seen that the input impedance of the network is not always inductive. By analysing the imaginary part we can notice that the imaginary part of the AI impedance has a zero in ω=0, and it is always positive only if:

$$g_m R > 1$$

(3)

Moreover, the imaginary part of the input impedance is monotonically growing, thus inductive, until its maximum is reached for:

$$\omega_{max} = \sqrt{\frac{g_m^2 - Rg_m^3}{C^2 - Rg_m C^2}}$$

(4)

The high-Q condition has been explained conceptually on the IV-plane with complex phasors (see Fig. 2) in order to clarify the Active Inductor behaviour and characteristics. Surely, a mathematical analysis can be compliant and equations can be obtained. Anyway, even if equations can be written considering the equivalent circuits, it is not straightforward to obtain useful design formulas due to the presence of the feedback loop. Anyway, the equivalent circuit in Fig. 5 has been analysed and the expression of the input impedance is shown in eq. (4).
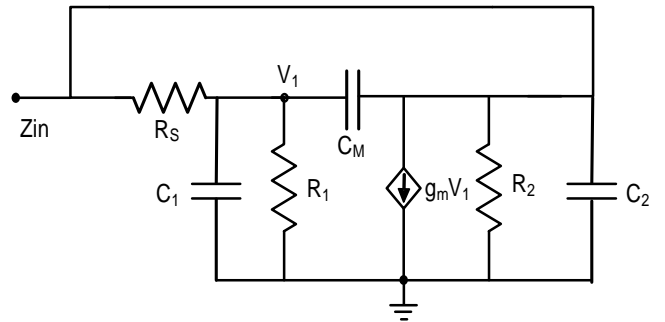

Fig. 5. Simplified schematic model of the single-transistor AI considering also transistor parasitics

$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{\left(1 + \frac{R_S}{R1} + sC_M R_S + sC_1 R_S\right)}{\frac{1}{R1} + \frac{R_S}{R_2} + g_m \frac{R_S}{R_1 R_2} + s\left(C_1 + C_2 + C_M \frac{R_S}{R_2} + C_1 \frac{R_S}{R_2} + g_m C_M R_S + C_M \frac{R_S}{R_1} + C_2 \frac{R_S}{R_1}\right) + s^2\left(C_M C_2 R_S + C_1 C_2 R_S + C_M C_1 R_S\right)}$$

(5)

The AI high Q behaviour can now be obtained by zeroing the real part of the input impedance at the desired frequency being it calculated as $Q=\omega L/R$ (where $L=Img(Zin)$ and $R=Re(Zin)$). As it is evident form eq. (5), due to the non-general formulation of the problem, the problem can be solved easier if treated with a numerical approach.

Anyway, in any case general design considerations can be still done. The use of highly linear devices, the use low-pass filter topology compensating network, the use of high precision passive components with high quality factors are general rules that allow to obtain a suitable design.

III. FILTERS EXAMPLE APPLICATIONS

As general examples it is here reported both an integrated and discrete solution implemented at 2GHz and already presented and discussed in []. In both cases the simple LC structure depicted in Fig 6. is applied for the designed filter.
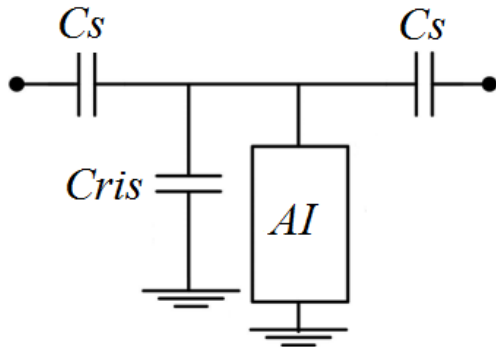

Fig. 7. Bandpass filter architecture.

As reported in [21], "the IC (using a 0.25um BiCMOS technology) AI implementation of the transconductance amplifier, see Fig. 8, is achieved by means of a common-emitter configuration, biased through the resistances Rb and Rc. The power dissipation is about 80μW biasing with a 1.2V power supply voltage. C_{DCB} capacitances are DC block while the capacitances C_{1-2} and resistances R_{1-2} form the compensation network. The topology of the compensating network and its components value, have been chosen in order to have an inductive behavior with minimum non-negative series resistance around 2000 MHz, providing a very high quality factor. In fact, simulated results of the applied bandpass filter give the S-parameter response depicted in Fig. 9. The filter is centered at 2 GHz with an insertion loss of 0.5dB and it has a 3dB bandwidth of about 6MHz with a

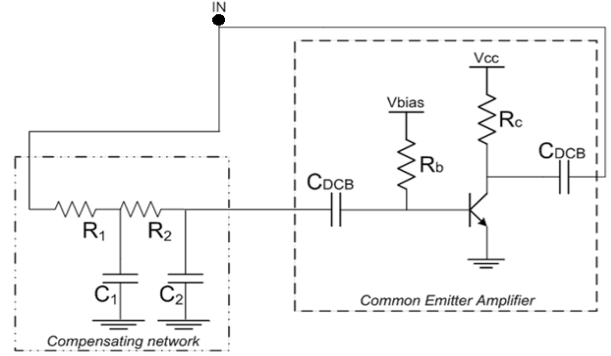quality factor of about 330. Both input and output matching are lower of -15dB".

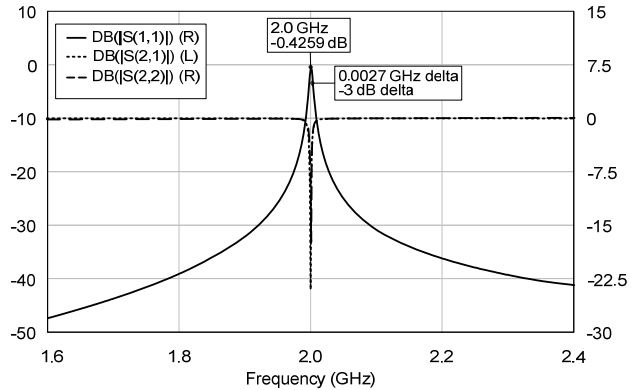Fig. 8. Single-transistor AI detailed schematic circuit [21].

Fig. 9 . Simulated S parameter response [21].

A discrete prototype board also presented in [21] is here reported being designed with a similar design approach. Figure 10 shows in the right upside the fabricated PCB: the amplifier is based on the BFP420 BJT from Infineon, in common-emitter configuration. Finally always in Fig. 10 it is shown the measured and simulated S parameters of the filter. The 3dB bandwidth is about 10MHz; it shows a P1dB compression point of -10dBm with a power supply voltage of 1.2V and a power consumption of 0.8mW. The noise figure (NF) of the circuit at 2000 MHz is approx. 6 dB.
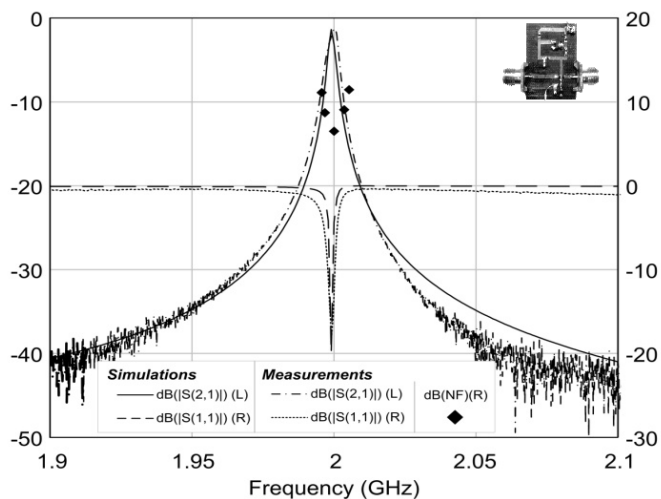
Fig. 10. PCB photo and measured and simulated S_{21} and S_{11}, together with the measured noise figure of the discrete element filter [21].

IV. CONCLUSION

We have here addressed a general review of RF and Microwave active filters design method by the use of a single transistor grounded active inductor (AI). The AI is composed by only a passive variable phase and amplitude compensating network and a single transistor amplifier, forming a similar gyrator-C architecture. As reported in the literature the design method can be applied with success for the design of bandpass filters with very high performances in terms integration and performances.

REFERENCES

[1] R. Kaunisto, P. Alinikula, K. Stadius, V. Porra "A Low-Power HBT MMIC Filter Based on Tunable Active Inductors", IEEE Microwave and Guided Wave Letters, vol.7, no.8, pp:209 – 211, August 1997.

[2] Y. Wu, X. Ding, M. Ismail, H. Olsson "CMOS Active Inductor and its Application in RF Bandpass Filter", pp:655 - 658, 2004 IEEE Radio Frequency Integrated Circuits Symposium.

[3] C. F. Campbell, R. J. Weber "Design of a Broadband Microwave BJT Active Inductor Circuit" Proceedings of the 34th Midwest Symposium on Circuits and Systems, pp:407 - 409 vol.1, 1991.

[4] X. He, W. B. Kuhn, "A 2.5-GHz low-power, high dynamic range self-tuned Q-enhanced LC filter in SOI", IEEE J. Solid- State Circuits, Vol. 40, No. 8, 1618{1628, Aug. 2005.

[5] Y. Wu, X. Ding, M. Ismail, H. Olsson "CMOS Active Inductor and its Application in RF Bandpass Filter", IEEE Radio Frequency Integrated Circuits Symposium, pp:655 - 658, 2004.

[6] S. Lucyszyn, I.D. Robertson "Monolithic Narrow-Band Filter Using Ultrahigh-Q Tuneable Active Inductors" IEEE Transactions on Micr. Theory and Techniques, vol.42, no.12, pp:2617–2622, Dec. 1994.

[7] A. Thanachayanont "Low-Voltage Low-Power High-Q CMOS RF Bandpass Filter" Elect. Letters, vol.38, no.13, pp:615 – 616, June 2002.

[8] Allidina K., J.P., Mirabbasi S., " A widely tunable active RF filter topology," 2006 IEEE International Symposium on Circuits and Systems, 21-24 May, 2006, pp. 879-882.

[9] S.E. Sussman-Fort, "Design concepts for microwave GaAs FET active filters", IEEE Transactions on Microwave Theory and Techniques, Vol. 37 , Issue: 9, pp. 1418 – 1424, 1989.

[10] B. Georgescu, I. G. Finvers, F. Ghannouchi, "2 GHz Q-enhanced active filter with low passband distortion and high dynamic range," IEEE J. Solid-State Circuits, Vol. 41, No. 9, Sep. 2006.

[11] Thanachayanont A. and A. Payne, "VHF CMOS integrated active inductor" Electronics Letters, Vol. 32, No. 11, 23 May 1996, pp. 999-1000.

[12] T. Soorapanth, S. S. Wong, "A 0-dB 30 MHz bandpass filter utilizing Q-enhanced spiral inductors in standard CMOS," IEEE J. Solid-State Circuits, Vol. 37, No. 5, May 2002.

[13] Gao Z. Yu M., and Ma J., "Wide tuning range of a CMOS RF bandpass filter for wireless application," 2005 IEEE Conference on Electron Devices and Solid-State Circuits, Dec 19-21, 2005, pp. 53-56.

[14] Sae-Ngow, S.; Thanachayanont, A., "A low-voltage, wide dynamic range CMOS floating active inductor," TENCON 2003. Conference on Convergent Technologies for Asia-Pacific Region, vol.4, no., pp. 1460-1463.

[15] R. Mukhopadhyay, S. W. Yoon, Y Park, C. H. Lee, S. Nuttinck, and J. Laskar, "Investigation of Inductors for Digital Si-CMOS Technologies", 2006 IEEE International Symposium on Circuits and Systems, 21-24 May, 2006, pp. 3750-3753.

[16] S. Sujin; R. Namsik; C. Heungjae; J. Yongchae; "Novel High-Q Inductor using Active Inductor Structure and Feedback Parallel Resonance Circuit", IEEE Symposium on Radio Frequency Integrated Circuits (RFIC),Vol. 1, pp. 467-470 , 2007.

[17] C. Andriesei, L. Goras, F. Temcamani, B. Delacressoniere, "CMOS RF active inductor with improved tuning capability",International Semiconductor Conference, Vol. 2 pp. 397 - 400 , 2009.

[18] L.Chun-Lee, A. A'ain, A.V.Kordesch, "CMOS Active Inductor Linearity Improvement Using Feed-Forward Current Source Technique", IEEE Transactions on Microwave Theory and Techniques, Vol. 57 , Issue 8,pp. 1915 – 1924, 2009.

[19] U.L.Rohde, A.K.Poddar, "Active inductor oscillator and noise dynamics", IEEE MTT-S International Microwave Symposium Digest (MTT), DOI: 10.1109/MWSYM.2011.5972933, pp. 1 – 4, 2011.

[20] Z. Yushi, Y. Fei, "Subthreshold CMOS active inductors with applications to low-power injection-locked oscillators for passive wireless microsystems", IEEE International Midwest Symposium on, pp. 885 – 888, 2010.

[21] Pantoli, L., Stornelli, V., Leuzzi, G., A low-voltage low-power 0.25 μm integrated single transistor active inductor-based filter, ANALOG INTEGRATED CIRCUITS AND SIGNAL PROCESSING (2016), 87(3), 463–469;

[22] L. Pantoli, V. Stornelli and G. Leuzzi, "Low-noise tunable filter design by means of active components," in ELECTRONICS LETTERS, vol. 52, no. 1, pp. 86-88, 1 8 2016;

[23] G. Leuzzi, V. Stornelli. S. Del Re, "A tuneable active inductor with high dynamic range for band-pass filter applications", IEEE Transactions on Circuits and Systems II: Express Briefs, Volume 58, Issue 10, Pages 647-651, 2011.

[24] Pantoli L, Stornelli V, Leuzzi G (2015). Class AB tunable active inductor. ELECTRONICS LETTERS, vol. 51, p. 65-67, ISSN: 0013-5194;

[25] Branchi, P, Pantoli L., Stornelli, V., Leuzzi, G. (2015). RF and microwave high-Q floating active inductor design and implementation. INTERNATIONAL JOURNAL OF CIRCUIT THEORY AND APPLICATIONS, ISSN: 0098-9886;

[26] Leuzzi, G., Stornelli, V., Pantoli L, Del Re, S. (2015). Single transistor high linearity and wide dynamic range active inductor. INTERNATIONAL JOURNAL OF CIRCUIT THEORY AND APPLICATIONS, ISSN: 0098-9886;

[27] Pantoli L, Stornelli, V., Leuzzi, G. (2014). Tunable active filters for RF and microwave applications. JOURNAL OF CIRCUITS, SYSTEMS, AND COMPUTERS, vol. 23, 1450088, ISSN: 0218-1266;

[28] Stornelli V, Pantoli L, Leuzzi G (2013). High Quality Factor L-Band AI-Based Band-Pass Filters. JOURNAL OF CIRCUITS, SYSTEMS, AND COMPUTERS, vol. 22, 3, ISSN: 0218-1266;

[29] Colucci P, Leuzzi G, Pantoli L, Stornelli V (2012). A Third Order Integrable UHF Bandpass Filter Using Active Inductors. MICROWAVE AND OPTICAL TECHNOLOGY LETTERS, ISSN: 0895-2477;

[30] V. Stornelli, L. Pantoli, G. Leuzzi, "An Assessment On Low Voltage Low Power Integrable Single Transistor Active Inductor Design for RF Filter Applications" (Invited Paper), IEEE International Conference on Integrated Circuit Design and Technology (ICICDT), June 27 - 29, 2016;

[31] Pantoli L, Stornelli V, Leuzzi G (2015). Class AB Gyrator-Based Active Inductor. In: IEEE. Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMiC), 2015 International Workshop on. Taormina, 29-30 Settembre 2015;

[32] Pantoli L, Stornelli V, Leuzzi G (2015). RF Active Circuit Simulating a Floating Inductance. In: IEEE, Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMiC), 2015 International Workshop on.. Taormina, 29-30 Settembre 2015;

[33] Pantoli L, Stornelli V, Leuzzi G (2015). A Wideband Class-AB Tunable Active Filter. In: IEEE, European Microwave Week 2015. EuMW 2015 - Conference Proceedings; EuMIC 2015: European Microwave Integrated Circuits Conference, Parigi, 7-8 Settembre 2015;

[34] Pantoli L, Stornelli, V., Leuzzi, G., Di Carlofelice, A. (2014). A single transistor post selector active tunable filter for radio receivers applications. In: IEEE. Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMiC), 2014 International Workshop on. doi: 10.1109/INMMIC.2014.6815106;

[35] Pantoli L, Stornelli, V., Leuzzi, G. (2013). Low voltage high-order agile active filter for microwave applications. In: IEEE. EuMC 2013: 43rd European Microwave Conference. p. 1203-1206;

[36] Pantoli L, Stornelli, V., Leuzzi, G. (2012). A single-transistor tunable filter for bluetooth applications. In: Conference Proceedings - 42nd European Microwave Conference, EuMC 2012. p. 1269-1272, ISBN: 978-287487027-9;

[37] Stornelli V, Leuzzi G, Pantoli L, Del Re S (2011). High Dynamic Range Bandpass Filters Design Based on Active Inductor. In: Microwave Integrated Circuits Conference (EuMIC), 2011 European. p. 168-171, Manchester, 10-11 October;

[38] Leuzzi G, Stornelli V., Del Re S, Pantoli L (2011). High quality factor integrable bandpass filter by using tunable active inductor. In: Integrated Nonlinear Microwave and Millimetre-Wave Circuits (INMMIC), 2011 Workshop on. Vienna, 18-19 April 2011;

[39] Leuzzi G, Stornelli V, Colucci P, Pantoli L (2014). LOW-NOISE ELECTRONIC CIRCUIT SIMULATING THE BEHAVIOR OF AN INDUCTANCE. US Patent n° US201414301526 20140611.