

## Preamplifier Introduction

### Matching the Preamplifier to the Detector and the Application

The primary function of a preamplifier is to extract the signal from the detector without significantly degrading the intrinsic signal-to-noise ratio. Therefore, the preamplifier is located as close as possible to the detector, and the input circuits are designed to match the characteristics of the detector. Different pulse processing techniques are typically employed, depending on whether the arrival time or the amplitude (energy) of the detected event must be measured. Pulse shaping for either application is normally implemented in a subsequent module. This module can be located at some distance from the preamplifier, provided that the signal fidelity is not degraded due to the length of the interconnecting coaxial cable.

Several types of detectors produce moderately large signals at their outputs, and this relaxes the restrictions on the noise contribution from the preamplifier. Detectors that typically fall in this category are: photodiodes operating with intense light pulses, photomultiplier tubes (PMT), scintillation detectors (scintillator mounted on a PMT), microchannel plate PMTs, microchannel plates, channeltrons, and electron multipliers. For such detectors, a wideband amplifier with a low input impedance can be used directly at the detector output to generate short, fast-rising pulses for timing or counting purposes. For pulse-amplitude (or energy) spectroscopy, a relatively inexpensive preamplifier, such as the Model 113 or the Model 142IH, can be used to integrate the charge in the pulse at the detector output.

Detectors with much better resolution are frequently used for energy spectroscopy with x rays, gamma rays, and charged particles. Typical detectors in this category are: Si(Li) (planar), germanium (coaxial, LO-AX™, and planar), silicon charged-particle detectors, and gas proportional counters. Because such detectors produce very small output signals, it is essential that the input stage of the preamplifier contribute little noise. The requirement for low noise and stable sensitivity with these detectors is met by using a charge-sensitive preamplifier with an FET (Field-Effect Transistor) input stage. For silicon charged-particle detectors and proportional counters the entire preamplifier usually is operated at room temperature. However, the excellent resolution of the cooled germanium and Si(Li) detectors necessitates lowering the temperature of the FET input stage of the preamplifier to reduce the noise. Operation at a temperature near 120° K is accomplished by mounting the FET near the detector inside the cryostat. Specifications for these cooled preamplifiers are incorporated with the relevant detector in the ORTEC Detector Catalog. The room-temperature preamplifiers are described on the next few pages. The signal at the output of the charge-sensitive preamplifier can be used for either timing or energy spectroscopy.

ORTEC manufactures a preamplifier to fit your detector, your application, and your budget. The applications information and selection guides will help you to choose the optimum preamplifier for your task.

### Preamplifier Types

Three basic types of preamplifiers are available: the current-sensitive preamplifier, the parasitic-capacitance preamplifier, and the charge-sensitive preamplifier. The following paragraphs describe their functions and primary performance characteristics.

#### Current-Sensitive Preamplifiers

Several detector types, such as photomultiplier tubes and microchannel plates, generate a moderately large and fast-rising output signal through a high output impedance. Pulse processing for timing or counting with these detectors can be rather simple. A properly-terminated 50-Ω coaxial cable is attached to the detector output, so that the current pulse from the detector develops the desired voltage pulse across the 50-Ω load presented by the cable. For scintillators mounted on 14-stage photomultiplier tubes, this voltage signal is usually large enough to drive the input of a fast discriminator without further amplification. For single-photon counting, 10-stage photomultiplier tubes, or microchannel plate PMTs, additional amplification is needed between the detector and the discriminator, and this is the function of the current-sensitive preamplifier.

The 50-Ω input impedance of the current-sensitive preamplifier provides proper termination of the 50-Ω coaxial cable, and converts the current pulse from the detector to a voltage pulse. If the rise time of the preamplifier is negligible compared to the detector rise time, and the voltage gain of the preamplifier is A, the amplitude of the voltage pulse at the preamplifier output will be

$$V_{\text{out}} = 50 I_{\text{in}} A \quad (1)$$

where  $I_{\text{in}}$  is the amplitude of the current pulse from the detector. For counting applications this signal can be fed to a fast discriminator, whose output is recorded by a counter/timer.

For timing applications the dominant limitation on timing resolution with photomultiplier tubes and microchannel plates is fluctuation in the transit times of the electrons as they cascade through the detector. This causes a jitter in the arrival time of the pulse at the detector output. However, if the detector signals are small enough to require a current-sensitive preamplifier, the effect of preamplifier input noise on time resolution must also be considered.

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The noise added to the signal by the preamplifier causes an uncertainty or jitter in the time at which the pulse crosses the threshold of the timing discriminator. The result is a degradation of the time resolution. Therefore, it is important to choose a current-sensitive preamplifier whose rise time is similar to the rise time of the pulse at the detector output.<sup>1</sup> A preamplifier rise time that is much faster than the detector rise time does not improve the signal rise time. But, it does contribute extra noise, because of the unnecessarily wide bandwidth. This excess noise will increase the timing jitter. Choosing a preamplifier rise time that is much slower than the detector rise time reduces the preamplifier noise contribution, but not enough to overcome the degradation in pulse rise time and amplitude. Consequently, the timing jitter becomes worse.

Although the optimum choice depends on the rise time and amplitude of the detector signal, as well as the characteristics of the preamplifier input stage, a good guideline is to choose a preamplifier rise time that is within a factor of 2 of the detector rise time (faster or slower). Rise times for photomultiplier tubes range from 1.5 to 10 ns, making the Models VT120, 9301, and 9305 Preamplifiers appropriate for consideration. The Model 9306 1-GHz Preamplifier is the optimum choice for timing with the 150-ps rise times encountered with microchannel plate PMTs.

Most fast preamplifiers with gains in excess of 10 must employ ac-coupling between internal amplifying stages to achieve fast rise times and to eliminate dc drift with temperature. This is an excellent solution if the average spacing between pulses is greater than 100 times the individual pulse width. But, when the average spacing between pulses becomes comparable to the pulse width, the ac-coupling causes the baseline between pulses to shift so that the preamplifier output signal circumscribes as much area above ground potential as it does below ground. This effect distorts the amplitude measurement in subsequent modules. The Model 9305 Preamplifier offers a solution to this problem in cases where lower gain ( $A=10$ ) and a slightly slower rise time (3 ns) is acceptable. The Model 9305 is dc-coupled and exhibits excellent dc stability. By operating a photomultiplier tube with the cathode at high voltage, the anode can be dc-coupled to the input of the Model 9305 Preamplifier. This scheme eliminates the baseline shift at high counting rates, and permits operation at much higher counting rates.

Most current-sensitive preamplifiers designed for timing applications have ac-coupled time constants in the range of a few hundred nanoseconds. The model 9326 overcomes that limitation by offering a low-frequency roll-off at an exceptionally low 10 kHz.

### Parasitic-Capacitance Preamplifiers

Photomultiplier tubes, electron multipliers, microchannel plates, and microchannel plate PMTs produce moderately large output signals with very fast rise times. Therefore, the most cost-effective preamplifier for pulse-amplitude measurements or energy spectroscopy with these detectors is the parasitic-capacitance preamplifier illustrated in Fig. 2.

Parasitic-capacitance preamplifiers have a high input impedance ( $\sim 5\text{ M}\Omega$ ). Hence, the current pulse generated by the detector is integrated on the combined parasitic capacitance present at the detector output and the preamplifier input. This combined capacitance is typically 10 to 50 pF. The resulting signal is a voltage pulse having an amplitude proportional to the total charge in the detector pulse, and a rise time equal to the duration of the detector current pulse. A resistor connected in parallel with the input capacitance causes an exponential decay of the pulse with a time constant  $\sim 50\ \mu\text{s}$ . An amplifier having a high input impedance and unity gain is included as a buffer to drive the low impedance of a coaxial cable at the output. The  $93\text{-}\Omega$  resistor in series with the output absorbs reflected pulses in long cables by terminating the cable in its characteristic impedance.

Parasitic-capacitance preamplifiers are not used with semi-conductor detectors because the gain of this type of preamplifier is sensitive to small changes in the parasitic capacitance. For partially-depleted semiconductor detectors the detector capacitance varies with the bias voltage applied to the detector diode. In addition, small movements of the interconnecting cable can change the input

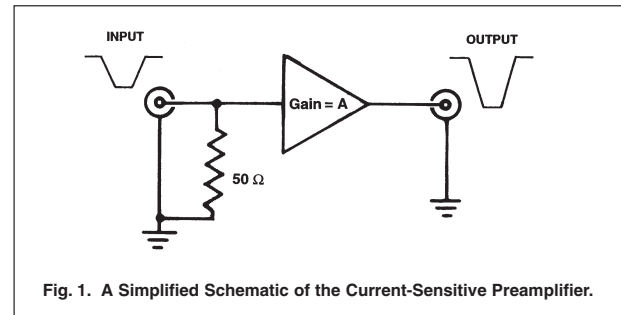


Fig. 1. A Simplified Schematic of the Current-Sensitive Preamplifier.

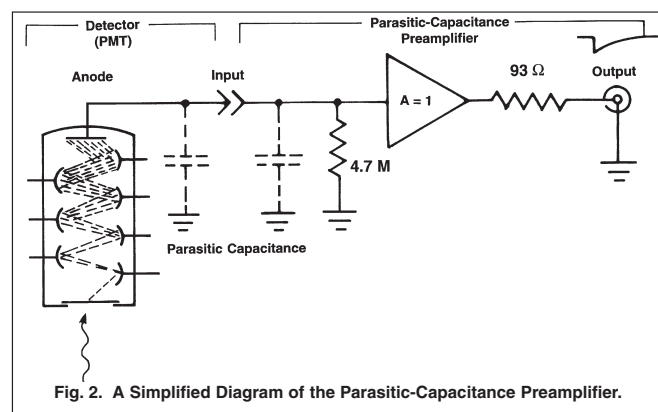


Fig. 2. A Simplified Diagram of the Parasitic-Capacitance Preamplifier.

<sup>1</sup>S. Cova, M. Ghioni, and F. Zappa, *Rev. Sci. Instrum.* **62** (11), Nov. 1991, pp. 2596–2601.

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capacitance by a few tenths of a pF. The gain changes caused by these effects are significant for semiconductor detectors, which have energy resolutions better than 1%. However, parasitic-capacitance preamplifiers, such as the ORTEC Model 113, provide more than adequate performance with photomultiplier tubes, microchannel plate PMTs, or scintillation detectors, and are highly recommended for those applications.

### Charge-Sensitive Preamplifiers

These preamplifiers are preferred for most energy spectroscopy applications. The signal from a semiconductor detector or ion chamber is a quantity of charge delivered as a current pulse lasting from  $10^{-9}$  to  $10^{-5}$ s, depending on the type of detector and its size. For most applications the parameters of interest are the quantity of charge and/or the time of occurrence of an event. A charge-sensitive preamplifier (Fig. 3) can deliver either or both. Because it integrates the charge on the feedback capacitor, its gain is not sensitive to a change in detector capacitance, and in the ideal case, the rise time of the output pulse is equal to the detector current pulse width.

The output voltage from the preamplifier has an amplitude  $V_o$ , and a decay time constant  $\tau_f$ , given respectively by

$$V_o = \frac{Q_D}{C_f} \text{ and } \tau_f = R_f C_f \quad (2)$$

where  $Q_D$  is the charge released by the detector,  $C_f$  is the feedback capacitor (0.1 to 5 pF), and  $R_f$  is the feedback resistor.  $R_f$  is a noise source and in direct-coupled system, is made as large as possible consistent with the signal energy-rate product and the detector leakage current. The preamplifier package is kept small to permit mounting it as close as practical to the detector, thus reducing input capacitance caused by cabling and decreasing microphonic noise, ground loops, and radio frequency pickup, all of which are sources of noise for the charge-sensitive preamplifier.

In the selection chart, sensitivity is generally expressed in mV per MeV of energy deposited in a given detector material. The charge released by the detector is a function of the photon or particle energy and the detector material, and is given by

$$Q_D = \frac{E e \times 10^6}{\epsilon} \quad (3)$$

where  $E$  is the energy in MeV of the incident radiation,  $e$  is the charge of an electron ( $1.6 \times 10^{-19}$  coulomb),  $10^6$  converts MeV to eV, and  $\epsilon$  is the amount of energy required to produce an electron-hole pair in the detector. Approximate values for  $\epsilon$  for various detectors are given in Table 1. For the special case of a proportional counter, the right hand side of Equation (3) must be multiplied by the gas gain of the proportional counter.

From Eqs. (2) and (3) the output voltage produced by a charge-sensitive preamplifier is

$$V_o = \frac{E(10^6)(1.6 \times 10^{-19})}{C_f \epsilon} \quad (4)$$

Therefore, the preamplifier gain can be expressed as

$$\frac{V_o}{E} = \frac{e(10^6)}{C_f \epsilon} \quad (5)$$

The sensitivity of a preamplifier with  $C_f = 1 \times 10^{-12}$  F connected to a room-temperature silicon detector is

$$\frac{V_o}{E} = \frac{(1.6 \times 10^{-19})(10^6)}{(1 \times 10^{-12})(3.62)} = \frac{44 \text{ mV}}{\text{MeV}} \quad (6)$$

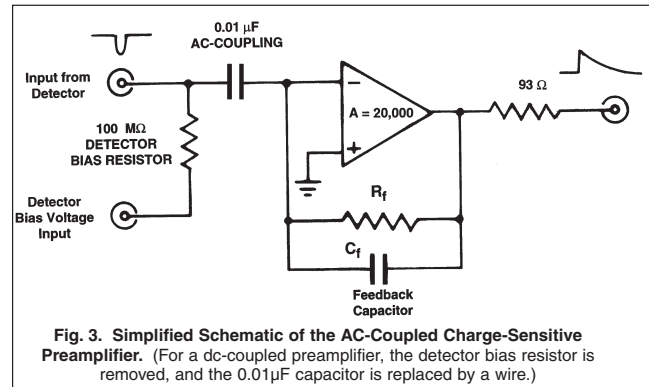


Fig. 3. Simplified Schematic of the AC-Coupled Charge-Sensitive Preamplifier. (For a dc-coupled preamplifier, the detector bias resistor is removed, and the 0.01 μF capacitor is replaced by a wire.)

Table 1. Values of $\epsilon$ for Various Detectors.	
Detector	$\epsilon$ (eV)
Silicon	3.62 (300° K)* to 3.71 (77° K)
Germanium	2.96 (77° K)
Proportional Counters	
Argon	26.4
Methane	29.2

\*Values in parentheses are temperatures at which the energy values were determined.

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The input of the preamplifier appears as a large capacitor to the detector because the effect of the feedback capacitor at the input is magnified by the open loop gain of the charge loop. This input capacitance must be much greater than the other sources of capacitance connected to the preamplifier input (such as the detector or input cabling) in order for the preamplifier sensitivity to be unaffected by external capacitance changes. Since  $C_f$  is generally  $\sim 1 \times 10^{-12}$  F, the preamplifier open loop gain must be very large, usually greater than 10,000. The stability of the preamplifier sensitivity is dependent on the stability of  $C_f$  (the feedback capacitor), and the preamplifier open loop gain.  $C_f$  is selected for good temperature stability, and the open loop gain is made very large so that small changes in it can be neglected. Preamplifier sensitivity variations can contribute to the error in measuring the energy of the detected radiation.

Noise in charge-sensitive preamplifiers is generally controlled by four components: the input field effect transistor (FET), the total capacitance at the input ( $C_f$ , the detector capacitance, etc.), the resistance connected to the input, and input leakage currents from the detector and FET. The FET is selected for low-noise performance, and in some applications it is cooled to near liquid-nitrogen temperature to improve its performance. In cooled-FET applications the detector and preamplifier are generally built as an integral assembly. With room-temperature preamplifiers, the user controls the major sources of input capacitance in most applications, because the preamplifier is designed with minimum internal circuit capacitance. These sources are from the detector selected for an experiment and from the cabling between the preamplifier and the detector. Figure 4 is a graph showing the noise versus external capacitance for a typical preamplifier.

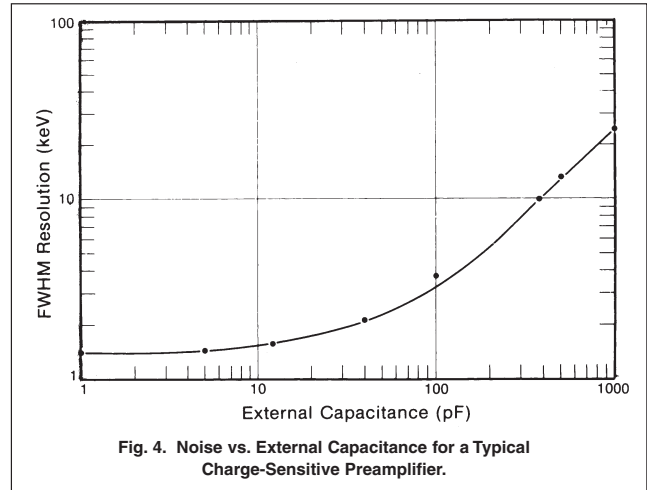


Fig. 4. Noise vs. External Capacitance for a Typical Charge-Sensitive Preamplifier.

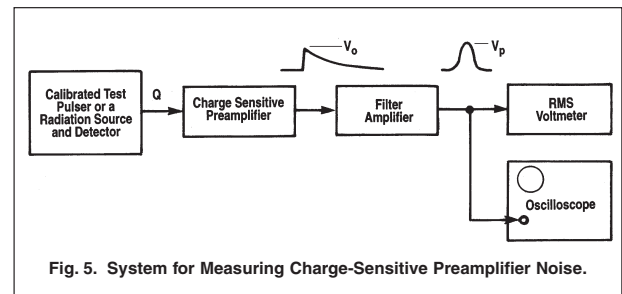


Fig. 5. System for Measuring Charge-Sensitive Preamplifier Noise.

The noise of a charge-sensitive preamplifier can be measured by the system shown in Fig. 5. Charge  $Q$ , equivalent to the known energy,  $E$ , must be injected into the preamplifier, and the amplitude of the pulse  $V_p$  resulting from this charge must be measured at the output of the filter amplifier to determine the system gain  $V_p/E$ . The charge can be injected by a detector and radiation source or a step pulse generator connected to the preamplifier input through a capacitor, sometimes referred to as a charge terminator. The preamplifier noise can be determined by measuring the root-mean-square (rms) noise voltage  $V_{rms}$  at the output of the filter amplifier in the absence of any pulses, and using the following equation:

$$\text{FWHM noise} = 2.35 \frac{E}{V_p} V_{rms} \quad (7)$$

Charge-sensitive-preamplifier noise performance is generally specified as the full width at half maximum (FWHM) of the energy line generated in the spectrum by a test pulser injecting charge into the preamplifier input. This value is normally given in keV. The parameter  $V_{rms}$  must be multiplied by 2.35 to convert it to a FWHM specification.

The rise time of the voltage pulse  $V_o$  at the output of the charge-sensitive preamplifier, in the ideal case, is equal to the charge collection time of the detector. When detectors with very fast collection times or large capacitances are used, the preamplifier itself may limit the rise time of  $V_o$ . If a time reference mark is being determined from  $V_o$ , it is desirable that the rise time  $t_r$  of  $V_o$  be as short as possible. For silicon detectors, the time resolution of the timing system following charge-sensitive preamplifiers is generally limited by the ratio of the FWHM preamplifier output noise  $e_{no}$  to the slope  $dV_o/dt$  of  $V_o$  at the timing threshold:

$$\text{timing resolution (FWHM)} = e_{no}/(dV_o/dt) \quad (8)$$

A plot of a charge-sensitive-preamplifier output rise time versus detector capacitance is shown in Fig. 6. It is desirable to keep the external capacitance at a minimum to obtain the best timing resolution, as well as the best energy resolution.

To estimate the maximum counting rate  $r_{max}$  that can be accommodated by a charge-sensitive preamplifier at a particular energy, it is necessary to identify the type of preamplifier being considered (see IEEE Standard 301-1988). With charged-particle detectors, the

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signal is normally extracted from the same detector electrode that accepts the bias voltage, and the preamplifier input is ac-coupled to the detector. The maximum counting rate tolerated by ac-coupled preamplifiers ( $r_{\max,ac}$ ) is controlled by the signal fluctuations and the maximum voltage  $V_m$  allowed at the charge loop output:

$$r_{\max,ac} = \frac{1.2 V_m^2 \epsilon^2 C_f \times 10^{25}}{E^2 R_f} \quad (9)$$

The units are:  $r_{\max,ac}$  in  $s^{-1}$ ,  $V_m$  in volts,  $\epsilon$  in eV,  $E$  in MeV,  $C_f$  in farads, and  $R_f$  in ohms. If the "energy-squared count-rate product" (i.e.,  $E^2CRP = E^2 r_{\max,ac}$ ) is listed for the ac-coupled preamplifier, the maximum counting rate tolerated at the energy  $E$  can be calculated by dividing the  $E^2CRP$  value by  $E^2$ .

The charge-sensitive preamplifiers used with germanium gamma-ray detectors and Si(Li) x-ray detectors are normally dc-coupled to the detector. For dc-coupled preamplifiers, the maximum counting rate accommodated at the energy  $E$  is controlled by  $R_f$  and  $V_m$ .

$$r_{\max,dc} = \frac{\epsilon V_m \times 6.25 \times 10^{12}}{E R_f} \quad (10)$$

If the "energy count-rate product" (i.e.,  $ECRP = E r_{\max,dc}$ ) is specified for the dc-coupled preamplifier, the maximum counting rate tolerated at the energy  $E$  can be calculated by dividing the  $ECRP$  value by  $E$ .

With pulsed-reset preamplifiers, the maximum counting rate limit for the preamplifier is the counting rate at which the percent dead time caused by the resetting becomes intolerable. The percent dead time resulting from preamplifier resetting is computed from

$$\text{Percent Reset Dead Time} = 100 E r T_{\text{reset}}/E_{\text{reset}} \quad (11)$$

where  $r$  is the counting rate of the events of energy  $E$ ,  $E_{\text{reset}}$  is the total energy accepted between resets, and  $T_{\text{reset}}$  is the dead time caused by each reset. A rough approximation for  $T_{\text{reset}}$  can be obtained by adding the preamplifier reset time to the amplifier overload recovery time. Typically, amplifier overload recovery from the large reset pulse is the major contribution to the reset dead time.

### Creating a Differential Output to Cancel Environmental Noise

When the coaxial cable connecting the preamplifier output to the shaping amplifier input is long and the cable runs through an electrically noisy environment, it is advantageous to employ differential signal transmission. Several amplifiers (Models 450, 671, 672, 973, and 973U) offer differential inputs for this purpose. A few preamplifiers include differential outputs to accommodate this function. If the preamplifier does not provide differential outputs, the box depicted in Figure 7 can be used to create a differential output.

All the components shown in Figure 7 are mounted in a small metal box located close to the preamplifier. Care must be exercised to ensure low-impedance grounds. The input on the left side of the box is connected to the normal preamplifier signal output with a coaxial cable that is as short as possible. This short cable must provide a low impedance path from the preamplifier ground to the metal box. The center conductor of this short cable transmits the normal preamplifier output signal through the box to the normal input of the shaping amplifier. The 93- $\Omega$  resistor in the box is used to transmit the preamplifier ground signal to the differential reference input of the amplifier. Both the "normal" and the "differential reference" cables are RG-62A/U, 93- $\Omega$  coaxial cables. Thus, the 93- $\Omega$  resistor in the box provides reverse termination of the differential reference cable. This termination matches the 93- $\Omega$  reverse termination included inside the preamplifier for the normal output signal.

To ensure that both cables are affected in the same way by electrical interference, the two cables are twisted together in a spiral as they are routed to the amplifier. When connected to the amplifier inputs, the normal signal includes the desired preamplifier signal plus

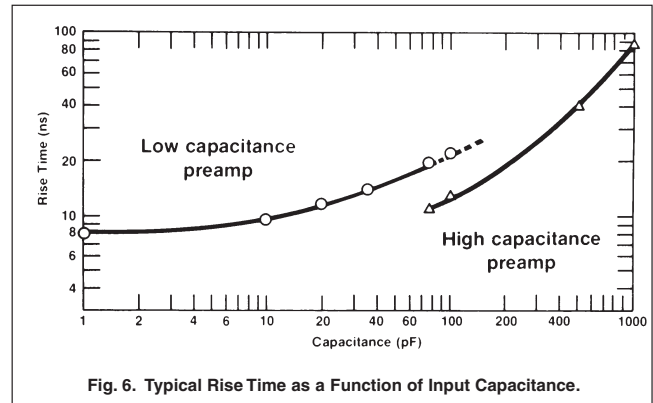


Fig. 6. Typical Rise Time as a Function of Input Capacitance.

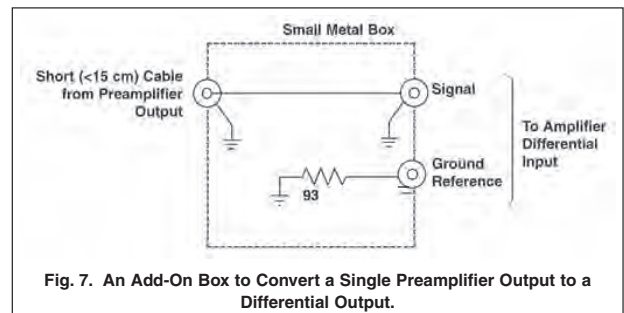


Fig. 7. An Add-On Box to Convert a Single Preamplifier Output to a Differential Output.

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any interfering noise from ground loops or the environment. The differential reference signal includes only the interfering noise. Hence, when the amplifier subtracts the differential reference from the normal signal, the interfering noise is removed from the signal. Amplifiers with differential inputs usually incorporate a differential gain balancing adjustment to allow matching of the gains on the two inputs for exact cancellation of the interfering noise.

Specifications subject to change  
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