

Power Efficient Class AB Op-Amps with High and Symmetrical Slew Rate

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ABSTRACT: The operational amplifier is widely used in various integrated circuits these days such as in analogue computers, simulation systems and in many electronic applications as filtering, buffering and comparison of signal levels. In this paper various schemes of power efficient class AB two stage op-amps with nearly symmetric slew rate and very simple architectures are introduced. These schemes have been implemented by using a current replication branch with scaled down transistors in combination with adaptive loads. The proposed operational amplifier has been implemented by modifying the existing power efficient class AB two-stage op-amps with current replication branch and adaptive loads with symmetrical and high slew rate. The improved architecture provides maximum output current several times higher than the bias current. Hence it is used to provide a push-pull output stage with maximum output current. Post layout simulations and comparisons are made for all these architectures where the proposed circuit has obtained much better slew rate when compared to the all existing schemes and the power consumption is slightly reduced. The circuits presented in this work are analysed by using the backend tool H-Spice and are designed in 90nm technology.

Keywords: Operational amplifiers, Class AB operation, Symmetrical slew rate, CMOS analog integrated circuits

I. INTRODUCTION

The designing of op-amps puts new challenges in low power applications because as technology advances the channel length of the device is reducing day by day. Hence the design of op-amp is becoming a complex task. Various advancements have been made through new techniques and technology which appeared recently. They allow us to implement the designs in multiple alternative ways. Involvement of design automation tools that are used in analog and mixed signal design are yet to be matured as in the case of digital design domain. For EDA designers, short channel effects in design automation for mixed signal design are also a challenging task. Designing of two-stage op-amps is a multi dimensional optimization problem because optimizations of one or more parameters can easily results into degradation of other parameters. To achieve high symmetrical slew rate in single stage op-amps very efficient schemes have been reported [1]-[3]. But only relatively low open loop gain Aol is possible for these schemes. This is the main drawback of single stage op-amps based on this technique. This is due to the inclusion of the output cascading transistors which are tended to increase the output resistance Rout for increasing Aol which is open loop gain. But it would seriously limit the maximum output current and the slew rate enhancement factor.

Conventional single stage class-A miller compensated op-amp is described initially. Then Two-stage op-amps with nearly symmetrical slew rate are presented in this brief. Class-AB operation also achieved for these op-amps but only for static input signals. The coming sections describe other existing and proposed topologies, simulation results and experimental values respectively. Finally some comparisons and conclusions are drawn from the obtained results.

II. EXISTING CLASS AB TWO-STAGE OP-AMPS

2.1 Conventional Class-A two-stage Miller Compensated Op-Amp

The conventional class-A two stage Miller compensated op-amp which is shown in fig 1(a) is characterized by a highly asymmetrical slew rate. Its positive slew rate is very much higher than the negative slew rate. Expression of the negative slew rate is $SR^- = 2IB/CL$. Biasing current is represented by IB and CL is load capacitance. It has much lower negative slew rate. This is due to the fact that nmos transistor which is placed at the output stage (MoN) acts as a dc current source. The magnitude of the current source is 2IB. In class-A op-amps

the only way to increase slew rate is by increasing I_B . But static power increases with the increment of I_B . This is the main limitation in class-A op-amps. Schematic diagram and transient simulations of the Conventional two-stage Miller op-amp are shown in fig 1(a) and fig 1(b) respectively.

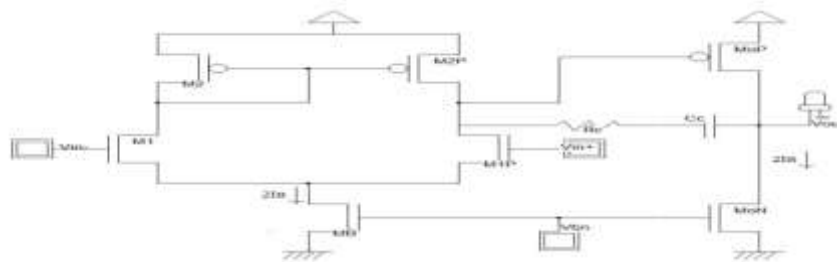


Fig. 1(a) Schematic diagram of Conventional Class-A two-stage Miller op-amp

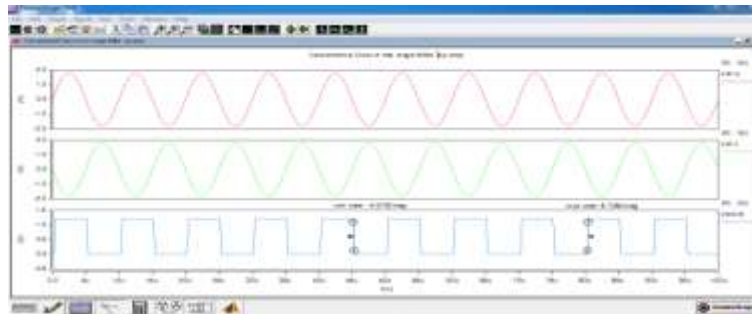


Fig. 1(b) Transient Simulations of Conventional Class-A two-stage Miller op-amp

2.2 Class AB-two Stage Op-amps

Class-AB op-amps avoid this limitation mentioned in class-A op-amps. There have been reported many class-AB two-stage op-amps in [4]-[6]. Most of them feature relatively modest effective slew rate improvement. This improvement in slew rate can be achieved by requiring additional complex circuitry and/or additional static power dissipation which is non negligible or it can be done by increasing power supply requirements. Current efficiency (CE) is defined as the ratio of the maximum current at the output (I_{outmax}) to the total op-amp static current (I_{Qtot}). The expression of current efficiency is $CE = I_{outmax} / I_{Qtot}$. Additional circuitry added to the circuit to achieve class-AB operation. So I_{Qtot} increases so that current efficiency decreases.

2.2.1 Free Class-AB Op-Amp

One of the schemes which have been reported in [7] is illustrated here in the fig 2(a). This circuit achieves class-AB operation. This needs very small additional hardware for achieving class-AB operation. This circuit is designed by adding two components R_{large} and C_{bat} . Resistive element R_{large} is implemented by a minimum size diode connected transistor. Capacitor C_{bat} is of very small value. This combination of C_{bat} and R_{large} works as floating battery. And that transfers ac variations which are taking place at the MoP gate to the MoN transistor's gate terminal. The output stage functions like a push-pull amplifier. All this process which is due to the additional components C_{bat} and R_{large} make the circuit to provide dynamic class-AB operation. This architecture provides large output positive current as well as negative current. The main advantage of this circuit is power dissipation or supply requirement are same as miller circuit. It does not need extra supply or increasing power dissipation. But the limitation is it operates only for a certain range of frequencies where $f > 1 / (2\pi R_{large} C_{bat})$. When f is more than the upper limit then only this free class-AB op-amp works. Schematic diagram and transient simulations of the Free class AB op-amp are shown in fig 2(a) and fig 2(b) respectively.

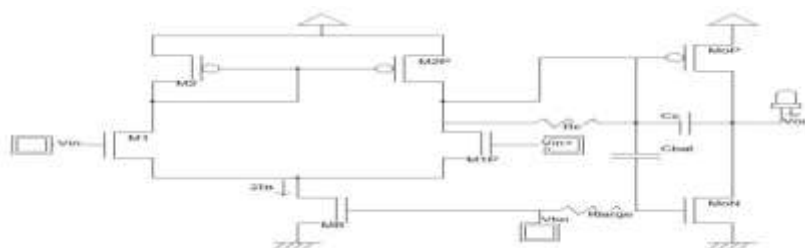


Fig. 2(a) Schematic diagram of Free-class AB op-amp

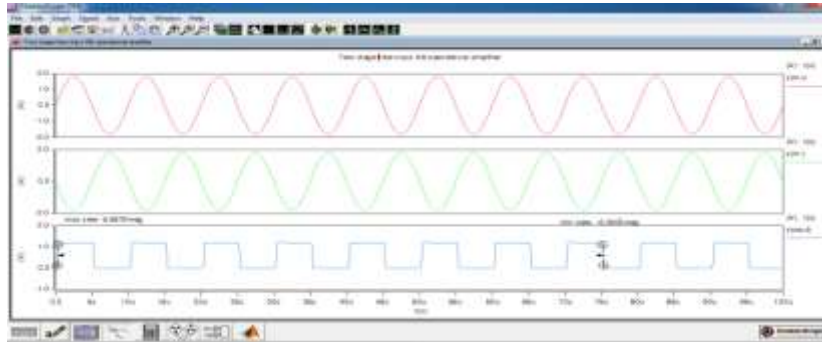


Fig. 2(b) Transient Simulations of Free-class AB op-amp

2.2.2 Op-Amp With Current Replication Branch

Class-AB operation can be achieved initially by transforming the output transistor MoN into an active amplifying device. This is done by simply adding a current replication branch which is formed by two scaled down transistors M2R and MoNR as shown in fig 3(a). Current replication branch is shown in square box. The role of this branch is transforming current variations in M1-M2 transistors which is denoted by I_a to the output transistor MoN, which in turn increases the maximum positive output current by the value twice the bias current $2I_B$.(which achieved when the transistor MoN is turned off).

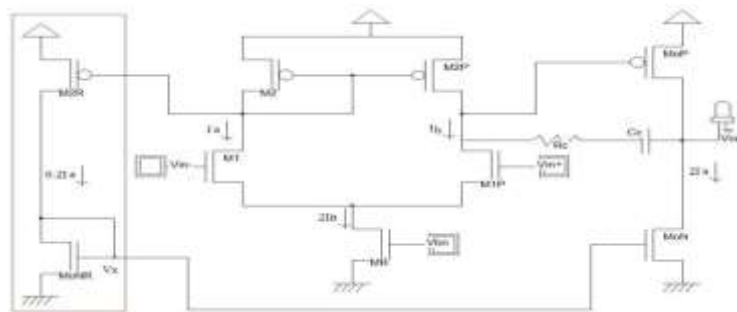


Fig. 3(a) Schematic diagram of Push pull op-amp with current replication branch M2R, MoNR.

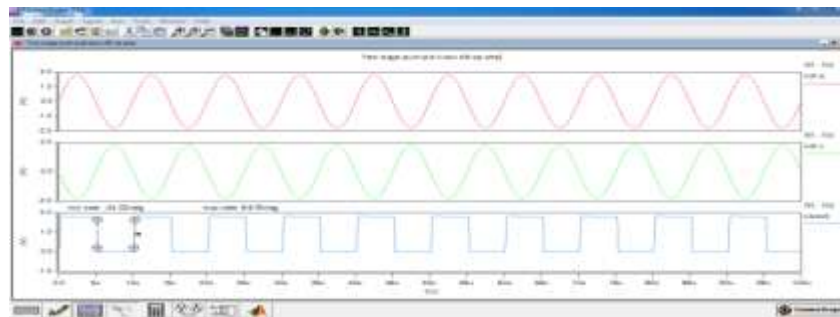


Fig. 3(b) Transient Simulations of Push pull op-amp with current replication branch M2R, MoNR.

This limitation of this circuit is the low value of negative output current. The maximum negative current is utmost twice the bias current in this circuit that achieved when transistor MoP is turned off. The main advantage is that the additional compensation is not required due to current replication branch. It has only one node with gain, which is in current replication branch and is from the gate terminal to the drain terminal of the transistor MoN. Miller compensation (with capacitor C_c and Resistance R_c) causes MoP transistor to act as low impedance diode connected load at the higher frequencies. So the gain (and Miller effect) is reduced between the gate terminal of MoN (which is denoted by the node V_x) and the output terminal of the op-amp to approximately a unity value and hence Miller multiplication is prevented by a large factor at node V_x (where V_x is low impedance node) at large frequencies. Since transistors in current replication branch are downscaled by a factor of 5, it has negligible dimensions hence reduces static power consumption and area.

Large negative slew rate can be achieved by large negative output currents. But current replication branch circuit give maximum output current which is limited to only twice the bias current $2I_B$. So in order to overcome this limitation and to achieve large negative output currents, non linear adaptive loads can be used

which is similar to the technique introduced in [8] and that reported in paper [2] and also [10]. The modifications are seen in the coming sections.

Schematic diagram and transient simulations of the Push pull op-amp with current replication branch are shown in fig 3(a) and fig 3(b) respectively.

2.2.3 Class AB Two-Stage Op-Amp Using Adaptive Loads

Class-AB operation can be achieved by adding an adaptive load to the circuit in the fig 1(a) at the input stage. Many combinations are possible by adding adaptive loads to the circuits in fig 1(a) and fig 2(a). Two of them are presented here and are shown by fig 4(a) and fig 5(a). Fig 4(a) is named as adaptive load type II and fig 5(a) is named as adaptive load type I. In these two cases, the adaptive loads exhibit huge variation of output resistance between the saturation region and triode region of the transistors M2triode-M2Ptriode. These two transistors are set at the boundary between ohmic region and constant current region by the biasing voltage VbR in quiescent conditions. In both schemes, when current in Ia or Ib increases, the transistors M2 triode or M2Ptriode pulled to go into linear mode (triode mode) hence develop large drain-source voltages. These changes made because the adaptive loads cause large variations at node voltage a and b, which lead to increase the maximum current at the output transistors MoP (with the current replication branch) and MoN.

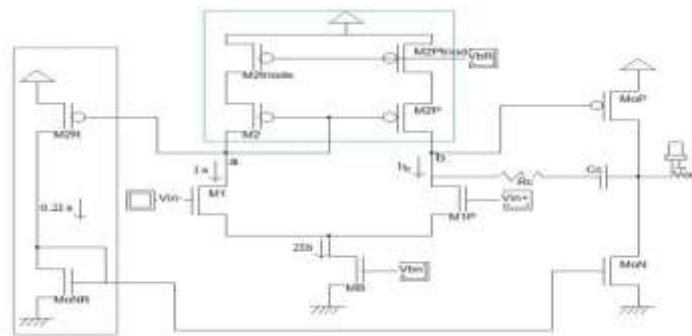


Fig 4(a) Schematic diagram of Class AB two-stage op-amp with current replicating branch using adaptive load II at the input stage.

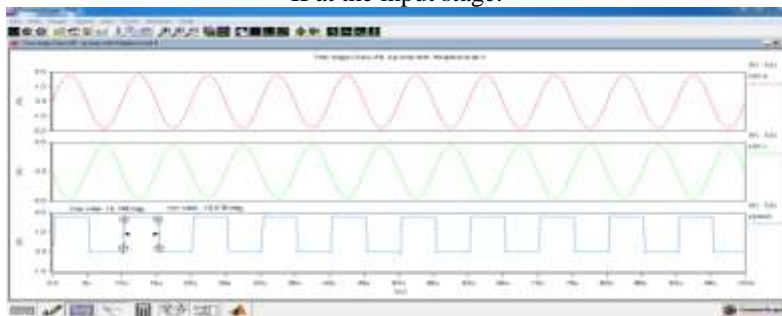


Fig 4(b) Transient Simulations of Class AB two-stage op-amp with current replicating branch using adaptive load II at the input stage.

The performance of the circuits with adaptive loads is nearly similar to the circuit shown in fig 6(a). In this circuit (fig 6(a)) the adaptive load is directly included in the current replication branch (with scaled down transistors). This causes extremely large negative output current to flow in output transistors. This circuit is formed by simply modifying the diode connected load in the current replication branch. Transistor MoNtriode is included in current replication branch between the gate terminal of transistor MoNR and the lower supply rails. The required bias voltage is $V_{btriode} = V_{ss} + V_{GS} + V_{DSsat} = V_{TH} = 2V_{DSsat}$ at gate of MoNR transistor. Where $V_{DSsat} = V_{GS} - V_{TH}$ is the minimum VDS voltage required to operate in saturation region. To generate it a small circuit is used. It is formed by using a diode connected transistor MBtriode with W/L ratio which is nearly equal to one fourth of MoNtriode and MoNR. Hence it obtains two times the VDSsat and thus its VGS voltage is the required Vbtriode voltage. This biasing voltage Vbtriode leaves a quiescent drain-source voltage for MoNtriode with the value of VDSsat, that causes MoNtriode to be operated (under static conditions) at the boundary between the ohmic region and constant current regions, similar to M2triode-M2Ptriode as in the fig 4(a) and fig 5(a). When the current in Ia increases gate source voltage of MoNR tend to be increased, and drain-source voltage of MoNtriode decreases, that brings this transistor into ohmic region and generates consequently a huge voltage increase at the node Vx and large output current in MoN also be generated correspondingly. Current through MoN corresponds to negative slew rate hence it increases which is nearly equal to its positive slew

rate.

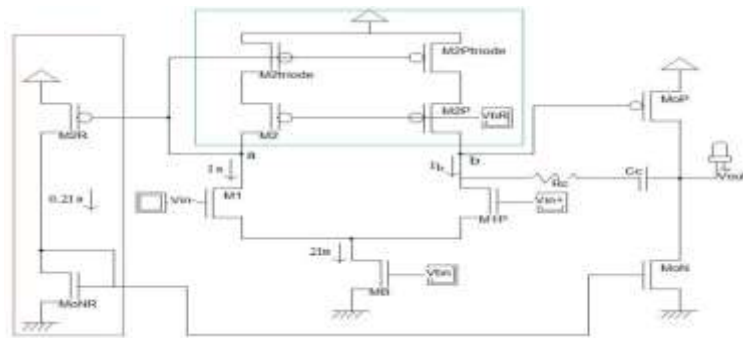


Fig. 5(a) Schematic diagram of Class AB two-stage op-amp with current replicating branch using adaptive load I at the input stage.

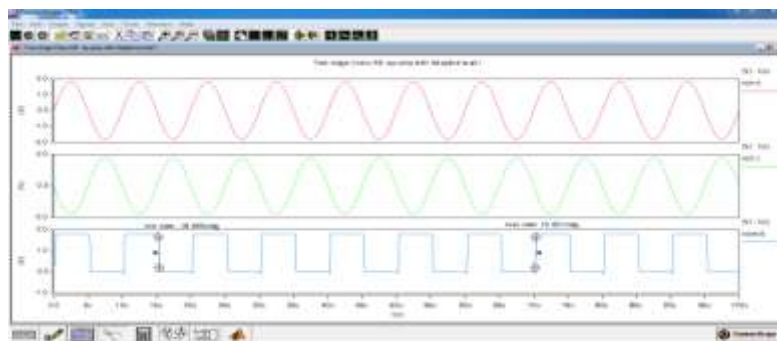


Fig. 5(b) Transient Simulations of Class AB two-stage op-amp with current replicating branch using adaptive load I at the input stage.

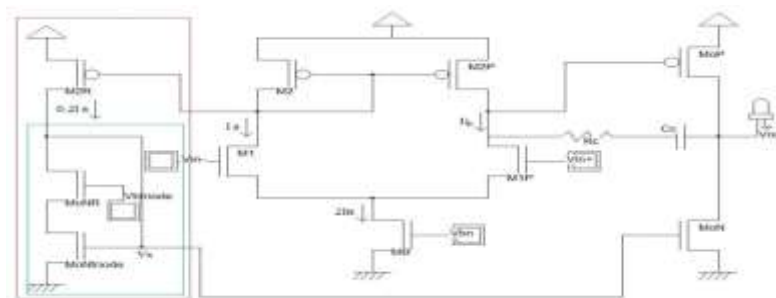


Fig. 6(a) Schematic diagram of class AB two-stage op-amp with current replicating branch using an adaptive load.

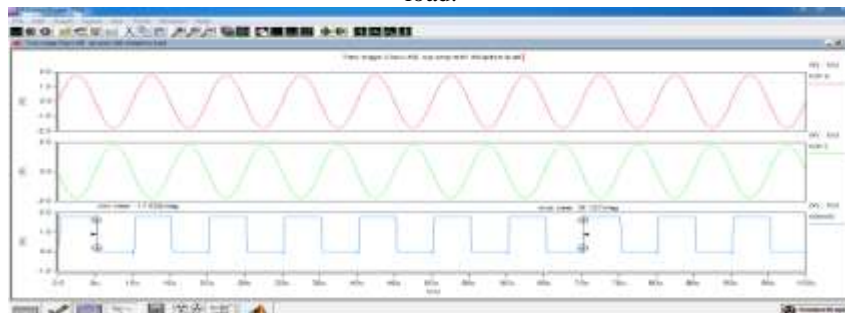


Fig. 6(b) Transient Simulations of class AB two-stage op-amp with current replicating branch using an adaptive load.

“Operational amplifier with current replication branch and adaptive load” is the denotation given to the circuit in fig 1(f). This circuit has two gain branches but is not harmful for the stability of the circuit in terms of ac response, and in some cases it is beneficial. The current replication branch is very helpful and compensates the current which passes through the miller capacitor as like in other multipath miller zero-cancellation schemes.

Transient Simulations of op-amps with adaptive load II, adaptive load I and op-amp with adaptive load and current replication branch are shown in fig 4(b), fig 5(b) and fig 6(b) respectively.

3 Proposed Class AB Two- Stage Op-Amp

The proposed operational amplifier has been implemented by modifying the existing power efficient class AB two-stage op-amps with current replication branch and adaptive loads with symmetrical and high slew rate. This op-amp is denoted by “Class-AB two-stage operational amplifier with current replication branch using two adaptive loads” and is shown in fig 7(a).

Current replication branch transforms current variations in M1-M2 transistors which is denoted by I_a to the output transistor MoN, which in turn increases the maximum positive output current by the value twice the bias current $2I_B$. Other advantage of this branch is that additional compensation is not required. Large negative slew rate is achieved by two adaptive loads. One of the adaptive load is directly included in the current replication branch (Transistor MoNtriode) between the gate terminal of transistor MoNR and the lower supply rails. The required bias voltage ($V_{btriode}$) for this transistor MoNtriode and the operation is same as the circuit in fig 6(a). Current through MoN corresponds to negative slew rate hence it increases which is nearly equal to its positive slew rate. Another load which is connected as is fig 4(a) is responsible for increasing the maximum current at the output transistors MoP (with the current replication branch) and MoN. The operation of this adaptive load is similar to the circuit in fig 4(a).

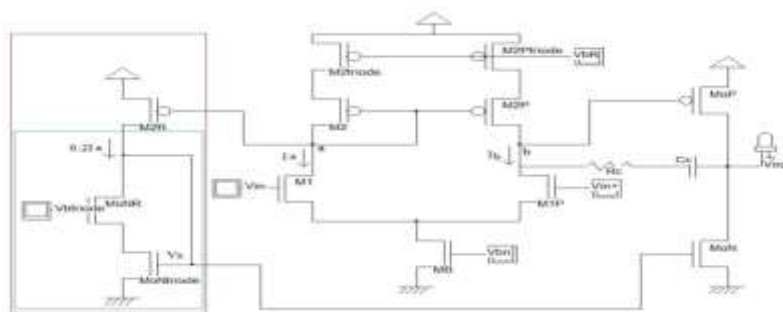


Fig. 7(a) Schematic diagram of Class-AB two-stage operational amplifier with current replication branch using two adaptive loads

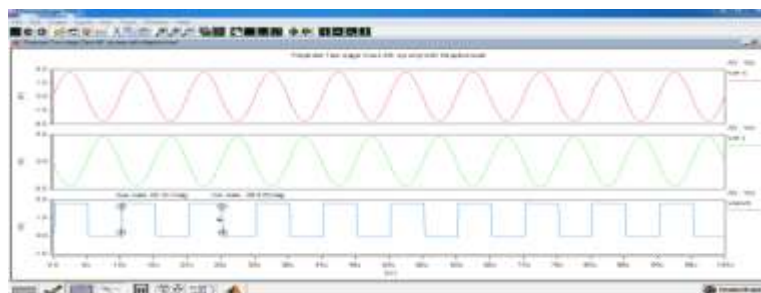


Fig. 7(b) Transient Simulations of Class-AB two-stage operational amplifier with current replication branch using two adaptive loads

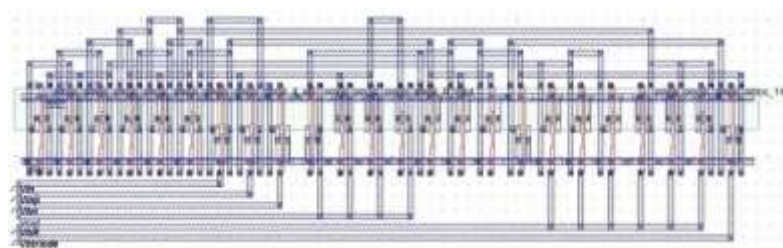


Fig. 7(c) Layout of Class-AB two-stage operational amplifier with current replication branch using two adaptive loads

The improved architecture provides maximum positive and negative output currents ($SR+$ and $SR-$) several times higher than the previous schemes. Schematic diagram, Transient simulations and the layout of the

Class-AB two-stage operational amplifier with current replication branch using two adaptive loads are shown in fig 7(a), fig 7(b) and fig 7(c) respectively.

III. SIMULATION RESULTS

Post layout simulations and comparisons are made for all these architectures where the proposed circuit has obtained much better slew rate when compared to the all existing schemes and the power consumption is slightly reduced. Slew rate comparison is shown with the help of the bar graph shown in fig 8(a) where only absolute value of the negative slew rate (SR-) is mentioned. Here bars correspond to fig 7(a) are the slew rates of the proposed op-amp (Two stage class-AB op-amp with current replication branch using two adaptive loads) which are higher than all the previous circuits. The power consumption is compared with the help of line graph shown in fig 8(b) where power consumption is reduced for the fig 7(a).

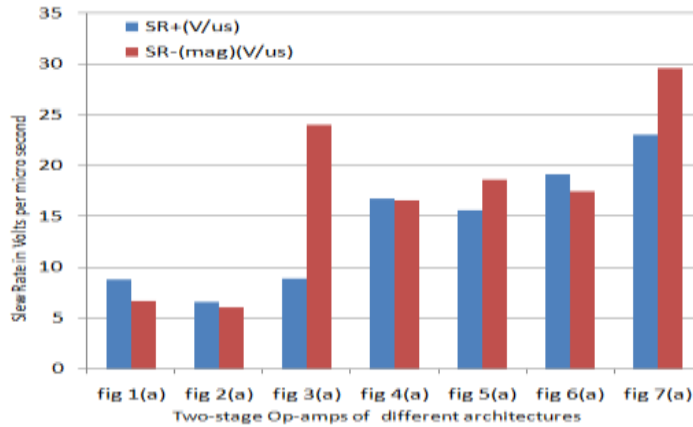


Fig 8(a) Bar graph comparing slew rates of different op-amps

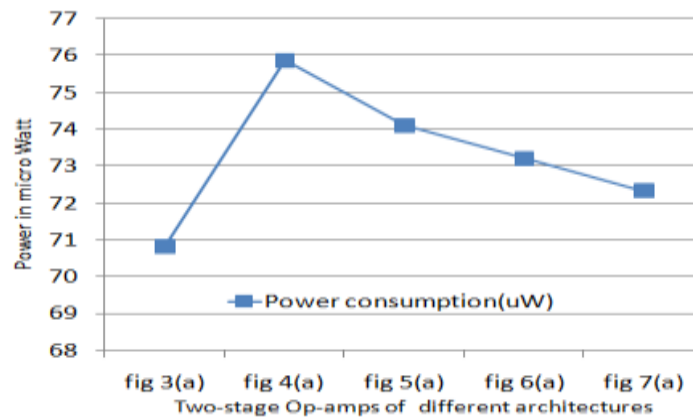


Fig 8(b) Line graph comparing power consumption of different operational amplifiers

Performance comparison table represents measured values of all the schemes are shown in table 1 where slew rates are improved and power consumption is reduced for the proposed op-amp. The circuits presented in this work are analysed by using the backend tool H-Spice and are designed in 90nm technology.

Table1. Performance comparison

Type of op-amp	Power (uW)	SR+ (V/us)	SR-(V/us)
Conventional two-stage Miller op-amp	140.69	8.728	-6.676
Free class AB op-amp	140.75	6.587	-6.060
Push pull op-amp with current replication branch	70.810	8.879	-24.03

Class AB two-stage op-amp with current replication branch using adaptive load II	75.870	16.74	-16.57
Class AB two-stage op-amp with current replication branch using adaptive load I	74.113	15.60	-18.65
Class AB two-stage op-amp with current replication branch using an adaptive load	73.214	19.13	-17.42
Class-AB two-stage operational amplifier with current replication branch using two adaptive loads	72.325	23.017	-29.57

IV. CONCLUSION

Power efficient class AB two-stage op-amp with current replication branch using two adaptive load has been implemented. It has been tested experimentally and compared with the various schemes of two-stage op-amps. The measured results show that it has achieved better performance both in terms of slew rate and power consumption. So it can be concluded that it is advantageous to include two adaptive loads one adaptive load directly in the current replication branch and other in the input stage.

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