Optical Coupling between Optical Devices and Opto-Electronic Printed Wiring Boards

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ABSTRACT Recently, several interconnection technologies such as optical interconnection, three-dimensional integration of semiconductor chips and wireless interconnection are under study, in order to solve the so-called pin bottleneck problem that causes inadequate inter-chip transmission capacity thus limiting the computer processing speed. We have been paying attention, among these, to the optical interconnection technology based on optical wiring, and are working on the structures of optical interconnector that enable efficient connection between, and mounting of, optical devices and optical waveguides. To be more precise, the structure consists of an optical interconnector made of ultraviolet ray curable resins having different refractive indexes, being mounted on the connecting part between optical devices and waveguides. In this work, the optical interconnector was formed on a VCSEL mounted on an FR-4 substrate, and its optical characteristics were studied. As a result, it has been confirmed that this optical interconnector is provided with an optical confinement capability, and enables high-efficiency, large positional tolerance connection between optical devices and waveguides.

1. INTRODUCTION

In recent years, as digital home appliances become widespread and computerization accelerates, data volume handled continues to grow thereby increasing the transmission bandwidth of network equipment such as servers and routers. This trend creates a need for performance improvement of data processing systems. However, although the integration degree and processing ability of LSI chips themselves improves year by year in accordance with the ITRS (International Technology Roadmap for Semiconductors) roadmap, the pin bottleneck problem arises causing an inadequate inter-chip transmission capacity and at the same time limiting computer processing speed. In order to solve this problem, several interconnection technologies including wireless interconnection as well as optical interconnection and three-dimensional integration of semiconductor chips are under study. We have been paying attention, among these, to the optical interconnection technology based on optical wiring, and are working on structures that enable efficient connection between, and mounting of, optical devices and optical waveguides. To be more precise, the structure consists of an optical interconnector made of ultraviolet ray curable resins (UV resin) having different refractive indexes, being mounted on the connecting part between optical devices and waveguides. In this work, the optical interconnector was formed on a VCSEL (Vertical Cavity Surface Emitting Laser) mounted on an FR-4 substrate, and its optical characteristics were studied. In this paper, the effectiveness confirmed of this optical interconnector will be presented.

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2. OPTICAL INTERCONNECTION TECHNOLOGY

2.1 Construction of Optical Interconnections

Current data processing systems are basically structured by electrical interconnections between electrical components centered on LSI chips. Accordingly, to solve the pin bottleneck problem by using optical interconnection, it is essential that optical wiring be as easy and simple to achieve interconnection as electrical wiring, allowing us to perform "optics-unconscious" interconnection. Figure 1 shows the schematics of interconnections that have been implemented so far.

In transmission equipment, interconnections between electronic components and equipment have a hierarchical structure such as, for example, "chip∼package∼module∼board/card∼backplane∼rack∼cabinet." Among these, in these days, optical fibers are used for interconnection between equipment such as the rack~cabinet part, and the use of optical fibers and waveguides is expanding in the backplanes connecting the board/card part [1].

On the other hand, in the interconnection between electrical components centered on LSI chips, although the study on the use of optical fibers for the board/card part between the module and backplane has recently been launched aimed at its realization in near future, the interconnection still relies on electrical means. Even now, interconnection techniques for the chip~package~module part remain yet in the research phase.

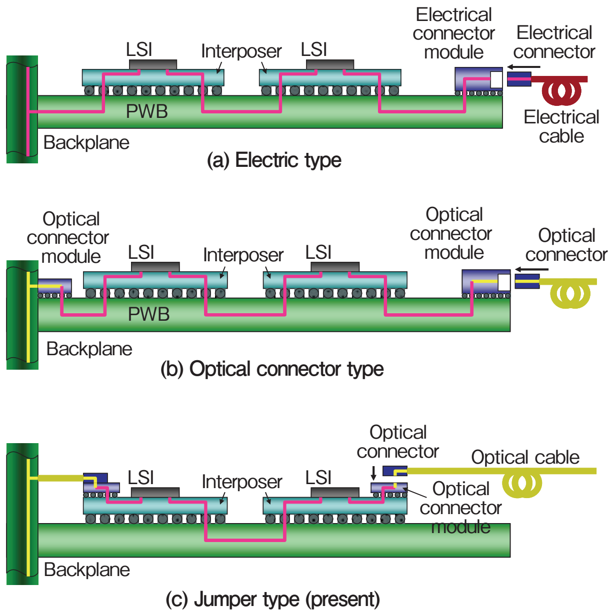


Figure 1 Schematic view of interconnection (I)

2.2 Opto-Electronic Printed Wiring Board

Study on the use of optical means for the chip~package~module part has lead to two possible candidates as shown in Figure 2 (a) and (b): the extension of the jumper type and the opto-electronic printed wiring board (OE-PWB) type, in which optical waveguides are incorporated in the substrate.

In the case of the extension of jumper type shown in Figure 2 (a), it is advantageous from the standpoint of technology development in that, it is an extension of the conventional technology that uses fiber and connector. But it can be disadvantageous from the standpoint of users involved in design and assembly in that, this technology means coexistence of numerous fibers and optical waveguides in a limited space on the substrate, raising possible problems of handling and heat dissipation.

On the other hand, in the case of the OE-PWB type shown in Figure 2 (b), in which optical modules as well as optical devices and packages are mounted for optical connection on a substrate with built-in optical waveguides, it is advantageous from the standpoint of users in that, since the handling and heat dissipation issues are similar to those in conventional electrical wiring boards, it enables optical interconnection that is as easy and convenient as electrical wiring, without being conscious of optical wiring. It is thus said that this technology will be introduced in future, if its reliability problems are solved.

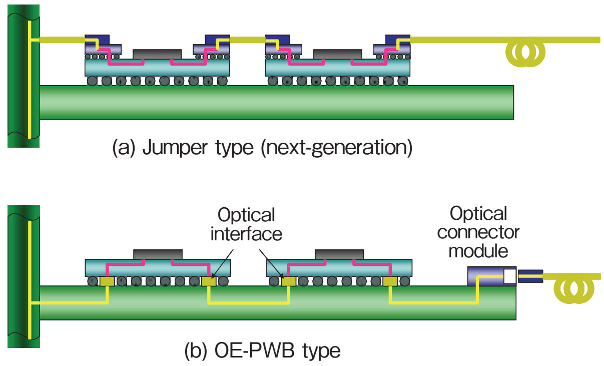


Figure 2 Schematic view of interconnection (II)

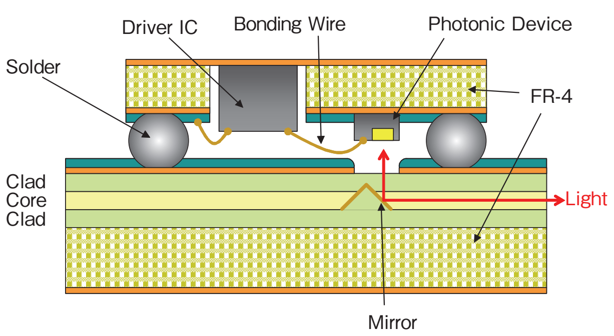
However, more detailed study on this OE-PWB technology has shown that this technology actually involves, beside the reliability problem, several problems such that the optical devices and optical waveguides must be, due to their optical characteristics, optically connected with high efficiency, that the mounting apparatus must have a large tolerance in mounting precision, and that sealing must be performed, to cope with the use environment, assuredly after mounting. In other words, the optical connection can not be achieved by simply surface mounting optical devices on an OE-PWB, but it is not until these problems are solved that this technology becomes as easy as electrical wiring. Thus, probably due to the developmental tasks mentioned above, not much study has been conducted in fact on the mounting structures of optical devices on the OE-PWB.

Accordingly, to achieve high coupling efficiency and large positional tolerance, we have proposed an optical structure, in which two UV resins with different refractive indexes and photomasks are used to form, on the optical devices and the optical port of an OE-PWB, an optical interconnector having a light-guiding function. In this work, the optical interconnector was fabricated by photomask pattern transfer on optical devices in an optical module, which comprises the optical devices mounted on an FR-4 substrate. The optical characteristics of the fabricated optical interconnector were measured, and the effectiveness of this optical interconnector structure was confirmed.

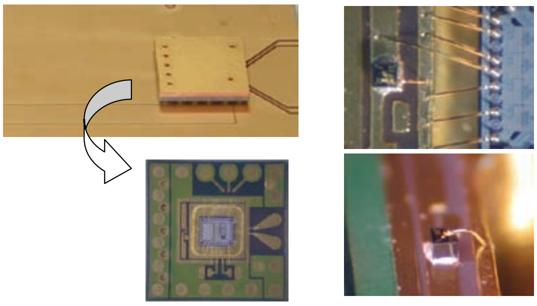
3. OPTICAL INTERCONNECTOR

3.1 Mounting Structure of Optical Devices on OE-PWB

Figure 3 shows a simple model of optical interconnector studied here, together with the photos of a prototype. The structure consists of an optical module accommodating optical devices and its driver IC, which is mounted on an



(a) Model



(b) Photos of prototype

Figure 3 Simple mounting structure of optical module on OE-PWB.

OE-PWB. Since optical devices generally have electrodes formed on the light-emitting and -receiving surface, wire bonding is needed for their mounting on the module. The loop of wire bonding has to be several tens to one hundred microns in height at least, and accordingly, the distance from the light-emitting and -receiving surface to the optical port on the OE-PWB becomes considerably large. In cases where a driver IC thicker than optical devices is used, the distance may become larger even a cavity structure is adopted for the module. In addition, since electrical circuits for module mounting are needed on the OE-PWB, circuit patterns with minimized functions become necessary on the optical waveguide, together with a resist layer to protect the surface circuitry. After mounting, need arises for some sealing to protect the bonding wires and optical devices, giving rise to the necessity for further increase in the device-to-OE-PWB clearance. In total, therefore, the distance from the light-emitting and -receiving surface of the optical device to the mirror surface of optical waveguide, as shown in Figure 3, would be several hundreds microns, and this is expected to result in a significantly large coupling loss.

Accordingly, as shown in Figure 4, an optical interconnector with a light-guiding function was formed on the optical port of the OE-PWB. The optical interconnector allows for confining the diffusive light beam within the coupler, thereby achieving beam injection into the optical device or optical waveguide with high efficiency and large positional tolerances.

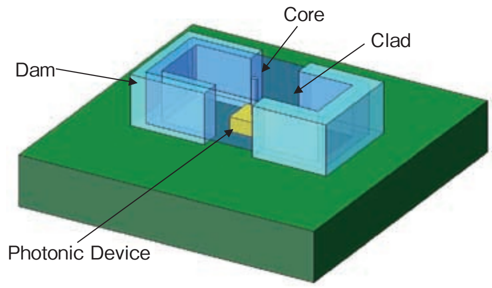


Figure 4 Optical interconnector.

3.2 Manufacturing Method

Below will be described in detail the method of forming the optical interconnector proposed here, onto the module substrate on which optical devices are mounted. Figure 5 illustrates the process steps. For this process, both the photomask and the UV resin were prepared in two types, for the core and the clad.

3.3 External View and Configuration

Figure 6 (a) and (b) show photos of the prototype, after the core and dam were fabricated. Acrylic UV resins having refractive index of 1.569 and 1.542 were used for the core and dam material and for the cladding material, respectively. The core diameter is 30 μm. Figure 6 (c) is a photo of the optical interconnector proposed here, with its clad being filled. The size of the clad is 1000 μm x 4000 μm x 500 μm (height). From Figure 6 (c), it can be confirmed that the VCSEL and the bonding wires are successfully embedded in the clad, together with the core, which is accurately located at the light-emitting spot. Since this prototyping was intended for confirmation of the effectiveness of the optical interconnector, measurements were made only for evaluation of optical power, without using a driver IC. For this reason, a special module substrate provided with a wiring pattern for power supply only was used in the prototyping.

4. OPTICAL CHARACTERISTICS

4.1 Measuring System

Figure 7 shows the measuring system used for evaluation of optical characteristics. A laser driver is used to power supply the module substrate provided with VCSEL and optical interconnector, to directly activate the VCSEL; and the emitted light passing through the optical interconnector is observed for its optical intensity distribution using near field pattern (NFP) measuring equipment; then the equipment is replaced with an optical power meter combined with graded-index multi-mode fiber (GI-MMF) to measure the *I-L* characteristics and the positional tolerance in optical coupling.

4.2 Optical Characteristics

The measurement results of the NFP and optical intensity distribution are shown in Figure 8, in which the NFPs in the cases of core only and clad filled are shown in (a), and the optical intensity distribution on the X axis of the

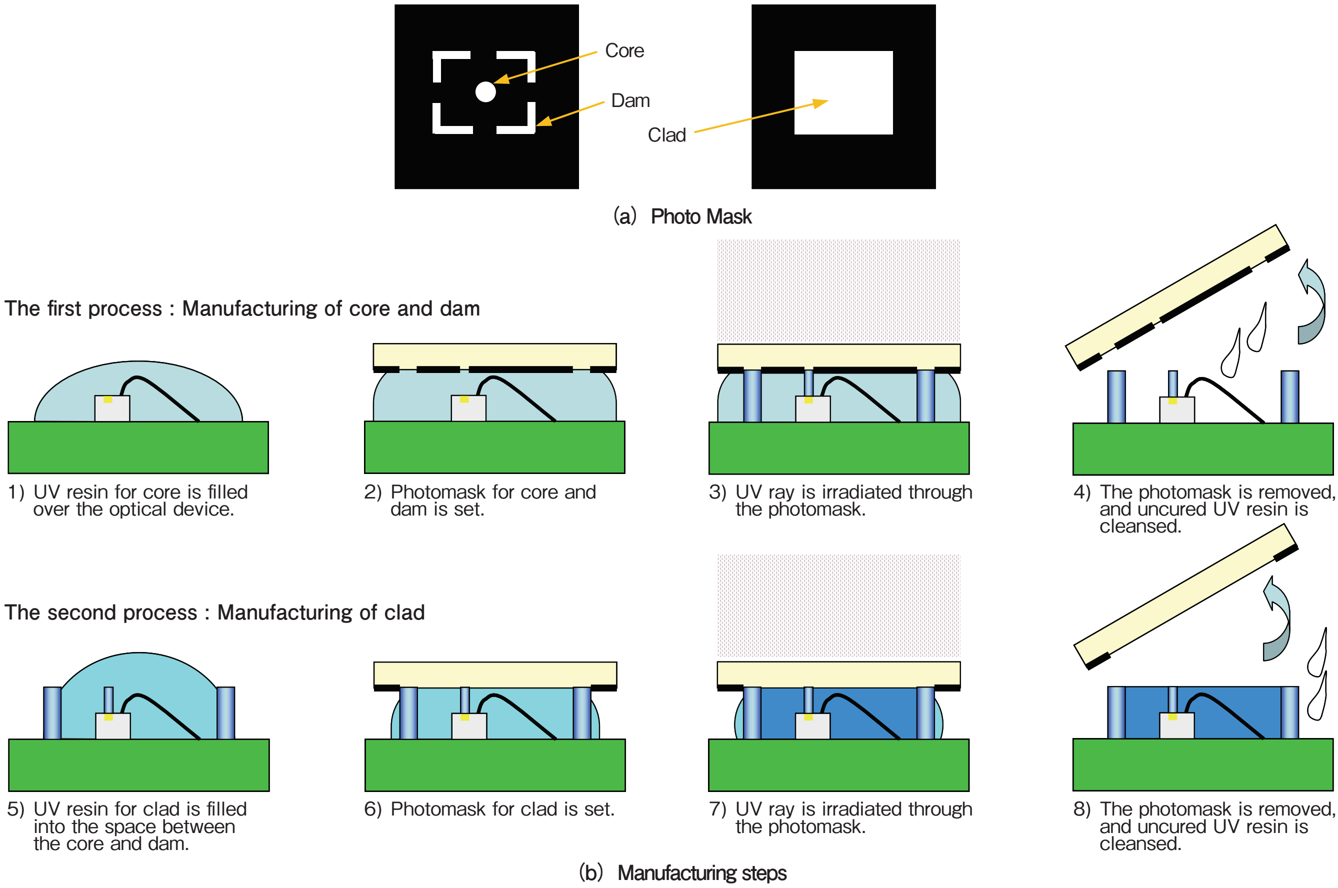


Figure 5 Manufacturing method of optical interconnector.

NFPs shown in (a) is presented in (b). It can be seen that in the case where the clad is filled, although a slight leak of light from the core to the clad can be observed, a strong intensity of light is propagated through the core. In the both cases, since the optical output has an intensity peak within the core diameter of 30 μm, it is considered that the light beam propagates being confined in the core. The leak from the core has been confirmed to be very weak.

The fact that the optical intensity, for the cases of core only and clad filled, has different peak positions may be attributable to several causes including: that the core surface is coated during cladding with a thin film of cladding material due to the small clearance caused by the thickness of the photomask, bringing about light scattering; that light leakage occurs due to the changes in optical propagation modes caused by the difference in the refractive index difference (Δn) of UV resin; and that the core

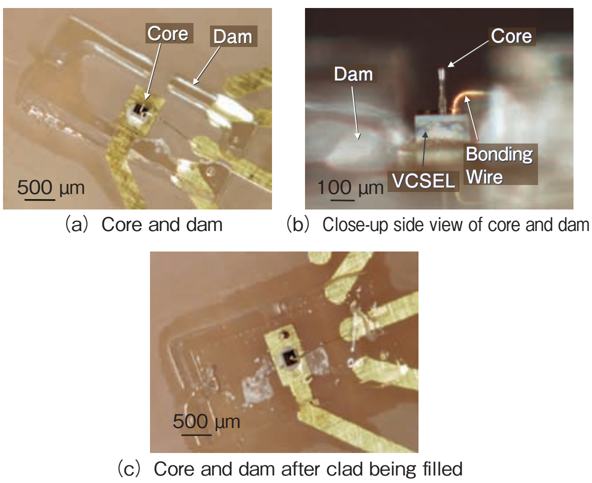


Figure 6 External views of prototyped optical interconnector.

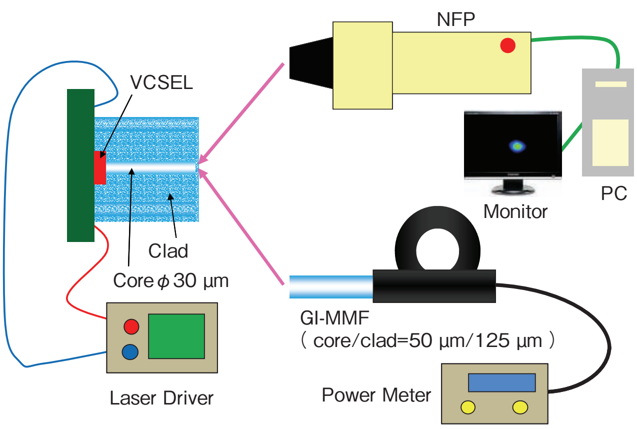


Figure 7 Measuring system.

possibly becomes inclined during the process of clad formation. After all, however, considering that the proposed optical interconnector has a peak optical output within the core diameter of 30 μm, the optical interconnector is functioning as an optical waveguide.

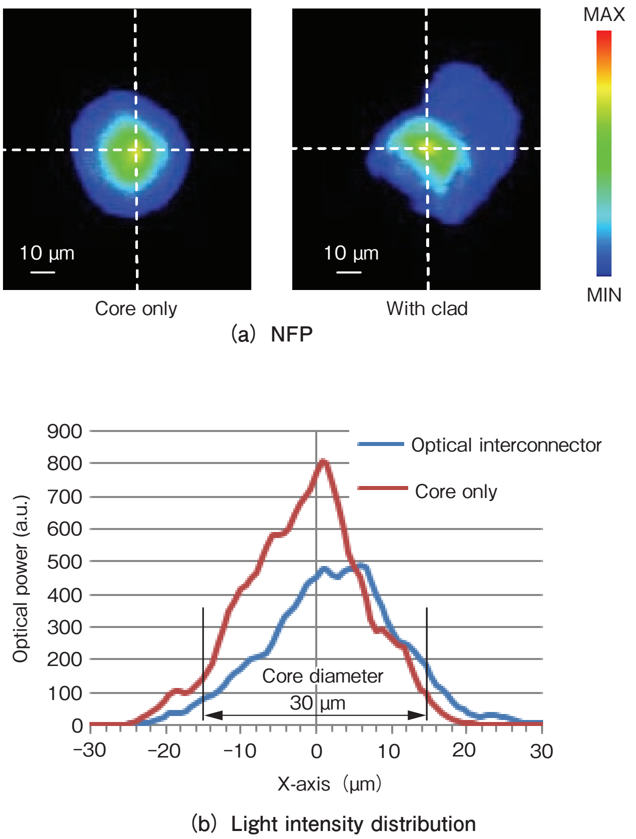


Figure 8 NFP and light intensity distribution.

Next, the *I-L* characteristics were evaluated using a GI-MMF (core/clad=50/125 μm). Measurements were carried out after adjusting the position of the fiber to obtain a maximum coupling efficiency. The measured objects were an optical interconnector with core only for purposes of comparison, an optical interconnector with cladding, and an elemental VCSEL. Figure 9 shows the results of *I-L* characteristics measurement. The results show that the optical interconnector with cladding results in an optical output that is comparable to, but slightly lower than, that of the optical interconnector with core only. This decrease in optical output may be attributable to, as mentioned before, several causes including: that the core surface is coated with a thin film of cladding material, bringing about light scattering; that light leakage occurs due to the changes in optical propagation modes caused by the difference in the refractive index difference (Δn) of UV resin, resulting in an increase in coupling loss with the GI-MMF; and that the core possibly becomes inclined during the process of clad formation. Comparison of optical output between the optical interconnector and elemental VCSEL shows that the output of the former has been significantly improved. This may be attributable to such causes that the waveguide formed on the light emitting surface of the VCSEL supports radiation-less light propagation that is less sensitive to the environment, and that the waveguide reduces the effects of light reflection at the interface between the light emitting surface and air, thereby increasing the light intensity. As stated above, the effectiveness of the optical interconnector proposed here has been confirmed.

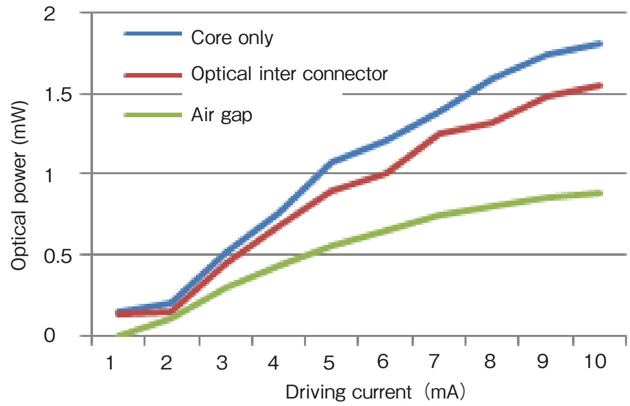


Figure 9 *I-L* curves.

Next, the positional tolerance for 1-dB down optical coupling efficiency was measured while shifting the GI-MMF in the X-axis direction. The results are shown in Figure 10. The positional tolerance for 1-dB down optical coupling efficiency of -15/+14 μm was obtained, confirming that the optical interconnector proposed has a broad positional tolerance.

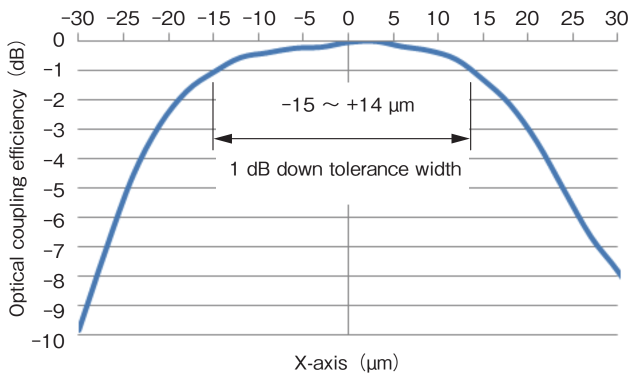


Figure 10 Positional tolerance.

5. ANALYTICAL STUDY OF OPTICAL COUPLING EFFICIENCY

In order to validate the coupling structure between the optical module and optical wiring board as proposed in Figure 4, positional tolerance in optical module-to-module coupling was analyzed using the ray tracing technique. The analytical model is shown in Figure 11. The analysis was carried out under the assumption of: refractive index of resin for core: 1.569; that for clad: 1.542; and radiation angle of light source: 20°. Figure 12 shows the result of analysis. The result shows a broad positional tolerance for 1-dB down coupling efficiency of -19/+19 μm, confirming the superior potential of this optical module.

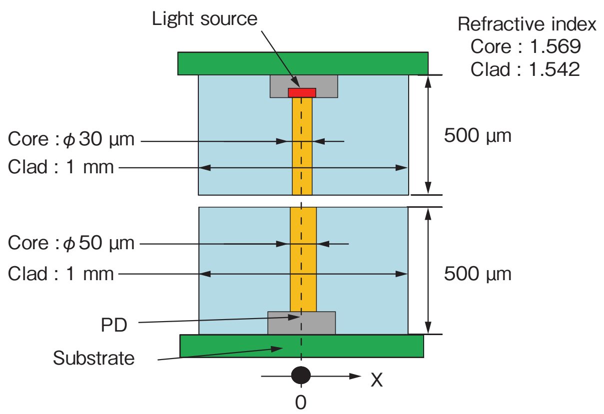


Figure 11 Analysis model.

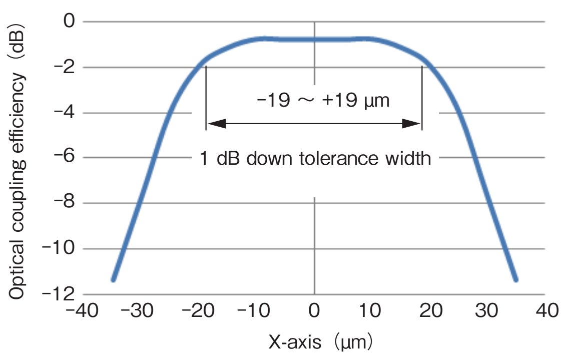


Figure 12 Analysis result.

6. CONCLUSION

We have proposed an optical interconnection structure capable of high-efficiency connection between, and mounting of, optical devices and optical waveguides, and, using ultraviolet curable resins, demonstrated this technology by fabricating an optical interconnector on an optical module that is provided with optical devices. Moreover, the optical characteristics of the structure have been measured and analyzed, thereby validating the effectiveness of this technology, in which an optical interconnector is mounted on the light-emitting and -receiving surface of the optical device in the module and on the optical port of OE-PWB. Furthermore, the connecting structure for optical wiring board has been studied using this optical interconnector, and it has been confirmed that the structure has a broad positional tolerance in alignment.

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