

CMOS Embedded High-Efficiency Cardiac Pacemakers Design

Huijia Ma

Beijing University of Technology, Beijing, 100124, China

Abstract. With the increasing incidence of sudden cardiac death in recent years, the importance of pacemakers has become particularly important. This paper study CMOS circuit design in pacemakers so that they can stay for a long time without charging. Firstly, compared with class A and B amplifier which has low efficiency and high distortion respectively, class AB amplifiers act as a balance between linearity and efficiency, achieving high current drive capability with very low static power consumption. A current mirror based on transduction multiplication to achieve ultra-low current consumption confirms the usefulness of AB amplifiers in pacemakers. This paper design a low power consumption circuit. Firstly, we compare the circuit diagrams of different A, B class amplifiers and analyze their characteristics. Secondly, we analyzed the principle of Class AB amplifier and verified its efficient characteristics. Finally, we studied the effect of this amplifier on a cardiac pacemaker.

Keywords: Cardiac Pacemakers; CMOS; AB Amplifier; High-efficiency; NPN Transistor.

1. Introduction

In the era of severe development of aging population, prevention of aging diseases is very important. However, cardiovascular diseases, which are the largest cause of death worldwide, account for a large proportion of the elderly population. Second, with the rapid development of semiconductor physics and integrated circuits, implantable disease treatment devices - pacemakers have gradually entered people's lives to treat heart dysfunction caused by heart disorders.

A pacemaker is a circuit in which electricity supplied by a battery is passed through wires that pass through the heart muscle, stimulate the heart to beat ("capture" the heart), and then return to the battery, thus completing the entire circuit. Over the past half-century, this technology has developed continuously in an amazing pace in which power efficiency is critical in several scenarios of very large-scale integration circuits requiring wearable devices [5]. Most of the CMOS require relatively high supply voltage like class A which limiting power efficiency.

This was proposed by S. Sirenko et al. Local Ca^{2+} release occurs when PLB phosphorylation or 2D12 increases the kinetics of Ca^{2+} pumping into the SR, and the collection of these rhythmic local Ca^{2+} wavelets generates a periodic high amplitude Ca^{2+} signal [12]. M. I. Elnaggar et al. designed an FPD controller for pacemakers that transmits to a patient's heart chamber model, precisely regulates and restores normal heart rate (HR), and outputs fast and stable pulses [13]. Those studies focus on output performance, high power density and precision, but neglect to analyzing power consumption. In this paper, we aim to compare three different types of amplifiers by analyzing the circuit and diagram. Then, we will list some modified AB class amplifiers which have been applied to some applications with specific features.

First, based on the circuit diagrams and input-output curves of Class A and B amplifiers, their advantages and disadvantages, as well as possible areas of error, are analyzed. Then, the principle of Class AB amplifier is analyzed in the same way and the advantages and disadvantages of several biasing methods are studied. Two topology circuits are designed and their advantages are derived from the equations. Finally, the efficient application of class AB amplifiers in pacemakers is studied by theoretical and circuit design.

2. Circuit Analysis of Different Amplifiers

2.1 Principle of Class A Amplifier

An amplifier in which each transistor is on for the entire cycle is called a “class A” amplifier [Fig 1]. It conducts during one complete cycle of the input signal and generate minimum distortion as well as maximum output signal..

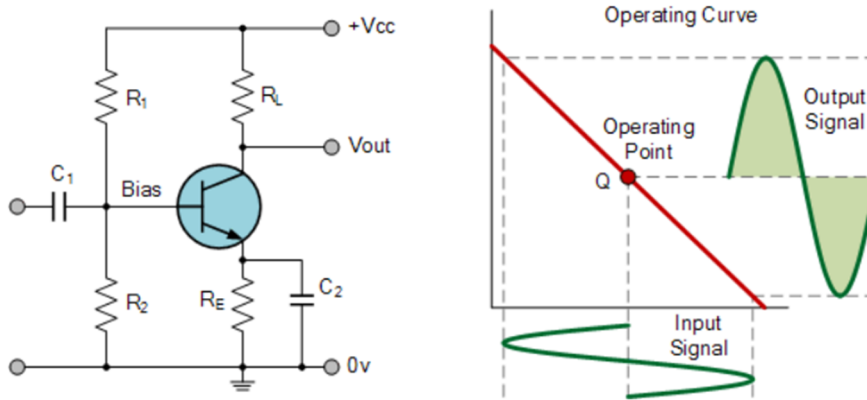


Figure 1. Basic diagram of class A amplifier

The class A amplifier is the ideal mode of operation because the output does not turn off distortion even during the negative half of the cycle. This is the simplest class A amplifier circuit. Its output stage uses a single-ended transistor with a load connected directly to the collector terminal.

However, this type of circuit has a very low efficiency because the current flow through the resistive load will waste much power, so the output transistor needs a larger heat sink.

2.2 Principle of Class B Amplifier

An amplifier in which the input signal goes positive, the positive biased transistor conducts which the negative transistor is switched off and when the input signal goes negative, the positive transistor switches off while the negative biased transistor turns on and conducts negative portion of the signal is called class ‘B’ amplifier Fig 2. Thus, the transistor conducts only half of the time.

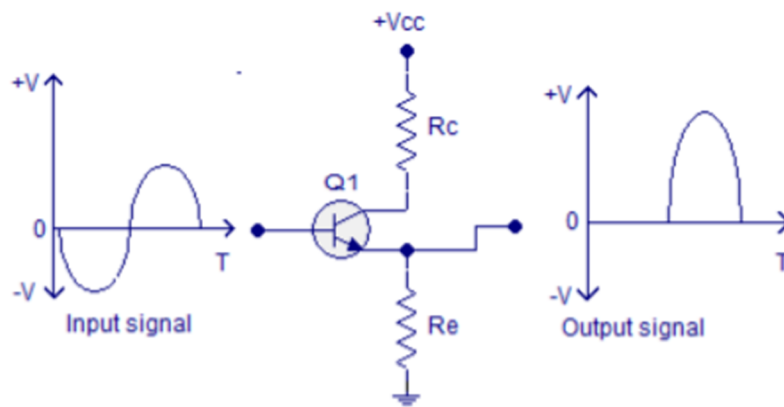


Figure 2. Basic diagram of class B amplifier

In order to achieve amplification for the entire cycle, a Class B amplifier that conducts in the negative half of the cycle must be added. Those two class B amplifiers is called push-pull operation [Figure 3].

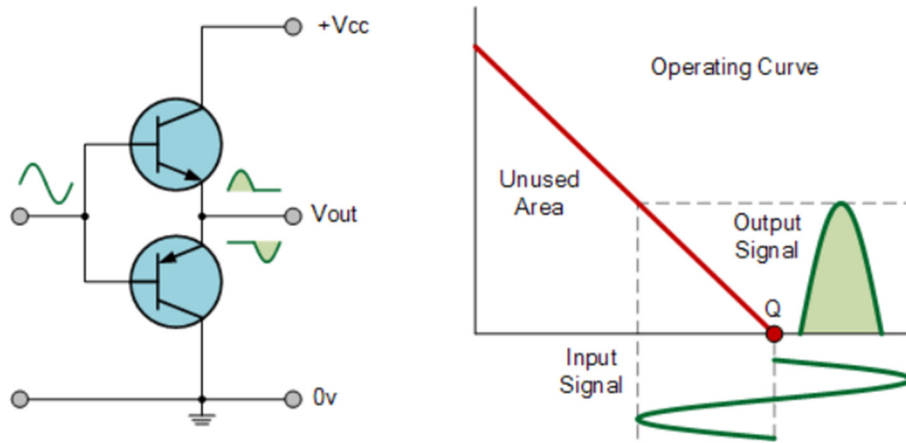


Figure 3. Push-pull class B amplifier

Class B amplifier is more efficient compared to Class A amplifier. No DC bias current, which greatly reduces power consumption. Since only signal current flows through the transistors, the output stage power consumption is reduced.

However, when the base DC voltage is zero, both transistors are cut off and the input signal voltage must exceed V_{BE} for the transistors to conduct. Therefore, there will be a period of time when neither transistor is on during the alternating positive and negative half-cycle of the input signal. This is called crossover distortion [Figure 4].

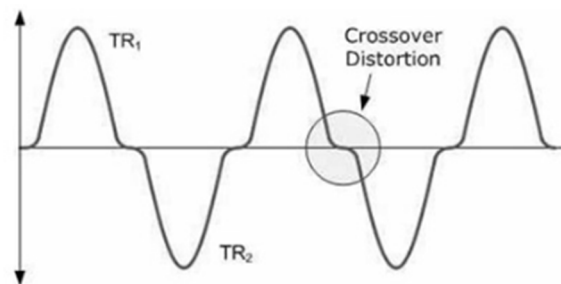


Figure 4. Crossover distortion

2.3 Principle of Class AB Amplifier

In order to overcome and eliminate the inefficiency of the class a amplifier and the distortion of the class B amplifier, and to take advantage of the advantages of both classes. a class amplifier and class B amplifier are combined to form a class AB amplifier. In the design, the conductivity of each transistor is slightly higher than the half cycle of class B conduction, but lower than the full cycle of class a conduction [Fig 5].

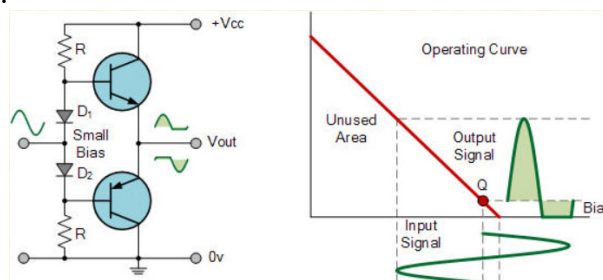


Figure 5. Class AB amplifier diagram

3. Bias Method for Class AB Amplifiers

3.1 Voltage Bias

The transistors are biased by applying a suitable fixed bias voltage to the bases of TR1 and TR2. When the input signal becomes positive, the voltage at the base of TR1 increases, producing a similar amount of positive output, which will increase the collector current flowing through TR1, thus providing current to the load R_L . However, since the voltage between the two bases is fixed, any increase in TR1 conduction will result in an equal and opposite decrease in TR2 conduction during the positive half cycle [6] [Fig 6].

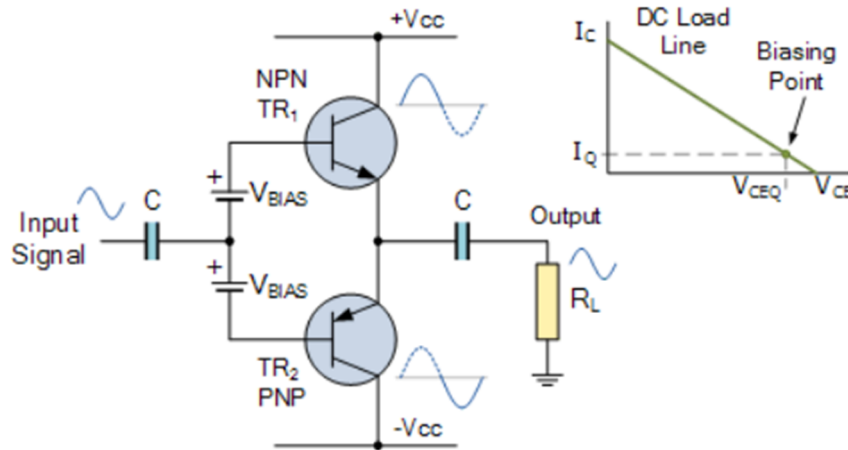


Figure 6. Voltage bias AB amplifier

3.2 Resistor Bias

The series connection of resistors and voltages can ship a voltage divider network that produces a fixed set of voltages [Fig 7].

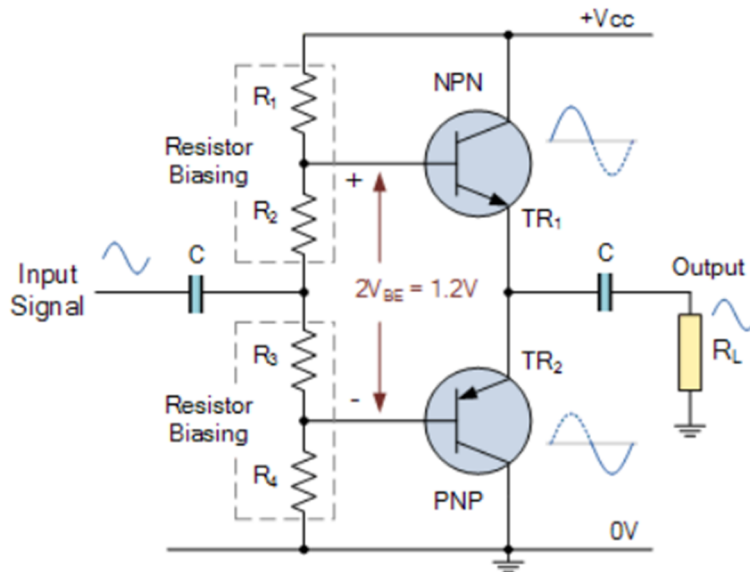


Figure 7. Resistor bias AB amplifier

3.3 Diode Bias

The diode can produce a constant voltage of 0.7V or more. This feature is used to provide a constant potential of 1.4V between the base of T1 and T2 transistors [Fig 5].

Class AB amplifiers eliminate crossover distortion and provide higher efficiency and signal amplification than class an amplifier. However, its efficiency is lower compared to class B amplifiers.

3.4 Circuit Topologies

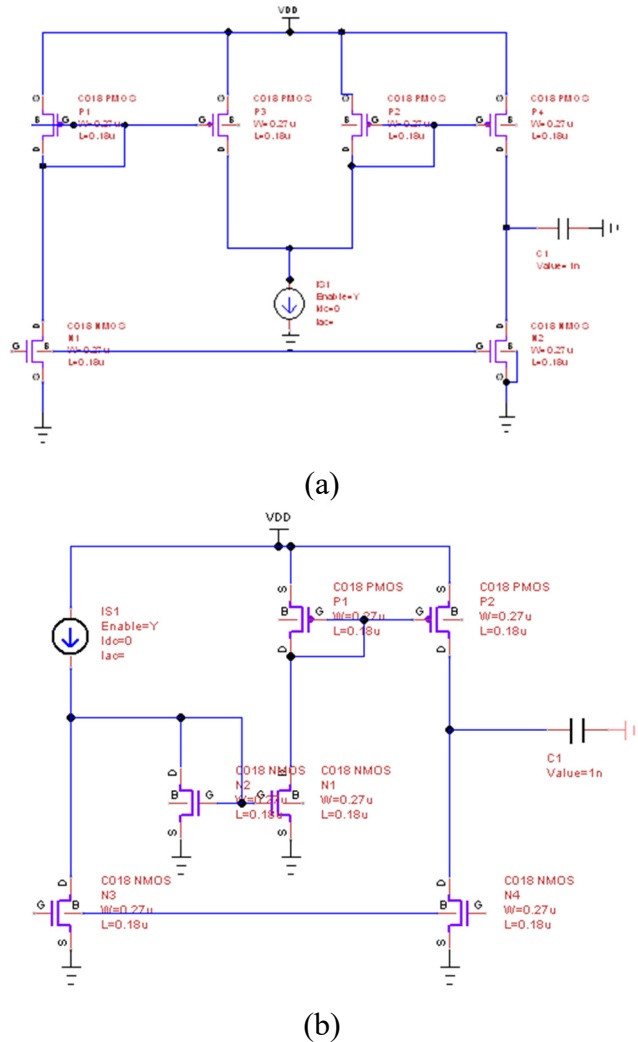


Figure 8. Circuit Topologies

This Class AB operation separates the signal output through the output transistor and the current reflector. In the quiescent state, the output current is zero and the output branch quiescent current must be such that the sum of the scaled versions of I_q at P2 and P3 in Fig 8(a) / the scaled versions of P1 and N1 in Fig 8 (b) is equal to I_{s1} [7]. This condition yield:

$$I_{q(a)} = \frac{k \cdot I_{AB}}{1 + \frac{k \cdot m}{h}}, \quad I_{q(b)} = \frac{k \cdot m \cdot I_{AB}}{1 + \frac{k \cdot m}{h}} \quad (1)$$

where h, k and m are the current mirrors gain factors.

The transconductance can be calculated by divide i_o to the v_i as: $g_m = g_{m_a} \left(1 + \frac{km}{h}\right) D(s)$, where g_{m_a} is the trans-conductance of the output transistor, and M_a and $D(s)$ are the frequency response contributions of the current reflector.

$$D(s) = \frac{1 + \left(\frac{1}{we} + \frac{1}{wc}\right) \frac{s}{gmmult} + \frac{1}{wewc} \frac{s^2}{gmmult}}{\left(1 + \frac{s}{we}\right) \left(1 + \frac{s}{wc}\right)} \quad (2)$$

Consider this output stage as the output stage of a Miller amplifier. Since the non-dominant pole of the op-amp is proportional to the output stage transconductance, we will reduce the output stage current by a ratio comparable to the increase in the output stage g_m/I_D ratio. Considering these factors, a 3 to 4 times reduction in electrostatic current over Class A current is achievable [7].

4. Design and Analysis of Cardiac Pacemaker

4.1 Pacemaker Circuit

In general, the pacemaker circuit can be divided into three parts: the amplifier circuit, the control circuit and the pacing circuit. The amplifier circuit is used to identify the movement of the heart. The ECG signal generated during the heartbeat has a specific waveform form, which can be recognized as long as the amplifier amplifies the waveform as necessary. After amplification of the ECG signal, appropriate processing and conversion is required to control the pacing circuit pulse generator. Since the patient's ECG signal varies, the controller needs to bring all incoming ECG waves to or above the threshold level. The pacing circuit is in a controlled state. When the patient's heart rate falls below the pacing state, the pacemaker outputs pacing pulses at a fixed frequency to stimulate the heart as needed. Pacemakers remain the primary implantable medical treatment to restore the normal rhythm of the diseased heart to exhibit a slower heart rate. Contraction of the heart by electrical stimulation [7].

While advances in microelectronic systems have made this possible, reduced power consumption and size remain central goals for increased functionality. Applying the class AB design to transducer amplifiers and using SOI CMOS can reduce current consumption to just 110 nA [1]. This perfectly demonstrates the advantages of fully depleted SOI CMOS in the micropower domain.

4.2 Perceptual Channel Requirements and Structure

The heart signal is a triangular waveform with a rise time of 2 ms and a fall time of 13 ms [8]. Since each patient is different, the detection voltage that triggers the pacemaker to send pacing pulses varies. To ensure that the characteristics of each patient can be matched, the threshold for testing must be variable [1].

A D/A converter can achieve amplifier and variable threshold can be implemented. When the sense amplifier is not operating, this converter can refresh every heartbeat cycle, because its output is a constant and much less power consumption which can be omitted[1]. Its basic structure is shown in Fig 9.

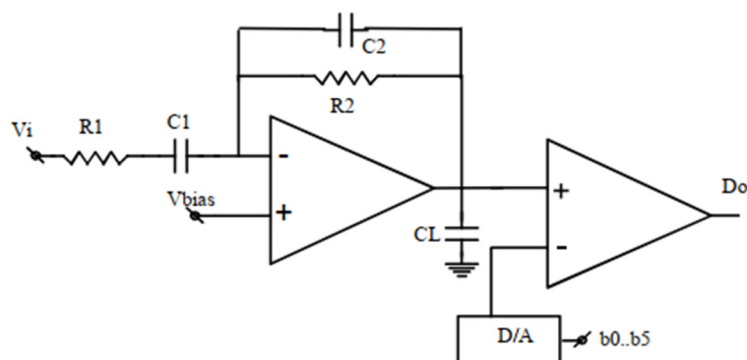


Figure 9. Basic sense channel architecture

R_1 and C_1 define the high pass characteristics at 70 Hz, while the low pass characteristics at 200 Hz can be defined by the first stage roll-off of the OTA. The implementation requires some external components, but due to its simplicity it won't consume much power [1]. In addition, some of these external components, such as C_1 , may also needed protection measures to prevent harm to the patient.

By optimizing the circuit at the circuit and technology level, the power consumption of the circuit can be significantly reduced [1].

4.3 Optimized OTA Architecture

Figure 10(a) shows a simplified schematic of the proposed OTA structure, and Figure 10(b) shows a single-transistor common-source amplifier. Assuming that the channel length of all devices in Fig 10 is L and the unit width is W_x , setting the bias voltage as V_B and the unit current as I_B , the single components are then scaled by integer factors K, H, S . The scaling factor can be achieved by placing more devices in parallel to ensure maximum matching. Under the above assumptions, the single component has cross-conductance g_m , input capacitance C_{GS} , and output resistance r_o . Scaling factors increase cross-conductance and capacitance, and decrease output resistance proportionally [9].

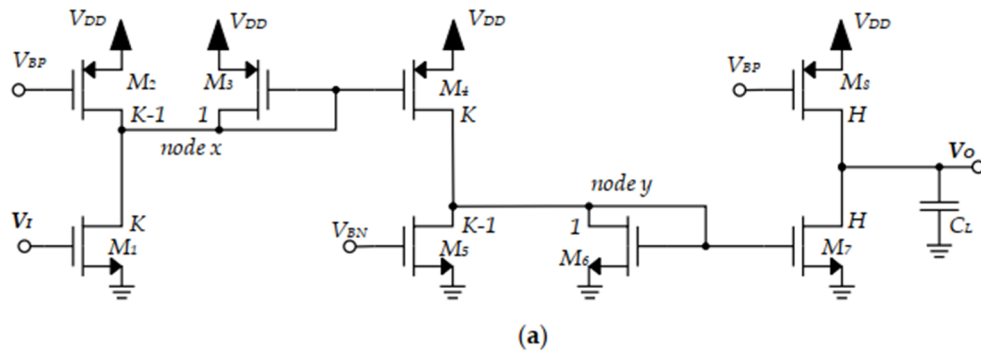


Figure 10. (a) Simplified topology of the amplifier,

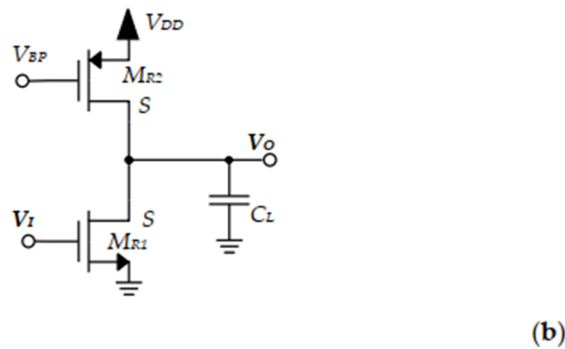


Figure 10. (b) conventional common-source amplifier

To make the above circuit have the same power consumption, set the amplifier $S = 2K+H$ in Fig. 10 (b). Both amplifiers have the same load capacitance C_L [9].

4.3.1 Small-signal Analysis

For the DC gain calculation, we assume that the output conductance $g_0 = r_o^{-1}$ of the MOS device is much lower than its cross-conductance g_m , making the two current mirrors M_3 - M_4 and M_6 - M_7 in Figure 10(a) show current gains of K and H , respectively. If the output resistance is taken into account, the current gain will be slightly lower.

However, in a practical implementation of the OTA architecture, a cascaded code current mirror can be used, in which case the current mirror will show very close to the ideal current gain due to the increase in the output resistance (g_{mro}^2). To simplify calculations and gain insight into the circuit behavior, it is convenient to split the DC gain of the amplifier in Fig 10(a) as follows:

$$\frac{v_o}{v_i} = \frac{v_o}{v_y} \frac{v_y}{v_x} \frac{v_x}{v_i} \quad (3)$$

Thus, the proposed OTA can be considered as a three-stage amplifier, where the first two stages are loaded by diode-connected MOS devices. Since the diode-connected loaded transistors are smaller than the common source devices driving them, the dc gain of both the first and second stages is approximately equal to k . Starting from these assumptions and performing simple calculations, the dc gain expression of the proposed OTA in Figure 10(a) (new) is:

$$A_{new} = \frac{K^2 g_{mN}}{g_{oN} + g_{oP}} \quad (4)$$

Whereas the DC gain of the conventional common-source amplifier in Fig 10(b) can be expressed as:

$$A = \frac{g_{mN}}{g_{oN} + g_{oP}} \quad (5)$$

It is clear from the above equation that the proposed structure shows an increase in DC gain of K^2 (about 20 dB when the factor K is in the range of 3) over the conventional common-source amplifier. The additional dc gain leads to better feedback performance at low frequencies, such as higher linearity and more accurate closed-loop gain [9].

4.4 A New Class AB OTA

Class AB amplifiers reduce power in many ways; first, by decoupling the output state requirements; second, by reducing quiescent current consumption when the signal to be processed (e.g. in this case the heart signal) is only "active" for a small part of the system cycle. Class AB amplifiers can be applied to such devices if they can operate at low voltages and guarantee low power consumption.

Because of its simple structure and the application of cross conductance multiplication effect, high bandwidth consumption rate is achieved [7]. Figures 8(a) and 8(b) shows a common-source structure. In our case, there are two ways to significantly reduce the power consumption. First, this structure provides a low impedance condition from the input to the driver stage output transistor. Second, the cross-conductance (g_m) of the output stage is increased due to the current reflection gain, significantly improving the output stage ratio (g_m/I_D). The circuit structure has general applications and in [7] we show implementations to achieve conversion frequencies up to 10 MHz.

5. Conclusion

A channel for an implantable cardiac pacemaker designed with SOI technology is brought up. Due to the optimization of the structure and the application of the class AB amplifier design, it plays a low power characteristics. The advantages and disadvantages of Class AB amplifiers and their applications are derived from the analysis of Class A, B and AB amplifiers. Finally, the pacemaker circuit is analyzed and further improvements can be made to the pacemaker by both optimizing the OTA frequency response and introducing new Class AB amplifiers.

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