

The Evolution Of Rail-to-Rail Amplifiers

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Process scaling and low-power optimization have drawn rail-to-rail amplifiers into common use. This article traces the development and improvement of the rail-to-rail amplifier's input stage, with a review of design trade-offs and example devices, culminating with the description of an input enhancement circuit that overcomes the typical trade-offs associated with these amps.

For simplicity, the focus is on MOSFET amplifiers. The input stage from a basic operational amplifier is shown in Fig. 1. A transistor pair, called a differential pair, sits on top of a current source to accommodate the differential input. While this topology provides differential gain and rejects common-mode signals, it has a limitation -- in operating range. The input voltage range is 0 V to 3.5 V with a 5-V single-supply. If the input voltage is raised above 3.5 V, the current source is forced out of saturation. Once the current source leaves the saturation region, the gain is distorted.

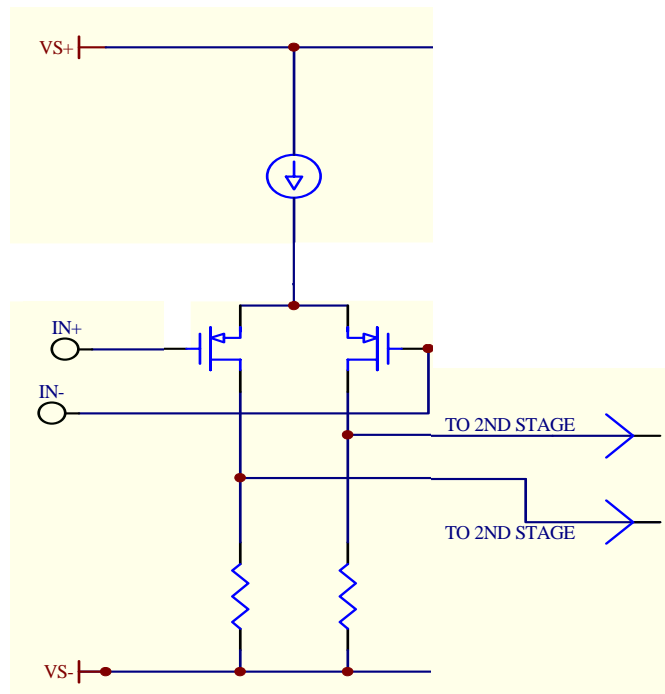


Fig. 1: Basic Op Amp Input Stage

For an example application, like an EKG, the quality of the design is directly related to the voltage range of signals that can be processed. A standard rail-to-rail op amp accommodates this challenge with a dual input stage (Fig. 2). When the input voltage approaches the lower supply rail, the pMOS transistor pair amplifies the signal. Conversely, the nMOS differential pair amplifies input signals that approach the upper supply rail. In this way, the input can span the entire supply voltage range. The most obvious trade-off to achieve this improvement in input range is the extra power required to bias the complementary differential pair.

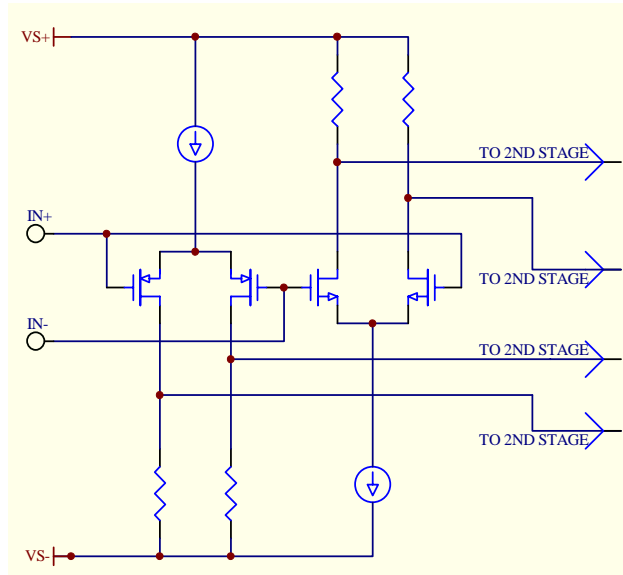


Fig. 2: Dual Input Stage For Rail-To-Rail Operation

A less obvious trade-off exists in the offset voltage with respect to the input bias voltage. The offset for the nMOS pair does not necessarily match the offset of the pMOS pair -- and occurs with opposing polarity. Somewhere near mid-supply there is a hand-off from one pair to the other. During the hand-off the offset voltage is the average of the offset from each pair. This creates a stair step characteristic as seen in Fig. 3. For added insight, the offset is plotted for a variety of temperatures. The pMOS input pair, active for low common-mode input voltages, exhibits a wide range of offset voltage versus temperature. The variation in the nMOS pair causes the distribution on the right side of the plot, for high common-mode input voltages.

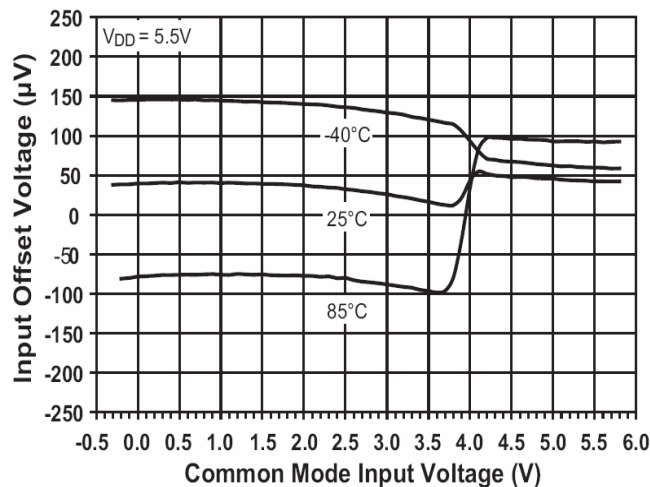


Fig. 3: Input Offset Voltage Vs. Input Common-Mode Voltage

In sensitive applications, like the EKG, any variation in offset voltage jeopardizes the accuracy of the system. The signal must first be amplified well beyond the offset voltage level to take advantage of rail-to-rail amplifiers with an input topology shown in Fig. 2.

In precision and low-power applications a new type of rail-to-rail amplifier is needed. The objective is to achieve a full-range of input voltages without the crossover distortion in the offset voltage that occurs during the hand-off region of the dual differential design. Let's return to the single differential design for guidance.

Remember that the input range of the topology (Fig. 1, again) does not allow for full-range input operation. A portion of the input range is preserved for biasing the current source in the saturation region. Can the biasing for the current source be accomplished in a manner allowing the input to span between the supply rails? Yes. An input-range enhancement circuit has been included in op amps (like the Intersil EL8178) to adjust the bias internally provided to the current source. Fig. 4 presents this innovative topology. Inside the enhancement circuit is a charge pump. While the mention of a charge pump usually beckons noise issues, this charge pump's operating frequency is beyond the bandwidth of the amplifier and there is no measurable change in the noise performance.

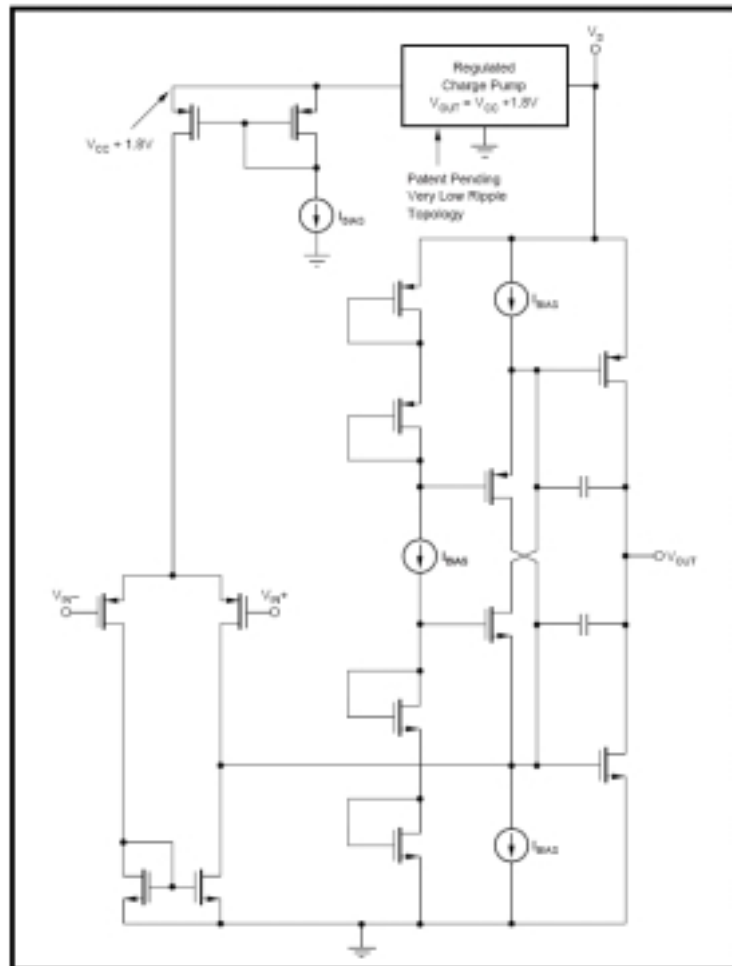


Fig. 4: Rail-To-Rail Input Stage With Input Range Enhancement Circuit

In addition, we must revisit the issue of offset voltage. Has it been improved as well? Fig. 5 shows that it has. The input range enhancement circuit allows a single differential pair to provide rail-to-rail operation without the need of a second, complementary differential pair. The offset voltage is completely dependent on the mismatch of only one set of transistors, so there is no crossover region. Careful layout and trimming can ensure that the input-referred offset voltage is less than $100\ \mu\text{V}$.

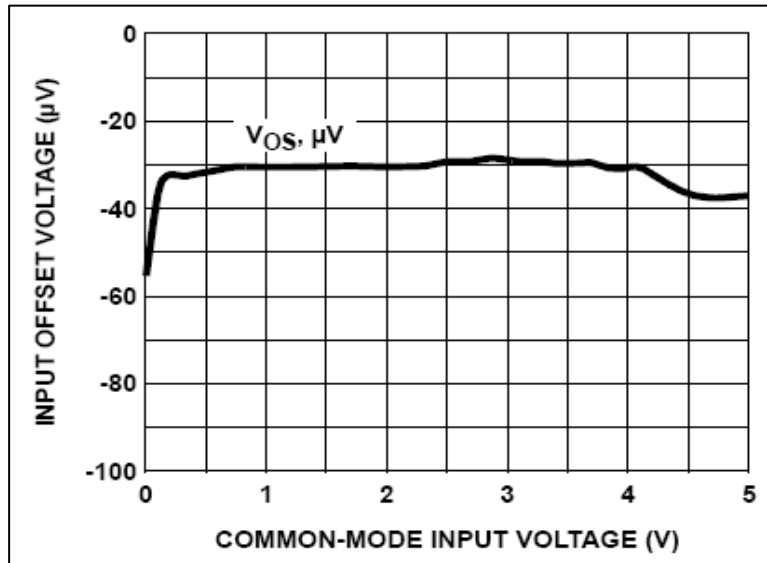


Fig. 5: Input Offset Voltage Vs. Input Common-Mode Voltage

The discussion so far has been limited to MOSFET implementations. Bipolar technologies can also benefit from this configuration. In addition to the improvement in offset voltage, a bipolar version would also exhibit a similar improvement in input bias current. The input bias current would only feed one matched differential pair, not two pairs with a crossover region.

This is a good example of the evolution of rail-to-rail amplifiers. The basic input stage, composed of a single-differential pair, doesn't allow a full-range of voltages at the input. A dual differential pair extends the input voltage range to the supplies, but suffers a non-linearity in the offset voltage (and input bias current in BJTs) because of the hand-off between the two pair. The third solution includes an internal enhancement to adjust the bias on the current source of a single differential pair to allow rail-to-rail operation with no discontinuity in offset voltage. Table 1 summarizes the performance of three examples of op amp. The final version, the EL8178, provides the specifications needed by low-power, high-resolution systems like a portable EKG machine.

Op Amp Input Type	Input Stage	Common-Mode Input Range (CMIR) on 5-V single-supply	Offset Voltage (Input-Referred)
Basic (EL5144)	Single differential pair	0 V to 3.5 V	25 mV
Rail-To-Rail (EL5111)	Dual differential pair	-0.5 V to 5.5 V	3 mV to 15 mV
Biased Rail-To-Rail (EL8178)	Single differential pair with input enhancement	0 V to 5 V	50 μ V – 100 μ V

Table 1: Performance Characteristics For Op Amps With Different Input Stages

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