1.3-μm Range Vertical-Cavity Surface-Emitting Laser (VCSEL) Module

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ABSTRACT We have developed an optical module using a vertical-cavity surface-emitting laser (VCSEL) chip based on a new material—GaInNAsSb and having a lasing wavelength in the 1300-nm band. This module has a structure that takes full advantage of the potential of this VCSEL chip, while eliminating components such as the lens, isolator, etc. Use of a passive alignment assembly structure using the original surface mounting (assembly) and high-precision molded plastic package makes for easier assembly, achieving this low-cost, ultra-compact (mini-TOSA size) module. The characteristics obtained include coupling efficiency to single-mode fiber of above 60 % lensless, optical output power of −5 dBm or better, and 2.5 Gbps 20-km isolatorless signal transmission has been confirmed. This module will in future be applicable in compact transceivers (SFF, SFP, XFP and other standards), for which market growth is anticipated.

1. INTRODUCTION

Optical modules having as their light source a VCSEL chip are already on the market in an 850-nm version for short-haul multi-mode transmission in data communications. And development work is actively under way at the present time on 1300-nm VCSEL chips for medium- and long-haul single-mode transmission, primarily for telecommunications applications.

Furukawa Electric has in the past developed Fabry-Perot (FP) and distributed feedback (DFB) surface-emitting lasers for medium- and long-haul single-mode transmission applications, and has introduced the related modules commercially [1)~4)].

We have long been engaged in VCSEL chip development, and for 1300-nm single-mode transmission we have embarked on the use of GaInNAsSb, a new and proprietary material system that upgrades crystal quality and characteristics.

Currently, within the growth in demand for access systems, Ethernet, etc., there is a need for the requisite system components (transceivers, etc.) to be lower in cost and more compact, together with a trend toward standardized specifications. The same is true of the laser light sources for optical modules. For example there will be demand for large numbers of smaller, lower-cost optical module light sources that can be incorporated into small form factor (SFF) and small form factor pluggable (SFP) transceiver modules for 2.5-Gbps transmission, or XFP (XFPMSA.org standard) transceiver modules for 10-Gbps transmission, which, it is expected, will become the mainstream of compact transceiver modules.

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Here we report on the development of a module of a size for a mini-transmitter optical subassembly (mini-TOSA) using a 1300-nm VCSEL chip, and capable of being mounted in a compact transceiver.

The development of the VCSEL chip and module reported here has been carried out with the assistance of funding for commercialization and development for fiscal year 2002 from the New Energy and Industrial Technology Development Organization (NEDO).

2. VCSEL CHARACTERISTICS & DEVELOPMENT TARGETS

2.1 Characteristics

Light sources for optical modules using laser diode chips have in the past used FP or DFB laser chips, which emit light from the edge of the chip. In VCSELs, by contrast, a mirror and an active layer are deposited perpendicular to the wafer surface during crystal growth to form a resonance cavity, so that light is emitted vertically from the wafer surface. Since the planes of optical emission are aligned on a single surface of the wafer, it is easy to achieve multi-channel arraying of light sources. Further, edge-emitting lasers have had to be cut and tested individually, whereas with the VCSELs testing can be done in the wafer state.

In addition the optical beam emitted is cylindrical in shape, so that the mode field diameter (MFD) can be made about the same as the optical fiber size of 7 to 9 μm. Thus in designing a module the coupling efficiency with the fiber can be increased, so that the lens that was formerly needed can be eliminated. It has the further advantage that, being robust with respect to returned light from the optical circuitry, no isolator is needed.

Accordingly an optical module light source using a VCSEL chip can be made at lower cost than those using a conventional edge-emitting laser.

2.2 Development Targets

At the outset of the project to develop a VCSEL module, the following targets were set:

To obtain characteristics equivalent to a DFB laser module, and support interchangeability with it.

(1) To take advantage of the VCSEL and eliminate both lens and isolator.

(2) To achieve mini-TOSA size (OD of 4 mm or less) to allow mounting in an SFF or SFP transceiver module.

(3) To comply with SONET/SDH standards for 2.5-Gbps transmission, OC-48/STM-16 and S16.1.

(4) To eliminate high-cost components and develop a cheaper, simpler assembly method, and achieve a fabrication cost one-third that for DFB laser modules.

The SONET/SDH standards referred to in (3) are shown in detail in Table 1. The S16.1 standard is for a transmission distance of 15 km, and L16.1 is the standard for 40 km. Obviously the target was L16.1 for long-distance transmission but this simultaneously would require a higher optical output and would greatly depend on the optical power of the VCSEL. For this reason we initially set ourselves the goal of satisfying S16.1, with a high lensless coupling efficiency of above 60% for the module.

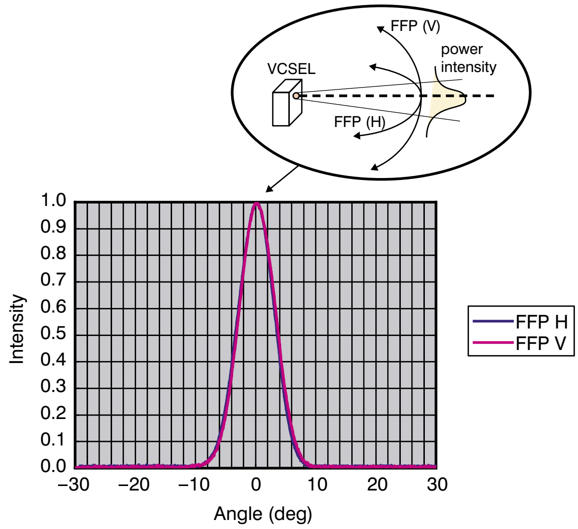


Figure 1 Typical far-field pattern of VCSEL chip.

3. BASIC CONSIDERATIONS

3.1 Coupling between VCSEL and Optical Fiber

3.1.1 Far-field Pattern for VCSEL Chip

Figure 1 shows a typical far-field pattern (FFP) for the 1300-nm VCSEL chip developed in this work.

The MFD of a conventional edge-emitting laser depends on the design but in general is an oval in shape, 1 to 3 μm in diameter.

Table 1 Communications parameters specified for ITU-T G.957 optical interface SDH.

Digital signal Nominal bit rate	bit/s	STM-16 2.488G	
Application code		S-16.1	L-16.1
Distance	km	15	40
Operating wavelength range	nm	1260 ~ 1360	1280 ~ 1335
Transmitter at reference point S			
Source type	SLM	SLM	SLM
Spectral characteristics			
-maximum RMS width	nm	—	—
-maximum −20dB width	nm	1	1
-minimum side mode suppression ratio	dB	30	30
Mean launched power			
-maximum	dBm	0	3
-minimum	dBm	−5	−2
Minimum extinction ratio	dB	8.2	8.2
Optical path between S and R			
Attenuation range	dB	0 ~ 12	10 ~ 24
Maximum dispersion	ps/nm	NA	NA
Minimum optical return loss of cable plant at S, including any connectors	dB	24	24
Maximum discrete reflectance between S and R	dB	−27	−27
Receiver at reference point R			
Minimum sensitivity	dBm	−18	−27
Minimum overload	dBm	0	−9
Maximum optical path penalty	dB	1	1
Maximum reflectance of receiver, measured at R	dB	−27	−27

The FFP or distribution pattern for VCSEL emission forms concentric circles, and in the example shown in Figure 1, at a bias current of 6.0 mA (bias 2.3 V) has a FWHM of 9.8°, I/e² of 11.7° and MFD of up to approximately 9.0 μm, thereby yielding a higher optical coupling level than edge-emitting lasers with smaller MFD. That is to say, the closer the spot size of the VCSEL is to the MFD of the optical fiber, the lower the optical coupling loss with the fiber will be, making it unnecessary to have the lens that is required with an edge-emitting laser module.

Figure 2 shows the distribution of the coupling tolerance of a butt joint between a VCSEL and a single-mode fiber. Since the VCSEL and optical fiber MFDs form concentric circles, the coupling tolerance distribution is the shape of concentric circles.

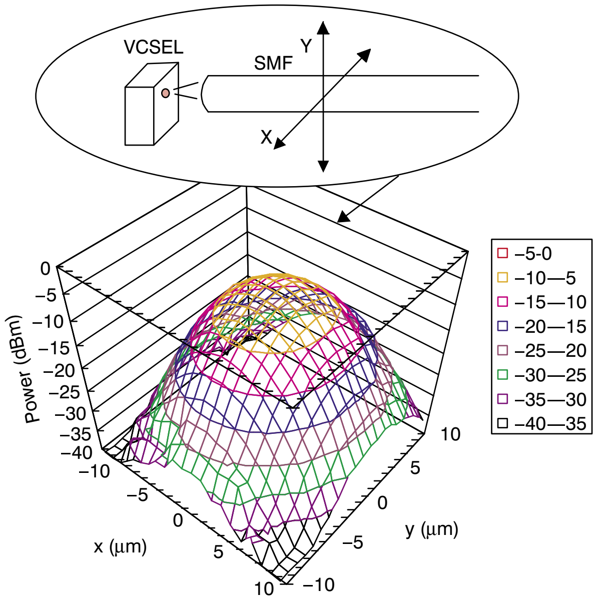


Figure 2 Coupling tolerance between VCSEL and single-mode fiber.

3.1.2 Simulation of Optical Coupling between VCSEL and Fiber

In designing the module a simulation was run of the relationship of the optical coupling efficiency (optical coupling loss) between the VCSEL and a single-mode fiber, with the distance and positional displacement between the VCSEL and the fiber as parameters. The amount of positional displacement corresponds to the component precision of the module and the component mounting precision during assembly. Since we have presupposed a decrease in costs and a smaller module, we considered a model in which VCSEL light impinges on the fiber without the use of a lens. Consideration was specifically given to two models: 1) the butt joint optical coupling model—a method of coupling the VCSEL and fiber in a butt joint; and 2) the reflection-type optical coupling model—a method of coupling the VCSEL and fiber taking advantage of reflection at the fiber end.

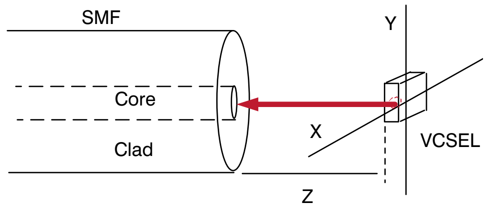


Figure 3 Butt-joint optical coupling model.

Let us refer to Figure 3 for the first of these—the butt joint optical coupling model. This is the model currently in general use, and because in using an edge-emitting laser it is necessary to interpose a lens between the laser chip and the optical fiber, optical coupling efficiency in the order of 60 % can be obtained.

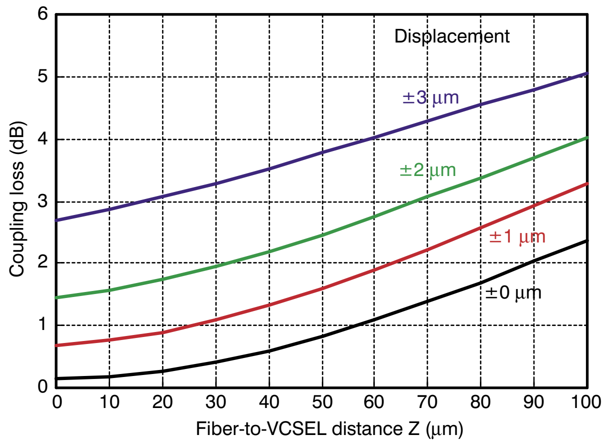


Figure 4 Simulation of butt-joint optical coupling model.

Figure 4 shows a simulation of the results for coupling in which no lens is used between the VCSEL chip and the optical fiber. These results are for a VCSEL with an MFD of 7.5 μm and an optical fiber with an MFD of 9.0 μm, with a plastic encapsulating material with a refractive index of 1.41 between the VCSEL and the fiber. They show the relationship between optical coupling loss and the distance Z from the optical fiber to the emitting plane of the VCSEL, with the positional displacement between the VCSEL and the fiber in the X,Y plane direction as a parameter. The shorter the distance Z and the smaller the displacement, the higher the optical coupling efficiency that can be obtained.

If we assume, for example, that fabrication of the optical module assembly can be accomplished with a distance Z of 5 to 15 μm and displacement of ±3 μm or less, an optical coupling efficiency of 50~95 % (optical coupling loss of 0.2~3.0 dB) can be obtained. With the VCSEL it is possible to obtain a high optical coupling efficiency without using a lens.

Next let us look at Figure 5, which shows the second or reflection-type optical coupling model, in which a single-mode fiber is polished at a 45° angle and a mirror surface is formed by deposition of gold or a dielectric multilayer filter, and VCSEL light is emitted directly from the side of the optical fiber without using a lens, achieving optical coupling between the mirror and the optical fiber core.

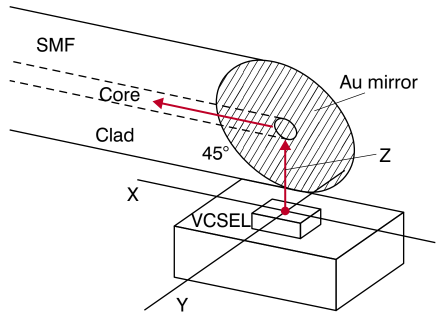


Figure 5 **Reflection-type optical coupling model.**

This model can also be applied in converting a cylindrical optical fiber into a planar waveguide. By adopting a module structure in which a VCSEL and optical fiber (waveguide) are mounted in a planar configuration we obtain the advantage of easier assembly than for the butt joint model.

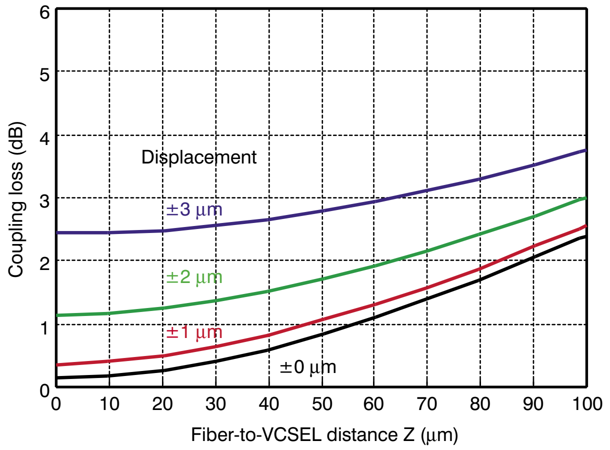


Figure 6 **Simulation of reflection-type optical coupling model.**

Figure 6 shows the result of simulation of the reflection-type optical coupling model, conducted, in the same way as for the butt-joint model, with a VCSEL MFD of 7.5 μm, fiber MFD of 9.0 μm and with a plastic encapsulating material with a refractive index of 1.41 between the VCSEL and the fiber. In assembling the module, if it is possible to achieve, for example, a distance Z between the light emitting surface of the VCSEL and the center of the fiber core of 67.5~77.5 μm (i.e., a distance from the outside of the fiber clad to the center of the core of 62.5 μm, to which is added the 5~15 μm from the light emitting surface of the VCSEL to the outer diameter of the fiber clad) and a positional displacement of ±3 μm or less in the XY plane between the VCSEL and the fiber, it will be possible to obtain an optical coupling efficiency of 48~74 % (optical loss of 1.3~3.2 dB). Thus the reflection-type optical coupling model also offers the promise that high optical coupling efficiency can be obtained without the use of a lens.

Figure 7 shows the results of a simulation of MFD dependence of coupling loss in a VCSEL for the reflection-type optical coupling model discussed above, conducted when the distance Z between the light emitting surface of the VCSEL and the center of the fiber core was 72.5 μm (distance from the light emitting surface of the VCSEL to the outer diameter of the fiber clad of 10 μm).

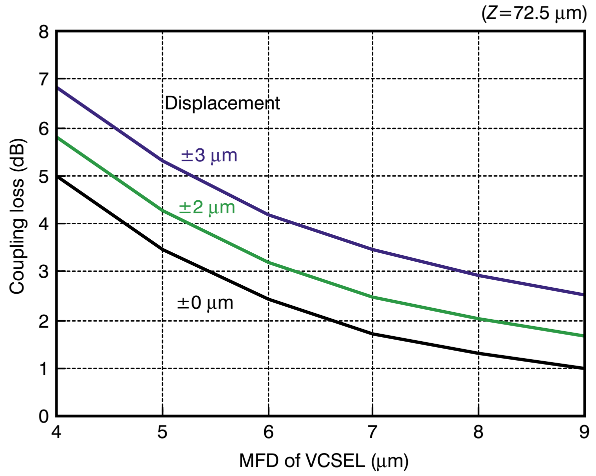


Figure 7 **Simulation of MFD dependence of coupling loss in VCSEL.**

It is possible to improve the optical coupling efficiency by bringing the MFD of the VCSEL closer to that of the fiber (~9.0 μm) and by reducing the amount of positional displacement. For example if an optical module using a VCSEL with an MFD of 8.0 μm could be assembled with a positional displacement of ±2 μm, it would be possible to achieve an optical coupling efficiency of 62 % (optical coupling loss of 2.1 dB).

Thus it will be seen that by achieving a VCSEL MFD of about 8 μm or more, it will be possible to get a distance to the optical fiber of about 10 μm or less and a positional displacement of about ±3 μm, using either the butt-joint or the reflection-type model, thereby obtaining an optical coupling efficiency as good as or better than that of conventional edge-emitting laser modules without the use of a lens.

In terms of the reflection-type model, the distance from the VCSEL to the fiber core must take account of the thickness of the clad, and the optical coupling efficiency will decrease accordingly. If, however, it is possible to reduce clad thickness without changing the MFD, or to adopt a simplified assembly with a module structure in which the VCSEL and the optical fiber (waveguide) are surface mounted, paying attention to the reflection-type optical module will hold great significance.

3.2 Designing VCSEL Characteristics

Now let us proceed to a discussion of the characteristics required of the VCSEL chip. Assuming that a module could be assembled with a VCSEL-to-fiber optical coupling efficiency of 60 % (optical loss of 2.2 dB), it would, in order to satisfy the target specifications of the OC-48/STM-16 communications standard (2.5-Gbps, 15-km transmission), be necessary, as shown, for example in the simulation of L-I characteristics in Figure 8 with VCSEL chip threshold current of 3 mA and slope efficiency of 0.2 W/A, to achieve a single-mode laser output power of 1.4 mW at a bias current of 10 mA.

If then, with a module bias current of 7 mA, modulation is applied so that current amplitude reaches 5.9 mA_{p-p}, the extinction ratio of the optical module would be 8.2 dB and its average optical output power would be 0.48 mW (–3.2 dB), sufficient to satisfy OC-48/STM-16 (2.5-Gbps, 15-km transmission).

The VCSEL chip has been designed and fabricated to satisfy these requirements.

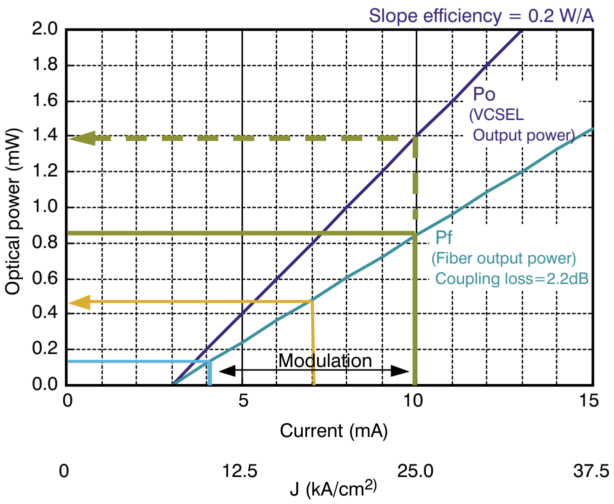


Figure 8 Simulation of L-I characteristic.

3.3 Module Design

Based on the above considerations we worked out and designed a module structure. In order to reach the development targets set forth above, we adopted a structure with a distance from the light-emitting surface of the VCSEL to the optical fiber of approximately 10±5μm and a positional displacement of approximately ±2μm, and could be assembled without alignment. As for the optical coupling of the VCSEL and fiber, we selected a reflection-type coupling model with a surface mounting module structure in which the components could be stacked one on top of the other like building blocks.

A molded plastic package was chosen for its ease of mass production and cost advantage. In order to reduce the distance from the light-emitting surface of the VCSEL to core of the optical fiber, we adopted a fiber with an outer diameter of 80 μm (40 μm from the outside of the clad to the center of the core), and an MFD of 9.0 μm. The part on which VCSEL light impinges was polished to form a mirror inclined at 45°, which was mounted on molded plastic with high-precision molded projections. As shown the structure is such that the end face of the optical fiber appears on the VCSEL side.

The VCSEL is high-precision mounted on a silicon optical bench (SiOB). The positional alignment between the VCSEL and the fiber was accomplished by two rail-shaped V-grooves formed in the SiOB and a two rail-shaped auto-alignment projections high-precision molded on the optical fiber side, making possible assembly without alignment [5), 6)].

The distance from the VCSEL light-emitting surface to the optical fiber depends primarily on variations in VCSEL chip thickness, and the amount of positional displacement depends primarily on precision of mounting between the VCSEL and the SiOB. We adopted a module structure that could be fabricated so that these values were ±5 μm and ±2 μm respectively. No lens or isolator was used.

Assembly is easy, by means of surface stacking of a molded lower plastic package with insertion molded lead frame circuitry, monitor photodiode (MPD), SiOB on which is mounted the VCSEL, and high-precision molded upper plastic package with integral fiber.

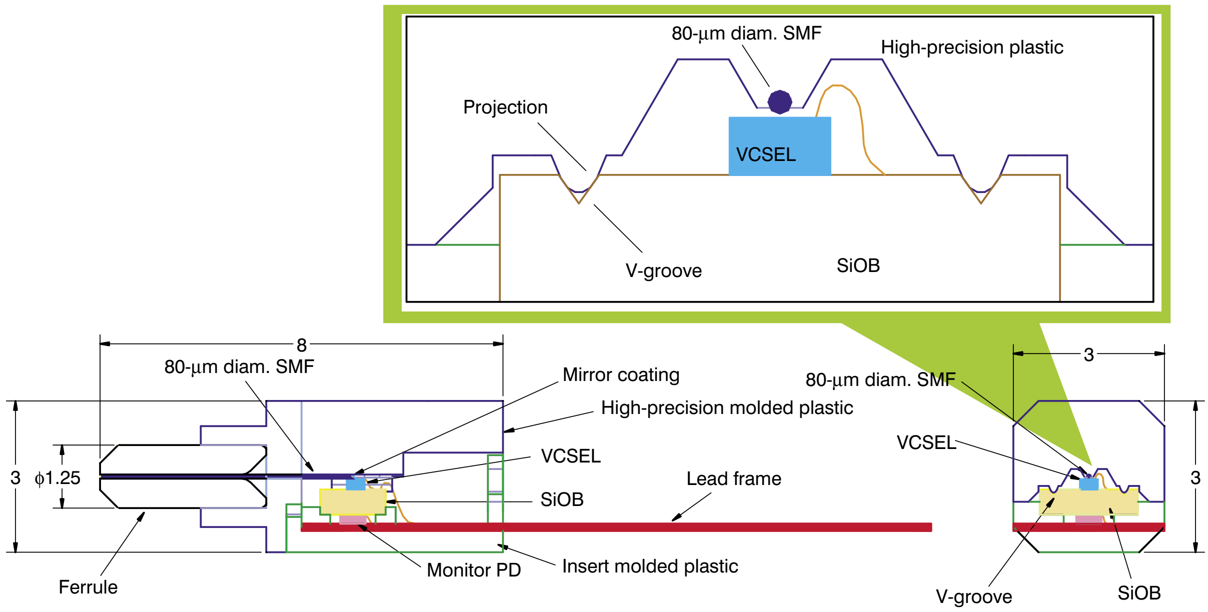


Figure 9 Schematic of VCSEL module.

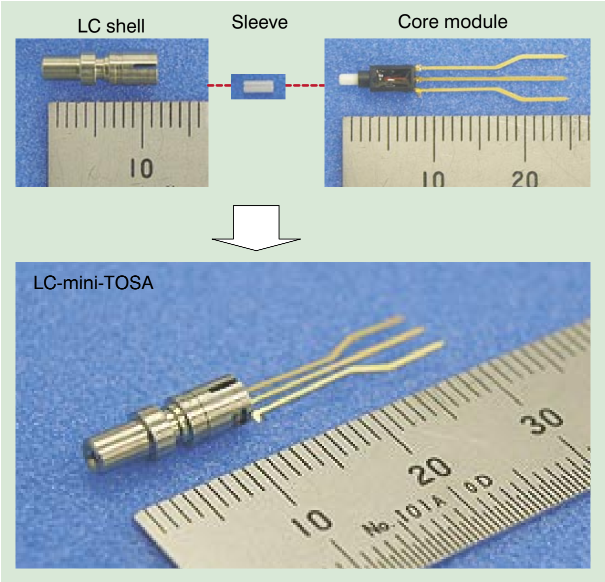


Figure 10 LC mini-TOSA VCSEL module prototype.

4. PROTOTYPE FABRICATION AND EVALUATION

Based on the basic studies and module design work described above, we proceeded to prototype fabrication. As Figure 10 shows, the prototype comprises an LC shell enabling LC connection, a connection sleeve for holding the ferrule, and the VCSEL core module designed as described above. The module is of the extremely compact mini-TOSA size, measuring 4 mm in diameter by 12 mm in length (not including the leads). Instead of the LC shell, an MU shell may also be used, enabling MU connection.

Let us now turn to the results of evaluation. Figure 11 shows the L-I characteristics and optical coupling efficiency of the VCSEL module at room temperature.

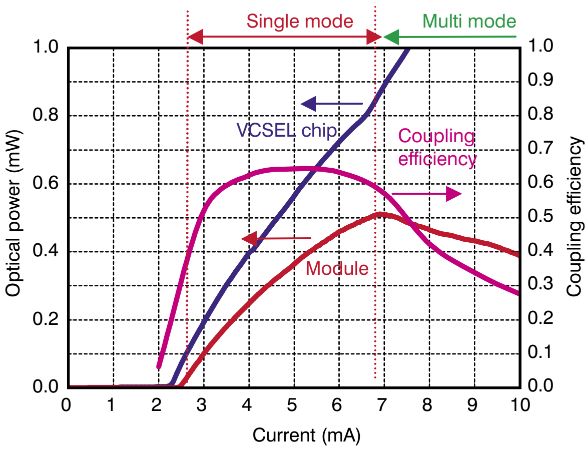


Figure 11 L-I characteristics and optical coupling efficiency of VCSEL module.

The VCSEL chip used had an MFD of 8 μm and a center wavelength of 1246 nm. The prototype module had a threshold current of 2.5 mA, and a single-mode maximum optical output power of 0.51 mW at 6.9 mA. The optical coupling efficiency of the module achieved the target value of above 60 %. It was found that in multi-mode lasing the coupling efficiency was lower than that of a single-mode fiber.

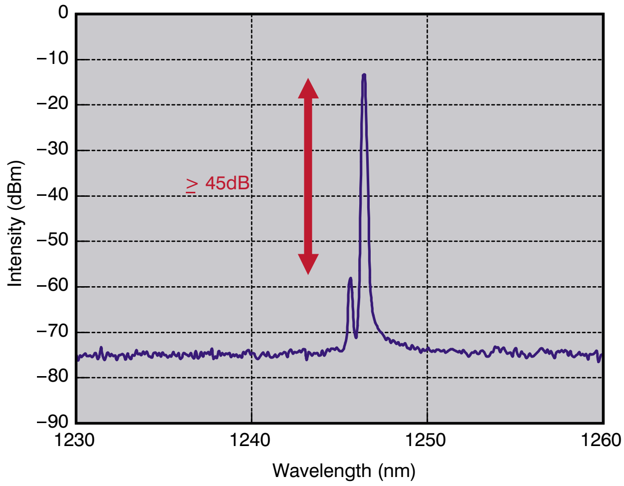
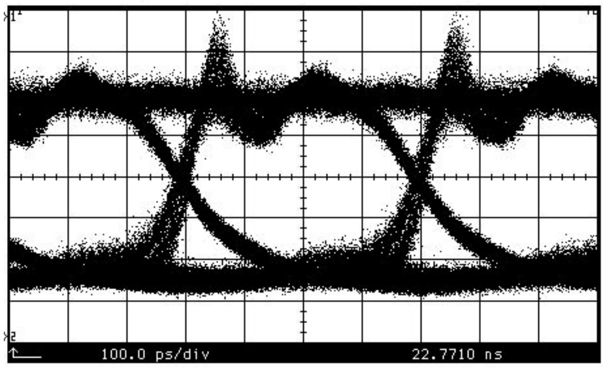


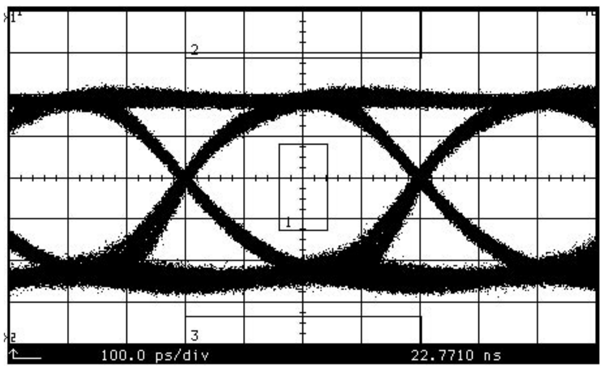
Figure 12 Lasing spectrum at If = 6 mA.

Figure 12 shows the lasing spectrum at room temperature and a current If of 6 mA. Excellent single-mode lasing was obtained—center wavelength 1246 nm and side-mode suppressed ratio (SMSR) of 45 dB or better.

Figure 13 shows the eye diagram for a transmission rate of 2.5 Gbps. At a bias current of 5 mA a satisfactory pattern was obtained, with an average output power of −3.7 dBm and an extinction ratio of 8.2 dB



a) Filter (Bessel Thomson) off



b) Filter (Bessel Thomson) on

Figure 13 2.5-Gbps eye diagram (mask margins 1.9%).

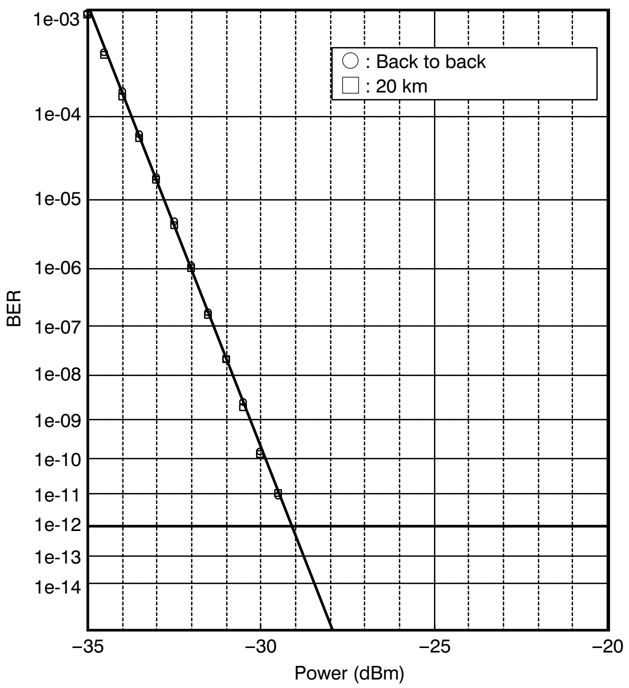


Figure 14 BER at 2.5 Gbps.

Figure 14 shows an evaluation of the bit error rate (BER) at 2.5 Gbps, extinction ratio of 9.5 dB and average output power of −4.1 dBm. Transmission was carried out with back-to-back connection, as well as at a distance of 20 km.

Even in 20-km transmission, characteristics equaled those in back-to-back connection. Excellent transmission results were obtained, with a dispersion power penalty for 20-km transmission of 0.1 dB or less and a minimum sensitivity (at BER = 10^{-12}) of −29 dBm.

By these means it was confirmed that the requirements of OC-48/STM-16 (S16.1) for 2.5 Gbps, the communications standard which we targeted, were satisfied despite the fact that the wavelength was slightly shorter, with an average output power of −5.0 dBm≤ Pf ≤0 dBm and a transmission distance of 15 km.

5. CONCLUSION

A prototype mini-TOSA module has been fabricated without the use of lens or isolator using passive alignment optical coupling technology based on a high-precision plastic molding. The optical coupling efficiency achieved between the VCSEL and a single-mode fiber was above 60 %. Further, 20-km transmission was achieved at optical output of −4.1 dBm, 2.5 Gbps in room temperature operation.

With future improvements in VCSEL chip characteristics, we intend to proceed with increasing single-mode lasing output power at temperatures as high as 85°C as well as realizing long-wavelength operation at 1260 nm or longer, and to confirm reliability.

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