

## Wide Tuning Range Active RF Bandpass Filter with MOS Varactors

Cristian ANDRIESEI<sup>1</sup>, Liviu GORAS<sup>1</sup>, Farid TEMCAMANI<sup>2</sup>,  
Bruno DELACRESSONNIÈRE<sup>2</sup>

<sup>1</sup> *Gheorghe Asachi* Technical University, Iași, Romania  
E-mail: lgoras@etc.tuiasi.ro

<sup>2</sup> ECIME/ENSEA, Cergy-Pontoise University, France  
E-mail: duress@ensea.fr

**Abstract.** The paper presents an improved tuning method implemented for a differential active inductor based RF bandpass filter. Derived from a previous designed transistor-only second order filter topology, independent frequency and quality factor tuning are demonstrated in 0.18  $\mu\text{m}$  CMOS technology. The circuit has been basically designed for a maximum frequency of 2.4 GHz, high enough to cover the main wireless standards, has small power consumption and can exhibit very high Q values. A wide frequency tuning range is obtained by using MOS varactors. The circuit absorbs 1 mW from a 1.8 V supply at 2.4 GHz central frequency.

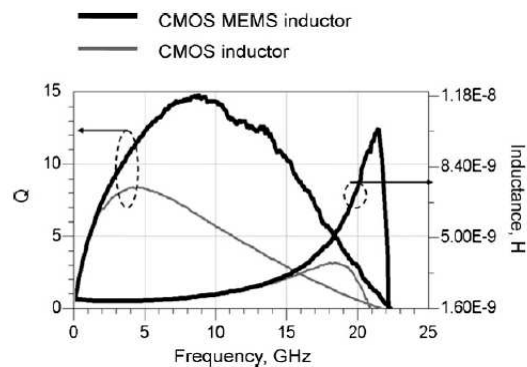
**Key words:** active inductor, CMOS RF bandpass filters, Q-enhancement, independent frequency and quality factor tuning.

### 1. Introduction

Inductors are key components in RF front-end implementations. Low noise amplifiers (LNA's), and voltage controlled oscillators (VCO's) are the main RF systems using on-chip silicon inductors. Many RF filter configurations using silicon (CMOS) inductors have been proposed in the literature too [1–4] but they are not yet included in practical circuit implementations of wireless standards. CMOS inductors are preferred to off-chip (coils) inductors for applications such as impedance matching networks, tuned LC tanks and transformers although they can not achieve the higher

quality values characteristic to off-chip inductors. Although their quality factor can be improved by using negative resistances, as in VCO's, high Q values are still difficult to obtain. These are also the main constraints in using such inductors in practical implementation of RF bandpass filters for wireless applications. An important aspect in designing reconfigurable 2<sup>nd</sup> order RF bandpass filters is independent tuning of the central frequency and quality factor. Such circuits might use varactors as well in order to obtain wider frequency tuning range with constant quality factor.

An alternative to silicon inductors which gains a growing interest on the market is represented by MEMS inductors [5–9] implemented in CMOS processes. Such inductors can reach high quality factor values rising up to 60–85 [9] but still not high enough to implement RF preselective filters with steep attenuation. In addition, not having tuning possibilities, they can not be used for multistandard reconfigurable RF filter implementations. Moreover, their high price still maintains them at prototype levels or for other applications where there are not so many constraints as in telecommunications transceivers, since they are not as widespread as CMOS devices. Last but not least, filters based on active on-chip inductors represent an attractive alternative. A comparison between CMOS and MEMS inductors is given in Fig. 1 [5] which reveals the effective advantage of MEMS over CMOS standard devices. In Fig. 2 the possibility of obtaining high quality factor values with such filters is shown [9] ( $f_0$  is the self resonance frequency or parasitic resonance frequency).



**Fig. 1.** Q factor and inductance for CMOS and CMOS MEMS inductor [5].

Nowadays, wireless transceivers make use of at least 10 switched external passive SAW filters [10, 11], their implementation being the main problem in an all-chip multi-standard system. Even in the case of software defined radio systems (SDR) where the trend is to translate all the functions of RF blocks to the digital part, the use of RF bandpass filters still remains a challenge.

In contrast to passive inductors mentioned above, active inductor implementations gain more interest today due to their performances regarding size, quality factor and tuning possibility. The most common active implementations, based on  $g_m$ -C structures, are not suitable for frequencies in the GHz range due to their high

chip size and power consumption. Consequently, a constant interest has been shown in literature to transistor-only based active inductors [12–19] which seems to be a promising solution for building reconfigurable RF bandpass filters. Based on the gyrator theory, transistor-only active inductors make use of the parasitic capacitors of the transistors in order to emulate the inductor behavior. The main advantage is the tuning possibility, fact that is not possible for passive implementations (CMOS and MEMS inductor).

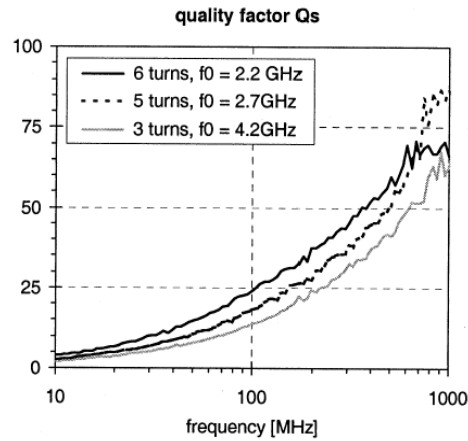


Fig. 2. MEMS inductor quality factor [9].

Even though these solutions have their drawbacks as well, i.e., noise, nonlinearity and power consumption, their advantages prevail.

Since only one second order bandpass filters do not satisfy the bandwidth and sideband attenuation requirements for GSM and wireless specifications, higher orders filters obtained by cascading second order structures [20–22] should be used.

This paper presents an RF bandpass filter topology designed for high frequencies up to 2.4 GHz which allows independent frequency and quality factor tuning over a wide frequency range from 600 MHz up to 2.4 GHz, covering all GSM frequencies. The circuit can be used to implement higher order active filters, suitable for RF wireless filtering as well.

## 2. Circuit description

The proposed filter configuration is based on the transistor only active inductor shown in Fig. 2a, where the parasitic capacitor of  $M_2$  is used to emulate the inductive behavior. In the same figure the equivalent small signal models for this inductor are shown as well. The simulated inductor is characterized by the followings relations:

$$Y(s) = s \cdot C_{gs1} + g_{o2} + \frac{(g_{o1} + g_{m1})(g_{m2} + s \cdot C_{gs2})}{g_{o1} + s \cdot C_{gs2}}, \quad (1)$$

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_{gs1}C_{gs2}}} \quad ; \quad Q = \sqrt{\frac{g_{m2}C_{gs1}}{g_{m1}C_{gs2}}} \quad (2)$$

Relation (1) gives the expression of the input impedance with the equivalent models presented in Fig. 1 while (2) gives, within some approximation, the center frequency and quality factor of the active filter based on the simulated inductor.

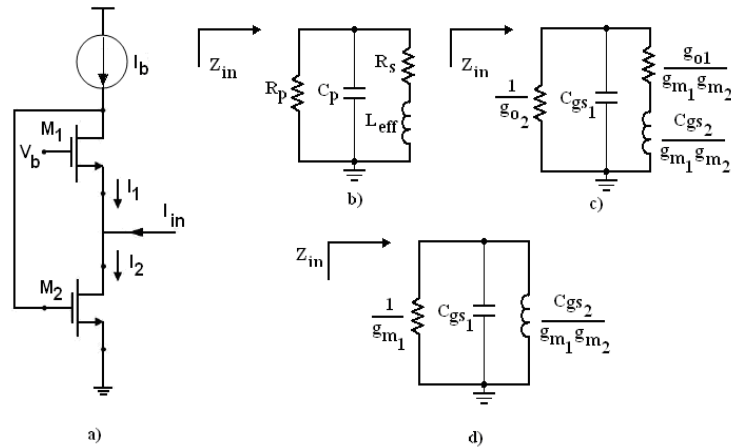


Fig. 2. Simulated inductor and equivalent circuit models.

A previously designed active RF bandpass filter based on the active inductor discussed above and described in [21] is presented in Fig. 3. In order to tune the quality factor of the filter, a dc coupled negative resistance implemented with a cross-coupled pair of nMOS transistors was used.

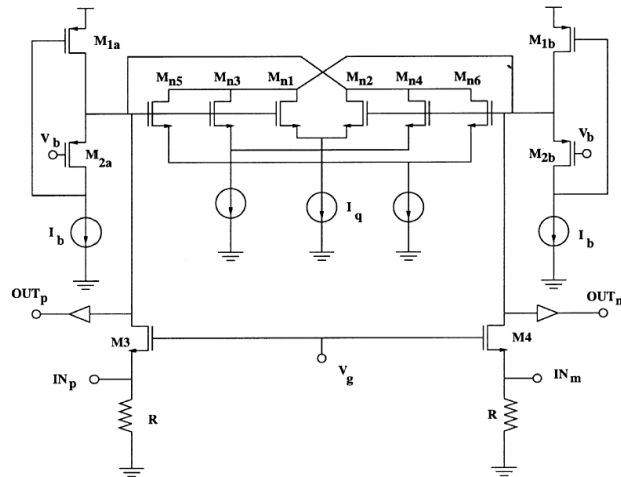


Fig. 3. Active RF filter based on the simulated inductor [21].

The direct coupling of the negative resistance to the simulated inductor has several effects. The most important one for the filter behavior consists in the quality factor tuning. The presence of the negative resistance in the transfer function determines a decrease of the bandwidth and a corresponding increase of  $Q$ . However, its variation influences the central frequency as well (decreasing the frequency as the quality factor increases). Another negative effect consists in changing the biasing for the transistors of the active inductor due to its direct coupling. In this case the negative resistance receives an extra current from the active inductor, fact that strongly affects the biasing of  $M_{1a}$  and  $M_{1b}$  and thus increasing the frequency deviation while changing the bias for both transistors.

The only possibility to have an independent tuning for this configuration using negative resistances consists in introducing a second negative resistance to the second node and decoupling them in dc. In this way, by keeping constant one of them and changing the second, an independent tuning is possible. The method was proposed and described in [23] for a single-ended topology and in [24] for a differential one.

The circuit proposed in this paper, shown in Fig. 4, is based on the previously topology presented in [24] and makes use of varactors in order to implement a wide frequency independent tuning range. The negative resistance used in the proposed circuit is presented in Fig. 5.

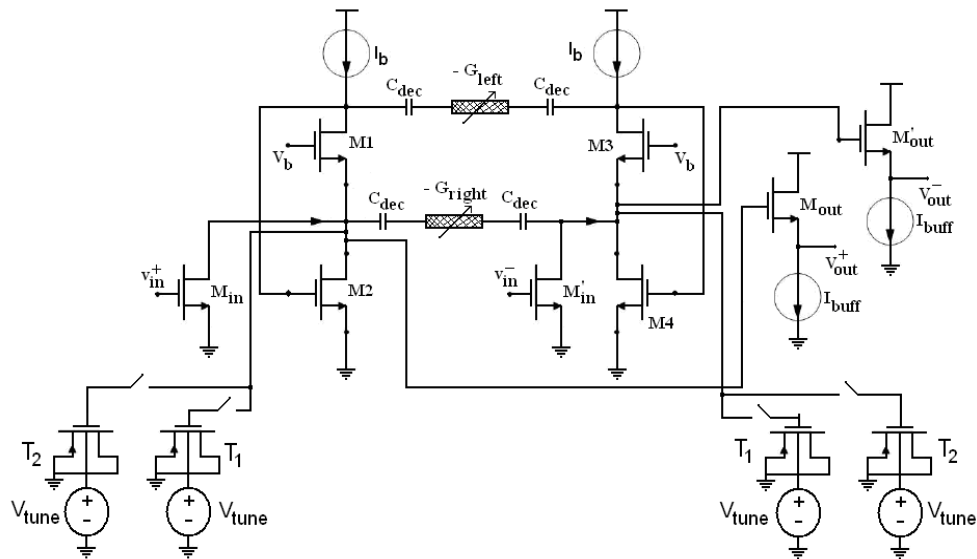


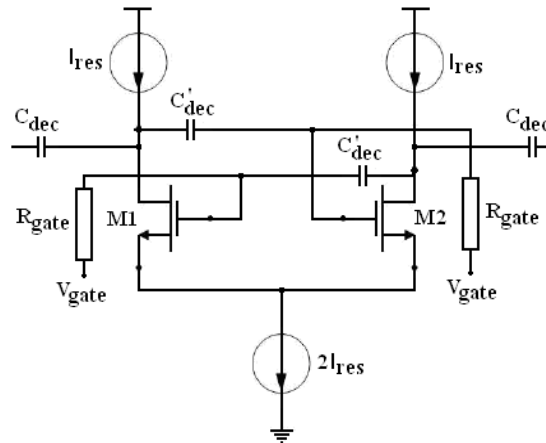
Fig. 4. Proposed wide frequency tunable RF filter.

Varactors are currently used in the design of VCO's in the transceiver part.

Due to stringent telecommunications standards requirements imposed to VCO's, MOS varactors are preferred since they are readily available in any CMOS process, have wider tuning range and higher quality factor.

There are many papers describing various process implementations of MOS varactors. In order to achieve the maximum value for the capacitance,  $C_{mos} = C_{ox} =$

$\varepsilon_{ox}S/t_{ox}$ , with  $S$  the transistor channel area and  $t_{ox}$  the oxide thickness but also the highest possible  $Q$  value, CMOS varactors work in accumulation and strong inversion. The biasing region is important when talking about power consumption. Thus, regarding the VCO design, those which use varactors working in accumulation mode are characterized by a lower power consumption and phase noise compared to those based on strong inversion.



**Fig. 5.** Differential dc decoupled negative resistance.

Regarding the tuning range, varactors working in accumulation have very large  $C_{max}$  to  $C_{min}$  ratio compared to other structures.

For our proposed circuit, since all varactors are connected to the node corresponding to the parasitic capacitor of the inductor, the value of the inductor is kept constant while the self resonance frequency is changed. After the change of the varactor value, a corresponding change of the negative resistance is required in order to obtain the required quality factor value but with no effect on the resonance frequency.

The capacitance values needed in the above application are much smaller (fF) compared to the VCO case (pF). Moreover, in the filter case, since the signal values are small, the capacitance remains unchanged compared to the case of VCO where the instantaneous capacitance value changes during the signal period.

### 3. Simulation results

The active bandpass filter shown in Fig. 4 was designed in a 0.18  $\mu\text{m}$  CMOS process for a center frequency of 2.4 GHz which is also the maximum frequency achievable by this method with a power consumption of 1 mW. Higher frequency values are still possible but with an extra power consumption for the active inductor.

The possibility of implementing an independent frequency and quality factor tuning is shown in Fig. 6. The center frequency is 2.4 GHz and is constant while the quality factor changes from 6 to 2000 with no problems of instability even for the

highest quality factor value. However, further change of the negative resistance value will cause instability, as reflected by the transient responses, shown in Fig. 6.

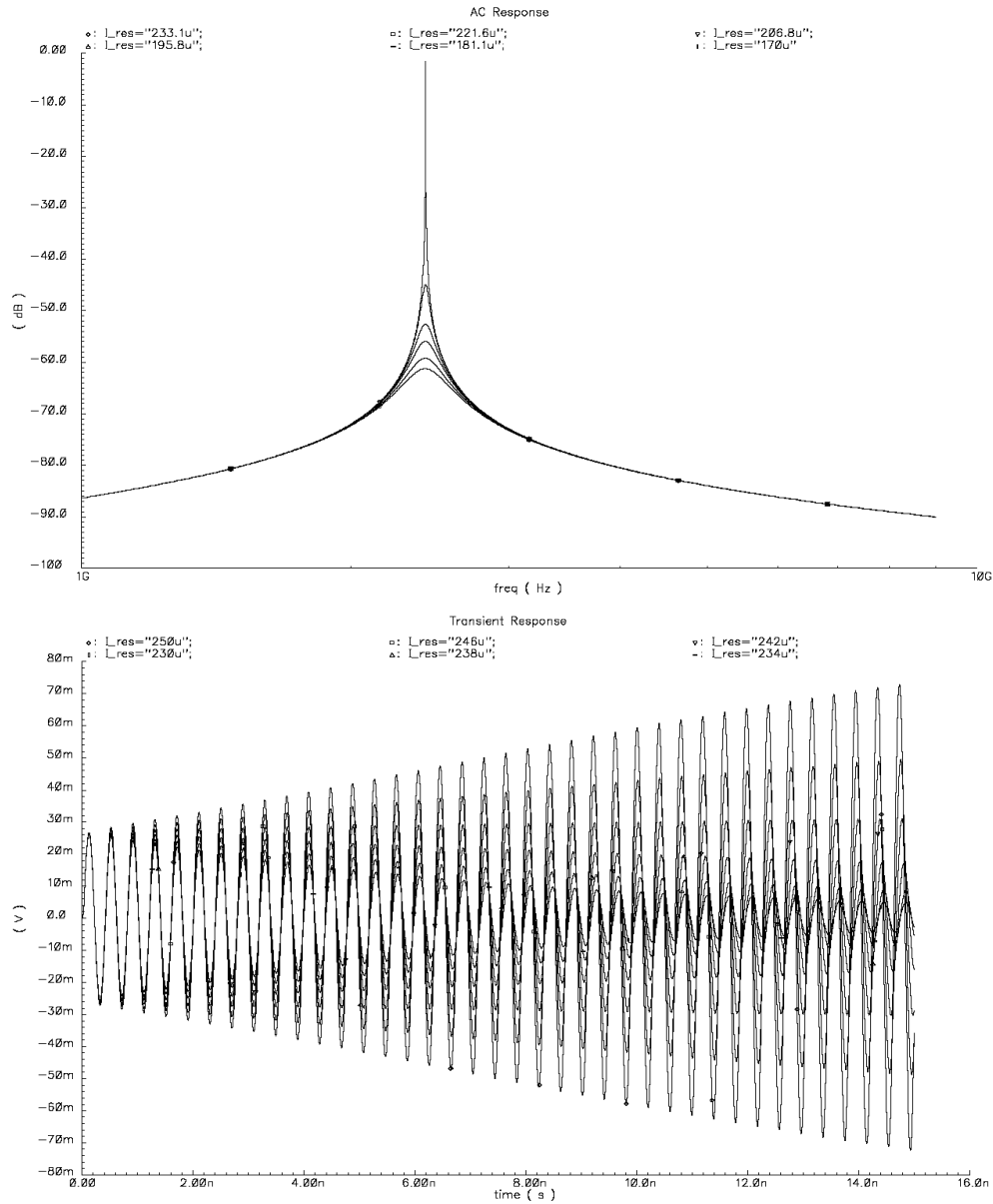
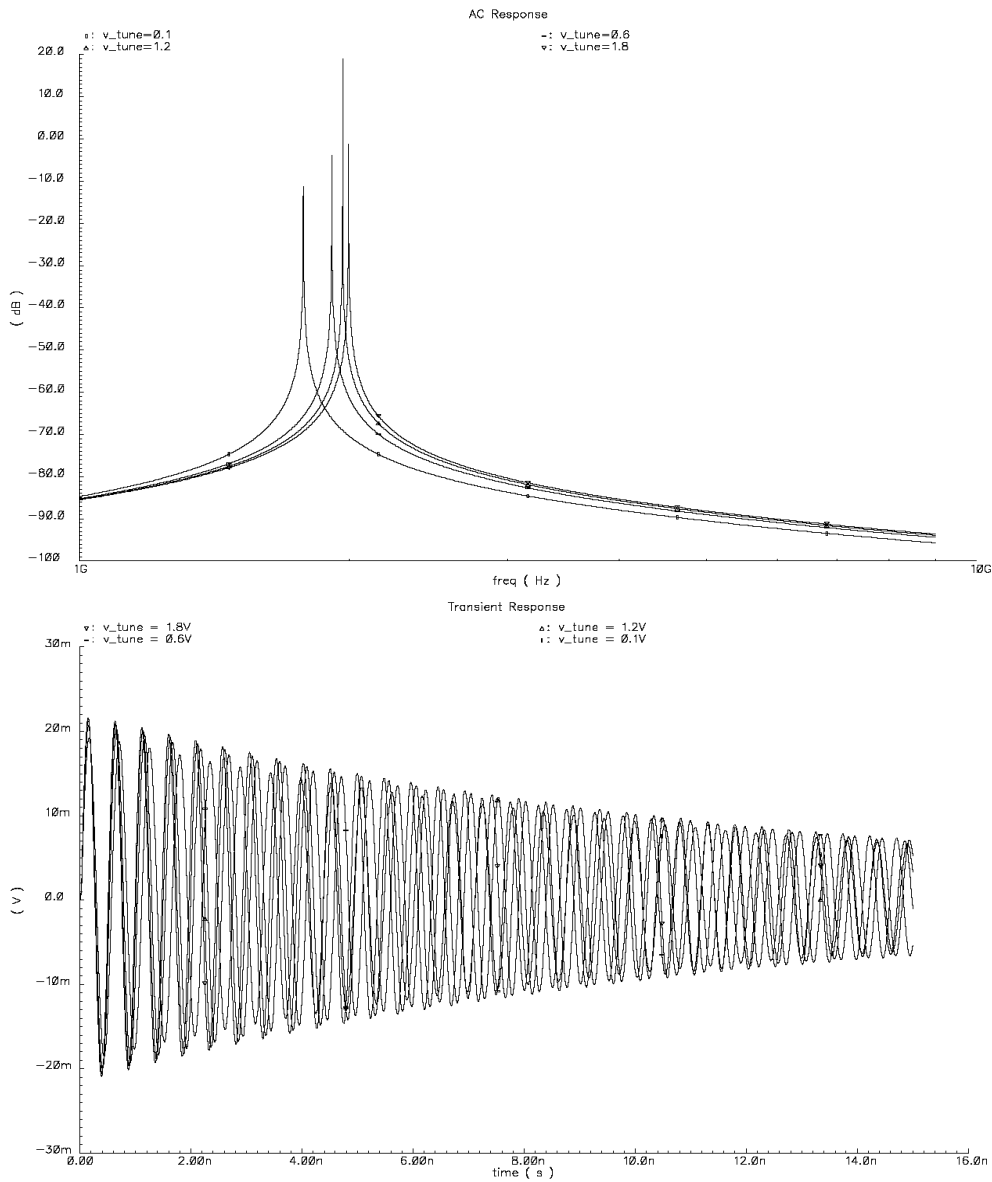


Fig. 6. Quality factor tuning,  $f_0 = 2.42$  GHz and transient response showing potential instability.

As the frequency and transient responses show, the quality factor change influences the amplitude only. This is not the case for other achievable bands where by using

varactors the center frequency as well as the transient response change. It has been observed that for the designed circuit a current higher than  $240 \mu\text{A}$  passing through  $M_1$  and  $M_2$  which simulate the negative resistance leads to instability.



**Fig. 7.** Frequency and time behavior for 1.8 GHz and 1.9 GHz GSM bands using varactors.

As mentioned above, the center frequency is changed by using varactors and then the quality factor is tuned. By using the first varactor  $T_1$  (3.5/1), the center frequency



can be decreased to the 1800 and 1900 MHz (GSM bands), the frequency tuning being possible in the frequency range 1.77–1.99 GHz. The filter behavior in this band is shown in Fig. 7 together with a transient response.

It can be seen that for all four frequencies, the filter is stable.

By using the second varactor  $T_2$  (6.5/6), the center frequency is further decreased in order to work in the lower GSM band, the frequency tuning being possible in the frequency range 600–990 MHz through a suitable change in  $V_{tune}$ . The frequency response for this GSM band is illustrated in Fig. 8.

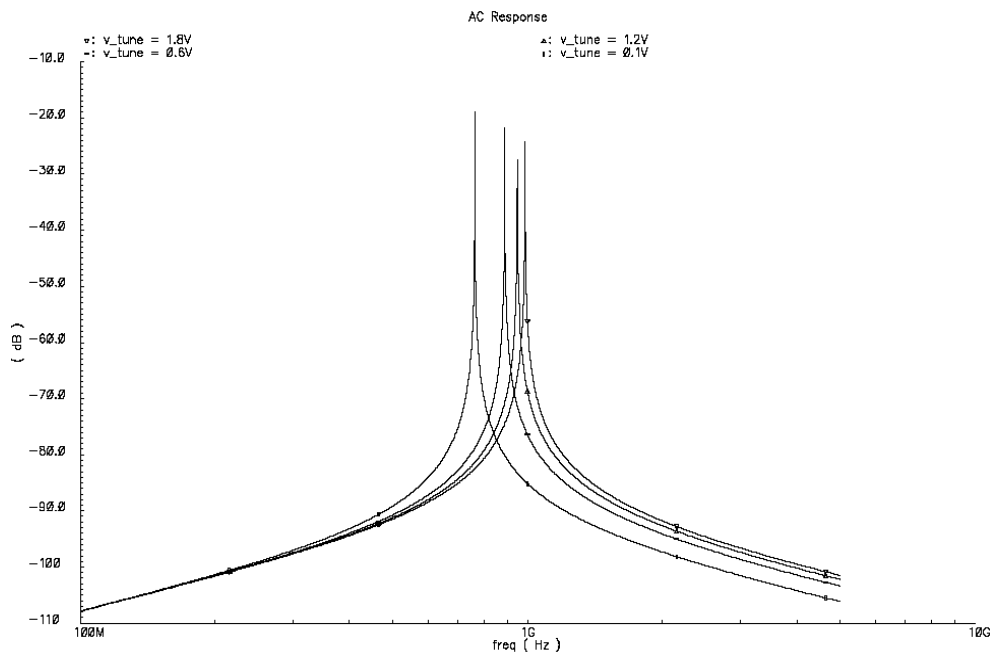


Fig. 8. Frequency behavior for the 600–990 GHz GSM band.

#### 4. Conclusion

A new wide frequency range tuning possibility was studied for a particular configuration of active all-NMOS RF bandpass filter. The tuning principle makes use of negative resistances aiming for an independent frequency and quality factor tuning. To achieve wide frequency tuning range only 2 varactors are used in order to cover the GSM bands with no extra power. A third possible varactor can be used in order to cover the UMTS frequencies as well. A maximum frequency of 2.4 GHz is achieved with this principle with small power consumption and very high quality factor (up to 2000) can be achieved without instability problems. The maximum power consumption is 1 mW for a 1.8 V supply being independent of the center frequency.

## References

- [1] HE X., KUHN W., *A 2.5-GHz Low-Power, High Dynamic Range, Self-Tuned Q-Enhanced LC Filter in SOI*, IEEE Journal of Solid-State Circuits, vol. **40**, no. 8, pp. 1618–1628, August 2005.
- [2] GEORGESCU B., PEKAU H., HASLETT J., MCRORY J., *Tunable Coupled Inductor Q-enhancement for Parallel Resonant LC Tanks*, IEEE Trans. on Circuits and Systems, vol. **50**, no. 10, pp. 705–713, October 2003.
- [3] KUHN W., NOBBOE D., KELLY D., OSBORN A., *Dynamic Range Performance of On-Chip RF Bandpass Filters*, IEEE Trans. on Circuits and Systems, vol. **50**, no. 10, pp. 685–694, October 2003.
- [4] LI D., TSIVIDIS Y., *Design Techniques for Automatically Tuned Integrated Gigahertz-Range Active LC Filters*, IEEE Journal of Solid-State Circuits, vol. **37**, no. 8, pp. 967–977, August 2002.
- [5] TSENG S.-H., HUNG Y.-J., JUANG Y.-Z., LU M. S.-C., *A 5.8-GHz VCO with CMOS-compatible MEMS inductors*, Sensors and Actuators A: Physical, Vol. **139**, pp. 187–193, 2007.
- [6] ELZAYAT A., DEGEBE M., DOMINGUE F., NERGUIZIAN V., *A Suspended MEMS inductor of a new geometry and a novel anchor for RF applications*, IEEE International Symposium on Industrial Electronics, Vol. **4**, pp. 3332–3337, 2006.
- [7] PARK E.-C., CHOI Y.-S., YOON J.-B., HONG S., YOON E., *Fully Integrated Low Phase-Noise VCOs With On-Chip MEMS Inductors*, IEEE Transaction on Microwave Theory and Technoques, Vol. **51**, No. 1, 2003.
- [8] YOON J.-B., CHOI Y.-S., KIM B.-I., EO Y., YOON E., *CMOS-compatible, surface micromachined, suspended spiral inductors for multi-GHz silicon RF ICs*, Electron Device Lett., Vol. **23**, pp. 591–593, Oct. 2002.
- [9] CHUA C.L., FORK D.K., VAN SCHUYLENBERGH K., LU J.-P., *Out-of-plane high-Q inductors on low-resistance silicon*, Journal of Microelectromechanical Systems, Vol. **12**, No. 6, pp. 989–995, 2003.
- [10] [www.triquint.com](http://www.triquint.com)
- [11] [www.epcos.com](http://www.epcos.com)
- [12] HARA S., TOKUMITSU T., *Broad-Band Monolithic Microwave Active Inductor and Its Application to Miniaturized Wide-Band Amplifiers*, IEEE MTT, 1988, Vol. **36**, No. 12.
- [13] THANACHAYANONT A., PAYNE A., *VHF CMOS integrated active inductor*, Electronics Letters, Vol. **32**, No. 11, May 1996.
- [14] WU Y., ISMAIL M., *A Novel CMOS Fully Differential Inductorless RF Bandpass Filter*, Proc. IEEE ISCAS, pp. 149–152, Vol. 4, 2000.
- [15] KARŞILAYAN A., SCHAUMANN R., *A High-Frequency High-Q CMOS Active Inductor with DC Bias Control*, Proc. 43<sup>rd</sup> IEEE Midwest Symposium on Circuits and Systems, pp. 486–489, Vol. 1, August 2000.
- [16] THANACHAYANONT A., NGOW S., *Low Voltage High-Q VHF CMOS Transistor-Only Active Inductor*, The 2002 45<sup>th</sup> Midwest Symposium on Circuits and Systems, MWSCAS-2002, vol. **3**, pp. III-552–III-555, Thailand.

- [17] LIANG K., HO C., *CMOS RF Band-Pass Filter Design Using the High Quality Active Inductor*, IEICE Trans. Electron., Vol. **E-88-C**, No. 12, 2005.
- [18] ALLIDIMA K., MIRABBASI S., *A Widely Tunable Active RF Filter Topology*, IEEE International Symposium on Circuits and Systems, ISCAS 2006 Proceedings, pp. 879–882, May 2006, Greece.
- [19] GAO Z., MA J.-G., *A CMOS Bandpass Filter with Wide-Tuning Range for Wireless Applications*, IEEE International Symposium on Circuits and Systems, ISCAS 2006 Proceedings, pp. 867–870, May 2006, Greece.
- [20] THANACHAYANONT A., *2-V 3.36-mW 2.5 GHz Fourth-Order Inductorless CMOS RF Bandpass Filter*, The Asia-Pacific Conference on Circuits and Systems, APCCAS-2002, Vol. **1**, pp. 127–130, Thailand.
- [21] WU Y., ISMAIL M., *RF Bandpass Filter Design Based on CMOS Active Inductors*, IEEE Transactions on Circuits and Systems, vol. **50**, no. 12, pp. 942–949, December 2003.
- [22] DINH A., GE J., *A Q-Enhanced 3.6 GHz, Tunable, Sixth-Order Bandpass Filter Using 0.18  $\mu\text{m}$  CMOS*, VLSI Design, Volume **2007**, Article ID 84650, 2007.
- [23] ANDRIESEI C., GORAS L., *On the Tuning Possibilities of an RF Bandpass Filter with Simulated Inductor*, International Semiconductor Conference-CAS 2007, vol. **2**, pp. 489–492, October 2007, Romania.
- [24] ANDRIESEI C., GORAS L., TEMCAMANI F., *Negative Resistance Based Tuning of an RF Bandpass Filter*, Fourth European Conference on Circuits and Systems for Communications, ECCSC 2008, vol. **1**, pp. 1–4, July 2008, Romania.