Third Order Band Pass Filter With Double-Gate MOSFET: A Simulation Perspective

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Abstract. It is an extended version of the mathematical analysis of the proposed 3rd order Band Pass Filter (BPF). This device design uses the Double-Gate (DG) MOSFET’s which provides a better performance and reliability of the band pass filter. This 3rd order BPF design improves the device performance characteristics, such as enhanced power efficiency and switching capabilities, due to the properties of DG MOSFET technology. Simulation analysis of the proposed filter model has been performed. The BPF model has been designed for lower and upper cut-off frequencies of 100 kHz and 1.7 MHz, respectively. The 3rd order BPF filter has been modeled to have Butterworth characteristics, thus having a maximally flat pass-band response.

1. Introduction
A system is required to pass signals that vary within the desired frequency range while rejecting all undesired frequency components of an electrical signal. Band-pass filters are frequency selective devices commonly used in applications such as wireless communication systems and audio amplifier circuits [1, 2]. The proposed system should have high performance and low power consumption features to support modern electronic devices while maintaining a compact device size. Considering the increasing demand for the downscaling of components to produce more compact analog electronic devices, a Band Pass Filter (BPF) using Double-Gate (DG) MOSFET has been proposed by Naidoo and Srivastava [3]. That circuit perspective has been extended to the simulation analysis in this present work. Traditional components such as operational amplifiers and single-gate MOSFETs have an increased power consumption and a larger electronic package size. The use of the DG MOSFET leads to a reduction in the filter circuit’s size, therefore reducing the overall weight of the circuit [4]. The performance and reliability of the filter also improved. Since the DG MOSFET has a comparatively smaller width and offers better gate control over the channel than single-gate MOSFET, DG MOSFET provides improved power efficiency and switching capabilities.

Sawigun et. al. [5] have analyzed the steps involved in designing a compact nano-power fourth-order band-pass filter. This filter has an adjustable centre frequency range of 125 Hz to 16 kHz and is operated from 0.5 V supply. The filter was cascaded with a second-order circuit network and fabricated in 0.18-μm CMOS technology. The band-pass filter design achieved a center frequency of 1 kHz, dynamic range of 55 dB, and 2 nW power consumption. Yang et. al. [6] have proposed a 14.4 nW fourth-order band-pass filter for biomedical applications. The pass-band of the designed filter was 523-1024 Hz. The filter achieved a power consumption of 14.4 nW and a dynamic range of 55 dB, this provides the best figure of merit in comparison to circuitry for similar applications at the time of this
work. D’Amico et al. [7, 8] have designed 3rd order 132 MHz low-pass filter at a 28-nm CMOS technology, which uses an op-amp two-stage topology, which operates from a 0.9 V supply voltage while consuming 340 µW and performs high linearity (IIP3 = 11.5 dBm at 21 and 22 MHz input tones) and large Signal-to-Noise ratio (58 dB).

Bao et al. [9] have designed a 3rd order inductor-free memristive chaotic circuit, which was derived from a 2nd order active BPF by replacing a resistor with an improved memristor and it consists of three op-amps, two multipliers, three capacitors, and six resistors. Ahmadi et al. [10] have designed a wide-bandwidth 2nd order voltage-mode all-pass filter derived from a single transistor BPF, and it has one transistor, two resistors, and two energy storage elements. This was implemented in 0.13-µm CMOS technology to have 55 ps group delay across 6 GHz bandwidth while consuming 18.5 mW from a 1.5 V supply. Yesil and Minaei [11] have presented two MOSFET only 2nd order voltage and transadmittance-mode BPF utilizing five transistors without any passive elements. As a result, both circuits possess low-power consumption and occupy a small chip area. In this present design, the authors used a four double-gate transistor with a 12 V power supply and function generator.

Modern devices require more components to be integrated on a single chip (VLSI, ULSI, etc.) to meet the low power and high-performance requirements. Single-Gate (SG) MOSFETs have a large physical size, leading to issues like an increased cost due to the large system construction. Issues such as short channel effects and increased leakage current need to be considered as they limit the device's performance [12-14]. The MOS devices used in the electronic development industry needs to offer an improvement in their performance and performance characteristics to counter the issues experienced due to the short channel effects, this leads to the use of DG MOSFETs. The scaling of MOSFETs offers advantages such as smaller device dimensions and improved performance. The DG MOSFET provides an improvement in the device scaling due to its 25 nm gate lengths compared to the 65 nm characteristic of MOSFET devices [4, 13, 15].

Here the 3rd order BPF has been realized by cascading a first-order high pass filter stage with a second-order low pass filter stage. The third order band-pass filter was initially designed using operational amplifiers. The mathematical analysis of the designed filter was performed to determine the filter's overall transfer function in ref. [3]. The transfer function of the individual filter stages was derived to calculate the desired cut-off frequencies' component values. The band-pass filter was designed using a differential structure to implement the DG MOSFET technology, the operational amplifiers were replaced with the BF998 IC to achieve this circuit [16-18]. The parameters of the designed filter were compared to existing filters to determine its feasibility. The proposed model offers improved device performance characteristics, such as enhanced power efficiency and switching capabilities, due to the DG MOSFET technology. The system has been designed for a broader range of RF applications, it can be utilized for applications in the Low Frequency (LF) and Medium Frequency (MF) range due to its larger pass-band [19-21]. The use of the DG MOSFET allows the system to maintain a small-scale design construction due to the reduction in the circuit's size and overall weight.

The work presented in the paper has been organized as follows: Section 3 describes the system design for the model. Section 3 has the simulation analysis and its discussion. Section 4 has its further extension as hardware implementation. Finally, Section 5 concludes the work and recommends the future aspect of the work.

## 2. System Description

The active components which can be used in filter designs include operational amplifiers (LM353) and SG MOSFETs (2N7000 N-Channel enhancement mode). However, some of these components have large power requirements and insufficient performance capabilities due to modern electronic devices' demands. Therefore, DG MOSFETs are suitable replacements since they improve the device's performance characteristics while having a small-scale design construction. The process to design the 3rd order BPF with DG MOSFET is shown in figure 1. It has been designed using a cascaded high pass filter stage and low pass filter stage. A first-order high pass filter stage will be connected in series with a second-order low pass filter stage to realize the third-order band-pass filter. The band-pass filter will
Figure 1. The design process for the third-order band-pass filter with Double Gate (DG) MOSFET.

The first stage filter will only pass frequencies above 100 kHz while attenuating any low-frequency signals. The second stage filter will allow frequencies below 1.7 MHz to pass while attenuating any high-frequency signals. The first stage of the filter requires the input signal from the function generator. The second stage will be cascaded with the first stage to realize the third-order band-pass filter. The filtered output can then be seen on the oscilloscope. The cascaded band-pass filter will only allow frequencies in the pass-band range of 100 kHz - 1.7 MHz to pass. Any other frequency signals will be attenuated, these signals will be significantly attenuated the further away they are from the pass-band.

Figure 2. High-level design block diagram.

The pass-band ripple is the amount of variation in the amplitude within the designated pass-band of the band-pass filter [1, 2]. The filter was modeled to have a Butterworth filter response. The filter model’s magnitude response will be analyzed to verify if it has a maximally flat pass-band response. Figure 3 shows the low-level design block diagram for the 3rd order BPF with DG MOSFET. Both of the filter stages will be powered by a 12 V power supply. The function generator will supply the input signal to the high pass filter stage. The second stage will be cascaded with the first stage to realize the third order band-pass filter. Figure 4 show the basic structures of double-gate MOSFET. This device consists of four terminals, this includes the source, drain, and two gate terminals. The key improvement of the DG MOSFET over the single gate MOSFET is that this device has a very small Si channel width, and the two gate terminals provide the user with two platforms to control the device.
3. Simulation Analysis and Its Discussion

The small-signal model for the first-order high-pass filter section and second-order low-pass filter section, respectively, are shown in figure 5. Ref. [18] has been used as a guide to formulate the small-signal models for the 3rd order BPF. In the small-signal models, transistors Q1 and Q2 represent the first-order high-pass filter section, and transistors Q3 and Q4 represent the second-order low-pass filter section. Kirchhoff’s voltage law was used to derive the voltage gain equations for these models, the capacitors were short-circuited.
The proposed solution, which is to utilize the BF998 Silicon N-channel dual-gate MOSFET, is shown in figure 6. This MOSFET leads to a reduction in the filter circuit's size, and therefore reduces the overall weight of the circuit. The band-pass filter’s performance and reliability will also be improved if the BF998 is used instead of SG MOSFET. The system will be suitable for high-frequency RF applications since utilizing a DG device reduces the input capacitance. The gate to channel coupling is doubled in the BF998 MOSFET, which is an improvement on the short channel effects experienced by SG MOSFETs. The BF998 MOSFET can be utilized for applications in the VHF and UHF band, including television tuners and professional communications equipment [22]. This BF909 MOSFET has been used as an alternative for simulation purposes [23].

![Figure 6. Circuit diagram of implemented the band-pass filter.](image)

In ref. [3], figure 7 shows the frequency response generated for the 3rd order BPF. It correlates closely with the theoretical frequency response of the BPF. The magnitude response was determined to be a combination of the first order high pass and second-order low pass magnitude responses in that work. Here, in this work, figure 7(a) shows the magnitude response, indicating the cut-off frequencies and bandwidth that the system achieved. The lower and upper cut-off frequencies are indicated using cursors 1 and 2, respectively. The cursor menu shows the cut-off frequency and -3 dB frequency point in variables $x_1$ and $y_1$ for the lower cut-off frequency and $x_2$ and $y_2$ for the lower cut-off frequency. The bandwidth of the band-pass filter is the difference between the upper and lower cut-off frequencies. Therefore, the dx variable in the cursor menu can analyze the difference between the cut-off frequencies $x_1$ and $x_2$. The bandwidth was found to be 1.65 MHz, which correlates closely to the value from the ref’s mathematical analysis [3].
Figure 7. (a) Cut-off frequencies and bandwidth, and (b) Centre frequency of proposed 3rd order BPF with DG MOSFET.

The magnitude response, as shown in figure 7(b), indicates the center frequency of approximately 416 kHz for the filter. The center frequency value from the mathematical analysis performed in ref. [3] was 412 kHz, which correlates closely to the center frequency of the filter’s magnitude response. Figure 8 shows the bode plot response of the band-pass filter with DG MOSFET. The bode plot was used to analyze the pass-band ripple. The pass-band ripple was found to be approximately 0.2 dB, thus the filter demonstrates ideal Butterworth characteristics.

Figure 8. Pass-band ripple of BPF filter with DG MOSFET.

The comparison of band-pass filter implementations for the different technologies has been detailed in Table I. The existing works as described in ref. [24] and ref. [25] have been designed for Very Low Frequency (VLF) applications, these works offer a limited filter pass-band of 20-26 kHz and 10 kHz - 20 kHz, respectively. Both of these works have a 4th order filter response and were designed using operational amplifiers. The developed system can be utilized for a broader range of RF applications, namely the Low Frequency (LF) and Medium Frequency (MF) range due to its larger pass-band. The frequency band used for Amplitude Modulation (AM) radio is 550 kHz - 1720 kHz (0.55 MHz - 1.72 MHz). Therefore, the proposed filter model has the required bandwidth for this frequency band. This filter is also suitable for Low Frequency (LF) aviation band applications (200 kHz) and Medium Frequency (MF) aviation band applications (300 kHz - 30 MHz).
kHz to 415 kHz). The 3rd order BPF model improves device performance characteristics, such as enhanced power efficiency and switching capabilities, due to the DG MOSFET technology.

Table 1. Comparison of band-pass filter implementations for the different technologies

| Parameters          | [24] | [25] | This work |
|---------------------|------|------|-----------|
| Technology used     | CMOS | CMOS | DG MOSFET |
| Filter type         | Butterworth | Butterworth | Butterworth |
| Filter order        | 4    | 4    | 3         |
| Lower cut-off freq. | 20 kHz | 10 kHz | 100 kHz |
| Higher cut-off freq.| 26 kHz | 20 kHz | 1.7 MHz |
| Bandwidth           | 6 kHz | 10 kHz | 1.6 MHz |
| Quality factor      | 3.8  | 1.4142 | 0.258     |
| Pass-band Ripple    | 0.1 dB | 0.1 dB | 0.2 dB |

4. Further Extension as Hardware Implementation

The implemented BPF circuit on a breadboard is shown in figure 9. The BF998 MOSFETs were soldered onto adapters to use on a breadboard. The filter circuit requires the 12 V power supply module to power the system. The system also requires the function generator to supply the input signal and an oscilloscope to analyze the filtered output signal. The two filter stages would be tested individually to ensure they generate the required frequency response before cascading them.

The filter in the first stage will only pass above 100 kHz while attenuating any low-frequency signals. The second stage filter will allow frequencies below 1.7 MHz to pass while attenuating any high-frequency signals. The function generator will supply the input signal to the input capacitor of the high-pass filter stage. The second stage will be cascaded with the first stage to realize the third-order band-pass filter. The filtered output will then be able to be analyzed on the oscilloscope. The cascaded band-pass filter will only allow frequencies in the pass-band range of 100 kHz-1.7 MHz to pass. Any other frequency signals will be attenuated, these signals will be significantly attenuated the further away they are from the pass-band. The hardware circuit will be communicated in a future article.

Figure 9. Hardware circuit of the filter system.

5. Conclusions and Future Recommendations

The design of the DG MOSFET based 3rd order BPF has been presented using simulation analysis. The designed BPF achieves a pass-band range of 100 kHz to 1.7 MHz, which is suitable for RF applications. The 3rd order BPF model offers an improvement in the device performance
characteristics, such as enhanced power efficiency and switching capabilities, due to the DG MOSFET technology.

In the future, the hardware circuit will be fully tested using an oscilloscope to analyze the parameters of the 3rd order BPF. The measured results from the hardware circuit will then be compared to the simulation results to determine if the design was successfully implemented.

6. References

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