Application Report
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# Wireline Data Transmission and Reception

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## ABSTRACT

Many types of wires are widely used to transmit data. Specifically, Category 3 and Category 5 (Cat3 and Cat5e, respectively)—also known as *unshielded twisted pair* or UTP lines—are now recommended for new telephone installations. Coaxial (coax) cables are used to distribute cable television (CATV) signals throughout a home. #12 and #14 American wire gauge (AWG) electric power distribution wire is also used for powerline communication applications such as Homeplug™. Because of the wide availability and comparatively low cost, these media can also be used for point-to-point communications and data transmission for remote applications. Each of these media types shares a common characteristic: for a given cable length, the high-frequency components of a given signal will be attenuated more than the low-frequency components. This application note describes a possible system architecture for transmitting a signal with high-frequency content, compensating for the frequency-dependent attenuation, and receiving this type of signal for further processing.

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## 1 Introduction

Two of the most widely-used wireline families are the coax cable and the Cat5e UTP cable. Typical attenuation characteristics for one cable from each family is represented in Figure 1. Both of these common cables are available from a variety of manufacturers. The cables measured in Figure 1 are manufactured by Belden and have been normalized to a length of 100m. Note that the 75Ω coax cable attenuation shown here is a nominal attenuation, whereas the Cat5e attenuation is a maximum attenuation.

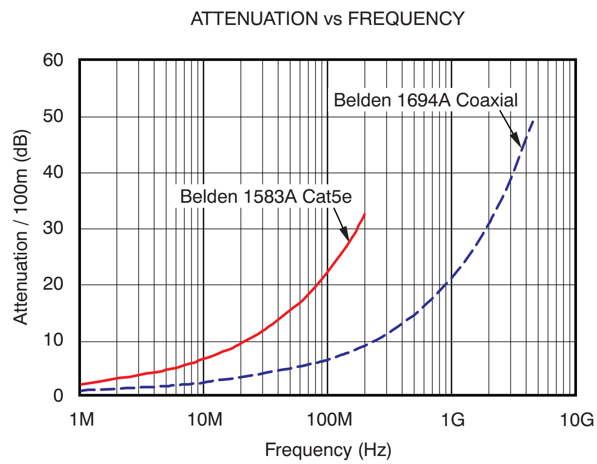



**Figure 1. Attenuation vs Frequency for Cat5e and 75Ω Coax Cables**

Now that we have a description of how the medium affects the signal integrity, we can start looking at a general block diagram of the signal chain.

## 2 High-Level Signal Chain

At the simplest level, for a system that requires only data transmission from board A to board B, Figure 2 presents a straightforward description.

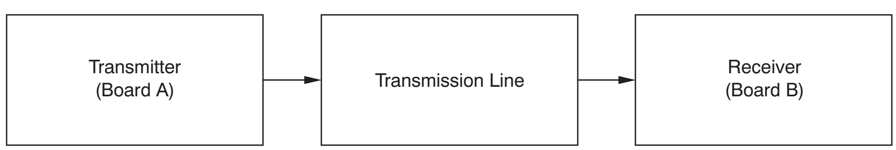



**Figure 2. High-Level Signal Chain Block Diagram**

### 2.1 Transmitter

The transmitter consists of a transmission amplifier, whose function is to amplify the signal and drive the line. In addition to frequency response and quiescent current, the two most important parameters to consider when selecting a transmission amplifier are output voltage swing and output current capability. These two parameters are interdependent; therefore, a V-I curve (or output voltage versus output current capability) should be among the first parameters looked at when selecting this amplifier component. The V-I curve for the OPA2673 is shown in Figure 3 as an example.

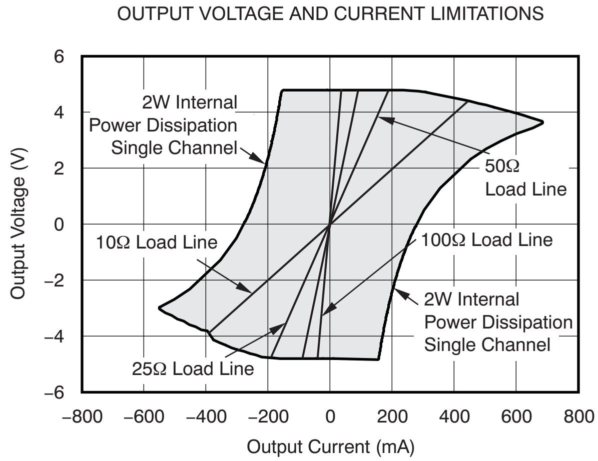



**Figure 3. Output Voltage and Current Limitations (OPA2673)**

In general, for high-speed wireline applications, a current feedback amplifier (CFA) is more appropriate than a voltage feedback amplifier (VFA) as a result of the high slew rate advantage generally offered by the CFA. Additionally, dual amplifiers are used more often for twisted-pair installations, where a differential signal is required; single amplifiers, on the other hand, are generally used more often with coax cable, where single-ended termination is more common.

For differential twisted-pair signal driving, the amplifiers listed in Table 1 are recommended. These amplifiers are a selection of the many devices currently available from TI. Refer to the DSL/Powerline Amplifier selection page on the TI web site at www.ti.com for a more complete list.

**Table 1. Dual Amplifiers for Use as Twisted-Pair Drivers**

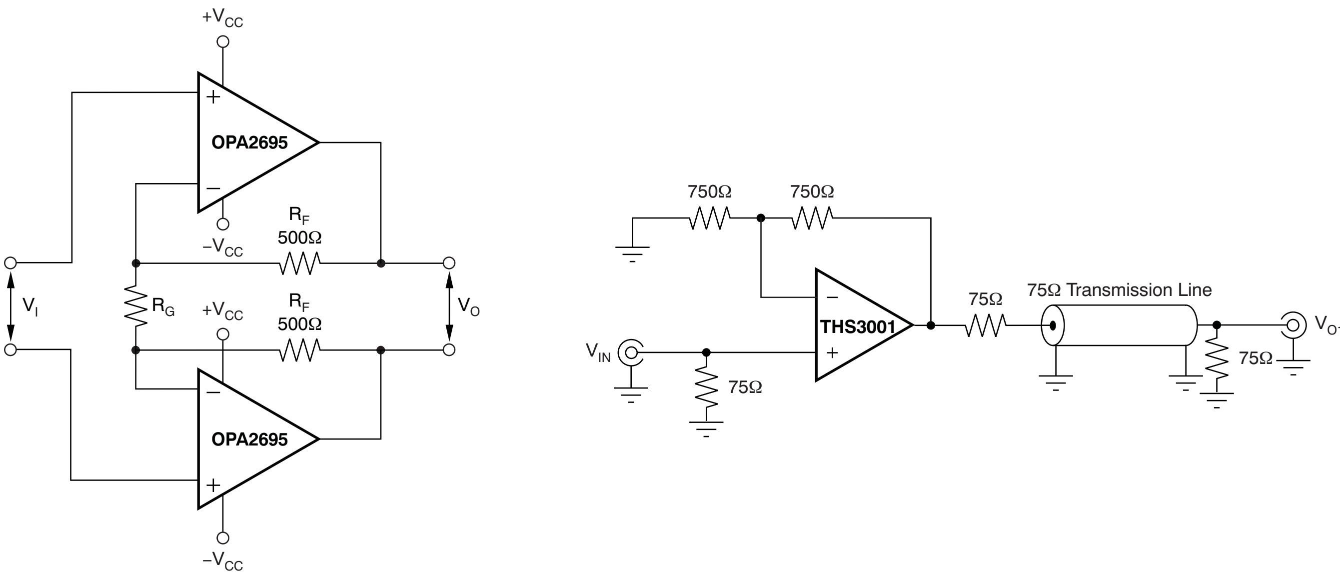
| Amplifier | Output Voltage into 100Ω Load (V) | Output Current (mA) | Quiescent Current (mA) | Bandwidth at G = +2V/V (MHz) |
|---|---|---|---|---|
| OPA2695 | ±3.9 ($V_S$ = ±5V) | ±120 | 25.8 | 850 |
| OPA2673 | ±4.8 ($V_S$ = ±6V) | ±700 | 32 | 450 |
| OPA2674 | ±5.0 ($V_S$ = ±6V) | ±500 | 18 | 225 |
| OPA2691 | ±3.9 ($V_S$ = ±5V) | ±190 | 10.2 | 225 |
| OPA2683 | — | +150/–110 | 1.88 | 150 |
| THS6043 | ±10.8 ($V_S$ = ±12V) | ±350 | 16.4 | 95 |
| THS6182 | ±13.9 ($V_S$ = ±15V) | ±600 | 23 | 80 |

For single-ended applications, such as a coax cable driver, the amplifiers listed in Table 2 can be used.

**Table 2. Single Amplifiers for Use as Coax Cable Drivers**

| Amplifier | Output Voltage into 100Ω Load (V) | Output Current (mA) | Quiescent Current (mA) | Bandwidth at G = +2V/V (MHz) |
|---|---|---|---|---|
| OPA695 | ±3.9 ($V_S$ = ±5V) | ±120 | 12.3 | 850 |
| OPA691 | ±3.9 ($V_S$ = ±5V) | ±190 | 5.1 | 225 |
| THS3001 | ±12.8 ($V_S$ = ±15V) | ±120 | 6.6 | 385 |
| THS3091 | ±12.5 ($V_S$ = ±15V) | +280 /–250 | 9.5 | 210 |

Typical application circuits for both types of drivers are shown in Figure 4**a** (for twisted pair) and Figure 4**b** (for coax).




a) Typical Twisted-Pair Driver Cable Circuit

b) Typical Coaxial Driver Cable Circuit

**Figure 4. Typical Application Driver Circuits**

Note that although it is possible to compensate the line attenuation by peaking the frequency response of the line driver, this technique is not normally implemented in practice for a couple of reasons. First, this compensation implies that a fixed cable length is used. Second, if the media are unshielded, the high-frequency content of the signal will be amplified and generate more radiation, which could contradict or violate applicable emissions standards.

## 2.2 Receiver

On the receiver side, depending on the maximum frequency component, the nature of the signal, and the length of the transmission line, there are two primary implementation approaches.

1. Take the loss inherent to the transmission line; or
2. Compensate the signal loss. This approach is normally referred to as *equalization*.

VFAs are normally used for this role because they traditionally provide lower input voltage noise and better dc precision. If the signal processing is single-ended or differential, there are several available options.

First, for differential processing, both dual amplifiers and fully-differential amplifiers can be used. A dual amplifier in the same configuration as the line driver (see Figure 4**a**) can more easily provide better back-matching over frequency because the amplifier input is high impedance. Table 3 provides a short selection guide for this type of device.

**Table 3. Dual Amplifiers for Differential I/O Receiver Functions**

| Amplifier | Input Voltage Noise (nV/√Hz) | Bandwidth at Gain (MHz) |
|---|---|---|
| OPA2695 | 1.8 | 850 (2V/V) |
| OPA2690 | 5.5 | 220 (2V/V) |
| OPA2822 | 2 | 200 (2V/V) |
| OPA2846 | 1.2 | 300 (10V/V) |
| THS4012 | 7.5 | 290 (1V/V) |
| THS4022 | 1.5 | 350 (10V/V) |

Note that if very wideband performance is required, CFAs may be a better option here.

Fully-differential amplifiers are also a very good option for fully-differential I/O. Table 4 lists a selection of amplifiers that meet this requirement.

**Table 4. Fully-Differential Amplifiers for Differential I/O Receiver Functions**

| Amplifier | Input Voltage Noise (nV/√Hz) | Bandwidth at Gain (MHz) |
|---|---|---|
| THS4509 | 1.9 | 2000 (2V/V) |
| THS4513 | 2.2 | 1400 (2V/V) |
| THS4503 | 6.8 | 175 (2V/V) |
| THS4520 | 2 | 450 (2V/V) |
| THS4521 | 4.6 | 135 (1V/V) |

For single-ended application, Table 5 provides a quick selection guide.

**Table 5. Single-Ended Amplifiers for I/O Receiver Functions**

| Amplifier | Input Voltage Noise (nV/√Hz) | Bandwidth at Gain (MHz) |
|---|---|---|
| OPA695 | 1.8 | 850 (2V/V) |
| OPA690 | 5.5 | 220 (2V/V) |
| OPA820 | 2.2 | 200 (2V/V) |
| OPA846 | 1.2 | 300 (10V/V) |
| THS4011 | 7.5 | 290 (1V/V) |
| THS4021 | 1.5 | 350 (10V/V) |

Receiving the signal with an amplifier is the simplest configuration, and works well for short distances and fairly low frequencies without any issues. At high frequencies, however, an unprocessed signal can benefit from equalization. An equalizer circuit is a circuit that compensates for any transmission losses. This technique can be achieved with operational amplifiers, as Figure 5 illustrates.

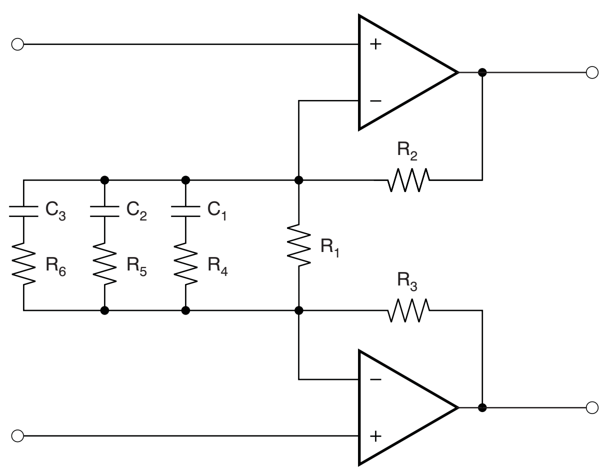



**Figure 5. Differential Equalizer Circuit**

An interesting function for some wireline applications is to receive a differential signal and yet maintain that signal as single-ended. This configuration is not easy to achieve with an operational amplifier because the input impedance is not balanced if an equalization circuit is used. Figure 6 shows such a single-ended equalization circuit with an operation amplifier.

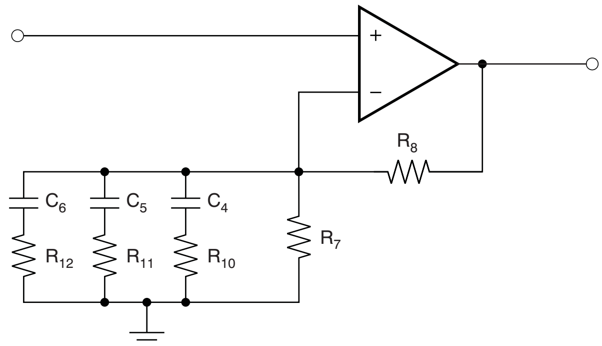



**Figure 6. Single-Ended Equalizer Circuit**

To achieve a differential input, single-ended output, equalization circuit requires two high-impedance inputs. The VCA82x family enables a very simple implementation of this function, as Figure 7 illustrates.

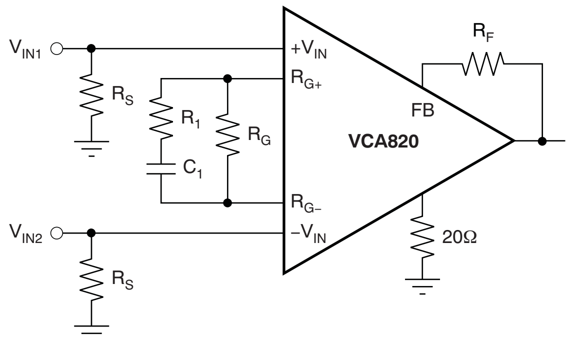



**Figure 7. Differential Equalizer Circuit (VCA820)**

A full cable equalizer for 100ft of a Belden 1694F coax cable is shown in Figure 8.

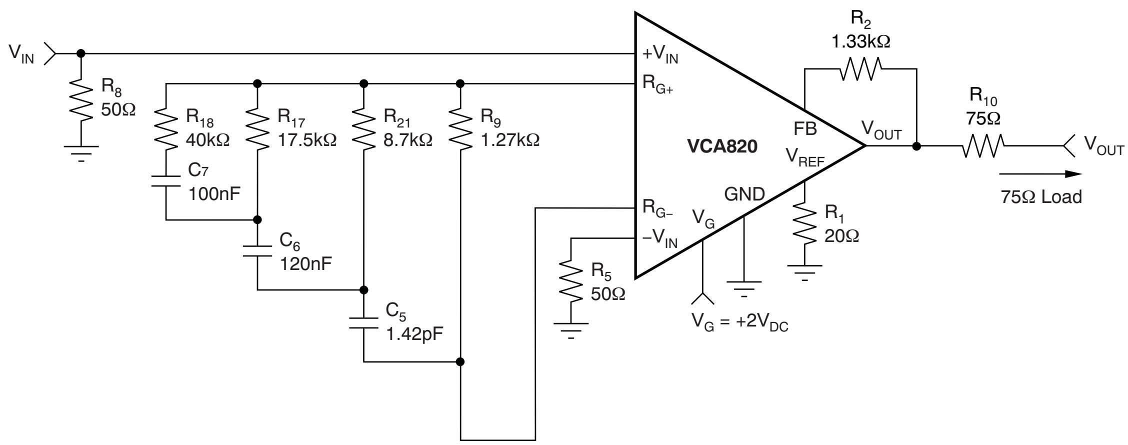



**Figure 8. Equalizer Circuit for 100ft of Belden 1694F Coax Cable**

This implementation has a maximum gain error of 0.2dB versus frequency from dc to 40MHz. We can then compare the frequency response of this circuit to the attenuation of the Belden 1694F coax cable; both responses are plotted together in Figure 9.

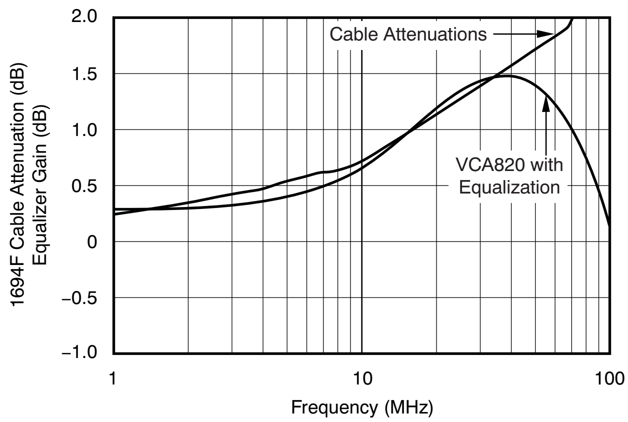



**Figure 9. Cable Equalization and Cable Attenuation Comparison**

## 3 Implementation Example

As an implementation example, we will use a Belden 8723 multi-conductor, shielded twisted-pair cable as a twisted pair, and evaluate its frequency response with a characteristic impedance of 52Ω. Note that because this twisted pair is recommended for both audio and control applications, we must evaluate its frequency response in order to determine the equalization. For this purpose, 100ft of cable was evaluated with the circuit shown in Figure 10.

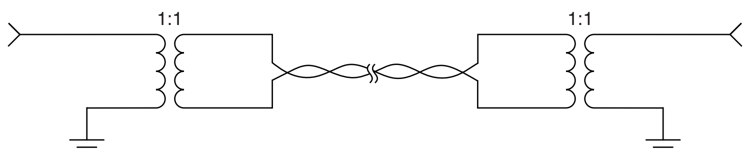



**Figure 10. Twisted Pair Evaluation Circuit Model**

The network analyzer is single-ended. Therefore, transformers are used at both the input and the output in order to realize the single-ended to differential conversion as well as the differential to single-ended conversion. The transformers are calibrated out to eliminate any influence on the measurement, as Figure 11 shows.

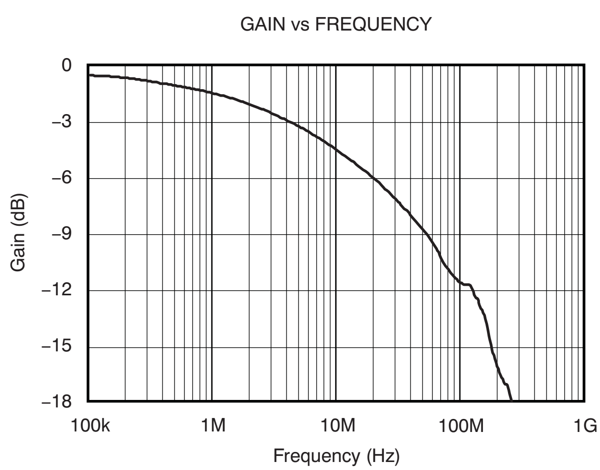



**Figure 11. Belden 8723 Shielded Twisted-Pair Frequency Response**

There are two notable points with this characteristic performance:

1. The insertion loss is 0.5dB.
2. The –3dB bandwidth is 4MHz.

To proceed with the design of both the transmission (Tx) and the reception (Rx) paths, first consider the signal we want to compensate for. The signal is differential on both the input and output, and is gained by 2V/V in the Tx path to compensate for back-matching losses. To simplify the design of the receiver, we use a differential noninverting configuration that requires a dual operational amplifier. This approach allows better Tx line matching over frequency because the amplifier input is high impedance and provides more variety in component selection. The proposed schematic is shown in Figure 12.

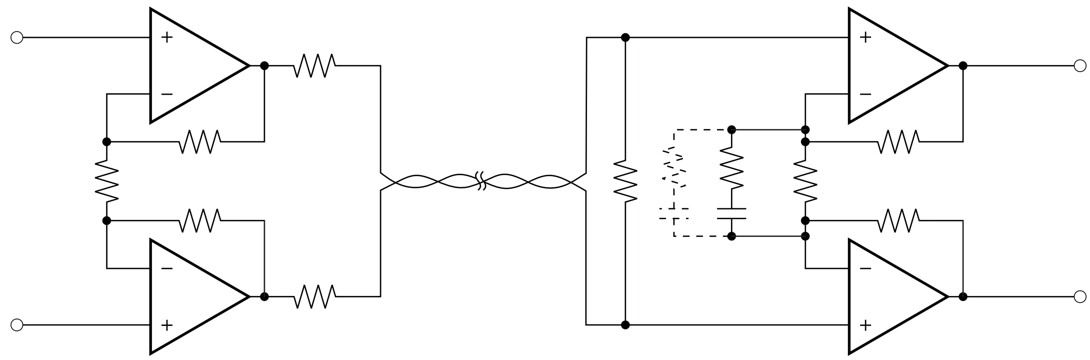


**Figure 12. Proposed Tx and Rx Schematic**

Notice that the gain curve can also be expressed as an attenuation and curve fitting a third-order gain function, to yield Figure 13, with poles located at 1.54MHz, 12.87MHz, and 141.1MHz.

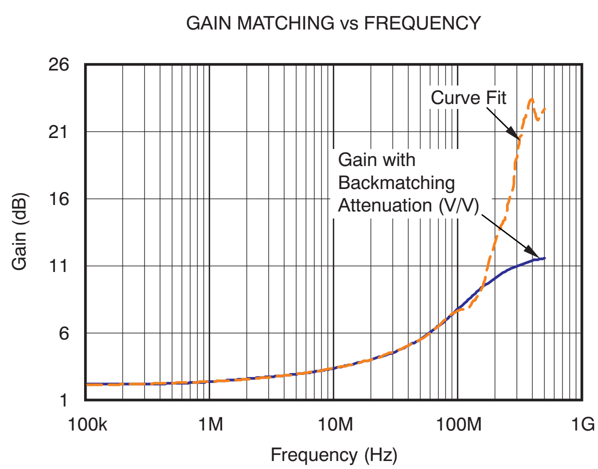



**Figure 13. Theoretical Gain Matching to the Attenuation**

The methodology used to determine the location of the poles is described in detail in the related application note, *A Numerical Solution to an Analog Problem* (SBOA124), available for download at www.ti.com.

In theory, if the amplifier has infinite bandwidth, the gain matches to 100MHz. In practice, however, as a result of the selected amplifier limitations and a conscious choice of over-compensating the amplifier for maximum flatness, the frequency compensation is limited to approximately 40MHz. The complete schematic for the developed Tx/Rx circuit, using an OPA683 for both the Tx and the Rx functions, is given in Figure 14; the corresponding performance measurement is shown in Figure 15.

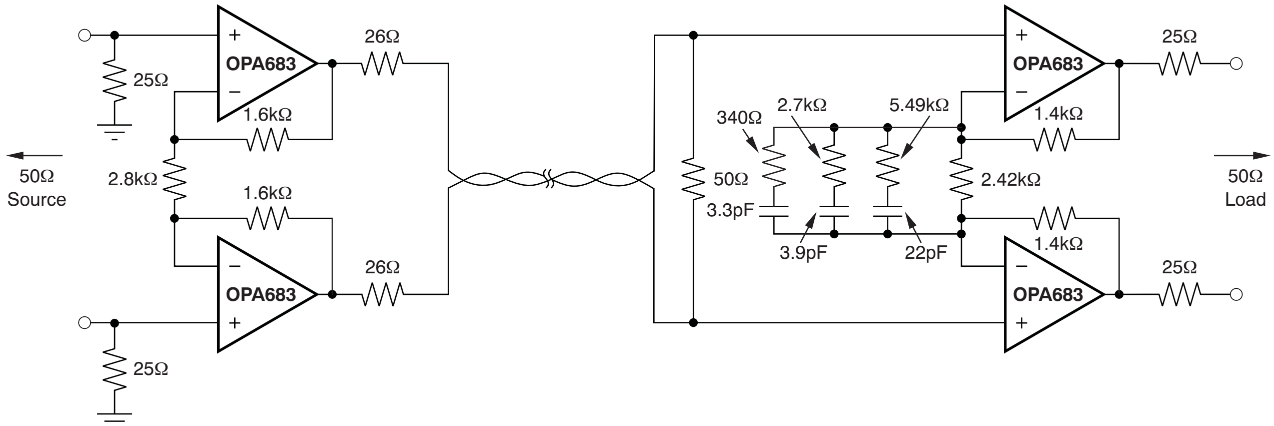



**Figure 14. Developed Tx and Rx Circuit with the OPA683**

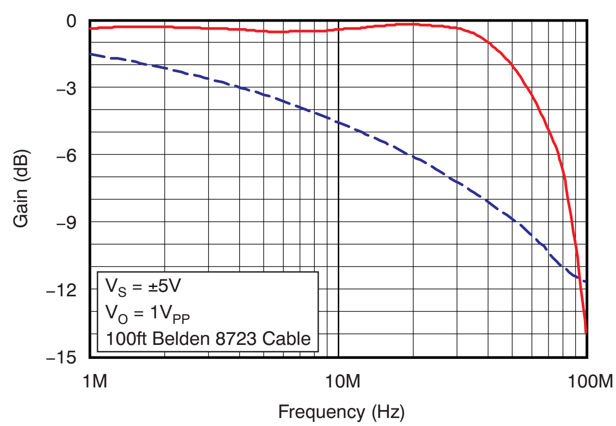



**Figure 15. Measured Circuit Performance**

The frequency response 0.2dB flatness is increased to greater than 30MHz and the -3dB increased from 4MHz to 55MHz.

## 4 Conclusion

This report provides some insights on the possible selections for either the transmission or the reception signal chain for typical wireline communications. It focuses on the application of equalization techniques and subsequent implementations with an example of performance improvement.

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