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# Design and simulation of high-swing fully differential telescopic Op-Amp

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**ABSTRACT**

This article describes the process of design and simulation of a high-swing fully differential telescopic Operational Amplifier (Op-Amp). Due to the Common Gate-Common Source (CG and CS) cascode structure, the gain is very high. To maximize this gain, the load must also be selected such as two current sources. This circuit has the higher voltage in output than current Op-Amps in accordance with desirable characteristics. The loss of power of this operating amplifier are very low and in milliwatts. With use of a power supply of 1.8 V, it achieves a high-swing 1.2 V, a differential gain of 76.333 dB, ω_uGB of 412 MHz, and > 50 dB CMRR. This new design through the simulations and analytically shows that the high-swing fully differential telescopic Op-Amp retains its high CMRR even at high frequencies.



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## 1. INTRODUCTION

The simplest Operational Amplifier (Op-Amp) is a high-gain differential amplifier. The amount of this gain in the range of $10^1$-$10^5$ is sufficient for Op-Amp applications. Op-Amp performance parameters are: open-loop gain, small signal bandwidth, large signal bandwidth, output swing, linearity, noise, offset and supply rejection [1], [2]. By designing an Op-Amp, these parameters are communicated with each other. Single cascode differential amplifiers with integrated components can hardly produce much gain. The bandwidth is determined by the load capacitance. To achieve the high gain, differential cascodes are used. These cascode connections lie between power supplies and load current sources. When the MOSFETs of each branch are aligned with each other, they create a telescopic-like structure. Therefore, this type of configuration is known as telescopic Op-Amp. The resulting circuit is symmetric with each of the output loads generated by the cascade current source. Their output swings are also limited due to the short-circuit problem of one of the inputs to the output in the applications such as source follower [3]. Another problem is power consumption. There are various designs that they have tried to reach high swing with low power consumption, but the power consumption value has not been reported [3]. In some papers, output swing is low or has not been reported too [4], [5]. The gain-boosted telescopic Op-amps can reach to high swing with low power consumption, but their design is classified into multiple design:

a. Folded cascode Op-amp [6].
b. The main Op-amp and the boosting Op-amp [7], [8].
c. The main Op-amp and the Multiplying Digital-to-Analog Converter (MDAC) architecture [9].
d. The main Op-amp and the Miller compensation [10].

So such a design implementation is very complicated. In this paper, author want to design a high-swing fully differential telescopic Op-Amp in 0.18 $\mu m$ CMOS technology. All simulations of this circuit are performed in HSPICE RF software. Other softwares such as Cadence can also be used in this regard [2].

Figure 1 shows the fully differential telescopic Op-Amp. The fully differential designs include the first and secondly switched current mirrors and the output which can be a circuit duo to boosting the gain and reaching the wide band [11]-[17], but this can cause the power consumption to increase. Biasing also can improve the gain with less dissipation, e.g. Wideband QFG dynamic biasing (QFG-DB) Op-amp, but it cannot to increase the output or input voltage [18]. Some applications such as Fully Differential Difference Transconductance Amplifier (FDDTA), require low output, so the high gain is not important in their design. Because they are utilized as a low pass filter [19]. The advantage of the fully differential design is that the differential mode signal path encompasses only the n-channel MOSFETs [20]. Only NMOS transistors conduct time-varying currents, and PMOS transistors transmit a constant current. This increases the Op-Amp speed, so the mobility of the n-channel MOSFET is greater than that of the p-channel MOSFET. In my design, we use the telescopic Op-Amp [8] of Figure 1. It is a combination of Common Gate-Common Source (CS-CG) that achieves higher gain due to double load of current source.

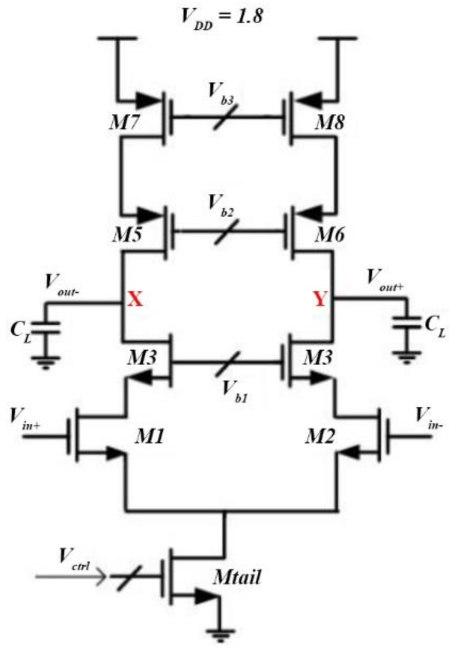



Figure 1. Telescopic cascode with NMOS inputs

Combination of CS-CG cascodes with components such as NMOS is for higher gain. Cascade load current sources with components such as PMOS are used to achieve greater drain resistance, which is used to combine CS-CG cascodes. The gain of the circuit in Figure 1 can be obtained by using half of the circuit as (1) [21].

$$A = g_{mN}[(g_{mN}r_{ON}^2) \parallel (g_{mP}r_{OP}^2)] \qquad (1)$$

Where $g_m$ is the cross-conductivity and $r_O$ is the drain resistors in the MOSFETs. So, the gain of the telescopic cascode Op-Amp increases. The output swing is as (2):

$$V_{cmo} = 2[V_{DD} - (V_{OD1} + V_{OD3} + V_{ODtail} + |V_{OD5}| + |V_{OD7}|] \qquad (2)$$

Where, the $V_{OD}$ is overdrive voltage of the MOSFETs, and $V_{ODtail}$ reduce through the Mtail MOSFET current source, $I_{total}$. The output voltage of this circuit is much less than that of a simple fully differential Op-Amp. So, in this paper, I want to design a new fully differential telescopic Op-amp with specifications as shown in Table1.

Table 1. The characteristic of high-swing fully differential telescopic OP-AMP circuit

| Parameter | Characteristic |
|---|---|
| Gain | > 60 dB |
| CMRR | > 50 dB |
| $\omega_{uGB}$ | > 2π × 400 MHz |
| Phase margin | > 60° |
| Slow Rate | > 200 V/μs |
| $V_{cmi}$ | = 1 V |
| $V_{cmo}$ | = 1.1 V |
| Output Swing | > 0.5 V |
| Power Consumption | > = 1.2 mW |
| Power supply ($V_{DD}$) | 1.8 V |

## 2. THE PROPOSED METHOD

According to the Table 1, author must also consider other features of the telescopic cascade and add to the MOSFETs including$\mu_n C_{ox} = 200\ \mu A/V^2$, $\mu_p C_{ox} = 80\ \mu A/V^2$, body modulation effects: $\lambda_n = 0.18\ V^{-1}$ and $\lambda_p = 0.36\ V^{-1}$, and the threshold voltage: $V_{THN} = |V_{THP}| = 0.45\ V$ [3], [4]. In this circuit, the total power consumption should not exceed 1.2 mW. The current source of $V_{DD}$ is$I_{tail} = 1.2\frac{mW}{1.80}V = 0.67\ mA$. So, each cascode branch of the Op-Amp requires 0.34 mA current, means$I_{tail}/2$. On the other hand, the common mode output voltage is $1.1\ V$. That is, each node X and Y in Figure 1 should be able to swing up to 1.1 volt and keep the transistors $M_3 - M_6$ in saturation area. With a $1.8\ V$ power supply, the total voltage available for $M_{tail}$ and each cascode branch is $0.7\ V$. Thus, we have (3):

$$V_{OD1} + V_{OD3} + |V_{OD5}| + |V_{OD7}| + V_{ODtail}] = 1.8 - 1.1 = 0.7 \tag{3}$$

Since $M_{tail}$ draws most of the current, one fifth of the voltage reaches to it, so $V_{ODtail} = 0.14\ V$ and $0.56\ V$ remains for the four cascade transistors. The $M_5 - M_8$ current sources have low mobility, so more voltage should be allocated per branch to them ($0.32\ V$). Therefore, in a cascade branch, we have$V_{OD5} + V_{OD7} = 0.32\ V$. The rest of the voltage is allocated to transistors $M_1$ and$M_3$. That is $V_{OD1} + V_{OD3} = 0.24\ V$. So, the overdrive voltage of transistors 5 and 7 is $0.16\ V$ and the voltage of transistors 1 and 3 is$0.12\ V$. The aspect ratio of $M_1 - M_{tail}$ can be evaluated by the bias current and the overdrive voltage of each MOSFET. The relation of drain current to saturation area is (4):

$$I_D = (1/2)\mu C_{ox}(W/L)(V_{GS} - V_{TH})^2 \tag{4}$$

To minimize the parasitic capacitors of the integrated devices, the minimum length of each MOSFET transistor is $L = 0.18\ \mu m$.

Then, $(W)_{1-4} = 38\ \mu m$, $(W)_{5-8} = 58.25\ \mu m$ and $W_{tail} = 58.775\ \mu m$ are obtained. So, the design was done according to the total power consumption, power supply and output swing. The amount of the gain can now be calculated from the (5),

$$A_v \approx g_{m1}[(g_{m3} r_{o3} r_{o1}) \parallel (g_{m5} r_{o5} r_{o7})] \tag{5}$$

By choosing a minimum channel length of $0.18\ \mu m$ for all MOSFET transistors we have $g_m$ and $r_o$ which are obtained from (6) and (7).

$$g_m = 2I_D/V_{OD} \tag{6}$$

$$r_o = 1/\lambda I_D \tag{7}$$

So, author have:

$$g_{m1-4} = \frac{2 \times 0.32 \times 10^{-3}}{0.123} = 5.203\ mA/V$$
$$g_{m5-8} = \frac{2 \times 0.32 \times 10^{-3}}{0.157} = 4.764\ mA/V$$
$$r_{o1-4} = \frac{1}{0.18 \times 0.32 \times 10^{-3}} \approx 17361.11\ \Omega$$

$$r_{o5-8} = \frac{1}{0.36 \times 0.32 \times 10^{-3}} \approx 8680.56\ \Omega$$

In this paper, author propose the circuit of Figure 2, called high-swing fully differential telescopic Op-Amp.

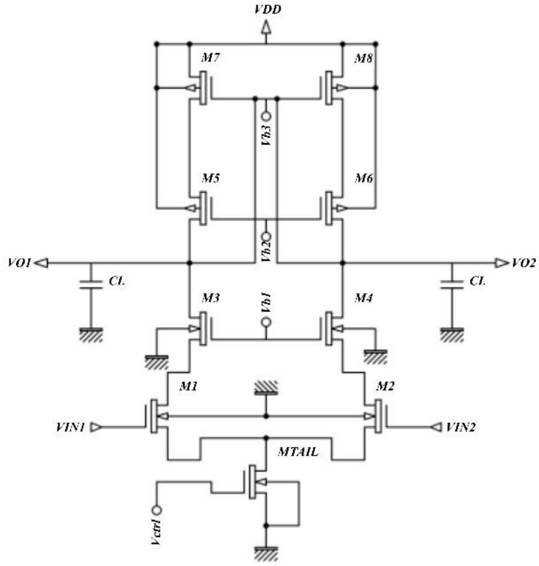
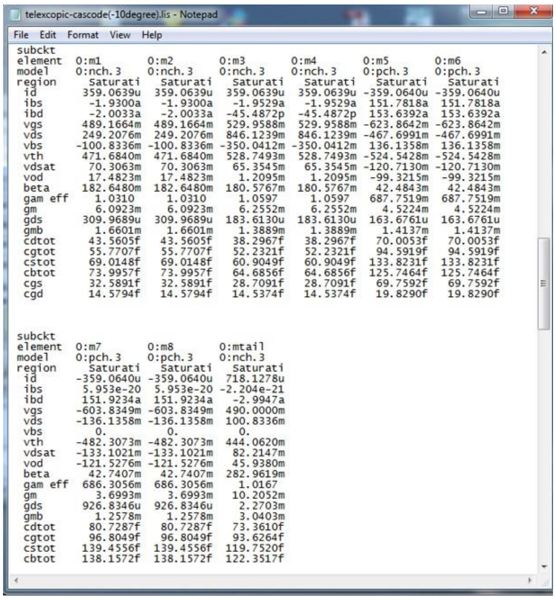



Figure 2. The proposed high-swing fully differential telescopic Op-Amp circuit

For doing simulation, firstly author must get the working point of all transistors using the ".op" command (all transistors are in saturation area) see Figure 3.



telexcopic-cascode(-10degree).lis - Notepad

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```
subckt
element  0:m1        0:m2        0:m3        0:m4        0:m5        0:m6
model    0:nch.3     0:nch.3     0:nch.3     0:nch.3     0:pch.3     0:pch.3
region     Saturati    Saturati    Saturati    Saturati    Saturati    Saturati
  id      359.0639u   359.0639u   359.0639u   359.0639u -359.0640u  -359.0640u
  ibs      -1.9300a    -1.9300a    -1.9529a    -1.9529a   151.7818a   151.7818a
  ibd      -2.0033a    -2.0033a   -45.4872p   -45.4872p   153.6392a   153.6392a
  vgs     489.1664m   489.1664m   529.9588m   529.9588m -623.8642m  -623.8642m
  vds     249.2076m   249.2076m   846.1239m   846.1239m -467.6991m  -467.6991m
  vbs    -100.8336m  -100.8336m  -350.0412m  -350.0412m  136.1358m   136.1358m
  vth     471.6840m   471.6840m   528.7493m   528.7493m -524.5428m  -524.5428m
  vdsat    70.3063m    70.3063m    65.3545m    65.3545m -120.7130m  -120.7130m
  vod      17.4823m    17.4823m     1.2095m     1.2095m  -99.3215m   -99.3215m
  beta    182.6480m   182.6480m   180.5767m   180.5767m   42.4843m    42.4843m
  gam eff   1.0310      1.0310      1.0597      1.0597   687.7519m   687.7519m
  gm        6.0923m     6.0923m     6.2552m     6.2552m    4.5224m     4.5224m
  gds     309.9689u   309.9689u   183.6130u   183.6130u  163.6761u   163.6761u
  gmb       1.6601m     1.6601m     1.3889m     1.3889m    1.4137m     1.4137m
  cdtot    43.5605f    43.5605f    38.2967f    38.2967f   70.0053f    70.0053f
  cgtot    55.7707f    55.7707f    52.2321f    52.2321f   94.5919f    94.5919f
  cstot    69.0148f    69.0148f    60.9049f    60.9049f  133.8231f   133.8231f
  cbtot    73.9957f    73.9957f    64.6856f    64.6856f  125.7464f   125.7464f
  cgs      32.5891f    32.5891f    28.7091f    28.7091f   69.7592f    69.7592f
  cgd      14.5794f    14.5794f    14.5374f    14.5374f   19.8290f    19.8290f


subckt
element  0:m7        0:m8        0:mtail
model    0:pch.3     0:pch.3     0:nch.3
region     Saturati    Saturati    Saturati
  id     -359.0640u  -359.0640u   718.1278u
  ibs      5.953e-20   5.953e-20 -2.204e-21
  ibd     151.9234a   151.9234a    -2.9947a
  vgs    -603.8349m  -603.8349m   490.0000m
  vds    -136.1358m  -136.1358m   100.8336m
  vbs       0.          0.          0.
  vth    -482.3073m  -482.3073m   444.0620m
  vdsat  -133.1021m  -133.1021m    82.2147m
  vod    -121.5276m  -121.5276m    45.9380m
  beta     42.7407m    42.7407m   282.9619m
  gam eff 686.3056m   686.3056m     1.0167
  gm        3.6993m     3.6993m    10.2052m
  gds     926.8346u   926.8346u     2.2703m
  gmb       1.2578m     1.2578m     3.0403m
  cdtot    80.7287f    80.7287f    73.3610f
  cgtot    96.8049f    96.8049f    93.6264f
  cstot   139.4556f   139.4556f   119.7520f
  cbtot   138.1572f   138.1572f   122.3517f
```

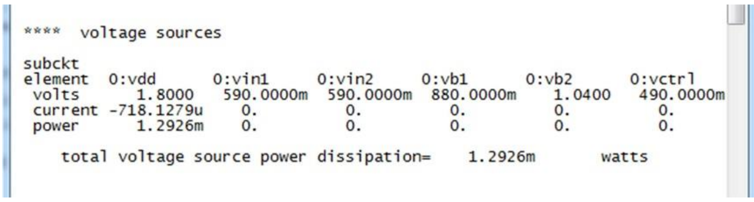
Figure 3. Working point of the proposed high-swing fully differential telescopic Op-Amp circuit

To keep the all transistors in the saturation area, the bias voltages, control voltage, and maximum and minimum input voltages, $V_{CMI}$, are calculated to drive the transistors to the saturation area as:

$$V_{ctrl} = V_{GStail}\ if\ V_{ODtail} > V_{GStail} - V_{th}$$

$$V_{b1} = V_{GS3} + V_{ODM1} + V_{ODtail}\ if\ V_{OD3} > V_{GS3} - V_{th}$$
$$V_{b2} = V_{DD} - V_{ODM7} - V_{GS5}\ if\ V_{OD5} < V_{GS5} - V_{th}$$
$$V_{b3} = V_{DD} - V_{GS7}\ if\ V_{OD7} < V_{GS7} - V_{th}$$
$$\{V_{inMax} = V_{DD} - 2V_{OD7} - V_{OD3}\ and\ V_{inmin} = V_{GS1} + V_{ODtail}\ if\ V_{OD1} > V_{Gs1} - V_{th}\}$$

So after simulation, all transistors are active and their current are regulated which the total power consumption of the circuit obtains as 1.2 $mW$ see Figure 4.


```
****  voltage sources

subckt
element  0:vdd      0:vin1     0:vin2     0:vb1      0:vb2      0:vctrl
 volts     1.8000   590.0000m  590.0000m  880.0000m    1.0400   490.0000m
 current -718.1279u    0.         0.         0.         0.         0.
 power     1.2926m     0.         0.         0.         0.         0.

    total voltage source power dissipation=    1.2926m       watts
```

Figure 4. Power consumption of the circuit ($P_{diss}$).

## 3. RESULTS AND DISSCUSION

In this section, author want to discuss about the simulation. According to the Figure 4, the current drawn from the power supply is 0.72 $mA$ and the total power consumption of the circuit is 1.2 $mW$. The output voltage response as shown in Figure 5 is 1.2 $V$.

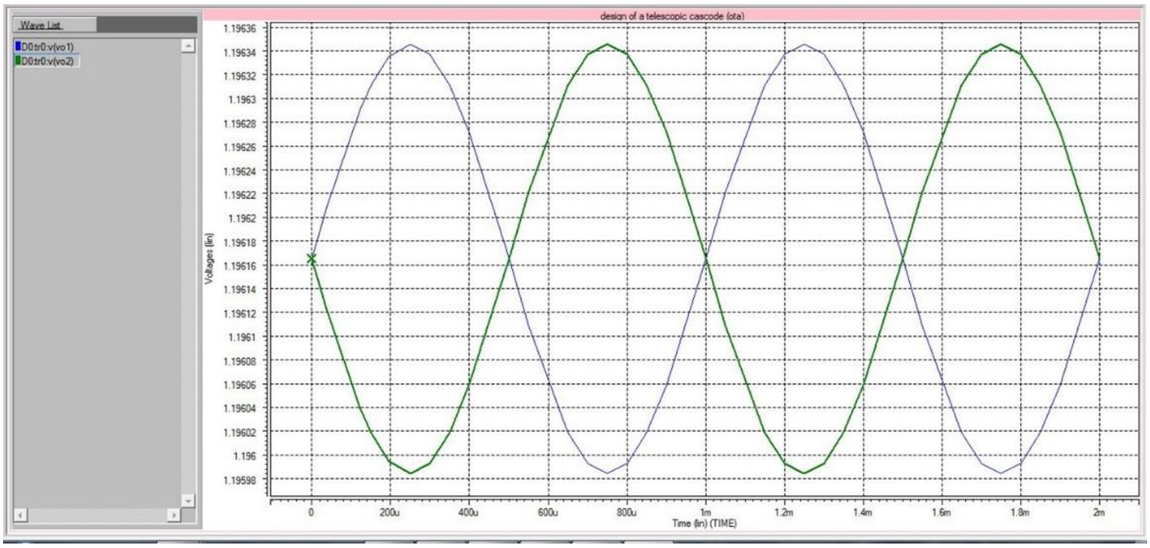



Figure 5. The output swing of the proposed high-swing fully differential telescopic Op-Amp circuit

In Figure 6, the circuit gain is greater than 60 $dB$ and 76.333 $dB$ ($111.75 - 35.417 = 76.333$ dB). So the Common Mode Rejection Ratio (CMRR) is greater than 50 $dB$.

At frequency of 412 MHz, the gain reaches one and thus the unity-gain frequency value, $\omega_{UGB}$, is 412 MHz see Figure 7.

According to the Figure 7, at the$\omega_{UGB} = 412\ MHz$, the output phase value of the system is$-61.7°$, so the Phase Margin (PM) of the circuit is$180℃ - 61.7℃ = 118.3℃$, which a desirable value is. Further, the Total Harmonic Distortion (THD) of the circuit is 0.332% for both $V_{O1}$ and $V_{O2}$ outputs see Figure 8.

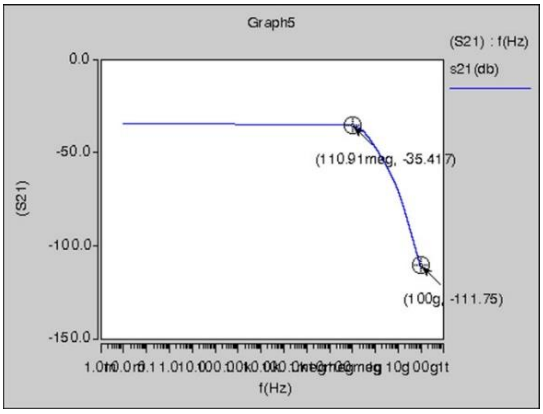



Figure 6. Frequency response of the proposed high-swing fully differential telescopic Op-Amp circuit

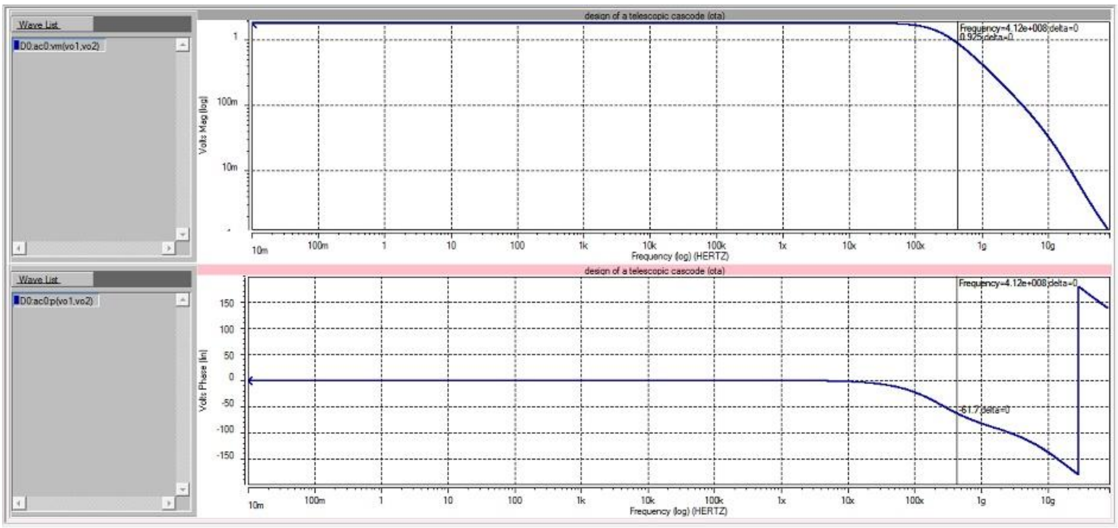
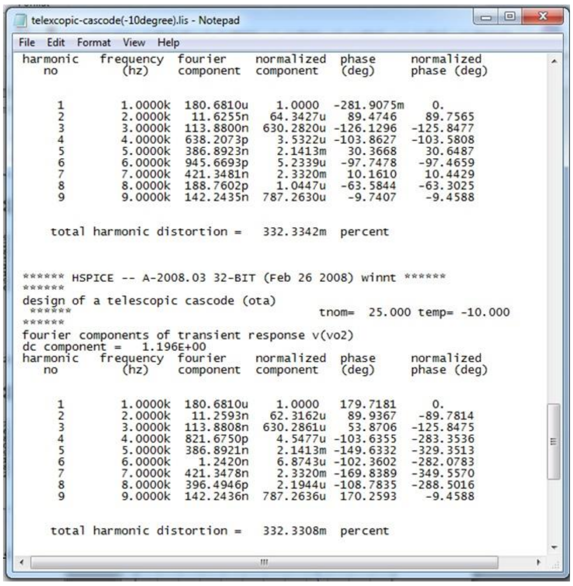



Figure 7. The $\omega_{UGB}$ and the output system phase of the proposed high-swing fully differential telescopic Op-Amp circuit



```
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File  Edit  Format  View  Help
harmonic    frequency  fourier    normalized  phase      normalized
   no          (hz)    component  component   (deg)      phase (deg)


    1        1.0000k  180.6810u    1.0000  -281.9075m    0.
    2        2.0000k   11.6255n   64.3427u    89.4746    89.7565
    3        3.0000k  113.8800n  630.2820u -126.1296  -125.8477
    4        4.0000k  638.2073p    3.5322u -103.8627  -103.5808
    5        5.0000k  386.8923n    2.1413m   30.3668    30.6487
    6        6.0000k  945.6693p    5.2339u  -97.7478   -97.4659
    7        7.0000k  421.3481n    2.3320m   10.1610    10.4429
    8        8.0000k  188.7602p    1.0447u  -63.5844   -63.3025
    9        9.0000k  142.2435n  787.2630u   -9.7407    -9.4588

    total harmonic distortion =   332.3342m  percent


****** HSPICE -- A-2008.03 32-BIT (Feb 26 2008) winnt ******
******
design of a telescopic cascode (ota)
 ******                                  tnom=  25.000 temp= -10.000
******
fourier components of transient response v(vo2)
dc component =   1.196E+00
harmonic    frequency  fourier    normalized  phase      normalized
   no          (hz)    component  component   (deg)      phase (deg)


    1        1.0000k  180.6810u    1.0000   179.7181     0.
    2        2.0000k   11.2593n   62.3162u    89.9367   -89.7814
    3        3.0000k  113.8808n  630.2861u    53.8706  -125.8475
    4        4.0000k  821.6750p    4.5477u -103.6355  -283.3536
    5        5.0000k  386.8921n    2.1413m -149.6332  -329.3513
    6        6.0000k    1.2420n    6.8743u -102.3602  -282.0783
    7        7.0000k  421.3478n    2.3320m -169.8389  -349.5570
    8        8.0000k  396.4946p    2.1944u -108.7835  -288.5016
    9        9.0000k  142.2436n  787.2636u   170.2593    -9.4588

    total harmonic distortion =   332.3308m  percent
```

Figure 8. The THD of the proposed high-swing fully differential telescopic Op-Amp circuit

Author can calculate the slow rate as (8) [7], [22].

$$SR \equiv dV_{OUt}/dt|_{Max} = I_{tail}/C_L = (2I_{DM1.2})/C_L \tag{8}$$

Where $I_{DM1.2}$ is the bias current of transistors 1 and 2. The value of the slow rate is obtained 261.25 volts per microsecond (MHz) from the simulation see Figure 9.

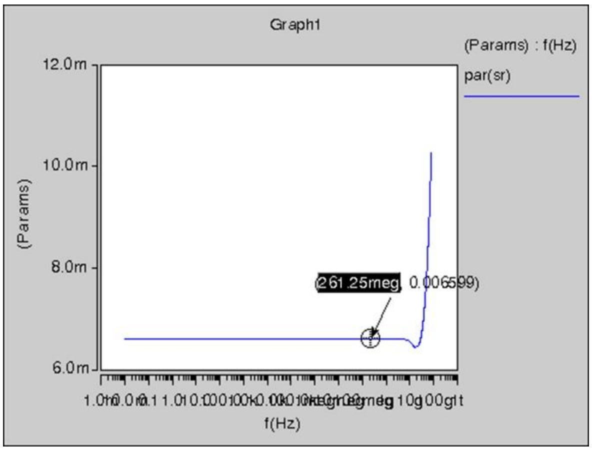


Figure 9. The slow rate of high-swing fully differential telescopic Op-Amp circuit

For noise analysis, I have to send the noise to the system, for example, with a 50 ohmic pull-up resistor (p1): p1 in 0 port=1 ac=0.1 dc=2.1 z0=50

The resistance value from the $V_{O1}$ output to $V_{DD}$ is calculated $g_{m5}r_{o5}r_{o7}$, which is $359\ k\Omega$. The output noise is $101.9337\mu Volts$ see Figure 10.

```
**** the results of the sqrt of integral (v**2 / freq)
     from fstart upto   71.6382g      hz. using more freq points
     results in more accurate total noise values.

**** total output noise voltage   =  101.9337u       volts
**** total equivalent input noise =    0.
```

Figure 10. The output noise of the proposed high-swing fully differential telescopic Op-Amp circuit

The characteristic table of the proposed high-swing fully differential telescopic Op-Amp circuit is as Table 2.

Table 2. The Characteristic of the proposed high-swing fully differential telescopic OP-Amp circuit

| Characteristic | Description |
|---|---|
| Power supply | 1.8V |
| Power consumption | 1.2 mW |
| Gain | 76.333 dB |
| $\omega_{UGB}$ | 412 MHz |
| Output Phase Value | -61.7° |
| PM | 118.3° |
| THD | 0.332% |
| Slow Rate | 261.25 MHz |
| Total Output Noise Voltage | 101.9337 µV |
| Output Swing Voltage | 1.2 V |
| CMRR | > 50dB |

The value of $(A_v \times \omega_{UGB})/P_{diss}$ obtains as:

$$(A_v \times \omega_{UGB})/P_{diss} = (76.333 \times 412 \times 10^6)/(1.2 \times 10^{-3}) \cong 26207.7 \times 10^9 dB \cdot Hz/Watt$$

The characteristic of this proposed Op-amp is good comparing the other Op-amps. Table 3 compares the characteristic of this Op-amp with other designs.

Table 3. Comparison the Characteristic of the proposed high-swing fully differential telescopic OP-Amp circuit with other circuits

| Characteristic | The proposed Op-amp | QFGDB op-amp [3] | Fully Differential Gain-Boosted Telescopic Cascode Op-amp [7] | Telescopic Op-amp for MDAC [9] | High-Swing CMOS Telescopic Operational Amplifier [8] | Folded-cascode Op-amp [6] | Telescopic Op-Amp with Improved Gain [10] | Dc-Gain Enhanced CMOS Telescopic Op-Amp [5] | Fully-differential Op-amp [15] |
|---|---|---|---|---|---|---|---|---|---|
| Power supply | 1.8 | < 1 | 3.3 | 1.8 | 3.3 | 3.3 | 5 | - | 1.8 |
| Power consumption (mW) | 1.2 | - | 3.89 | 0.051 | - | 9-14 | - | 5 | - |
| Gain (dB) | 76.333 | 60.5 | 129 | 62.81 | 105 | - | 85 | > 61 | > 60 |
| $\omega_{UGB}$ (MHz) | 412 | 65 | 161 | 285.6 | 93 | 1.3GHz | 177.1 | 1GHz | > 50 |
| Output Phase Value (°) | -61.7 | - | - | - | - | - | - | - | - |
| PM (°) | 118.3 | 81 | 70.6 | 57.42 | 78 | - | - | 81 | 60 |
| THD (%) | 0.332 | - | - | - | - | - | - | - | - |
| Slow Rate (V/μs) | 261.25 | - | 92 | 2.19 | 133 | - | - | - | > 100 |
| Total Output Noise Voltage (μV) | 101.9337 | - | - | - | - | - | - | - | - |
| Output Swing Voltage (V) | 1.2 | - | 3 | - | 2.4 | - | - | - | > 2.7 |
| CMRR (dB) | >50 | >50 | >50 | - | >50 | - | - | - | - |

## 4. CONCLUSION

This paper presents the design of an of high-swing fully differential telescopic Op-Amp circuit with 0.18 CMOS technology. The results of the circuit simulation with HSPICE RF software show that the circuit parameters have acceptable values. One of the important features that this paper wants to acquire is higher voltage than current Op-Amps in accordance with desirable parameters. Finally, by compromising the circuit parameters, we were able to obtain a good performance from the circuit design. As the amplification of signals in many electronic circuits plays a key role and can be easily implemented with Op-Amp, this design can demonstrate this reality which can implemented in a Very Large-Scale Integration (VLSI) chip.

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