

## FAST SETTLING LOW-PASS FILTER

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Noise reduction by filtering is the most commonly used method for improving signal-to-noise ratio. The increase in settling time, however, can be a serious disadvantage in some applications such as high-speed data acquisition systems. The nonlinear filter described here is a simple way to get a four-to-one improvement in settling time as compared to a conventional filter.

To understand the circuit, first consider the dynamics of a single-pole RC filter (Figure 1). Filtering reduces broadband or "white" noise by the square root of the bandwidth reduction as shown by the following calculation:

$$e_n^2 = \int_{f_1}^{f_2} e_B^2 df = e_B^2 \cdot f \Big|_{f_1}^{f_2}$$

$$e_n = e_B (f_2 - f_1)^{1/2}$$

Where:

$e_n$  = total noise (Vrms)

$e_B$  = broadband noise (V/√Hz)

$f_1, f_2$  = frequency range of interest (Hz)

In other words, if the frequency range ( $f_2 - f_1$ ) is reduced by a factor of 100, the total noise would be reduced by a factor of 10.

Unfortunately, settling time depends on bandwidth. The penalty for the noise reduction is increased settling time. For a single-pole filter, the time needed for the signal to settle to any given accuracy can be calculated as follows:

For  $V_O/V_{IN}$  at time =  $t_s$

$$\frac{V_O}{V_{IN}} = 1 - e^{-(t_s/[R_1 \cdot C_1])}$$

$$-\left(\frac{V_O}{V_{IN}} - 1\right) \cdot 100 = \%$$

therefore

$$t_s = -\ln(\%/100) \cdot R_1 \cdot C_1$$

Where:

$t_s$  = settling time (s)

% = percent accuracy at  $t_s$

$R_1 \cdot C_1$  = RC time constant ( $\Omega \cdot F$ ) or (s)

For example, if a settling to 0.01% is needed,

$$\ln(0.01/100) = -9.2$$

In other words, it takes 9.2  $R_1 \cdot C_1$  time constants for an input step to settle to within 0.01% of its final value.

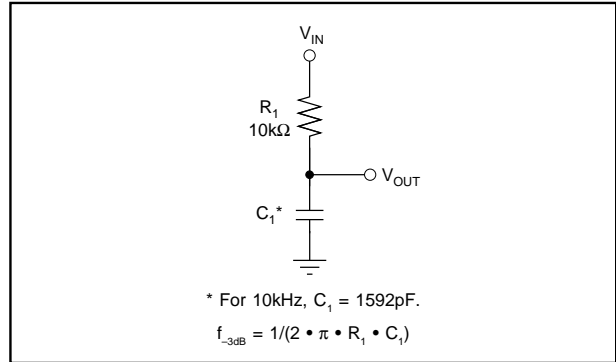


FIGURE 1. Conventional Single-Pole RC Filter.

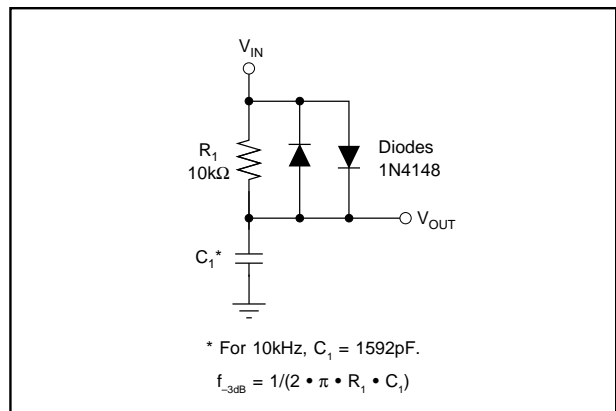


FIGURE 2. Diode-Clamped Nonlinear Filter (can improve 0.01% settling time for a conventional filter by 2/1 for a 20V step).

### NONLINEAR FILTER

To understand how a nonlinear filter can improve settling time, consider the simple diode clamped nonlinear filter, shown in Figure 2. Settling time is improved because the filter capacitor,  $C_1$ , is charged faster through the low forward biased diode impedance ( $R_{ON}$ ) during the initial portion of a large input step change. When the difference between the input and output voltage becomes less than the forward biased diode drop (about 0.6V), the diode turns off and  $C_1$  reacts with  $R_1$  alone. At this point, the circuit behaves like a normal single-pole RC filter.

Assuming diode  $R_{ON}$  is negligible, the improvement in settling time depends on the ratio of the input step voltage to the forward biased diode voltage. For a step of  $-10\text{V}$  to  $+10\text{V}$  (a 20V step), the improvement is  $\ln(0.60/20)$  or 3.5 time constants. In other words, for a 20V step, the simple

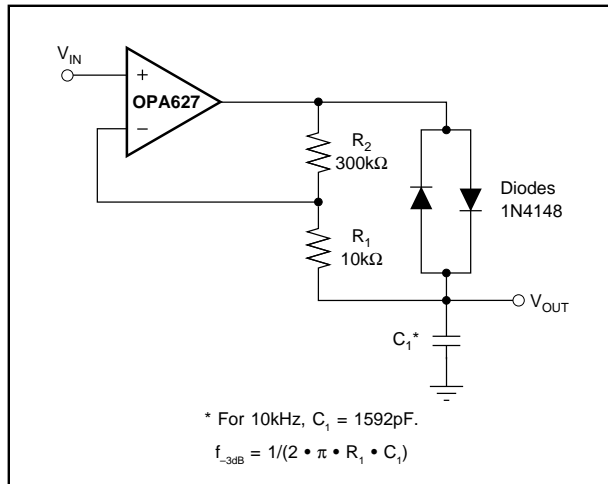


FIGURE 3. Improved Nonlinear Filter (can improve 0.01% settling time for a conventional filter by 4/1 for a 20V step).

diode clamped nonlinear filter can improve 0.01% settling time from 9.2 time constants to

$$(9.2) - (3.5) = 5.7 \text{ time constants.}$$

For smaller differences between the input step change, and the forward biased diode voltage, the simple diode-clamped nonlinear filter affords less improvement. As the step change approaches the forward biased diode voltage, the simple nonlinear filter offers no improvement.

### IMPROVED NONLINEAR FILTER

By reducing the threshold to below one diode drop, the settling time can be improved for smaller inputs. The improved nonlinear filter shown in Figure 3 lets you adjust the threshold to a small arbitrary value by adjusting the ratio of  $R_1$  and  $R_2$ .

To see how the improved nonlinear filter works, notice that the op amp forces the voltage at its inverting input to be the same as at the noninverting input. For small differences between the output voltage and the input voltage, the difference is dropped across the 10kΩ resistor,  $R_1$ , and the filter behaves like a single-pole filter with an  $R_1 \cdot C_1$  time constant. The voltage divider formed by  $R_1$  and  $R_2$  amplifies the voltage difference across  $R_1$ , as seen at the top of  $R_2$ , by  $(1 + R_2/R_1)$ . As the voltage across the  $R_1, R_2$  divider becomes larger, one of the diodes (which one depends on signal polarity) begins to conduct, and the capacitor is rapidly charged through it. This occurs at a voltage difference between the input and output of about  $0.6V/(1 + R_2/R_1)$  or about 20mV with the values shown. With the diode forward biased, the time constant of the filter becomes very small, limited only by op amp slew rate or current limit.

To determine the component values for the improved nonlinear filter, consider the noise-reduction requirements of the filter. For example, if you want to filter the noise of a 20V full-scale signal to 0.01% resolution, the peak noise must be filtered to less than 0.01% of 20V, i.e. 2mV peak. A clamp

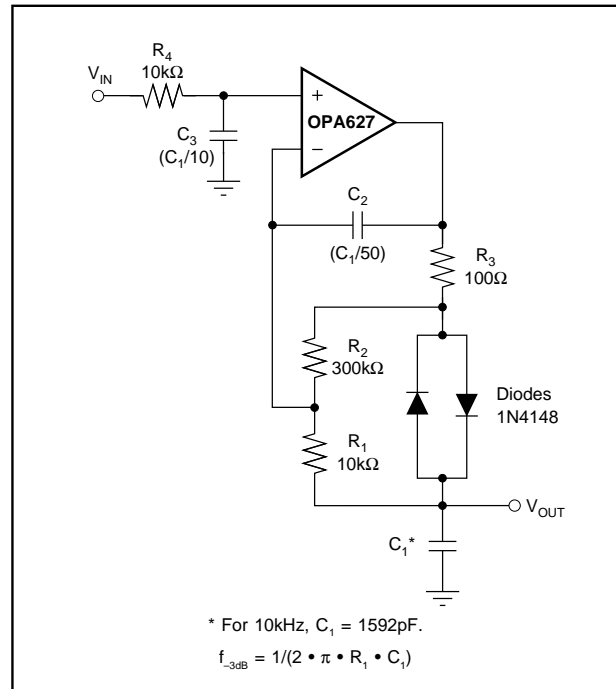


FIGURE 4. Improved Nonlinear Filter with  $R_4, C_3$  Prefilter and  $R_3, C_2$  Network to Assure Op Amp Stability in Driving  $C_1$ .

threshold of ten times this peak (20mV) is an arbitrary but ample threshold. The component values shown in Figure 3 set the filter's threshold to 20mV. For a 20V step as before, the improvement in settling time is  $\ln(0.02/20) = 6.9$  time constants. In other words, for a 20V step, the improved nonlinear filter can improve 0.01% settling time from 9.2 time constants to  $(9.2) - (6.9) = 2.3$  time constants—a four-to-one improvement.

### SOME SIGNALS REQUIRE PREFILTERING

In some instances, the input signal may have noise peaks above the 20mV threshold of the nonlinear filter. If the noise of the input signal to the nonlinear filter is greater than the 20mV threshold, the filter will mistake the noise for a step input and fail to filter it out. To prevent this situation an input prefilter can be added to the nonlinear filter as shown in Figure 4.

The prefilter's bandwidth is set by  $R_4$  and  $C_3$ . To minimize the prefilter's effect on settling time, its bandwidth is set ten times higher than the bandwidth of the nonlinear filter. At this higher bandwidth, the prefilter's effect on settling time is negligible, and the noise at the prefilter's output is  $\sqrt{10}$  times greater than 2mV (a little over 6mV peak). A noise level of 6mV provides a comfortable margin for a 20mV threshold.

### ASSURE OP AMP STABILITY

Op amps tend to become unstable and oscillate when driving large capacitive loads. The  $C_2, R_3$  network, shown in Figure 4, assures op amp stability when driving large values of  $C_1$

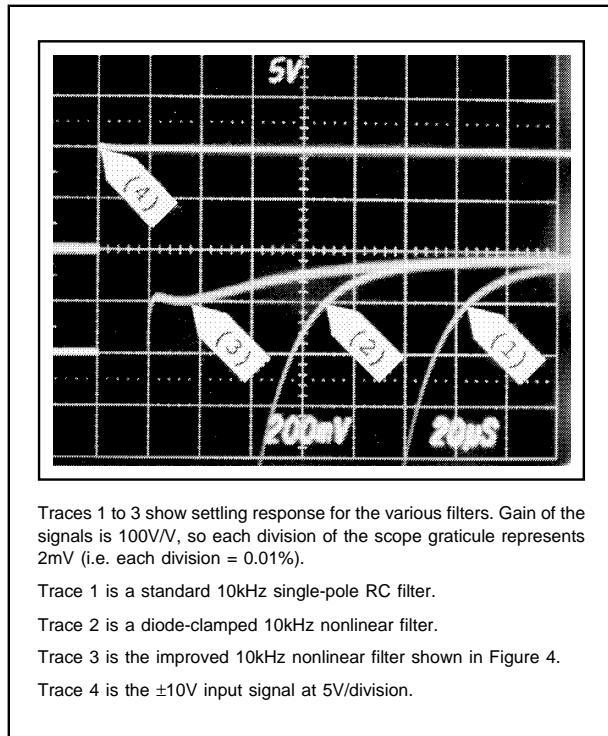


FIGURE 5. Settling-Time Response of Standard and Non-linear Filters.

through the low impedance of the forward biased diode network. The  $C_2$ ,  $R_3$  network may not be needed if  $C_1$  is small.

When choosing the op amp for the improved filter, make sure it has high output drive capability for charging  $C_1$ , and that its slew rate, settling time, and DC precision are adequate for the necessary filter response. The OPA627 shown has an excellent combination of DC precision, high slew rate, fast settling time and high output drive capability. The 16MHz bandwidth of the OPA627 gives excellent results for filters with -3dB bandwidths up to 100kHz. Also, notice that the op amp noise adds (at unity gain) to the signal noise. When a low noise op amp is used, this noise will be negligible in most instances.

The OPA627 contributes only a 6% increase in noise to the minimum theoretical noise of the 10kΩ resistor used in the filter. Remember that noise adds as the square root of the sum of the squares. To determine how much the 4.5nV/√Hz noise of the OPA627 adds to the 12.8nV/√Hz noise of the 10kΩ resistor, calculate the noise of the two components and compare that to the noise of the resistor alone:

$$\sqrt{(4.5)^2 + (12.8)^2} / 12.8 = 1.06, \text{ a 6\% increase}$$

Figure 5 is a triple exposure scope photo showing the filter output error settling time response for the three circuits to a -10V to +10V input step (20V). The bandwidth of each filter is set to 10kHz. The settling response is in a gain of 100 so that each box represents 2mV, or 0.01% of a 20V step. The filter has settled to 0.01% when the trace is within one box

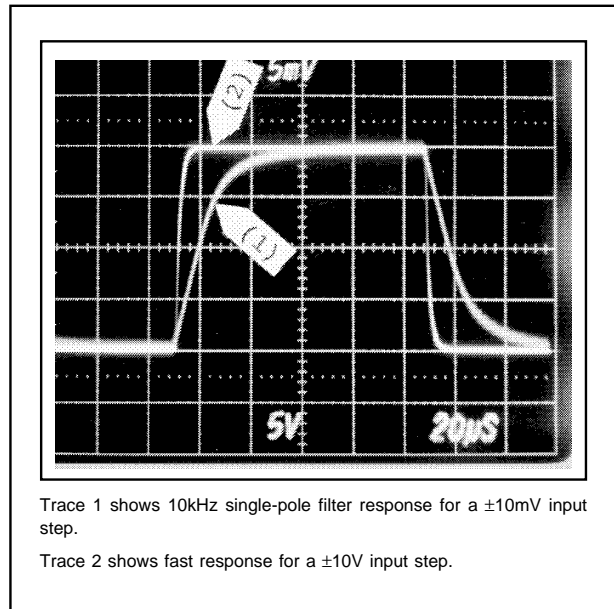


FIGURE 6. Comparison of Large and Small Signal Step Response of the Improved Nonlinear Filter.

FILTER TYPE	THEORETICAL SETTTLING TIME (time constants)	THEORETICAL SETTTLING TIME (µs) <sup>(1)</sup>
Single-Pole RC	9.2	147
Diode-Clamped Nonlinear	5.7	91
Improved Nonlinear	2.3	37

NOTE: (1) Settling to 0.01% of final value for a 10kHz filter.

TABLE I. Theoretical Settling Times for Various Filters.

of the base grid.

For a 10kHz filter, one RC time constant is 15.9µs. Ignoring input slew rate, and diode forward resistance (good approximations for the 10kHz filter when using an OPA627 op amp), the theoretical settling times are shown in Table I.

Notice that the actual measurements shown by the scope photos agree to the theoretical values within the resolution of the photographs.

Figure 6 is a double exposure scope photograph of the improved nonlinear filter operating at a high and low signal level. At the low level (a ±10mV input step), the response is that of a 10kHz single-pole RC filter as expected. At the high level (a ±10V input step), the greatly improved settling response is observed.

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