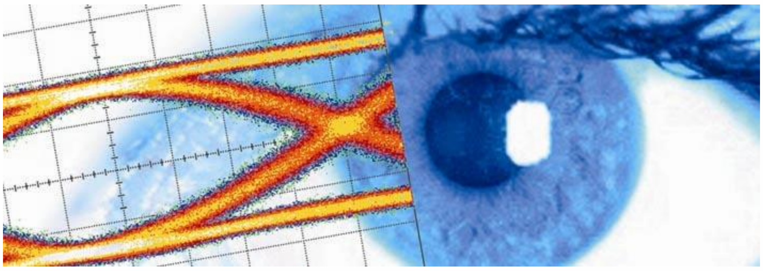
SHF Communication Technologies AG

Wilhelm-von-Siemens-Str. 23D • 12277 Berlin • Germany

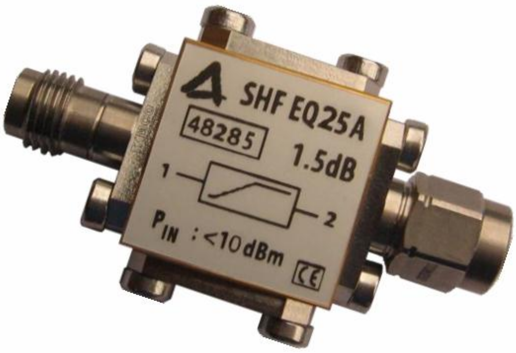
Phone +49 30 772051-0 • Fax +49 30 7531078

E-Mail: sales@shf.de • Web: http://www.shf.de



Application Note

Discrete Linear Equalization Filters for Cable Loss Mitigation



Introduction

In many test and measurement scenarios, the test signal has to be transmitted to the DUT (Device Under Test) through a linear and often lossy channel. Similarly, in the analysis of the DUT response, the resultant signal has to be transmitted to an analyzer. A classic case of such a transmission medium is a long piece of coaxial cable, and the test signal often is from a pattern generator (BPG). The analyzer can be an oscilloscope or a bit error analyzer (EA).

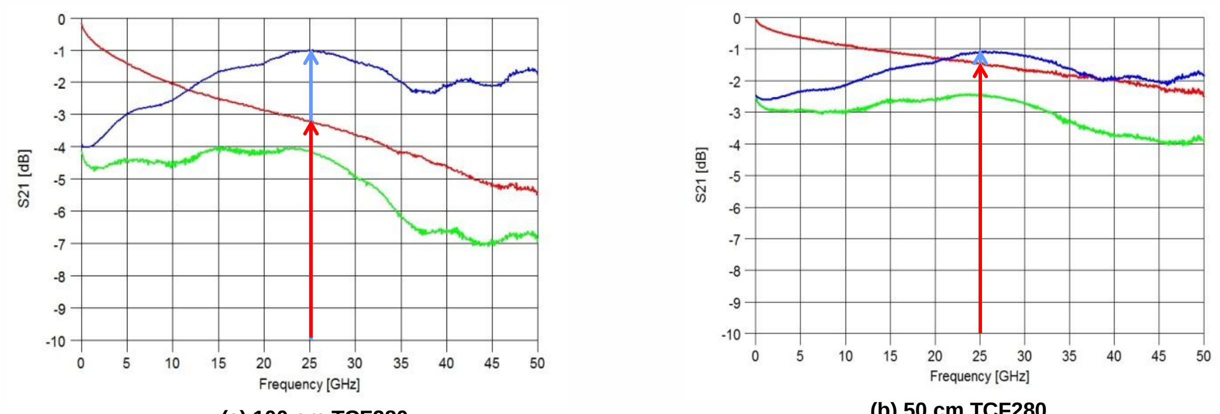
In semiconductor high speed IC testing around a wafer prober, the signal source and analyzer quite often has to be located at a distance of up to a meter from the microwave probes. Delivering, and receiving a true full signal to and from the IC on-wafer becomes an important issue to overcome.

As the speed of the signal and data rate increases, the level of impairment can be so severe rendering the transmitted signal un-usable. To preserve the original signal quality, the impact of the channel/medium such as the coaxial cable(s) has to be mitigated in real time.

The purpose of this note is to highlight how a simple passive impedance-matched equalization filter, with a small number of discrete compensation strength, can effectively compensate for a significant degree of impairment caused by a piece of coaxial cable of various lengths. This simple technique can be particularly useful in cases where adaptive equalization is not available. For example, when the signal source only generates simple NRZ or PAM, and pre-emphasis is not or cannot be implemented.

Basic concept

Figure 1 shows the basic concept of using an equalization filter to 'compensate' or 'equalize' the frequency dependent loss of a coaxial cable. In Figure 1a, the red trace is the response of a 100 cm 50 GHz coaxial cable. The blue trace is the response characteristics of the equalization filter EQ25 A, in configuration 3dB, designed to have a response gain peak of ~3 dB at the Nyquist frequency of around 25 GHz. The Nyquist frequency value corresponds to the data rate in the region of 56 GBaud, whereas the gain value matches the insertion loss of the cable at Nyquist.



(a) 100 cm TCF280
2.5 dB @ 16 GHz, 3.2 dB@ 25 GHz

(b) 50 cm TCF280
1.2 dB @ 16 GHz, 1.4 dB @ 25 GHz

Figure1 Cable loss compensation using a passive impedance-matched equalization filter

The function of the equalization filter is to compensate for the early roll off of the cable by boosting the high frequency portion in the response characteristic, similar to the way an FIR filter is used to pre(de)-emphasis the signal. With this added high frequency response component, the over-all response of the 'medium' is maintained up to the Nyquist frequency, and the original signal can be transmitted in as close to its original form as possible, as illustrated by the green trace.

In the situation that a lower over-all loss is desired, a shorter piece of cable can be used. Then the cable insertion loss is almost halved at the same Nyquist frequency, and less compensation strength is needed. A filter with lower gain peak can be used to deliver a similar compensation effect. Figure 1b shows how the impact of a 50 cm 50 GHz cable is compensated for with a 1.5 dB gain peak filter.

In the above illustrations, the coaxial cable is of the SHF provided TCF280 series of flexible microwave cables (50 GHz) commonly used in laboratory test and measurement applications. These instrument-grade cables exhibit excellent phase stability and ruggedness. In some applications where a higher frequency of 65 GHz might be more desirable, then the TCF219 series can be considered, although the insertion loss will be slightly higher. Typical loss characteristic of these cables is given in the Appendix, and more technical details of this product range, as well as other cable types can be found on the SHF home page, www.shf.de .

The cables used in the above examples can be of other brands, as long as the loss value at the desired Nyquist frequency can be selected to approximately match the filter gain peak value.

Further, this compensation concept can be extended to work with other loss medium or channel for as long as the frequency dependent loss is a linear mechanism. For example, this lossy channel can be a transmission line on a PCB board, in a back plane product, which tends to exhibit a strong frequency dependent, but linear, loss behavior. The same can be said to an active element such as a modulator which might exhibit an earlier than desired frequency roll off for the intended operating data rate.

In the event that at Nyquist the loss value of the cable and the available filter(s) do not form a perfect match, then the signal will either under or over compensated. In this situation, as will be shown later that over-compensation appears to favor towards a better BER performance, whilst under-compensation has the opposite impact on BER.

Filter characteristics

Two sets of equalization filters are available covering two data rate regimes of around 32 and 56 GBaud. For operation around 32 GBaud, the Nyquist frequency is set to 16 GHz, and three discrete response gain peak values of 1.5, 3 and 6 dB are available providing three basic compensation strengths. For operation in the 56 GBaud regime, the Nyquist frequency is set to 25 GHz, and the basic compensation strengths available are currently limited to 1.5 and 3 dB.

This type of passive gain peaking equalization filters are designed to exhibit 50 ohm impedance match. Figure 2 shows the input and output s-parameters of the EQ16 A family of devices. The excellent impedance matching characteristic suggests that these filters can be cascaded with negligible impact from residue multi-path signal reflections, which can manifest as a ‘noise-like’ feature in the eye pattern. This impedance-match design has important benefits.

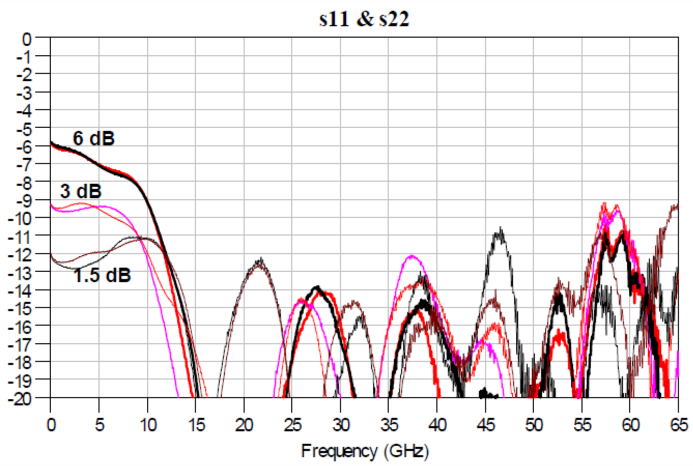


Figure 2 EQ16 A input and output reflection characteristics

First, with the three gain peak values, it becomes possible to cascade and yield additional compensation strengths of 4.5, 7.5, 9 and 10.5 dB.

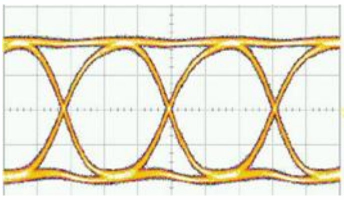
Second, since both the cable and filter are passive elements, and signal amplitude after compensation will be reduced. An amplifier gain block can be deployed to boost the final output signal level. When cascaded after the cable/filter, the gain of the amplifier can absorb the loss incurred by the cable/filter combination.

Equalization examples

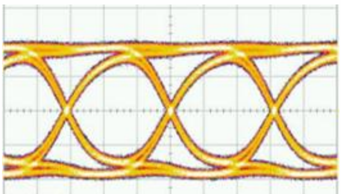
In this section, some examples of the EQ16 A (16 GHz Nyquist, 32 GBaud range), and EQ25 A (25 GHz Nyquist, 56 GBaud range) are given to show the effectiveness of this simple approach in mitigating the detrimental impact of cable insertion loss of at least up to 100 cm length. Results for both NRZ and PAM4 data format are given.

EQ16 A, 32 GBaud Regime

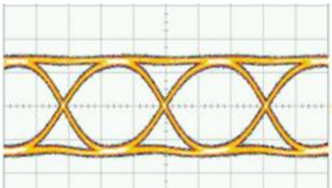
In the region of 25 to 32 GBaud, the impact of cable loss is not so serious for as long as the cable length is kept to a minimum. In the event a 100 cm cable is needed to transmit the signal to the DUT, the eye patterns below shows the effectiveness of the EQ16 in configuration 1.5dB in maintaining the signal quality at the end of the 100 cm cable (TCF280, 2 dB @ 16 GHz).



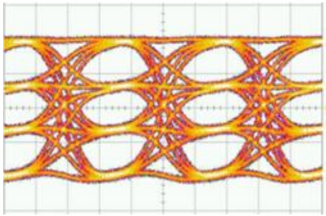
32 Gbps NRZ at BPG output



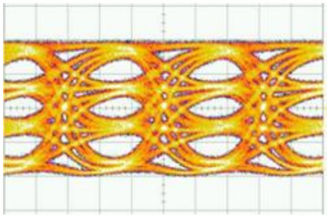
After 100 cm TCF280 cable



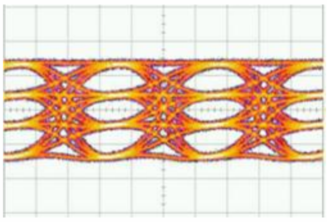
100 cm cable+EQ16-1.5dB



PAM4 at BPG output



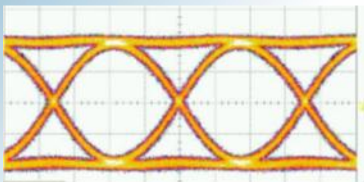
After 100 cm TCF280 cable

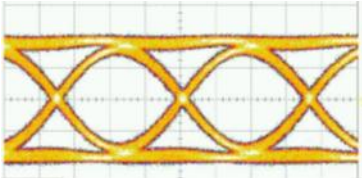


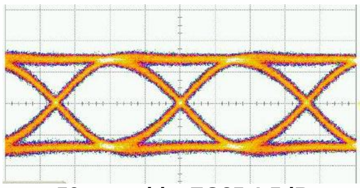
100 cm cable+EQ16-1.5dB

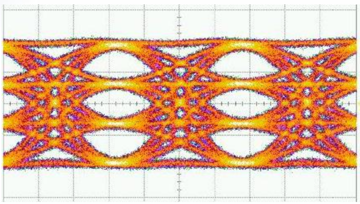
EQ25 A for 56 GBaud regime

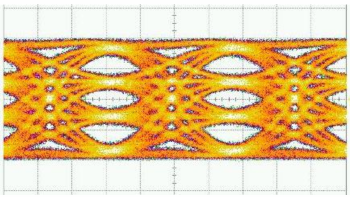
In the 56 GBaud regime, after a cable length of 50 cm (~1.5 dB loss at Nyquist), the NRZ signal quality is reasonably well preserved. However, the impact on a PAM4 signal is more serious, and would benefit from a modest level of equalization using a 1.5 dB filter.

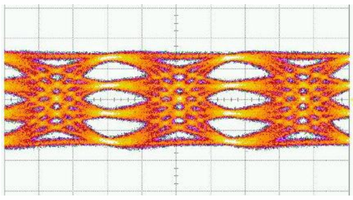

56 Gbps NRZ at BPG output


After 50 cm TCF280 cable

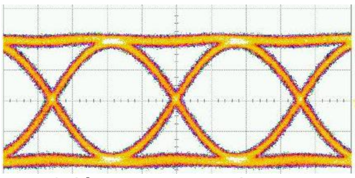

50 cm cable+EQ25-1.5dB

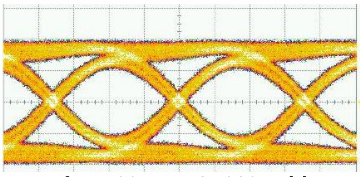

PAM4 at BPG output

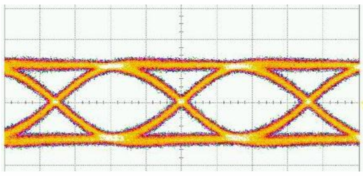

After 50 cm TCF280 cable

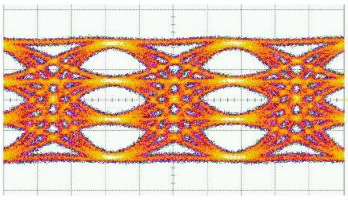

50 cm cable+EQ25 A-1.5dB

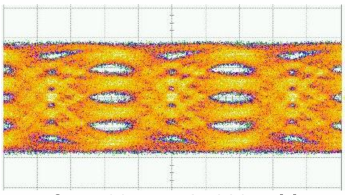
With a 100 cm cable, the benefit of equalization, for PAM4 in particular, is clearly shown below.

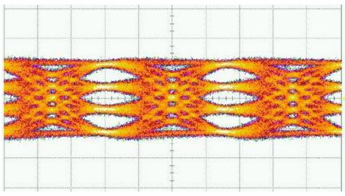

56 Gbps NRZ at BPG output


After 100 cm TCF280 cable


100 cm cable+EQ25 A-3dB

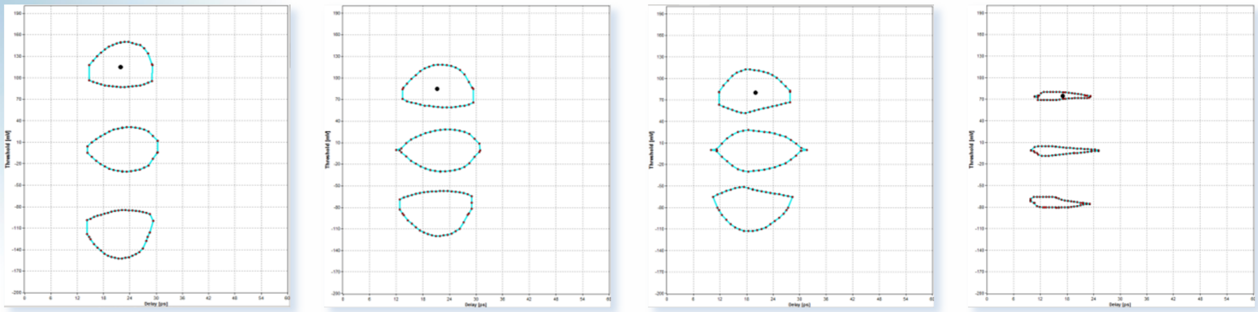

PAM4 at BPG output


After 100 cm TCF280 cable


100 cm cable+EQ25 A-3dB

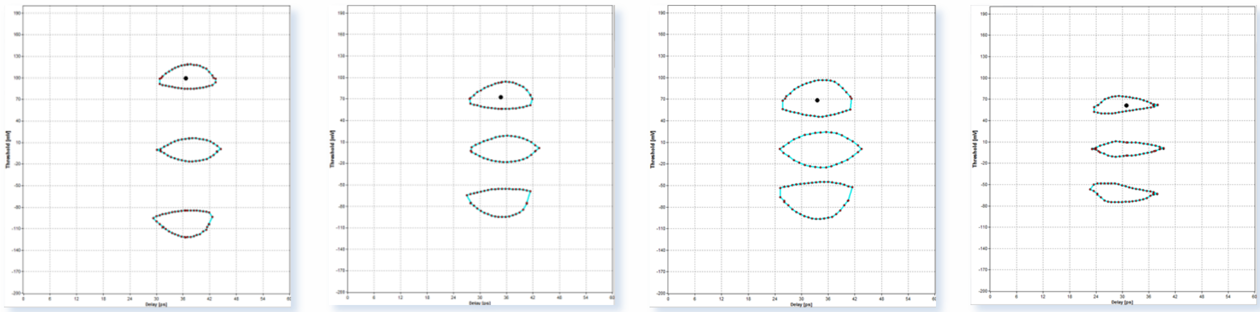
BER analysis in 32 GBaud PAM4

The impact of cable under various level of loss impairment, and the benefit of equalization is also reflected in the BER performance. The following data shows the 10^{-6} BER eye contours for a 28 GBaud PAM4 signal, captured by the SHF 11104 A Error Analyzer, under various signal conditions. The 28 GBaud PAM4 signal, PRBS sequence length 2^{11}-1, was generated via the two MSBs of a 3-bit DAC.



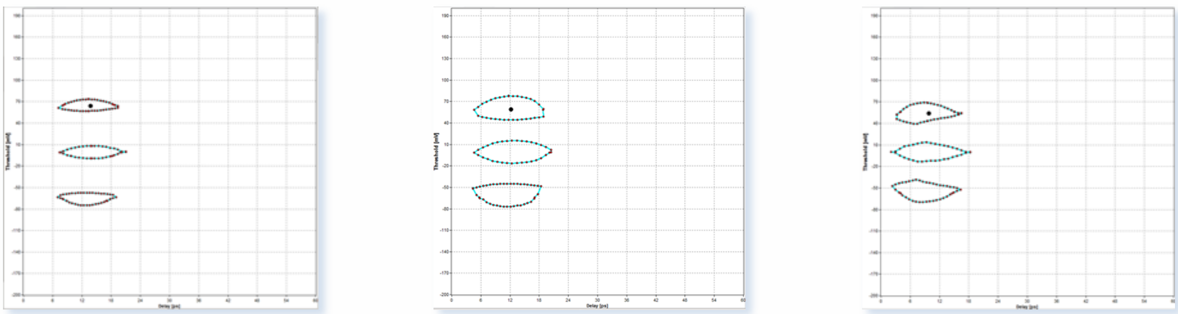
No filter **+1.5 dB filter** **+3 dB filter** **+6 dB filter**

Cable: 70 cm TCF280 (~ 1.5 dB loss @ 16 GHz)



No filter **+1.5 dB filter** **+3 dB filter** **+6 dB filter**

Cable: 50 cm TCF219 (~ 1.5 dB loss @ 16 GHz)



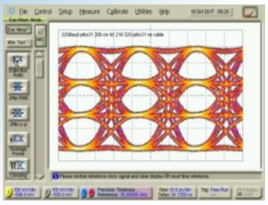
+1.5 dB filter **+3 dB filter** **+6 dB filter**

Cable: 100 cm TCF219 (~ 3 dB loss @ 16 GHz)

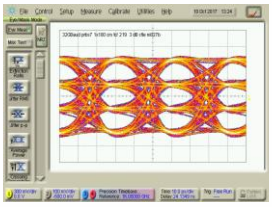
From these BER measurement data, it seems to suggest that under-compensation should be avoided, whilst a slight over-compensation can lead to better BER performance. However, too much over-compensation can lead to severe performance degradation. It is likely that this is related to the over-all measurement system response including the input respond characteristic of the error analyser. The slight over-compensation may indeed also compensate for the bandwidth/speed limitation of the error analyzer.

Cable-filter-amplifier in cascade

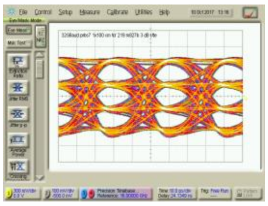
In many test and measurement applications, an amplifier is often needed to boost the signal amplitude after equalization. In figure 3, a 65 GHz bandwidth amplifier with 10 dB small signal gain (the SHF M827 B) was used to absorb the loss of a 100 cm TCF219 cable compensated by an EQ16 A-3dB filter. The eye patterns compare the signal quality after compensation in various configurations to highlight any potential reflection and low frequency effects. These effects would have manifested as 'noise'-like broadening causing eye closure. Any low frequency cut-off effect should be apparent through comparing the PRBS7 and PRBS31 response.



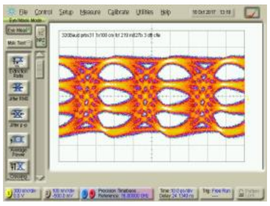
PRBS31
Reference signal



PRBS7
Cable+filter+ amplifier



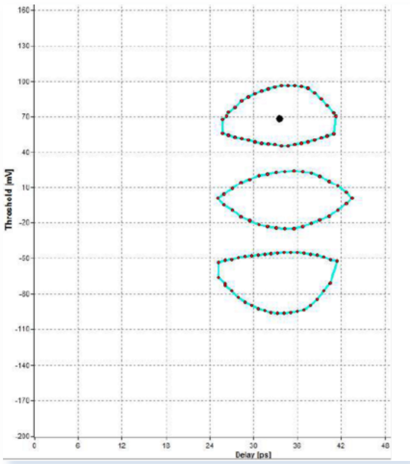
PRBS7
Cable+amplifier+filter



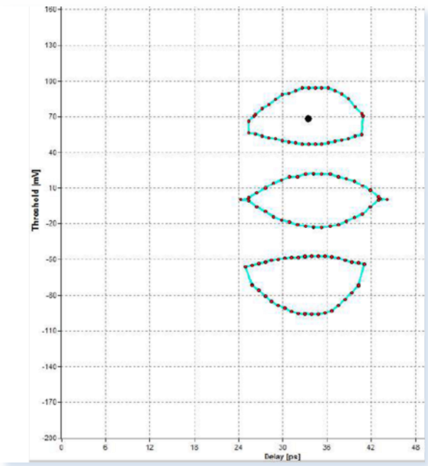
PRBS31
Cable+amplifier+filter

Figure 3 Tolerant to reflection and pattern length effects

The apparent absence of increase in 'noise' added to the signal tends to support the excellent s11 and s22 levels, and the low frequency -3 dB corner of the filters are sufficient for PRBS 31 length. Further evidence can be seen in the BER performance for PRBS 11 and 31 pattern lengths for the cable + filter test configuration, as shown in Figure 4. The BER 10^{-6} eye contour behaviour between PRBS11 and 31 pattern lengths is essentially the same.



PRBS11 50 cm TCF219 +EQ16 A-3dB



PRBS31 50 cm TCF219 +EQ16 A-3dB

Figure 4 Pattern length comparison for BER performance

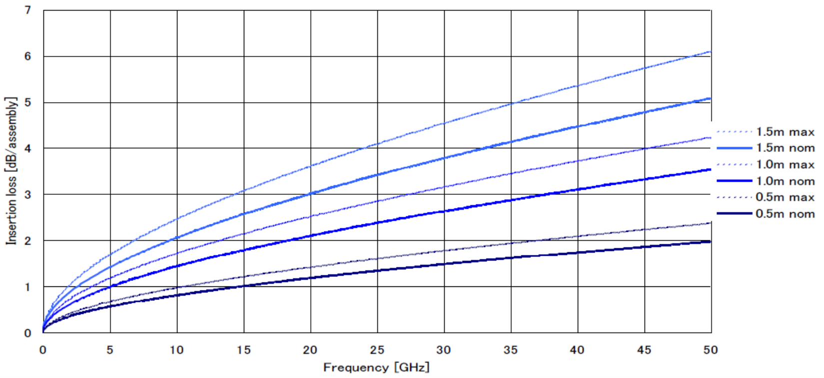
Summary

- Passive equalization filters can effectively mitigate the frequency-dependent loss of long lengths of coaxial cables commonly encountered in a variety of test and measurement scenarios.
- Passive gain peaking filter construction exhibits good 50 ohm impedance matching to enable different cable-filter placement configurations and the inclusion of a linear amplifier gain block to boost the final test signal amplitude.
- Three discrete filter values of compensation strength, 1.5, 3 and 6 dB, and their combinations appear adequate to cover the equalization needs for cable lengths commonly used in test and measurements, up to 100 cm at least.
- This approach is a highly effective and low cost solution for cable loss compensation.
- This solution may be applied to cover other lossy medium/channel, for as long as the loss mechanism is a linear frequency dependent behaviour.

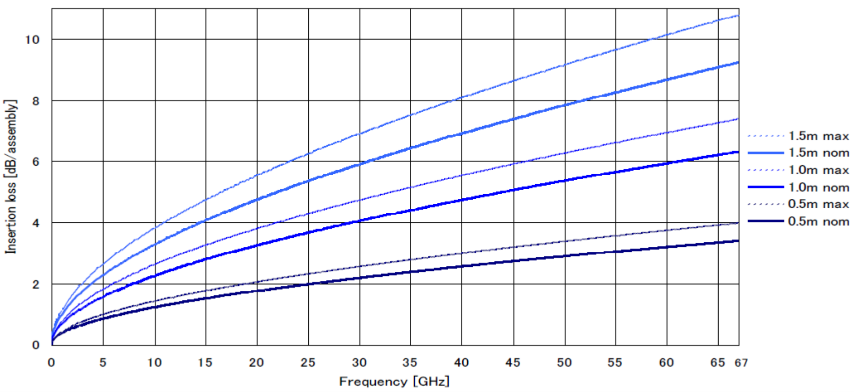
Appendix

In test and measurement applications involving high speed data in both NRZ and PAM, microwave coaxial cables using either 2.4 or 1.85 mm connectors are preferred. Typically, a 2.4 mm connector cable exhibits less loss compared to the 1.92 mm counter-part, although the 2.4 mm cable exhibits a lower moding frequency of 50 GHz vs. 65 GHz for the 1.92 mm cable. The choice between 2.4 and 1.92 mm often depends on the desire for lower loss.

Typical TCF280 and TCF219 cable insertion loss characteristics are given below for cable lengths of 50, 100 and 150 cm. More details and background data can be found in our home page www.shf.de.



Cable Loss-50 GHz Cable TCF 280 (2.4 mm)



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Cable Loss-65 GHz Cable TCF 219 (1.85 mm)