A Wide Tuning Range 4 th-Order Gm-C Elliptic Filter for Wideband Multi-standards GNSS Receivers

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***Abstract*—A 4 th order Gm-C elliptic low-pass filter with a wide continuous tuning range is presented. The continuous tuning is achieved by means of a new tuning circuit which adjusts the bias current of the Gm cell's input stage to control the cut-off frequency. With this tuning circuit, power efficiency is achieved by scaling down the power consumption proportionally to the cut-off frequency while keeping the linearity near constant over a wide range of frequencies. To extend the tuning range of the filter, Gm switching was employed which also acts on the Gm cell's input stage without adding any switches in the signal path. The filter was fabricated using UMC 180-nm CMOS technology on an active area of 0.23 mm^2. Its cut-off frequency ranges continuously from 7.4 to 27.4 MHz. This wide range of possible tuning makes the filter suitable for modern wideband GNSS signals in zero-IF receivers. The filter consumes 2.1 and 7.5 mA (from 1.8 V) at its lowest and highest cut-off frequencies, respectively, and achieves a high input IP3 of up to -1.3 dBV$_{\mathrm{RMS}}$.**

I. INTRODUCTION

Mobile wireless communication systems, such as global navigation satellite system (GNSS), Wi-Fi and LTE-cellular, are adopting signals with tens of MHz of bandwidth in order to improve their performances [1], [2]. On the other hand, mobility also demands for longer battery life and multi-standard compatibility to deal with different service coverages. All these requirements are nowadays achievable thanks to software defined radios which rely on flexible hardware architectures, such as direct-conversion radio frequency front-end, as well as on low-power technologies such as complementary metal-oxide-semiconductor (CMOS). Continuous time active low-pass filters in CMOS technology are a key building block in direct-conversion integrated circuit (IC) front-ends. In a design re-use approach, a reconfigurable continuous time low-pass filter that can satisfy requirements of the different standards is necessary. Moreover, the coexistence of many systems (ex. GNSS, Wi-Fi and LTE), on the same mobile equipment is very common nowadays and therefore interferences rejection requirements are becoming more and more stringent. This is directly reflected in the low-pass filter's requirements in terms of selectivity and linearity.

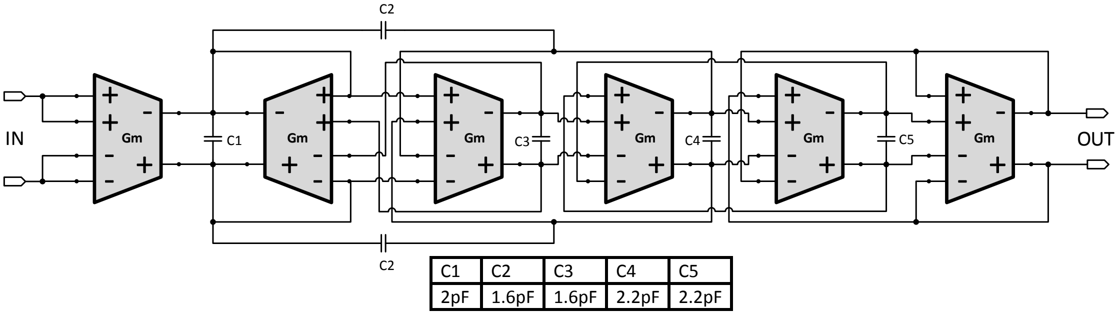
In the particular case of GNSS applications the elliptic configuration for the low-pass filter is of interest because of their better selectivity and steeper roll-off transition as compared to the same order filters of the other configurations. The abrupt roll-off transition strongly mitigates out of band interferers while allowing sampling frequencies to be slightly above the Nyquist limit. This enables lower clock frequencies for analog to digital converters which means lower power consumption without suffering from aliasing noise.

This paper presents a 4 th order Gm-C elliptic low-pass filter in CMOS technology for modern GNSS receivers IC front-ends. It employs a new Gm control circuit to improve the usual weak linearity of the Gm-C filters over tuning its cut-off frequency. As aiming the multi-standard receivers, the filter also incorporates Gm switching to achieve a wide continuous tuning range of 7.4-27.4 MHz. The large continuous tuning range can cover the bandwidth of all new GNSS signals (such as Galileo-E5) in zero-intermediate frequency (IF) or low-IF receivers.

II. FILTER DESIGN

The filter topology of Fig. 1 is derived from the LC-ladder network which is known to be less sensitive to component mismatches as compared to bi-quadratic topologies. A Gm-C implementation has been chosen owing to the fact that it is more power efficient in contrast to active-RC filters and has great potential of working at high frequencies since the gain-bandwidth product (GBW) of the Gm cell only needs to be slightly higher than the cut-off frequency of the filter. Moreover, Gm-C implementation enables the continuous tuning of the filter's cut-off frequency over a wide range of frequencies by tuning the transconductance of the Gm cell.

The presented low-pass filter in Fig. 1 is designed to approximate a 4 th order elliptic transfer function. It only consists of the capacitors and identical operational transconductance amplifiers (OTAs)-also know as Gm cells. Generally, tuning of the Gm-C filters can be done by switching the capacitors or tuning the transconductance (g_m) of the Gm cells. Besides a discrete control, capacitor switching also suffers of the limitation that the minimum capacitance has to satisfy the noise requirements ($\propto 1/C$) at the highest tuning frequency. As a result the maximum capacitance may be too large. In addition, it requires switches in series with the capacitors or even sometimes floating switches which may introduce huge parasitic effects. In contrast, in Gm tuning –tuning the transconductance of the Gm cell– a constant value of capacitance is used which leads to an optimal balance of noise, chip area and frequency response accuracy. However, tuning the Gm cell outside its intrinsic range degrades linearity as well as accuracy of the filter responses. Indeed, on one hand, pushing the bias of the Gm cell to a low current level not only reduces Gm but also lowers the second pole of the Gm cell and reduces its linearity. On the other hand, over a certain level of current Gm shows a kind of saturation. The intrinsic range lies in-between these two cases. Hence, to further extend the tuning range of the filter, Gm switching can be employed. This can be implemented by connecting in parallel small OTAs



C1	C2	C3	C4	C5
2pF	1.6pF	1.6pF	2.2pF	2.2pF

Fig. 1. Block diagram of the 4 th order elliptic Gm-C low-pass filter with dual input OTAs (Gm cells); Gm cells are identical and capacitors' value are shown in the table.

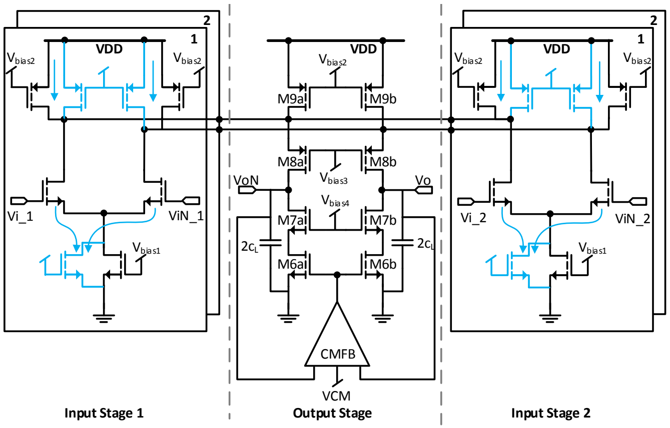
and switching on or off only their biasing so that no switches' parasitic is added in the signal path.

The proposed filter tuning scheme exploits the two aforementioned methods of tuning to implement fine and coarse tuning. The fine tuning is achieved by controlling the transconductance of the Gm cell, and results in a continuous tuning of the filter's cut-off frequency. The coarse tuning is achieved by Gm switching and results in extending the tuning range.

Generally, Gm-C filters suffer from the weak linearity performance due to their open-loop nature. Therefore, the topological linearity improvement method proposed in [3] is employed to improve the linearity performances of the filter. The use of this linearity improvement method is possible thanks to the symmetrical structure of the filter in Fig. 1. Moreover, the proposed tuning circuit is designed to improve the linearity by keeping the input differential pair's overdrive above the minimum which is needed for the required linearity.

III. OTA Design and tuning

The Gm cell (OTA) is the main building block of the presented elliptic filter in Fig. 1, therefore the OTA's specifications define the main performances of the filter. Elliptic filters can provide the best selectivity and rapid roll-off as compared to the same order filters of the other types and their selectivity is directly dependent to the quality factor (Q) of the filter's poles. To achieve high Q poles in the filter, the OTA should have high gain alongside with much larger internal poles than its GBW. The folded cascode has been chosen as the core structure of the OTA mainly because it places its internal poles much higher than the internal poles of the other OTA's topologies without any compensation, which is crucial to keep the Q of the filter's poles constant over tuning the transconductance of the OTA [4]. Moreover, the folded cascode topology allows to have more than one input stage for the OTA. Fig. 2 shows the schematic of the OTA. It is composed of dual input stages, an output stage and a common-mode feedback (CMFB) amplifier. The use of dual input OTA allows the reuse of some parts of the circuit: output stage, bias circuit and CMFB amplifier for another OTA. It helps to reduce the overall power consumption of the OTAs and thus of the filter. To achieve a high gain in the OTA two cascade transistors are employed in the output stage of the OTA. Moreover, to avoid the problems that the internal pole of the OTA can cause on the Q of the filter over its tuning, transistor M8 and M9 have been designed with a short length to reduce their parasitic capacitance and push the internal pole far away from GBW of the OTA. A CMFB amplifier sets the output common-mode (CM) voltage to 900 mV (half of the VDD) and ensures the CM stability of the filter. The bias current of the output stage ($\sim 115\mu A$) is constant over tuning of the OTA's transconductance and it is determined by the load driving requirement for the maximum speed.



	M6	M7	M8	M9
W(µm)	8	4	20	14.4
L(µm)	1	0.5	0.25	0.3

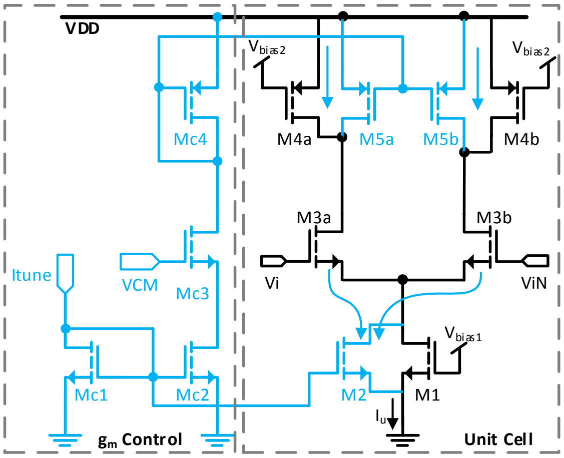
Fig. 2. Schematic of the dual input OTA (Gm cell in Fig. 1); Mxa and Mxb have the same size as it is shown in the table.

A. Fine Tuning

The input stage of the OTA with the proposed g_m control circuit is shown in Fig. 3. The transconductance (g_m) of the OTA is set by the transconductance of the input differential pair (M3). The biasing of M3 consists of a fixed part provided by M1 and M4 and a variable part which is implemented by changing the bias current in M2 and M5. The latter are biased by means of two current mirrors (Mc2 and Mc4) to make sure that the current in the tail and load change together in respect to Itune while Mc3 is used to render the control circuit as a scaled branch of the input differential pair. The simulated minimum ($g_{m,min}$) and maximum transconductance ($g_{m,max}$) of the OTA are 75 μS and 169 μS, respectively. It means that the continuous g_m tuning ratio ($g_{m,max}/g_{m,min}$) is 2.25 which leads to the same tuning ratio of the filter's cut-off frequency only based on the fine tuning scheme.

B. Coarse Tuning

Tuning the Gm cell beyond its intrinsic transconductance by regulating its bias current degrades the linearity as well as accuracy of the filter responses. Therefore, to further extend the



	MC1	MC2	MC3	MC4	M1	M2	M3	M4	M5
W(µm)	4	4	6	12	2	22.4	3	3	30
L(µm)	3	3	0.5	1	3	3	1	0.3	0.5

Fig. 3. Fine tuning scheme of the transconductance; g_m control circuit is shown in blue; Mxa and Mxb have the same size as it is shown in the table.

tuning range, other means of tuning is required. Considering the differential pair in Fig. 3 as a unit cell of the input stage, to extend the tuning range of the OTA, thanks to its folded cascode topology, more than one unit cell can be used in parallel of each other. However, increasing the number of parallel unit cells increases the parasitic capacitance at the node of M8 and M9 (see Fig. 2) and reduces the internal pole of the Gm cell which in turn degrades the filter's Q over its tuning. This is why in our implementation, only two unit cells are employed at each input of the OTA, as it is shown in Fig. 2 where one unit cell is drawn in a sheet and the parallel one is represented with an overlapping sheet. Both unit cells are always connected but the second one will be biased to duplicate the overall g_m of the OTA when necessary. Since $g_{m,max}/g_{m,min}$ ratio of the fine tuning scheme is higher than 2, the coarse tuning scheme does not cause any discontinuity in the overall tuning range of the transconductance.

To summarize, tuning the g_m continuously tunes the cut-off frequency of the filter. The coarse tuning divides the tuning range of the filter's cut-off frequency to lower-band (LB) and higher-band (HB) of frequencies; when only one unit cell is biased in each input stage of the Gm cell the fine tuning scheme can tune continuously the cut-off frequency in LB and when the second unit cell is also biased the fine tuning scheme tunes the cut-off frequency in HB.

C. Linearity Improvement

To enhance the linearity of the filter, two methods are employed. One method is the topological linearity improvement proposed in [3]. By this method, each unit cell is driven with two in-phase signals rather than a differential signals, therefore, differential signal swing is significantly reduced. This does not alter the overall filter response due to the symmetry of the Gm cell as well as the filter's topology. The reduced differential swing at the input of the Gm cell results in the better linearity performance of the filter without increasing the power consumption.

The other method which is original to the best of our knowledge, is the fine tuning scheme with the proposed g_m control circuit. The linearity depends on the overdrive voltage of the OTA's differential input (M3). The minimum M3's overdrive happens at the $g_{m,min}$ which should satisfy the linearity requirements of the filter. Increasing the cut-off frequency increases the M3's bias current which in turn increases the overdrive of the M3 and therefore improves the linearity performance of the filter.

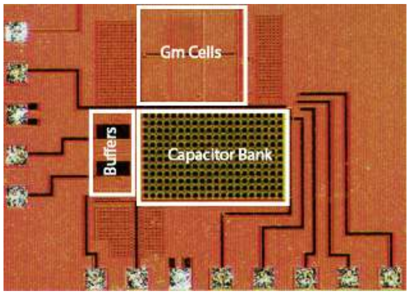


Fig. 4. Micro photograph of the chip.

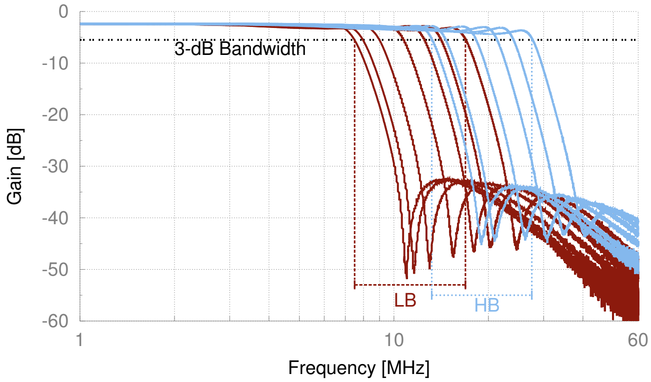


Fig. 5. Measured frequency response of the 4 th order elliptic low-pass filter with tunable cut-off frequency of 7.4-27.4 MHz; LB tuning range (red) is 7.4–16.8 MHz and HB tuning range (blue) is 13.2–27.4 MHz.

IV. MEASUREMENT RESULTS

The 4 th order elliptic low-pass filter was fabricated using UMC 180-nm CMOS technology. Fig. 4 shows the micro photograph of the filter with an active area of 0.23 mm^2. Two linear low noise off-chip buffers (AD8351) were used to make single-ended to differential conversion and vice versa to facilitate the measurement process, and their effects were de-embedded from the measurement results. Moreover, to isolate the filter from the parasitic capacitance of the off-chip output buffer, two on-chip buffers were also used which have a negligible effect on the filter response. Fig. 5 shows the frequency response of the filter. As it is shown in the figure, the cut-off frequency tuning range from 7.4 to 16.8 MHz (LB) is obtained only by fine tuning when the Gm cell has one unit cell biased in its input stage, whereas the tuning range from 13.2 to 27.4 MHz (HB) is achieved when the second unit cell of the Gm input stage is also biased. The overlap between LB and HB yields a continuous tuning range of the filter's cut-off frequency from 7.4 to 27.4 MHz.

The measured in-band ripple of the filter's responses is less than 2 dB and stop-band attenuation is more than 33 dB over the entire tuning range while the notch attenuation in the transition-band is higher than 45 dB at 1.45 of the cut-off

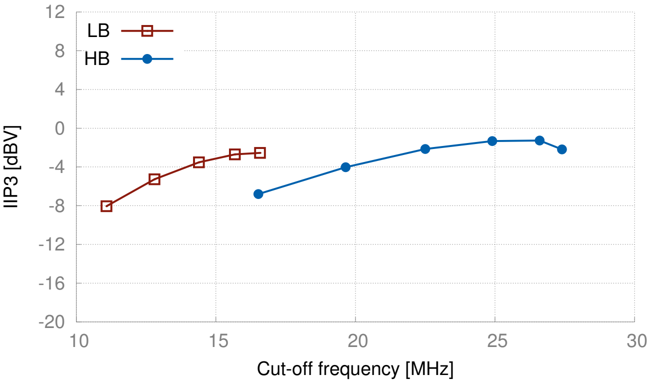


Fig. 6. Measured IIP3 for two tone at 5 and 6 MHz versus the cut-off frequency of the filter between 11 and 27.4 MHz. LB and HB are the cases when the Gm cell uses one and two unit cells at its input, respectively.

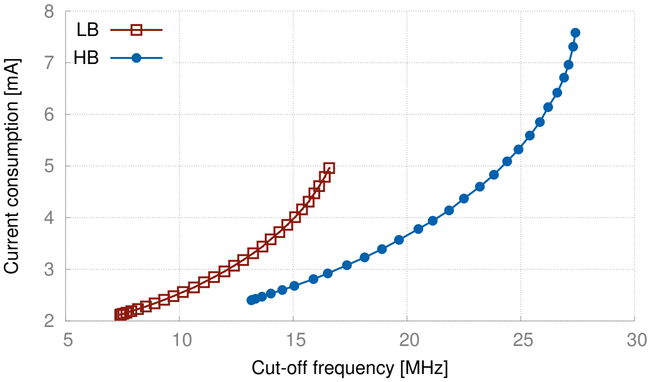


Fig. 7. Measured dependence of the current consumption on the cut-off frequency of the filter for both LB and HB band of tuning.

frequency. This very steep roll-off response of the filter allows sampling a signal with a sampling frequency slightly above the cut-off frequency of the filter.

The in-band linearity performance of the filter is characterized by measuring the input referred third-order intercept point (IIP3) of the filter for the two frequency tones at 5 and 6 MHz. Fig. 6 shows the measured IIP3 of the filter over tuning its cut-off frequency. It shows that a high value IIP3 over -8 dBV_{RMS} (1.13 V_{p-p}) is achievable for cut-off frequencies between 11-27.4 MHz. The maximum measured IIP3 is -1.3 dBV_{RMS} (2.44 V_{p-p}) for cut-off frequency near 27 MHz, the linearity degrades slightly in return of tunability of the cut-off frequency but still above the required value.

The filter's current consumption and its dependency to the filter's cut-off frequency in both LB and HB frequency bands are shown in Fig. 7. The current consumption at the high-end of the HB frequency band (27.4 MHz) is 7.58 mA from a 1.8 V supply and it scales down logarithmic by reducing the band-width of the filter to 2.4 mA at the low-end (13.16 MHz) of the HB frequency band. In the LB frequency band (7.4–16.8 MHz), the filter shows the same logarithmic trend of reduction of power consumption by reducing its band-width and consumes between 2.12 and 5.3 mA. The reduction of the filter's power consumption with respect to its band-width makes the filter very power efficient with average normalized power consumption of 105 pW/pole/Hz.

Finally, the measured filter's performances are summarized in Table I and compared to the performances of the recently published CMOS filters [3], [5]–[7]. The values in Table I are reported for the highest cut-off frequency of their respective filters. The proposed filter achieved a high range of tuning as well as satisfactory results regarding noise and power consumption.

TABLE I. PERFORMANCE COMPARISON WITH STATE OF THE ARTS.

	This Work	[5] TCAS'14	[6] TCASI'11	[3] E-Lett.'11	[7] TCAS'10
Filter Type	Elli[1]	Butter[2]	Elli[1]	Cheby[3]	Cheby[3]
Technology [nm]	180	180	180	130	500
Area [mm^2]	0.23	0.125	0.25	0.12	1.5
Order	4	4	3	5	3
Supply [V]	1.8	1.8	1.8	1.5	5
Power [mW]	3.8-13.6	4.68	2.3	21	180
Bandwidth [MHz]	7.4-27.4	0.3-12	17	70-280	6-12
IIP3 [dBV_{RMS}]	-1.27	-4.3	15.2	7	20
Gain [dB]	-2.5	0	0	0	0
IMFDR [dB]	49	42.63	51.5	53.08	62.07
Input Noise [dBV]	-77.9[4]	-68.2	-62	-72.6	-73.1
FOM[5]	151.3	150.8	155	164.3	146.6

[1] Elliptic, [2] Butterworth, [3] Chebyshev, [4] Simulation, [5] Introduced in [8].

V. CONCLUSION

A 4 th order Gm-C elliptic low-pass filter with a continuous cut-off frequency tuning range of two octaves has been presented. The wide continuous tuning has been achieved by combining a new Gm tuning circuit with the Gm switching techniques to cover all the new wideband modernized GNSS signals. The filter uses constant capacitors, leading to an optimal balance of noise, chip area and frequency response accuracy. The measured filter's responses show a very steep roll-off which allows the signal to be sampled slightly above the cut-off frequency of the filter. Measurements show that IIP3 remains near constant over a wide tuning range thanks to the new g_m control circuit. The new tuning circuit scales down the current consumption with respect to the band-width of the filter which makes the filter very power efficient.

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