Optical Transceiver Modules for Gigabit Ethernet PON FTTH System

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ABSTRACT The Gigabit Ethernet Passive Optical Network (GE-PON) Fiber To The Home (FTTH) system is expected to be the standard optical communication access system in the next generation. In Japan, full-scale introduction of FTTH services will begin in 2005. We have developed bi-directional transceiver modules for an optical network unit (ONU) and optical line terminal (OLT) that are compliant with the IEEE802.3ah standard for GE-PON using optical sub-assembly (OSA) which has a unique passive alignment structure.

1. INTRODUCTION

FTTH systems are expected to be the key infrastructure for broadband access systems in the future. Japan began the introduction of FTTH systems in 2003, and according to the Ministry of Internal Affairs and Communications, there were over 2 million subscribers by July 2004. From 2005, the major carriers begin introduction of a new system based on the IEEE802.3ah 1000BASE-PX standard for Gigabit Ethernet PON (GE-PON). We have developed single-fiber bi-directional optical transceiver modules, which are necessary both for optical network unit (ONU) installed at the subscriber's premises and for the optical line terminal (OLT) at the central office. We have also developed a new optical sub-assembly (OSA), which is the key device for the transceivers. The compact high-accuracy plastic package encloses the optical fiber and the active optical components in a passive-aligned configuration. In addition, a micro-miniature WDM filter formed directly on the end facet of the optical fiber is used, assuring miniaturized, low-cost conversion. In this paper we describe these optical transceivers.

2. OVERVIEW OF GE-PON FTTH SYSTEM

This standard was adopted as the 802.3ah 1000BASE-PX standard for Ethernet by the IEEE in June 2004. The demand specification of the physical layer is specified as PX10 for the 10-km version of transmission distance, and PX20 for the 20-km version.

The architecture of GE-PON is shown in Figure 1. The difference from the current 100-Mbps FTTH system using media converters which use one fiber for each subscriber is that it uses 1310 nm and 1490 nm for the upstream and downstream wavelengths, respectively, and provides a maximum of 1.25-Gbps single fiber bidirectional commu-

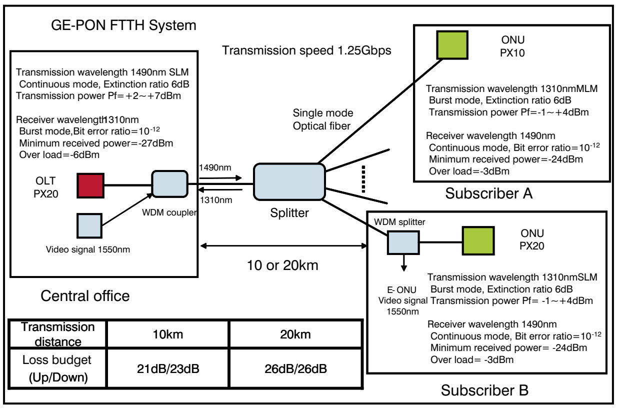

Figure 1 GE-PON FTTH system architecture.

nication paths on the passive double star (PDS) transmission line with 16 branches. There is an economical advantage in sharing the optical fiber between OLT in a center office and the branching point (splitter) by two or more subscribers. Moreover, although not prescribed by the IEEE802.3ah standard, down-linking the video signal which is based on the ITU-T983.3 standard is also taken into consideration, whereby, using the 1550-nm wavelength band, video delivery through the fiber is carried out (3 wave multiplex).

In a GE-PON system, the OLT performs time sharing (TDM) communication between subscribers ONUs through two or more optical fibers of different distances. Therefore, in order for the OLT to receive the up-link signal without a collision with different power levels from each ONU, the receiver of the OLT must be able to follow each power level instantaneously and to communicate in order (burst mode communication). The down stream direction is continuous mode, as in conventional communication systems.

The loss budget for GE-PON systems has the specification of a 10-km and a 20-km version according to IEEE802.3ah standard, in which the fiber loss differs

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accordingly. In an actual system, the practical course is to use the 20-km specification for the OLT and to choose either the 10-km or the 20-km version for the ONU according to the circumstances.

3. DESIGN OF OPTICAL TRANSCEIVER MODULES

3.1 Transceiver Module for ONU

Figure 2 is a block diagram of the transceiver module developed for the 10-km version ONU, and Figure 3 is a photograph. Since the transceiver module for the ONU was incorporated in the ONU apparatus installed in the subscriber's premises, it was designed in conformity with the small form factor (SFF) standard. The SC type receptacle was adopted as the optical connector.

The transceiver module for the ONU consists of a case, an SC connector receptacle and a printed circuit board, forming an optical sub-assembly (OSA) and driver circuit. The OSA is the passive alignment assembly structure in a plastic package, and contains a band pass filter, photo detector (PD), an electric signal amplifier IC and a fiber with WDM filter on the receiver side, and a Fabry-Perot laser diode and monitor PD on the transmission side. The OSA is described more fully in Section 4 below. Using a custom-designed IC which integrates trans-impedance preamplifier and a limiting amplifier, the characteristic of this device realizes 2R functions by the OSA alone, and achieves reduced component count and lower power consumption.

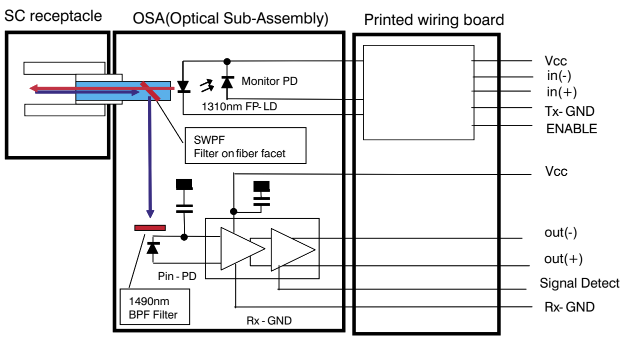

Figure 2 Block diagram of transceiver module for ONU.

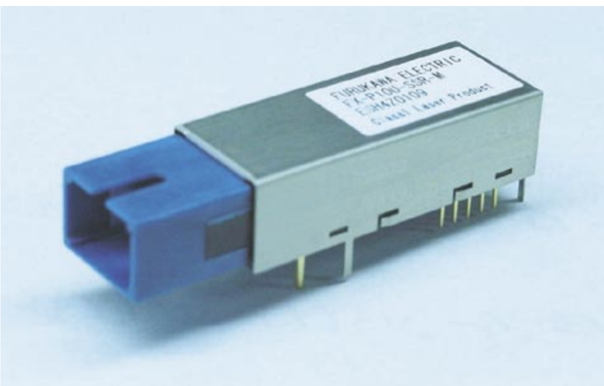

Figure 3 Photo of SFF transceiver module for ONU.

3.2 Transceiver Module for OLT

Figure 4 is a block diagram of the transceiver module for the 20-km version OLT and Figure 5 is a photograph.

Based on a need for installing high-density boards inside the transmission equipment rack the height of the transceiver module for the OLT had to be 8.5 mm or less, conforming to the transceiver size for the standard full-service access network ATM-PON. The SC type receptacle was adopted as the optical connector.

In GE-PON, the optical output power of the OLT needs a distributed feedback (DFB) laser having a 1490-nm single longitudinal mode wavelength of high output power. For this reason, in the OSA a can package was adopted for the transmitting laser and a high coupling efficiency design was adopted using an aspheric lens. The receiver side had the same structure as the OSA for ONU, having a fiber with WDM filter, receiving PD, and receiving amplifier with a passive alignment assembly in a plastic package. The receiving amplifier for the OLT is also a custom-designed IC corresponding to the 2R functional burst receiver which integrates a trans-impedance preamplifier and limiting amplifier.

4. STRUCTURE AND CHARACTERISTICS OF OSA

4.1 Structure of OSA for ONU

The performance and cost of a bi-directional transceiver module depend on the OSA.

It is especially important for the OSA for the ONU that it is small and low in power consumption. In our development of this transceiver module, a number of new tech-

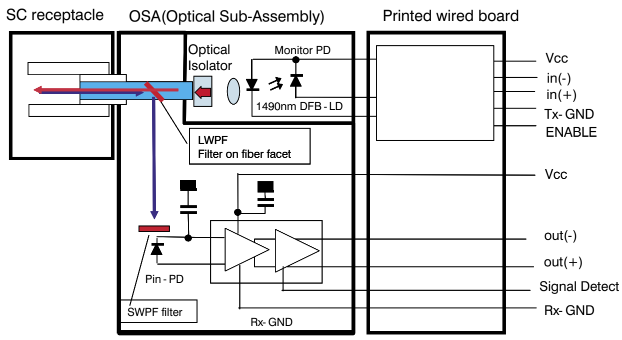

Figure 4 Block diagram of transceiver module for OLT.

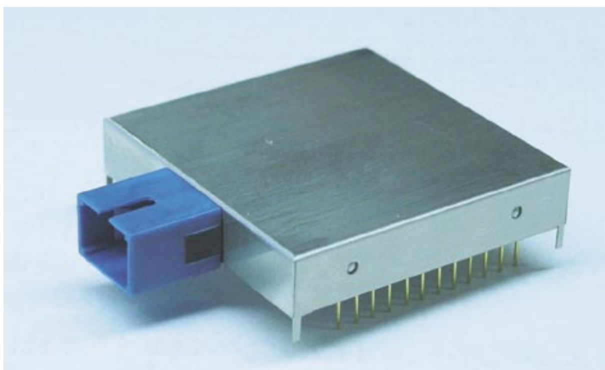

Figure 5 Photo of transceiver module for OLT.

nologies were developed for the purpose of simplifying the process of OSA assembly, reducing the component count, and improving integration density. These are:

1) Passive alignment assembly package equipped with omega grooves for fiber fixation and molded projections by high-precision plastic molding technology [1)~3)].
2) Dielectric multilayer film WDM filter vapor deposition technology on a fiber facet polished at 30° [3)].
3) Spot size conversion using quartz waveguide (SSC-PLC) for passive alignment assemblies with V-grooves [4)].

Figure 6 shows a cross-sectional view of the OSA for the ONU.

The OSA consists of a fiber with WDM filter, a lead-frame package, and a plastic package containing a ceramic ferrule. The lead-frame package contains a receiver PD and electric amplifier mounted on a silicon substrate on the receiver side, an FP-LD mounted on a silicon substrate on the transmission side, a monitor PD, and pre-molded electric terminals.

Figure 7 is a photograph of the OSA for the ONU. It measures 13.0 mm in length (without leads), 5.0 mm in height and 6.2 mm in width. Details of the main parts are described below.

4.2 Precision Molded Plastic Package

The high-precision plastic package was developed with the molding technology for the MT connector, which is a highly precise plastic ferrule, to perform relative positioning of the fiber and optical element by passive alignment. Figure 8 is sectional views of the receiving (Rx) part of the OSA, the SSC-PLC part, and the transmitting (Tx) part.

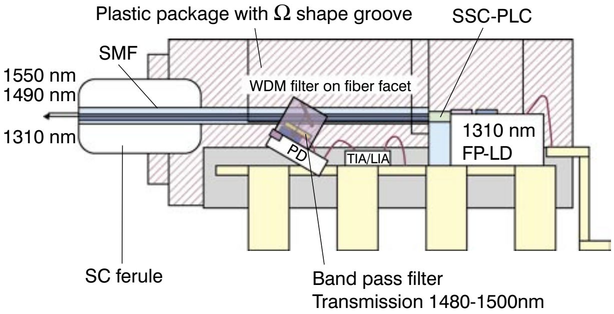

Figure 6 Structure of OSA for ONU transceiver.

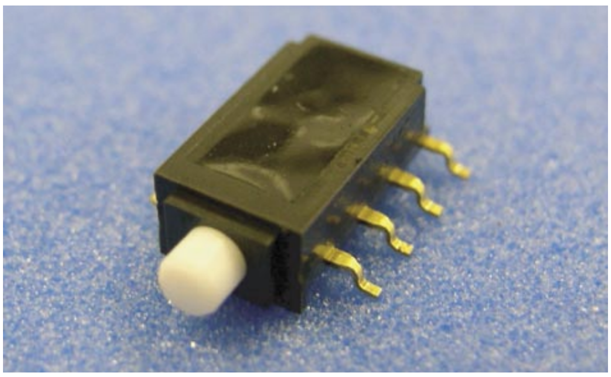

Figure 7 Photo of OSA for ONU transceiver.

This plastic molding has three features. 1) A hole that positions the fiber on the plastic package; 2) Projections for aligning with V-grooves in the silicon substrate on which the optical element is mounted; 3) Carry out incidence of the downstream light signal that is reflected by the WDM filter on the facet of a polished fiber to the PD through the side of the fiber, by having prepared an opening in the side of the fiber positioning hole in the package.

This fiber fixing groove, called an omega groove because of its cross-section shaped like an Ω, has the feature that the inserted fiber cannot come loose, unlike with the conventional V-groove. We used a pin-PD with an input window 80 μm in diameter to reduce coupling loss, and a receiving sensitivity of more than 1.0 A/W was obtained. Positioning of the transmission side light axis is done automatically in such a way that the two V-grooves provided on the silicon substrate (SiOB: Silicon optical bench) on which the optical element was installed and on the SSC-PLC mentioned below engage with the shaped projections on the plastic molding. In order to realize low loss coupling of a single mode fiber with the LD, the relative position accuracy of the plastic projections and the fiber hole is managed to ±0.5 μm, and the light axis of the single mode fiber, SSC-PLC and LD assembles are settled in ±1 μm. The photographs, alignment state of the projection of the plastic package with the V-groove on the silicon substrate, and the cross-section of the omega groove are shown in Figure 9.

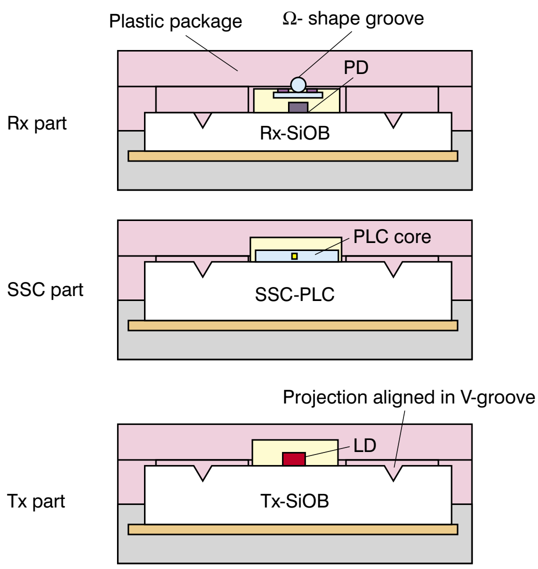

Figure 8 Cross-sections of OSA.

Figure 9 Cross-sections of V-groove alignment on silicon substrate (left) and omega groove of plastic mold (right).

4.3 WDM Filter on the Fiber Facet

In order to separate the upstream and downstream signals in a GE-PON system, wavelength separation with a WDM filter is required. The conventional WDM filter is deposited onto a glass substrate etc., cut into chips several millimeters square, and mounted in the OSA. We have developed a new technology whereby a WDM filter is deposited on the facet of a polished fiber with 30° angle directly in order to minimize filter size. Insertion fixation is then carried out, the fiber with its filter is seated into the omega groove of the above-mentioned plastic package, and the signal light is coupled with the PD by filter reflection. Thus the WDM filter circuit, which accounts for the major portion of the OSA cost, was realized simply by the fiber assembly process within a package. Fiber coupling with the LD has been done within the omega groove in the plastic molding by butt coupling a fiber polished at 30°. Figure 10 is a photograph of the filter formed of the fiber facet. Figure 11 shows the transmission spectrum wavelength characteristic of the WDM filter. It gets 20 dB as the transmission loss difference between the maximum wavelength of 1360 nm in the upstream band and the minimum wavelength of 1480 nm in the downstream band. Furthermore, in order to set both the crosstalk within the module of the wavelength of 1310 nm of LD for transmission and the isolation between the transmission light and the downstream video signal of 1550 nm to 40 dB or more, a band pass filter with a pass band from 1480 nm to 1500 nm is inserted in front of the PD in addition to the fiber end filter. In order to fully acquire the characteristic of a band pass filter, the PD was mounted with an angle of 30°, and it is so devised that the reflected light impinges almost at right angles to the PD.

Figure 10 WDM filter vapor-deposited on the facet of angle-polished fiber.

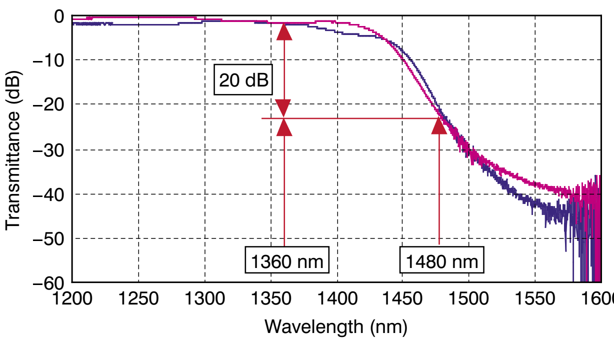

Figure 11 Characteristic of the short wavelength pass filter (SWPF) on a 30 °polished fiber facet.

4.4 SSC-PLC

As compared with earlier optical fiber communications systems, GE-PON system requires a higher power signal light because of PDS system of 16 light branches by the splitter. The optical output demand specification for the ONU is from −1 to +4 dBm. On the other hand, in the passive alignment assembly structure used to meet the need for lower cost, although it is joined together by coupling a fiber and LD directly without lens, the coupling loss due to the difference of the mode field diameter of the fiber and the LD was about 10 dB, and it is difficult to obtain high coupling efficiency beyond that level. Furthermore, by the single fiber bi-directional module, since the insertion loss of the WDM filter is also added, for obtaining a desired optical output, it is indispensable to reduce the coupling loss between the LD and the fiber.

In order to meet the conflicting demands of low cost and high output power, we have achieved a coupling loss improvement as well as passive alignment within a high-precision plastic package, by inserting between the LD and the fiber an SSC-PLC that effects beam spot size conversion. The optical coupling structure using an SSC-PLC is shown in Figure 12. The SSC-PLC is a minute optical waveguide with a length of 500 µm, which has a taper part with a length of 300 µm, and connection loss is reduced by changing the spot size of LD light into that of the fiber. Figure 13 shows the results of calculations of coupling loss vs. waveguide width for each coupling of the SSC-PLC with the LD and with the single-mode fiber. The refractive-index difference of the waveguide core and clad is 0.8 %. It is expected as a result of calculation that by making the LD side and the fiber side of the waveguide 4.5 µm and 10 µm in width, respectively, it would be possible to set the coupling loss between the LD and a single-mode fiber to a minimum of 4 dB.

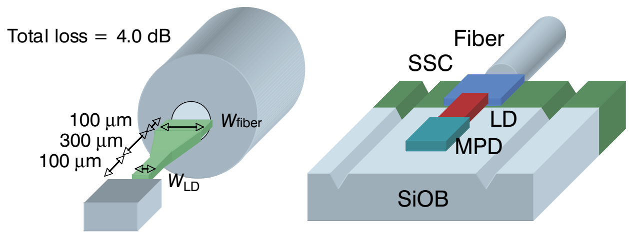

Figure 12 Structure of SSP-PLC.

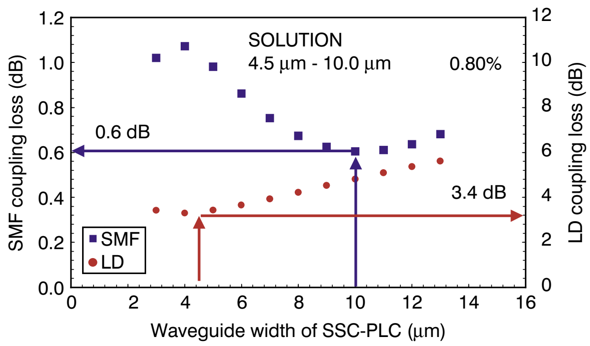

Figure 13 Calculated result of coupling loss between fiber and LD and SSC-PLC.

The optical output-current characteristic of the OSA for the ONU without a fiber filter obtained experimentally to verify the effect of SSC-PLC is shown in Figure 14. The coupling loss with the single-mode fiber and the 1310-nm FP-LD through the SSC-PLC was estimated as 4.4 dB showing good agreement with the design. As for the fiber output P_f at 85°C, more than +3 dBm was obtained.

4.5 Characteristics of OSA for ONU

Figure 15 shows the optical output-current characteristic of the OSA for the ONU using SSC-PLC, and a histogram of the total coupling loss. As a result of adding WDM filter loss, mounting variation, and drop in emitting efficiency of LD caused by the generation of heat due to the built-in amplifier IC etc., the total loss was approximately 8 dB±1 dB. The optical coupling efficiency within the same assembly lot shows normal distribution, so that reproducibility of assembly is obtained.

On the other hand, as for the receiving sensitivity of the OSA for the ONU for the 1490-nm wavelength, more than 1.0 A/W was obtained. As for the overload, +3 dBm was obtained.

4.6 Structure and Characteristics of OSA for OLT

For the OSA for the OLT of a GE-PON system it is indispensable for reasons of the specification to use a DFB-LD having a 1490-nm wavelength. Particularly in the 20-km version an optical output of from ±2 to ±7 dBm is called for. Figure 16 shows the OSA for the OLT developed here. It is of hybrid construction with a metal can packaged DFB laser having an aspheric surface lens and a plastic package OSA containing a PIN-TIA/LIA with a built-in WDM filter (LWPF) that is the same as for the receiver side

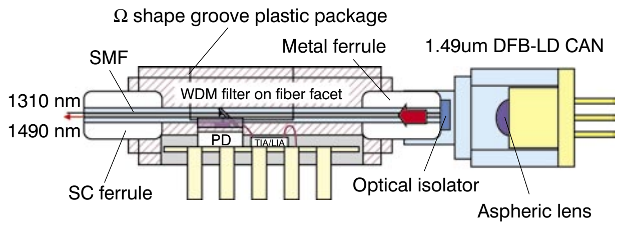

Figure 16 Schematic diagram of OSA for OLT transceiver.

of the OSA for the ONU. In order to perform alignment and laser welding fixation, the metal ferrule was insertion-molded to a high-precision plastic mold package. To reduce the influence of the reflected return light, an optical isolator was mounted on the facet of the metal ferrule. Figure 17 is a photograph of the OSA for the OLT. Its size is 24 mm in length (without leads), a maximum of 5.6 mm in height, and 6.2 mm in width.

Figure 18 shows the temperature dependence of the optical output vs. current characteristic of the OSA for the OLT. The optical output was more than 5 mW (+7 dBm), which satisfies the upper limit of the target specification for 85°C. The total insertion loss of the DFB-LD assuming a maximum filter transmission loss of 1 dB was 3 dB. As for the receiving sensitivity at 1310-nm wavelength, 1.0 A/W or more was obtained.

5. TRANSCEIVER CHARACTERISTICS

5.1 Transceiver for ONU

The result of evaluating the burst mode transmitter characteristic required for an ONU transceiver is shown in Figure 19. Burst transmission was carried out in the wave-

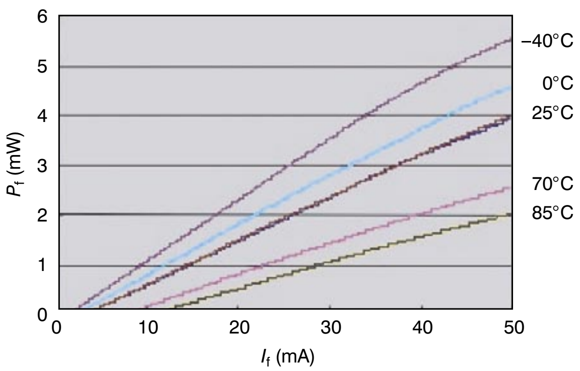

Figure 14 L-I characteristics of ONU OSA without WDM filter.

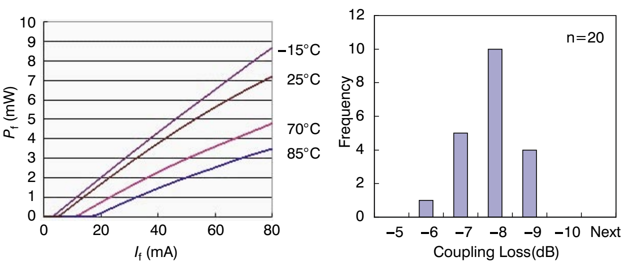

Figure 15 L-I characteristics and histogram of coupling loss of ONU OSA.

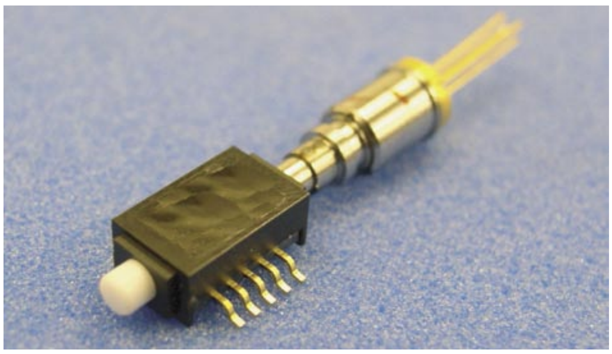

Figure 17 OSA for OLT transceiver.

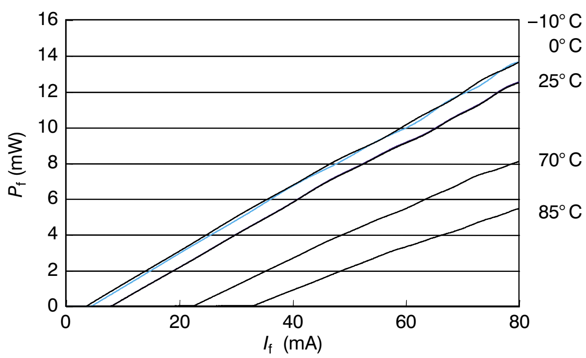

Figure 18 Temperature dependence of L-I characteristics of OSA for OLT transceiver.

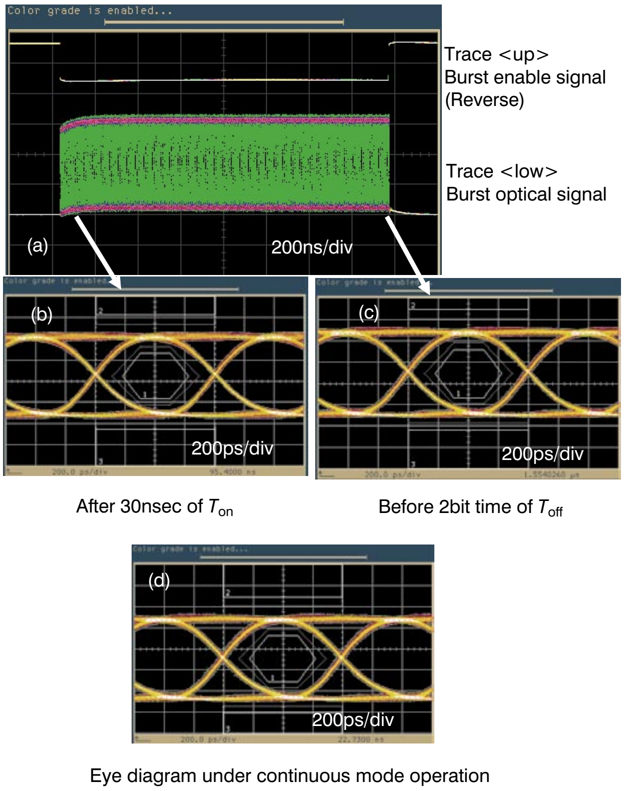

Figure 19 Eye diagram of ONU transceiver in burst mode operation.

form shown in (a) in the figure, and measurement of the rise time and fall time and the transmitting eye at the time of burst transmission was obtained.

Both T_{on} and T_{off} times were several nanoseconds. The eye patterns under the burst transmission mode shown in (b) and (c) in the figure are equivalent to the eye pattern shown in (d) measured in continuous light emitting mode, and in all cases sufficient margin was obtained for the IEEE802.3ah standard.

The receiving characteristic of the transceiver for the ONU is shown in Figure 20. The minimum received power of −29.0 dBm was obtained at a bit error rate of 10^{-12} in simultaneous transmission/reception operation. A 5-dB margin was obtained with respect to the target minimum

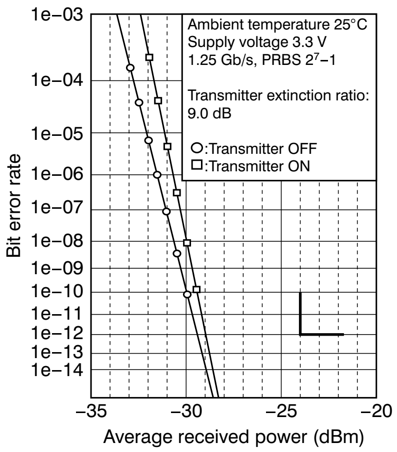

Figure 20 Bit error rate of ONU transceiver.

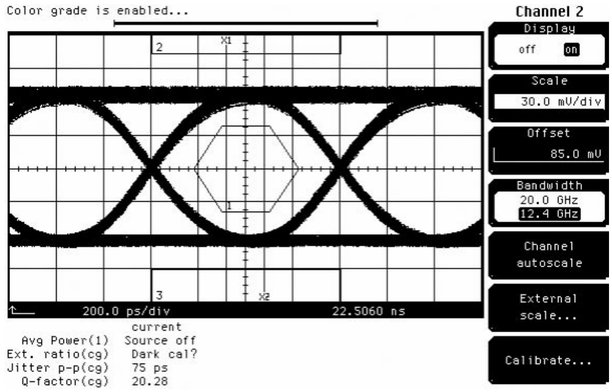

Figure 21 Eye diagram of OLT transceiver.

receiving sensitivity specification of −24 dBm. In addition, sensitivity degradation by crosstalk in simultaneous transmission/reception operation (Tx on) was 0.5 dB.

5.2 Transceiver for OLT

The eye pattern of the transceiver for the OLT under continuous mode operation is shown in Figure 21. A good eye pattern was obtained at 1.25 Gbps.

The burst receiving characteristic of the transceiver for the OLT was measured connecting two ONUs to an OLT transceiver under the input conditions shown in Figure 22. It was measured under the severest conditions for burst received signals, i.e., inputting an optical signal overload as a dummy signal, inputting an optical signal of the minimum receiving sensitivity into the measurement signal, and setting the burst interval to 0 ns. The settling time of the receiver was about 300 ns, and it was confirmed that there was sufficient margin with respect to the 400 ns of the IEEE802.3ah standard.

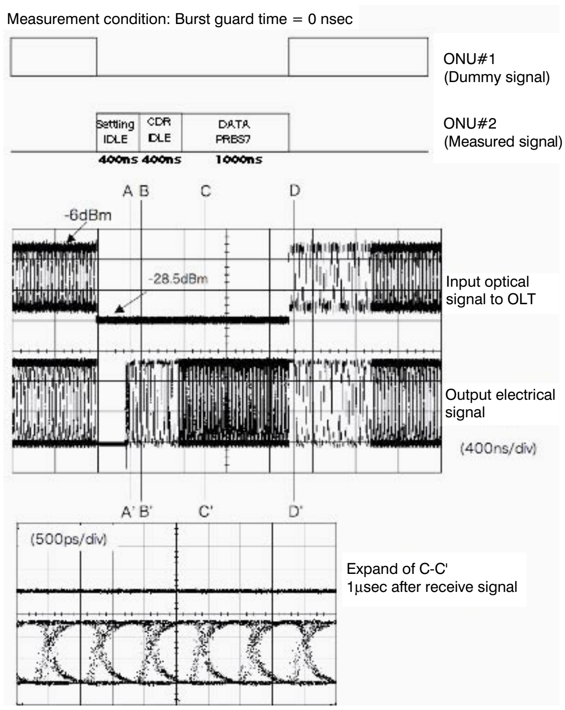

Figure 22 Burst mode receiver characteristics of OLT transceiver.

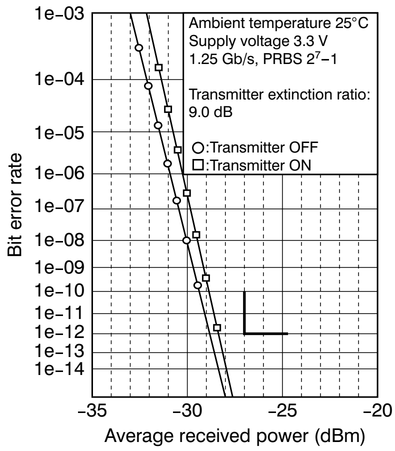

Figure 23 Bit error rate of OLT transceiver.

Figure 23 is the bit error rate of the transceiver for the OLT. The minimum receiving sensitivity at a bit error rate of 10^{-12} in simultaneous transmission/reception operation was −28.5 dBm, and a 1.5-dB margin was obtained with respect to the target minimum receiving sensitivity specification of −27 dBm.

Sensitivity degradation by crosstalk in simultaneous transmitting/receiving operation (Tx on) was 0.5 dB.

6. CONCLUSIONS

We have developed bi-directional transceiver modules for GE-PON FTTH systems.

The OSA developed here was able to achieve miniaturization of the transceiver module, and simultaneously reduce the cost by means of a passive alignment structure. The completed transceiver module fully satisfies the IEEE802.3ah standard, and application to ONU and OLT apparatus can be expected.

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