Journal of Theoretical and Applied Information Technology
10th March 2014. Vol. 61 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

A REVIEW ON CMOS GM-C BAND PASS FILTERS IN RF APPLICATION

MOHAMMAD ARIF SOBHAN BHUIYAN, MASTURA BINTI OMAR, MAMUN BIN IBNE REAZ, KHAIRUN NISA MINHAD, FAZIDA HANIM HASHIM

Department of Electrical, Electronic and Systems Engineering,
University Kebangsaan Malaysia,
43600, UKM, Bangi, Selangor, Malaysia
E-mail: md.arif.sobhan@gmail.com

ABSTRACT

Fully integrated CMOS band-pass filter is a prerequisite of all modern transceivers. The filters are expected to encompass very low power dissipation, relatively higher Q-factor with proper centre frequency tuning. But there is some trade off among the parameters. Conventional band-pass filters suffer from some inevitable drawbacks which are not prominent in CMOS Gm-C configuration. In this paper, a review on the advancement of Gm-C filter circuits, illustrated in different literatures, is discussed with their merits and demerits. This review will serve as a comparative studies and reference for the researchers in designing future high performance band-pass filters for wireless transceiver frontend applications.

Keywords: *CMOS, Low Power, Bandpass Filter, RF*

1. INTRODUCTION

The usage of wireless devices such as RFID, Bluetooth, Zigbee and Wi-Fi devices, medical instruments, sensors etc. has been experiencing a rapid jump in the last few years as a result of rapid scale down of CMOS technology [1-5]. This in turn led the researchers fabricate and manufacture high performance, compact and low-cost wireless systems by eliminating many bulky components [6-9]. As a result individuals as well as industries are becoming benefited.

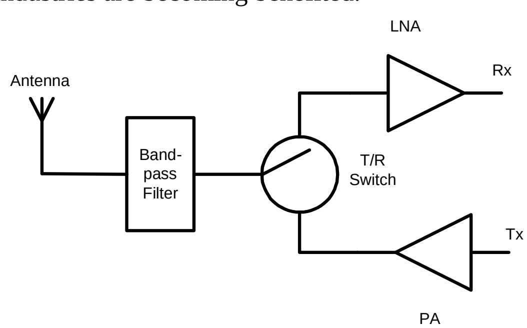

Figure 1. Bandpass filter at the transceiver front end

The overall performance of a wireless device greatly depends on the performance of its transceiver [10-13]. Band-pass filters are the essential components of all wireless transceiver front ends as shown in figure 1. To design band pass filter with high quality factor, inductors play an important role [14-17]. Higher cost that came from large size of silicon area to entertain on-chip passive spiral inductors is one of the prime disadvantages. Another disadvantage of on-chip spiral inductor is its deficiency of tuning ability which makes the design a little bit complicated [18, 19]. As a result the usage of on-chip spiral inductors is decreasing day by day for high frequency applications [20].

Fully integrated continuous-time transconductance-C (Gm-C) filters have been widely used for high frequency applications such as digital video, RF/IF filters, etc. [21, 22]. Gm-C filters offer many advantages in terms of low power and high frequency capability [23]. However, one of the major problems as the frequency increases is the phase error of the employed integrator. Any non linearity of the transconductance element results in signal-level-dependent frequency response deviations of gain and phase in integrators and filters. The frequency response of high-frequency filters is very sensitive to excess phase shifts in the integrator; therefore, to avoid deviations in filter characteristics, a high DC gain integrator is required with parasitic poles located much higher than the filter cut-off frequency to keep the integrator phase at -90' in the frequency range of interest [23, 24]. Recently, design techniques based on negative resistance load (NRL) without any limitation in the bandwidth of a transconductor circuit, has been reported in the literature [25]. It

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

leads to an improved Gm- C integrator with theoretically infinite DC-gain and wide bandwidth as well. Unfortunately, this method requires additional tuning circuit since the output impedance varies when the overall transconductance is modified. This paper presents a detail review on the merits and demerits of each Gm- C filter circuit from its architecture and performance point of view illustrated in recently reported literatures.

2. ADVANCES IN GM-C FILTERS

The basic Gm-C filter, consisting of a capacitor and a transconductance, is shown in Figure 2 and its transfer function is given by:

$$\mathrm{Vo/Vi} = \frac{G_m}{sC_L} \qquad (1)$$

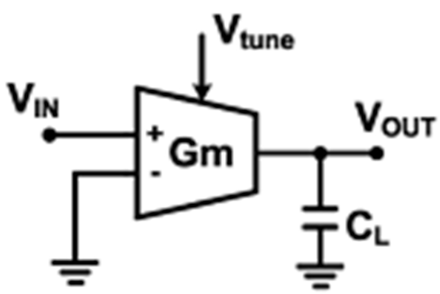

Figure 2. Typical Gm-C configuration [26]

A Gm-C filter is a kind of the continuous-time filter which needs the operational transconductance amplifier (OTA) to be a basic building block [27, 28]. Gm-C filters are popular for on-chip applications due to their advantages of high frequency performance and low power consumption, but have linearity problems [29]. In order to overcome the disadvantage of linearity of Gm-C filters, many linearization techniques for transconductors have been reported such as resistive source degeneration, dynamic source Degeneration, tunable feedback, combination of dynamic source degeneration and tunable feedback, transconductor with bias feedback etc. [30, 31]. Besides the non-ideality of the transconductors causes excessive phase shift and inherently limits the upper operational frequencies, which restricts this type of filter from being used in gigahertz frequencies [31].

2.1 Automatic Qo and frequency tuning

To generate tuneable high quality factor and also to increase the output impedance, the output is linked in parallel with negative GM cells as shown in Figure 3.

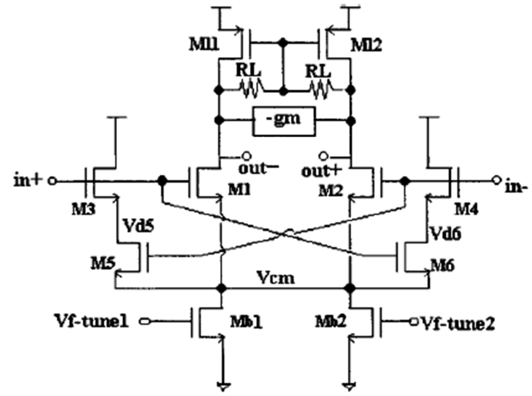

Figure 3. Negative G_m cells [32].

In the Gm cell, M1 and M2 play the role of input transistors whereas transistor M3, M4, M5 and M6 play the function of active bias circuit. This design is more likely same the normal GM cells except that the outputs of the circuit linked together by cross couple method at the inputs [32].

To realize the design concept, a sixth order GM – C band pass filter is constructed by cascading three bi-quad stages as shown in figure 4. The filter can be tuned automatically in terms of both frequency and central frequency.

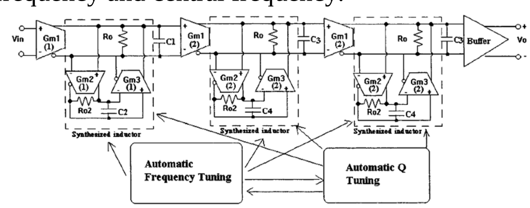

Figure 4. Three bi-quad stages of band pass filter [32]

This filter is designed particularly for high-frequency applications. Every bi-quad stage output is connected in parallel with negative GM cells. The consequences of this feature boosts up the quality factor. Besides, the noise performance and power consumption also improve the linearity of the filter.

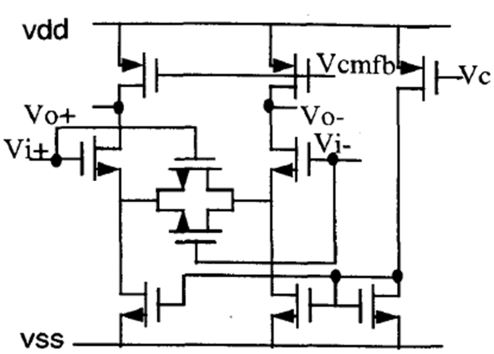

Figure 5. Linearized OTA [33].

Journal of Theoretical and Applied Information Technology
10th March 2014. Vol. 61 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

The second order biquadratic band pass filter has been constructed by using this circuit for improved quality factor as illustrated in figure 6.

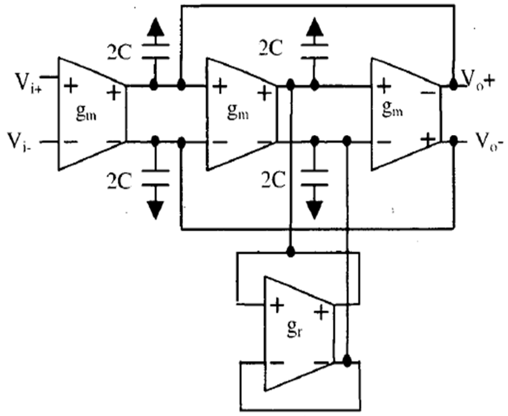

Figure 6. Second Order Biquadratic Band Pass Filter [33].

The transfer function of this filter is expressed as

$$H(s) = \frac{\frac{g_m}{C}\left(s + \frac{g_0 - g_r}{C}\right)}{s^2 + \frac{2g_0 - g_r}{C}s + \frac{g_m^2 - g_0 g_r + g_0^2}{C^2}} \quad (2)$$

Where, the output impedance of OTA is g_o. Next, the centre frequency can be approximated by following function:

$$\omega_0 \approx \frac{g_m}{C} \quad (3)$$

while the quality factor is given by

$$Q \approx \frac{g_m}{2g_0 - g_r} \quad (4)$$

Therefore, from the equations it is clear that the quality factor and the centre frequency of the OTA can be adjusted by simply varying the values of g_m and g_r.

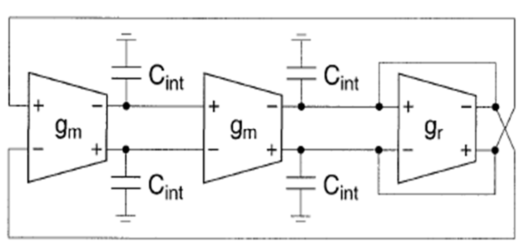

Figure 7. Fully differential two integrator loop Gm-C filter [34].

For constructing band pass filter in Gm-C, another popular topology is by using two integrator loops as shown in Figure 7. For differential signals the loop is placed in negative feedback configuration but for common mode signal it is placed on positive feedback mode. The positive loop gain has to be less than one to make the two integrator loops stable.

To make the common-mode control efficient at very high frequencies, common mode feed forward (CMFF) have to be linked together with common mode feedback circuit (CMFB). Common mode voltage reference is included in the gain block so that it is connected to the output [34]. To make CMFB stable, the integrating capacitors C_{int} is used rather than differential signal processing as shown in the Figure 8.

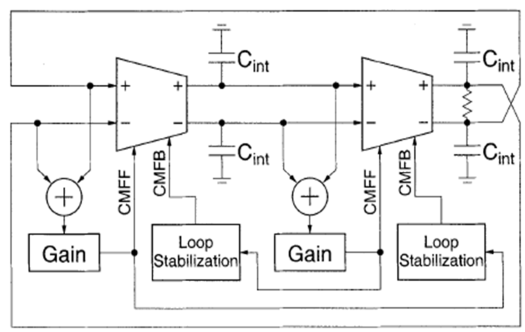

Figure 8. Two integrator loop transconductance with both CMFF and CMFB [34].

Sometimes CMFF and CMFB is merged together to construct the differential transconductance that have fully symmetric and fully balanced feature. Such architecture is shown in Figure 9.

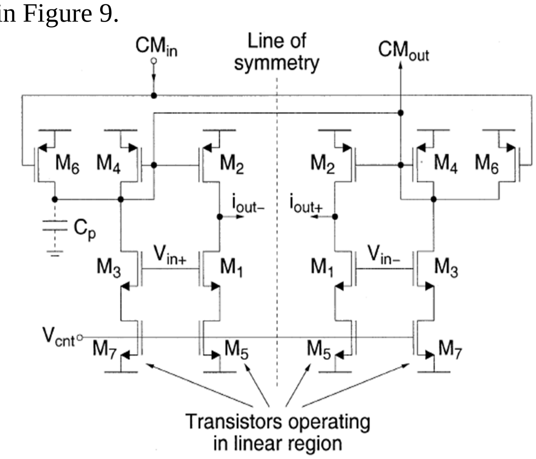

Figure 9. Schematic of the proposed differential transconductor [34].

2.2 Low power consumption design

The transconductor with a large G_m/I_{bias} ratio is usually comes with low power feature. At small bias current, it can obtain large G_m values by

Journal of Theoretical and Applied Information Technology
10th March 2014. Vol. 61 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

keeping the dynamic range within a specific suitable range. G_m/I_{bias} ratio can be express as

$$\frac{G_m}{I_{bias}} = \frac{1}{2a(V_{od})} \quad (5)$$

where, V_{od} is the overdrive voltage.

Gm-C circuit topology, therefore, can be modified to design a band pass filter that has low power consumption [35]. Opposite to the usual convention of utilizing a fixed bias, the input node is connected to the load of PMOS transistor as shown in Figure 10.

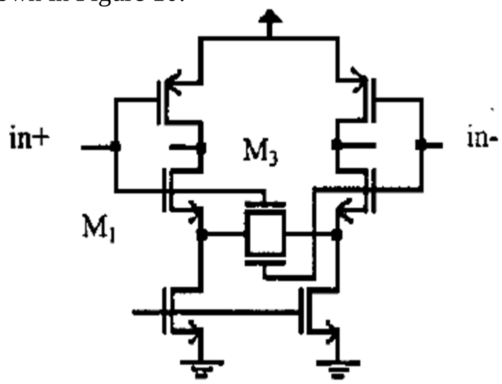

Figure 10. Transconductance for low power consumption [35].

Together with M1 NMOS transistor and the PMOS transistor providing the transconductance of the circuit. At low bias current, the larger transconductance can be achieved by using this method. However, the linear range is reduced but the main concern is the dynamic range. Due to the low current operation, the usage of complementary transistor and using the proposed transistor, the output noise is also lessened. This results in huge drop in the power consumption as well as considerable reduction in dynamic range. It also leads to have higher output resistance to avoid external pass band loss [35]. To realize the circuit topology, fourth order band pass filter is designed as shown in Figure 11.

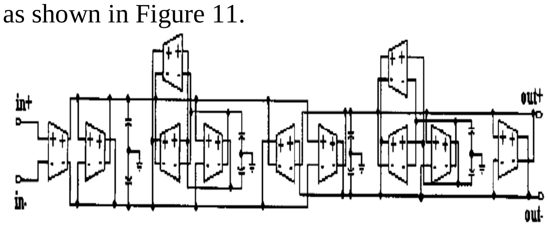

Figure 11. Fourth order band pass filter.

The filter is operating from a passive doubly that terminate the LC ladder until to the lower sensitivity of the filter response to its components. Passive component are scaled accurately according to impedance level that require by the design.

Further direct tuning capability of the bi-quad topology make it attractive for the design of low power filters. To determine low input impedance in high pass-notch and low pass-notch stages, buffers are place between the bi-quad as shown in Figure 12.

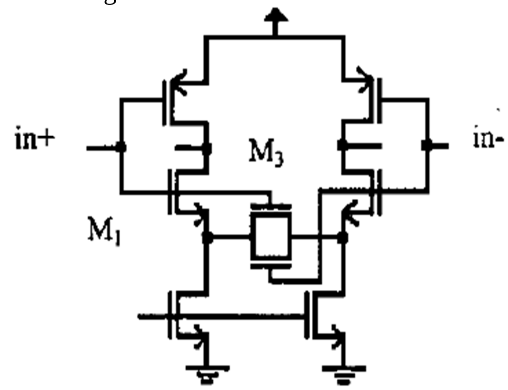

Figure 12. Bi-quad stage.

Transconductance of the element can be expressed as:

$$g_m = 4k_1k_3\sqrt{I_B}/(k_1 + 4k_3)\sqrt{k_1} \quad (6)$$

Subscript 1 and 3 denote to input and linearization transistors, respectively. Furthermore, IB is the bias current fixed through reference bias voltage, while k is equal to $\mu C_{ox}W/2L$ [36]. Transconductance of the circuit is shown in Figure 13.

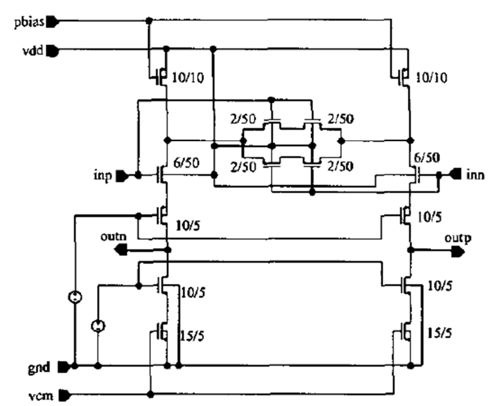

Figure 13. Unit transconductor element.

In this circuit, by varying both the bias current and the bias voltage, transconductance can be tuned accordingly. Since the low transconductance value required with satisfactory integrator phase response, the Gm-C element produces low current that will reduce the power consumption as well [37].

Journal of Theoretical and Applied Information Technology
10th March 2014. Vol. 61 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Performance comparison of recently reported Gm-C band pass filters is given in the table 1 below:

Table 1: Performance comparison of GM-C band pass filters.

Ref.	CMOS Process	Centre frequency (MHz)	BW (MHz)	Q factor	Wide Tuning Range	Power Source (V)	Power Consumption (mW)	Area (mm^2)
[31]	65nm	80	10	NA	No	1.2	13.2	0.25
[38]	0.18um	10 - 126	NA	0.1-0.6	Yes	0.9	5.2	NA
[39]	0.25um	10.7	0.5	NA	Yes	2.5	6	0.3
[40]	1.5Um	10.7	0.3	NA	NA	2.5	220	6
[41]	0.35um	3.25	NA	NA	Yes	2.5	NA	NA
[23]	0.35um	54 – 74	NA	50-70	Yes	2.2	NA	NA
[34]	0.5um	85 – 110	NA	5-40	Yes	3.3	92.4	0.81
[32]	0.5um	70	0.2	350	No	2.5	120	0.96
[33]	0.5um	100	NA	20-50	Yes	NA	NA	NA
[35]	0.6um	(5.2 - 5.8) KHz	0.152	20-30	Yes	3.0	0.54	1.07
[37]	0.6um	3	1	NA	NA	2.5	1	NA

The Gm-C filters have the privilege that it can operate at very small voltages by means of transconductance tuning [22, 35]. Despite of operating the MOS devices in the weak inversion, the Gm stage is able to support filter applications in the range of KHz upto few MHz. This type of filter usually have a linearly current-controlled transconductance as well as tuning frequency characteristics [22]. One of the best transconductance control methodology is based on the master-slave technique using the control circuit [22]. In order to achieve both, low-voltage operation and transconductance tuning, the bulk terminals of the transistors are generally not connected to constant voltages as in conventional circuit topologies, but they are used to adjust their bias. Biquad topology as well as low power transconductor architectures can also be adopted to obtain desired tuning at very low voltages [35, 37]. Triode-biased input MOSFETs whose transconductance is widely tuned with drain bias is adopted, it can ensure wide frequency tuning of the filter [42]. Besides in these filters, the Q factor can be boosted up with negative-Gm cells in parallel at the output [32].

As we can see from Table 1, GM-C band pass filters are made to operate in between 5 KHz to 110 MHz, which is quite low in comparison to spiral and active inductor based band pass filters. Therefore, extensive research on GM-C based filters is needed so that it can operate at gigahertz frequencies. Although the filters are operated at low supply voltages but the amount of power consumption in filters are relatively high. An adaptive DC-blocking circuit to suppress the idle current can result in minimizing the power consumption of the transconductor [42]. Most of the architectures have the provision for tuning the central frequency and achieving high quality factor.

5. CONCLUSION

Tank circuit is the heart of every filter. In order to overcome the limitations of on-chip passive inductors, Gm-C transcondutance is one of the best alternatives for CMOS technology specially in MHz frequencies when low power operation is one of the primary goal. A detailed review on advancement of Gm-C configuration for band-pass filter applications is presented in this paper with necessary schematic diagrams and performance analyses. We expect that the circuit-design methods and the associated discussions presented in this paper will help the scientists designing RF front-end circuits and will lead to realization of low-cost, small-size wireless communication terminals for various industrial and home appliances.

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

REFRENCES:

[1] F. M. Yasin, M. K. Khaw and M. B. I. Reaz, "Radio frequency identification: Evolution of transponder circuit design," *Microwave Journal*, vol. 49, pp. 56-70, 2006.

[2] S. S. B. M. Sallah, H. Mohamed, M. Mamun, and M. S. Amin, "Cmos Downsizing: Present, Past And Future," *Journal of Applied Sciences Research*, vol. 8, pp. 4138-4146, 2012.

[3] W. M. Kader, H. Rashid, M. Mamun, and M. A. S. Bhuiyan, "Advancement of CMOS Schmitt Trigger Circuits," *Modern Applied Science*, vol. 6, pp. 51-56, 2012.

[4] K. A. Rosli, M. Mamun, M. A. S. Bhuiyan, and H. Husain, "A Low Loss Wide Swing Cascode Current Mirror in 0.18-µm CMOS Technology," *Journal of Applied Sciences Research*, vol. 8, pp. 4096-4102, 2012.

[5] M. J. Uddin, A. N. Nordin, M. Reaz, and M. A. S. Bhuiyan, "A CMOS power splitter for 2, 45 GHz ISM band RFID reader in 0, 18 µm CMOS technology," *Tehnički vjesnik*, vol. 20, pp. 125-129, 2013.

[6] N. B. Romli, M. Mamun, M. A. S. Bhuiyan, and H. Husain, "Design of a Low Power Dissipation and Low Input Voltage Range Level Shifter in Cedec 0.18-µm Cmos Process," *World Applied Sciences Journal*, vol. 19, pp. 1140-1148, 2012.

[7] M. B. I. Reaz, M. Islam, M. Sulaiman, M. Ali, H. Sarwar, and S. Rafique, "FPGA realization of multipurpose FIR filter," *Proceeding of 4th International Conference on Parallel and Distributed Computing, Applications and Technologies- 2003*, 2003, pp. 912-915.

[8] F. M. Yasin, M. K. Khaw, and M. B. I. Reaz, "Techniques of RFID systems: Architectures and applications," *Microwave Journal*, vol. 49, pp. 62-74, 2006.

[9] L. F. Rahman, M. B. I. Reaz, M. A. Mohd. Ali, and M. Kamada, "Design of an EEPROM in RFID tag: Employing mapped EPC and IPv6 address," *Proceeding of IEEE Asia Pacific Conference on Circuits and Systems*, 2010, pp. 168-171.

[10] F. I. B. A. Aziz, M. Mamun, M. A. S. Bhuiyan, and A. A. A. Bakar, "A Low Drop-Out Voltage Regulator in 0.18 µm CMOS Technology," *Modern Applied Science*, vol. 7, p. p70, 2013.

[11] F. B. Arith, M. Mamun, M. A. S. Bhuiyan, and A. A. A. Bakar, "Low Voltage Schmitt Trigger In 0.18 µm CMOS Technology," *Advances in Natural and Applied Sciences*, vol. 7, pp. 33-38, 2013.

[12] J. Uddin, M. B. I. Reaz, M. A. Hasan, A. N. Nordin, M. I. Ibrahimy, and M. A. M. Ali, "UHF RFID antenna architectures and applications," *Scientific Research and Essays*, vol. 5, pp. 1033-1051, 2010.

[13] K. A. Rosli, R. M. N. H. R. Daud, M. Mamun, and M. A. S. Bhuiyan, "A Comparative Study on SOI MOSFETs for Low Power Applications," *Research Journal of Applied Sciences, Engineering and Technology*, vol. 5, pp. 2586-2591, 2013..

[14] J. Jalil, M. Bin Ibne Reaz, and M. A. M. Ali, "CMOS Differential Ring Oscillators: Review of the Performance of CMOS ROs in Communication Systems," *IEEE Microwave Magazine*, vol. 14, pp. 97-109, 2013.

[15] M. A. B. T. Arifin, M. Mamun, M. A. S. Bhuiyan, and H. Husain, "Design of A Low Power and Wide Band True Single-Phase Clock Frequency Divider," *Australian Journal of Basic and Applied Sciences*, vol. 6, pp. 73-79, 2012.

[16] D. K. Shaeffer and T. H. Lee, "A 1.5-V, 1.5-GHz CMOS low noise amplifier," *IEEE Journal of Solid-State Circuits*, vol. 32, pp. 745-759, 1997.

[17] H. Aljarajreh, M. Reaz, M. Amin, and H. Husain, "An Active Inductor Based Low Noise Amplifier for RF Receiver," *Electronics and Electrical Engineering*, vol. 19, pp. 49-52, 2013.

[18] W. Yixiao, Y. Le, L. Huailin, and H. Ru, "Cost-efficient CMOS RF tunable bandpass filter with active inductor-less biquads," *Proceeding of IEEE International Symposium on Circuits and Systems*, 2012, pp. 2139-2142.

[19] Y. Wang, L. Ye, H. Liao, and R. Huang, "Cost-efficient CMOS RF tunable bandpass filter with active inductor-less biquads," *Proceeding of IEEE International Symposium on Circuits and Systems*, 2012, pp. 2139-2142.

[20] H. Aljarajreh, M. Rozi Rifin, M. Mamun, S. Amin, and W. M. D. W. Zaki, "Low Noise Amplifiers in RFID Systems," *Journal of Engineering and Applied Sciences*, vol. 8, pp. 21-28, 2013.

[21] C. Garcia-Alberdi, A. J. Lopez-Martin, L. Acosta, R. G. Carvajal, and J. Ramirez-Angulo, "Tunable Class AB CMOS Gm-C Filter Based on Quasi-Floating Gate Techniques," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 60, 2013, pp. 1300-1309.

[22] R. Arya, G. Souliotis, S. Vlassis, and C. Psychalinos, "A 0.5 V 3 rd-order Tunable gm-

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

C Filter," *Radioengineering*, vol. 22, pp. 175, 2013.

[23] H. Elhallabi, Y. Fouzar, and M. Sawan, "High frequency cmos gm-c bandpass filter with automatic on-chip tuning," *Proceeding of 8th IEEE International Conference on Electronics, Circuits and Systems*, 2001, pp. 823-826.

[24] A. Assi and M. Sawan, "High performance CMOS transconductor for mixed-signal analog-digital applications," *Analog Integrated Circuits and Signal Processing*, vol. 19, pp. 303-317, 1999.

[25] S. Szczepanski, R. Schaumann, and B. Pankiewicz, "A CMOS transconductance element with improved DC gain and wide bandwidth for VHF applications," *Analog Integrated Circuits and Signal Processing*, vol. 10, pp. 143-156, 1996.

[26] S. Koziel, S. Szczepanski, and R. Schaumann, "A general approach to continuous-time Gm-C filters," *International Journal of Circuit Theory and Applications*, vol. 31, pp. 361-383, 2003.

[27] E. Lauwers and G. Gielen, "Systematic design of high-frequency gm-C filters," in Analog Circuit Design, M. Steyaert, A. Roermund, and J. Huijsing, Eds., ed: Springer US, 2002, pp. 21-45.

[28] M. O. Shaker, S. A. Mahmoud, and A. M. Soliman, "High-Order Gm-C Filters with Current Transfer Function Based on Multiple Loop Feedback," *Proceeding of IEEE International Conference on Signal Processing and Communications*, 2007, pp. 85-88.

[29] L. Haidong, P. Xiaohong, and W. Wuchen, "Design of a Gm-C low pass filter with low cutoff frequency," *Proceeding of Asia Pacific Conference on Postgraduate Research in Microelectronics & Electronics*, 2009, pp. 125-128.

[30] R. Weng and R. Kuo, "An ω 0-Q Tunable CMOS Active Inductor for RF Bandpass Filters," *Proceeding of International Symposium on Signals, Systems and Electronics*, 2007, pp. 571-574.

[31] H. Le-Thai, H.-H. Nguyen, H.-N. Nguyen, H.-S. Cho, J.-S. Lee, and S.-G. Lee, "An IF bandpass filter based on a low distortion transconductor," *IEEE Journal of Solid-State Circuits*, vol. 45, pp. 2250-2261, 2010.

[32] Y. Choi and H. C. Luong, "A high-Q and wide-dynamic-range 70 MHz CMOS bandpass filter for wireless receivers," *IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing*, vol. 48, pp. 433-440, 2001.

[33] H. Liu and A. I. Karsilayan, "A high frequency bandpass continuous-time filter with automatic frequency and Q-factor tuning," *Proceeding of IEEE International Symposium on Circuits and Systems*, 2001, pp. 328-331.

[34] P. Kallam, E. Sánchez-Sinencio, and A. I. Karsilayan, "An enhanced adaptive Q-tuning scheme for a 100-MHz fully symmetric OTA-based bandpass filter," *IEEE Journal of Solid-State Circuits*, vol. 38, pp. 585-593, 2003.

[35] E. Raisanen-Ruotsalainen, K. Lasanen, M. Sijander, and J. Kostamovaara, "A low-power 5.4 kHz CMOS gm-C bandpass filter with on-chip center frequency tuning," *Proceeding of IEEE International Symposium on Circuits and Systems*, 2002, pp. IV-651-IV-654 vol. 4.

[36] M. M. Reja, K. Moez, and I. Filanovsky, "A wide frequency range CMOS active inductor for UWB bandpass filters," *Proceeding of 52nd IEEE International Midwest Symposium on Circuits and Systems*, 2009, pp. 1055-1058.

[37] A. Hassan, K. Sharaf, H. El-Ghitani, and H. Ragaie, "A new low power transconductor for Gm-C filters," *Proceeding of IEEE International Symposium on Circuits and Systems*, 2002, pp. IV-249-IV-252 vol. 4.

[38] E. Lebel, A. Assi, and M. Sawan, "Field programmable Gm-C array for wide frequency range bandpass filter applications," *Proceding of IEEE International Symposium on Circuits and Systems*, 2005, pp. 1952-1955.

[39] C. Y. Wu and C. Y. Chou, "The design of a CMOS IF bandpass amplifier with low sensitivity to process and temperature variations," *Proceeding of IEEE International Symposium on Circuits and Systems*, 2001, pp. 121-124.

[40] J. Silva-Martinez, M. S. Steyaert, and W. Sansen, "A 10.7-MHz 68-dB SNR CMOS continuous-time filter with on-chip automatic tuning," *IEEE Journal of Solid-State Circuits*, vol. 27, pp. 1843-1853, 1992.

[41] H. Barthelemy, S. Meillere, J. Gaubert, N. Dehaese, and S. Bourdel, "OTA based on CMOS inverters and application in the design of tunable bandpass filter," *Analog Integrated Circuits and Signal Processing*, vol. 57, pp. 169-178, 2008.

[42] S. Hori, M. Tadashi, M. Noriaki, and Y. Nobuhide, "Low-power widely tunable Gm-C filter with an adaptive DC-blocking, triode-biased MOSFET transconductor," *Proceeing of 30th European Solid-State Circuits Conference*, 2004, pp. 99-102.