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Thermal Sensing Methods used in ON Semiconductor Devices

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APPLICATION NOTE

Introduction

This application note will describe the standard methods used by ON Semiconductor devices for temperature measurement. It will also discuss the various sources of error that arise and the techniques used to minimize them.

Transistor Basics

For a given collector current, Ic, the basic equation that relates the temperature of a transistor to the base−emitter voltage Vbe is:

$$T := \frac{q \cdot Vbe}{K \cdot Ln\left(\frac{Ic}{Is}\right)} \qquad \text{(eq. 1)}$$

where:

T is the absolute temperature in degrees Kelvin
K is Boltzmann's constant (1.38 x 10^{-23} JK^{-1})
q is the charge on the electron (1.6 x 10^{-19} coulombs)
Ic is the collector current
Is is the reverse saturation current

Theoretically this equation can be used to determine the transistor temperature by setting Ic and measuring the base−emitter voltage. In practice this leads to large errors due to the dependence of the equation on Is, which can vary widely between transistors. In order to cancel out the dependency on Is and get a more accurate temperature measurement, a different technique is required.

2−Current Sensing Method

The method used to eliminate dependence on Is is to switch 2 currents through the transistor and measure Vbe for each one. The difference in Vbe measurements can then be used to determine the transistor temperature.

Re−arranging Equation 1 to get Vbe gives:

$$Vbe := \frac{K \cdot T}{q} \cdot Ln\left(\frac{Ic}{Is}\right) \qquad \text{(eq. 2)}$$

The difference in Vbe for 2 currents, where Ic1 is the high level current and Ic2 is the low level current, is:

$$Vbe1 - Vbe2 := \frac{K \cdot T}{q} \cdot \left(Ln\left(\frac{Ic1}{Is}\right) - Ln\left(\frac{Ic2}{Is}\right)\right) \qquad \text{(eq. 3)}$$

which gives:

$$Vbe1 - Vbe2 := \frac{K \cdot T}{q} \cdot Ln\left(\frac{Ic1}{Ic2}\right) \qquad \text{(eq. 4)}$$

Setting Ic1 as a fixed multiple, N, of Ic2 gives:

$$\Delta Vbe := \frac{K \cdot T}{q} \cdot Ln(N) \qquad \text{(eq. 5)}$$

This is the equation used internally in 2−current ON Semiconductor devices to calculate temperature based on the difference in Vbe measurements. The typical value used for N is 17. The internal circuitry used in 2−current devices is shown in Figure 1.

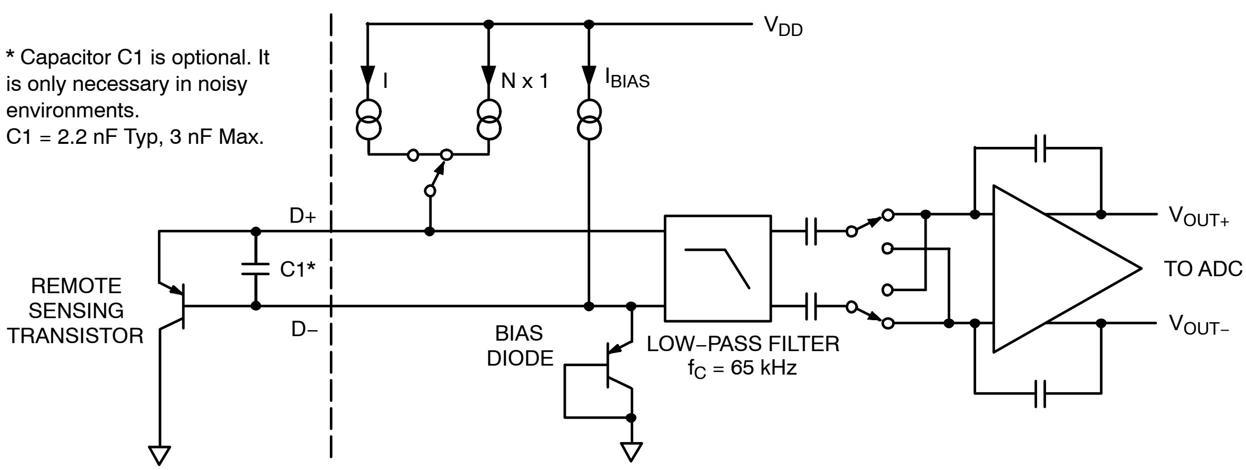

Figure 1. Internal Circuit for 2−current Device

As can be seen in Figure 1, there is an internal low pass filter to help with noise immunity. Typically the D− pin is biased above ground, which also helps to protect against noise interference. Figure 1 shows a diode connected transistor as the biasing element. Some devices use a resistor as the biasing element to reduce the biasing voltage. The connection of the remote sensor as shown in Figure 1 is for an internal sensor on a processor. If using a discrete transistor it must be connected as a diode−connected transistor. Connections for NPN or PNP transistors are shown in Figure 2.

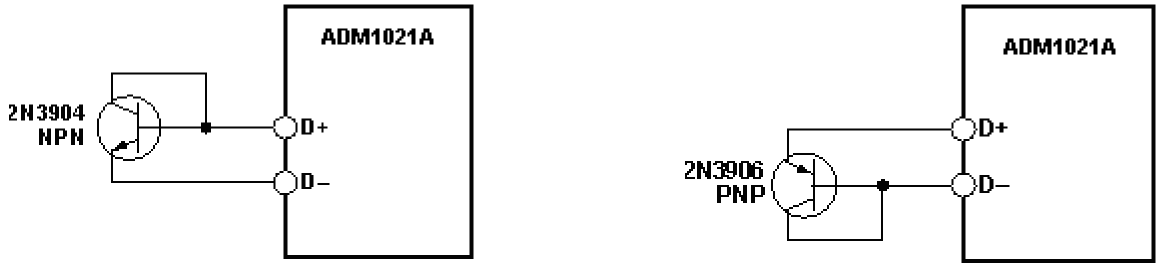

Figure 2. Connections for Discrete NPN and PNP Transistors

The typical D+ and D− waveforms for a 2−current device are shown in Figure 3.

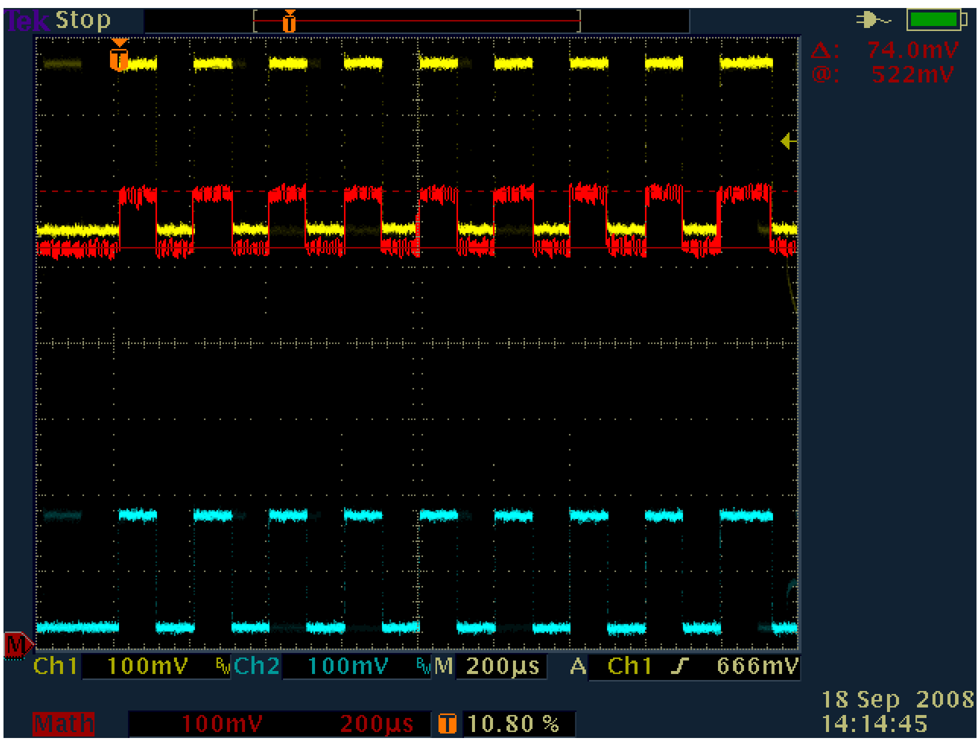

Figure 3. D+/D− Waveforms for a 2−current Device

In Figure 3 the yellow trace is D+, the blue trace is D− and the red trace is the differential voltage. The differential voltage here is ~74 mV which is typical for room temperature.

Sources of Error in Temperature Measurement

In order for a stable reading to be made it is usual for the device to take multiple measurements and average the results. This digital filtering reduces variations from reading to reading, but there are other factors that can introduce errors that must be taken into account. These are:

- nf, the transistor non−ideality factor
- High frequency noise
- Capacitance across D+/D−
- Series Resistance

Errors due to non−ideality factor nf:

Equation 5 assumes an ideal transistor. Most transistors deviate from the ideal model, and this deviation is taken into account by adding a correction factor, nf, to the equation.

$$\Delta Vbe := \frac{nf \cdot K \cdot T}{q} \cdot Ln(N) \qquad \text{(eq. 6)}$$

On Semiconductor devices use a value of 1.008 as the nf value when calculating temperature. The difference between a transistors actual nf value and the assumed 1.008 nf value will give rise to a temperature error. This error can be seen in Figure 4.

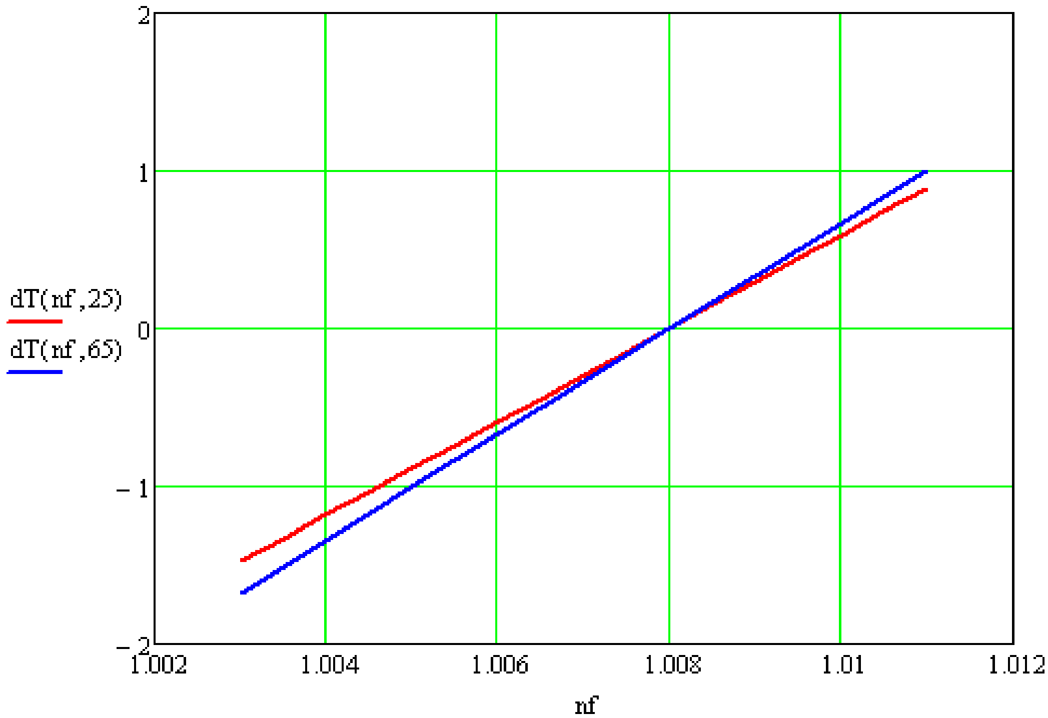

Figure 4. Temperature Error due to nf Variations at 25°C and 65°C

In Figure 4 the red plot is the error over a range of nf values at 25°C and the blue plot is the error for a range of nf values at 65°C.

Errors due to high frequency noise:

In a noisy environment like a motherboard the D+/D− lines can pick up interference which can introduce errors into the temperature measurement. This interference can be reduced by taking care with the layout of the D+/D− lines. The lines should be routed together to reduce differential noise and especially noisy sections of the motherboard should be avoided if possible. Ground plane shielding should also be used to reduce interference. Typical error curves for common mode and differential mode noise are shown in Figure 5.

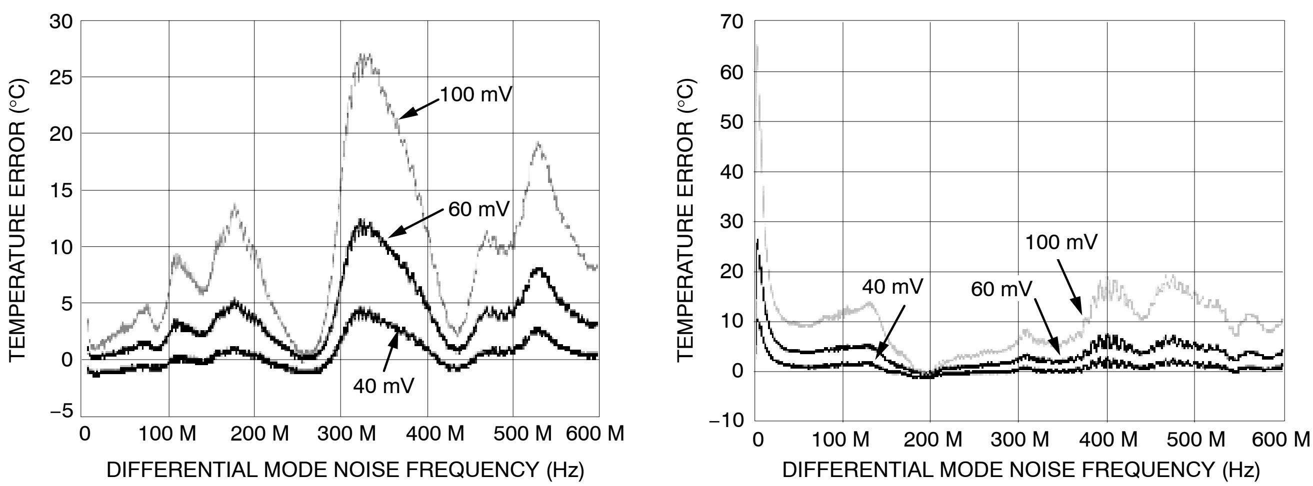

Figure 5. Temperature Error due to Common Mode and Differential Mode Noise

Errors due to capacitance across D+/D−:

In order to help reduce noise interference it is common to put a capacitor across the D+ and D− lines close to the device. Care must be taken with the chosen capacitor value as the devices are sensitive to this capacitance, and large errors can be introduced if an inappropriate value is used. A typical plot of temperature error due to D+/D− capacitance is shown in Figure 6.

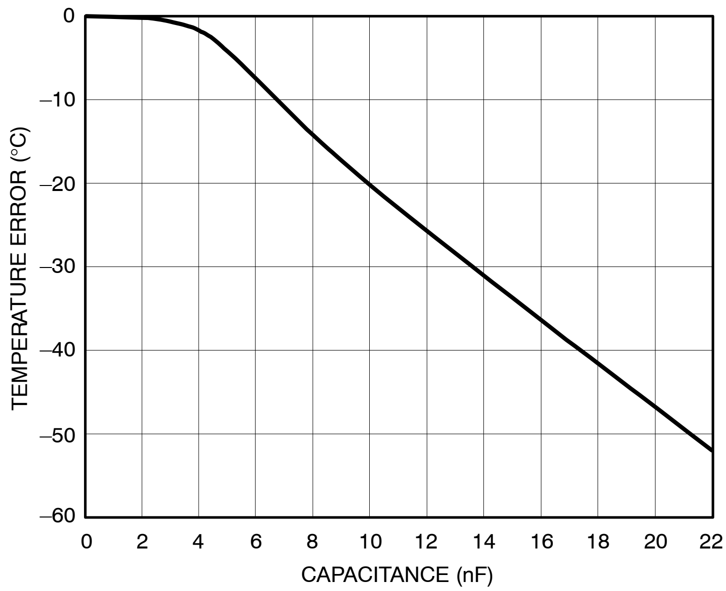

Figure 6. Temperature Error due to D+/D− Capacitance

Errors due to series resistance:

Any resistance that is in series with the sensing diode will introduce an error in the temperature measurement with a 2−current device. The switched current sources will cause a voltage drop across the series resistance which will be seen as an offset. Because of this the magnitude of the temperature error will depend on both the series resistance and the values of the high and low currents being switched through the transistor. The temperature error can be calculated using:

$$\text{Temperature Error} := \frac{(I1 - I2) \cdot R \cdot q}{k \cdot nf \cdot \ln(N)} \quad \text{(eq. 7)}$$

where:

I1 is the high level current
I2 is the low level current
R is the series resistance
q, K, nf and N are as previously defined

Example: The ADT7481 is a 2−current device with a high level current of 233 μA and a low level current of 13 μA. For a series resistance of 4 Ω the expected voltage error will be (233 μA – 13 μA)*4 = 0.88 mV which will translate into a temperature error of 3.5°C.

The effect of series resistance on 2−current devices prevents the use of a low pass filter on D+/D− to help with noise issues. Although internal offset registers can be used to correct small offset errors, for useful filters the resistor must be as large as possible due to the limitation on the allowable capacitor values across D+/D−, so the error due to the resistance will be large. To address this, another method of temperature sensing must be used

3−Current Sensing Method

The method used to eliminate the offset due to series resistance is to add a 3rd current source to the switching cycle. Figure 7 shows the internal structure of a 3−current device. By adding a 3rd current to the sequence it can be shown that, with a carefully chosen measurement sequence, the measurement is independent of resistance in the sensor path, typically up to 3 kΩ. As well as removing errors due to parasitic resistance it also allows relatively large value resistors to be added to D+ and D− to form a low pass filter to reduce the effects of noise.

Definitions:

K = Boltzmann’s Constant
q = electron charge
n = non−ideality factor
I1 = Low level current
I2 = Mid level current
I3 = High Level Current
N21 = Ratio of I2 to I1
N31 = Ratio of I3 to I1
Vbe1 = Vbe with Ie = I1
Vbe2 = Vbe with Ie = I2
Vbe3 = Vbe with Ie = I3
ΔVbe21 = Vbe2 – Vbe1
ΔVbe32 = Vbe3 – Vbe2
Re = Resistance in emitter path
Rb = Resistance in base path

The differential base emitter voltage for low and mid currents is given by:

$$\Delta Vbe21(T) := \frac{n \cdot K \cdot T}{q} \cdot Ln(N21) + I1 \cdot (N21 - 1) \cdot \left(Re + \frac{Rb}{\beta + 1}\right)$$

The differential base emitter voltage for mid and high currents is given by:

$$\Delta Vbe32(T) := \frac{n \cdot K \cdot T}{q} \cdot Ln\left(\frac{N31}{N21}\right) + I1 \cdot (N31 - N21) \cdot \left(Re + \frac{Rb}{\beta + 1}\right)$$

Apply a gain of A to ΔVbe21 and B to ΔVbe32 then calculate the difference:

$$A \cdot \Delta Vbe21(T) - B \cdot \Delta Vbe32(T) := \frac{n \cdot K \cdot T}{q} \cdot Ln\left(\frac{N21^{A+B}}{N31^{B}}\right) + I1 \cdot \left(Re + \frac{Rb}{\beta + 1}\right) \cdot [A \cdot (N21 - 1) - B(N31 - N21)]$$

Therefore, if the following condition is met, the above expression is independent of path resistance:

$$A \cdot (N21 - 1) := B \cdot (N31 - N21)$$

Selecting B to be 1, A is given by:

$$A := \frac{N31 - N21}{N21 - 1}$$

Using this value for A, the temperature (in Celsius) of the transistor can be calculated from:

$$T := \frac{(A \cdot \Delta Vbe21 - \Delta Vbe32) \cdot q}{n \cdot K \cdot ln\left(\frac{N21^{A+1}}{N31}\right)} - 273$$

Figure 8 shows the typical D+ and D− waveforms for a 3−current device.
Figure 9 shows the connection for a low pass filter on D+ and D−.

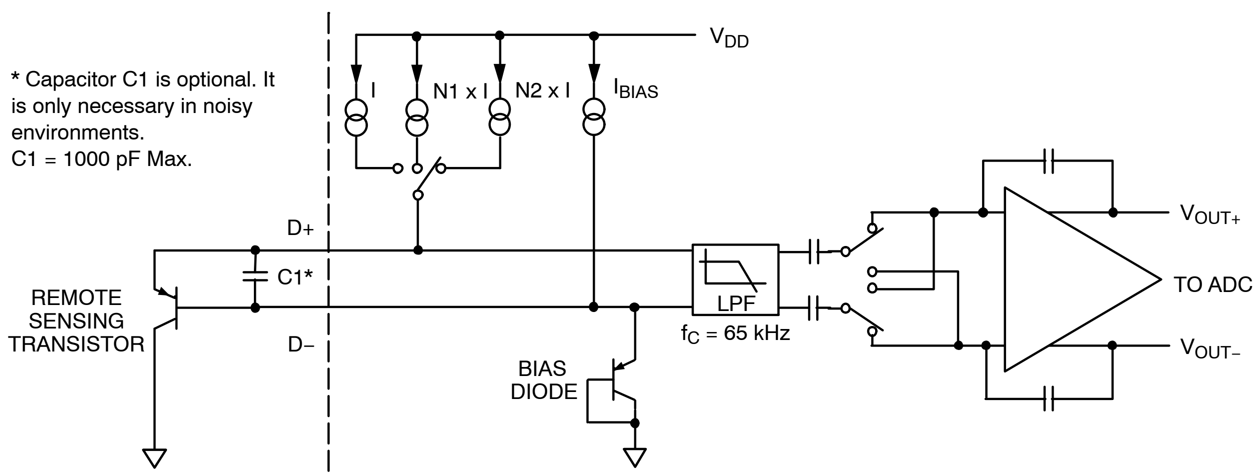

Figure 7. Internal Circuit for 3−current Device

Table 1. 2−CURRENT AND 3−CURRENT TEMPERATURE SENSING DEVICES

Device	# Remote Channels	# Currents	Accuracy	Supply Voltage
ADM1032	1	2	±1°C	3 – 5.5 V
ADT7461	1	3	±1°C	3 – 5.5 V
ADT7461A	1	3	±1°C	3 – 3.6 V
ADT7481	2	2	±1°C	3 – 3.6 V
ADT7482	2	3	±1°C	3 – 3.6 V
ADT7483A	2	2	±1°C	3 – 3.6 V
ADT7484A	1	3	±1°C	3 – 3.6 V
ADT7485A	1	3	±1°C	3 – 3.6 V
ADT7486A	2	3	±1°C	3 – 3.6 V
ADT7488A	2	3	±1°C	3 – 3.6 V
NCT1008	1	3	±1°C	2.8 – 3.6 V

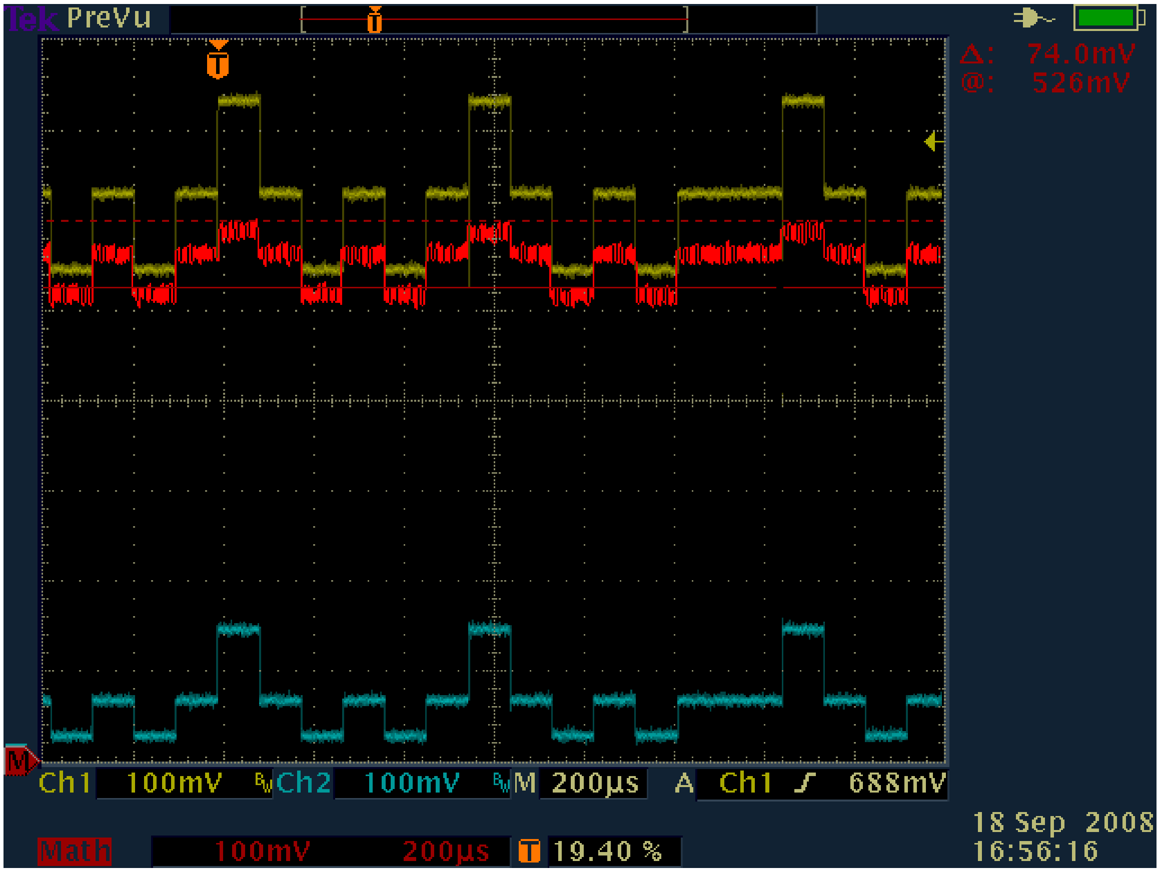

Figure 8. Typical D+/D− Waveforms for 3−current Device

In Figure 8 the yellow trace is D+, the blue trace is D− and the red trace is the differential voltage.

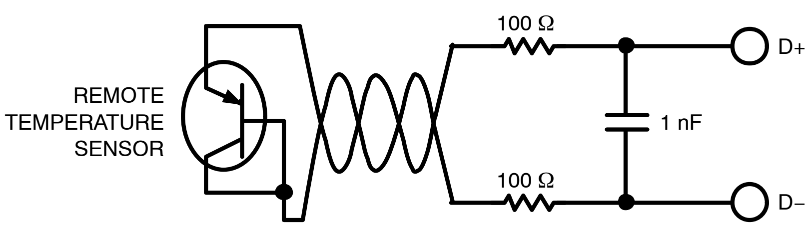

Figure 9. Low Pass Filter Added for Noise Immunity

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