

## Rail-to-Rail Amplifier With Integrated Charge Pump Improves Input Offset

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In modern electronic systems, the negative power supply is disappearing and the positive power supply voltage is decreasing. This trend is driving the prevalence of rail-to-rail amplifiers. While the supply voltage is changing, the signal level often remains the same. For example, the standard video signal drive level is 2 V and when the power supply comes down to 2 V, the amplifier/buffer must be linear or accurate within the full 2 V supply range. This TechNote focuses on the development of the rail-to-rail amplifier's input stage and discusses in detail the input enhancement circuit that overcomes the deficiencies associated with rail-to-rail amplifiers.

For simplicity, we will limit our discussion to MOSFET amplifiers. The input stage from a basic operational amplifier is shown in Fig. 1. A transistor pair, called a differential pair, sits atop a current source to accommodate the differential input. While this topology provides differential gain and rejects common-mode signals, its limitation is in its operating range. The input voltage range is 0 V to 1.5 V with a 3 V single-supply. If the input voltage is raised above 1.5 V, the current source is forced out of saturation. Once the current source leaves the saturation region, the gain is distorted.

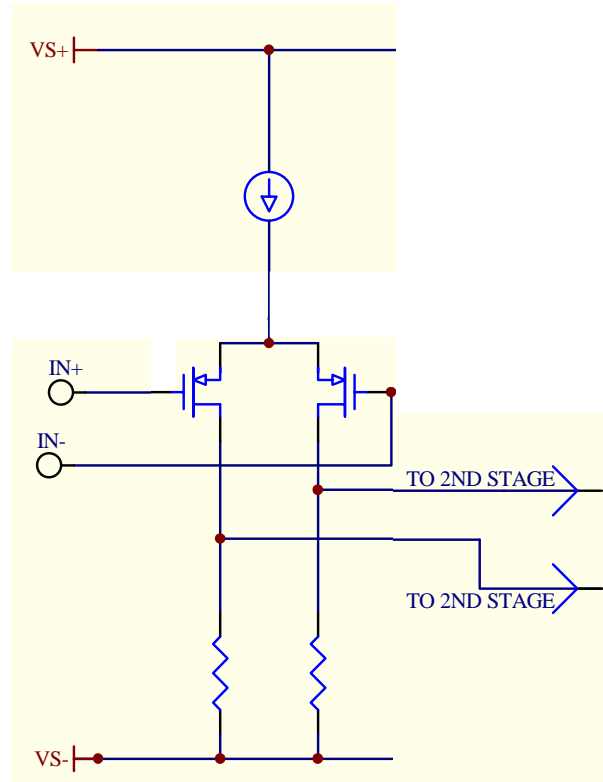
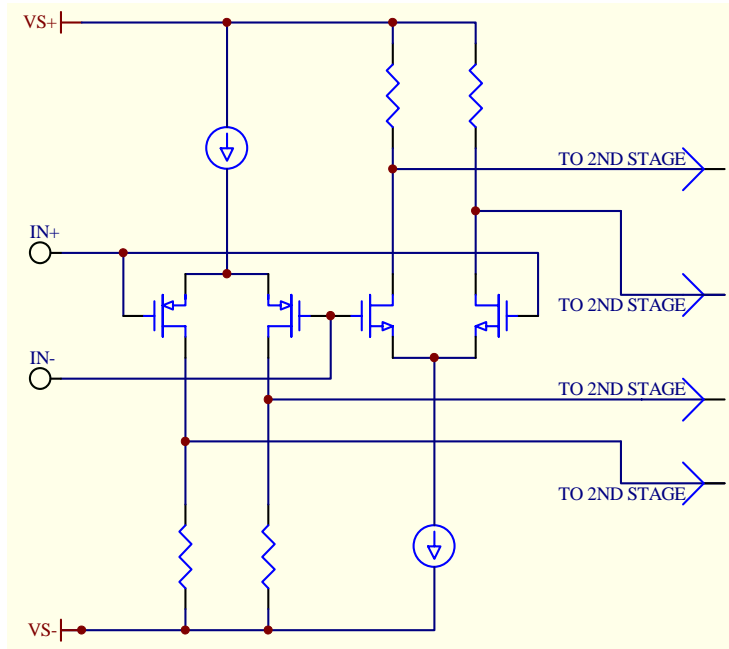


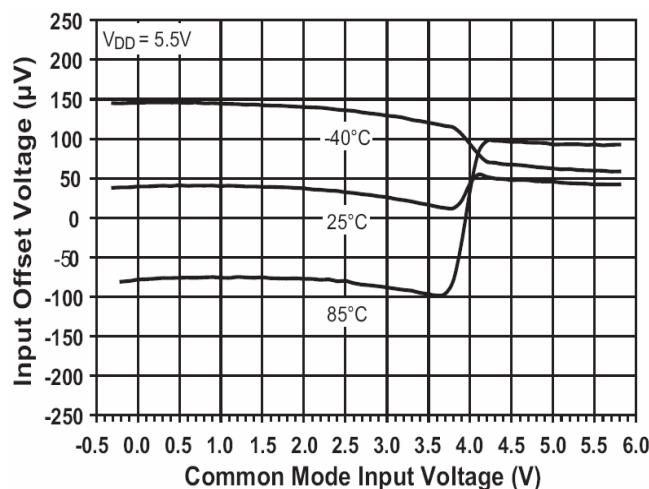
Fig. 1: Basic Op Amp Input Stage

For an example application like current sensing, or voltage sensing such as EKG, the quality of the design is directly related to the processed voltage range of signals.. A standard textbook rail-to-rail op amp topology accommodates this challenge with a dual input stage, as shown in 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 (see Fig. 3).

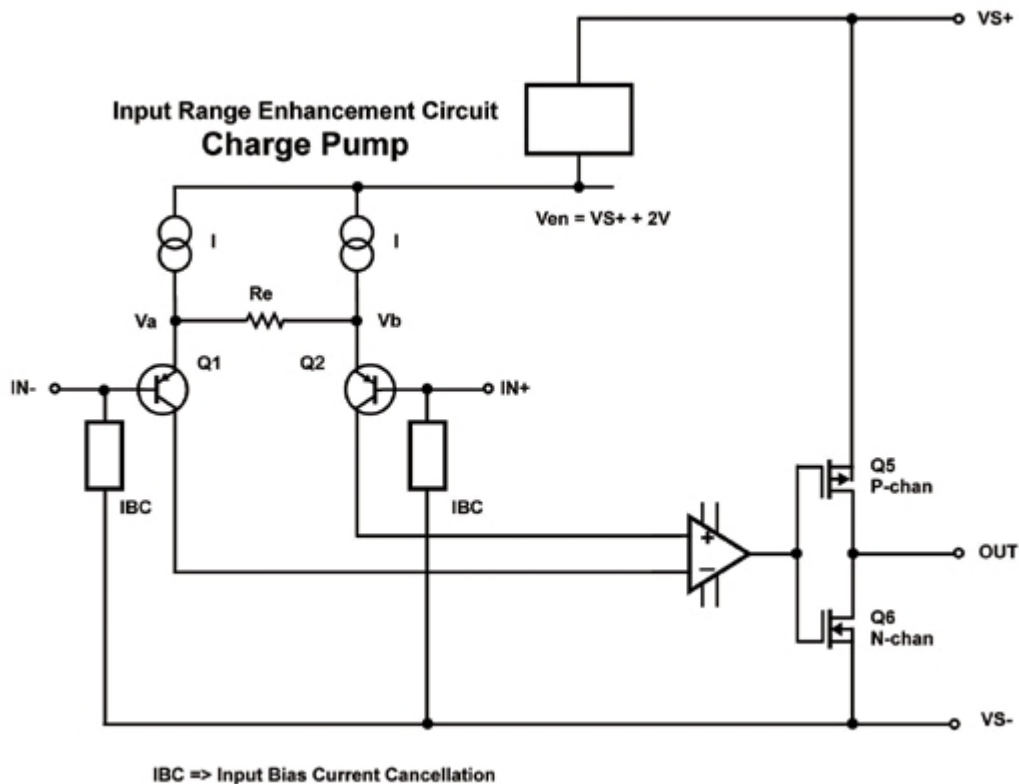


**Fig. 3: Input Offset Voltage Versus Input Common-Mode Voltage**

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.

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

In precision and low-power applications, a new type of rail-to-rail amplifier is needed. The goal is to achieve a full-range of input voltages without 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. The input range of the topology in Fig. 1 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? An input-range enhancement circuit has been included in op amps like the EL8178 to adjust the bias internally provided to the current source. Fig. 4 presents this innovative topology.

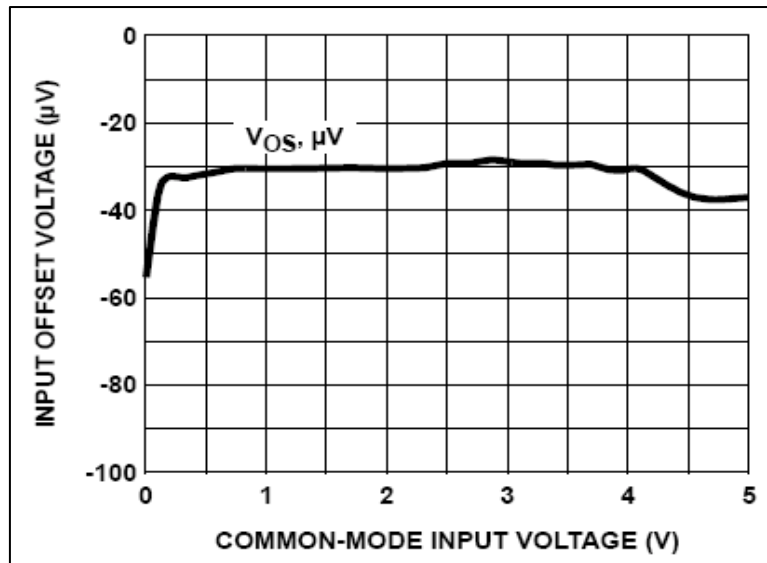


**Fig. 4: Rail-To-Rail Input Stage With Range Enhancement Circuit**

Inside the enhancement circuit is a charge pump. While the mention of a charge pump usually beckons noise issues, the charge pump's operating frequency is beyond the

bandwidth of the amplifier. Therefore, there is no measurable change in the noise performance of the amplifier.

In addition we must revisit the issue of offset voltage. Fig. 5 fulfills our goal of maintaining the offset voltage. 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 thus 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.

Thus is 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 pairs. 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 example op amps. The final version, the EL8178, provides the specifications needed by low-power, high-resolution systems like a portable EKG machine.

<b>Op Amp Input Type (Example)</b>	<b>Input Stage</b>	<b>Common-Mode Input Range (CMIR) On 5 V Single-Supply</b>	<b>Offset Voltage (Input-Referred)</b>
<b>Basic (EL5144)</b>	Single differential pair	0 V to 3.5 V	25 mV
<b>Rail-to-Rail (EL5111)</b>	Dual differential pair	-0.5 V to 5.5 V	3 mV to 15 mV
<b>Biased Rail-to-Rail (EL8178)</b>	Single differential pair with input enhancement	0 V to 5 V	50 $\mu$ V – 100 $\mu$ V

**Table 1: Characteristics For Example Op Amps With Three Different Input Stages**

### About The Authors

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