DEVELOPMENT OF HBT-IC MODULES FOR 50-GBPS OPTICAL COMMUNICATION SYSTEMS

***AOKI Ikuro* [*1] *KOBAYASHI Shinji* [*1] *YAKIHARA Tsuyoshi* [*1] *MATSUURA Hiroyuki* [*1] *MIURA Akira* [*1]**

We have been striving to develop heterojunction bipolar transistor IC (HBT-IC) modules for next-generation 40-Gbps dense wavelength division multiplexing (DWDM) optical communication systems,employing Yokogawa's proprietary ultra-highspeed HBT devices. With the advantages of HBTs' ultra-high speed and low jitter, we have developed a line-up of standard logic ICs offering high-quality output waveforms, including a 4:1 multiplexer (MUX), 1:4 demultiplexer (DEMUX), and D flip-flop (DFF), as well as a lithium-niobate (LN) optical modulator driver-IC obtaining a flat gain of 23±1 dB in a range from 30 kHz through 33 GHz along with a high 5-Vpp or larger output voltage. Of special note is the operation of a 2:1 MUX IC module with two 22.5-Gbps inputs (into a 45-Gbps output) which has already been demonstrated.

This paper introduces HBT-IC modules (currently available as beta test versions for evaluation), each of which contains the abovementioned various new ICs mounted on an aluminum substrate to form a packaged module with interfacing connectors. Also mentioned in this paper are mass-produceable ceramic-packaged modules that are suitable to be set into communication equipment, meeting the commercial needs of the next-generation 40-Gbps DWDM optical communication systems.

INTRODUCTION

The quantum leap of the Internet and related multimedia networks has sharply advanced today's communication technologies in pursuit of enhancements in speed and capacity. While the wavelength division multiplexing (WDM) technique dramatically boosted transmission capacity and brought 10-Gbps transmission systems to the commercial stage, development of even higher multiplexing and faster baseband signal transmission is underway. Efforts have been intense in the research and development of 40-Gbps dense DWM (DWDM) optical communication systems, which are spotlighted as the next generation of optical communication technology with the most potential.

*1 Corporate R&D Center

We have been working on the development of ultra-highspeed compound semiconductor devices since 1983. By uniting the ultra-highspeed electronic device technologies gained through our development of various ultra-highspeed devices with long years of expertise in high-precision measurement technologies, we are now working on the development of transmitter and receiver modules. These will be key components of the next-generation 40-Gbps DWDM optical communication field, supporting the basis of the upcoming high-speed, high-capacity communication networks.

As the devices for ultra-highspeed communication, we are focusing on heterojunction bipolar transistor ICs (HBT-ICs) to advance development as they have low base input impedance and are less effected by noise components in the compound semiconductor substrate than field-effect transistor ICs (FET-ICs). For this, a premise that the devices should be designed for use also with a direct current is taken into consideration.[(1), (2)] The

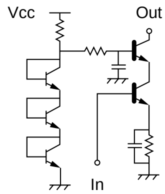

Figure 1 Elemental Amplifier

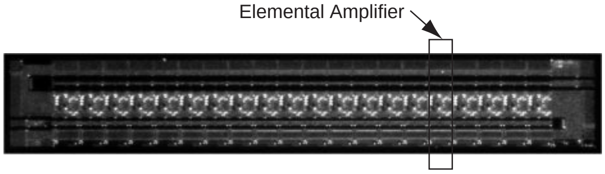

Figure 2 IC Chip of Twenty-stage Cascade Distributed Amplifier

following introduces an optical modulator driver-IC and a group of ultra-highspeed logic ICs which are slated to comprise transmitter and receiver modules in the next-generation 40-Gbps optical communication systems.

OPTICAL MODULATOR DRIVER-IC MODULE

There are two kinds of 40-Gbps DWDM optical modulators: lithium-niobate (LN) modulators(3) and electro-absorption (EA) modulators. An LN modulator features the merit of having such a wide bandwidth that a single design can cover the entire bandwidth of WDM. However, it requires a high drive voltage of 5 Vpp or larger. On the other hand, an EA modulator requires a low drive voltage of 2 to 3 Vpp but its loss and absorption characteristics impose limitations that narrow the applicable bandwidth. Hence multiple EA modulators need to be designed for divided wavelength bands. Provided we develop a driver IC for LN modulators that require a high drive voltage, it could also be used for EA modulators requiring a low drive voltage. As for frequency-output characteristics, flatness is required in a super wide range extending from 10 kHz to beyond 30 GHz.

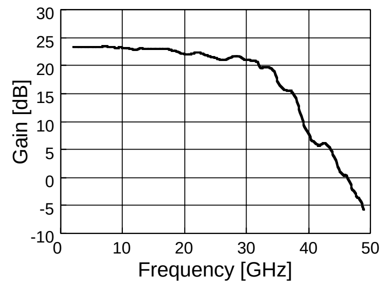

Figure 4 Frequency-gain Characteristics of Optical Modulator Driver-IC Module

At the outset of developing an optical modulator driver-IC meeting the requirements above, we posted a goal of achieving the output amplitude of at least 5 Vpp at 40-Gbps and have focused our efforts on attaining it.

The driver IC has a distributed amplifier configuration where cascode-type unit amplifier are arranged on a distributed amplifier-transmission line with phase aligned (see Figure 1). Thanks to this distributed amplifier configuration, allocating multiple elemental amplifiers in parallel for high output, is likely to keep the good performance in a wide bandwidth.

Figure 2 shows an optical modulator driver-IC chip in which the elemental amplifiers are allocated in parallel at twenty stages. The size of the chip is 1 mm by 6 mm. Figure 3 shows a photograph of a driver IC module equipped with V-connectors and containing two distributed amplifiers: one as a pre-driver and the other as a driver. Figure 4 shows the gain characteristics of the overall module through small signal frequency performance measured by a network analyzer. As is shown in the figure, the module exhibits a gain of 23±1 dB and power consumption of 2.3 W in a frequency range of 30 kHz to 33 GHz. Figure 5 shows the eye diagram output when applying pseudo random binary sequence (PRBS) signal pulses at 43-Gbps with a PRBS length of $2^{31}-1$ bits. A fine eye diagram with an output amplitude of 6 Vpp is obtained. As for jitter, root-mean-square jitter measured at 5.5 Vpp is 1.1 picoseconds as shown in Figure 6.

This Yokogawa driver IC module has been used to drive an LN modulator supplied by Sumitomo Osaka Cement Co., Ltd. for evaluation of optical output waveforms with satisfactory results.

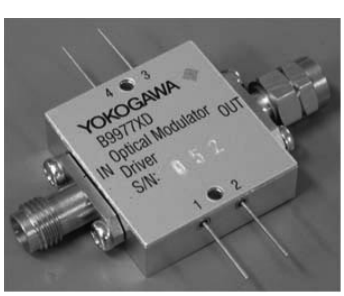

Figure 3 Optical Modulator Driver-IC Module
(26 × 24.2 × 7.5 mm)

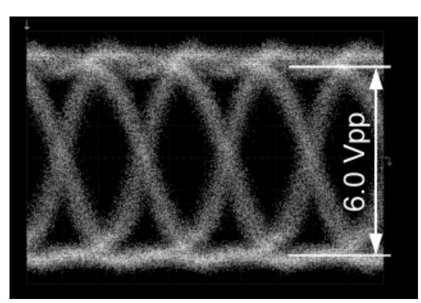

Figure 5 Output Waveform of Optical Modulator Driver-IC Module with 43-Gbps, $2^{31}-1$ PRBS Input Data

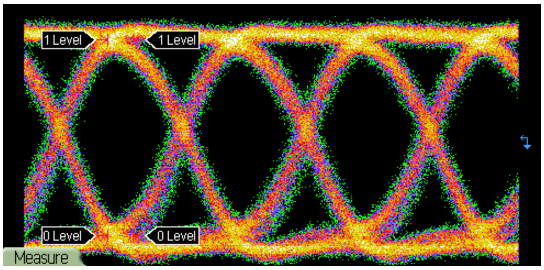

Figure 6 Output Waveform (Containing 1.1-ps Jitter) of Optical Modulator Driver-IC Module with 40-Gbps, 2^{31}–1 PRBS Input Data

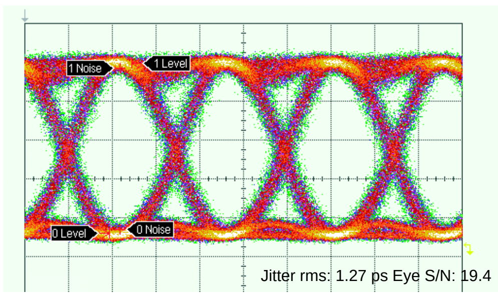

Figure 7 Output Waveform of LN Optical Modulator (supplied by Sumitomo Osaka Cement Co., Ltd.) with 43-Gbps, 2^{31}–1 PRBS Input Data

More specifically, ultra-highspeed 43-Gbps electrical signal pulses were input into the driver IC module, optically modulated through the LN modulator, then demodulated with a photodiode back to 43-Gbps electrical signal pulses and the output waveform was examined. Figure 7 shows the eye pattern monitored when inputting a 43-Gbps, 2^{31}–1 long PRBS.

Even though the initially posted goal — output amplitude of a minimum 5 Vpp at 40-Gbps — has already been attained, we are continuously striving to make improvements in various aspects, such as refinements in the packaging technology, to achieve even higher power and flatter frequency characteristics.

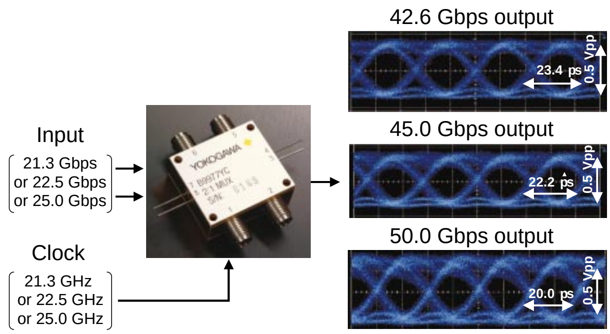

Figure 9 Output Waveforms of 2:1 MUX IC Module with 2^{31}–1 PRBS Input Data

ULTRA-HIGHSPEED LOGIC IC MODULE FOR OPTICAL COMMUNICATION

From among the key ultra-highspeed logic circuits comprising a 40-Gbps DWDM optical communication system, we have developed a group of ultra-highspeed 40-Gbps logic ICs including:

- Multiplexers (MUXs), which are devices for funneling several different streams of electric signals over a common communication line
- Demultiplexers (DEMUXs) for reversing the process of a multiplexer
- D flip-flops (DFFs) for retiming

For signals as ultra-highspeed as 40-Gbps, semiconductors having exceedingly good jitter characteristics are required since the jitter characteristic (small fluctuations along the time axis caused by phase noise and so on) has a catastrophic effect on the error rate. In principle, the HBT devices we are currently developing are expected to exhibit lower jitter, and hence be superior in processing 40-Gbps signals that require the jitter characteristic to be less than several picoseconds.

In the development of standard logic ICs, we initially addressed a 2:1 MUX IC. This standard logic IC has differential buffer inputs and open collector outputs, and its external logic interface voltages are 0 to -0.5 V. Figure 8 shows a 2:1 MUX IC module containing the developed 2:1 MUX IC chips which are connected with an aluminum substrate. K-connectors are used for high-speed signals. By using three 2:1 MUX IC modules, four

Figure 8 2:1 MUX IC Module (23.2 × 26.6 × 9 mm)

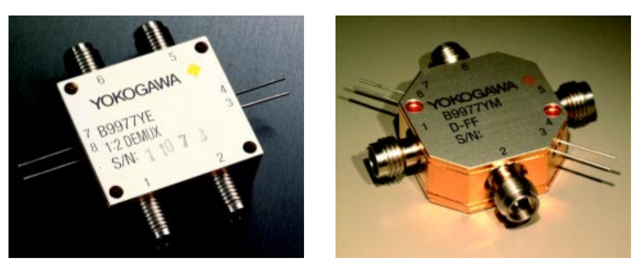

Figure 10 1:2 DEMUX IC Module (Left) and DFF IC Module (Right)

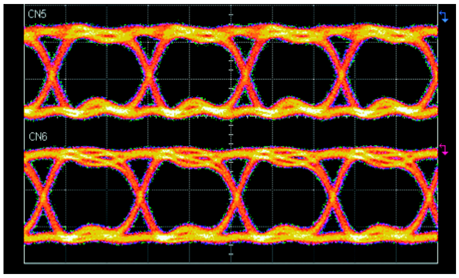

Figure 11 Output Waveforms of 1:2 DEMUX IC Module with 43-Gbps, 2^{31}–1 PRBS Input Data

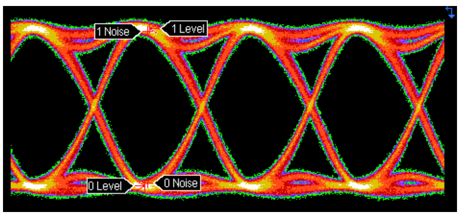

Figure 12 Output Waveforms of DFF IC Module with 43-Gbps, 2^{31}–1 PRBS Input Data

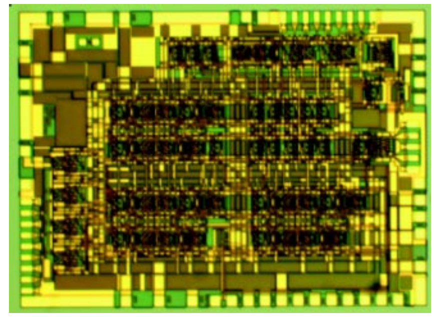

Figure 13 4:1 MUX IC Module Chip
(43-Gbps, 2.8 × 3.8 mm, 3.5 W, 2000 Circuit Elements Integrated)

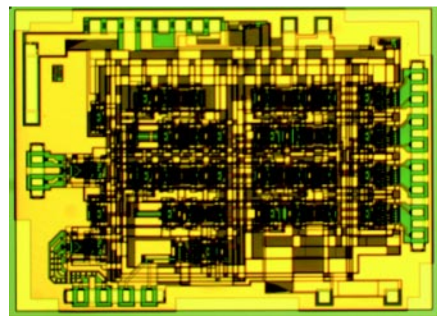

Figure 14 1:4 DEMUX IC Module Chip
(43-Gbps, 2.8 × 3.8mm, 3.2 W, 1600 Circuit Elements Integrated)

10-Gbps communication lines can be bound into a 40-Gbps line. Figure 9 shows the 42.6-Gbps waveform resulting when two 21.3-Gbps, 2^{31}–1 PRBS signals are input; the 45-Gbps output waveform with two 22.5-Gbps, 2^{31}–1 PRBS inputs; and the 50-Gbps output waveform with two 25-Gbps, 2^{31}–1 PRBS inputs. The power consumption is 1.1 W.

In the same fashion, ultra-highspeed HBT devices are integrated into a 1:2 DEMUX IC module and a DFF IC module (see Figure 10). Figures 11 and 12 show the output waveforms of these modules when a 43-Gbps, 2^{31}–1 PRBS signal is input. The power consumption is 1.7 W and 1 W, respectively. These IC modules have been verified as being error-free by using a bit error rate tester (BERT) during measurement of a PRBS eye diagrm with a length of 2^{31}–1 bits, thereby proving them to be ultra-highspeed logic IC modules applicable to 40-Gbps optical communication systems.

Anticipating the commercialization of 40-Gbps DWDM optical communication, we tackled the integration of a 4:1 MUX and a 1:4 DEMUX, aggregating various IC modules. The developed 4:1 MUX and 1:4 DEMUX IC chips, shown in Figures 13 and 14, are 2.8 by 3.8 mm, and have approximately 2000 and 1600 circuit elements, respectively. Power consumption of the 4:1 MUX IC chip is 3.5 W and for the 1:4 DEMUX IC chip, 3.2 W. Each of these IC chips is packaged into a module. V-connectors are used for 40-Gbps signals or faster, and K-connectors for other signals. Figure 15 shows a 43-Gbps PRBS output waveform of the 4:1 MUX IC module, and Figure 16 shows four 10.75-Gbps output waveforms of the 1:4 DEMUX IC module when a 43-Gbps PRBS signal is input. With a single module, these high-integration IC modules provide functions that could only previously be realized by a combination of many logic IC modules, thus offering drastic cost reductions (of about one fifth to a quarter). These high-integration IC modules were made available as beta test version samples from February 2002. Concurrent with the development of high-integration IC modules, increasing the speed of ICs is being tackled and our 4:1 MUX IC has already demonstrated 48-Gbps operation in the on-wafer state. Figure 17 shows a 48-Gbps output waveforms of 4:1 MUX IC in the on-wafer state.

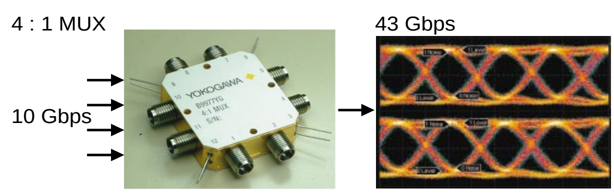

Figure 15 43-Gbps, 2^{31}–1 PRBS Output Waveform of 4:1 MUX IC Module (Amplitude: 0.5 Vpp)

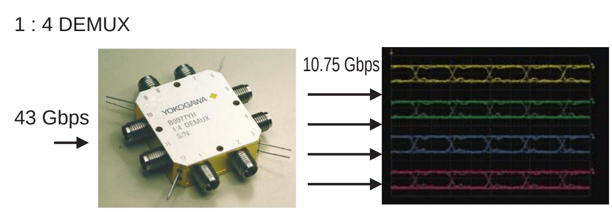

Figure 16 2^{31}–1 PRBS Output Waveforms of 1:4 DEMUX IC Module with 43-Gbps Inputs (Amplitude: 0.5 Vpp)

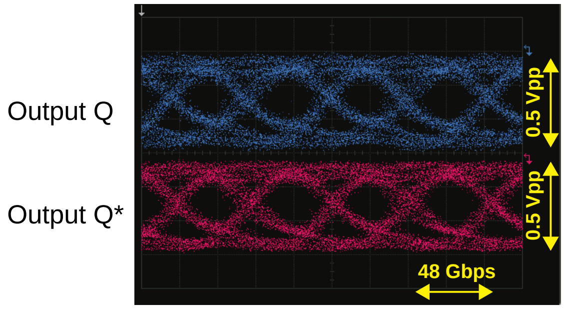

Figure 17 48-Gbps Output Waveforms of 4:1 MUX IC in the on-wafer state

(a) 4:1 MUX (b) LN driver (c) 1:4 DEMUX

Figure 18 Ceramic-packaged Modules for Commercial Use

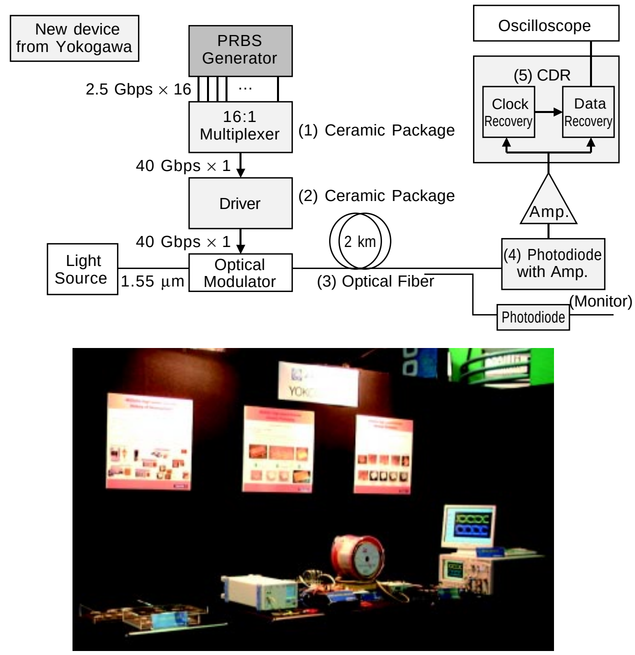

Figure 19 Demonstration at "Super Comm", May 2002
(Above: Outline of Demonstrated System; Below: Photograph of Demonstrated System at Exhibition)

All of the abovementioned modules are supplied with V- or K-connectors to be suitable for use in the development of the next-generation optical communication system. However, these structures, i.e., modules with connectors, will be impractical for use in configuring communication equipment when they are commercialized in the not-so-distant future. Hence, we are striving to further develop ceramic-packaged modules in which high-speed signal input/output lines are configured into coplanar waveguide (CPW) transmission line and are interfaced with external circuits by means of wire bonding. Figure 18 shows part of the line-up of ceramic-packaged modules (4:1 MUX, LN driver, and 1:4 DEMUX modules) geared toward future mass-production for commercial use and designed to be embedded into equipment. We plan to add to this line-up.

Lastly, let us introduce our cost-effective solution for very short reach (VSR) 40-Gbps optical communication systems which was demonstrated at the "Super Comm" that was held in June 2002 in Atlanta, Georgia, USA.

Figure 19 outlines the system that was demonstrated and exhibited the performance of our IC modules in a VSR 40-Gbps optical communication system. A PRBS generator is used to generate sixteen 2.5-Gbps signals, which are bound into a 40-Gbps signal by a ceramic-packaged 16:1 multiplexer module, then amplified by another ceramic-packaged driver IC module to drive an LN optical modulator (supplied by Sumitomo Osaka Cement Co., Ltd.). The optically modulated signal is transmitted over a 2 km long fiber-optic cable and demodulated back to electric signals by a Yokogawa proprietary photodiode. A clock and data recovery (CDR) circuit then reproduces the clock and data signals from the received waveform. Figure 20 shows the ceramic-packaged 16:1 multiplexer and driver IC modules used for an optical modulator, and Figure 21 shows the CDR IC module used for data and clock signal recovery. This CDR IC module is comprised of a one-chip IC (bottom of Figure 22) into which the portion of the circuit enclosed by a dotted line in the

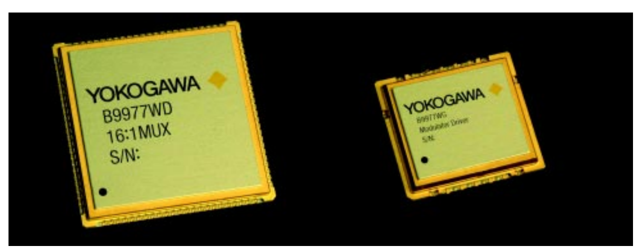

Figure 20 Ceramic-packaged 16:1 MUX and Optical Modulator Driver IC Modules

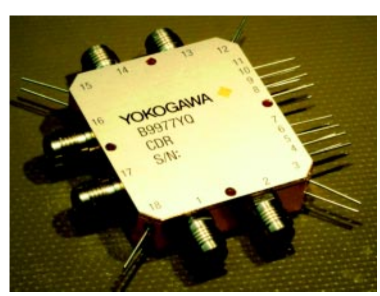

Figure 21 CDR IC Module (37 × 35 × 11 mm)

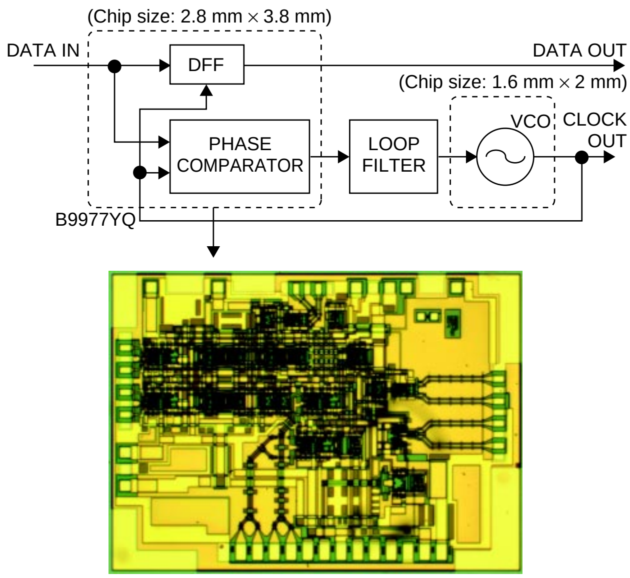

Figure 22 CDR IC Chip

upper left of Figure 22 is packed, forming a CDR circuit with an external loop filter and voltage-controlled oscillator (VCO). Figure 23 shows the output data waveform and clock waveform of the CDR.

CONCLUSION

From among Yokogawa-proprietary ultra-highspeed HBT-based IC modules for 40-Gbps DWDM optical communication, some of the line-up of logic IC modules and optical modulator driver modules are available as beta test version samples. We believe that currently developed anticipated solutions to the realization of even higher integrated modules and connector-free modules in a ceramic package will boost commercialization of the next-generation 40-Gbps DWDM optical communication systems.

We have also initiated research and development for eventual subsequent 80-Gbps optical communication systems, with an eye toward the union of HBT devices and resonant tunneling diodes (RTD) capable of ultra-highspeed switching at 2 picoseconds or less. ◆

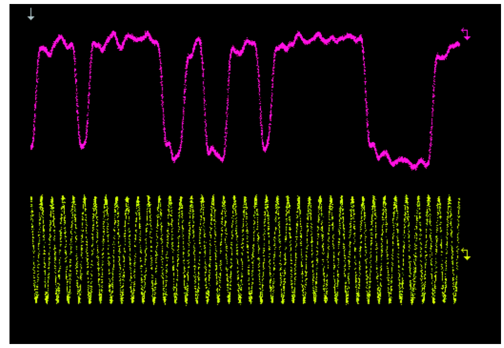

Figure 23 Output Data Waveform and Clock Waveform of CDR

REFERENCES

(1) Shinji Kobayashi, Kenji Uchida, Kentaro Tezuka, Sadaharu Oka, Tadashi Fujita, Ikuro Aoki, Tsuyoshi Yakihara, Hiroyuki Matsuura, Akira Miura, “Development and Applications of Ultra-highspeed HBT Devices,” Proceedings of the Optical Communication System Research Technical Committee (Japanese), OCS40G-5, Institute of Electronics, Information and Communication Engineers, June 14, 2001, pp. 23–28

(2) Ikuro Aoki, Shinji Kobayashi, Sadaharu Oka, Tadashige Fujita, Kenji Uchida, Kentaro Tezuka, Hideki Takada, Hirotoshi Kodaka, Tsuyoshi Yakihara, Hiroyuki Matsuura, and Akira Miura, “Development and Application of Ultra High-speed HBT for Measurement,” Ando Technical Bulletin, November 2001, pp. 59–65

(3) Akira Miura, Katsuhiro Yamanaka, and Akihisa Hashimoto, “An Electrooptical Modulator (Optical Waveguide) IC in an Optical Link Used for Voltage Sensor Isolation,” Proceedings IECON84, 1984, pp. 795–801