Application Report

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Implementing a Variable-Length Cat5e Cable Equalizer

Xavier Ramus
Abhijeet Godbole

High-Speed Products
Power Design Group

ABSTRACT

Unshielded twisted pair (UTP) cables have long been used to transmit data over long distances, starting with telephone line networks. As a result of the relatively low cost, these cables have also been adopted for various uses including video distribution. All UTP cables attenuate the signal over frequency with maximum attenuation at maximum signal frequency. This attenuation will also increase as the cable length increases. This application note focuses on a continuously-adaptable equalization technique of Category-5 enhanced (Cat5e) cable for applications intended to be used with various length of Cat5e cable. As an example, a voltage-controlled amplifier (VCA) implementation is developed for standard video distribution for distances up to 500 feet (152.4 m).

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1 Introduction

Cat5e cable consists of four twisted pairs of wire that allows a red (R), green (G), and blue (B) signal on each of three lines, freeing the fourth line to transmit audio, timing, or control signals.

In theory, equalization techniques can be used at either the transmit (Tx) or receive (Rx) amplifier. In practice, however, equalization is generally used on the Rx side in order to limit noise and maximize signal-to-noise ratio (SNR). This practice imposes a flatness requirement on the Tx side. For more information on the Tx side and its interaction with the Rx side, refer to the Texas Instruments application report, *Wireline Data Transmission and Reception* (literature number SBOA123).

Focusing only on the Rx side for the balance of this report, we will start by looking at the Cat5e transmission media characteristics; then we will consider the proposed implementation based on the VCA822; and finally, we implement and evaluate the circuit.

2 Cat5e Cable Attenuation Characteristics

Table 1 shows the typical electrical characteristics of Cat5e cable.

Table 1. Electrical Characteristics for Cat5e UTP Cable

Property	Nominal Value	Tolerance	Units
Characteristic impedance at 100MHz	100	±15	Ω
Nominal characteristic impedance at 100MHz	100	±5	Ω
DC-loop resistance	≤ 0.188		Ω/m
Capacitance at 800Hz	52		pF/m
Inductance	525		nH/m

The characteristic impedance for a lossless transmission line is given by Equation 1:

$$Z_O = \sqrt{\frac{L}{C}} \quad (1)$$

Applying Equation 1 to the typical cable inductance and capacitance (from Table 1), we find that it is equal to 100.5Ω.

For the Sewell Cat5e cable used for this project, the frequency responses for various cable lengths are shown in Figure 1.

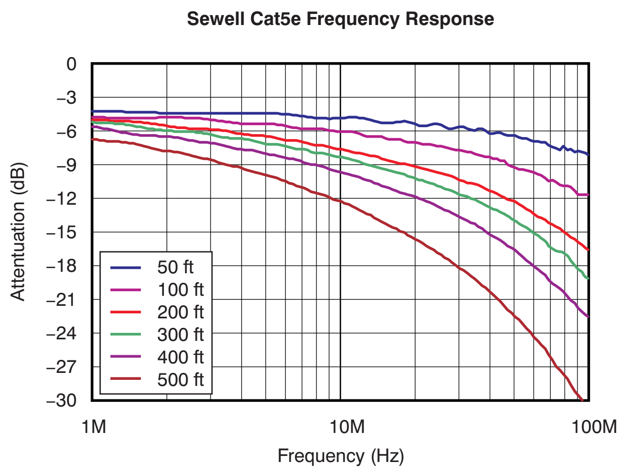


Figure 1. Typical Attenuation Characteristics of Cat5e Cable

Using TI application report SBOA124, *A Numerical Solution to an Analog Problem*, as a starting point, we can determine the pole location associated with the longest cable length. This network determines the maximum attenuation for which the circuit can compensate. It is understood that this calculated network may need some adjustment to actual component values and test environments.

3 Equalizer Circuit Description

A differential cable equalizer can be easily implemented using a voltage-controlled amplifier (VCA). Texas Instruments offer a selection of high-speed VCAs (as shown in Table 2) that could be used in this application.

Table 2. VCA82x Device Comparison

Device	Bandwidth (G = 2V/V)	Comments
VCA820	168MHz	Linear in dB Gain control
VCA821	710MHz	Linear in dB Gain control
VCA822	168MHz	Linear in V/V Gain control
VCA824	710MHz	Linear in V/V Gain control

The VCA selected for this investigation is the VCA822, a wideband, variable gain amplifier. For the VCA822, the maximum gain is set by using independent feedback and gain resistors, and the gain control voltage attenuates the signal from the maximum gain. The gain-adjust range for the VCA822 is 40dB. Figure 2 illustrates the internal schematic of the VCA822.

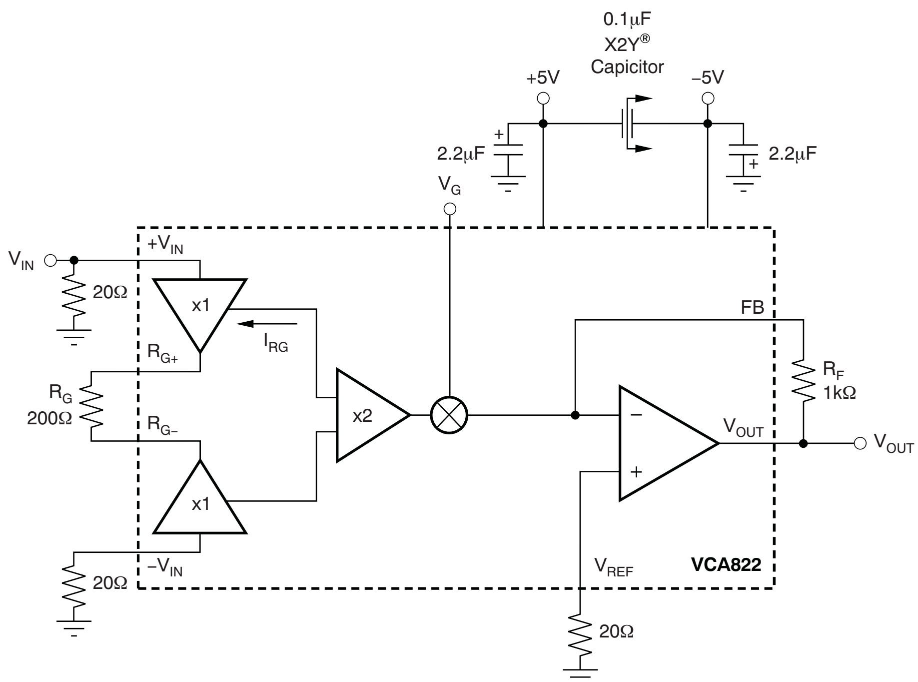


Figure 2. VCA822 Internal Schematic

The VCA822 input stage places the transconductance element between two input buffers, using the output currents as the forward signal. As the differential input voltage increases, a signal current is generated through the gain element. This current is then mirrored and gained by a factor of two before reaching the multiplier. The other input of the multiplier is the voltage gain control pin, V_G. Depending on the voltage present on V_G, up to two times the gain current is provided to the transimpedance output stage. The transimpedance output stage is a current-feedback amplifier that provides the high output current and high slew rate capability.

The proposed schematic for the Cat5e cable equalizer is shown in Figure 3.

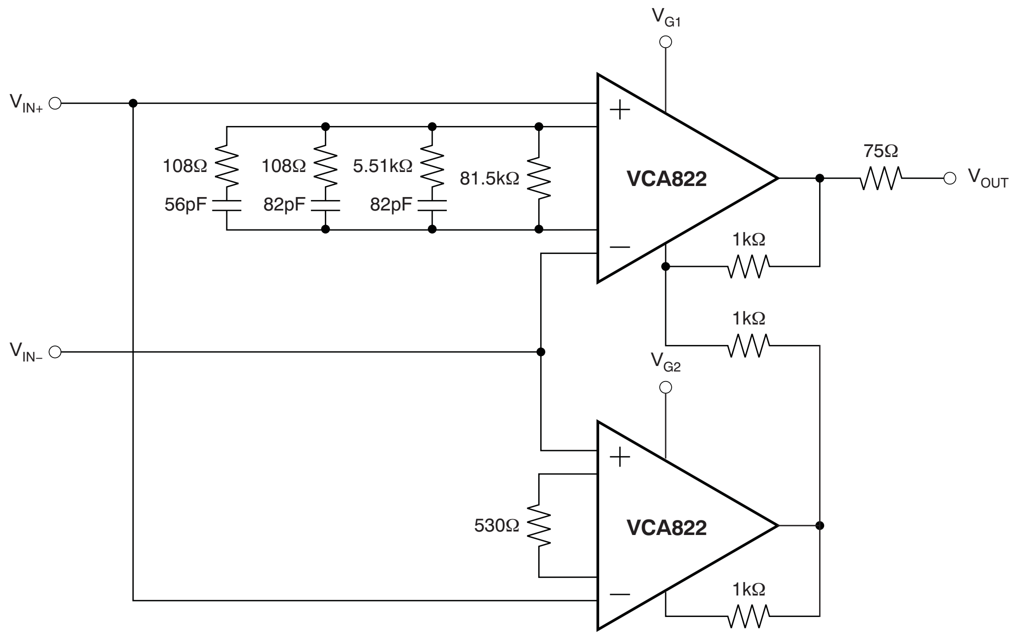


Figure 3. Equalizer Circuit Using the VCA822

This circuit uses two VCA822s and takes advantage of the high impedance nature of both devices. Notice that the top VCA is connected in a noninverting configuration while the bottom VCA is connected in an inverting configuration. The signal passing through the inverting amplifier is inverted again before finding its way to the output. Remember that the output stage of the VCA822 is an operational amplifier; therefore, if a gain resistor is used in conjunction with a feedback resistor, the resulting signal is inverted in relation to the output. In the example shown in Figure 3, both feedback and gain resistors have the same value; thus, the bottom VCA822 has its gain inverted by this configuration to the output of the top VCA device.

Additionally, the bottom VCA is amplified by a fixed gain over frequency while the top VCA has an equalization circuit to set the gain. Note that the resistor setting the dc gain for the equalization VCA is very large compared to the feedback resistor, resulting in a small gain at dc. To understand the behavior of this circuit, we will analyze it in two steps by successively eliminating one amplifier from the equation by adjusting the gain control voltage.

Because the VCA822 has a 40dB gain adjust range, it can attenuate the maximum gain by 40dB. Keep in mind that by setting the gain of the first VCA in the equalization circuit, you eliminate (in effect) the signal that passes through the noninverting amplifier. Referring to Figure 4, then, the gain for each case is shown in the subsequent section.

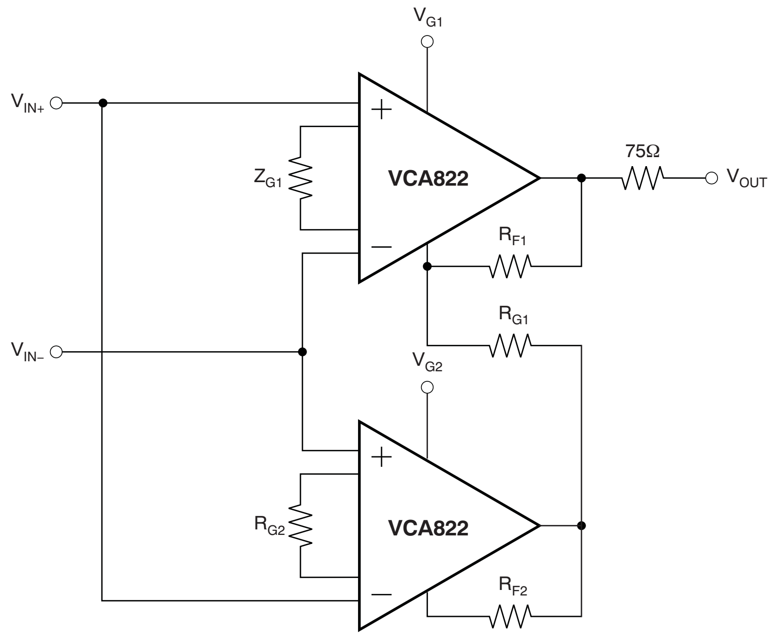


Figure 4. Analysis Schematic

3.1 Gain-Setting Examples

Case #1

V_{G1} = –1V (input signal fully attenuated); V_{G2} = 1V (input signal at maximum gain)

$$\frac{V_{OUT}}{V_{IN+} - V_{IN-}} = \frac{R_{F1}}{R_{G1}} \bullet \frac{R_{F2}}{R_{G2}} \bullet (V_{G2} + 1) \tag{2}$$

Case #2

V_{G1} = 1V (input signal at max gain); V_{G2} = –1V (input signal fully attenuated)

$$\frac{V_{OUT}}{V_{IN+} - V_{IN-}} = \frac{R_{F1}}{Z_{G1}} \bullet (V_{G1} + 1) \tag{3}$$

It is now possible to see that by simply combining Equation 2 and Equation 3 by superposition, the gain equation for this circuit appears as Equation 4.

$$\frac{V_{OUT}}{V_{IN+} - V_{IN-}} = \frac{R_{F1}}{R_{G1}} \bullet \frac{R_{F2}}{R_{G2}} \bullet (V_{G2} + 1) + \frac{R_{F1}}{Z_{G1}} \bullet (V_{G1} + 1) \tag{4}$$

From the circuit in Figure 3, we can see that the poles have been located at 350kHz, 1.8MHz, and 26.3MHz. To summarize, at frequencies less than 350kHz, the gain equation (Equation 4) is dominated by the bottom VCA, while it is dominated by the top VCA (the equalizer circuit) at frequencies above 350kHz. The gain control voltage (V_{G1} and V_{G2}, respectively) allow the designer to have full control on the total contribution of each amplifier. This characteristic enables this circuit to adjust the required equalization for various Cat5e cable lengths.

The frequency responses of Case #1 and Case #2 of this analysis, as well as a similar case where both VCAs are fully contributing to the output, are shown in Figure 5.

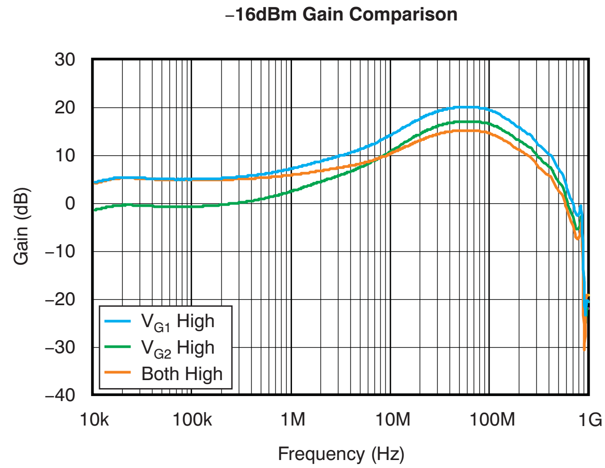


Figure 5. Frequency Response of the Circuit for Various Gain Voltage Combinations

4 Physical Implementation

The circuit shown in Figure 3 was implemented using two VCA822ID amplifiers. The layout for this design is illustrated in Figure 6.

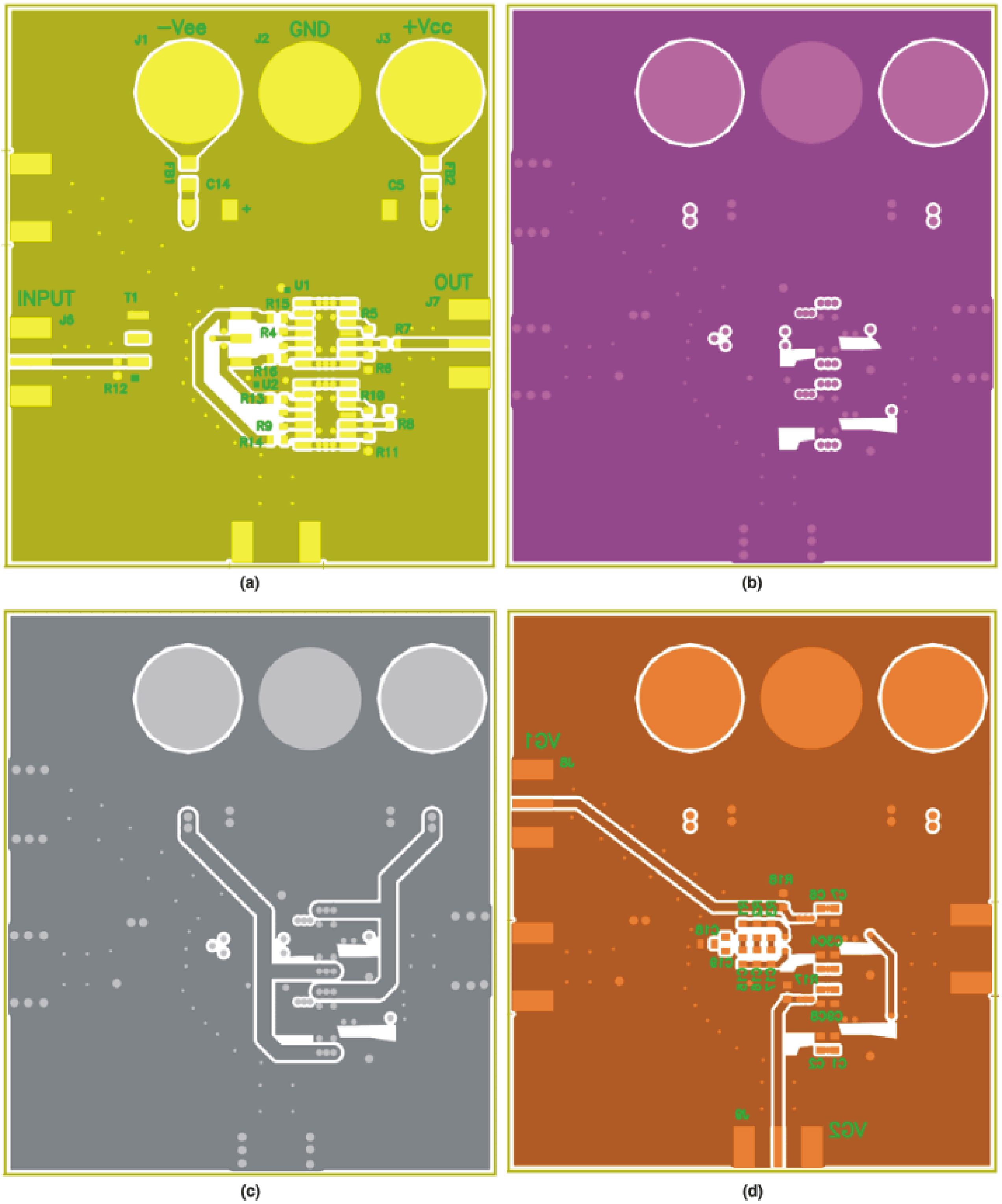


Figure 6. Evaluation Board Layout (Top View): (a) Top Layer, (b) Mid Layer 1; (c) Mid Layer 2; (d) Bottom Layer

This layout is implemented with a four-layer printed circuit board (PCB). Components are placed on both top and bottom layers, with the ground and power supply on the mid layers. Ground filling is also used on the top and bottom layers.

The schematic associated with this layout is given in Figure 7. We can see that four 0.1μF bypass capacitors are used for each VCA because of the number of supply pins for the SO-14 package. Several placeholder capacitors are also set for each of the gain control voltage pins, V_{G1} and V_{G2}. The input is connected through a transformer to emulate a fully differential signal driving the high-impedance input stage of the VCA822. The equalization circuit described earlier can be seen on the bottom layer.

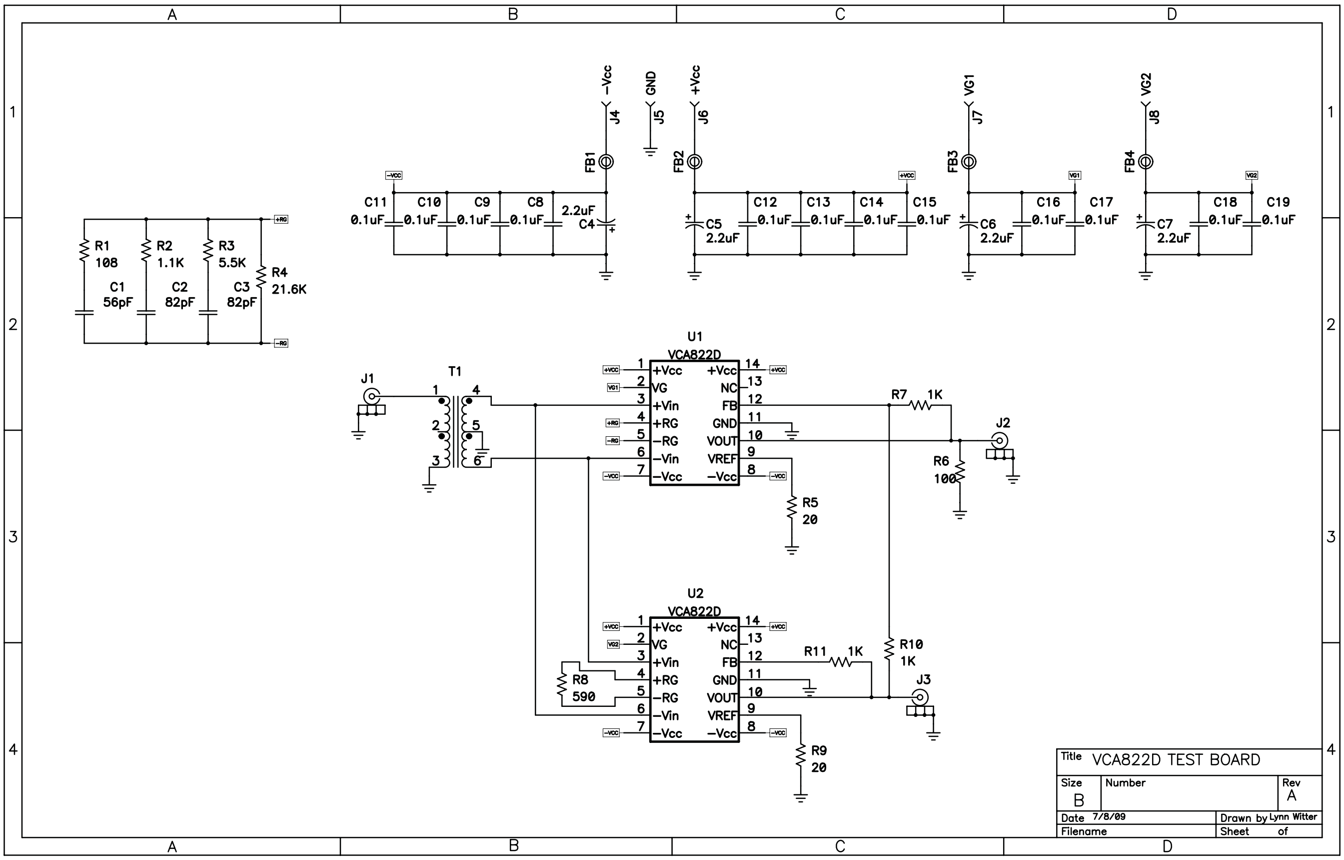


Figure 7. Schematic

5 Results and Discussion

5.1 Frequency Domain Analysis

The primary objective of the equalizer circuit is to shape the frequency response in order to compensate for the Cat5e cable loss. Different cable lengths cause different levels of attenuation, with the longest cable length showing the worst attenuation.

This circuit was tested for six different cable lengths varying from 50ft to 500ft. The gain control voltage of the amplifiers was adjusted for each cable length, such that the amplifier output remains constant at $1V_{PP}$ over the desired frequency band (0Hz to 20MHz). Table 3 shows the various gain voltage combinations for different lengths of cable. Figure 8 shows the equalized response with different cables inserted in the signal path. Figure 8 also shows that independent of the cable length, good flatness to greater than 20MHz is achieved by this circuit. Further improvement may be achieved by using the higher bandwidth VCA821 or VCA824 devices.

From Table 3, it is clear that for shorter cable lengths, it is not required to boost a high-frequency signal, whereas for longer cables, high frequencies require maximum compensation. As a result, the gain control voltage for the equalization VCA (U1 in Figure 7) is negative for shorter cable lengths. For the VCA822, the closer the gain control voltage is to –1V, the more this VCA is attenuating. The equalization VCA is, in this manner, removed from the loop. The longer the cable length, the more that U1 contributes to the output signal.

Table 3. Gain Control Voltage Settings for Different Lengths of Cat5e Cable

Cable Length (feet)	V_{G1}	V_{G2}
50	-0.5V	0.50V
100	-0.3V	0.55V
200	0.10V	0.65V
300	0.20V	0.70V
400	0.40V	0.80V
500	0.75V	0.85V

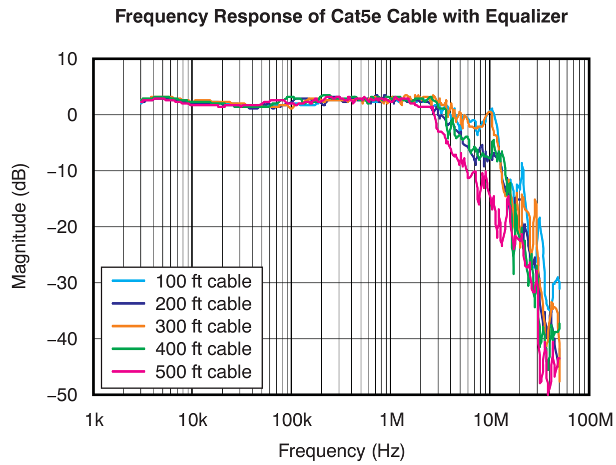


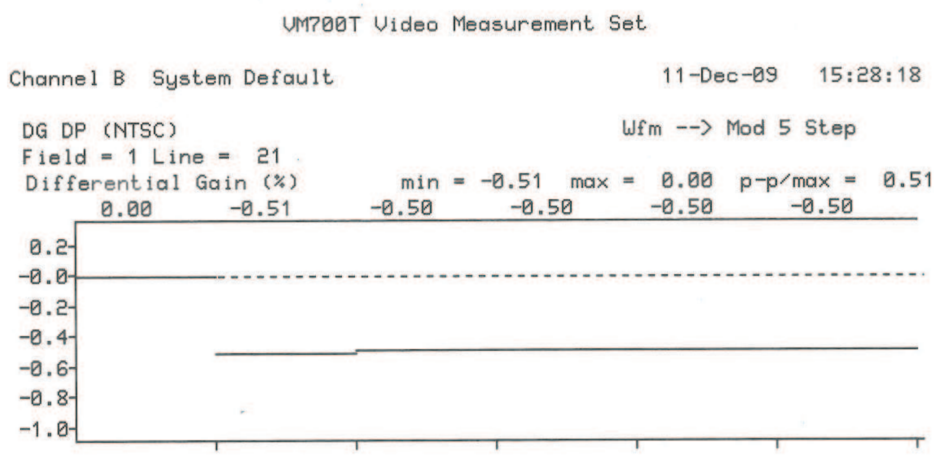
Figure 8. Equalized AC Responses for Different Lengths of Cat5e Cable

5.2 Differential Gain-Differential Phase Measurement (dGdP)

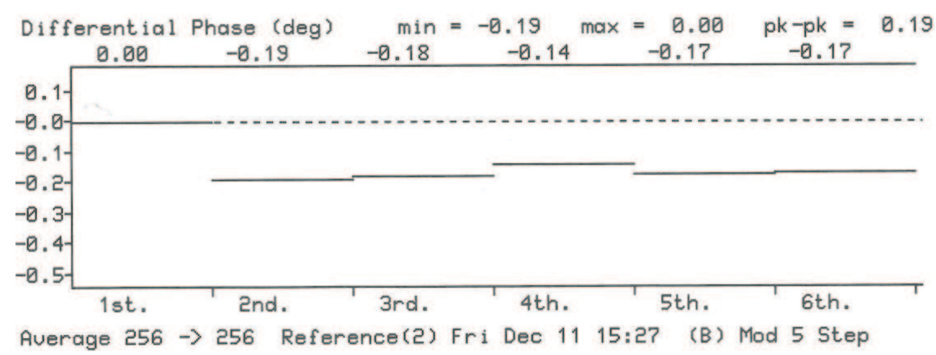
One of the most critical factors within a composite video system is how well an amplifier reproduces the composite video signal. Differential gain is the error in the amplitude of the color signal as a result of a change in luminance (or brightness) level. Differential phase is the error in the phase of the color signal because of a change in luminance level. This characteristic is usually specified as the parameter ***dGdP*** in amplifier data sheets.

Typically, amplifiers that have a dGdP error of less than 1% are considered to be good, because the human eye cannot discern the differences of color saturation if the differential gain error is 1% or lower.

In this test, we used the VM700T, a video test measurement instrument, to measure the dGdP of the equalizer circuit. A five-step modulated signal (NTSC format) from a video signal generator was used as the tested video signal. The dGdP error increased with the Cat5e cable length. The worst-case differential gain and differential phase error was 0.5% and 0.19% max, respectively, for a 500ft cable. Figure 9 shows the dGdP responses for a 500ft cable.



(a) Differential Gain



(b) Differential Phase

Figure 9. Differential Gain (a) and Differential Phase (b) Measurements for 500ft Cat5e Cable

6 Conclusion

Cat5e UTP cables are extensively used for communication wiring because of the low cost and performance characteristics. In this report, we implemented an adjustable equalizer for various Cat5e cable lengths that compensated the cable loss at high frequencies. An application for composite video signal using the VCA822, a wideband, variable gain amplifier, was implemented that clearly demonstrated how this equalizer circuit allows optimization for various cable lengths by adjusting the gain control voltage of both VCA components. This equalizer circuit was also tested for differential gain and phase performance, and found to be within the acceptable human tolerance limit.