1. Introduction

Investigation is underway on the high-speed signal transmission standards of 56 Gbps and 112 Gbps.[1] Ordinarily, signals outputted from a transmission circuit within an IC chip are transmitted to the PCB signal wiring via the transmission-side PKG as shown in Fig. 1, and inputted to the reception-side PKG and the reception circuit within the IC chip. Hitherto, to reduce transmission loss within the PCB signal wiring, there have been developments such as a low dielectric constant material, and conductor surfaces with reduced roughness.[2, 3] As this research and development progresses, and as signal speeds have increased in recent years, transmission degradation factors can no longer be ignored. The first issue is the reflection loss due to the via-stub structure of the inter-layer connection through-hole; and the second is the delay-time differences between differential wiring (a phenomenon known as “skew”) caused by unevenly distributed glass fiber cloth in the insulation layer. The tolerance margins for these two items steadily decline in tandem as the signal speed increases. In response, a variety of techniques have been developed, including using back drilling to reduce stub length and placing the glass cloth at an oblique angle to reduce unevenness, etc.[4–7] However, these techniques are neither sufficient to completely eliminate the via stub, nor the skew between the differential wiring.

Therefore, with the aim of realizing a transmission configuration that is both stub-less and skew-free, we developed a novel transmission configuration, whereby a flexible printed circuit (FPC) dedicated to high-speed transmission was created and connected with the PKG via solder bumps (Fig. 2). In these configurations, only high-speed signals from the PKG with an IC chip mounted were allowed to be transmitted in a FPC, and miscellaneous signals of low frequency and power supply paths were transmitted in a conventional PCB. FPC interconnects configurations using connectors have been proposed.[8] On the other hand, since the proposed configurations use a ball grid array (BGA) instead of a connector, it is advantageous
for connection loss and signal density.

A module was created for evaluation, with measurements and simulations of its transmission characteristics conducted. Results showed a major improvement in the 56 Gbps high-speed transmissions.

2. Experimental Method

2.1 Creation of low-loss FPC

For this study, a stripline structure was selected due to its superior characteristics, including its radiative (emission) properties, wiring density, etc. For high-speed transmissions, the design must reduce both conductor loss and insulation loss while adjusting to the characteristic impedance. A thick insulation layer and wider wiring width is effective in reducing conductor loss, while the selection of a material with a low dielectric loss tangent is effective in reducing insulation loss.

Table 1 shows the design specifications for high-speed transmission wiring inside the FPC. This substrate was designed by VECSATR CT-Z (Kuraray) as a base film and ADFLEMA NC0204 (Namics) as an adhesive, and the wiring is designed to the 100 Ω differential impedance. For comparative verification, and with the aim of making the effects of the via stub and cloth glass explicit, the wiring configuration was also constructed using a conventional high-speed transmission PCB (R-5785, Panasonic) with a 100 Ω differential.

Table 2 shows the design specifications of the evaluation module. The transmission line length is 100 mm, and either the top or bottom layer of each of the transmission-side PKG and the reception-side PKG is connected with the FPC using a BGA. On the package surface, probe pads for scattering parameter (S-parameter) measurements are formed, having 4-port measurements (ground-signal-ground-signal-ground, GSGSG). The PCB for comparative verification was designed such that the PKG bottom layer is connected using a BGA, and such that layer 6 of an 8-layer PCB serves as the signal layer, with the thicknesses of layers 7 and 8 becoming the stub length within the signal transmission wiring. A vector network analyzer (Keysight Technologies, N5245A) was used for S-parameter measurements. Using a 0.25 mm differential probe (ACP40-GSGSG250), differential S-parameters were measured in frequencies ranging from 10 MHz to 40 GHz. An overview of the measurement system is shown in Fig. 3.

2.3 Verification by circuit simulations

A circuit simulator (Keysight Technologies, Advanced Design System (ADS)) was used for eye-pattern analysis. As shown in Fig. 4, transmitter (TX) and receiver (RX) circuits were set at both sides of the 4-port for S-parameter measurement data file, and an analysis model was created such that the eye-pattern waveform was shown on a moni-
tor after passing through the RX circuit. The specification details for the TX and RX were set with reference to commercial high-speed transmission circuits.

3. Results and Discussions

3.1 FPC transmission characteristics

To begin with, we evaluated the transmission characteristics in FPC substrate. Figure 5 is a cross-sectional photograph of the prototype FPC. It can be seen that the strip-line structure, sandwiched between a 0.1 mm thick base film layer and an adhesion layer, was formed according to the design specifications in Table 1. Figure 6 shows the results of the transmission characteristics measurements (input differential insertion loss SDD21). It was clear that the FPC had roughly the same transmission characteristics as the high-speed transmission PCB. It is thought that, by making the signal wiring dimensions in the FPC and the dielectric tangent value of the insulation layer approximate to those of a PCB, both conductor loss and dielectric loss were similar to those of a PCB.

Figure 7 shows the measurement results for skew between the differential wiring. With the PCB transmission, a roughly 2 ps skew is generated over a 100-mm wiring length. However, with the FPC transmission, despite the same wiring length, virtually zero skew was demonstrated by actual measurements. This result was caused by the presence of glass fiber cloth in the insulation layer. As a result, we could realize the skew-free transmission line in the FPC without glass fiber cloths.

3.2 Evaluation module transmission characteristics

Figure 8 shows the external appearance of the prototype evaluation module. As seen in Fig. 8(a), the PKG is placed at 100 mm intervals on the PCB, where the PCB and the PKG are connected at a 0.8 mm pitch using a BGA.
8(b) and 8(c) show the FPC at the PKG bottom-layer and top-layer, connected at a 0.8 mm pitch using a BGA.

Figure 9 shows the measurement results for insertion loss (SDD21) with the three connection-type configuration. While roughly equivalent insertion losses were measured up to the vicinity of 20 GHz, we confirmed that waveform disturbance occurs in high-frequency ranges above 20 GHz. As shown in Fig. 10, this phenomenon can be thought to have been due to return loss (SDD11). We found that in reflection loss measurement results, resonance peak occurs at 20 GHz and above. This is thought to have been due to effects of the interlayer via formed by mechanical drilling. The drilling-via existed at the PKG core layer and in the PCB. Furthermore, depending on the drilling conditions, there can be temporary widening of the gap between the ground and signals within the transmission wiring, resulting in the occurrence of resonance.

Figure 11 shows eye-pattern simulation results. Testing was performed for three data rates patterns, namely, transmission rates of 14 Gbps, 28 Gbps, and 56 Gbps. Figure 12 shows the simulation results, with the eye heights shown for comparison. We found that the use of the FPC transmission configuration facilitated a 30% to 60% improvement over the PCB transmissions. Furthermore, results for 56 Gbps showed improvement tendencies that differed from those of the other transmission rates (14 Gbps and 28 Gbps).

To better understand this phenomenon, time-domain reflectometry (TDR) analysis was performed. Figure 13 shows the analysis model. Two waveform rise times (Tr) were set: 36 ps and 9 ps. Figures 14 and 15 show the simulation results. From 0 ns to approximately 0.1 ns, the 100 Ω
differential transmission wiring is shown transmitting within the PKG, then within the connection area leading into the PCB or FPC at 0.1 to approximately 0.2 ns, and from 0.2 ns and thereafter, transmission occurs at the 100 Ω differential transmission line within the PCB or FPC. In the interval from 0.1 ns to 0.2 ns, within all connecting structures, a discontinuous area of characteristic impedance exists, arising from the BGA connection; we clarified that the behavior of each connection configuration changes with different rise times (Tr). When one considers that the rise times of Tr 36 ps and Tr 9 ps correspond to the 14 Gbps and 56 Gbps transmission rates, the characteristic impedance decline amounts match the eye-opening trends.

The above-described results clarify that, due to transmission-speed differences, the optimal FPC connection structure differs between the PKG top layer and the PKG bottom layer. Since the differential wiring within the PKG has a narrow wiring pitch of approximately 0.1 mm, the PKG core layer existing between this and the 0.8 mm pitch BGA pad is thought to have functioned well at 56 Gbps as a buffer layer.

4. Conclusion

With the aim of improving high-speed signal transmission characteristics, we investigated a stub-less, skew-free transmission configuration using a FPC. For differential signals of 14 Gbps to 56 Gbps, we verified that this configuration facilitated a 30% to 60% extension of transmission length. During this verification process, we also confirmed that the optimal configuration differs according to transmission speed. With our developed FPC transmission configuration, and without the use of a conventional FPC connector, the connection is made with the PKG via a BGA connection. This makes it easy to further increase wiring density, and this configuration will also be useful in responding to future demands for bandwidth expansion.

References

[1] Optical Internetworking Forum Document: Implementation Agreement OIF-CEI-03.1 “Common Electrical I/O (CEI) – Electrical and Jitter Interoperability agreements for 6G+ bps, 11G+ bps and 25G+ bps I/O,” Feb. 2014.

[2] W. P. Ting, F. P. Tseng, and K. C. Chiou, “Advanced Materials with Low Dielectric Properties and Highly Thermal Conductivity,” IEEE International Microsystems, Packaging, Assembly and Circuits Technology Conference 2016.

[3] O. Suzuki, A. Yoshi, H. Tsubura, M. Sato, N. Obata, and Y. Kokaji, “Nano Anchoring Copper Foil for Next Generation Printed Wiring Boards,” IEEE Pan Pacific Microelectronics Symposium 2016.

[4] G. Shiue, C. Yeh, L. Liu, H. Wei, and W. Ku, “Influence and Mitigation of Longest Differential via Stubs on Transmission Waveform and Eye Diagram in a Thick Multilayered PCB,” IEEE Trans. CPMT, Vol. 4, No. 10, pp. 1657–1670, Oct. 2014.

[5] J. Zhang, Q. B. Chen, H. Wang, J. Fan, A. Orlandi, and J. L. Drewniak, “Stub Length Prediction for Back-Drilled Vias Using a Fast Via Tool,” IEEE Electrical
Design of Advanced Packaging and Systems 2010.

[6] W. Beyene, Y. C. Hahm, D. Secker, D. Mullen, and Y. Shlepnev, “Design, Modeling, and Characterization of Passive Channels for Data Rates of 50 Gbps and Beyond,” IEEE Electronic Components & Technology Conference 2014.

[7] J. Loyer, R. Kunze, and X. Ye, “Fiber Weave Effect: Practical Impact Analysis and Mitigation Strategies,” DesignCon 2007.

[8] H. Braunisch, J. E. Jaussi, J. A. Mix, M. B. Trobough, B. D. Horine, V. Prokofiev, D. Lu, R. Baskaran, P. C. H. Meier, D. H. Han, K. E. Mallory, and M. W. Leddige, “High-Speed Flex-Circuit Chip-to-Chip Interconnects,” IEEE Transactions on Advanced Packaging 2008.