SUMMARY Passive optical network topology has been widely adopted in access networks due to its low-cost and yet flexible network structure. To further promote the passive optical networks, the cost reduction of optical modules is critical. Relatively expensive combination of a conventional index-coupled distributed feedback laser diode (IC-DFB-LD) and an optical isolator is commonly used for passive optical networks with transmission distance more than 30 km. Although gain-coupled DFB-LDs (GC-DFB-LD) have been widely investigated in the hope of eliminating the isolator in optical modules, their limited output power keeps them from practical use in passive optical networks. In this paper, we describe the development of 1.31 μm and 1.49 μm gain-coupled distributed feedback lasers with high output power and optical feedback tolerance for isolator-free optical modules in access networks. The relative intensity noise (RIN) degradation was well suppressed below –120 dB/Hz at ~3.5 dB optical feedback in the temperatures range from 0°C to 85°C from both 1.31 μm and 1.49 μm GC-DFB-LDs. Optical feedback tolerance of 1.31 μm and 1.49 μm GC-DFB-LDs were improved by more than 6 dB and 4 dB as compared with conventional IC-DFB-LDs. Dispersion power penalty after over 30 km transmission at 1.25 Gbps were achieved less than 0.3 dB and 0.7 dB under –15 dB optical feedback conditions. The proposed 1.31 μm GC-DFB-LD prototypes experimentally demonstrated 14 mW output power with 5000-hour operation at 85°C. Our devices are found to fully comply with IEEE 802.3ah standard and seem to be promising for the low-cost optical modules in long-reach access network applications. The details of the device structure as well as transmission experiments are also reported.

key words: gain coupled distributed feedback lasers, optical feedback, optical feedback semiconductor lasers

1. Introduction

Passive optical network (PON) is a very cost-effective network topology since many subscribers share the common single-mode optical fiber connected to an optical line terminal (OLT). The addition of subscribers is easily realized by connecting the optical fiber at a coupler near by the subscribers. The above advantages make PON an attractive candidate to realize low-cost and yet flexible access networks.

PONs have been proposed and implemented in a number of standards. The ITU-T/FSAN-based first-generation asynchronous transfer mode (ATM)-PON (A-PON) and broadband PON (B-PON) are ATM-based systems. The gigabit-PON (G-PON, successor of B-PON) supports both ATM and other traffic protocol by using time division multiplexing (TDM) and generic framing procedure. Ethernet-PON (E-PON) handles information traffic based on Ethernet protocol and provides sufficient bandwidth for emerging services, such as Internet Protocol (IP) TV, video-on-demand (VoD), IP telephone, video conferencing.

All PONs are single-channel systems consisting of a single upstream wavelength channel of 1.31 μm and a single downstream wavelength channel of 1.49 μm. Given the exponentially increasing number of subscribers and ever increasing data traffic demand, the transmission bit rate of PONs are likely to be upgraded in the very near future.

In North America, the majority of PON deployments are based on ITU-T/FSAN-group B-PON and are slowly migrating toward G-PON. While in Asia (mainly Japan and Korea), IEEE-based gigabit Ethernet (GE)-PON has been deployed. Both G-PON and GE-PON services are, based on best effort/TDM and require relatively high transmission bit rate up to 1 Gbps. GE-PON system is divided into PX-10 and PX-20 according the transmission distance of 10 km and 20 km, respectively. Fabry-Perot laser diodes (FP-LDs) and distributed-feedback laser diodes (DFB-LDs) are used as light sources for PX-10 and PX-20, respectively. Although low-cost FP-LD is ideal for PON applications, its relatively poor transmission characteristics limit its use for PX-10 only [1]–[4].

To further encourage the adaptation of PX-20 system, the cost reduction of DFB-LD is crucial. In order to reduce the optical module cost, uncooled DFB-LDs have been developed for the temperature range between ~40°C and over 85°C [5]–[7]. However, conventional index coupled DFB-LDs (IC-DFB-LD) are sensitive to the external optical feedback and require additional optical isolator (ISO) to shut out reflection return light for stable operation.

Since PON system has many optical fiber end facets that generate optical reflections, DFB-LDs with optical reflection tolerance are critically needed to improve the relative intensity noise (RIN) characteristics for the reliable network operation [8]–[10].

The Gain-coupled laser diodes (GC-DFB-LD) have been recognized to have robust RIN characteristics against optical feedback [11]. The optical modules without ISOs are very cost-effective because the ISO is an especially expensive device in the optical module. While the RIN characteristics were improved, the output optical power level of GC-DFB-LD is not high enough to be used for PON applications [12], [13].

In this paper, we successfully demonstrate the GC-DFB-LDs with improved output power and high optical feedback tolerance complying to the standard defined in IEEE 802.3ah [14]. In the next chapter, we will report the
details of the structure and experimental results of ISO-free GC-DFB-LD of 1.31 \( \mu m \) for optical network unit (ONU) applications. GC-DFB-LDs lasing at 1.49 \( \mu m \) for optical line terminals (OLTs) are also discussed in chapter 3.

2. Device Structure and Characteristics of GC-DFB-LD for ONU

2.1 Device Structures and Characteristics

Figure 1 shows the schematic diagram of a GC-DFB-LD with buried hetero structure grown by three-step metal organic vapor phase epitaxy (MOVPE) growths. The 1.3 \( \mu m \)-strain compensated multiple quantum wells (SC-MQW) consists of a 30-nm thick InGaAsP (\( \lambda_g = 1.3 \mu m \)) waveguide layer for optical absorption and 10 periods of 0.8% compressive strained InGaAsP (\( \lambda_g = 1.4 \mu m \)) quantum wells with 0.4% tensile strained InGaAsP (\( \lambda_g = 1.1 \mu m \)) barriers, sandwiched between 25-nm thick lattice matched InGaAsP (\( \lambda_g = 1.1 \mu m \)) as separated confinement layers. The device length was a 350 \( \mu m \). The antireflection (AR) coating was deposited on the front facet, while the high-reflection (HR) coating was provided on the rear facet for high slope efficiency characteristic. The grating pattern on n-InP substrate was formed by interference exposure lithography and wet chemical etching. The grating depth was optimized to control the coupling coefficient (\( \kappa \)). The \( \kappa \) of the GC-DFB-LDs were calculated from oscillation spectra wave forms in condition of under threshold current [15], [16]. The estimated \( \kappa \) and \( \kappa_{gain}/\kappa_{index} \) of the GC-DFB-LD were around 40 cm\(^{-1}\) and 2%, respectively.

Figure 2 shows the temperature dependence of the output power characteristics as a function of injected current under the CW operation for the temperatures between 0\(^\circ\)C and 90\(^\circ\)C. The threshold currents and the slope efficiencies were 4.5 mA and 0.44 W/A at 25\(^\circ\)C, and 19.2 mA and 0.20 W/A at 85\(^\circ\)C, respectively. The characteristic temperature and the degradation in the slope efficiency were estimated to be 44 K and −3.4 dB, respectively. We fabricated the GC-DFB-LD sample that has similar optical output characteristics as conventional IC-DFB-LD by optimizing the waveguide layer for optical absorption, MQW structures and the mesa width of BH structure [17]. Stable single mode operation maintaining side mode suppression ratio (SMSR) exceeding 40 dB was experimentally demonstrated over 15 mW of the output power at the temperature up to 90\(^\circ\)C. We confirmed that the most of the GC-DFB-LDs were oscillating at the long wavelength side of the stop band. This is evidence that the fabricated GC-DFB-LD oscillated with in-phase. The in-phase oscillation of the GC-DFB-LD is expected to contribute to the stability of the single mode operation.

The GC-DFB-LD was packaged in a TO-CAN coaxial module without optical ISO. The coupling efficiency between the GC-DFB-LD chip and the optical single mode fiber was estimated to be about 40%. Figure 3 shows a test system setup to evaluate the optical feedback tolerance of the fabricated GC-DFB-LD consisting of a polarization controller (PC), an optical 3-dB coupler, a variable optical attenuator (ATT), a power meter, and an HR terminator.

First we measured the RIN characteristics with optical feedback with various temperatures. The amounts of optical feedback power were monitored by the power meter shown in Fig. 3. The results were compared with those of conventional IC-DFB-LDs with the same MQW structures as the GC-DFB-LD. As for the characteristics of our conventional IC-DFB-LD, the threshold currents and the slope efficiencies were 5.9 mA and 0.46 W/A at 25\(^\circ\)C, and 22.6 mA and 0.23 W/A at 85\(^\circ\)C, respectively. The module output powers were set constant at the fiber output power of 4 dBm. Figure 4 shows the dependence of the RIN values at 1.25 GHz with the optical feedback power. For the conventional IC-
DFB-LDs, the RIN values degraded over −120 dB/Hz when the optical feedback power exceeded −10 dBm. In contrast, the RIN degradation of the GC-DFB-LD was well suppressed below −120 dB/Hz in the operating temperature range from 0°C to 85°C, even when the optical feedback power was increased up to −4 dBm. This result indicates that the GC-DFB-LD is less sensitive to the optical feedback by 6 dB in comparison with conventional IC-DFB-LDs. The result also indicates that the RIN value better than −120 dB/Hz can be secured in our GC-DFB-LD even with the optical feedback level of −8 dB. This condition fully complies with the stringent requirement of IEEE802.3ah and experimentally demonstrates that the fabricated GC-DFB-LD without ISO can realize low-cost PX-20 systems.

2.2 Transmission Characteristics

We carried out 1.25 Gbps direct modulation experiments with non-return-to-zero (NRZ) signal under $2^{23} − 1$ pseudorandom bit sequence. The TO-CAN coaxial modules were set on a circuit board with a thin-film 50-Ω resistance in series to match the impedance. The applied modulation voltage was controlled with the optical output average power of 3 dBm and the dynamic extinction ratio of 6 dB. The eye patterns were measured using a fourth-order Bessel-Thomason receiver response with $f_r = 0.9375$ GHz. Those results of back-to-back eye diagrams are shown Fig. 5(a) the GC-
DFB-LD without optical feedback (OFB) at 25°C, (b) with −15 dB OFB at 25°C, (c) with −15 dB OFB at 85°C, and (d) the IC-DFB-LD with −15 dB OFB at 85°C. Clear eye opening was maintained with −15 dB OFB at 85°C.

Transmission characteristics under −15 dB optical feedback were measured for 30 km transmission without optical isolator. Bit error rates are shown and compared in Fig. 6(a) for GC-DFB-LD at 85°C and (b) for IC-DFB-LD at 85°C, respectively. Error free transmissions were successfully achieved by both GC-DFB-LD and IC-DFB-LD. The dispersion power penalty is defined as the difference in averaged received power at 10−12 of BER, between back-to-back and after the transmission. In the case of the GC-DFB-LD, the dispersion power penalty after 30 km transmission was less than 0.3 dB under −15 dB OFB at 85°C. In contrast, the dispersion power penalty of the IC-DFB-LD was 1.1 dB with the same conditions above. The power penalty of the GC-DFB-LD after 30 km transmission was improved as compared with the IC-DFB-LD.

The dispersion power penalties of the eight GC-DFB-LDs and the five IC-DFB-LDs are plotted with three different transmission conditions in Fig. 7. For eight modules of the GC-DFB-LDs, dispersion power penalty were found to be less than 0.3 dB at each temperatures under all conditions. The distributed value of dispersion power penalty is small and stable. A mean and a standard deviation were 0.16 dB and 0.08 dB, respectively. While a maximum dispersion power penalty of the five IC-DFB-LDs in all conditions was 1.1 dB. A mean and a standard deviation of dispersion power penalty were 0.63 dB and 0.25 dB, respectively. The reason of the power penalty deterioration for the IC-DFB-LDs at 85°C is not clearly understood. However, we deduce that the deterioration power penalty of IC-DFB-LD is affected by the instability of the oscillation mode.

A series of long-term aging tests were conducted on the forty-eight GC-DFB-LDs after the burn-in test. Figure 8(a) shows the driving current trace of the aging test at the ambient temperatures of 85°C. The lasers were operated at the constant output power level of 14 mW and the operation currents were around 100 mA at 85°C. We set up the measurement at the output of 14 mW, because the optical power of more than 7 dBm is expected from the optical fiber of the module if we assume the coupling efficiency of 40% between the LD chip and the optical fiber. No significant increase in the driving current was observed for 5,000 hours of operation at 85°C, 14 mW. The failure criterion was set at 20% increase in operating current [18]. The lasers with the operating current increase proportional to the aging time have the median life estimated to be around $1.3 \times 10^5$ hours.
Figure 8(b) shows the average value of the fifteen GC-DFB-LDs after randomly chosen (closed circle) and the average value that was added three times the standard deviation (open circle) at the beginning, 2,000 hours and 5,000 hours. Excellent reliabilities are experimentally demonstrated for the GC-DFB-LDs based on our experimental results.

3. Device Structure and Characteristics of GC-DFB-LD for OLT

3.1 Device Structures and Characteristics

We made a slight modification in the MQW active layers for the 1.49 µm GC-DFB-LD for OLT applications as compared to the one already shown in Fig. 9. The 1.49 µm SC-MQW consisting of a 30-nm thick InGaAsP (λg = 1.49 µm) waveguide layer for optical absorption and ten periods of 0.8% compressive strained InGaAsP quantum wells with 0.4% tensile strained InGaAsP barriers, sandwiched between 25-nm thick lattice matched InGaAsP (λg = 1.1 µm) as separate confinement layers. The device length is 350 µm. The AR coating was deposited on the front facet, while the HR coating was provided on the rear facet.

Figure 10 shows the temperature dependence of the output power to the current characteristics under the CW operation at the temperatures between −40°C and 90°C. The threshold currents and the slope efficiencies were 4.6 mA and 0.30 W/A at 25°C, and 16.0 mA and 0.20 W/A at 85°C, respectively. The characteristic temperature and the degradation in the slope efficiency were estimated to be 45 K and −2.7 dB, respectively. Stable single mode operation maintaining SMSR exceeding 40 dB was obtained with the output power of more than 15 mW at the temperature up to 90°C. The estimated k and κ_{gain}/κ_{index} of the GC-DFB-LD were around 50 cm⁻¹ and 2%, respectively.

Figure 11 shows the optical feedback power dependence of the RIN values at 1.25 GHz. As for the characteristics of our conventional IC-DFB-LD for OLT, the threshold currents and the slope efficiencies were 7.1 mA and 0.38 W/A at 25°C, and 26.6 mA and 0.25 W/A at 85°C, respectively. For the conventional IC-DFB-LD, the RIN values exceed −120 dB/Hz when the optical feedback power is increased to −8 dBm. In contrast, the RIN degradation of the GC-DFB-LD is well suppressed below −120 dB/Hz at...
the operating temperatures from 0°C to 85°C, even when the optical feedback power is increased up to −4 dBm. Those results indicate that the GC-DFB-LD is less sensitive to the optical feedback by 4 dB in comparison with the conventional IC-DFB-LD. The results also indicate that the RIN value better than −120 dB/Hz can be secured for the GC-DFB-LD even with the presence of −8 dB-optical feedback.

3.2 Transmission Characteristics

We carried out 1.25 Gbps direct modulation experiments with NRZ signal under $2^{23} − 1$ pseudo-random bit sequence.

The TO-CAN modules were set on a circuit board with a thin-film 50-Ω resistance in series to match the impedance. The applied modulation voltage was controlled so that the optical output average power of 5 dBm and the dynamic extinction ratio of 6 dB were obtained. Back-to-back eye diagrams are shown in Fig. 12(a) without OFB, (b) with −15 dB OFB at 25°C, (c) without OFB at 85°C, and (d) with −15 dB OFB at 85°C. Clear eye opening was maintained with −15 dB optical feedback at 85°C. Transmission characteristics under −15 dB OFB were measured for 30 km transmission without ISO. Bit error rates were shown in Fig. 13(a) for the GC-DFB-LD at 85°C and (b) for the IC-DFB-LD at 85°C, respectively. The BER measurement of the GC-DFB-LD shows no error floor up to $10^{-12}$, and a small dispersion power penalty for 30 km transmission less than 0.38 dB at 85°C. On the other hand, the dispersion power penalty of the IC-DFB-LD showed the deterioration of 1.37 dB at 85°C. Figure 14 shows the dispersion power penalty of 30 km transmission at 1.25 Gbps at 0°C, 25°C, and 85°C as functions of optical feedback power with 3.0 dBm average output power under direct modulation. These experimental results clearly prove the transmission characteristics improvements realized by the 1.49 μm GC-DFB-LD.

4. Conclusion

We have proposed and experimentally demonstrated low cost isolator-free 1.31 μm and 1.49 μm GC-DFB-LD optical modules for the ONU and OLT of GE-PON (PX20) Access Network applications. Experimental results of the 1.3 μm and the 1.49 μm GC-DFB-LD proved their performance tolerance against external optical feedback, while exhibiting a low threshold current less than 20 mA and a slope efficiency as high as 0.20 W/A at 85°C. The optical feedback tolerance of the 1.31 μm and the 1.49 μm GC-DFB-LDs were improved more than 6 dB and 4 dB compared with that of the conventional IC-DFB-LD under −15 dB optical feedback condition. The transmission penalties over 30 km single mode optical fiber were found to be less than 0.3 dB and
0.7 dB under −15 dB optical feedback at 85°C, respectively. The 1.31 μm GC-DFB-LD also achieved high stable operation at a constant output power of 14 mW, over 5,000 hour at 85°C. The fabrication process of the proposed GC-DFB-LD is suitable for the low-cost chip production. We believe the newly proposed GC-DFB-LDs are promising candidates for the low-cost, isolator-free optical modules in the long reach PON applications.

References


Koji Nakamura received the B.E. and M.E. degrees in Electrical Engineering from Meiji University in 1990 and 1992, respectively. In 1992, he joined the Research and Development Laboratories, Oki Electric Industry Co., Ltd., Tokyo, Japan, where he has been engaged in research and development of III-V epitaxial growth technology, semiconductor lasers and optical devices for optical communication systems.

Satoshi Miyamura received the B.E. and M.E. degrees in Electrical and Computer Engineering and Computer Science from Kanazawa University in 2002 and 2004, respectively. In 2004, he joined the Research and Development Laboratories, Oki Electric Industry Co., Ltd., Tokyo, Japan, where he has been engaged in research and development of semiconductor lasers and optical devices for optical communication systems.

Hiromi Yaegashi received B.S. and M.S. degrees in applied physics from Tohoku University, Japan, in 1987 and 1989 respectively. In 1989, he joined Oki Electric Industry Co., Ltd., Japan, where he has been engaged in research and development of semiconductor waveguide devices and laser diodes for Optical communication systems. He is member of the Japan Society of Applied Physics.