INVITED PAPER *Special Section on Progress in Optical Device Technology for Increasing Data Transmission Capacity*

# Recent Progress with Next Generation High-Speed Ethernet Optical Device Technology

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**SUMMARY** Ethernet has become an indispensable technology for communications, and has come into use for many applications. At the IEEE, high-speed standardization has been discussed and has seen the adoption of new technologies such as multi-level modulation formats, high baud rate modulation and dense wave length division multiplexing. The MSA transceiver form factor has also been discussed following IEEE standardization. Optical devices such as TOSA and ROSA have been required to become more compact and higher-speed, because each transceiver form factor has to be miniaturized for high-density construction. We introduce the technologies for realizing 100GbE and those applicable to 400GbE. We also discuss future packages for optical devices. There are many similarities between optical device packages and electrical device packages, and we predict that optical device packages will follow the trends seen in electrical devices. But there are also differences between optical and electrical devices. It is necessary to utilize new technology for specific optical issues to employ advanced electrical packaging and catch up the trends.
***key words:*** *Ethernet, transceiver, MSA, TOSA, ROSA, package*

## 1. Introduction

In recent years, with the rapid increase in data traffic on the Internet, the number of Over The Top (OTT) information service provider data centers has been increasing. The networks within these data centers are connected via Ethernet, which has become a major presence in large-capacity communications, even compared to the synchronous optical network (SONET) and synchronous digital hierarchy (SDH) systems used by traditional telecommunications carriers [1]. Because Ethernet offers flexible implementation, it can be applied not only to electrical cables but also to optical fibers, and has seen its area of application expanded greatly. At present, the standardization of 200 and 400 Giga bit Ethernet (GbE) has been discussed following the standardization of 100GbE as 802.3bs by the Institute of Electrical and Electronics Engineers (IEEE) [2]. The discussions in the IEEE standardization committees are about the protocols, but the actual physical medium dependent (PMA) implementations are also discussed under transceiver form factor and optical device multi source agreements (MSA) in parallel with the IEEE's discussions.

In this paper, we describe the IEEE standardization for high speed operation and discuss the transceiver form factor in the context of the IEEE standards. Then the newly emerging technologies for realizing 100GbE and 400GbE are introduced, and the future package types for optical devices are also discussed by focusing on the similarities between electrical and optical packages.

## 2. High-Speed Ethernet Standardization

The IEEE standard for 100GbE was released in 2010, and the standard for 400GbE was released at the end of 2017 [2], [3]. In IEEE 802.3bs, the 1.3 $\mu$m band is adopted just as for 100GbE, and for improving the per-wavelength transmission speed, 4-level Pulse-Amplitude-Modulation (PAM4) is adopted, which is able to support communication over up to 10 km. With the specification of 400GBASE-DR4 (which is applicable to 500 m transmission), 50 GBaud PAM4 $\times$ 4 wavelengths was adopted based on using high-speed devices, and 25 GBaud PAM4 $\times$ 8 wavelengths was adopted for the specifications of 400GBASE-FR8 and LR8 (which are applicable to 2 km and 10 km transmission respectively). Figure 1 shows the increasing transmission speed of the IEEE standards. PAM4 modulation achieved 50 Gbps/$\lambda$, and the possibility of 100 Gbps/$\lambda$ by increasing the baud rate from 25 Gbaud to 50 Gbaud has been discussed. 200 or 400GbE will be achieved by using PAM4 and wavelength division multiplexing (WDM), which was adopted for 100GbE [4]. For further increasing the transmission speed, the incorporation of new technologies for multi-level phase modulation such as Quadrature Phase Shift Keying (QPSK), Quadrature Amplitude Modulation (QAM), and Discrete Multi Tone modulation (DMT), and high baud rates in excess of 100 Gbaud, will be required as shown in Fig. 2.

The IEEE has also discussed long-range standards ex-

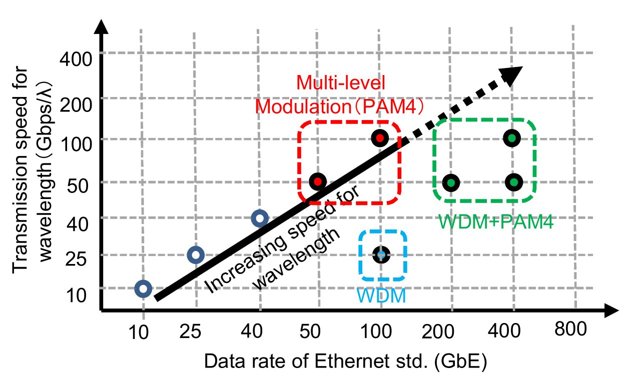


**Fig. 1** Correspondence between data rate and transmission speed per wavelength for Ethernet standards.

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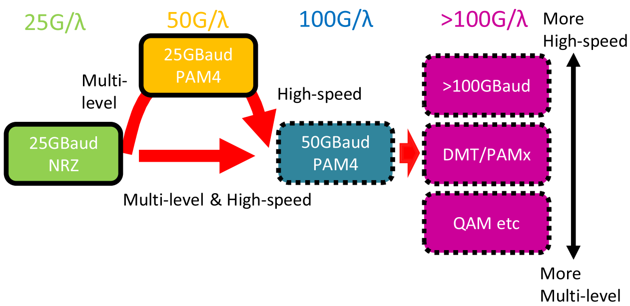


**Fig. 2** Schemes for increasing transmission speed.

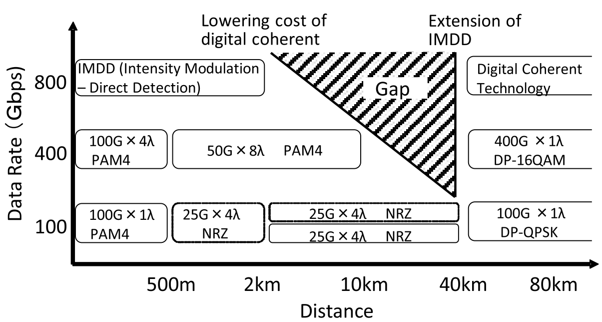


**Fig. 3** Correspondence between transmission distance and data rate.

ceeding 10 km. This discussion is based on the premise that high sensitivity avalanche photo diode (APD) [5], [6] and semiconductor optical amplifiers (SOA) integrated with electroabsorption modulator integrated lasers (EML) [7] which enable high transmitter output power will be applied, but link budgets that fully satisfy the targeted 40 km transmission have not been obtained, and the range extension is limited [8]. In addition, the standardization of 50, 100 and 200 Gbps is also being discussed as IEEE 802.3 cd [9]. This standardization is based on using 1 to 4 waves of the 25 or 50 GBaud PAM4 which was newly adopted for 400 GbE, and can be realized at lower cost than the conventional standard.

Meanwhile, the Optical Internetworking Forum (OIF) has been studying 400G-ZR, targeting distances of 80–120 km using a digital coherent technology [10]. The challenge here is to optimize the performance of the components and lower the power consumption to reduce costs. Studies of line width relaxation (500 kHz), transmitter output power reduction (−10 dBm), etc. have been reported [10], but it is also both necessary and important to reduce the signal processing power for dispersion compensation, forward error correction (FEC) etc. [10].

Figure 3 shows the corresponding range for each modulation format. Although a modulation format which accommodates distances for 10 km to 40 km of 400 Gbps transmission will be realized by either extending the capability of direct detection such as PAM or reducing the cost of digital coherent operation, it is difficult to predict at this time which technology will dominate. At 100GbE, digital coherent technology has been selected as a candidate for extending the range to 80km. It seems that introducing digital coherent technology will be discussed more aggressively even for long distances at 400GbE of 40 km or more [11].

We have to find a balance point between relaxing the specifications for digital coherent signal processing and applying signal processing to short distance communication in the future.

## 3. Transceiver Form Factor

The Ethernet standard was established for 10 Mbps at the time of its birth [12], and the standardization of Ethernet has progressed from 10 Mbps to 1Gbps by using electrical cables. Optical fiber first appeared as a transmission medium at the time the standard for 10 Gbps transmission was established. Meanwhile, optical parts such as optical fibers, lenses, laser diodes (LD), photo diodes (PD) require special handling for assembly, because of the need for precise alignment of these parts. Earlier optical communication equipment was implemented using discrete optical components and peripheral parts such as LDs, PDs, LD drivers, transimpedance amplifiers (TIA) etc. In the early 2000s, pluggable optical transceivers appeared. The transceivers could be plugged-in to the front panel of the optical communication equipment, and multiple vendors proposed an MSA for a unified electrical and mechanical interface (I/F) for these pluggable optical transceivers. Based on this idea, the XENPAK and then the XFP form factors were for the first time standardized in parallel with the standardization of 10GbE using optical fiber as the transmission medium [13], [14]. Furthermore, based on the recognition that the optical components built into these optical transceivers also need to be standardized for compatibility among the transceiver vendors, the optical device vendors mostly those in Japan, established an MSA for transmitter optical sub-assemblies (TOSA) and receiver optical sub-assemblies (ROSA) referred to as XMD [15]. This MSA has greatly contributed to the popularization of standards along with the transceiver MSA. Optical transceivers which have multiple features such as integration of the transmitter and receiver, unified electrical and optical I/Fs and pluggability have brought significant advantages such as improving the freedom of device configuration and procurement for communication equipment vendors. Subsequently, new form factor MSAs are being born along with the standardization activities of the IEEE, and this has become a major feature of optical transceivers.

Figure 4 plots the time when each form factor entered mass-production and the data rate vs. footprint (size) of the form factor. An increase in the data rate vs. footprint of the form factor is a major force in the introduction of a new form factor. For example, at 100GbE, the initial form factor was Centum gigabit Form factor Pluggable (CFP), following which the CFP2 and CFP4 form factors were released, and now the Quad Small Form Factor Pluggable 28Gbit/s (QSFP28) has been released [16], [17]. Comparing the data rate vs. footprint with the mass production rate of the form factors, there has been a tenfold times-increase in five years, and it is found that this adheres well to Moore's Law. On the other hand, it can be seen that the rate of transition between the different transmission capacities, for example, from 10GbE to 100GbE, is ten times in ten years, about twice as long. This may explain why the forthcoming transmission capacity standards require the introduction of new technology, not just miniaturization, thus requiring a longer development period. We predict the future by extrapolating these changes: Octal Small Form Factor Pluggable (OSFP) and QSFP Double-Density (QSFP-DD) will appear in volume production around 2021 for 400GbE because 40GbE transceivers appeared in 2011 [18], [19]. Then 800GbE products will appear around 2022-2024. A Chip-On-Board (COB) type of form factor is beginning to be studied due to changing needs and the emergence of new technologies such as silicon photonics [20] that are coming into practical use. In Fig. 4, the Consortium for On-Board Optics (COBO) does not follow the trend, but it can be said that as a form factor it will apply new technologies that are completely different from the existing ones [21].

Table 1 summarizes the data rate, transceiver size, number of wavelengths, number of electrical I/Fs and power consumption of the main form factors. Four-wavelength integration as the number of wavelengths used up to 400 Gbps is mainstream, which is in common with the technology developed at 100GbE. It is expected that new forms will be required for both the optical and electrical I/Fs because the number of wavelengths used will increase beyond 400 G.

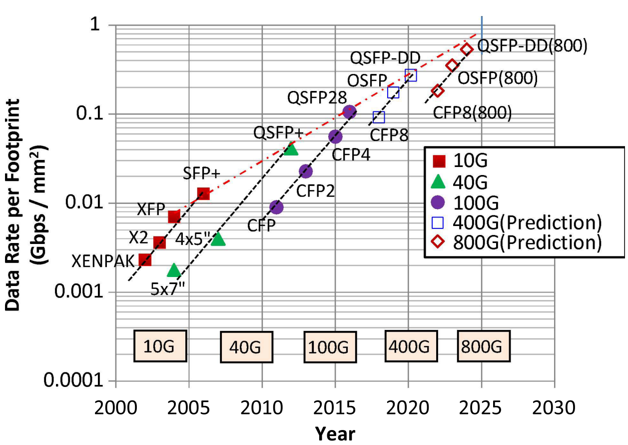


**Fig. 4** Trend of transmission speed vs. footprint and time of appearance in the market.

**Table 1** Basic specifications for each form factor.

| | CFP2 | QSFP28 | CFP8 | OSFP | QSFP-DD | COBO |
|---|---|---|---|---|---|---|
| Data Rate (Gbps) | 100 | | 400 | | | 400+ |
| Width (mm) | 40 | 18 | 40 | 23 | 19 | 20 |
| No. of Wavelengths | 4 | 4 | 8 | 4 | 4 | 4+ |
| No. of Electrical I/Fs | 4 | 4 | 16 | 8 | 8 | 8+ |
| Power Consumption (W) | 9 | 3.5 | 14 | 12 | 12 | - |

## 4. Integration Technology for Realizing 100 & 400G

One of the main features of 100GbE is the adoption as a prerequisite of WDM, which had been handled as an option below 100 Gbps, and in the case of 2 km or more, 100GbE consists of four 25 Gbps transmission lanes with four wavelengths of LAN-WDM. Therefore, each form factor needs to incorporate transmitters at four wavelengths and receivers at four wavelengths. Because the CFP form factor is larger than other form factors, 8 individual TOSAs and ROSAs can be arranged in parallel, and furthermore the multiplexer (MUX) and demultiplexer (DEMUX) can also be incorporated in the transceiver. One wavelength TOSAs have already been realized at 10GbE, and the TOSA only needs to increase its transmission speed from 10 Gbps to 25 Gbps. The main development items are the high-frequency transmission lines for packaging the TOSAs and ROSAs and the optical devices such as LDs or PDs. When the required form factor shifted from CFP to CFP 2 or CFP 4, it became difficult to install 8 TOSAs and ROSAs at individual wavelengths in a small CFP2/4 transceiver form factor. Since the rear with the optical output is narrowed and the allowable length of the TOSA is also reduced, as shown in Fig. 5, the LDs and PDs for the four wavelengths are installed in one package which also incorporates an optical MUX/DEMUX to reduce the space they occupy [22]–[29]. 100GbE employs four-wavelength WDM, and realizes 100 Gbps transmission by multiplexing four wavelengths at a transmission speed of 25 Gbps per wavelength. The technical issue is realizing an optical system capable of integrating four waves for miniaturization, and it is essential to establish a miniature MUX/DEMUX, a method of aligning the LDs or PDs and MUX/DEMUX, and the suppression of optical and electrical signal crosstalk among the lanes [30]–[36].

### 4.1 Precise Lens-Assembly Techniques

Increasing a multiplexer with a 100GbE TOSA requires precise lens alignment on the order of submicrons for multi-lane optical module devices because the position of each the

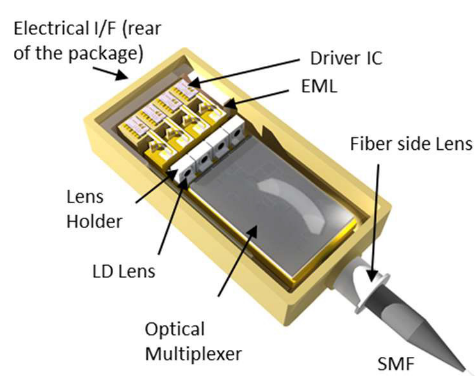


**Fig. 5** Perspective view of optical multiplexer integrated with 100GbE TOSAs.

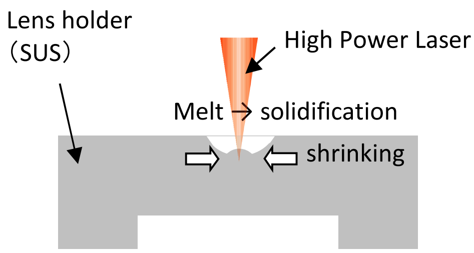


**Fig. 6** Principle of laser hammering for precise lens-assembly.

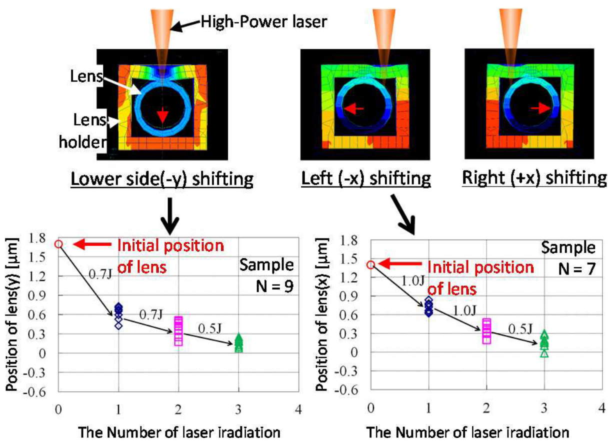


**Fig. 7** Simulation and experimental results of relative position of lens as a function of the number of laser hammering.

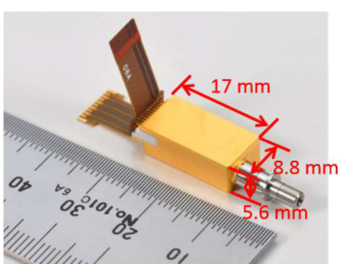


**Fig. 8** 100GbE TOSA outline

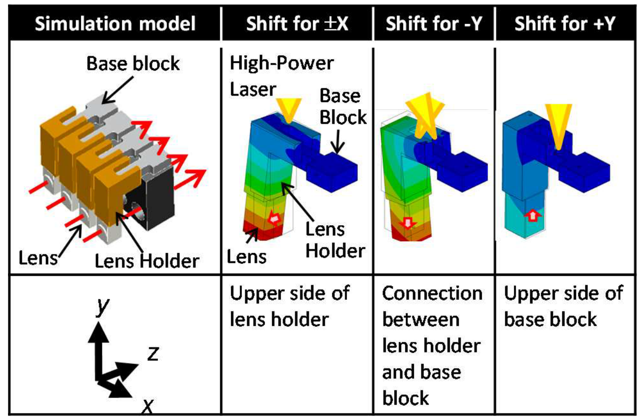


**Fig. 9** Laser hammering scheme for high density optics integration.

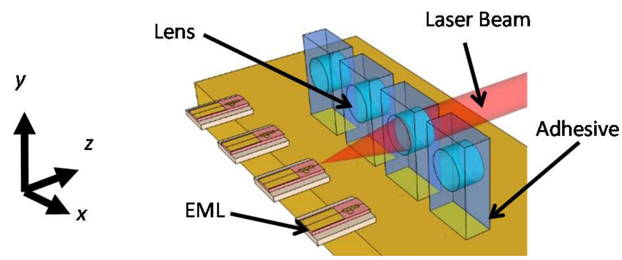


**Fig. 10** Schematic diagram of optics with adhesive bonding.

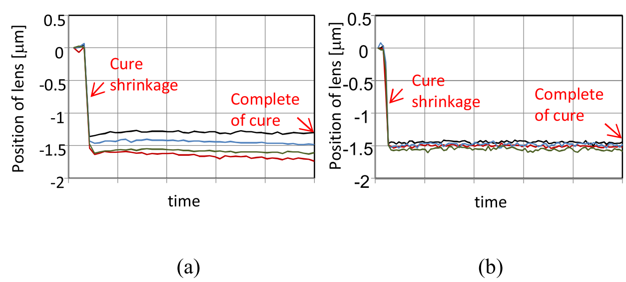


**Fig. 11** Experimental results for relative position of the lens in the y-axis as a function of the duration of UV irradiation (a) before and (b) after optimizing cure conditions.

four EMLs and the fiber position are fixed and they need adjustments of less than 1 micron. We realized a package size of 8.8 mm × 17.0 mm × 5.6 mm by applying a fine alignment method for the lenses [37]–[39] using a high power laser irradiation method which we called laser hammering. Figure 6 shows the plastic deformation when a high power laser is used to irradiate the lens holder. A finite element method (Quick Welder) was used for the calculation in this example. The lens is held at the top by a lens holder which is made of stainless steel. When the high power laser irradiates the upper side of the lens holder for a short time, the stainless steel surface melts and then solidifies, and stress is applied in the direction of contraction around the irradiated point on the surface. Therefore, it is possible to move the lens slightly downwards, and a movement of 0.3 micron was confirmed in this calculated example. By applying the same principle to another part of the lens holder, it is also possible to move the lens upwards [37], [38]. Since this technique can be realized by irradiating with a high power laser from the top only, it is possible for it to be applied even in the case of high density integration. Figure 9 shows an example for higher density integration by changing the fixing location of the lens and deforming the lens holder appropriately [40].

In order to realize further miniaturization, we have established a high precision bonding technique for the lenses, omitting the lens holder and base [40], [41]. In order to realize submicron lens bonding accuracy, it is necessary to reduce variations due to curing shrinkage as shown in Fig. 10. In general, the adhesive which join the lens and base shrinks during the cure, and the lens will be moved from its position before curing. As shown in Figs. 11 (a) and (b), it was confirmed that the bonding accuracy was improved by more

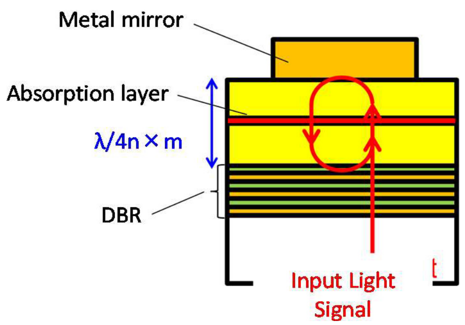


**Fig. 12** Schematic diagram of structure of resonant cavity avalanche photo diode.

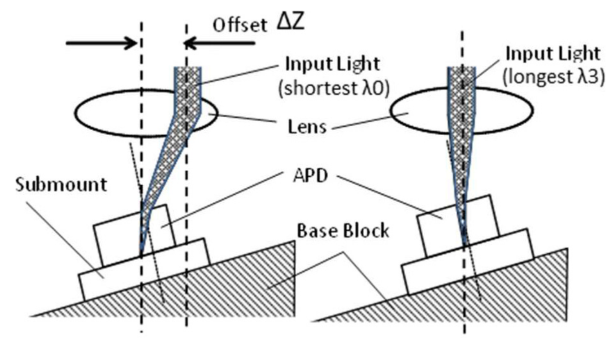


**Fig. 13** Schematic diagram of wavelength dependency compensation for an APD with a DBR structure for (a) shortest wavelength $\lambda 0$ and (b) longest wavelength $\lambda 3$.

than three times by optimizing the resin material and ultra violet (UV) irradiation conditions.

### 4.2 Wavelength Dependent Compensation for High Responsivity Resonant Cavity Avalanche Photo Diode

For the PD, reconciliation between high speed and high sensitivity is key [42]–[44]. In order to increase the response speed, it is common to decrease the PD diameter in order to reduce the parasitic capacitance. For example, at 10 Gbps, a PD diameter of about 20 $\mu$m is often used, but the diameter at 25 Gbps may need to be as small as half of that to reduce the capacitance. Furthermore, in the case of an APD, it is important to concentrate the light in the absorption layer of the APD. Figure 12 shows a schematic diagram of a high responsivity resonant cavity APD device structure [42]. The distributed Bragg reflector (DBR) structure is located between the light receiving surface and the absorption layer, and the metal mirror is arranged on the opposite side of the light receiving surface. This structure confines the incident light between the metal mirror and the DBR, so we obtain a high responsivity of 0.94 A/W. The DBR structure not only causes wavelength dependence of the responsivity, but also causes dependence on the incident angle of the input light. We introduce a wavelength dependence compensation technique by adjusting the incident angle of the input light according to the wavelength by offsetting the position of the lens [45]. This technique is realized by arranging zero offset for the longest wavelength $\lambda 3$ channel, and arranging a certain offset for the shortest wavelength $\lambda 0$ channel of the ROSA as shown in Fig. 13. Figure 14 shows the experimental results for the wavelength dependency of APD responsivity. In Fig. 14, ΔZ is the offset of the APD axis from the input light axis of the lens. There is some degradation of responsivity of the APD with wavelength in the case without offset compensation, but with offset compensation, responsivity variation between $\lambda 0$ and $\lambda 3$ seems to be relatively small. As a result, the wavelength dependency of the APD can be canceled, and this compensation technique realizes wide wavelength range and high responsivity at the same time.

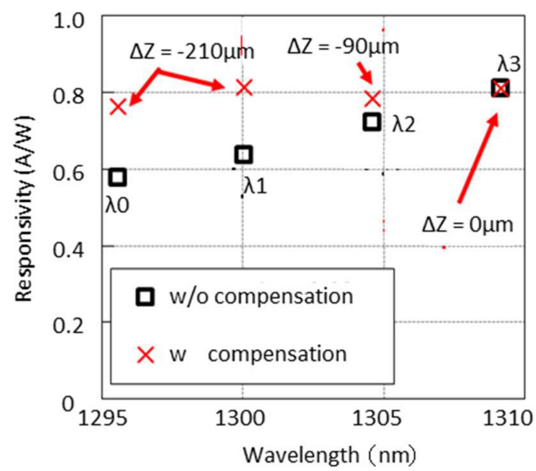


**Fig. 14** Experimental results for responsivity of the APD as a function of the wavelength with and without compensation.

### 4.3 High-Speed Electrical FPC Connection

This is the first time that flexible printed circuit board (FPC) has been seriously applied as an electrical I/F medium for 10 Gbps transmission. Previously, coaxial cables were generally used to transmit high speed signals [46]. However, coaxial cable is very expensive, and moreover it is not at all suitable as an electrical I/F medium for parallel transmission applications, because of the large space occupies.

Therefore, we have established a high-speed signal transmission technology using FPC. The most important issue is realizing low signal reflection at the connection between the FPC and the printed circuit board (PCB). Figure 15 shows the connection between the PCB and the FPC [47]. The FPC has a three-layer structure, the transmission line is the inner layer L2, and the connection with the PCB is in the outer layer L3. While the transmission line L2 is impedance matched by changing $W_S$ between the ground patterns in L2 alongside the transmission line, the connecting portion L3 and the PCB transmission line are also impedance matched. A reflection at the connection of

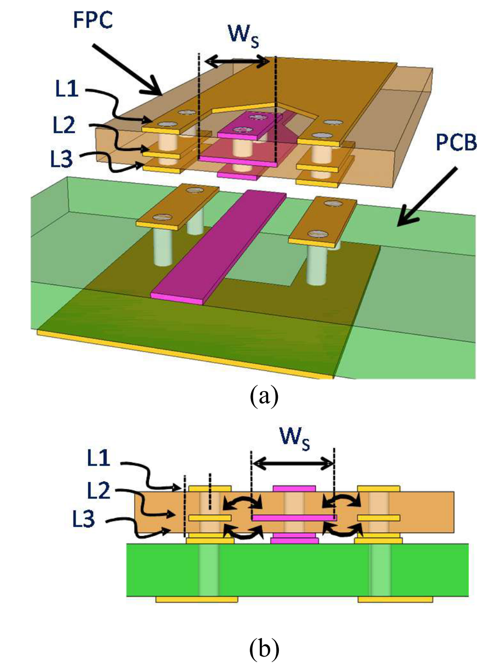


**Fig. 15** Schematic of PCB to FPC connection (a) perspective view and (b) cross-section.

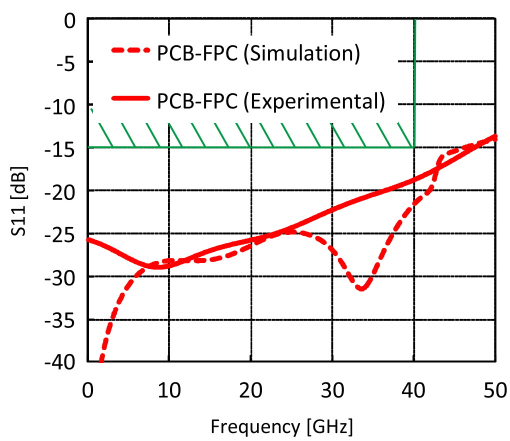


**Fig. 16** Simulation and experimental results of the reflection characteristics of the PCB to FPC connection.

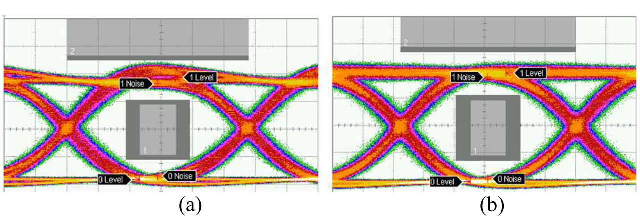


**Fig. 17** Eye pattern of EML TOSA using NRZ $2^{31} - 1$ PRBS electrical signal at 43Gbps (a) FPC and (b) coaxial connection.

−18 dB or less was obtained up to 40 GHz, and met the criterion of −15 dB as shown in Fig. 16, which is necessary not to affect the waveform of the transmitted signal. Finally, the optical signal waveform converted from the electrical signal was also able to achieve a quality equivalent to that through a coaxial connector as shown in Figs. 17 (a) and (b).

## 5. TOSA/ROSA for Beyond 400GbE

How will optical devices change in systems beyond 400GbE, such as 800GbE or more? Current optical device packages are broadly classified as Butterfly type, BOX type and TO-CAN [48], [49]. On the other hand, a surface mounting type like COBO is also being investigated.

Figure 18 shows the progression of package types for optical and electrical devices [50]. There are many similarities between optical device packages and electrical device packages. TO-CAN type transistors were mass-produced in the 1950s. After that, evolution was divided into two types of package. One is discrete packages and the other is specialized packages which are optimal for integrated circuits (IC). After the discrete package type became molded, it has become a surface mount type. This surface mount type package has been used widely. The IC package types have taken the forms of the dual inline package (DIP), the Quad Flat Package (QFP), the Pin Grid Array (PGA), the Ball Grid Array (BGA), and the Chip Scale Package (CSP) and now the System-In-Package (SIP) type has been regularly used. Optical devices have also used the TO-CAN product from the 1980s. The package types for optical devices have also changed according to the required electrical I/F port density. The subsequent generation of the TO-CAN package became the Butterfly type with lead pins on the side, and the BOX type appeared. The density of the I/F ports of the BOX type was improved by using FPC according to the required speed and integration. For the next generation, a BGA type in which the I/F ports are arranged two-dimensionally on the package bottom is reported [51]. The TOSA/ROSA package follows the same progression as the electronic device packages, which indicates that increasing the density of the electrical I/F ports is a common issue for both the optical and electronic devices.

Assuming that the same trend continues into the future, there are possibilities that the packages into which electrical devices such as drivers, TIAs and control circuit ICs, and optical devices such as EMLs, LDs, and optical MUX/DEMUX, are integrated as one package like SIP will come out as products in the beyond 400G era. In order to realize the integration of optical functions, integration technology such as silicon photonics will be indispensable. The competing axis is multi-level modulation, multiple wavelengths, low power consumption, miniaturization, etc.

TO-CAN packages with only simple functions that do not require integration into optical devices are thought to survive, just as discrete types continue to be used in electronic devices. For example, access applications such as Fiber To The Home (FTTH) require low cost, high output power and high sensitivity, but not extensive integration. Nevertheless, simple TO-CAN packaging may be required for enabling 100 Gbps transmission or seamless packaging in the future. It is more important for such applications to

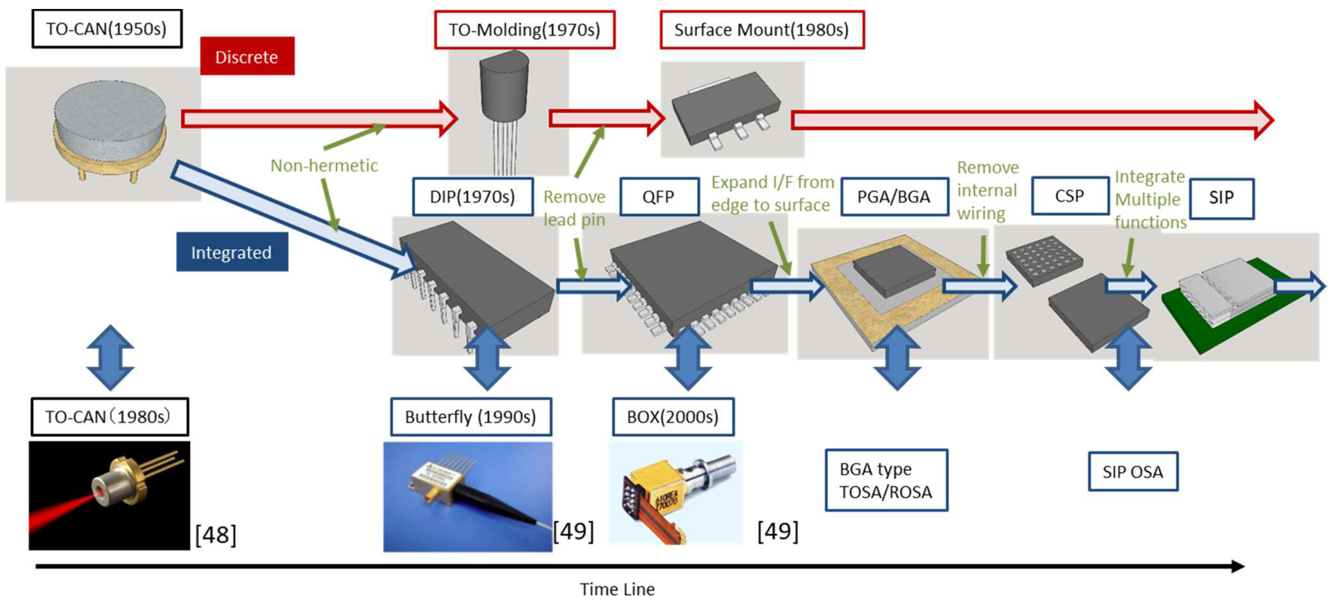


**Fig. 18** Progression of package types for electrical and optical devices.

realize low cost devices with only simple functions than small size and multiple functions with integration, and TO-CAN will remain in the market.

The integration of optical devices advances to BGA, CSP, and SIP, and we think that it is appropriate that packages evolve not only for the integration of optical components but also in the direction of fusing with electronic components. Integration is indispensable for applications requiring data rates of several Tbps, such as Computer-com, which is expected to come on stream in 10 to 20 years. In order to integrate a plurality of technologies such as multiple wavelengths, and multi-level and phase modulation, new integration technologies including silicon photonics are required. In terms of packaging, optical and electrical I/Fs are required to be multi-channel and multiplexed, and further evolution of the technology is required. The competing axis of optical devices will range across multi-level, multi-wavelength, low power consumption, miniaturization and so on, and various packages will appear depending on the application.

One of the major differences between optical and electrical devices is that an optical device package requires a hermetic seal. The transition from metal to molded structures without the package being hermetically sealed is indispensable for cost reduction. To realize molded optical devices, it is essential to ensure reliability of the optical chips under non-hermetic conditions. Another difference is tolerance of physical distortion. In the current optical device packages, if the package is distorted, the optical axis shifts from its original position and we lose all the optical performance. However, to achieve high-density packaging, it is essential to realize packaging that overcomes distortion. It is expected that it will be important to utilize planar optical systems such as silicon photonics. It is also important to utilize wavelength multiplexing due to its advantages for optical communication. It is currently indispensable to control the temperature of the optical devices by utilizing thermo-electric coolers (TEC), if precise wavelength control is needed. We may need to develop new technologies that make TECs unnecessary.

## 6. Conclusions

We discussed the trend of IEEE standardization for next-generation high-speed Ethernet, and the optical transceiver form factors which have been discussed concurrently with this standardization. We introduced TOSA/ROSA optical device packaging technologies for realizing 100GbE, and, further, 400GbE, which is currently being discussed, and examined future trends. Although the standardization of first generation 400GbE has been completed at the IEEE, subsequent discussion aiming at lower cost is being pursued. However it is possible to achieve this by applying the packaging technology developed at 100GbE. Precise lens-assembly techniques, wavelength dependency compensation for high responsivity resonant cavity APDs, and high-speed electrical FPC connections are described as technologies that can support 400GbE. We consider the optical devices of the future by focusing on the similarities between electrical and optical packages and it seems that they can be largely divided into two directions depending on the required functions. One is for applications that do not require integration, such as access systems, and the low cost TO-CAN package and its derivative packages are likely to survive into the future for this. The other is for applications requiring integration such as WDM for client services, computer-com, data centers, etc. We also need efforts to utilize technology for further integration, such as silicon photonics etc.

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