

Selecting Equipment for the Measurement of High-Speed Digital Signals

1. Introduction

With the spread of artificial intelligence (AI) and high-performance computing, the amount of data being handled by transponders, servers, and storage devices is increasing dramatically. Within these devices, high-speed digital signals are exchanged at data rates of several tens of Gigabits per Second. To properly handle such high-speed signals, designers must pay careful attention not only to the characteristics of those digital signals but also to the behavior of analog signals. Therefore, selecting the appropriate measuring instruments is needed to accurately evaluate signals.

This document begins by outlining the fundamental principles of digital signals and their measurement techniques. It then explores the roles of sampling oscilloscopes and related components, highlighting how variations in their performance and characteristics can significantly affect measurement results.

2. Nature of Digital Signals

A rectangular wave with a 50% duty cycle is a fundamental digital signal waveform, composed of the fundamental frequency along with odd harmonics such as the 3rd, 5th, and 7th multiples combined. Mathematically, this means that a rectangular wave can be represented as the sum of odd harmonics through the Fourier series expansion.

Furthermore, as the multiples increase, the amplitude of each harmonic gradually decreases. In other words, the sharp shape of a rectangular wave is produced by harmonic components, such that removing these components causes the waveform to become rounded. Thus, the characteristics of a rectangular wave are explained by the presence of harmonics and their attenuation properties.

$$f(x) = \frac{\pi}{4} \left(\sin(x) + \frac{1}{3} \sin(3x) + \frac{1}{5} \sin(5x) + \frac{1}{7} \sin(7x) + \dots \right)$$

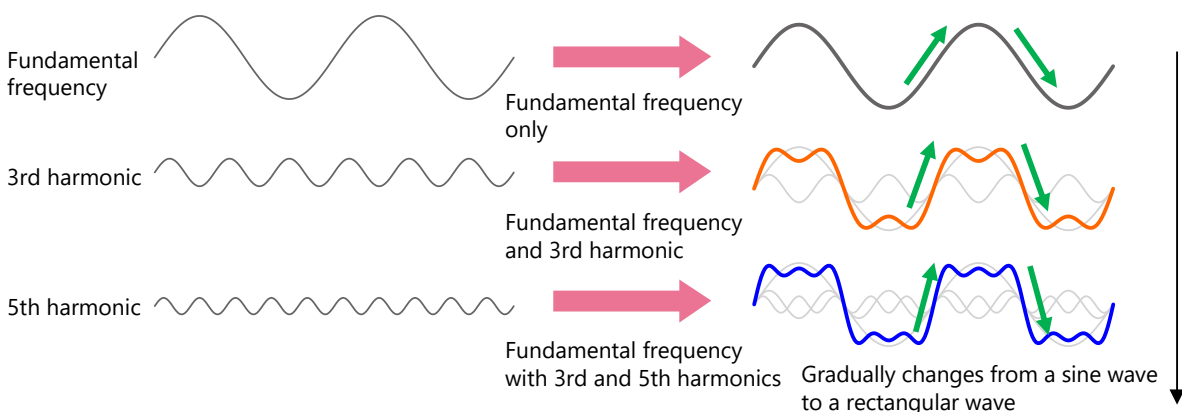


Figure 1 Compositions of Rectangular Waveforms

However, with actual signals, if the duty is not 50% for some reason, jitter may occur as a result of reflections, etc. Instead of a multiple odd-number integer harmonic of the reference frequency, a multiple even-number harmonic may be superimposed. However, this document considers only rectangular waveforms with an ideal 50% duty.

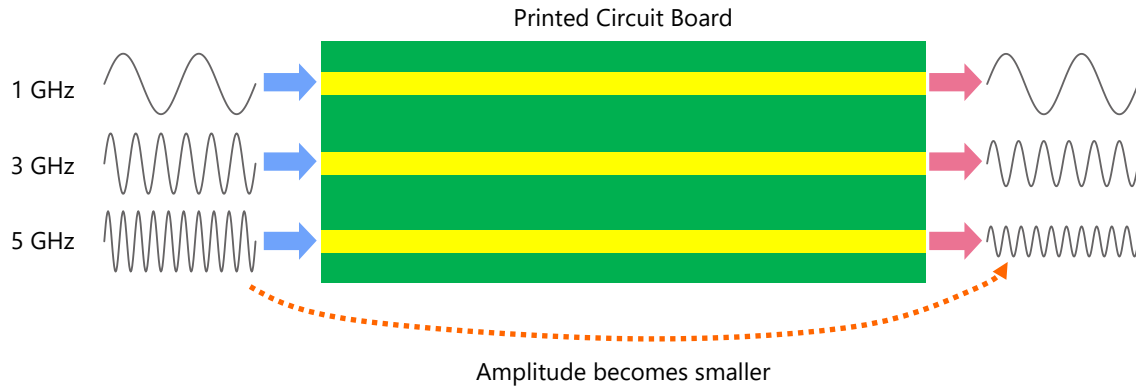


Figure 2 Transmission Path Loss

Digital signals are typically transmitted from the transmitting circuit to the subsequent receiving circuit over a printed circuit board. On the transmission line, the loss of higher-frequency components is generally greater than that of lower-frequency components. As a result, the high-frequency components are attenuated, which can distort the signal waveform. The degree of attenuation along the transmission path can be evaluated using a network analyzer. A network analyzer can acquire the so-called scattering parameters (S-parameters). Among these, the S_{21} parameter indicates the amount of signal attenuation that is incurred from the input to the output of the transmission path. A network analyzer can evaluate the frequency characteristics of the attenuation.

Based on the frequency characteristics of digital signals, the following chapters will provide a detailed explanation of how the measurement system affects the measurement results.

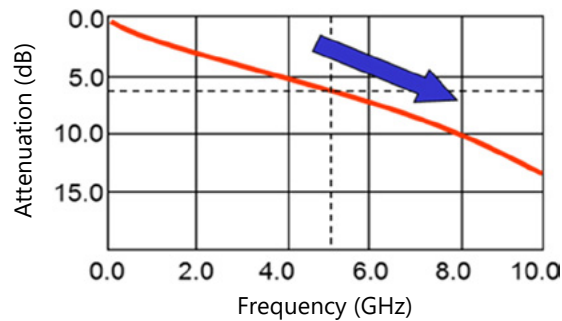


Figure 3 Frequency Characteristics of Transmission Line

3. Effect of Sampling Oscilloscope Performance on Waveform Differences

This section describes the impact of performance differences in sampling oscilloscopes, which are used to measure digital signal waveforms, on the measurement results.

3.1 Differences in Waveforms due to Bandwidth

Sampling oscilloscopes are generally used for measuring high-speed digital signals. As explained in Section 2, rectangular waves contain many harmonic components, and to observe these properly, a sufficient bandwidth corresponding to the speed of the signal being measured is necessary.

For example, consider the case of measuring a 10-Gbit/s electrical signal using the Non-Return-to-Zero (NRZ) method. In this case, the fundamental frequency is half the signal rate, that is, 5 GHz, which is also known as the Nyquist frequency. However, to accurately observe the rising and falling waveforms of a digital signal, it is necessary to correctly capture not only the fundamental frequency but also the higher harmonic components, such as the third and fifth multiples. This is because the steep edge portion of the rectangular waveform is composed of harmonic components, and without sufficient bandwidth, the waveform appears blurred.

For the fifth harmonic, let us once again review the equation for the Fourier series expansion of a rectangular wave.

$$f(x) = \frac{\pi}{4} \left(\sin(x) + \frac{1}{3} \sin(3x) + \frac{1}{5} \sin(5x) + \frac{1}{7} \sin(7x) + \dots \right)$$

The above equation shows that, although the amplitude of the harmonics decreases, the overall impact on the waveform is minimal.

To accurately observe an ideal waveform, a wideband measuring instrument capable of sufficiently covering the harmonic components of the signal is necessary. For example, in the case of a 10-Gbit/s NRZ signal, theoretically, a frequency of 35 GHz is required for the 7th harmonic and 45 GHz for the 9th harmonic. This is because, to faithfully observe the sharpness of the signal rise and fall edges, it is necessary to measure up to the higher-order harmonic components.

On the other hand, for an NRZ signal with a data rate of 28 Gbit/s, the 7th harmonic requires a bandwidth of 98 GHz, while the 9th harmonic requires as much as 126 GHz of bandwidth. However, very few measuring instruments are capable of supporting such a high bandwidth, and those tend to be very expensive. Therefore, instead of covering all the harmonic components, it is necessary to decide how much to invest within a practical bandwidth range.

Given these considerations, when evaluating the waveform quality of digital signals such as rectangular waves, it is common to use a sampling oscilloscope with a bandwidth that can cover at least up to the 5th harmonic of the fundamental frequency. For example, for a 10-Gbit/s signal, the fundamental frequency is approximately 5 GHz, and equipment with a bandwidth of 25 GHz or more, which is five times the fundamental frequency, is recommended. Furthermore, in actual measuring environments, since the signal is also affected by losses and reflections from transmission lines and connectors, as well as external noise, selecting a wider bandwidth allows these influences to be taken into consideration, enabling the more faithful reproduction and observation of the original waveform and edge characteristics of the signal. Similarly, when measuring a 28-Gbit/s data signal used in a 100G Physical layer (PHY), considering the fundamental frequency of 14 GHz and its fifth harmonic, a bandwidth of 70 GHz is required.

In general, when evaluating optical communication devices, it is often stipulated that the signal be measured after passing it through a Low-Pass Filter (LPF) at approximately 75% of the bit rate (for 10 Gbit/s, a 7.5-GHz LPF), such that the required bandwidth differs from that needed for measuring electrical signals.

Figures 4 and 5 show the waveforms of a 28-Gbit/s signal observed using sampling oscilloscopes with 50- and 70-GHz bandwidths. When observed with a 70-GHz bandwidth, the signal's rise and fall times (10% to 90%) were approximately 14.2 ps. On the other hand, when observed with a 50-GHz bandwidth, the rise and fall times were about 17 to 18 ps, which is 1.2 to 1.3 times greater than in the case of the 70-GHz bandwidth.

The main cause of this difference is that the bandwidth limitation of the oscilloscope prevents adequate observation of the harmonic components. In particular, the frequency components from the fifth harmonic and higher are essential for accurately reproducing the sharp rise and fall of the signal. With a 50-GHz bandwidth, however, some of these harmonics extend beyond the available range, making them unobservable. As a result, the waveform becomes rounded, and the measured rise and fall times are longer than they are.

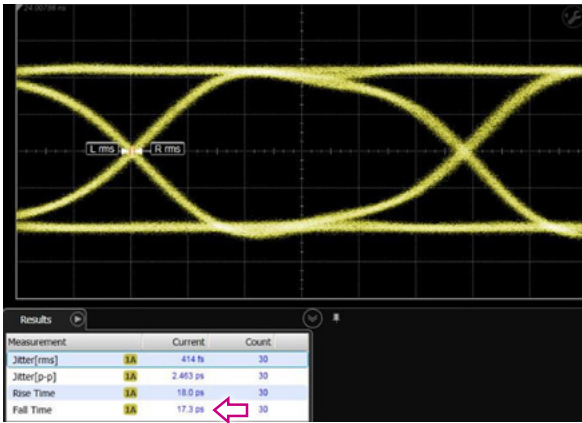


Figure 4 Waveform Measured with 50-GHz Oscilloscope

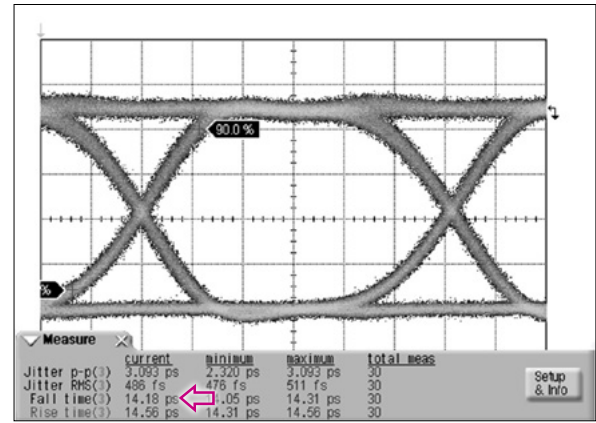


Figure 5 Waveform Measured with 70-GHz Oscilloscope

3.2 Differences in Waveforms due to Trigger

A point requiring careful attention when observing high-speed signals in the Gbit/s class with a sampling oscilloscope is the trigger precision. With a sampling oscilloscope, an asynchronous trigger signal relative to the target signal serves as the reference, and the input signal is sampled at regular intervals to reconstruct the waveform. Here, suppose the reference trigger signal exhibits a lot of jitter (timing fluctuations). In that case, the jitter displayed on the reconstructed waveform will appear to be greater than that present in the input signal.

As the signal speed increases, the time width per bit becomes shorter, so for measurements of ultra-high-speed signals exceeding, for example, 20 Gbit/s, the effect of jitter caused by the measurement system cannot be ignored. Therefore, to perform high-precision jitter measurements, engineers need to suppress the jitter components inherent in the measuring equipment itself.

As a specific example, consider observing a 28-Gbit/s signal with a sampling oscilloscope with a bandwidth of 70 GHz. Here, Figure 6 shows the observed waveform when using the "high-precision trigger" function, and Figure 7 shows the case when it is not used. When using a high-precision trigger, the measured jitter value is 486 fs (RMS), but it can be confirmed that it increases to 1.062 ps (RMS) with a regular trigger. This indicates that jitter caused by the measurement system has a significant impact on the observed results.

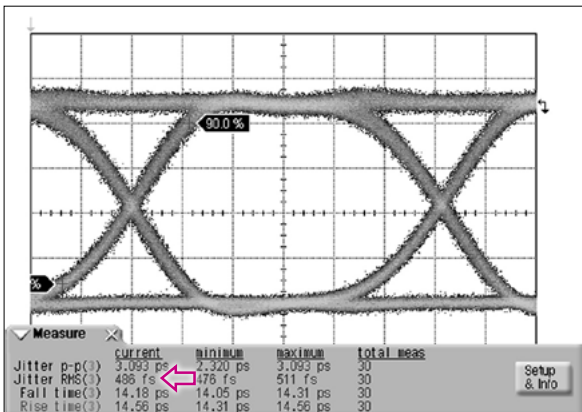


Figure 6 Waveform with Precision Trigger

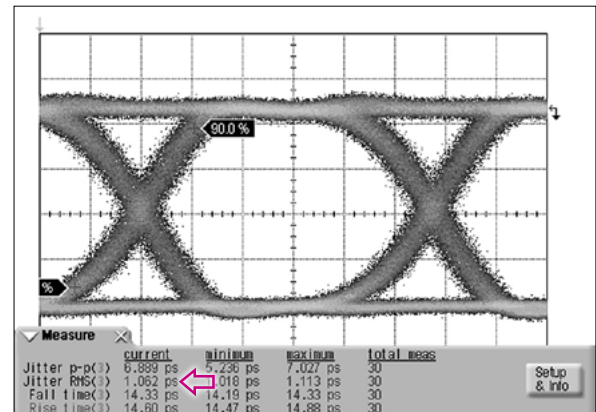


Figure 7 Waveform without Precision Trigger

Even when the same waveform is input, differences in the trigger precision and bandwidth of the sampling oscilloscope can cause variations in the observed waveform. Therefore, the measured waveform does not necessarily accurately reflect the actual signal, and there is a risk of incorrect evaluation due to trigger and bandwidth limitations.

To perform accurate signal evaluation, it is important to fully understand the signal characteristics and frequency band of the measurement target and to choose appropriate measurement tools and oscilloscopes.

4. Characteristics of Peripheral Devices

This section explains the effects of the characteristics of components, such as the connectors, filters, and cables used when observing waveforms.

Figures 8 and 9 show the results of observing two types of 10-Gbit/s signals with different waveform qualities. In both cases, observations were conducted using an oscilloscope with a 50-GHz bandwidth and high-precision triggering, inputting a signal with an amplitude of 2 Vp-p through an 80-cm cable. From these observations, the rise and fall times of PPG-1 are approximately 28 ps. On the other hand, the waveform of PPG-2 has faster rise and fall times of about 12.5 ps.

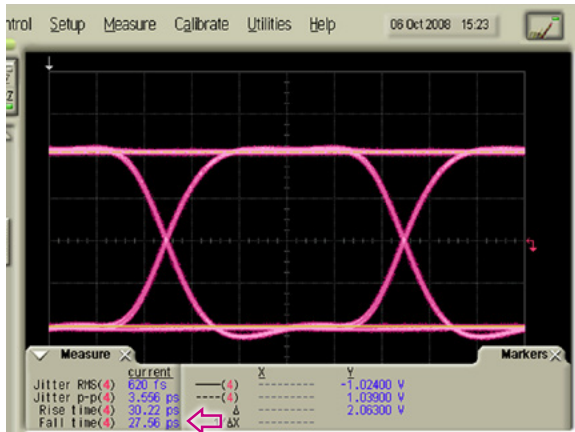


Figure 8 PPG-1 Waveform

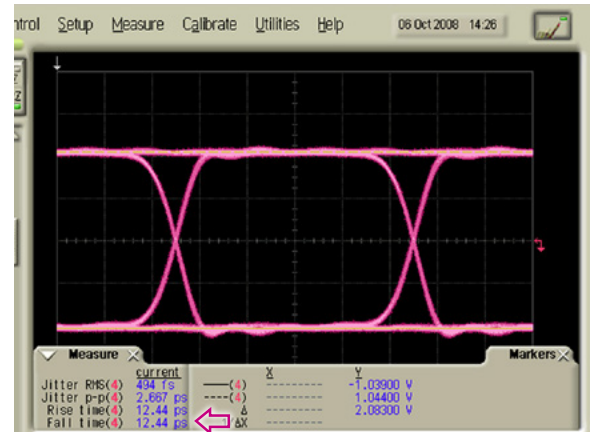


Figure 9 PPG-2 Waveform

The spectrums of these two waveforms are shown below.

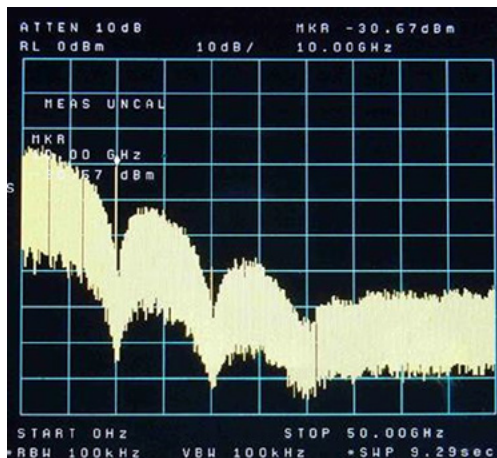


Figure 10 PPG-1 Spectrum

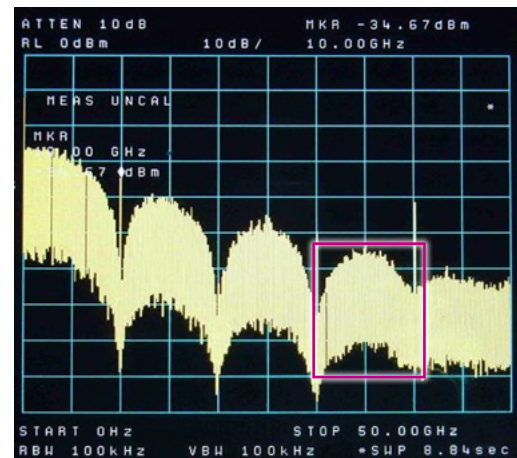


Figure 11 PPG-2 Spectrum

For the spectrum below 30 GHz, both show almost the same characteristics, but the PPG-2 spectrum shows a slightly higher level at around 35 GHz. This indicates that the waveform of PPG-2 has steeper rising and falling edges, and is closer to an ideal rectangular wave shape. As a result, Figure 11 indicates that the spectrum contains a significant amount of the 7th harmonic component.

To understand the impact of such spectral differences on waveform measurements, the following section explains how waveforms are altered when passing through passive components such as connectors and filters. Specifically, we observed the waveform as it passed through an SMP-SMA adapter with frequency characteristics suitable for 10-Gbit/s signals.

To evaluate the transmission characteristics of the adapter, S-parameters were measured using a vector network analyzer. Figure 13 presents these results. While the frequency response of S_{21} shows some amplitude fluctuations, it is confirmed that the bandwidth is sufficiently extended up to approximately 50 GHz.



Figure 12 SMA-SMP Adapter

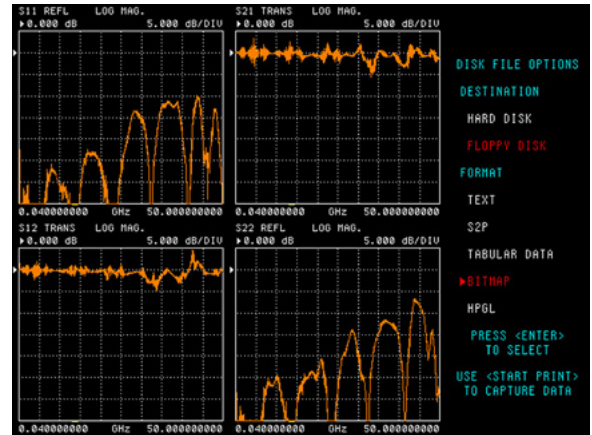


Figure 13 S-parameters of SMA-SMP Adapter

When passed through this type of device, there is almost no effect on the observed waveform.

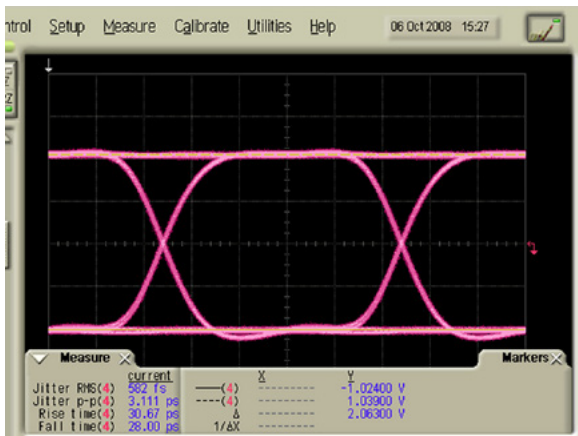


Figure 14 PPG-1 Waveform after Passing Through SMP

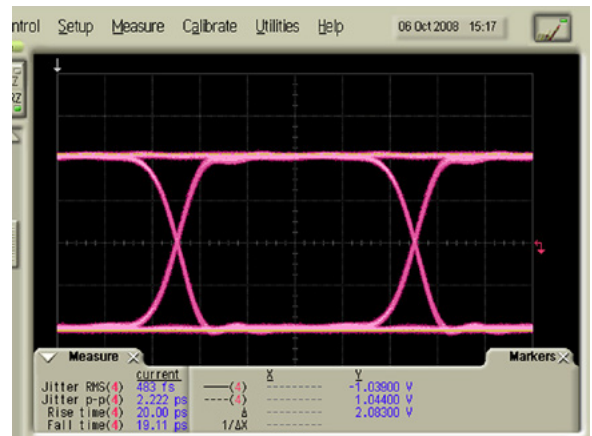


Figure 15 PPG-2 Waveform after Passing Through SMP

Next, Figure 17 shows the S-parameters of the BNC-SMA male/female adapter.

The frequency characteristic S_{11} is approximately 0 dB near 43 GHz, indicating that the signal is reflected at this frequency.



Figure 16 BNC Adapter

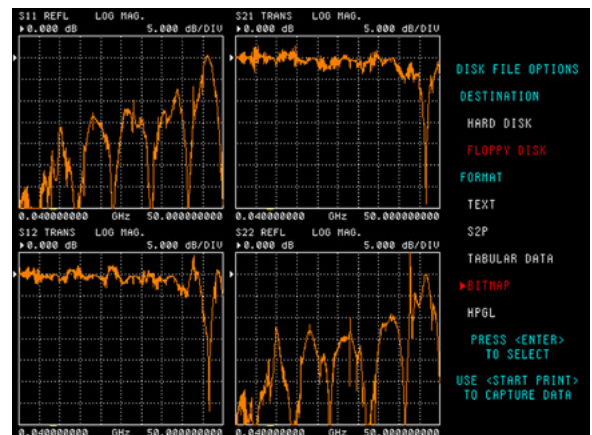


Figure 17 S-parameters of BNC Adapter

Figures 18 and 19 show how the characteristics of this BNC adapter affect the waveforms.

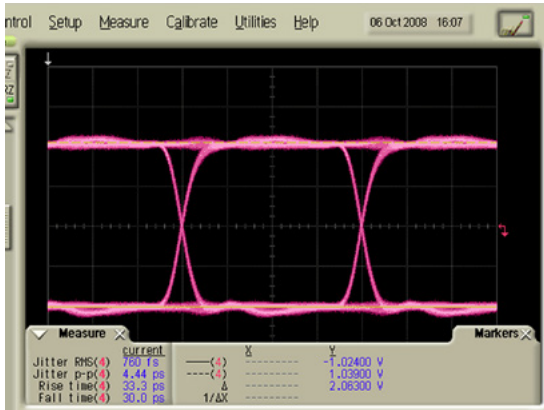


Figure 18 PPG-1 Waveform after Passing Through BNC

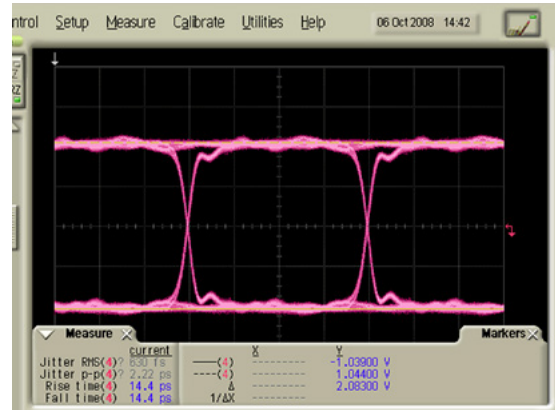


Figure 19 PPG-2 Waveform after Passing Through BNC

Distortions in the waveform baseline are observed for both waveforms. This phenomenon is primarily attributed to reflection; PPG-2, which contains a larger proportion of components above 30 GHz, tends to be more significantly influenced. If the transmission line's frequency characteristics do not adequately support the signal bandwidth, introducing signals with rapid rise and fall times can cause the waveform to deteriorate. Therefore, the input signal waveform should be tailored to match the characteristics of the transmission line. Next is an example of passing signals with fast rise and fall times through an LPF tailored to the transmission line.

The following explains the case of using an LPF with a cutoff frequency of 6.8 GHz. Figure 20 shows the measured S-parameters for this LPF.

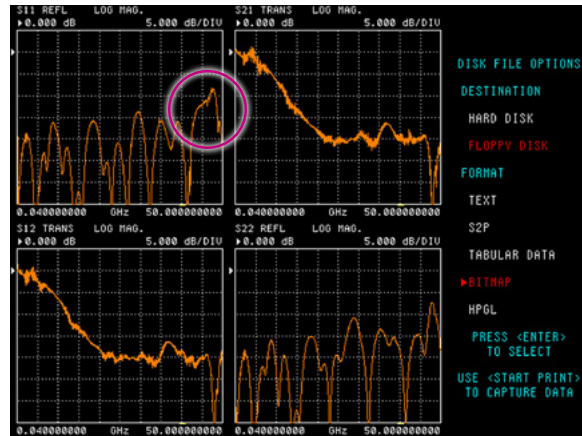


Figure 20 S-parameters of LPF with a 6.8-GHz Cutoff Frequency

For S_{21} , there is attenuation of about 10 dB/decade from around 6.8 to 20 GHz, but beyond 20 GHz, the attenuation is constant. Moreover, S_{11} shows that reflections increase beyond 40 GHz. Figures 21 and 22 show the waveforms after passing through this LPF.

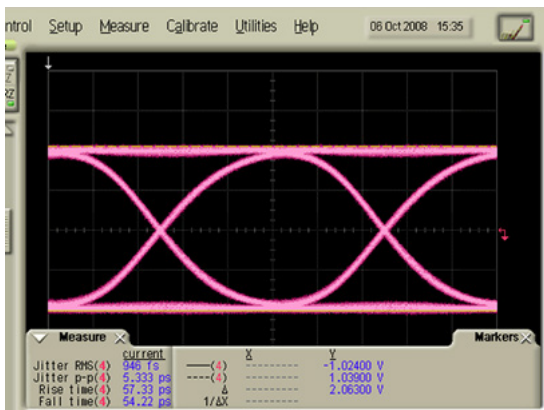


Figure 21 PPG-1 Waveform after Passing Through LPF

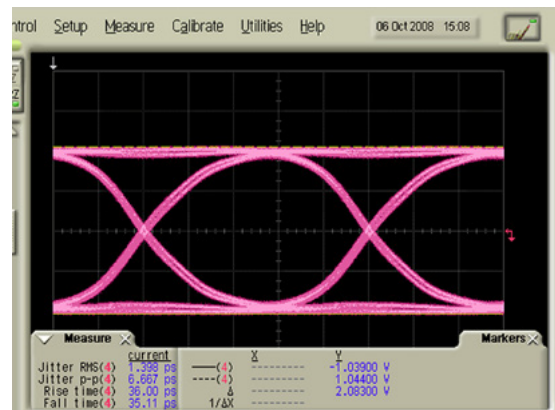


Figure 22 PPG-2 Waveform after Passing Through LPF

Since the LPF limits the signal's bandwidth, both waveforms exhibit increased jitter due to Intersymbol Interference (ISI). However, PPG-2 has faster rise and fall times, resulting in more jitter. The main reason for this is that the PPG-2 waveform contains more harmonic components. In particular, the reflection components around 40 GHz are believed to contribute to the increase in jitter. Furthermore, this LPF may not sufficiently attenuate those frequency components above 20 GHz.

These results show that, in a measurement system with an insufficient frequency bandwidth or reflection characteristics, signals with more harmonic components - waveforms with fast rise and fall times - are more susceptible to the effects of ISI and reflections. This trend is also observed when the signal passes through a BNC adapter.

To measure high-speed signals with high precision, it is important to carefully consider the frequency and reflection characteristics of the cables, adapters, filters, and other components used in the measurement system, and create an environment in which the harmonic components of the signals can be reliably transmitted and measured.

Finally, Figures 23 and 24 show the waveforms observed using an 80-cm coaxial cable with a 27.5-GHz bandwidth and an 80-cm coaxial cable with a 40-GHz bandwidth for a 32-Gbit/s signal, respectively. In the observations obtained using coaxial cables with a bandwidth of up to 27.5 GHz, there is an undershoot on the lower part of the waveform. This is a distortion caused by the coaxial cable's bandwidth being insufficient for the input signal.

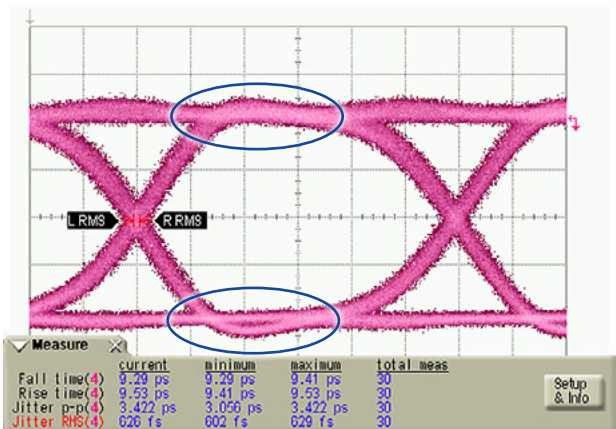


Figure 23 When Using Cables up to 27.5 GHz

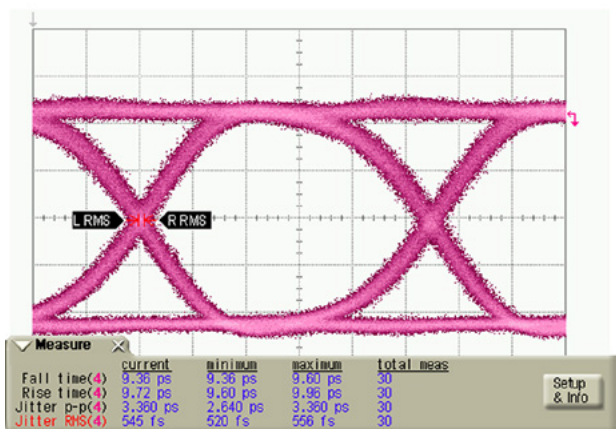


Figure 24 When Using Cables up to 40 GHz

5. Summary

This document has explained the impact of the bandwidth and trigger precision of the sampling oscilloscope on the observed waveforms, as well as the effect of the frequency characteristics of peripheral devices such as adapters and filters on the observed waveforms.

To precisely measure high-frequency signals, it is necessary to thoroughly confirm that the signal source, cables, adapters, and measuring instruments used for observation all satisfy the conditions for precisely measuring the target signal.

Anritsu will continue to propose better measurement methods to enhance quality and add value to our customers' products.

Related Products

Signal Quality Analyzer-R MP1900A

The Signal Quality Analyzer-R MP1900A series is a high-performance BERT with an 8-slot modular design. PPG, ED, and jitter/noise addition functions can be expanded according to the measurement application, making it ideal for signal integrity analysis of devices progressing toward higher speeds.

Furthermore, it supports the physical layer measurements of high-speed network interfaces as well as the measurement of bus interfaces such as PCI Express in a single unit.



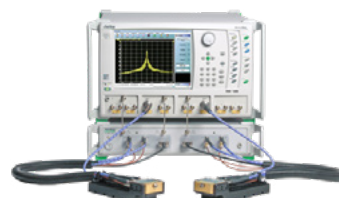
BERTWave MP2110A

The MP2110A is a measuring instrument suitable for the manufacturing evaluation of optical modules ranging from 10G to 800G, integrating a 4-channel sampling oscilloscope (eye pattern analysis) and BERT (bit error rate testing) into a single unit.



Broadband Vector Network Analyzer ME7838 series

The VectorStar ME7838 Series wideband VNA is a 2-port device capable of single sweeps across wide bands from 70 kHz up to 110, 125, 145 GHz, and 220 GHz. It can be extended to be capable of measurements up to the millimeter-wave band at 1.1 THz.



Coaxial Cable, Connectors

Anritsu has manufactured and trademarked K connectors that can be used up to 40 GHz.

These are highly regarded and are widely used in many commercial components and test fixtures.

The V connector covers frequencies up to 65 GHz coaxially, adopts the 1.85-mm outer dimension recommended by the International Electrotechnical Commission (IEC), and is compatible with commercially available 2.4-mm connectors.



Terminator, Attenuator, Components

Anritsu offers terminators, attenuators, bias tees, and other components compatible with the frequency bands of K and V connectors.

