Qualified USB 2.0 High-Speed Data Transmission Standard for Hyperboloid-Based Modular Connectors

Introduction

In high-performance interconnect systems, modularity and signal integrity are critical to meeting the demands of modern applications across industrial, defence, and medical sectors. Our unique L series modular connectors, featuring snap in tool free contacts, integrated signal, power, and data transmission contact technologies, and Hypertac® hyperboloid contact technology with unparallel long cycle life, have now been tested and certified to support the USB 2.0 high-speed data transmission standard.

This advancement enables seamless integration of USB 2.0 connectivity within ruggedized modular architectures, ensuring reliable data transmission while maintaining mechanical robustness and electromagnetic compatibility. By combining the flexibility of modular design with the precision of hyperboloid contacts, our solution addresses the growing need for compact, high-speed, and durable interconnects in environments where performance and reliability are paramount.

This white paper outlines the technical rationale, design considerations, and application benefits of this new capability, demonstrating how it extends the functionality and versatility of our unique connector platform.

Scope

The purpose of the tests performed on the new modules is to evaluate the electrical performance of CAT5e and CAT6A modules in USB 2.0 standard cables. The report presents test data collected during the evaluation of these products, including both simulation analysis and electrical measurements on physical prototypes. The test procedure, along with the equipment used and best testing practices applied, are also detailed.

Electrical performance was first assessed through simulation analysis; followed by empirical testing using test fixtures and a High-speed Interconnect Analyzer. The test results presented in this test report confirm the success of the testing process and demonstrate the suitability and readiness of the products for market release.

Background

The USB (Universal Serial Bus) specifications define the electrical, mechanical, and protocol standards for connecting and powering electronic devices through a hub-and-spoke topology centered around a host controller. Originally introduced to standardize peripheral connectivity, the USB standard has continuously evolved to support higher transfer rates, from USB 1.x at 12Mbps to USB4 reaching up to 80 Gbps, as well as enhanced power delivery capabilities. The introduction of USB Power Delivery (USB PD), supporting up to 240 W, and the adoption of the USB-C connector have made USB a cornerstone of modern data and power transfer technology. Over time, each new USB generation has brought performance and complexity.

USB Evolution Overview:

- USB 1.x (1996) Introduced the basic concept of a universal serial bus, offering data rate up to 12 Mbps.
- USB 2.0 (2000) Branded as “High-Speed USB”, it increased data rates to 480 Mbps.
- USB 3.x (2008) Introduced “SuperSpeed USB”, significantly boosting data throughput and power capabilities. It was later unified under the umbrella of USB 3.2, which introduced multiple generations with increasing transfer rates and dual-channel transmission modes.

- USB4 (2019) The latest major version, integrating Thunderbolt 3 protocols for high-speed data and display tunneling, offering base speed of 20 Gbps and optional higher speeds to 80 Gbps.

USB 2.0 standard is one of the most widely used system bus architectures, valued for its plug-and-play simplicity and cost effectiveness, and support for multiple data rates: high-speed (480 Mbps), full speed (12 Mbps) and low speed (1.5 Mbps). It is employed across a broad range of applications in both computing and embedded system design.

To ensure compliance and signal integrity, USB cables must not exceed specified attenuation limits (Insertion Loss, measured in dB). Detailed specifications for this product are shown in the Figure below (reference Universal Serial Bus Specification Revision 2.0, April 2000).

The USB 2.0 interface utilizes a 4-wire serial bus, consisting of D+, D- VBUS and Ground conductors. The D+ and D- lines carry data using differential signaling, with additional single-ended signal states defined for specific operational conditions.

The VBUS provides a nominal 5V power supply to peripheral devices that draw power directly from the host or hub, while Ground serves as the common return path.

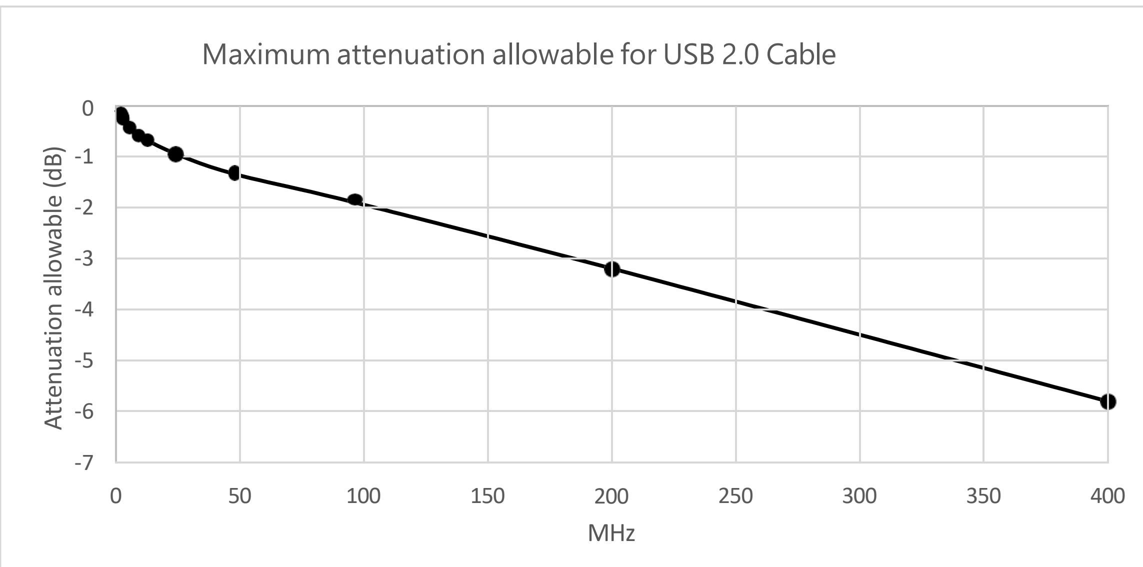


Figure 1. Differential insertion loss limit for USB 2.0 standard (USB specifications Revision 2.0 section 7.1.17 Cable attenuation)

Electromagnetic Simulation of CAT5e / CAT6A data transmission modules in USB 2.0

Smiths Interconnect's new CAT5e / CAT6A Data Transmission modules are designed for use with standard cable categories, enabling data transmission that meets the technical requirements of Ethernet protocol applications.

The CAT5e data transmission module delivers electrical performance up to 100 MHz bandwidth, with a differential impedance of 100 ohms, compliant with the ANI TIA 568 C.2 standard. It supports UTP and STP cabling for data transmission up to 1 Gbps in accordance with IEEE 802.3 standard. The module operates over a wide temperature range of-55°C to 125°C, passes vibration and shocking tests (0-33 Hz and 15g), and is RoHS compliant (except exemption 6c).

The modular connector meets the UL1977 and EN 45545-2 (HL3 R22 and R23) standards, ensuring protection against fire risk, electrical failures and personal injuries. Its 1mm inner contacts are suitable for crimping standard cables AWG 24 to 18 or AWG 30 to 22. These solutions have been tested for over 100,000 mating cycles as a connector, offering significantly higher durability compared to typical commercial alternatives. In addition, they provide EMI/EMC protection against external electromagnetic interference, featuring a 360° shielding for enhanced signal integrity.

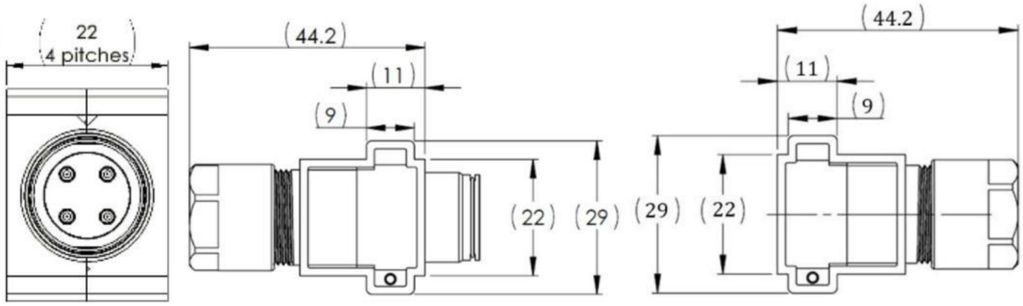


Figure 2. Example of Male and Female L-Series CAT 5e Modules

The CAT 6A data transmission module delivers electrical performance with a bandwidth up to 500 MHZ, compliant with the ANSI TIA 568 C.2 standard. It supports STP, S/STP and S/FTP cable types for data transmission up to 10 Gbps, in accordance with the IEEE 802.3 standard. The module operates over a wide temperature range of -55°C to 125°C, conforming to the IEC 61984:2008 standard. It successfully passes vibration and shocking tests (0-33 Hz and 15g), and RoHS compliant (except exemption 6c). The modular connector meets UL1977 and EN 45545-2 (HL3 R22 and R23) requirements, ensuring protection against fire risk, electrical failures and personal injuries. Its 0.5mm inner contacts are suitable for crimping standard cables AWG 26 to 22. The connector has been tested for more than 100,000 mating cycles, offering durability far exceeding typical commercial alternatives. Additionally, it provides comprehensive EMI/EMC protection against external electromagnetic signals interference through 360° shielding, ensuring consistent signal integrity in demanding environments.

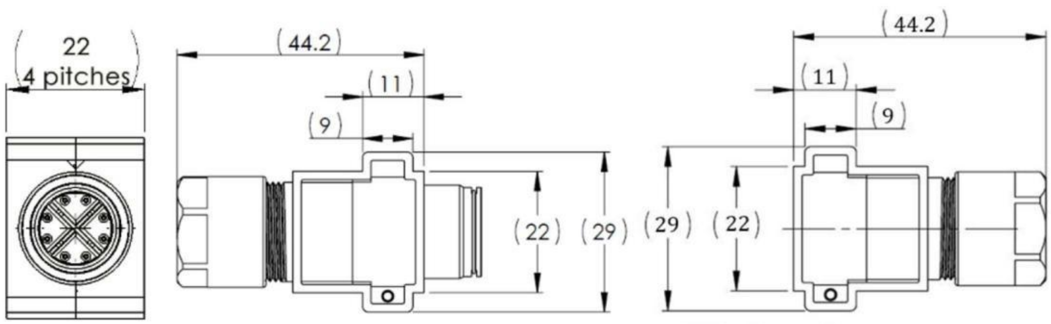


Figure 3. Example of Male and Female L-Series CAT 6A Modules

CAT 5e/CAT 6A data transmission modules were analyzed using Ansys HFSS electromagnetic simulator and tested with a DSX-8000 cable analyzer from Fluke Network.

The purpose of the simulation was to evaluate performance and determine the correlation between simulated results and measured test data, particularly under conditions relevant to USB technology. These simulations were conducted in accordance with the electrical requirements of the USB specification.

Notably, the differential pair signaling in USB applications exhibits a characteristic impedance of 90 ohms in the differential model, compared to 100 ohms for the CAT 5/CAT 6 Ethernet standard, and operates across a higher frequency range.

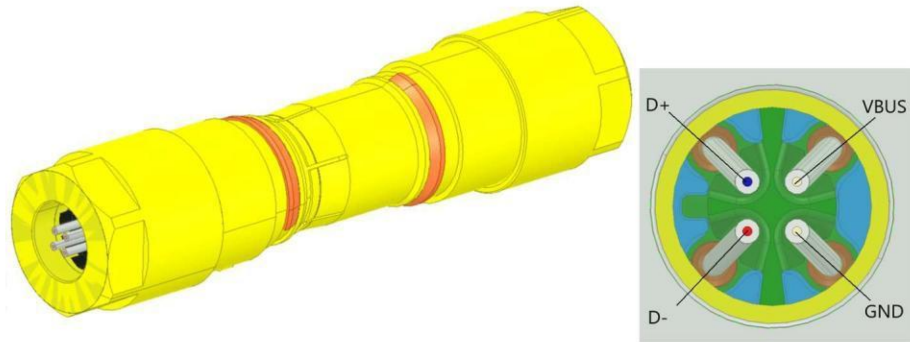


Figure 4. CAT5e module designed in SolidWorks and simulated in Ansys HFSS for USB 2.0 electrical performance analysis of D+ and D– signal pair

CAT5e module was evaluated against the USB 2.0 electrical specification. In this configuration, two wires were used for differential-mode excitation, designated as D+ and D-, with a differential impedance of 90-ohm. The input and output ports were configured for differential signaling with 90 Ω differential impedance and 22.5 Ω common-mode impedance.

Before performing the frequency response analysis of the model, it is necessary to determine the maximum data rate supported by the channel For USB 2.0 high-speed mode, the data rate is 480 Mbps. This signal employs non- return-to-zero (NRZ) line code, a binary modulationschemein which a logic "1" is represented by a positive voltage and a logic "0" by a negative voltage.

The Nyquist criterion defines the required bandwidth for NRZ baseband transmission: for a given bit rate B (in bit/s), NRZ signaling requires a baseband bandwidth of B/2 Hz. Therefore, for USB 2.0 operating at 480 Mbps, the necessary frequency range extends up to 240 MHz (with simulations performed up to 250 MHz for margin)

The results are presented in terms of Insertion Loss, Return Loss and Impedance response of the CAT 5e module, over the - - 250 MHz frequency range. This preliminary analysis indicates that the CAT 5e module when used in USB 2.0 standard cables may not provide optimal electrical performance for high-speed applications.

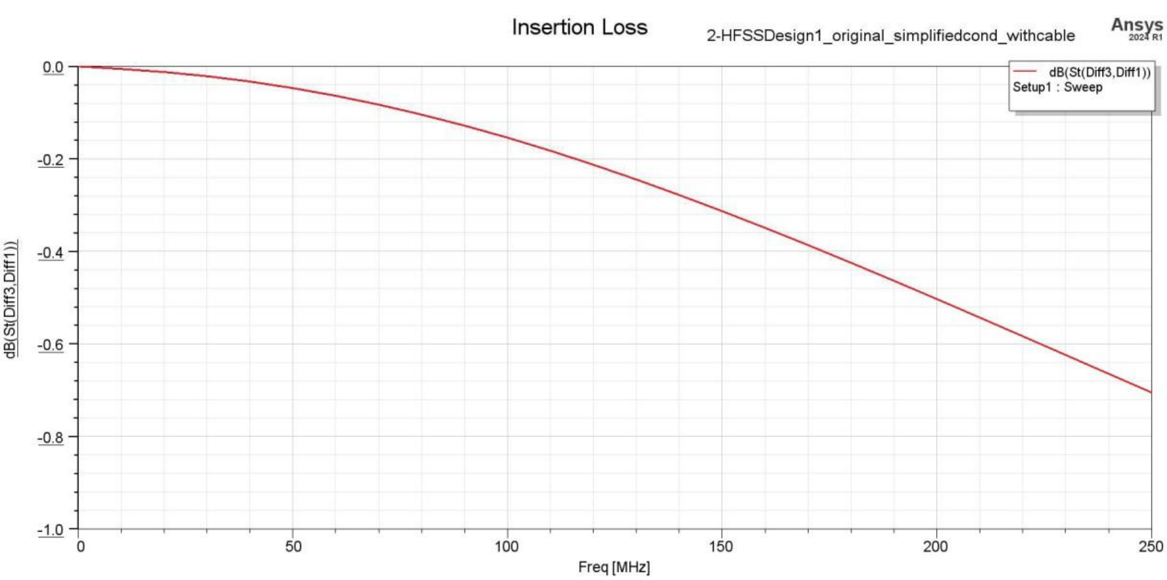


Figure 5. Insertion Loss of CAT5e Model for USB 2.0 Electrical Specification Testing

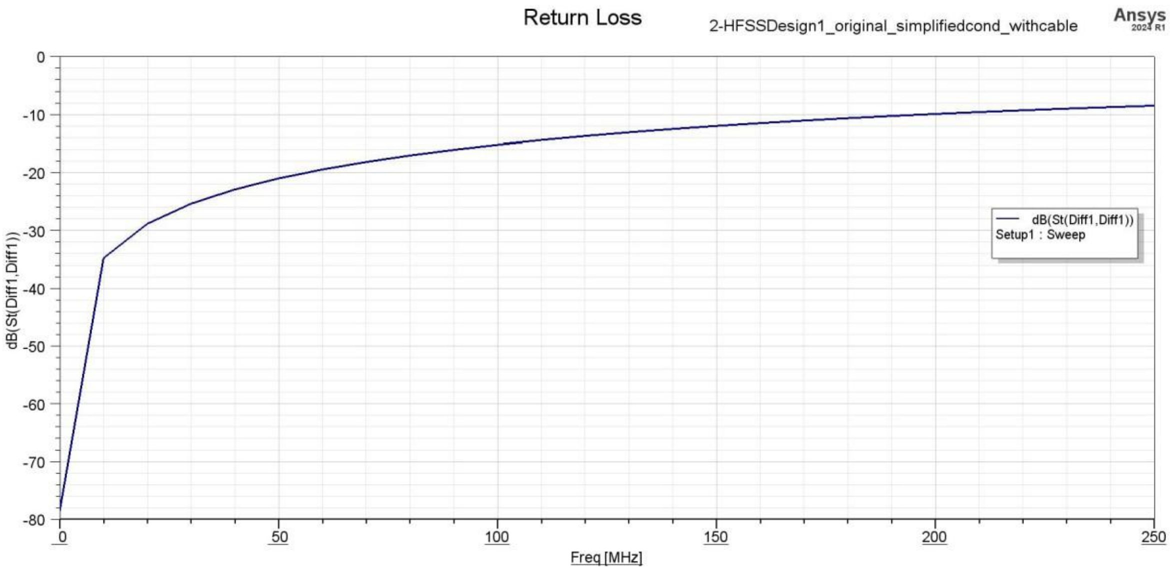


Figure 6. Return Loss of CAT5e Model for USB 2.0 Electrical Specification Testing

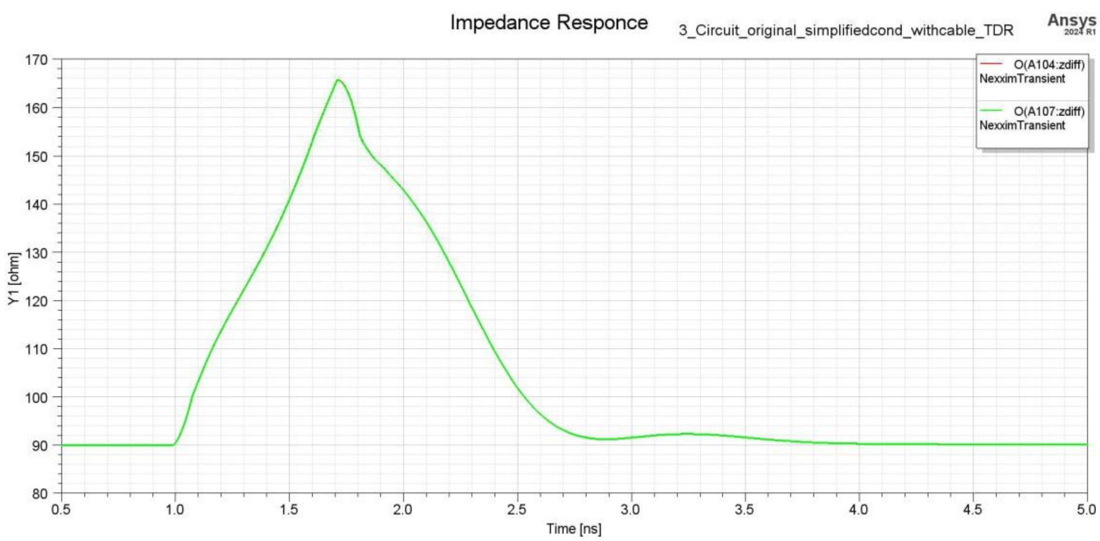


Figure 7. Impedance response of CAT5e Model for USB 2.0 Electrical Specification Testing

The CAT6A module was simulated according to USB 2.0 standard. Although the CAT6A module includes eight wires, in this configuration only four wires are utilized, while the remaining four are left unconnected. Specifically, two wires are assigned for differential signal transmission, and the other two are used for power supply (VBUS) and ground (GND). The signal layout used in this simulation is illustrated in the following figure.

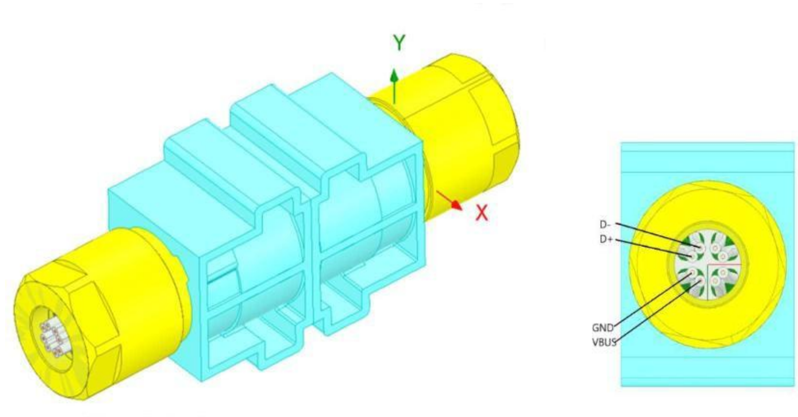


Figure 8. CAT 6A module designed in SolidWorks and simulated in Ansys HFSS for USB 2.0 electrical performance analysis of D+ and D– signal pair

The Insertion Loss, Return Loss and Impedance response of the CAT 6A module are presented over the frequency range up to 250 MHz. This preliminary analysis indicates that the CAT 6A module, when used in USB 2.0 standard cables, demonstrates superior performance compared to the CAT 5e module.

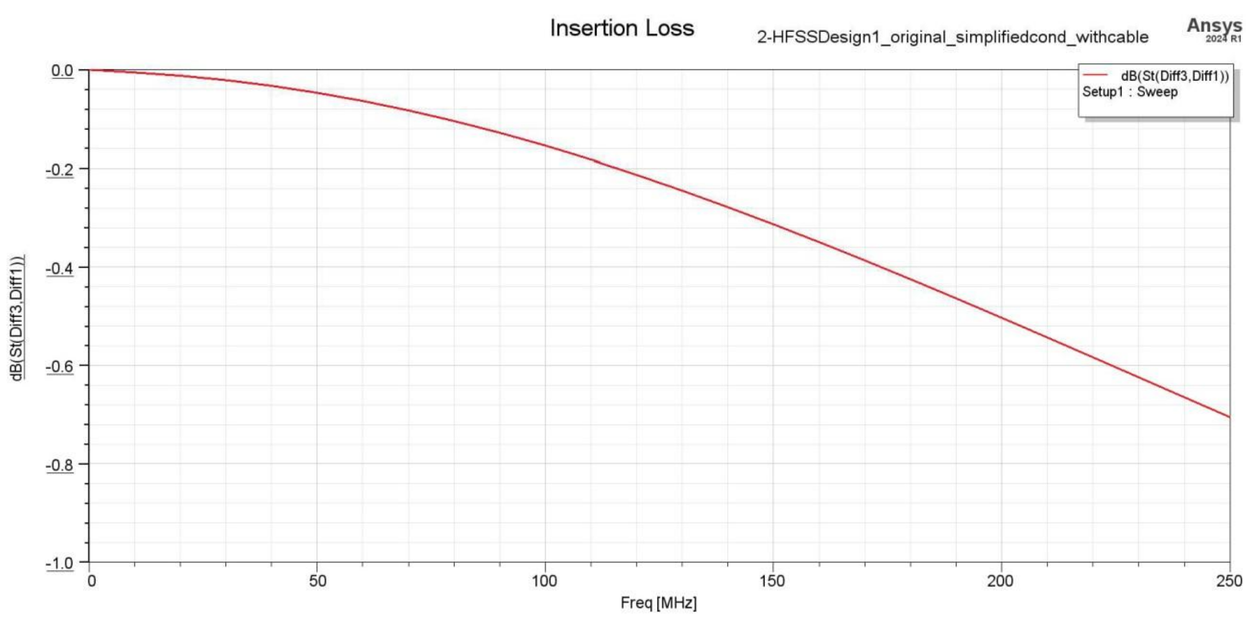


Figure 9. Insertion Loss of CAT 6A Model for USB 2.0 Electrical Specification Testing

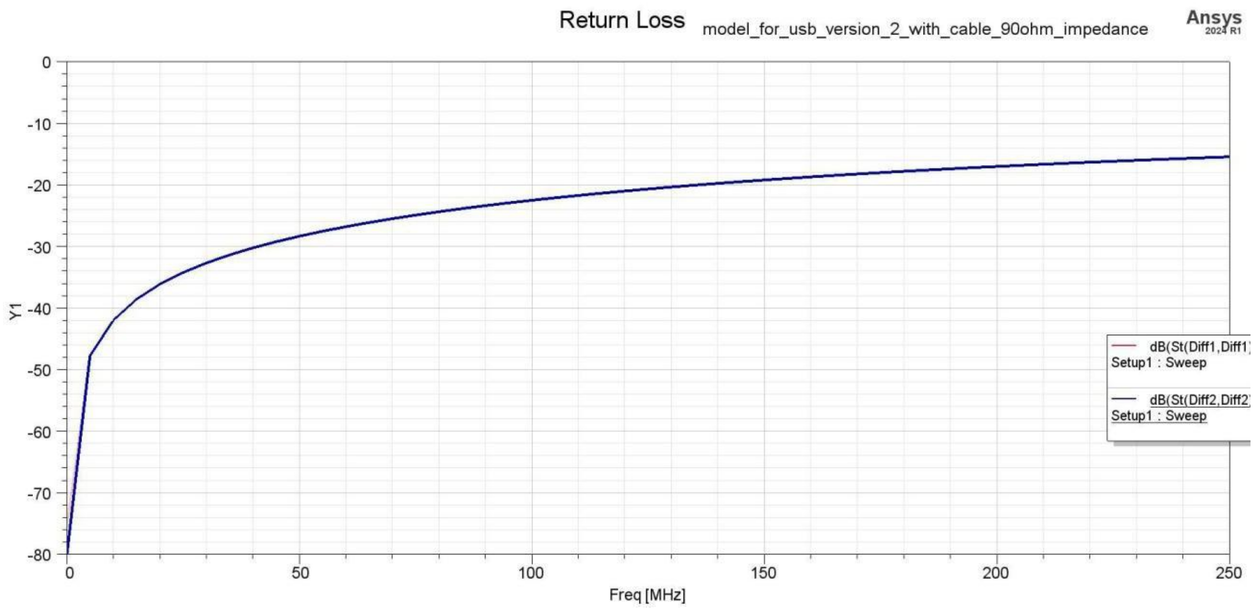


Figure 10. Return Loss of CAT 6A Model for USB 2.0 Electrical Specification Testing

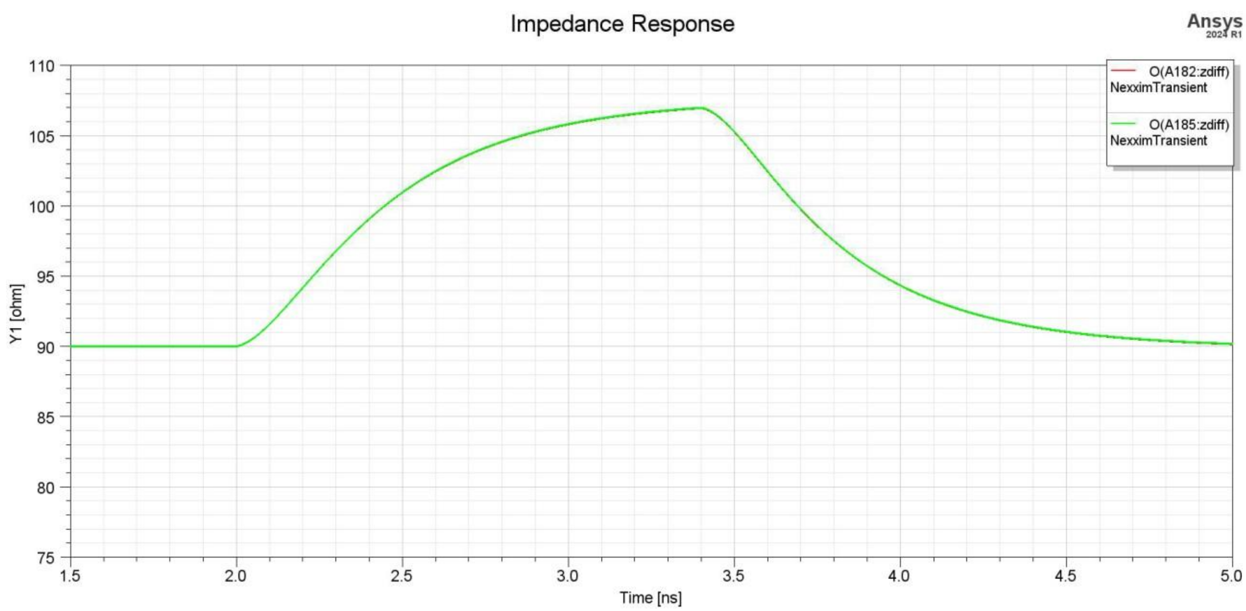


Figure 11. Impedance response of CAT 6A Model for USB 2.0 Electrical Specification Testing

Electrical measurement of CAT 5e and CAT 6A modules in USB 2.0

This section presents the results of the comprehensive electrical testing conducted in July 2025 at our manufacturing facility in Genoa. The tests were carried out using the measurement setup recommended by Teledyne Lecroy specialists, ensuring the highest accuracy in evaluating the electrical performance of USB standard cables with the module installed.

A USB 2.0 standard cable with male-to-male terminations was used for the test. The cable is 1 meter long and features 4-pin male connectors on both ends. The data signal is transmitted through the green and white wire pair

Figure 12. USB 2.0 standard cable and wiring diagram

Figure 13. wiring diagram of USB 2.0 standard cable connected to CAT 5e module.

Figure 14. wiring diagram of USB 2.0 standard cable connected to CAT 6A module

The instruments and tools used to perform the electrical measurements of USB 2.0 standards cables equipped with CAT5e and CAT6A modules are listed below:

- WavePulser 40iX High-speed interconnect analyzer connected to a laptop with WavePulser Signal Integrity Studio software.
- Four Coaxial cables for connecting the USB 2.0 test fixtures.
- Two USB 2.0 test fixtures equipped with USB-A female connector.
- One USB 2.0 cable, 1-meter in length, with male-to-male termination
- Two USB 2.0 cables, each 1-meter long, with male-to-male termination, connected to the CAT5e module.
- Two USB 2.0 cables, each 1-meter long, with male-to-m Male termination, connected to the CAT6A module.

Figure 15. Example of experimental setup using WavePulser 40iX Interconnect Analyzer

The WavePulser 40iX High-speed interconnect analyzer was connected to the laptop via a USB cable with WavePulser Signal Integrity Studio software. This software enables the acquisition and analysis of all electrical parameters in the experimental setup, including insertion loss, return loss, and signal integrity.

Figure 16. WavePulser Signal Integrity Studio software graphical interface

Two types of electrical test fixtures were used to interface the WavePulser 40iX interconnect analyzer with standard USB cables. These USB test fixtures are approved by the USB-IF (USB Implementers Forum).

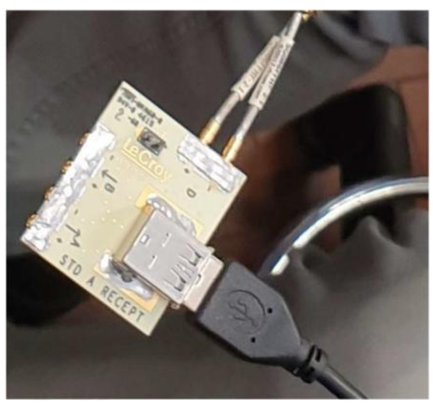


Figure 17. Test fixtures for interconnecting USB standard cables with the WavePulser analyzer, all equipped with female USB 2.0 connector

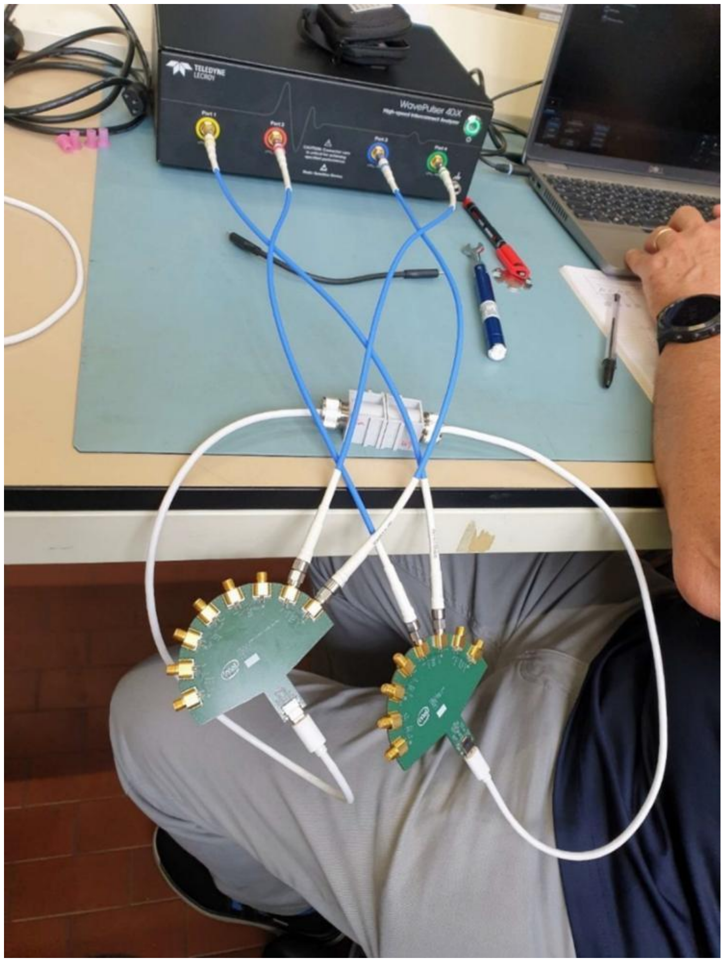


Figure 18. Electrical Test using the setup shown above (WavePulser 40iX + Test Fixture + coaxial cables

Setup for electrical measurement of USB 2.0 standard cable using WavePulser 40iX interconnect analyzer

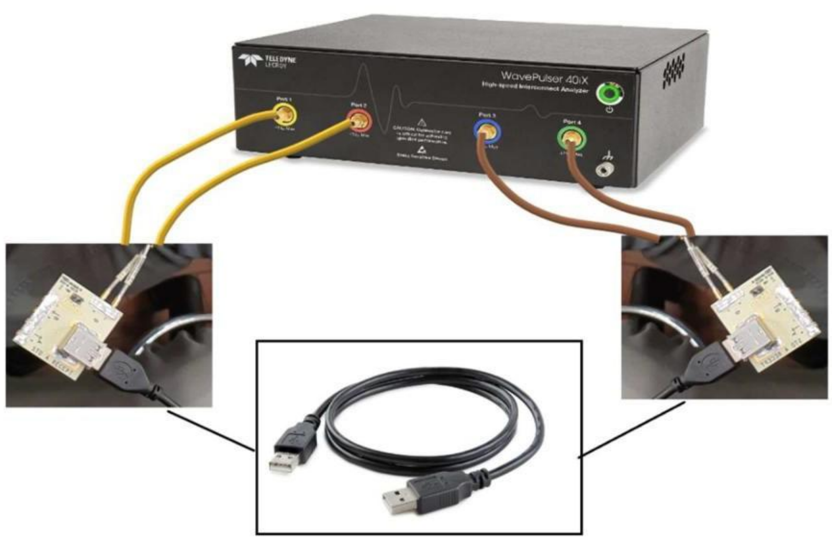
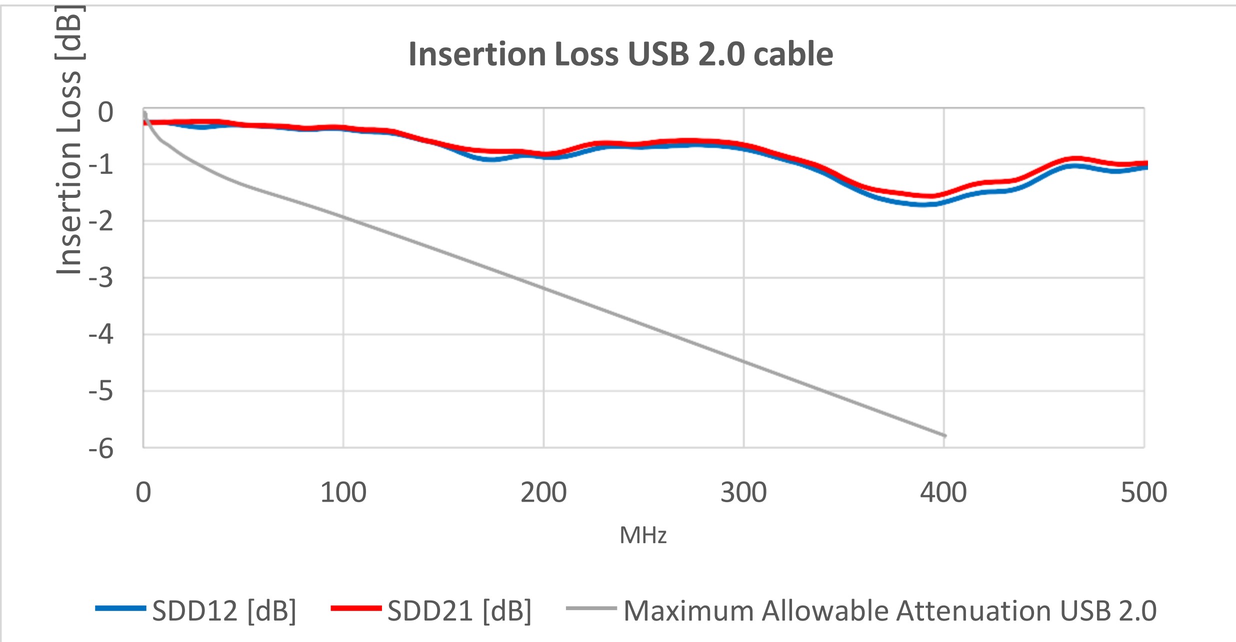


Figure 19. Experimental setup for measuring USB 2.0 standard cable electrical performance

The following section presents the results of electrical measurements performed using the WavePulser 40iX interconnect analyzer, connected to the four RF coaxial cables that carry the differential signal. These coaxial cables were connected to the USB test fixture boards equipped with female terminals, which were used to measure the USB cable under test.

The following are the results obtained using the setup with the 1m USB2.0 cable, which will be the reference measurement. The grey line represents the maximum allowable attenuation for a USB 2.0 cable, as specified in the Universal Serial Bus Specification, Revision 2.0. The blue and red lines correspond to the Insertion Loss of the differential signal pair.



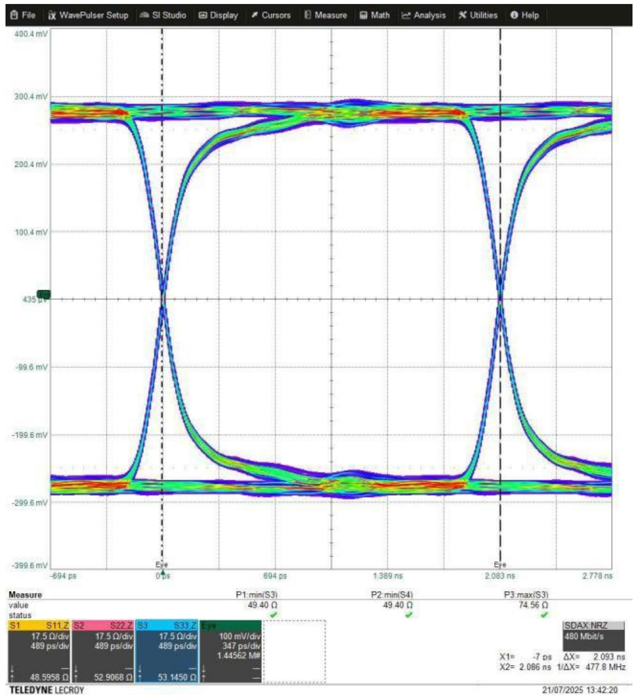


Figure 20. Insertion loss and signal integrity of 1-meter USB 2.0 standard cable

Electrical setup for measuring the electrical performance of USB 2.0 standard cable with CAT 5e module

In this section, the results of the electrical measurements are presented using the WavePulser 40iX interconnect analyzer connected with the 4 RF coaxial cables carrying the differential signal., These cables were connected to the USB test fixture boards equipped with female terminals, that were used to measure the USB 2.0 cable connected to the CAT 5e module under test. Two samples were tested, referred as sample #1 and sample #2.

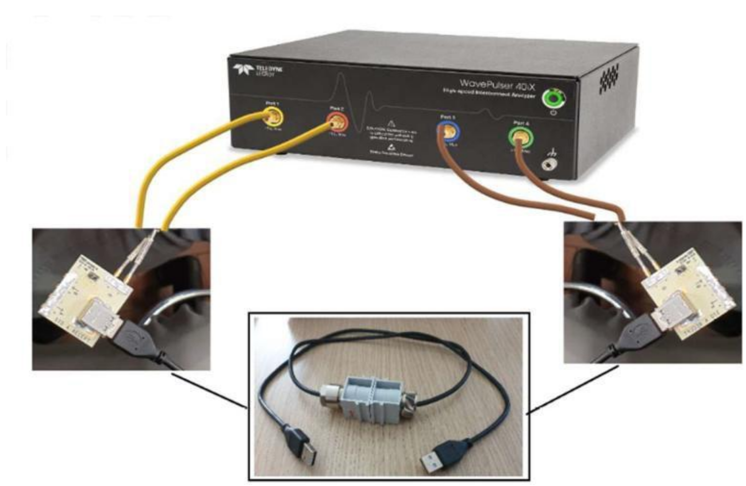
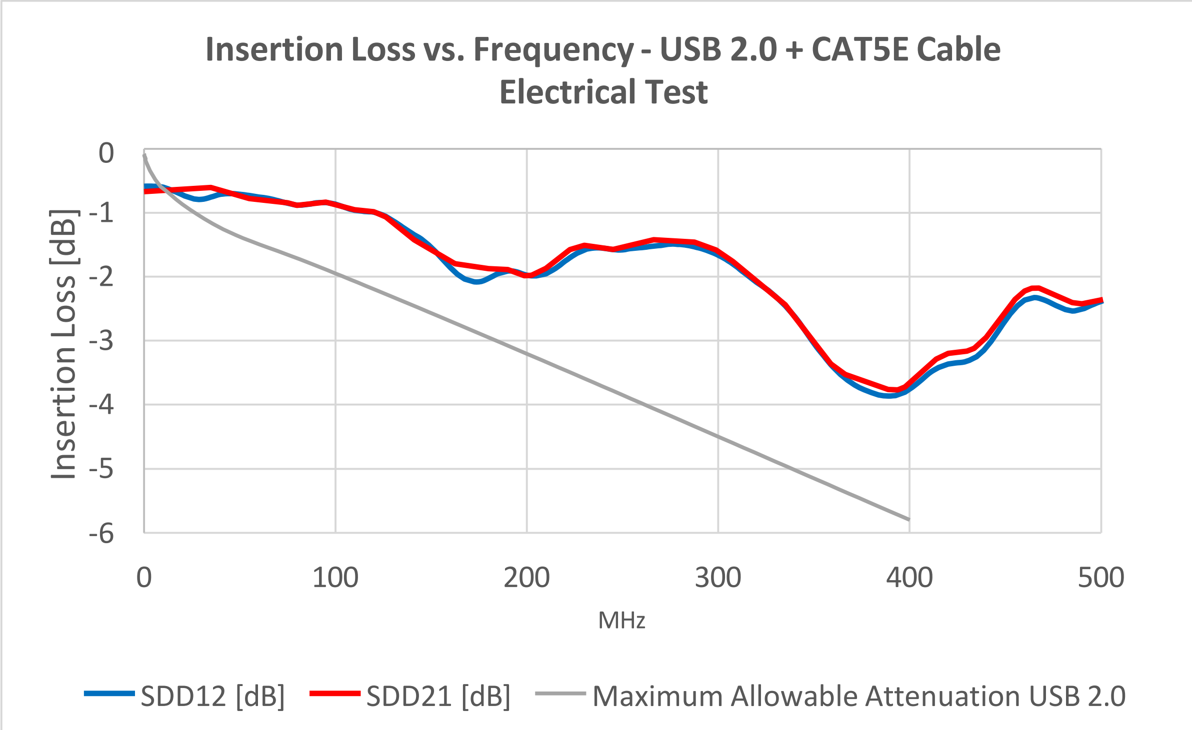


Figure 21. Experimental setup used for measuring the electrical performance of USB 2.0 standard cable with CAT5e module

The results obtained for Sample #1 ans Sample #2, consisting of a 1 m USB 2.0 cable connected to the CAT 5e module, are presented below



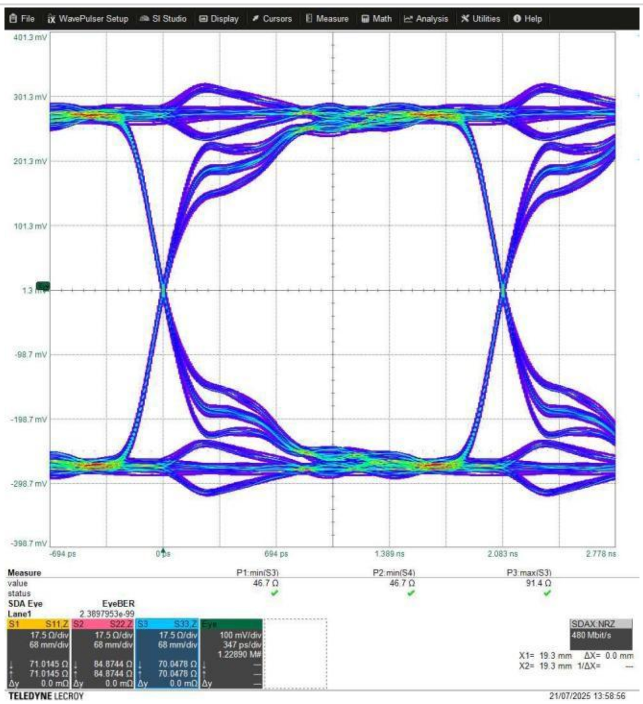


Figure 22. Insertion loss and signal integrity of 1-meter USB 2.0 standard cable with CAT5e module - Sample #1

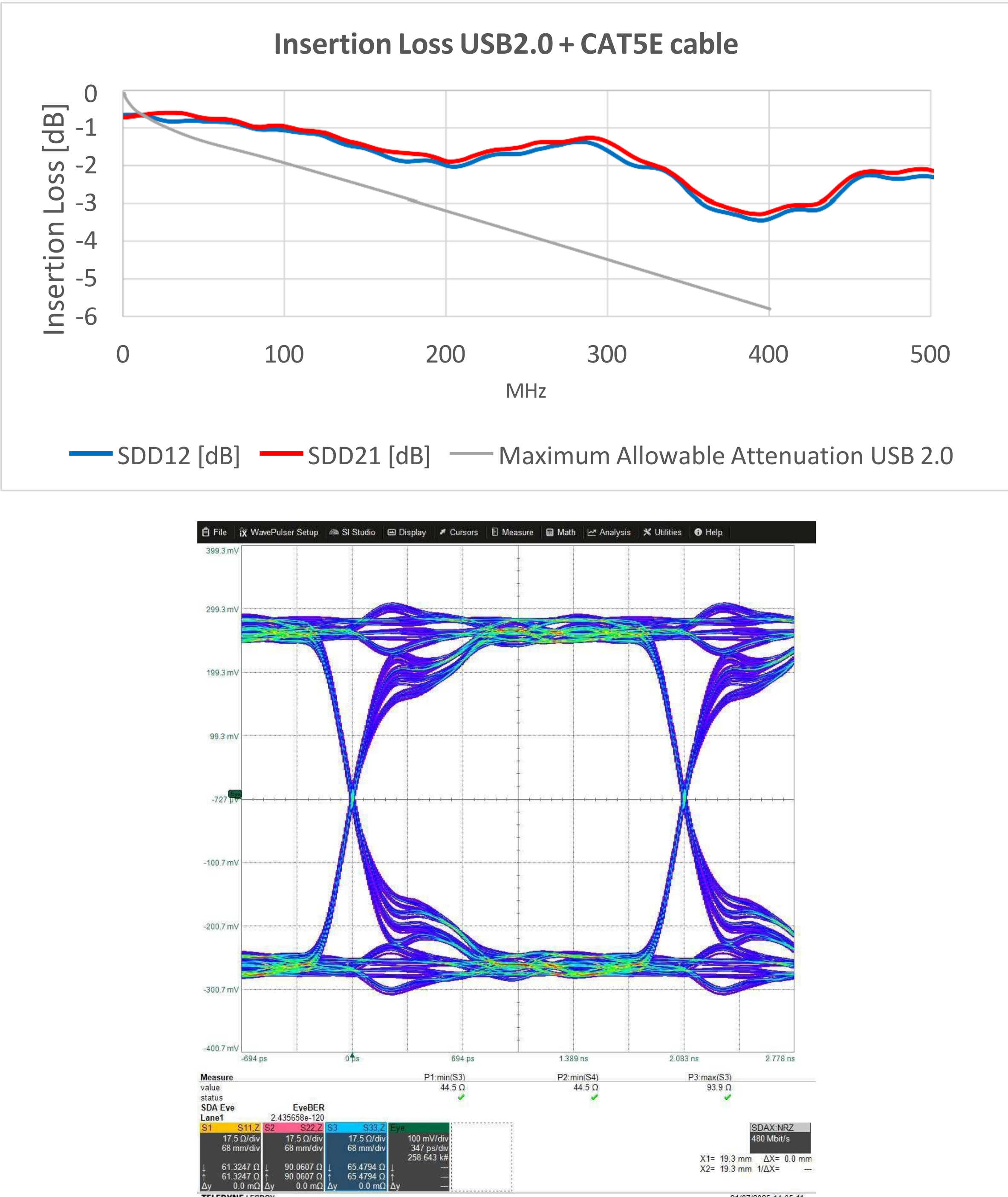


Figure 23. Insertion loss and signal integrity of 1-meter USB 2.0 standard cable with CAT5e module - Sample #2

Electrical setup for measuring electrical performance of USB 2.0 standard cable with CAT6A module

In this section, the results of the electrical measurements are presented using the WavePulser 40iX interconnect analyzer connected with the 4 RF coaxial cables carrying the differential signal., These cables were connected to the USB test fixture boards equipped with female terminals, that were used to measure the USB 2.0 cable connected to the CAT 6A module under test. Two samples were tested, referred as sample #3 and sample #4.

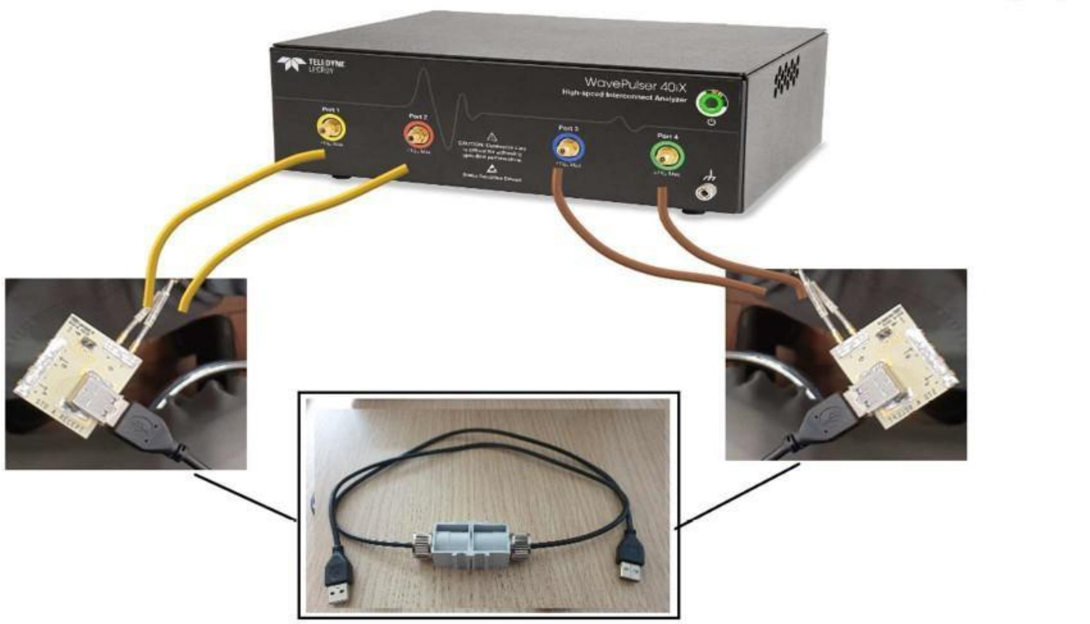
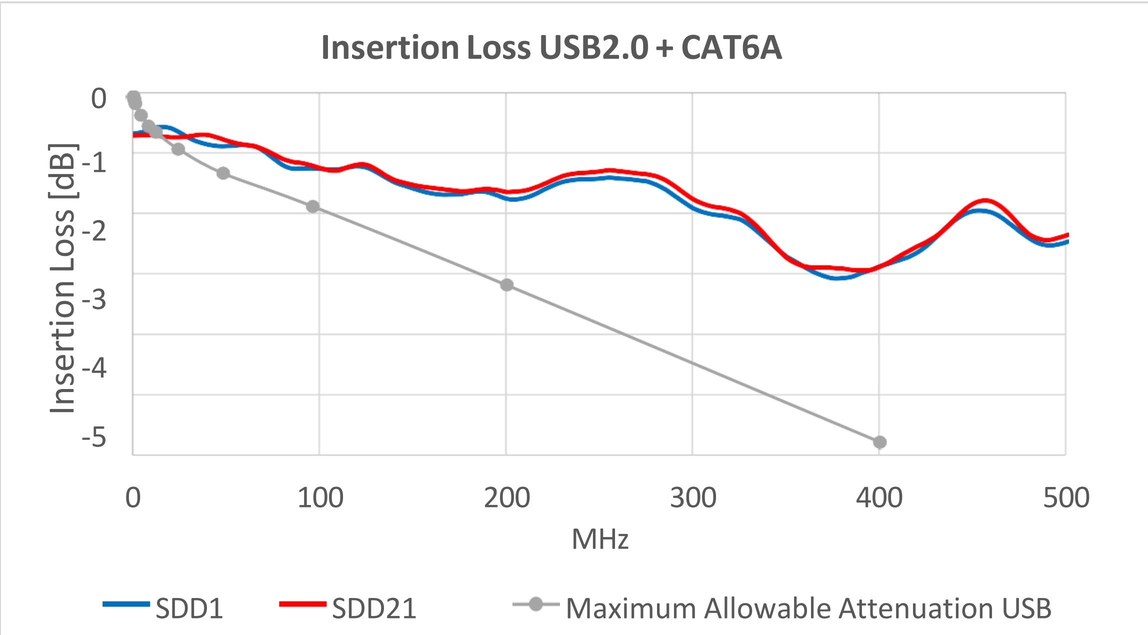


Figure 24. Experimental setup used for measuring the electrical performance of USB 2.0 standard cable with CAT6A module

The results obtained for Sample #3 and Sample #4, consisting of a 1 m USB 2.0 cable connected to the CAT 6A module, are presented below



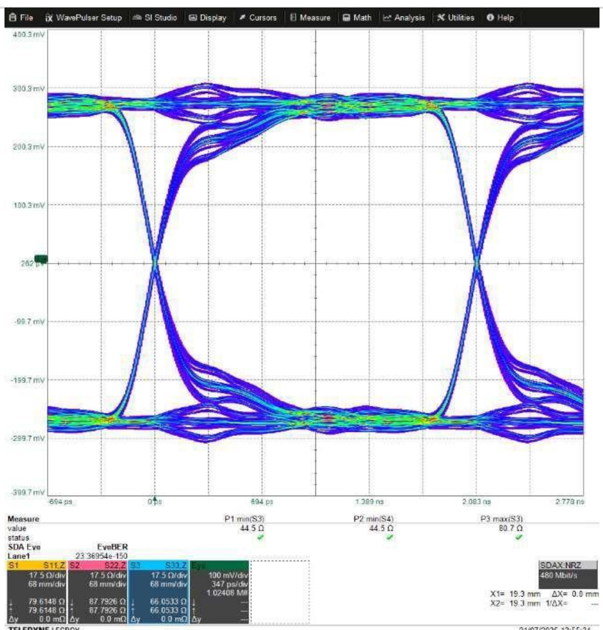
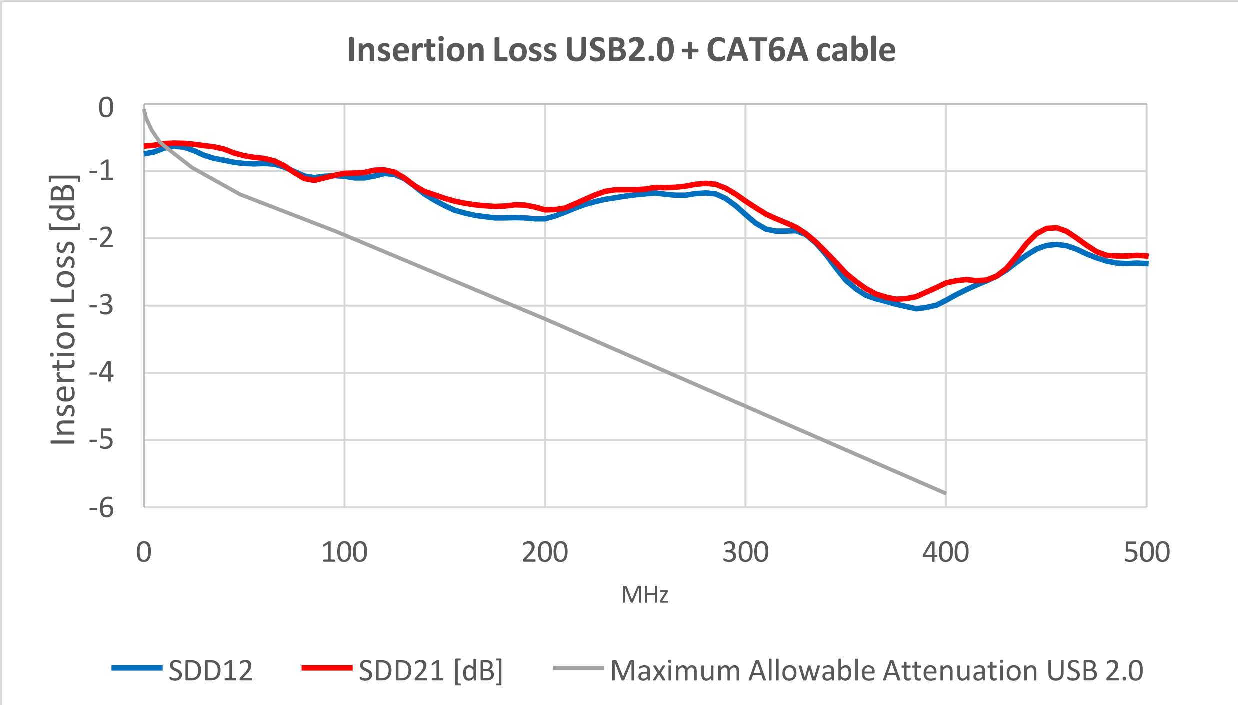


Figure 25. Insertion loss and signal integrity of 1-meter USB 2.0 standard cable with CAT 6A module - Sample #3



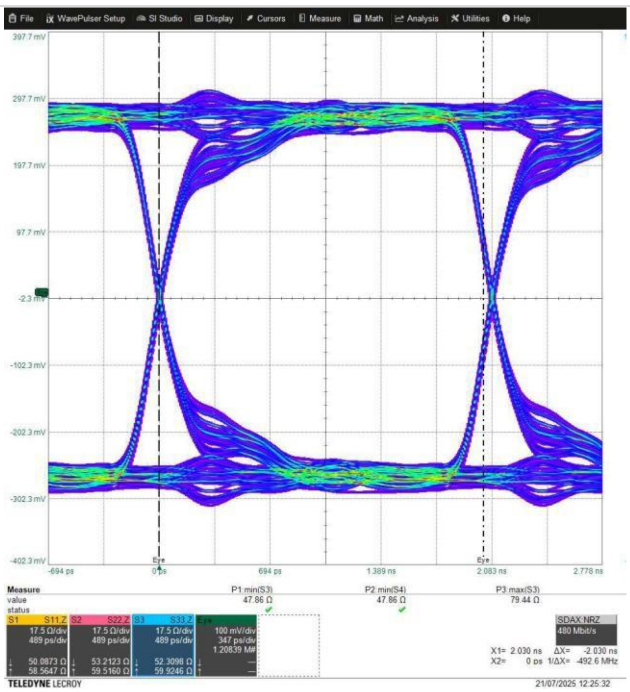


Figure 26. Insertion loss and signal integrity of 1-meter USB 2.0 standard cable With CAT 6A module - sample #4

CONCLUSION

- The electrical measurement campaign demonstrated that the CAT5e and CAT6A data transmission modules can be effectively integrated in USB 2.0 standard cables. Among the two types of modules, CAT6A module exhibited superior performance, as confirmed by the Insertion Loss behavior, which remained below the maximum allowed limit specified in the literature.
- The eye diagram analysis provided valuable insight in the signal integrity. For the USB 2.0 standard, with a maximum data bit rate of 480 Mbps, the comparison of the test results confirms that the CAT6A-based configuration offers better overall signal quality and is therefore the preferred solution.
- Smiths Interconnect's data transmission modules not only support high-speed USB 2.0 performance but provide several technical advantages over competing solutions:
  1) 100,000 mating cycles: enhanced durability ensures consistent electrical performance over repeated connections and disconnections
  2) Wide operating temperature range of -55°C to +125°C guarantees reliable performance in harsh environments where standard commercial solutions may fail due to material degradation, signal instability, or mechanical stress
  3) Snap-in tool free contacts: enable quick and easy installation without the need for specialized tools
  4) Superior Signal integrity: parameters such as Insertion loss, Return loss, Near-End Crosstalk remain fully compliant to ANSI/TIA-568 standard, even after 100,000 mating cycles

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