

Development of 200G/Lane 60 GHz Optical Sampling Oscilloscope

Yuki Yokoyama, Shuichi Matsuda, Keisuke Kishida, Ryota Takasu

[Summary]

Demand is growing rapidly for testing optical transceivers meeting high-speed Ethernet standards such as 800GbE and 1.6TbE in order to support high-speed transmissions required by data centers faced with rising data volumes. To solve this challenge in accordance with the IEEE 802.3dj standard, we developed the MP2110A-080 60 GHz optical sampling oscilloscope to simultaneously measure PAM4 signals of up to 120 Gbaud across four lanes. Evaluation demonstrated an amplitude deviation of 0.22 dB from the optical reference receiver required frequency response. Furthermore, the maximum variation in key measurement items over an input level range of -1 to -4 dBm was 0.25 dB for TDECQ, 0.07 dB for Outer ER, and 0.5% for Linearity, achieving high conformance with ideal characteristics and high-accuracy testing.

1 Introduction

The widespread rollout of cloud computing services using AI and machine learning is rapidly increasing the amount of information handled by data centers^{1), 2)}. Expanding the transmission capacity of servers and network equipment in data centers is an urgent priority in addressing this challenge, and the transition to 800GbE and 1.6TbE high-speed Ethernet—speeds that far surpass conventional rates—is progressing. In particular, demand for optical transceivers using the OSFP (Octal Small Form Factor Pluggable) form factor operating at 106.25 Gbaud PAM4 per lane (106 Gbaud in this article) is forecast to surge from 2025. The total bit rate at the physical layer is approximately 212.5 Gbit/s, and Ethernet standards treat this as a 200 Gbit/s class per lane (200G/lane) accounting for overhead such as FEC.

Development and manufacturing of high-speed optical transceivers uses optical sampling oscilloscopes (scopes hereafter) to evaluate signal waveform quality and for production-line testing. In 2017, Anritsu developed³⁾ the MP2110A BERTWave™ integrating a 25 Gbit/s 4-channel BERT (Bit Error Rate Tester) with a scope for optical transceiver development and manufacturing. Subsequently, Anritsu has offered new solutions addressing the demand for high-speed optical transceiver testing primarily in the manufacturing market, commercial PAM4 (4 Pulse Amplitude Modulation) signal analysis, and a 53 Gbaud-compatible CRU (Clock Recovery Unit) option⁴⁾.

However, conventional scopes are limited to measurements up to 60 Gbaud and are unable to support 800GbE

and 1.6TbE optical transceivers outputting signals at 106 Gbaud and requiring a wider bandwidth. Therefore, we have extended the bandwidth of the MP2110A scope and developed a 60 GHz bandwidth 4-channel model (MP2110A-080 hereafter) that can measure PAM4 signals up to 120 Gbaud simultaneously across four lanes.

Developing this option to measure optical waveforms output from 106 Gbaud transceivers simultaneously across four lanes required new designs for an O/E (Optical to Electrical) conversion module with an optical bandwidth of 60 GHz and a sampler module with an electrical bandwidth of 80 GHz. This article explains the key points in designing these component technologies and presents methods for analyzing PAM4 signals used in high-speed optical transceivers. It also reports the validity of measurement results obtained using this option.

2 Oscilloscope Outline

2.1 Overview and Structure

Figure 1 shows the front of the MP2110A-080. The new cabinet design is based on the MP2110A and accommodates the MP2110A-080 scope board in the top slot and the MP2110A-055 53 Gbaud CRU board in the bottom slot. While the cabinet structure follows that of the MP2110A, cooling has been enhanced to suppress heat generated by the FPGA (Field-Programmable Gate Array) mounted on the scope board, ensuring stable measurement while accommodating the thermal load associated with high-speed signal processing.



Figure 1 External View of MP2110A with 080 Option Installed

Figure 2 shows the MP2110A-080 block diagram. The scope has four input terminals (Ch A to Ch D) for the 4-channel data signals, as well as a trigger clock input terminal (Trigger Clock Input) for synchronizing measurements. The CRU has a Data Input terminal for the clock recovery signal, as well as a Data Output terminal for capturing the internally branched signal. It also has a Recovered Clock Out terminal to output the clock signal recovered from the input data signal, which is supplied as a trigger to the scope. The CPU controls the Scope and CRU systems via Ethernet, managing the overall system operation by configuring measurement conditions and transferring data.

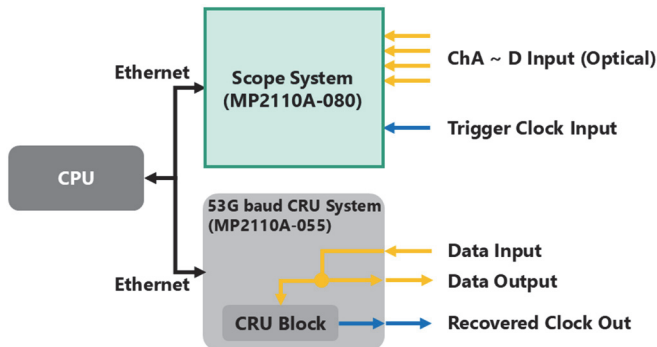


Figure 2 MP2110A-080 Block Diagram

2.2 Scope Configuration

Figure 3 shows the detailed MP2110A-080 scope block diagram. First, each signal input to optical channels Ch A to Ch D is converted to an electrical signal by an O/E conversion module (O/E module hereafter) and is then fed to a sampler module that samples each channel input signal based on the timing signal from the trigger system. The signal output from the sampler module is amplified by the IF (Intermediate Frequency) circuit and then converted to digital data by the ADC (Analog to Digital Converter). The converted data is analyzed by software processing at the FPGA and CPU, and finally displayed as Eye pattern analysis results.

The trigger system receives a clock signal synchronized

with the input signals of Ch A to Ch D from the Trigger Clock Input terminal. The first-stage Pre-Scaler 1 adjusts the supplied trigger clock frequency to fall within the input range of the DDS (Direct Digital Synthesizer). If the trigger clock frequency is lower than the DDS input range, a PLL (Phase Locked Loop) is used to up-multiply it. The DDS adjusts the output frequency to control the sampling timing. Unwanted components in the DDS output, such as image and harmonic components, are removed by the subsequent Band Pass Filter. The signal is then converted by Pre-Scaler 2 to a frequency at which the sampler module can operate. Finally, high-speed pulses are generated by the SRD (Step Recovery Diode) driver for output as timing signals driving the sampler module. The MP2110A-080 samples high-speed signals at 106 Gbaud using this series configuration.

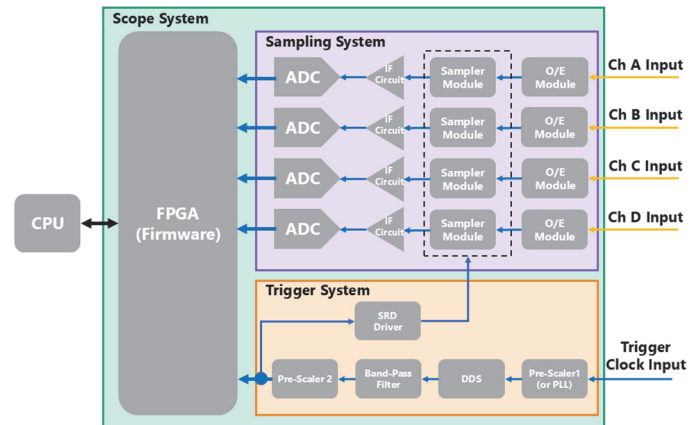


Figure 3 MP2110A-080 Scope Block Diagram Details

3 Design Requirements

IEEE 802.3dj⁵⁾ specifies a 4th-order Bessel-Thomson response with a 3-dB bandwidth of 53.125 GHz as the characteristic of the reference receiver, which serves as the measurement standard for 106 Gbaud optical signals. However, in practice it is difficult to accurately approximate a wide-band characteristic of 60 GHz in hardware, and the standard states that deviations from the ideal response can be compensated for in software. In order to account for compensation accuracy, the scope hardware requires a wider input bandwidth than the 3-dB bandwidth. To achieve this wider bandwidth, the MP2110A-080 incorporates a new in-house developed O/E module with a 3-dB bandwidth of 60 GHz, and a sampler module with a 3-dB bandwidth of 80 GHz, assuring a system-wide bandwidth of 60 GHz. The developed O/E and sampler modules are described in the next two sections.

3.1 60 GHz O/E Module Development

Figure 4 shows the internal block diagram of the 60 GHz O/E module. The bandwidth of the existing MP2110A O/E module is 35 GHz, which is insufficient for measuring 106 Gbaud signals. To measure signals up to 120 Gbaud, the bandwidth must be extended to 60 GHz, taking the Nyquist frequency into account. To achieve a wider bandwidth, a new high-frequency module was developed that integrates the optical system from the optical fiber, a PD (Photo Diode), and a TIA (Transimpedance Amplifier) into one unit. Using a lens structure in the optical system made it possible to use a PD with a light-receiving diameter of 12 μm . Reducing the PD light-receiving diameter reduces the PD capacitance and shortens the charge travel distance, resulting in a faster response time. As a result, the PD bandwidth was extended by approximately 1.9 times compared to a conventional 20 μm PD.

A new MMIC (Monolithic Microwave Integrated Circuit) dedicated to this module was designed for the subsequent TIA using the company's in-house ultra-high-speed InP process. Furthermore, parasitic elements were reduced by positioning the PD bare chip and TIA MMIC chip as close as possible to each other and mounting using the shortest possible wire bonding interconnects. The TIA chip output is routed using a quartz thin-film substrate with a V-connector, achieving wideband electrical signal output. These design choices achieved a bandwidth exceeding 60 GHz with noise characteristics of 8.4 μW (typ.) at 53 GHz and distortion characteristics of 0.7 dB (typ.) at an optical input of 4 mW.

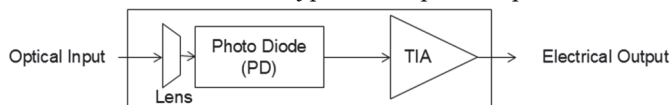


Figure 4 60 GHz O/E Module Block Diagram

3.2 80 GHz Wideband Sampler Module Development

Figure 5 shows the equivalent circuit diagram for the developed sampler module. The module structure is suited to high-frequency operation and consists primarily of a thin-film substrate and MMIC. The input converted to an electrical signal by the preceding O/E module is supplied to the RF input of the sampler module. A strobe pulse corresponding to the sampling period supplied from the external trigger circuit is applied to the LO input, and track-and-hold operation is performed by the internal sampling MMIC. The resulting IF output voltage is then amplified in the next stage, digitally converted by the

ADC, and finally processed as a waveform. The following technologies extended the bandwidth of the conventional sampler module from 40 GHz to 80 GHz.

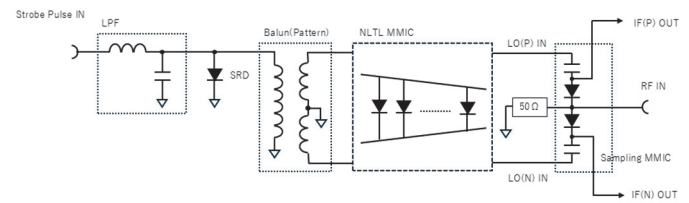


Figure 5 80 GHz Wideband Sampler Module Block Diagram

(1) New NLTL MMIC Design

An NLTL (Nonlinear Transmission Line) is a circuit with a structure in which nonlinear elements are arranged periodically along a transmission line, and as the input waveform propagates, the phase velocity varies due to voltage dependence. At high potential, the capacitance increases and the phase velocity decreases, while at low potential, the capacitance decreases and the phase velocity increases. As a result, the trailing low-potential side catches up with the leading high-potential side, and the edge is compressed in time, causing the falling edge of the waveform to steepen.

This nonlinear effect generates harmonic components, making it possible to obtain high-frequency pulses and wideband signals. In this development, the company's in-house NLTL technology was applied to newly design an MMIC for the sampler module. Previously, pulse shortening of the strobe input pulse was achieved using only an SRD, but the addition of an NLTL MMIC enabled further pulse shortening and extension of harmonic components, contributing to the wider bandwidth.

(2) New Design of Low-Parasitic-Capacitance Sampling Circuit MMIC

The sampling circuit MMIC consists of track diodes operating as high-speed switches and a hold capacitor that retains the sampled charge. Reducing parasitic capacitance is key to extending the sampling bandwidth. To this end, the diode element cell was miniaturized using Anritsu's GaAs process, minimizing parasitic capacitance.

(3) Flip-Chip Mounting of MMIC on Thin-Film Substrate

The MMIC in the conventional sampler module was connected to the thin-film substrate by wire bonding, but this method causes parasitic inductance due to the wire length, which was a limiting factor in bandwidth extension. Therefore, the MMIC connection was changed to flip-chip mounting,

significantly reducing the parasitic inductance component. Figure 6 shows the analysis results of the NLTL output pulse waveform and frequency spectrum. The NLTL output pulse has a steep fall time of 10 ps, and the corresponding frequency spectrum extends beyond 100 GHz. These efforts achieved an 80 GHz bandwidth while improving the conversion efficiency of the sampling output, minimizing parasitic capacitance, and without degrading noise characteristics.

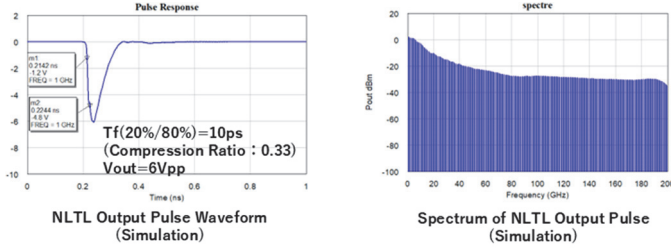


Figure 6 NLTL Output Pulse Waveform and Frequency Spectrum

3.3 PAM4 Analysis

IEEE 802.3dj specifies the measurement requirements for 106 Gbaud PAM4 signals. As with 53 Gbaud PAM4 signals, the primary evaluation parameter is TDECQ (Transmitter and Dispersion Eye Closure Quaternary)⁴. Table 1 shows the parameter differences for 106 Gbaud signals as specified in IEEE 802.3dj Draft 2.2 compared to 53 Gbaud signals specified in IEEE 802.3bs⁶. As speeds increase, simply extending the bandwidth is no longer sufficient to ensure communication quality, and channel degradation and reduced system margin are more pronounced. For this reason, the IEEE 802.3dj measurement requirements are more stringent in order to guarantee signal quality across the entire system. It should be noted that since IEEE 802.3dj is currently in draft form, its content is subject to future revision.

Table 1 Differences in Measurement Requirements Defined by IEEE 802.3dj Draft 2.2 and IEEE 802.3bs

Requirement	IEEE 802.3dj	IEEE 802.3bs
3-dB Bandwidth	53.125 GHz	26.5625 GHz
Target SER ^{*1}	4.56E-4	4.8E-4
Equalizer Specification	15 Tap FFE ^{*2} + DFE ^{*3}	5 Tap FFE
Tap Coefficient Constraints	Added Stricter Numerical Upper Bound Constraints	Basic Constraints Only

*1 SER: Symbol Error Ratio

*2 FFE: Feed Forward Equalizer

*3 DFE: Decision Feedback Equalizer

The IEEE 802.3 standard specifies multiple evaluation metrics to ensure interoperability of optical transceivers

used in high-speed Ethernet communications. TDECQ is one typical metric for evaluating the transmission performance of optical transceivers using PAM4 signals. Figure 7 shows a PAM4 waveform and a TDECQ measurement image. The amount of noise added to the transmitted signal is evaluated until the target SER is reached using an ideal receiver model. A smaller TDECQ value indicates a higher quality optical transmission waveform, and is defined by Eq. (1).

$$TDECQ = 10 \log_{10} \left(\frac{\text{Outer OMA}}{6} \times \frac{1}{Q_t R} \right) \text{ (dB)} \quad \dots (1)$$

Q_t : SER (Symbol Error Rate) specified by IEEE802.3dj

$$Q_t = 3.428 \text{ at } 4.56 \times 10^{-4}$$

R : Additional noise required to achieve SER = 4.56×10^{-4}

Measurement requires applying the reference receiver characteristics defined in the standard (4th-order Bessel-Thomson response) and the reference equalizer (FFE and DFE), as well as measurement under conditions simulating actual system operation. This allows fair evaluation of transmitter quality from the receiver's perspective by normalizing to the receiver level, while suppressing discrepancies in evaluation caused by measurement instrument characteristics. Moreover, this ensures that identical standard-based results are obtained from different vendors, thereby guaranteeing interoperability.

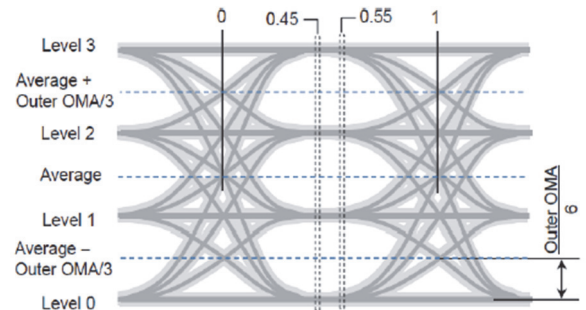


Figure 7 PAM4 Waveform and TDECQ Measurement

Figure 8 outlines the TDECQ measurement process. First, one period of the signal output from the transmitter is captured. The pattern used for measurement is SSPRQ (Short Stress Pattern Random Quaternary), as defined in IEEE 802.3. This pattern is designed to reproduce the effects of ISI (Inter-Symbol Interference) and nonlinear distortion within a short period, and the standard explicitly specifies use of SSPRQ for TDECQ measurement. Next, a 4th-order Bessel-Thomson filter as defined in the standard is applied to the acquired signal waveform, after which the tap coefficients of the FFE are calculated. The tap coefficients must be optimized to minimize the TDECQ value within the constraints

specified by the standard. However, since the tap resolution is extremely high and an exhaustive search of all combinations would result in enormous computational cost, IEEE 802.3 specifies optimization using the MMSE (Minimum Mean Square Error) algorithm. The MMSE method minimizes the mean square error (MSE) between the received signal and the ideal signal, and MSE is defined by Eq. (2).

$$MSE = E[|y(n) - d(n)|^2] \dots \quad (2)$$

$y(n)$: Output signal after FFE

$d(n)$: Ideal signal

In actual calculations, tap coefficients that minimize the MMSE are determined by matrix operations as expressed by Eq. (3).

$$w = R^{-1}p \dots \quad (3)$$

w : Vector of determined tap coefficients

R : Autocorrelation matrix ($X^T X$)

p : Cross – correlation vector ($X^T d$)

X : Data matrix

d : Ideal signal corresponding to the data matrix

After obtaining the tap coefficients, FFE is applied to the signal waveform. Subsequently, random noise following a Gaussian distribution is added. As shown in Figure 7, the threshold values corresponding to the four levels of the PAM4 signal are determined based on the center value of each Eye opening. Using these threshold values, the amount of noise required to reach the target SER is searched, and TDECQ is finally calculated based on that noise amount.

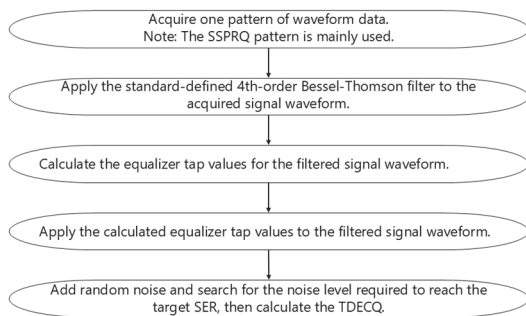


Figure 8 TDECQ Measurement Process

4 Performance Test

4.1 System Frequency Characteristics

Figure 9 compares the measured frequency response of the entire MP2110A-080 system and the ideal 4th-order Bessel-Thomson response. Here, the system response has been

software-corrected to approximate a 4th-order Bessel-Thomson response with a 3-dB bandwidth of 53.125 GHz. The system exhibits a flat response close to the ideal characteristics in the low-frequency region, and follows the ideal up to 60 GHz with a gradual roll-off in the high-frequency region. The standard deviation of the amplitude error of the system response relative to the ideal characteristics at each frequency point is 0.22 dB.

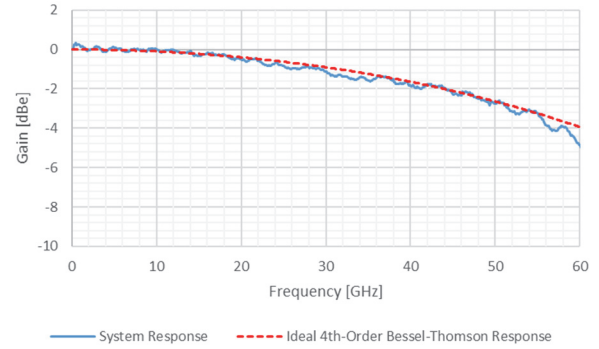


Figure 9 System Frequency Characteristics with Applied Digital Filter (53.125 GHz)

4.2 Optical Signal Waveform and Sensitivity Performance

The validity of the optical signal waveform and sensitivity performance were verified using a scope with the developed 080 option. Figure 10 shows the measurement setup for verification. The measurement conditions are as follows: 106 Gbaud rate, SSPRQ input pattern, and only a 15-tap FFE applied as the equalizer.

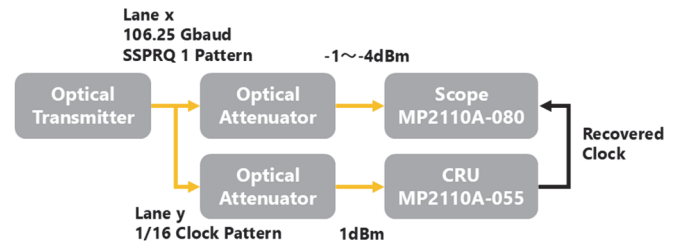


Figure 10 System Evaluation Setup

Figure 11 shows an example of the measured waveform when the optical input level to the scope is -2 dBm. It exhibits little waveform distortion, with an excellent TDECQ value of 2.11 dB. Figure 12 shows the results of evaluating the optical input level dependence for the main measurement items: TDECQ, Outer ER (Extinction Ratio), and Linearity. The scope optical input level was adjusted using an external variable optical attenuator. For a scope with ideal characteristics, the measurement results would be independent of the optical input level, and the graph plots would be flat. The measurement results show the average values

obtained from 10 repeat measurements under each condition. The variation in each measurement item over input levels from -1 to -4 dBm confirms the stable results regardless of input level, with peak-to-peak values of 0.25 dB for TDECQ, 0.07 dB for Outer ER, and 0.5% for Linearity.

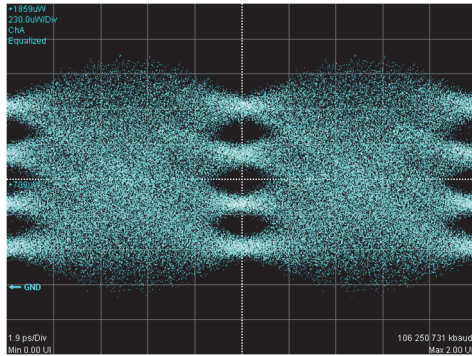


Figure 11 Example of observed optical waveform (106 Gbaud)

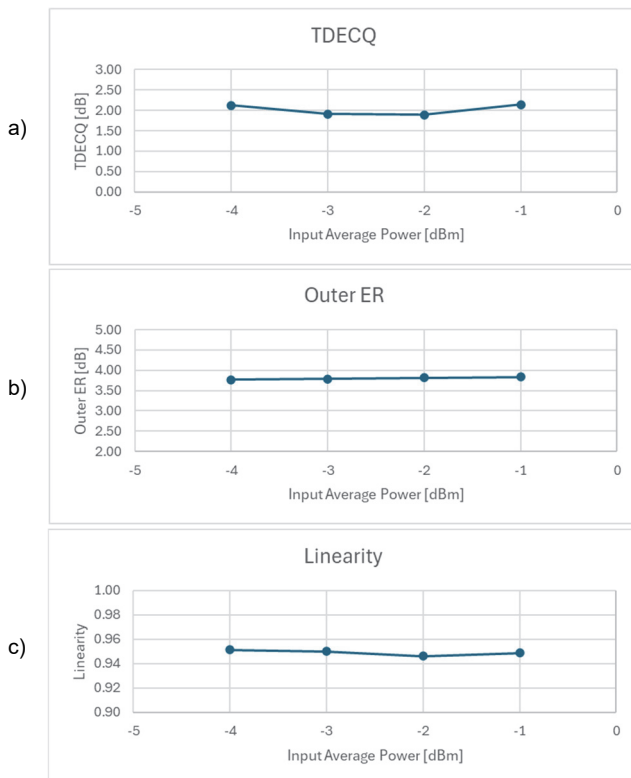


Figure 12 Optical input level dependence of each measurement result
a) TDECQ, b) Outer ER, c) Linearity

5 Conclusions

The rapid increase in data volumes handled by data centers is driving demand for 800GbE- and 1.6TbE-compatible optical transceivers. To meet these test requirements, we have extended the bandwidth of the MP2110A scope by developing the MP2110A-080 option for simultaneously

measuring signals of up to 120 Gbaud across four lanes. Stable performance with little input level dependence over a range of -1 to -4 dBm is achieved for the key TDECQ, Outer ER, and Linearity measurements, supporting provision of an 800GbE- and 1.6TbE-compatible 4-channel oscilloscope for high-accuracy measurements.

Going forward, we will continue to contribute to improving the production efficiency and evaluation quality of optical transceivers that support high-speed, large-capacity communication infrastructure by providing optimal solutions for testing optical transceivers.

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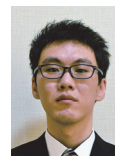
Authors



Yuki Yokoyama
Product Development Dept.
Service Infrastructure Solutions
Test & Measurement Company



Shuichi Matsuda
Product Development Dept.
Service Infrastructure Solutions
Test & Measurement Company



Keisuke Kishida
Product Development Dept.
Service Infrastructure Solutions
Test & Measurement Company



Ryota Takasu
Product Development Dept.
Service Infrastructure Solutions
Test & Measurement Company

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